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100 – Rosetta 1

100.01 – Comet 67P/Churyumov-Gerasimenko: First science results by Rosetta/OSIRIS

ESA's Rosetta mission arrived on August 6, 2014, at target comet 67P/Churyumov-Gerasimenko after 10 years of cruise. OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System) is the scientific imaging system onboard Rosetta. It comprises a Narrow Angle Camera (NAC) for nucleus surface and dust studies and a Wide Angle Camera (WAC) for the wide field coma investigations.

We present the first science results achieved by OSIRIS from the arrival at the comet throughout the mapping phase. The overview will cover surface morphology and activity of the nucleus as seen in gas, dust, and local jets.

Acknowledgements

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100.02 – Albedo and color variegations on 67/P Churyumov-Gerasimenko as observed by OSIRIS/Rosetta

The ESA Rosetta spacecraft is in orbit around its target 67/P Churyumov-Gerasimenko since August 6th 2014. The OSIRIS camera system composed of the NAC (Narrow angle camera) and the WAC (Wide angle Camera) has the capability to image both the nucleus and the coma at different wavelengths from 0.245 microns up to 1 micron using filters. First images acquired from 100km distance have already revealed a very complex shape and potential areas with photometric variations. From August 2014 to the Philae landing event in November 2014, the nucleus surface will be mapped at multiple resolutions (1m up to 20 cm), helping in the landing site selection process. Such images will be obtained at very different incidence, emission and phase angles, allowing us to correct from topographical features the photometric properties of the surface.

This presentation will focus on the albedo and colors variations, and on the spectral slopes derived from the OSIRIS filters. Of particular interest will be the identification of ices on the surface, and the mineralogical differences between different areas characterized by different topographic features.

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100.03 – The Strength of Comet 67P/Churyumov–Gerasimenko

Recent Rosetta images of comet 67P/Churyumov-Gerasimenko provide the highest resolution view to date of a cometary surface. 67P consists of two-quasi-ellipsoidal lobes connected by a narrow 'waist' of smooth material, similar to 103P/Hartley 2. Cliffs, roughly estimated at 200 to 700 m in height, bound a portion of this waist. These cliff faces are largely free of regolith, are sharply bounded along their upper edge, and outline a shallow concavity. This suggests that formerly overlying material has collapsed off the cliff face sometime in the recent past, although there do not seem to be definitive rubble features at the bottom of the slope. If this is the case, we can make an order of magnitude estimation of the underlying material's cohesive strength based on the height at which these cliffs collapsed.

The maximum stable height of a cliff is directly related to its cohesive strength, and inversely proportional to the local gravitational acceleration. Because 67P is small, spins relatively quickly, and likely has a low bulk density, the mass movement of material on its surface is driven by both gravitational and rotational potential differences. We model the surface acceleration of 67P using a very simple model of two connected spheres of typical cometary density (0.3 g cc^{-1}) that are rotating about a common center of mass at a period of 12.7 hours. In the region near the neck, the expected surface acceleration is $\sim 0.05 \text{ mm s}^{-2}$. Under these conditions, a vertical cliff 200-700 m high, with an angle of internal friction of 30° , will collapse if the supporting cohesion is less than 0.9-3.0 Pa. This estimate is comparable to the estimated strengths of other comets such as D/1993 F2 Shoemaker-Levy 9 (<6.5 Pa), 16P/Brooks 2 (<2 Pa), 81P/Wild 2 (>17 Pa), C/2012 S1 ISON (1-5 Pa). This is further evidence that comet nuclei are objects with astonishingly low strength, and are perhaps composed of cold powders bound only by van der Waals forces.

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100.04 – Millimeter and Submillimeter Observations of comet 67P/C-G with the MIRO Instrument

The Microwave Instrument for the Rosetta Orbiter (MIRO) makes millimeter and submillimeter observations of the nucleus and coma of Rosetta's target comet. This presentation summarizes the instrument and its observations, with details presented in later talks. MIRO makes continuum measurements at 190 and 563 GHz (1.6 and 0.5 mm) to study the thermal and electrical properties of the nucleus near-surface (depths from ~ 1 millimeter to 10 centimeters). MIRO also makes spectroscopic measurements of 8 lines near 560 GHz (H_2O , H^{217}O , H^{218}O , CO, NH_3 , and three CH_3OH transitions). The abundance, gas velocity, and temperature of those species are measured as functions of time and location. To interpret its data, the MIRO team has developed sophisticated nucleus and coma models. Our goal is to understand the dominant physical processes that create the coupled nucleus-coma system.

MIRO has clearly detected water in the coma since 6 June 2014 (heliocentric distance 3.9 AU). Water production varies both with location on the nucleus and time-of-day. We also see an overall increase in production as the comet approaches the Sun. At the time of this writing, only H_2O and H^{218}O have been detected by MIRO. Our analysis of spectral data uses a non-LTE coma model, accounting for the boundary layer at the nucleus, regions dominated by gas collisions, electron collisions, and radiative processes.

MIRO's continuum channels have detected the nucleus since 19 July 2014, and it has been spatially resolved since early August. Initial results are consistent with a very low thermal inertia surface, as expected for a porous, dusty layer. We expect to provide information on spatial variability of nucleus properties at the meeting. MIRO has developed a 3-D nucleus thermal/radiative model to assist in observation planning and interpretation.

In addition to its science objectives, MIRO provides information in support of spacecraft operations. Measurements help predict the gas drag on the spacecraft, and were used in determining the shape of un-illuminated regions of the

nucleus and in selecting possible landing sites.

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100.05 – Evolution of H₂O coma of comet 67P/Churyumov-Gerasimenko observed from the Microwave Instrument on the Rosetta Orbiter (MIRO)

As the Rosetta spacecraft approached its target comet 67P for its rendezvous early August 2014 and started scientific observations, the Microwave Instrument on the Rosetta Orbiter (MIRO) has observed the comet in two frequency bands at 190 GHz and 562 GHz. MIRO has a spectrometer connected to the 562 GHz receiver, designed to observe molecular lines of H₂O (including three oxygen isotopologues), CO, NH₃, and CH₃OH, which are volatiles emitted by the comet nucleus. The scientific goal of the spectral measurement is to assess the abundances and isotopic ratios of cometary volatiles, and to understand the spatial and temporal evolution of the activity. The first spectral line of comet 67P detected by MIRO is the H₂O rotational transition line at 556.936 GHz. It was first seen on June 6, 2014 at the heliocentric distance of 3.9AU and at the MIRO-to-comet distance of 360,000 km. Since the first detection, MIRO has regularly observed this line with a nadir mode and a coma-scanning mode while it approached the comet from >100,000 km to <100 km, allowing us to track the spatial and temporal evolution of water outgassing activity. In addition, MIRO detected the water isotopologue H₂18O line in July, 2014. The detected lines are analyzed with a Non-LTE radiative transfer model and an optimal estimation method to retrieve a H₂O outgassing rate, distribution, expansion velocity and gas kinetic temperature. In this paper, we will present the MIRO H₂O spectral line observations and the line analysis retrieval results, and discuss the implication on the temporal and spatial evolution of the water outgassing activity and distribution.

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100.06 – Inhomogeneity in composition and surface morphology implied from continuum observations of 67P/Churyumov-Gerasimenko with Microwave Instrument on the Rosetta Orbiter (MIRO)

In the summer and fall of 2014, the MIRO instrument on the Rosetta spacecraft will measure the thermal emission from the surface of 67P/Churyumov-Gerasimenko with an anticipated maximum spatial resolution of about 20 meters in the sub-millimeter channel (562 GHz) and 70 meters in the millimeter channel (190 GHz). The planned observations will provide antenna temperatures for scans of large portions of the surface. We have developed a software package that enables the reduction of the observational data into estimates of near-surface thermal properties. The relative positions of the comet, spacecraft and the sun, the pointing of the MIRO telescope, and the orientation of the comet are derived from flight dynamics data provided by the Rosetta project. The thermal profiles and the radiative transfer of the millimeter and sub-millimeter radiation are computed numerically. The thermal properties of the near-surface materials are then derived from fitting the observations to the numerical results. We will present maps of the thermal properties and, when possible, provide correlation of salient features with topographic information available from the science camera and the resulting digital shape model.

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100.07 – First Far-Ultraviolet Observations of a Comet Nucleus: Rosetta-Alice Reflectance Spectroscopy of 67P/Churyumov-Gerasimenko

The Alice ultraviolet spectrograph aboard the ESA/NASA Rosetta mission is now orbiting comet 67P/Churyumov-

Gerasimenko (C-G). Alice is an imaging spectrograph that operates from 700-2050 Å with a characteristic filled-slit resolution near 10 Å. On approach to and now in orbit with 67P/C-G, Alice has obtained numerous reflectance spectra of the cometary nucleus. These are the first reflectance spectra below 2000 Å of any cometary nucleus. We observe a very dark FUV surface with no strong H₂O absorption band. We will describe the spatially-unresolved but rotationally-resolved spectra we have obtained, analyzing them for albedo and albedo slope, as well as spectral absorption features.

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100.08 – Spatially Resolved Far-Ultraviolet Surface Reflectance of Comet 67P/Churyumov-Gerasimenko as Observed by Rosetta Alice

Alice, NASA's light weight and low power far-ultraviolet (FUV) imaging spectrograph onboard ESA's comet rendezvous mission Rosetta (Stern et al. 2007), is in the process of characterizing the nucleus, coma, and nucleus/coma coupling of its primary target comet 67P/Churyumov-Gerasimenko (C-G), a Jupiter Family comet with a distinct bi-lobed shape. With a spectral range from 700-2050 Å and spatial resolution of 30 m by 150 m at the comet from a spacecraft distance of 30 km, Alice will map the surface of C-G obtaining the very first far-ultraviolet (FUV) spectral data set of a spatially resolved comet nucleus, studying the chemical heterogeneity of the nucleus, and determining albedo and color variation between the two lobes. Following successful instrument re-commissioning in March 2014, Alice began studying the surface at the end of July as Rosetta approached its target and determined, as expected from the UV behavior of many refractory materials, that C-G has a low FUV albedo. Subsequent observations made during the pre-landing and landing phases of the mission, where the comet traveled from 3.7 to 3.0 AU from the Sun, will be presented. The analysis of the FUV spectra of C-G, highlighting spectral features of the landing site region and other regions of interest, will be discussed in the context of contemporaneous in situ and remote sensing measurements from other Rosetta instruments.

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100.09 – Measurement of the Gas Environment in the Inner Coma of Comet 67P/Churyumov-Gerasimenko with the Alice Far-ultraviolet Spectrograph on Rosetta

Alice is a lightweight, low-power far-ultraviolet (700 – 2050 Å) spectrograph onboard Rosetta designed for in situ imaging spectroscopy of a cometary coma during the rendezvous with comet 67P/Churyumov-Gerasimenko. Among its primary objectives is the determination of the production rates and spatial distributions of the key parent species H₂O, CO, and CO₂, their atomic dissociation products, and their evolution as the comet approaches perihelion in August 2015.

Following successful instrument re-commissioning in March 2014, Alice began to search for CO emission as Rosetta approached the comet during June and July 2014. Through this period only upper limits were obtained. After orbit insertion on August 6, 2014, the 5.5° long slit of the spectrograph permitted observations of the inner coma above the limbs of the nucleus when the instrument was pointed towards the nadir from distances of ~100 km. Depending on the orientation of the slit relative to the nucleus, several emissions of HI and OI (primarily Lyman- γ and OI λ 1304) were detected. Our preliminary analysis of the relative line intensities suggests electron impact dissociation of H₂O as the source of these emissions. Subsequent observations made during the pre-landing phases of the mission will also be presented and discussed in the context of contemporaneous in situ and other remote sensing measurements.

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101 – Exoplanet Atmosphere Theory

101.01D – Non-grey thermal effects in irradiated planets atmospheres

The large diversity of exoplanets in terms of irradiation temperature, gravity and chemical composition discovered around stars with different properties call for the development of fast, accurate and versatile atmospheric models. We

derive a new, non-grey analytical model for the thermal structure of irradiated exoplanets. Using two different opacity bands in the thermal frequency range, we highlight the dual role of thermal non-grey opacities in shaping the temperature profile of the atmosphere. Opacities dominated by lines enable the upper atmosphere to cool down significantly compared to a grey atmosphere whereas opacities dominated by bands lead both to a significant cooling of the upper atmosphere and a significant heating of the deep atmosphere.

We compare our analytical model to a grid of temperature-pressure profiles for solar composition atmospheres obtained with a state-of-the-art numerical model taking into account the full wavelength, temperature and pressure dependence of the opacities. We demonstrate the importance of thermal non-grey opacities in setting the deep temperature of irradiated giant planets atmospheres. In the particular case of highly irradiated planets we show that the presence of TiO in their atmospheres alters both the optical and the thermal opacities. The greenhouse effect – a semi-grey effect – and the “blanketing effect” - an intrinsically non-grey effect – contribute equally to set the deep temperature profile of the planet atmosphere. We conclude that non-grey thermal effects are fundamental to understand the deep temperature profile of hot Jupiters.

Our calibrated analytical model matches the numerical model within 10% over a wide range of effective temperature, internal temperature and gravities and properly predicts the depth of the radiative/convective boundary, an important quantity to understand the cooling history of a giant planet. Such a fast and accurate model can be of great use when numerous temperature profiles need to be calculated, such as in atmospheric retrieval calculation, when calculating the long-term evolution of the planet or when performing population synthesis models.

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101.02 – A radiative-convective equilibrium model for young giant exoplanets: studies of τ pictoris b and HD95086 b

We developed a radiative-convective equilibrium model for young giant exoplanets, in the context of direct imaging. Input parameters are the planet's surface gravity (g), effective temperature (T_{eff}) and elemental composition. Under the additional assumption of thermochemical equilibrium, the model predicts the equilibrium temperature profile and mixing ratio profiles of the most important gases. Opacity sources include the H₂-He collision-induced absorption and molecular lines from H₂O, CO, CH₄, NH₃, VO, TiO, Na and K. Line opacity is modeled using k -correlated coefficients pre-calculated over a fixed pressure-temperature grid. Absorption by iron and silicate cloud particles is added above the expected condensation levels with a fixed scale height and a given optical depth at some reference wavelength. Model predictions are compared with the existing photometric and spectroscopic measurements of τ Pictoris b and photometric data of HD95086 b coming from GPI commissioning.

This model will be used to interpret future photometric and spectroscopic observations of exoplanets with SPHERE, mounted at the VLT.

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101.03 – Magnetic Effects on Hot Exoplanet Atmospheres

Through the process of thermal ionization, intense stellar irradiation renders hot exoplanetary atmospheres electrically conductive. Simultaneously, lateral variability in the irradiation drives the global circulation with peak wind speeds of order \sim km/s. The interactions between the atmospheric flows and the background planetary magnetic field give rise to Lorentz forces that can act to perturb the flow away from its purely hydrodynamical counterpart. In this talk, I will discuss the consequences of magnetohydrodynamic effects on hot planetary atmospheres. Specifically, I will show the results of analytical and numerical calculations that exhibit qualitative deviations from conventional global circulation solutions and discuss potential implications for observational characterization of close-in giant planets.

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101.04 – Effects of Magnetism on the Atmospheres and Evolution of Hot Jupiters

Magnetic effects imprint potentially observable features of close-in extrasolar giant planets, or "hot Jupiters," through two mechanisms: the Lorentz force, which modifies atmospheric dynamics, and Ohmic dissipation, which may have a large impact on the structure and evolution of a planet. We present results from a 3D anelastic magnetohydrodynamic (MHD) model, taking into account purely resistive MHD. We demonstrate that magnetic effects may cause a transition from the expected superrotation in purely hydrodynamic models to subrotation (i.e. wind reversal) at high equilibrium

temperatures and magnetic field strengths. This reduction of wind speeds correspondingly reduces hot spot displacement, forcing MHD atmospheric hot spots to be found westward of their hydrodynamic counterparts. For the case of HD 209458b, we do not expect that atmospheric Ohmic dissipation has a large enough magnitude to explain its observed radius, even when scaling the dissipated power into the planetary convective zone. However, the efficacy of Ohmic dissipation is expected to be greater for hot Jupiters with a lower mass than HD 209458b, as these planets have less partial degeneracy and larger pressure scale heights. Hence, Ohmic dissipation can likely explain why a subset of transiting hot Jupiters appear inflated, but other mechanisms may be required to explain those with a mass comparable to or greater than 0.7 Jupiter masses.

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101.05 – Electron densities and alkali atoms in exoplanet atmospheres

We describe a detailed study on the properties of alkali atoms in extrasolar giant planets, and specifically focus on their role in generating the atmospheric free electron densities, as well as their impact on the transit depth observations. We focus our study on the case of HD 209458 b, and we show that photoionization produces a large electron density in the middle atmosphere that is about two orders of magnitude larger than the density anticipated from thermal ionization. Our purely photochemical calculations though result in a much larger transit depth for K than observed for this planet. This result does not change even if the roles of molecular chemistry and excited state chemistry are considered for the alkali atoms. In contrast, the model results for the case of exoplanet XO-2 b are in good agreement with the available observations. Given these results we discuss other possible scenarios, such as changes in the elemental abundances, changes in the temperature profiles, and the possible presence of clouds, which could potentially explain the observed HD 209458 b alkali properties. We find that most of these scenarios can not explain the observations, with the exception of a heterogeneous source (i.e. clouds or aerosols) under specific conditions, but we also note the discrepancies among the available observations.

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101.06 – Effect of condensate cycles in driving atmospheric circulation on brown dwarfs and directly imaged giant planets

Growing observations of brown dwarfs and directly imaged giant planets, including properties of the L/T transition, chemical disequilibrium, brightness variability, and surface maps have provided evidence for strong atmospheric circulation on these worlds. Previous studies that serve to understand the atmospheric circulation of brown dwarfs include modeling of convection from the interior both in a two-dimensional and global fashion, a two-layer shallow water model and a global circulation model with dry thermal perturbation at the bottom of atmosphere. These models show that interactions between the stably stratified layer and the convective interior can drive an atmospheric circulation, including zonal jets and/or vortices. However, these models are dry models, not including the condensation cycles such as silicate and iron in hot dwarfs. Condensation of water has previously been shown to play an important role on driving the zonal jets on four giant planets in our solar system. As such, condensation cycles of various species is believed to be an important source in driving the atmospheric circulation of brown dwarfs and directly imaged planets as well. Here we present results from three-dimensional simulations for the stably stratified atmospheres of brown dwarfs based on a general circulation model that includes the effect of a condensate cycle. Large-scale latent heating and molecular weight effect due to condensation of a single species are treated explicitly in our model. We examine the atmospheric circulation patterns of brown dwarfs caused by large-scale latent heating that results from condensation of silicates in hot dwarfs and water in the cold dwarfs. By varying the parameters such as abundances of condensates, effective temperature and rotational period, we explore possible configurations of the circulation, and determine implications for the observed cloud patchiness and brightness variability for brown dwarfs.

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101.07 – Effects of bulk composition on the atmospheric dynamics on close-in exoplanets

Depending on the metallicity of the protoplanetary disk, the details of gas accretion during planetary formation, and atmospheric loss during planetary evolution, the atmospheres of exoplanets could exhibit a variety of bulk compositions (e.g., Moses et al., 2013). Examples include hydrogen-dominated atmospheres like Jupiter, more metal-rich (but still hydrogen-dominated) atmospheres like Neptune, evaporated atmospheres dominated by helium in analogy to helium white dwarfs, or of course carbon dioxide, water vapor, nitrogen, and other heavy molecules as exhibited by terrestrial planets in the solar system. Despite differing opacities that will impact the radiative energy deposition (e.g., Lewis et al., 2010), differing bulk compositions also differ in molecular weight and heat capacity. The latter two fundamental

parameters might have crucial effects on various aspects of atmospheric structure and dynamics. Molecular weight may influence the scale height, Brunt-Väisälä frequencies and therefore gravity wave speeds in the atmosphere. A lower molecular weight or a lower heat capacity would likely result a larger deformation radius in which the atmospheric flow is more significantly influenced by the gravity and buoyancy effects instead of the rotation effects. We use a three-dimensional general circulation model to simulate generic sub-Jupiter exoplanets, especially those close to their host stars-known as “hot Neptunes” or close-in “super-Earths”. We found that the atmosphere with lower molecular mass favors zonal jets and equatorial superrotation, and that with lower heat capacity favors day-to-night divergent flow. Our results suggest that super Earths and hotNeptunes will exhibit large meteorological diversity due to bulk composition effects. Since atmospheres with fast zonal jets tends to have smaller day-night temperature difference due to larger circulation efficiency and larger hot spot phase shift than that with day-to-night divergent flows, these molecular-weight effects have important implications for infrared light curves and other observables.

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101.08 – Atmospheric Dynamics of Terrestrial Exoplanets Over a Wide Range of Orbital and Atmospheric Parameters

Since the mid-1990s, nearly 1800 exoplanets have been discovered around other stars. Exoplanet discovery and characterization began with giant planets, but as the observational techniques are advancing the emphasis is gradually shifting to smaller worlds. The recent discoveries of terrestrial exoplanets and super Earths extending over a broad range of orbital and physical parameters suggests that these planets will span a wide range of climatic regimes. Characterization of the atmospheres of warm super Earths has already begun and will be extended to smaller and more distant planets over the coming decade. The habitability of these worlds may be strongly affected by their three-dimensional atmospheric circulation regimes, since the global climate feedbacks that control the inner and outer edges of the habitable zone---including transitions to Snowball-like states and runaway-greenhouse feedbacks---depend on the equator-to-pole temperature differences, pattern of relative humidity, and other aspects of the dynamics. Here, using an idealized moist atmospheric general circulation model (GCM) including a hydrological cycle, we discuss the dynamical principles governing the atmospheric dynamics on such planets. We show how the planetary rotation rate, planetary mass, surface gravity, heat flux from a parent star, optical thickness and atmospheric mass affect the atmospheric circulation and temperature distribution on such planets. Our simulations demonstrate that equator-to-pole temperature differences, meridional heat transport rates, structure and strength of the winds, and the hydrological cycle vary strongly with these parameters, implying that the sensitivity of the planet to global climate feedbacks will depend significantly on the atmospheric circulation. We elucidate the possible climatic regimes and diagnose the mechanisms controlling the formation of atmospheric jet stream, Hadley and Ferrel cells and latitudinal temperature differences. Finally, we will discuss how the atmospheric dynamics influence the global-scale climate feedbacks that control the width of the habitable zone, and their effects on the global climate.

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101.09 – A theoretical study of polarization in scattered light from planetary and exoplanetary atmospheres

Scattering of mostly unpolarized (linearly polarized fraction of order~10⁻⁵) starlight by planetary atmospheres partially polarizes the scattered light (order ~0.1). The degree of polarization in scattered light is extremely sensitive to the geometry of the system, which is usually known and the nature of scattering particles, which is often unknown. There has been growing interest in observing polarized light scattered from exoplanetary atmospheres, particularly due to the recent detections of clouds and hazes on a number of exoplanets. The primary motivation of such observations has been the enhanced contrast between the planet and its star when observed in polarized light. There is also a possibility of constraining the geometry of the system, thus providing information about the inclination of the orbit, when it is uncertain from photometry alone. There have been reports of observing polarized light scattered from an exoplanet, though they are disputed.

Several groups have numerically modeled the polarized light from exoplanetary atmospheres, but the model atmospheres are close analogues of either Earth or Jupiter with clouds of water or ammonia. While useful for initial investigations, such atmospheres are unrealistic for many close in exoplanets whose atmospheres are thought to contain hazes and clouds of silicates and metals. We will undertake a modeling study, using the vector radiative transfer model VLIDORT to study the phase space of expected atmospheric composition and the observable polarization signal.

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102 – Titan 1: Atmosphere Structure and Time Variability

102.01 – Using The Cassini-UVIS Instrument As An Imager To Quantify The Interactions Between Saturn's Magnetosphere And Titan's Upper Atmosphere

The Cassini Ultraviolet Imaging Spectrograph (UVIS) includes two spectrographic channels that provide both images and spectra covering the wavelength ranges from 56 to 118 nm (EUV) and 110 to 190 nm (far-UV). While most studies focused on analyzing spectra, very few have used the capability of UVIS to produce images.

We present here an exploratory work, in which each UVIS observation of Titan is converted into a set of images at specific wavelengths (NI and NII atomic features as well as N₂ bands). This approach allows for the investigation of a wider set of observations, than when analyzing emission spectra alone. We focus on spotting interesting/unexpected features such as airglow. A library of images will be created for further investigations.

A specific application of this work concerns Titan's nightglow and we attempt to answer a major question that remains: How to quantify the interactions between Saturn's magnetosphere and Titan's upper atmosphere? Our extensive set of images of the nightside of Titan helps us to detect the moment/place at which the nightglow appears and to investigate the following points:

- Do we have nightglow all the time or is its occurrence correlated to an orbital position?

- Does the intensity of nightglow fluctuate in an understandable way; as a function of the orbital position (RAM angle) for example?

- Is there a latitudinal repartition of nightglow? An altitude distribution?

We will provide a temporal and spatial description of the airglow. Further investigations will study the magnetospheric contribution by imaging all observations of Titan at various positions in its orbit. Between 2004 and now, we have 4851 observations in the Far-UV and this presentation will show the first results from that set of images.

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102.02 – N² and CH⁴ Densities Retrieved from Dayglow and Occultation Observations of Titan's Upper Atmosphere

The EUV and FUV dayglow of Titan's upper atmosphere is primarily produced by solar driven processes on molecular nitrogen (N²). Since the arrival of Cassini at the Saturnian system in 2004, the Ultraviolet Imaging Spectrograph (UVIS) on Cassini has obtained many orbits of dayglow emission observations from Titan's limb between 800-1300 km. Some of the emission features are attenuated by methane (CH⁴) below about 1000 km. Analysis of Titan's dayglow features with varying amounts of CH⁴ absorption allows for the retrieval of both N² and CH⁴ density profiles in Titan's upper atmosphere. Although retrievals of density profiles from occultations are widely used for probing the upper atmosphere of Titan, retrievals from the dayglow are relatively new. Since the dayglow observations are not limited to a geographic point on the limb they can provide important complementary information on a global scale. This is particularly important for Titan, where variability in the upper atmosphere can be up to an order of magnitude from one Cassini orbit to the next. We retrieve N² and CH⁴ densities from the dayglow for Titan orbits during which there are also occultations and compare the results. We report any differences and offer insight to global scale compositional variability in the context of the two sets of observations.

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102.03 – Model observed tholin profiles in the atmosphere of Titan

We present a recent attempt in analyzing the stellar occultation data from the Cassini/UVIS instrument. The mean optical depth as a function of line of sight impact parameter is derived for the spectral range between 1700 and 1900 Å from many occultations. Vertical profiles of tholin particles from ~300 to ~1000 km are obtained, and strong spatial variation is seen. One distinct depletion region is clearly seen at ~500 km or below, depending on the occultations. A 1-D transport model is developed and used to interpret the distribution of tholins. Parameters that affect the aerosol profiles are (1) size distribution, (2) mass, and (3) fractal dimension. Processes considered include (1) new aerosol production via ion-neutral and neutral-neutral chemical reactions, (2) aerosol coagulation, and (3) dynamical transport via gravitational settling. Sensitivity of the resulting tholin profile to the processes is examined and discussed.

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102.04 – Planetary Ageostrophic Instability Leads to Superrotation

Superrotation -- when the equatorial belt of an atmosphere spins faster than the underlying planet -- is a common phenomenon in the Solar system, yet the mechanisms that support and maintain it have been poorly characterized. We find that 'spontaneous' superrotation (i.e., without directly forcing the equatorial atmosphere) develops in numerical simulations but only for a very specific set of conditions. This led us to investigate large-scale fluid instabilities in wind profiles with only latitudinal structure, and as a result we identified a new type of instability that we call the 'planetary ageostrophic' or 'Rossby-Kelvin' instability. The Rossby-Kelvin instability develops over a broad range of latitudes in strong meridional shear between the mid latitudes and the equator, and the resulting pattern drives acceleration of the equatorial wind. Our model accounts for how superrotation may have spontaneously developed on Titan (and Venus) while it did not on Earth or Mars by identifying the parameter regimes in which the Rossby-Kelvin instability is active. Our results suggest these control parameters have more general, predictive power, and can be used to classify the atmospheric circulations of a broad range of planets, exoplanets, and paleoclimates.

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102.05 – Mapping variations in Titan's atmospheric HNC and HC³N distributions using ALMA

We present the first spectrally and spatially-resolved maps of HNC and HC³N emission from Titan's atmosphere, obtained with the Atacama Large Millimeter Array (ALMA) on 2013 November 17. These maps show anisotropic spatial distributions for both molecules, with resolved emission peaks in Titan's northern and southern hemispheres. The HC³N maps are consistent with enhanced concentrations of this molecule over Titan's poles, whereas the HNC is offset in latitude and longitude. Differences between the spectral line shapes and integrated flux distributions of HNC and HC³N show that these species are not co-spatial and are consistent with an HNC/HC³N abundance ratio that increases towards higher altitudes. From spatial variations in the HC³N line profile, the locations of the HC³N peaks are shown to be variable as a function of altitude. The integrated emission peaks for HNC and the upper-atmosphere HC³N component (at altitudes above about 300 km) are found to be asymmetric with respect to Titan's polar axis, indicating that the mesosphere may be more longitudinally-variable than previously thought. Disk-averaged HNC and HC³N spectra have been modeled using the RADTRANS planetary atmosphere code and the resulting best-fitting vertical abundance profiles are found to be in reasonable agreement with previous measurements for these species.

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102.06 – Titan's South Pole Temporal Evolution of HC₃N and other trace gases

Up until mid 2012, Titan's Northern atmosphere exhibited the enriched chemical compounds found at the time of Northern Spring Equinox (NSE) since the Voyager days (November 1980), with a peak around the NSE in 2009. Since then, a reversal in the abundances of some species from north to south has been observed with the appearance for the first time at Titan's south pole of some species such as HC₃N at 663 cm⁻¹ and C₆H₆ in large quantities. These species had previously been clearly observed only at high northern latitudes. Though not present in the south until February 2012, the 663 cm⁻¹ emission appeared in CIRS spectra recorded on 24 July 2012 next to the CO₂ band at 667 cm⁻¹ and has been increasing since then. This is another strong indication of the buildup of the gaseous inventory in the southern stratosphere, as expected as the pole moves deeper into winter shadow. Downwelling nitrile gases that accumulate in the absence of ultraviolet sunlight, evidently increased quickly during 2012 and may be responsible also for the reported haze decrease in the north and its appearance in the south from its 220 cm⁻¹ feature (Jennings et al. 2012a,b). HC₃N has increased by 2 orders of magnitude in the south over the past 2 years, while decreasing rapidly in the north. We find other interesting although weaker transitions from north to south for molecules including HCN, C₃H₄ and C₄H₂, which need to be monitored more in the future.

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Jennings, D. E., et al. 2012b, ApJ 761, L15

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102.07 – Post-equinox Variations of Titan’s Mid-stratospheric Temperatures from Cassini/CIRS Observations

Since Cassini orbit insertion about Saturn in July 2004, the Composite Infrared Spectrometer (CIRS) onboard the spacecraft has been routinely making observations of Titan designed for measuring the temperature structure of the upper stratosphere and lower mesosphere. Results through 2009 (northern spring equinox) were published in [1]. Here we will discuss changes between equinox and southern mid-autumn.

From northern mid-winter through spring equinox, strong meridional temperature gradients were restricted to the winter hemisphere; north polar temperatures in the mid-stratosphere were 25 K colder than the equator, while the south pole was 5 K colder than the equator [1]. After equinox, the southern stratosphere began cooling, as the northern stratosphere continued to slowly warm, with the temperatures at low- to mid-latitudes becoming roughly symmetric about two Earth years after equinox. When mapping observations of the polar region resumed in late 2012, the southern polar mid-stratosphere had cooled by over 25K, and had become colder than the northern polar region was at the beginning of Cassini observations. As of July 2014, middle stratospheric temperatures at the south pole had dropped to ~115 K, about 30 K colder than late northern winter polar temperatures observed by CIRS in 2004, and were nearly isothermal in altitude between 0.5 and 8 mbar. The northern polar stratosphere has continued to slowly warm, with temperatures in mid 2014 of ~155 K, ~10 K warmer than at equinox.

From the observed zonal mean temperatures, the zonal mean winds can be estimated from the gradient wind approximation. In northern mid-winter, the calculated stratospheric winds showed a strong prograde jet (~200 m s⁻¹) at northern midlatitudes, with much weaker winds, less than 90 m/s, in the southern hemisphere. In the 5 years after equinox, the winds in the northern stratosphere have decelerated to just over 100 m s⁻¹, while southern hemisphere winds have accelerated to over 200 m/s.

[1] Achterberg, R. K. et al. (2011) *Icarus*, 211, 686-698.

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102.08 – Titan’s South Polar cloud optical properties modelization

Cassini/ISS cameras detected, in June 2012, a newly formed large cloud in the south polar region of Titan. Images of this cloud in filters at 889 nm (MT3) and 935 nm (CB3) clearly reveal different important characteristics. The cloud patch is observed beyond the latitude -77 degrees and with values of the SZA higher than 90 degrees. In this work, we analyze the radiance factor I/F in the methane 890-nm (MT3) filter by using radiative transfer simulations in order to retrieve constraints on the cloud properties, as its opacity, the size of the droplets and the refractive index.

The cloud simulation requires the use of a three-dimensional Monte-Carlo radiative transfer model in spherical geometry since the plane-parallel approximation breaks down for high solar zenith angle (SZA). To model the outgoing intensity and because the cloud is not spherically symmetric but has a finite size and is located near the pole, we first use the source function computed in the atmosphere including the effect of haze and methane, but without cloud. Then, we add the cloud as a lower boundary condition, with a specific term of scattered intensity. We then re-integrate the radiative transfer equation from the cloud level to the top of the atmosphere to obtain outgoing intensity in the presence of the cloud. Doing that, the cloud is treated as an additive term.

The haze optical properties are taken from Tomasko et al. (2008), and the methane absorption is taken from the band model of Karkoschka and Tomasko (2012). The phase Function and single scattering albedo of the cloud are calculated by the Mie theory. The effective size of particles is allowed to vary between 3 μm and 5 μm, whereas the effective variance is fixed at 0.2. We use as optical constants for the cloud particles, the real refractive index of 1.4, while the imaginary part *k*, is left as a free parameter between 10⁻⁵ and 10⁻³.

We then find, with our analysis, that the optical depth of the cloud can only take values between 0.8 and 2.6, and the imaginary refractive index, *k*, should be smaller than about 5x10⁻³.

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102.09 – Evolution of Titan’s South Pole 220 cm-1 Ice Cloud

Titan’s atmosphere at the South Pole has been undergoing rapid and surprising changes as southern Winter approaches. Clouds began forming suddenly at the pole in 2012, seen by Cassini in both the visible and infrared [1, 2, 3]. In particular, the ice cloud identified by a spectral line at 220 cm⁻¹ became visible for the first time in the south. Since then the cloud has greatly increased in radiance. Cassini CIRS has been observing the 220 cm⁻¹ feature since the beginning of the mission in 2004. This emission feature was originally found in the north, where it has gradually decreased since 2004. The cloud in the south has evolved in shape and by late 2013 its thermal emission had developed into a collar morphology with a radius of about 10 degrees of latitude. From Cassini ISS images it appears that the visible cloud reported by West et al. [1] fit inside the central minimum of the 220 cm⁻¹ emission collar. The collar was not

centered at the pole but was shifted approximately 4 degrees toward the Sun from the pole. This shift coincides with the tilt of the atmospheric axis originally reported by Achterberg et al. [4]. At the same time, maps of emission from the gases HC₃N, C₄H₂ and C₆H₆ [5] exhibited a ring-shape as well, but in addition a central peak at the 4-degree offset position. The maximum of the 220 cm⁻¹ emission matched the minimum emission from the gases, suggesting a relationship between the cloud material and the gases. As condensation and newly formed gases concentrated at the pole, temperatures at the South Pole have become extremely low [6]. During 2014 the cloud and gas emission patterns have continued to evolve, with the ring structure becoming less distinct. We expect the emission from the 220 cm⁻¹ ice cloud to increase and its structure to continue to develop as Cassini watches Titan move through late southern Autumn.

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103 – Rosetta 2 / Comet Coma Chemistry and Nuclear Outbursts

103.01 – VIRTIS-Rosetta observations of the nucleus of 67P/Churyumov-Gerasimenko during the Comet Characterisation phase (July-August 2014)

The paper will describe the major results obtained during the comet nucleus characterization phase, July-August 2014, of the Rosetta Mission by the instrument VIRTIS (Visible, Infrared and Thermal Imaging Spectrometer), the dual channel spectrometer onboard Rosetta. The nucleus observations in this phase were performed in a wide range of illumination conditions and with spatial sampling varying from the initial 500m down to 20m. VIRTIS covers the spectral range from 0.25 to 5micron with a mapping channel (VIRTIS-M) and the range 2-5micron with a High Spectral Resolution channel (VIRTIS-H). Both channels have been used to generate maps correlated to various properties (temperature, albedo, composition) of the illuminated areas. Special emphasis was placed on mapping those surface regions considered reachable areas for the Philae Lander descent, and to those area in the “neck” of the nucleus which from the very early Osiris observations did show hints of surface outgassing activity.

Authors acknowledge the support from national funding agencies, ASI, DLR and CNES.

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Contributing team(s): VIRTIS Team

103.02 – Thermal properties of comet 67P derived from Rosetta/VIRTIS, and orbital observations of Philae landing site

The Rosetta spacecraft has reached its final target, comet 67P/Churyumov-Gerasimenko, in early August 2014. The VIRTIS imaging spectrometer onboard the Rosetta orbiter has intensively observed both the nucleus and the coma environment in the 0.25-5 microns wavelength range. Nucleus observations are performed with both channels: VIRTIS-M for spectral mapping and VIRTIS-H for high spectral resolution. Dayside surface temperatures in various illumination conditions can be retrieved from the long wavelength range. This allows us to infer local thermal properties. The very irregular shape of 67P results in unusual patterns in the heating / cooling regime of the object, e.g. sudden transitions from day to night.

We will present thermal analyses of observations performed during the first mapping phase of the pre-landing activity (August 2014), with a focus on thermo-physical modeling of comet 67P on both regional and local scales, and a special emphasis on the expected landing site. These observations document the state of the comet surface at a time of large heliocentric distance and low activity.

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Contributing team(s): the Rosetta-VIRTIS team

103.03 – Preliminary results seen with Rosetta/ROSINA: early cometary activity of 67P/Churyumov-Gerasimenko

On 1 August 2014, the ROSETTA spacecraft approached the comet 67P/Churyumov-Gerasimenko (67P/CG) close enough to start its detailed characterisation. In this phase, the distance between Rosetta and 67P/CG is below 1'000 km, at a heliocentric distance of less than 3.6 AU. The Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) [1] measures the composition of 67P/CG's atmosphere and ionosphere, and additionally derives the bulk velocity of gas. ROSINA consists of the COmetary Pressure Sensor (COPS) and two mass spectrometers for the analysis of neutral gas and cometary ions in the coma of the comet: the Double Focusing Mass Spectrometer (DFMS) and the Reflectron Time Of Flight mass spectrometer (RTOF). Since beginning of August, the ROSINA sensors are continuously monitoring the density and chemical composition of the coma of 67P/CG. The goal of this work is not only to determine the abundance of major species like CO₂, CO, and H₂O, but also to analyse the development of the composition as a function of the heliocentric distance. We will present the first mass spectra of RTOF as well as the total density and the molecular composition measurements obtained at 67P/CG.

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Contributing team(s): the ROSINA team

103.04 – Early Activity of Cometary Species from ROSINA/DFMS at 67P/ Churyumov-Gerasimenko

The European Space Agency's Rosetta spacecraft arrived after a journey of more than 10 years at comet 67P/Churyumov-Gerasimenko. ROSINA is an instrument package on board Rosetta. It consists of two mass spectrometers and a COmetary Pressure Sensor (COPS). The two mass spectrometers, the Double Focusing Mass Spectrometer (DFMS) and the Reflectron Time of Flight (RTOF) complement each other with high mass resolution (e.g to resolve ¹³C from CH), high dynamic range (to detect low abundant isotopes and species), high mass range (to detect organics), and high time resolution. ROSINA is designed to measure the neutral gas and plasma composition in the coma of 67P/Churyumov-Gerasimenko in addition to the physical properties of the neutral component of the coma. For the first time, a comet can be observed in situ from its early activity towards and after perihelion. Little is known about what drives initial cometary activity very far from the Sun. Remote sensing observations to date are highly constrained to a limited number of a few bright comets (e.g. Hale-Bopp) and a limited number of species. Rosetta provides the first measurements of the early activity of a comet in situ and detected the first cometary molecules early August. We will focus on early activity of cometary species from the high resolution mass spectrometer ROSINA/DFMS.

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103.05 – Preliminary Inventory in the Early Coma of Comet 67P/Churyumov-Gerasimenko

After a 10-year journey, the European Space Agency's Rosetta mission encountered its target comet Churyumov-Gerasimenko. Rosetta will accompany the comet to perihelion and beyond. On board the Rosetta spacecraft is the ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) experiment. ROSINA consists of a pressure sensor

and two complementary mass spectrometers. One is the Double Focusing Mass Spectrometer, which has high dynamic range and a mass resolution $m/\Delta m = 3000$ at 1% peak height ($m/\Delta m = 9000$ at 50% peak height) at mass 28 amu/q. It is therefore well suited to detect minor species in the lower mass range up to mass 140 amu [1].

ROSINA has been taking data since May 2014 and first signals of the comet were detected at the beginning of August. We will present a preliminary inventory of species seen by ROSINA in the early coma of comet Churyumov-Gerasimenko.

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103.06 – Chemical Recycling of HCN in Cometary Comae

Modeling is essential to understand the important physical and chemical processes that occur in cometary comae, especially the relationship between putative parent and daughter molecules, such as, HCN and CN. Photochemistry is a major source of ions and electrons that further initiate key gas-phase reactions, contributing to the plethora of molecules and atoms observed in comets. The effects of photoelectrons that interact via impacts are important to the overall excitation and dissociation processes in the inner coma. We consider the relevant processes in the collision-dominated, inner coma of a comet within a global modeling framework to understand observations of HCN and CN. The CN source(s) must be able to produce highly collimated jets, be consistent with the observed CN parent scale length, and have a production rate consistent with the observed CN production. HCN fulfills these conditions in some comets (e.g., 1P/Halley, Hale-Bopp) while it does not in others (e.g., 8P/Tuttle, 6P/d'Arrest, 73P/S-W3, 2P/Encke, 9P/Tempel 1 and C/2007 W1).

We investigate the chemistry of HCN with our chemical kinetics coma model including a network with other possible CN parents, as well as a dust component that may be a potential source of CN. It is seen that the major destruction pathways of HCN are via photo dissociation (into H and CN) and protonation with water group ions - primarily H₃O⁺. We point out the intriguing “recycling” of HCN via protonation reactions with H₃O⁺, H₂O⁺, OH⁺, and subsequent dissociative recombination. It seems that HCN molecules observed in the coma can consist of those initially released from the nucleus and those that are freshly formed at different locations in the coma via these protonation/dissociation reactions. We will investigate implications for reconciling discrepancies between observations of HCN and CN in cometary comae.

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103.07 – Comparative CO/CO₂ Production in NEOWISE-Observed Comets

NEOWISE [1,2] is the NASA Planetary Division-funded mission that utilizes data from the Wide-Field Infrared Survey Explorer (WISE) spacecraft to detect and characterize moving objects. NEOWISE has provided a large statistical sampling of comets in various states of activity, containing a variety of types of comets. This data set provides a unique opportunity to discern the trends in their observable properties and compare the ensemble properties between comet types, and may allow us to discern subtypes. The WISE spacecraft has discovered 22 new cometary bodies and observed over 160 comets, yielding the largest sample of comets yet observed at thermal-IR wavelengths. This collection offers a diverse range of comet behavior including highly active and inactive bodies from both long period comet (LPC) and short period comet (SPC) populations.

We have conducted analyses of the physical properties of the NEOWISE-observed comets. In particular, our analysis constrains the quantity and nature of the ejected coma dust for large particles, and provides estimates of the nucleus

sizes and albedos, as well as the production rates and extent of the CO/CO₂ gas species. WISE is sensitive to CO and CO₂ emission lines that fall within the 4.6 micron band pass (W2), at 4.3 and 4.7 microns, respectively. The quantity of dust present is found from the signal in the three other bands, centered at 3.4, 12, & 22 microns, and the dust signal in W2 is deduced, such that excess signal in W2 can be identified. We find detectable signal excess in nearby comets ~1AU distance from the Sun, as well as those as distant as 4.5AU, and approximately a third of both LPCs and SPCs show 4.6 micron infrared excess in our data. We will discuss in depth the production rates for the CO/CO₂ gas species derived from the entire sample of comets.

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103.08 – A New Analysis of Comet 29P/Schwassmann-Wachmann 1 Archival Images to Constrain Physical and Dynamical Properties of its Nucleus

We present results from a continuing effort to model the nuclear activity of comet 29P/Schwassmann-Wachmann 1 (SW1). SW1 is a unique comet in a nearly circular orbit, just outside the orbit of Jupiter, and undergoes frequent outbursts in activity though receiving a nearly constant insolation. Our goal is to develop a thermophysical model of SW1's nucleus, incorporating measured physical, thermal, and dynamical properties of the nucleus to describe the activity drivers of both the constant background level and frequent outbursts. Thus far our efforts have included a reanalysis of Spitzer infrared images of SW1, from which we have obtained new values of SW1's effective radius and beaming parameter [1]. Here we present our current work on constraining the spin state of the nucleus and surface areas of outburst activity. Using image enhancement techniques [2] on a collection of R-band observations of SW1 before, during, and after outburst events spanning 2002 to 2010 [3], we are using the revealed coma morphology (primarily in the form of jet features) to identify possible orientations of the nuclear spin axis and possible spin periods. An existing Monte Carlo coma modeling routine [4,5] uses this information as well as active areas' locations and extents, and dust grain speeds as inputs in order to generate a synthetic coma. The synthetic coma is then compared to the enhanced and unenhanced images to look for a match. This technique has been successfully used previously on several comets. Once trusted constraints have been made on the spin state and active areas, the results will be folded into a thermophysical model currently in the beginning stages of development. [1] Schambeau, C. A., et al.: 2014, *Icarus*, Submitted. [2] Samarasinha, N. H. and Larson, S. M.: 2014, *Icarus*, 239, 168-185. [3] Fernandez, Y. R., et al.: 2010, *AAS/Division for Planetary Sciences Meeting Abstracts*, 42, 964. [4] Samarasinha, N. H.: 2000, *The Astrophysical Journal*, 592, L107-L110. [5] Samarasinha, N. H., et al.: 2012, *AAS/Division for Planetary Sciences Meeting Abstracts*, 44, #506.03. We thank the NASA Outer Planets Research program (NNX12AK50G) for support of this work.

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103.09 – Physical Mechanism of Comet Outbursts: The Movie

During experiments conducted in 1976 at the NASA Ames Research Center's Vertical Gun Facility (VGF), the author studied low velocity impacts into simulated regolith powders and gravels, in order to examine physics of low-velocity collisions during early solar system planetesimal formation. In one "accidental" experiment, the bucket of powder remained gas-charged during evacuation of the VGF vacuum chamber. The impactor, moving at 5.5 m/s, disturbed the surface, initiating eruptions of dust-charged gas, shooting in jets from multiple vents at speeds up to about 3 m/s, with sporadic venting until 17 seconds after the impact.

This experiment was described in [1], which concluded that it simulated comet eruption phenomena. In this hypothesis, a comet nucleus develops a lag deposit of regolith in at least some regions. At a certain distance from the sun, the thermal wave penetrates to an ice-rich depth, causing sublimation. Gas rises into the regolith, collects in pore spaces, and creates a gas-charged powder, as in our experiment. Any surface disturbance, such as a meteoroid, may initiate a temporary eruption, or eventually the gas pressure becomes sufficient to blow off the overburden. Our observed ejection speed would be sufficient to launch dust off of a kilometer-scale comet nucleus.

Film (100 frames/s) of the event was obtained, but was partially torn up in a projector. It has recently been reconstituted (Centric Photo Labs, Tucson) and dramatically illustrates various cometary phenomena. Parabolic curtains of erupted material resemble curtains of material photographed from earth in real comet comas, "falling back" under solar wind forces.

In retrospect, the mechanism photographed here helps explain:

*sporadic eruptions in Comet P/Schwassmann-Wachmann 1 (near-circular orbit at ~6 A.U., where repeated recharge may occur).

*sporadic eruptions on "asteroid" 2060 Chiron (which stays beyond 8.5 A.U.).

*the thicker dust curtain (and longer eruption?) than predicted for the Deep Impact experiment in Comet Tempel 1.

The film is posted on the Planetary Science Institute website, www.psi.edu/hartmann.

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104 – Exoplanet Atmosphere Observations

104.01 – Global Weather Maps of Exoplanets and Brown Dwarfs

Clouds and atmospheric circulation play a critical role in shaping the composition, structure, and thermal emission of giant planets and their more massive brown dwarf cousins. Characterization of these objects' dynamic atmospheres has so far been largely limited to measurements of globally averaged thermal emission. We present the first two-dimensional, global map of any substellar object beyond the Solar System. Our map, obtained via Doppler Imaging, allows unambiguous identification of large-scale surface features. Geographic localization of such features provides the best constraints yet on brown dwarf global atmospheric circulation and represents a major step toward understanding the complex processes governing the atmospheres of cool substellar objects. Future giant telescopes now under construction will allow us to make maps like this of dozens of objects beyond the Solar System, including some extrasolar planets.

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104.02 – Composition and Thermal Structure of WASP-43b from Phase-resolved Emission Spectroscopy

Previous exoplanet thermal emission measurements as a function of orbital phase (so-called 'phase-curve observations') have revealed day-night temperature contrasts and hot-spot offsets relative to the substellar point. However, the interpretation of these broadband photometry measurements were limited due to an inherent degeneracy between the atmospheric composition and thermal structure. We will present the first spectroscopic phase-curve measurements for the hot-Jupiter exoplanet WASP-43b spanning three full planet rotations using the Hubble Space Telescope. With these data, we will show a 2D map of the planet's atmospheric thermal structure, discuss its day-night heat redistribution, and demonstrate an altitude dependence in the hot-spot offset relative to the substellar point. We will also present a precise determination of WASP-43b's water abundance and discuss how its inferred metallicity trends with the Solar System planets.

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104.03 – The Atmospheric Circulation of the Hot Jupiter WASP-43b: Comparing Three-Dimensional Models to Spectrophotometric Data

While HD 189733b and HD 209458b remain two of the most well characterized transiting hot Jupiters, WASP-43b will soon be joining these ranks. This 2 Jupiter-mass, 1 Jupiter-radius planet orbits a K7 star with an orbital period of 19.5 hours, and already has an array of observational constraints. Because the planet receives a similar stellar flux as HD 209458b but has a rotation rate four times faster and a much higher gravity, studying WASP-43b serves as a test of the effect of rotation rate and gravity on the circulation of a hot Jupiter when stellar irradiation is held approximately constant. Here we present 3D atmospheric circulation models of WASP-43b using the SPARC/MITgcm, a state-of-the-art coupled radiation and circulation model, exploring the effects of composition, metallicity, and frictional drag (a crude parameterization of possible Lorentz forces) on the circulation. We find that the circulation regime of WASP-43b is not unlike other hot Jupiters, with equatorial superrotation that yields an eastward-shifted hotspot and large day-night temperature variations (~600 K at photospheric pressures). We then compare our model results to the observations of Stevenson et al., which utilize the Wide Field Camera 3 aboard HST to collect spectrophotometric phase curve measurements of WASP-43b from 1.12-1.65 microns. Our results show the 5x solar model lightcurve provides a good match to the data, with a phase offset of the lightcurve flux peak and planet/star flux ratio similar to observations; however, the model nightside appears to be brighter than the observations. Nevertheless, our 5x solar model provides an excellent match to the WFC3 dayside emission spectrum. This is major success, as the result is natural outcome of the 3D dynamics, with no model tuning. This differs significantly from 1D models that generally can only match observations when appropriately tuned. In sum, these results demonstrate that 3D circulation models can provide tremendous insights in interpreting exoplanet atmospheric observations, even at high spectral resolution, and highlight the potential for future observations using HST, JWST and other next-generation telescopes to characterize exoplanet atmospheres.

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104.04D – Constraining the Thermal Structure, Abundances, and Dynamics of the Exoplanet HD 209458b

HD 209458b has been extensively studied from the UV to IR as it is one of the brightest of the transiting exoplanets and has a large planet-to-star contrast. However its thermal profile and abundances remain constrained to at best 3 orders of magnitude (Line et al. 2014), largely due to a lack of spectral coverage. We expand HD 209458b's wavelength coverage with ground and space observations. Our ground H, K, and L-band secondary eclipse spectroscopy, which explores HD 209458b's emission mechanisms, is motivated by multiple detections of bright 3.3 μm emission on HD 189733b, resembling the CH₄ ν_3 band and potentially non-LTE fluorescence (Swain et al. 2010; Waldmann et al. 2012). CH₄ fluorescence has previously been observed on Titan (Kim et al. 2000), Saturn, and Jupiter (Drossart et al. 1999; Brown et al. 2003), thereby likening exoplanets to their Solar System counterparts. We find that the hotter HD 209458b lacks to ~3 σ a bright 3.3 μm feature as seen on HD 189733b, which is consistent with thermochemical equilibrium predictions (Moses et al. 2011). We measure HD 209458b's longitudinally-varying thermal structure with Spitzer/IRAC full-orbit phase curve observations, and revise a previous 4.5 μm emission measurement downward by ~35%. This change is significant because the high 4.5 and 5.8 μm brightness temperatures were interpreted as a thermal inversion (e.g., Line et al. 2014). While our 4.5 μm photometric emission point does not require an inversion, the shape of the phase curve, particularly the location and brightness temperature of the hot spot, suggests that HD 209458b has a dayside inversion. However the nightside is much cooler than predicted by a GCM. This discrepancy is potentially due to the GCM lacking quenching where vertical mixing outpaces reaction rates, causing increased CO and CH₄ abundances at higher altitudes. We explore evidence for CH₄ quenching with IRAC 3.6 micron data, which overlap the wings of the CH₄ ν_3 band, allowing us to longitudinally-measure the CH₄ content across HD 209458b's disk. The shape of the phase curve indicates the radiative time constant and thus the presence of a thermal inversion. This presentation also covers the reduction and analysis methods of the datasets.

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104.05 – Connecting planetary and stellar heavy element enrichment: A new window into planet formation

Planets are formed from the same materials as their parent stars, yet emerge with distinctly non-stellar compositions. This is clear within the solar system, where we can see compositional patterns, yet we have only a small sample size that may not be representative of exoplanet populations. Here we make an important step to connect giant planet

composition to stellar composition for transiting planets. We study a population of relatively cool transiting gas giants below 1000 K, which are not affected by the hot Jupiter radius anomaly. Using planetary thermal evolution models, for these planets we can ascertain their bulk metallicity Z_{planet} from their masses, radii, and ages. We compare these values to Z_{star} , derived from stellar [Fe/H], to derive giant planet metal enrichments, $Z_{\text{planet}}/Z_{\text{star}}$, for a population of nearly 40 gas giants. This is the first large sample of planets for which planetary bulk composition can be compared to stellar composition. We show a number of trends of $Z_{\text{planet}}/Z_{\text{star}}$ with planetary mass and stellar [Fe/H]. These trends place new constraints on planet formation and population synthesis models and show that the enrichment of Jupiter and Saturn fit well within the exoplanet population. Intriguingly, we show that metal-enriched gas giants persist to masses of $\sim 10 M_{\text{Jupiter}}$, near the brown dwarf mass boundary, which suggests observational differences between these "super Jupiters" in orbit around stars and low-mass brown dwarfs. We suggest that new knowledge on the star-planet composition connection will be gained by relating $Z_{\text{planet}}/Z_{\text{star}}$ to the stellar abundances of other planet forming elements, like C, O, Si, and Mg.

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104.06D – Super-Earths, Warm-Neptunes, and Hot-Jupiters: Transmission Spectroscopy for Comparative Planetology

We used the Kepler, Hubble, and Spitzer Space Telescopes to probe the diversity of exoplanetary atmospheres with transmission spectroscopy, constraining atomic and molecular absorption in Jupiter- and Neptune-sized exoplanets. The detections and non-detections of molecular species such as water, methane, and carbon monoxide lead to greater understanding of planet formation and evolution. Recent significant advances in both theoretical and observational discoveries from planets like HD189733b, HD209458b, GJ436, as well as our own work with HAT-P-11b and GJ1214b, have shown that the range of measurable atmospheric properties spans from clear, molecular absorption dominated worlds to opaque worlds, with cloudy, hazy, or high mean molecular weight atmospheres. Characterization of these significant non-detections allows us to infer the existence of cloud compositions at high altitudes, or mean molecular weights upwards of $\sim 1000x$ solar. Neither scenario was expected from extrapolations of solar system analogs. We present here our published results from GJ1214b and HAT-P-11b, as well as our recent work on HAT-P-7b and HAT-P-13b. We search for evidence of atmospheric hazes and clouds, and place constraints on the relative abundance of water vapor, methane, and carbon monoxide-- in the case of cloud-free atmospheres. We conclude by discussing how our results compare to transmission spectra obtained for other similar planets, and use these combined data to develop a better understanding for the nature of these distant and alien worlds.

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104.07 – An optical transmission spectrum (4000–10000 Å) of the super-Earth GJ 1214b

One of the most surprising results of the Kepler mission has been the abundance of super-Earths (1.25–2 Earth-radii) and Neptune-sized planets (2–6 Earth-radii), including the close-in "hot" Neptunes. Given the degeneracies in mass-radius relationships, distinguishing between the diversity of worlds that may exist at this transition requires measurements of the transmission spectra of their atmospheres. The recently launched Arizona-CfA-Católica Exoplanet Spectroscopy Survey (ACCESS) is addressing this need by compiling a uniform sample of exoplanet optical transmission spectra from hot Jupiters through hot Neptunes to super-Earths, enabling comparative studies of exoplanets over a wide range of masses, radii, and irradiation conditions. Here we present our first results from a planet at the hot Neptune / super-Earth transition: an optical transmission spectrum of GJ 1214b obtained during three transits with Magellan/IMACS. We discuss the experimental techniques used to collect the spectrum, the statistical methods employed in the data analysis, and the application of the optical spectrum to proposed models of GJ 1214b's atmosphere.

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104.08 – Ground-Based Detection of Exoatmospheric Calcium

Data acquired with HDS@Subaru for HD209458b is re-analyzed. A new pipeline performs an automated search for the exoatmospheric presence of several elements without any a-priori assumptions on its existence or strength. We analyzed thousands of lines in the full spectral range of this optical echelle spectrograph using a robust method to correct for the telluric contamination. We recover previous detections of Sodium and H α , and present the first strong detection of Calcium in an Extrasolar Atmosphere as well as the tentative detection of other elements. The Calcium detection is in disagreement with theoretical thermal-equilibrium models.

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104.09 – Transit spectroscopy with JWST: Systematics, starspots and stitching

We explore the capabilities of JWST to obtain transit and eclipse spectra of a variety of exoplanets to provide constraints on their atmospheric properties, starting with hot Jupiters and Neptunes. We use the NEMESIS spectral modelling and inversion tool (Irwin et al. 2008) to calculate synthetic spectra for a range of exoplanet types from simple atmospheric models. Using a similar approach to Barstow et al. (2013), we add estimated noise levels to the synthetics before inverting the noisy spectra to check whether we accurately recover the input atmospheric state. The 5 – 12 μ m MIRI LRS instrument on JWST ($R \sim 100$) probes an important part of the infrared spectrum, especially for thermal emission; since a secondary eclipse spectrum relies on the contrast between the exoplanet and its host star, the signal is maximised at longer wavelengths. However, the spectral coverage of the LRS is insufficient to break degeneracies between temperature and composition without some constraint from other instruments. The ideal scenario would be to stitch together observations from NIRSpec ($R \sim 100$, 0.6 – 5 μ m), MIRI LRS, and MIRI MRS (integral field unit providing $R \sim 3000$ spectra across 12 gratings between 5 and 27 μ m) to form a complete spectrum with broad wavelength coverage, which would enable the temperature structure and atmospheric composition to be uniquely retrieved. This means that it is necessary to consider in our analysis systematic offsets between parts of the spectrum obtained with different instruments. These offsets may have an astrophysical origin – for example due to stellar activity or temporal variability of the planet itself – or they may be instrumental effects. We explore the influence of these noise sources on our ability to accurately retrieve the true atmospheric state from transit and eclipse spectra. We can simultaneously retrieve temperature structure and H $_2$ O, CO $_2$, and CH $_4$ abundances of a hot Jupiter orbiting a sun-like star at 250 parsecs if a single eclipse each is observed with NIRSpec and MIRI LRS.

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105 – Titan 2: Atmospheric Chemistry

105.01 – A Coupled Ion-Neutral Photochemical Model for the Titan Atmosphere

Recent observations from the Cassini-Huygens spacecraft and the Herschel space observatory drastically increased our knowledge of Titan's chemical composition. The combination of data retrieved by Cassini INMS, UVIS, and CIRS allows deriving the vertical profiles of half a dozen species from 1000 to 100 km, while the HIFI instrument on Herschel reported on the first identification of HNC. Partial data or upper limits are available for almost 20 other CHON neutral species. The INMS and CAPS instruments onboard Cassini also revealed the existence of numerous positive and negative ions in Titan's upper atmosphere.

We present the results of a 1D coupled ion-neutral photochemical model intended for the interpretation of the distribution of gaseous species in the Titan atmosphere. The model extends from the surface to the exobase. The atmospheric background, boundary conditions, vertical transport and aerosol opacity are all constrained by the Cassini-Huygens observations. The chemical network includes reactions between hydrocarbons, nitrogen and oxygen bearing species (including some species containing both nitrogen and oxygen, such as NO). It takes into account neutrals and both positive and negative ions with m/z extending up to about 100 u. Ab initio Transition State Theory calculations are performed in order to evaluate the rate coefficients and products for critical reactions.

The calculated vertical profiles of neutral and ion species generally agree with the existing observational data; some differences are highlighted. We discuss the chemical and physical processes responsible for the production and loss of some key species. We find that the production of neutral species in the upper atmosphere from electron-ion recombination reactions and neutral-neutral radiative association reactions is significant. In the stratosphere, the vertical profile of (cyano)polyynes is extremely sensitive to their heterogeneous loss on aerosols, a process that remains to be constrained experimentally and/or theoretically.

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105.02 – A Complete Understanding of Hydrocarbon Chemistry in Titan's Atmosphere: from C-1 to C-3

Propene (C₃H₆) has been missing from detection in Titan's stratosphere for nearly 30 years until recently it is unveiled by the Composite Infrared Spectrometer (CIRS) onboard Cassini spacecraft (Nixon et al., 2013). A one-dimensional photochemical model of Titan with an updated eddy diffusion profile (Li et al., 2014) is used to study its vertical profile. We find that the stratospheric mixing ratio of propene peaks at 100 km with a value of 3×10^{-9} , which is in good agreement with the Cassini observation. Another important species that is missing from the hydrocarbon family in Titan's stratosphere is allene (CH₂CCH₂), which is an isomer of propyne. Based on the photochemical model, we provide the evidence that its abundance is on the margin of detection limit. We suggest further effort in detecting allene, which will complete the family of C-3 hydrocarbons.

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105.03 – Laboratory Investigations of Titan Haze Formation: Characterization of Gas Phase and Particle Phase Nitrogen

Prior to the arrival of the Cassini-Huygens spacecraft, aerosol production in Titan's atmosphere was believed to begin in the stratosphere where chemical processes are predominantly initiated by far ultraviolet (FUV) radiation. However, the discovery of very heavy ions, coupled with Cassini Ultraviolet Imaging Spectrograph (UVIS) occultation measurements that show haze absorption up to 1000 km altitude (Liang et al., 2007), indicates that haze formation initiates in the thermosphere. The energy environment of the thermosphere is significantly different from the stratosphere; in particular there is a greater flux of extreme ultraviolet (EUV) photons and energetic particles available to initiate chemical reactions, including the destruction of N₂ in the upper atmosphere. The discovery of previously unpredicted nitrogen species in measurements of Titan's atmosphere by the Cassini Ion and Neutral Mass Spectrometer (INMS) (Vuitton et al., 2007). Additionally, measurements obtained by the Aerosol Collector Pyrolyzer (ACP) carried by Huygens to Titan's surface may indicate that Titan's aerosols contain significant amounts of nitrogen (Israël et al., 2005, 2006). The degree of nitrogen incorporation in the haze particles is important for understanding the diversity of molecules that may be present in Titan's atmosphere and on its surface.

We have conducted a series of Titan atmosphere simulation experiments using either spark discharge (tesla coil) or FUV photons (deuterium lamp) to initiate chemistry in CH₄/N₂ gas mixtures ranging from 0.01% CH₄/99.99% N₂ to 10% CH₄/90% N₂. We obtained in situ measurements using a high-resolution time-of-flight aerosol mass spectrometer (HR-ToF-AMS) to measure the particle composition as a function of particle size and a proton-transfer ion-trap mass spectrometer (PIT-MS) to measure the composition of gas phase products. These two techniques allow us to investigate the effect of energy source and initial CH₄ concentration on the degree of nitrogen incorporation in both the gas and solid phase products.

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105.04 – Modeling of synchrotron-based laboratory simulations of Titan's ionospheric photochemistry

The APSIS reactor has been designed to simulate in the laboratory with a VUV synchrotron irradiation the photochemistry occurring in planetary upper atmospheres. A N₂-CH₄ Titan-like gas mixture has been studied, whose photochemistry in Titan's ionospheric irradiation conditions leads to a coupled chemical network involving both radicals and ions. In the present work, an ion-neutral coupled model is developed to interpret the experimental data, taking into account the uncertainties on the kinetic parameters by Monte Carlo sampling. The model predicts species concentrations in agreement with mass spectrometry measurements of the methane consumption and product blocks intensities. Ion chemistry and in particular dissociative recombination are found to be very important through sensitivity analysis. The model is also applied to complementary environmental conditions, corresponding to Titan's ionospheric average conditions and to another existing synchrotron setup. An innovative study of the correlations between species concentrations identifies two main competitive families, leading respectively to saturated and unsaturated species. We find that the unsaturated growth family, driven by C₂H₂, is dominant in Titan's upper atmosphere, as observed by the Cassini INMS. But the saturated species are substantially more intense in the measurements of the two synchrotron experimental setups, and likely originate from catalysis by metallic walls of the reactors.

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105.05 – Tracing the gas composition of Titan's atmosphere with Herschel : Advances and Discoveries

The nitrogen-dominated atmosphere of Titan exhibits a great diversity and complexity of molecules and high organic material abundances. The origin of Titan atmosphere is poorly understood and its chemistry is rather complicated. In the framework of the Herschel guaranteed time key programme "Water and Related Chemistry in the Solar System" (Hartogh et al 2009), we carried out observations of the atmosphere of Titan with HIFI, PACS and SPIRE onboard Herschel (Rengel et al. 2014; Courtin et al. 2011, Moreno et al. 2011, 2012). Here we will review key results and discoveries on the atmosphere of Titan obtained with Herschel:

- an inventory of species detected including some isotopes from a new survey between 51 and 671 microns.
 - the determination of the abundance of trace constituents and comparisons with previous efforts.
 - the unexpected detection of hydrogen isocyanide (HNC), a specie not previously identified in Titan's atmosphere, and the measurement of 16O/18O ratio in CO in Titan for the first time published.
 - the determination of the vertical profile of water vapor over the 100-450 km altitude range, distribution which does not follow previous predictions and allows to strength an Enceladus' activity as the source for the current water on Titan.
- With the advent of Herschel, these advances and discoveries allow a further characterization of the complex atmosphere of Titan and help to advance the study of the abundance distribution and the investigation of a variety of processes in Titan atmosphere.

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105.06 – Spectroscopic Confirmation of Ethyl Cyanide in Titan's Atmosphere using ALMA

In the last few decades, many molecular species have been detected in the atmosphere of Titan. The first detection of a new molecule on Titan using high-resolution microwave spectroscopy was by Bézard et al. (1993), who observed multiple emission lines from methyl cyanide (CH³CN) near 221 GHz. The presence of ethyl cyanide (CH³CH²CN) has long been predicted by photochemical models, and the protonated form (CH³CH²CNH⁺) was previously inferred from Cassini INMS measurements (Vuitton et al. 2006). Here, we present the first spectroscopic detection of ethyl cyanide in Titan's atmosphere, obtained using high spectral/spatial-resolution observations carried out with the Atacama Large Millimeter/sub-millimeter Array (ALMA). We have detected over 30 rotational emission lines from CH³CH²CN in the frequency range 220-350 GHz, and will present a preliminary model for the column density, as well as maps of the CH³CH²CN distribution in Titan's daylight hemisphere.

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105.07 – C⁴N² ice in Titan's atmosphere: reality or myth?

Voyager 1 IRIS detected a spectral emission feature at 478 cm⁻¹ in Titan's atmosphere at high northern latitudes. Now one Titan year later we rediscovered it in Cassini CIRS limb spectra at 70°N. Thus far the feature has always been associated with the lower polar stratosphere during early northern spring. No known trace organic vapor in Titan's atmosphere has a spectral feature at 478 cm⁻¹, and the only known or suspected condensate that does is C⁴N² ice. However, the C⁴N² ν_8 and ν_9 vapor features at 472 cm⁻¹ and 108 cm⁻¹, respectively, have never been observed in Titan's atmosphere, leading to a C⁴N² vapor upper limit at least 2 orders of magnitude lower than equilibrium with the ice phase would suggest. In this study we analyze the spectral shapes and strengths of the 478 cm⁻¹ feature in the IRIS and CIRS data sets in an effort to determine particle sizes, mole fractions, and vertical distributions of the putative condensate cloud responsible for the feature, and then discuss the pros and cons of its identify with C⁴N² ice.

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105.08 – Condensation of Ices in Titan's Stratosphere

Processes in Titan's upper atmosphere, such as photochemical destruction of methane along with the destruction of nitrogen molecules from energetic electrons, result in the production of a number of hydrocarbon and nitrile compounds which are capable of condensing at the colder temperatures of Titan's mid to lower stratosphere. Stratospheric ices can contribute to the opacity of Titan's atmosphere as well as affect the chemistry of the more optically thick clouds seen in the troposphere, should they survive long enough to serve as condensation nuclei. There are a number of observations from both Cassini and Voyager data that point to the condensation of trace species in Titan's atmosphere, including HCN, C₂H₅CN, HC₃N, C₂H₂, C₂H₆, and C₄N₂. These and about a dozen other species have now been added to the Titan CARMA microphysics model, which shows condensation occurring between 50 and 100 km in Titan's atmosphere. Results on condensation altitudes as well as particle size will be presented, and implications for the optical properties of Titan's stratospheric aerosol particles will be discussed.

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105.09 – The surprising composition of Titan's high-altitude southern polar cloud

Titan's middle atmosphere is currently experiencing a rapid change of season after northern spring arrived in 2009. A large cloud was observed by Cassini's imaging science subsystem for the first time above Titan's southern pole in May 2012, at an altitude of 300 km (West et al., DPS 305.03, 2013). This altitude previously showed a temperature maximum and condensation was not expected for any of Titan's atmospheric gases. We analysed VIMS observations of the polar cloud and could determine its composition from near-infrared spectral features. We will present constraints on the properties of Titan's high-altitude southern polar cloud, as well as new temperature retrievals at the south pole that can help in understanding its surprising composition.

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106 – History of Planetary Astronomy: Joint Session with the AAS Historical Astronomy Division

106.01 – Origins of the Lunar and Planetary Laboratory, University of Arizona

The roots of the Lunar and Planetary Laboratory (LPL) extend deep into the rich fabric of G. P. Kuiper's view of the Earth as a planet and planetary systems as expected companions to most stars, as well as the post-war emergent technology of infrared detectors suitable for astronomy. These concepts and events began with Kuiper's theoretical work at Yerkes Observatory on the origin of the Solar System, his discovery of two planetary satellites and observational work with his near-infrared spectrometer on the then-new McDonald 82-inch telescope in the mid- to late-1940s. A grant for the production of a photographic atlas of the Moon in the mid-1950s enabled him to assemble the best existing images of the Moon and acquire new photographs. This brought E. A. Whitaker and D. W. G. Arthur to Yerkes. Others who joined in the lunar work were geologist Carl S. Huzzen and grad student E. P. Moore, as well as undergrad summer students A. B. Binder and D. P. Cruikshank (both in 1958). The Atlas was published in 1959, and work began on an orthographic lunar atlas. Kuiper's view of planetary science as an interdisciplinary enterprise encompassing astronomy, geology, and atmospheric physics inspired his vision of a research institution and an academic curriculum tuned to the combination of all the scientific disciplines embraced in a comprehensive study of the planets. Arrangements were made with the University of Arizona (UA) to establish LPL in affiliation with the widely recognized Inst. of Atmospheric Physics. Kuiper moved to the UA in late 1960, taking the lunar experts, graduate student T. C. Owen (planetary atmospheres), and associate B. M. Middlehurst along. G. van Biesbroeck also joined the migration to Tucson; Binder and Cruikshank followed along as new grad students. Astronomy grad student W. K. Hartmann came into the academic program at UA and the research group at LPL in 1961. Senior faculty affiliating with LPL in the earliest years were T. Gehrels, A. B. Meinel, H. L. Johnson, and F. J. Low, each with their own grad students and associates. Work began on IR spectroscopy and a rectified lunar atlas. Kuiper and Johnson started the search for future observatory sites in N. America and Hawaii.

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106.02 – Planetary Radio Astronomy: The 60 Years from Burke and Franklin to ALMA

For nearly 60 years, radio astronomy has played a major role in the characterization and monitoring of thermal structure, composition, and temporal changes of the planets and small bodies in our solar system. At this, the 60th anniversary of the initial detection of radio emission by a planet, the role radio astronomy has played in the early characterization of solar system objects, in raising basic scientific questions and motivating planetary exploration missions, and in providing insight into the structure and temporal variations of planets is explored. The evolution of the instrumentation capabilities from crude total-power, or bolometric measurements averaged over an entire planetary disk to today's instrumentation providing radio images of planets and comets with high spectral resolution is also discussed. Major developments such as precise total-power calibration, ultra-large apertures, microwave and millimeter-wave array technology, and supporting laboratory spectroscopy have played major roles in enhancing the effectiveness of radio astronomical observations. The newest generation instruments such as the upgraded Jansky Very Large Array (VLA) and the Atacama Large Millimeter Array (ALMA) now usher in a whole new level of capability in observation of solar system objects.

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106.03 – History of the Terminal Cataclysm Concept: A Cataclysm That Never Happened?

The “terminal cataclysm” (or “late heavy bombardment”) concept of the last 40 years exhibits curious epistemology, with changing definitions and inconsistent evidence.

Pre-Apollo evidence showed that the impact rate prior to ~3.5 Ga ago averaged ~150x the post-mare rate [1]. In 1973-4, Tera et al. [2,3] introduced the term “terminal cataclysm,” widespread metamorphism ~3.9 Ga ago, possibly caused by the Imbrium impact [3, p.15], or more likely by “formation of several major basins [in a] short time interval (less than 0.2AE)” [3, p.18]. In 1990, Ryder [4] reported a strong spike in ages for Apollo impact melt rocks ~3.8-4.0 Ga ago, and proposed this as proof that a Moon-wide cataclysmic bombardment occurred at that time, with no earlier cratering. Three inconsistencies soon appeared. (1) In 2002, Cohen et al. [5, also 2002 & 2005] dated lunar meteorite clasts (aiming at non-Apollo lunar regions) and found no spike or anomaly at 3.9 Ga. (Yet they inferred “support for the lunar cataclysm hypothesis.”) (2) The Nice model in early 2000s predicted many planetesimals scattered from the outer to the inner Solar System [6], with a plausible (unconstrained) date of 3.9 Ga - but asteroidal meteorite impact melt clasts (like lunar meteorites) show no spike at 3.9. (3) Meanwhile, reports of pre-4.0 impact melts have increased among upland breccia clasts.

Nice and Grand Tack modelers have introduced “sawteeth” spikes before 4.0 and gradual declines after 3.8 (both had been proposed earlier), thus softening the “cataclysm” spike. A 2014 model by Marchi, Bottke, Morbidelli, Kring, et al. [7] illustrates a curve of impact flux vs. time, 4.4 to 3.5 Ga, showing no spike at 3.9 Ga - signaling a possible demise of the terminal cataclysm hypothesis.

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[7] Marchi S. et al. 2014. *Nature* 511, 578-582

Author(s): William K. Hartmann¹

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106.04 – Discovery of a Previously Unrecognised Allusion to the Aurora Borealis in Paradise Lost, and Implications for Edmund Halley Scholarship

This research reveals that John Milton employed an allusion to the aurora borealis in the epic poem *Paradise Lost* which has not been recognised in more than three centuries of scholarly analysis. It further disproves the long-held belief, made popular by the astronomer Edmund Halley, that no notable aurora was visible in England in the seventeenth century. A study of the personal Latin diary of the Elizabethan historian William Camden shows that the famous aurora of 1621 was visible in England. While Pierre Gassendi has been credited with creation of the term 'aurora borealis' based on his report of the 1621 aurora, this study reaffirms a neglected analysis from 1986 that established the term originated with Galileo in 1619.

Author(s): Clifford J. Cunningham¹

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106.05 – Christiaan Huygens : Sailing and Flying on Other Worlds

In Christiaan Huygens posthumous book, "The Celestial Worlds Discover's" (1698) he lays out an optimistic vision of a universe of various worlds, some populated by beings like ourselves, and even with a few who might be scientists

wondering about the same questions. He offers, in essence, a truly modern perspective on planetary physics and astrobiology.

He notes that other worlds may have fluids forming clouds and rain, but that these fluids might be different from water, since for example Jupiter and Saturn are far from the sun and this 'water of ours' would be 'liable to frost.' He even speculates that other atmospheres might be thicker than ours, which would be favorable for the locomotion of the 'volatile animals.' Rather germane to present studies of Titan's seas and giant planet interiors, he even wonders if there might be layers of fluids of different densities : "There may also be many forts of Fluids ranged over one another in Rows as it were. The Sea perhaps may have such a fluid lying on it, which tho' ten times lighter than Water, may be a hundred Time heavier than Air".

Huygens considered that mariners on other worlds might use the same pulleys and anchors (noting essentially the universality of function of such devices) yet that other planets might have advantages or disadvantages for any given approach. Indeed, he rues how easy navigation must be on Jupiter and Saturn, having the benefit of so many moons from which Longitude could be determined (a vexing challenge of his day). He even notes that other worlds might have magnetic fields, allowing their sailors to use the compass.

As post-Cassini exploration of Titan contemplates a number of vehicle types, from hot air balloons to sailboats which can exploit the thick atmosphere and low gravity of that environment, it is fitting to recall the perspective of Titan's discoverer on other worlds as being similar, but different. The same laws of physics and logic of design apply, but with different environmental parameters and working materials.

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106.06 – Recreating Galileo's 1609 Discovery of Lunar Mountains

The question of exactly which lunar features persuaded Galileo that there were mountains on the moon has not yet been definitively answered; Galileo was famously more interested in the concepts rather than the topographic mapping in his drawings and the eventual engravings. Since the pioneering work of Ewen Whitaker on trying to identify which specific lunar-terminator features were those that Galileo identified as mountains on the moon in his 1609 observations reported in his *Sidereus Nuncius* (Venice, 1610), and since the important work on the sequence of Galileo's observations by Owen Gingerich (see "The Mystery of the Missing 2" in *Galilaean IX*, 2010, in which he concludes that "the Florentine bifolium sheet [with Galileo's watercolor images] is Galileo's source for the reworked lunar diagrams in *Sidereus Nuncius*"), there have been advances in lunar topographical measurements that should advance the discussion. In particular, one of us (E.T.W.) at the Scientific Visualization Studio of NASA's Goddard Space Flight Center has used laser-topography from NASA's Lunar Reconnaissance Orbiter to recreate what Galileo would have seen over a sequence of dates in late November and early December 1609, and provided animations both at native resolution and at the degraded resolution that Galileo would have observed with his telescope. The Japanese Kaguya spacecraft also provides modern laser-mapped topographical maps.

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110 – Comets K1 (PanStarrs) and A1 (Siding Spring)

110.01 – Probing the Molecular Complexity of Cometary Volatiles: The Case of C/2012 K1 (PanSTARRS)

Small bodies are considered to contain the most primitive material remaining from the formation of our solar system. Cometary ices trace the pristine volatile component and provide an important source of information regarding the physical and chemical conditions of the early Solar Nebula. However, not all observed species are native to the comet nucleus and some are likely formed in the coma (at least in part) with previous observations unable to ascertain the precise origin of fundamental species including H₂CO, HCN, CO, CS, and HNC. Simultaneous, spatially and spectrally-resolved molecular emission maps of comets at mm and sub-mm wavelengths provide the key information required to probe the origin and nature of these volatiles. After months of monitoring cometary activity through OH observations at the NRAO GBT and the Nançay radio telescope, we observed comet C/2012 K1 (PanSTARRS) using ALMA Bands 6 and 7, sampling emission lines from HCN, CO, CS, HCO⁺, CH₃OH, H₂CO and HNC. In order to recover any extended flux resolved out by the interferometer, we simultaneously measured HCN and CH₃OH with the APEX observatory. We will present full details of these unique observations, and an analysis of the observed spectra.

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110.02 – The CO₂ abundance in Comet C/2012 K1 (PanSTARRS) as Measured by Spitzer

One of the most abundant volatiles in cometary nuclei is CO₂. However, because of heavy atmospheric absorption due to telluric CO₂, ground-based observations of CO₂ in comets are not possible. Therefore, at the present time the only way to quantify the CO₂ abundance in comets is through space-based observations. Imaging through the 4.5 micron channel of the IRAC instrument on the Spitzer Space Telescope has proven to be an effective way to measure CO₂ production rates in comets. We present analysis of Spitzer IRAC images of Comet C/2012 K1 (PanSTARRS) obtained on UT May 25, 2014, when it was at a heliocentric distance of approximately 1.8 AU. The images show clear evidence for the presence of gas (likely CO₂, but as there is also CO emission in the band pass, a contribution from CO cannot be completely ruled out), including gas arcs in the coma morphology. We will present CO₂ production rates derived from these data. We also obtained high spectral resolution optical spectra of C/2012 K1 with the ARCES spectrometer mounted on the 3.5-meter Astrophysical Research Consortium Telescope at Apache Point Observatory one week after the Spitzer observations. We employ the ARCES observations to measure the flux ratio of the 5577 Angstrom line to the sum of the 6300 and 6364 Angstrom lines (sometimes referred to as the oxygen line ratio). Recent work suggests that the oxygen line ratio can be used as a ground-based proxy for CO₂ measurements in comets. We will compare inferred CO₂ abundances from our oxygen line ratio measurements to the "ground truth" provided by the Spitzer observations in an effort to evaluate both the applicability of the oxygen line ratio as an indirect measure of CO₂ in comets and also the abundance of CO₂ in comets in general.

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110.03 – SOFIA (+FORCAST) Infrared Spectrophotometry of Comet C/2012 K1 (PanStarrs)

Observing and modeling the properties of small, primitive bodies in the solar system whose origins lie beyond the frost line (> 5 AU) provides critical insight into the formation of the first Solar System solids and establishes observation constraints for planetary system formation invoking migration – the 'Grand Tack' epoch followed by the 'Nice Model' events – that yielded terrestrial planets in the habitable zone. The characteristics of comet dust can provide evidence to validate the new, emerging picture of small body populations – including comet families – resulting from planetary migration in the early Solar System. Here we present preliminary results of infrared 8 to 27 micron spectrophotometric observations of comet C/2012 K1 (PanStarrs), a dynamically new ($1/a < 50e-6$) Oort Cloud comet, conducted with the NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) facility during a series of three flights over the period from 2014 June 06-11 UT. During this interval comet C/2012 K1 (PanStarrs) was at a heliocentric distance of ~1.64 AU and a geocentric distance of ~1.74 AU (pre-perihelion). As a "new" comet (first inner solar system passage), the coma grain population may be extremely pristine, unencumbered by a rime and insufficiently irradiated by the Sun to carbonize its surface organics. We will discuss the derived coma grain properties inferred from modeling of the spectral energy distribution derived from the SOFIA (+FORCAST) data and highlight our preliminary conclusions. Continued observations of comets, especially dynamically young Oort Cloud targets, in the 5-37 micron infrared spectral range accessible with SOFIA (+FORCAST) will provide key observational clues to ascertaining the origins of silicates within our protoplanetary disk, and will serve to place our early disk evolution within the context of other circumstellar disks observed today that may contain the seeds of rocky, terrestrial planets.

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110.04 – Observation of Comet Siding Spring by the High Resolution Imaging Science Experiment (HiRISE) on Mars Reconnaissance Orbiter (MRO)

Comet C/2013 A1 (Siding Spring) will pass Mars at a distance of about 137,000 km on Oct 19, 2014. The primary observing campaign will be October 17 through October 21. The solar phase angle will be 108 degrees at closest approach. The NASA Mars Reconnaissance Orbiter (MRO) project has dedicated 5 days for comet observation. The MRO/HiRISE telescope has a 50 cm aperture and an instantaneous field of view of one micro-radian per pixel, so the best image have a scale of 140 m/pixel. The CCD detectors are backside illuminated with three broadband color filters. The CCDs are operated at much higher temperatures, 20C to 30C, than those used for astronomical observations, so the

exposure time is limited to maximum of about 2.5 seconds.

While HiRISE will observe +/-60 hours with respect to closest approach(CA), the prime nucleus data will be obtained +/-2 hours wrt CA. It is expected that the nucleus and inner coma will be detected in both the red and blue-green channels.

Preliminary results of the HiRISE observations will be presented.

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110.05 – Hubble Space Telescope View of Comet C/2013 A1

Comet C/2013 A1 (Siding Spring) is a dynamically new comet whose physical and chemical status should be the least evolved since the formation of comets during the planetary system formation processes. Its close encounter with Mars on October 19, 2014 at a distance of 138,000 km allows for imaging its nucleus and inner coma by MRO/HiRISE at 140 m/pix resolution. Such an encounter offers us the opportunity to do cometary flyby science for a dynamically new comet for the first time ever. We observed C/Siding Spring using Hubble Space Telescope (HST) from October 2013 to March 2014 when the comet was at 4.58, 3.77, and 3.28 AU from the Sun, and will observe it again during its close encounter with Mars at 1.40 AU heliocentric distance. One of the objectives of these observations is to study the long-term evolution of the dust coma of C/Siding Spring, including its dust features and color, in order to provide context for better understanding the evolution of the activity of a dynamically new comet from the “flyby” observations during its Mars encounter. Our early observations show that C/Siding Spring’s coma contains two dust features, and the spatial distribution and temporal evolution of the color of its coma are consistent with the existence of icy grains. New observations to be performed during the encounter will reveal the evolution of the dust features and color from previously observed, as well as any newly developed features. We will report our results from the HST observations, including the preliminary results from the encounter observations.

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110.06 – NASA/IRTF, Chandra, and HST Observations of Comet C/2013 A1 (Siding Spring)’s Encounter with Mars

On Oct 19th of this year, circa 18:30 UT, dynamically new Oort Cloud comet C/2013 A1 (Siding Spring) will fly within 138,000 km of the planet Mars. This distance is so small (~1/3 the mean Earth-Moon distance, and 16 times closer than any comet has approached the Earth in the modern spaceflight era) that Mars will be moving through the comet's outer atmosphere, or coma, carrying Mars, and its orbiting and ground based roving spacecraft fleet with it. In this way the Mars fleet will be participating in a close comet flyby, and in addition to supporting the encounter by leading NASA's CIOC campaign, our group is also obtaining remote sensing observations of the comet in September - October 2014. We have received 5 partial days of observing time in late September at the NASA/IRTF facility, when the comet is brightest from the Earth, to use the SPeX NIR spectrometer at 2-5 um to characterize the comet's pre-encounter gas and dust production contemporaneously with the BOPPS balloon mission. During the encounter, we will use 54 ksec of Chandra time and 10 orbits of HST time to monitor the comet's nucleus, dust, and the comet-Mars gas/ion interaction and x-ray emission. Both the comet and Mars are known x-ray emitters, and Mars' flight through the comet's outer coma downstream wrt the solar wind suggests there will be an important transfer of energy, neutrals, and ions into the Martian exosphere, likely enhancing the Martian x-ray signal.

In this paper we report on our preliminary results from our IRTF, Chandra, and HST observations and put them in context with other measurements taken during the 2014 Comet Siding Spring Observing Campaign.

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110.07 – TRAPPIST monitoring of comet C/2013 A1 (Siding Spring)

C/2013 A1 (Siding Spring) is a long period comet discovered by Robert H McNaught at Siding Spring Observatory in

Australia on January 3, 2013 at 7.2 au from the Sun. This comet will make a close encounter with Mars on October 19, 2014. At this occasion the comet will be extensively observed both from Earth and from several orbiters around Mars. On September 20, 2013 when the comet was around 5 au from the Sun, we started a monitoring with the TRAPPIST robotic telescope installed at La Silla observatory [1]. A set of narrowband cometary filters designed by the NASA for the Hale-Bopp Observing Campaign [2] is permanently mounted on the telescope along with classic Johnson-Cousins B, V, Rc, and Ic filters.

We observed the comet continuously at least once a week from September 20, 2013 to April 6, 2014 with broad band filters. We then recovered the comet on May 20. At this time we could detect the gas and started the observations with narrow band filters until early November, covering the close approach to Mars and the perihelion passage.

We present here our first results about comet Siding Springs. From the images in the broad band filters and in the dust continuum filters we derived $A(?)_f$ values [3] and studied the evolution of the comet activity with the heliocentric distance from September 20, 2013 to early November 2014.

We could also detect gas since May 20, 2014. We thus derived gas production rates using a Haser model [4]. We present the evolution of gas production rates and gas production rates ratios with the heliocentric distance.

Finally, we discuss the dust and gas coma morphology.

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110.08 – A Smorgasbord of Comet Narrowband Photometry: Results from 209P/LINEAR, PanSTARRS (2012 K1), Jacques (2014 E2), and Siding Spring (2013 A1)

We report on narrowband filter observations of four comets obtained or scheduled to be obtained from Lowell Observatory in 2014. Comet 209P/LINEAR is a recently discovered Jupiter-family object -- implying it either has a very small size or has very low activity -- and our measurements reveal the latter option to be the case, with a water production rate near perihelion of only 2.5×10^{25} molecules/s, the smallest value we've detected.

The associated active area is less than 0.01 km^2 and, combined with a nucleus size based on radar measurements, the active fraction is only about 0.03%. Similar to several other heavily evolved Jupiter-family comets, LINEAR has a "typical" chemical composition, thus providing further evidence that carbon-chain depletion seen in other comets is not a consequence of evolution.

Comet PanSTARRS (2012 K1) was observed four consecutive months prior to its conjunction with the Sun, with a final water production rate at 1.9 AU of 9×10^{28} molecules/s, along with a relatively low dust-to-gas ratio. Comet Jacques (2014 E2) was observed shortly after discovery in March and again in April, revealing a very low dust-to-gas ratio; further observations are scheduled for late August and September.

Finally, while we have no data in-hand, measurements of Comet Siding-Spring (2013 A1) are planned for mid-October, including the nights surrounding its encounter with Mars. A summary of results from these campaigns will be presented.

This research is supported by NASA's Planetary Astronomy Program.

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110.09 – The Water Production Rate of Recent Comets (2013-2014) by SOHO/SWAN: 2P/Encke (2013), C/2013 R1 (Lovejoy), and C/2013 A1 (Siding Spring)

The all-sky hydrogen Lyman-alpha camera, SWAN (Solar Wind Anisotropies), on the SOlar and Heliospheric Observatory (SOHO) satellite makes observations of the hydrogen comae of comets. Most water vapor produced by the comet is ultimately photodissociated into two H atoms and one O atom producing a huge atomic hydrogen coma that is routinely observed in the daily full-sky SWAN images in comets of sufficient brightness. Water production rates are calculated using our time-resolved model (Mäkinen & Combi, 2005, Icarus 177, 217), typically yielding about 1 observation every 2 days on the average. Here we describe the progress in analysis of observations of comets observed during 2013-2014 and those selected from the archive for analysis. These include comets 2P/Encke (2013), 45P/Honda Mrkos-Pajdusakova (2011), C/2013 R1 (Lovejoy), as well as C/2013 A1 (Siding Spring), for which results are expected. A status report on the entire SOHO/SWAN archive of water production rates in comets will be given. SOHO is an international cooperative mission between ESA and NASA. Support from grants NNX11AH50G from the NASA Planetary Astronomy Program and NNX13AQ66G from the NASA Planetary Mission Data Analysis Program are gratefully acknowledged.

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111 – Exoplanet Atmospheric Retrieval

111.01 – Transit Spectroscopy: new data analysis techniques and interpretation

Planetary science beyond the boundaries of our Solar System is today in its infancy. Until a couple of decades ago, the detailed investigation of the planetary properties was restricted to objects orbiting inside the Kuiper Belt. Today, we cannot ignore that the number of known planets has increased by two orders of magnitude nor that these planets resemble anything but the objects present in our own Solar System.

A key observable for planets is the chemical composition and state of their atmosphere. To date, two methods can be used to sound exoplanetary atmospheres: transit and eclipse spectroscopy, and direct imaging spectroscopy.

Although the field of exoplanet spectroscopy has been very successful in past years, there are a few serious hurdles that need to be overcome to progress in this area: in particular instrument systematics are often difficult to disentangle from the signal, data are sparse and often not recorded simultaneously causing degeneracy of interpretation.

We will present here new data analysis techniques and interpretation developed by the “ExoLights” team at UCL to address the above-mentioned issues. Said techniques include statistical tools, non-parametric, machine-learning algorithms, optimized radiative transfer models and spectroscopic line-lists.

These new tools have been successfully applied to existing data recorded with space and ground instruments, shedding new light on our knowledge and understanding of these alien worlds.

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Contributing team(s): ExoLights, ExoMol

111.02 – Tau-REx: A new look at the retrieval of exoplanetary atmospheres

The field of exoplanetary spectroscopy is as fast moving as it is new. With an increasing amount of space and ground based instruments obtaining data on a large set of extrasolar planets we are indeed entering the era of exoplanetary characterisation. Permanently at the edge of instrument feasibility, it is as important as it is difficult to find the most optimal and objective methodologies to analysing and interpreting current data. This is particularly true for smaller and fainter Earth and Super-Earth type planets.

For low to mid signal to noise (SNR) observations, we are prone to two sources of biases: 1) Prior selection in the data reduction and analysis; 2) Prior constraints on the spectral retrieval. In Waldmann et al. (2013), Morello et al. (2014) and Waldmann (2012, 2014) we have shown a prior-free approach to data analysis based on non-parametric machine learning techniques. Following these approaches we will present a new take on the spectral retrieval of extrasolar planets.

Tau-REx (tau-retrieval of exoplanets) is a new line-by-line, atmospheric retrieval framework. In the past the decision on what opacity sources go into an atmospheric model were usually user defined. Manual input can lead to model biases and poor convergence of the atmospheric model to the data. In Tau-REx we have set out to solve this.

Through custom built pattern recognition software, Tau-REx is able to rapidly identify the most likely atmospheric opacities from a large number of possible absorbers/emitters (ExoMol or HiTran data bases) and non-parametrically constrain the prior space for the Bayesian retrieval.

Unlike other (MCMC based) techniques, Tau-REx is able to fully integrate high-dimensional log-likelihood spaces and to calculate the full Bayesian Evidence of the atmospheric models. We achieve this through a combination of Nested Sampling and a high degree of code parallelisation. This allows for an exact and unbiased Bayesian model selection and a fully mapping of potential model-data degeneracies.

Together with non-parametric data de-trending of exoplanetary spectra, we can reach an unprecedented level of objectivity in our atmospheric characterisation of these foreign worlds.

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111.03 – A Uniform Retrieval Analysis of Transit Transmission Spectra: Quantifying the detection of Clouds, Hazes and Water

Transit transmission spectra observations allow us to probe the composition and scale heights of the terminator regions of extra solar planet atmospheres. We know that clouds and hazes are ubiquitous in our solar system planets.

Furthermore, recent observations have suggested that clouds and hazes may play an important role in sculpting exoplanet transmission spectra. Previous modeling of these data has focused on simple pre-computed data-model comparisons with little statistical rigor or an exact quantification of the detection significances of water, clouds or hazes. We undergo a uniform retrieval analysis of several transit transmission spectra (HD189733b, HD209458b, WASP12b GJ436b, GJ1214b) making use of all available space-based data sets for a given planet, mainly the Hubble Space Telescope Wide Field Camera-3 and the Space Telescope Imaging Spectrograph, in order to quantitatively determine the impact of clouds and hazes on transmission spectra. We will quantify for the first time, within a nested Bayesian model comparison framework, the detection significances of clouds, hazes, and water for planets that span a wide range of

effective temperatures and radii. Finally, we will explore the role that clouds and hazes can have in influencing our ability to retrieve the water abundances from transmission spectra.

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111.04 – An Open-Source Bayesian Atmospheric Radiative Transfer (BART) Code, and Application to WASP-12b

Atmospheric retrievals for solar-system planets typically fit, either with a minimizer or by eye, a synthetic spectrum to high-resolution (??/? ~ 1000-100,000) data with S/N > 100 per point. In contrast, exoplanet data often have S/N ~ 10 per point, and may have just a few points representing bandpasses larger than 1 μm . To derive atmospheric constraints and robust parameter uncertainty estimates from such data requires a Bayesian approach. To date there are few investigators with the relevant codes, none of which are publicly available. We are therefore pleased to announce the open-source Bayesian Atmospheric Radiative Transfer (BART) code. BART uses a Bayesian phase-space explorer to drive a radiative-transfer model through the parameter phase space, producing the most robust estimates available for the thermal profile and chemical abundances in the atmosphere. We present an overview of the code and an initial application to Spitzer eclipse data for WASP-12b. We invite the community to use and improve BART via the open-source development site GitHub.com. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G. JB holds a NASA Earth and Space Science Fellowship.

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111.05D – Bayesian Atmospheric Radiative Transfer (BART) Thermochemical Equilibrium Abundance (TEA) Code and Application to WASP-43b

We present a new, open-source, Thermochemical Equilibrium Abundances (TEA) code that calculates the abundances of gaseous molecular species. TEA uses the Gibbs-free-energy minimization method with an iterative Lagrangian optimization scheme. It initializes the radiative-transfer calculation in our Bayesian Atmospheric Radiative Transfer (BART) code. Given elemental abundances, TEA calculates molecular abundances for a particular temperature and pressure or a list of temperature-pressure pairs. The code is tested against the original method developed by White et al. (1958), the analytic method developed by Burrows and Sharp (1999), and the Newton-Raphson method implemented in the open-source Chemical Equilibrium with Applications (CEA) code. TEA is written in Python and is available to the community via the open-source development site GitHub.com. We also present BART applied to eclipse depths of WASP-43b exoplanet, constraining atmospheric thermal and chemical parameters. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G. JB holds a NASA Earth and Space Science Fellowship.

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111.06D – Bayesian Atmospheric Radiative Transfer (BART): Model, Statistics Driver, and Application to HD 209458b

Multi-wavelength secondary-eclipse and transit depths probe the thermo-chemical properties of exoplanets. In recent years, several research groups have developed retrieval codes to analyze the existing data and study the prospects of future facilities. However, the scientific community has limited access to these packages. Here we premiere the open-source Bayesian Atmospheric Radiative Transfer (BART) code. We discuss the key aspects of the radiative-transfer algorithm and the statistical package. The radiation code includes line databases for all HITRAN molecules, high-temperature H₂O, TiO, and VO, and includes a preprocessor for adding additional line databases without recompiling the radiation code. Collision-induced absorption lines are available for H₂-H₂ and H₂-He. The parameterized thermal and molecular abundance profiles can be modified arbitrarily without recompilation. The generated spectra are integrated over arbitrary bandpasses for comparison to data. BART's statistical package, Multi-core Markov-chain Monte Carlo (MC3), is a general-purpose MCMC module. MC3 implements the Differential-evolution Markov-chain Monte Carlo algorithm (ter Braak 2006, 2009). MC3 converges 20-400 times faster than the usual Metropolis-Hastings MCMC algorithm, and in addition uses the Message Passing Interface (MPI) to parallelize the MCMC chains. We apply the BART retrieval code to the HD 209458b data set to estimate the planet's temperature profile and molecular abundances. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G. JB holds a NASA Earth and Space Science Fellowship.

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111.07D – The Elemental Compositions and Cloud Properties of Hot Jupiters: A Comprehensive Atmospheric Retrieval Study of Hot Jupiter Transmission Spectra

Recent transit surveys using the Hubble Space Telescope have provided an unprecedented set of high-SNR hot Jupiter transmission spectra. Here, I present the main conclusions from a comprehensive atmospheric retrieval study of eight hot Jupiters using the new self-consistent atmospheric retrieval framework SCARLET. For each planet, I derive statistically robust constraints on the metallicity and carbon-to-oxygen ratio of the atmospheric gas, as well as the particle size and vertical extend of clouds and hazes, by combining self-consistent modeling of the atmospheric chemistry and physics with robust Bayesian statistics.

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111.08 – Interpreting Gemini Planet Imager Spectroscopy of the Young Giant Planets HR 8799 c and d

During the first-light run of the Gemini Telescope's newest facility instrument, the Gemini Planet Imager (GPI), K-band spectra of exoplanets HR 8799 c and d were obtained. Combined with previous ground based multi-band photometry and spectroscopy, the new datasets place strong constraints on the atmospheric composition, cloud properties, and thermal profile of these two giant planets. Comparison of the data to our newest atmospheric models confirms that thick clouds combined with horizontal variation in the cloud cover is required to best reproduce the planets' spectral energy distributions. The data also provide further evidence that future modeling efforts must include cloud opacity, possibly including cloud holes, disequilibrium chemistry, and super-solar metallicity. In short there is now little doubt these planets are as complex and dynamic as the giants of our own solar system. In our presentation we will not only discuss the challenges of characterizing these objects but will also look forward to the future of exoplanet direct imaging by both GPI and SPHERE.

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Contributing team(s): The Gemini Planet Imager Collaboration

111.09 – Cloud signatures in transit spectra of exoplanet atmospheres

We present an analytical model for the transmission spectrum of a transiting exoplanet, extending previous models to incorporate condensation cloud base and top. We show that a cloud base (position where the cloud evaporates) can produce an observable inflection point in the spectrum. The wavelength and magnitude of the inflection can be used to break the degeneracy between the atmospheric pressure and the abundance of the cloud-forming material (for a given cloud particle size); moreover, we can derive the abundance of the cloud constituent by measuring the magnitude of the inflection drop. An observed inflection also provides a specific point on the atmospheric P-T profile, giving us a thermometer to directly validate or rule out postulated cloud species. We have applied the model to the transit spectrum of HD189733b, where we identify a possible inflection and examine its implications about the T-P profile of the atmosphere and the abundance of the candidate cloud material.

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112 – Titan 3: Surface Composition and Hydrology

112.01 – Spectral Characteristics of Titan's Surface

Cassini/Huygens and ground-based measurements of Titan reveal an eroded surface, with lakes, dunes, and sinuous washes. These features, coupled with measurements of clouds and rain, indicate the transfer of methane between Titan's surface and atmosphere. The presence of methane-damp lowlands suggests further that the atmospheric methane (which is continually depleted through photolysis) may be supplied by sub-surface reservoirs. The byproducts of methane photolysis condense onto the surface, leaving layers of organic sediments that record Titan's past atmospheres.

Thus knowledge of the source and history of Titan's atmosphere requires measurements of the large scale compositional makeup of Titan's surface, which is shrouded by a thick and hazy atmosphere. Towards this goal, we analyzed roughly 100,000 spectra recorded by Cassini's Visual and Infrared Mapping Spectrometer (VIMS). Our study is

confined to the latitude region (20S—20N) surrounding the landing site of the Huygens probe (at 10S, 192W), which supplied only measurement of the vertical profiles of the methane abundance and haze scattering characteristics. VIMS near-IR spectral images indicate subtle latitudinal and temporal variations in the haze characteristics in the tropics. We constrain these small changes with full radiative transfer analyses of each of the thousands of VIMS spectra, which were recorded of different terrains and at different lighting conditions. The resulting models of Titan's atmosphere as a function of latitude and year indicate the seasonal migration of Titan's tropical haze and enable the derivation of Titan's surface albedo at 8 near-IR wavelength regions where Titan's atmosphere is transparent enough to allow visibility to the surface. The resultant maps of Titan's surface indicate a number of terrain types with distinct spectral characteristics that are suggestive of atmospheric and surficial processes, including the deposition of organic material, erosion of sediments and potential sources of methane.

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Contributing team(s): Cassini VIMS team

112.02 – Surface of Titan : model and VIMS observations

The Huygens probe has allowed to describe the atmosphere and the surface of Titan in detail. To date, the surface reflectivity as observed by DISR is not fully understood.

In this work, we first propose a model of the surface reflectivity made of a layer of ice covered by a layer of fluffy aerosols. This well explains the observed surface reflectivity by DISR, with a reflectivity having a maximum (peak) at 750 nm and a blue slope at longer wavelength and a red slope at shorter wavelength. Our model essentially relies on our ability to model the radiative transfer inside the continuous layer of aerosol sedimented at the surface. However, we also find a shift in the reflectivity peak between the surface reflectivity as observed by DISR and the results obtained when using the aerosol refractive index of airborne aerosols. We propose an explanation for this effect.

The second part of the work consists in checking the data. We find that this shift in the reflectivity peak also exists in the data. Using a model of radiative transfer, with a description of the atmosphere properties derived from analysis made by Huygens instruments, we are able to reproduce the intensity observed by VIMS, and we can retrieve the surface albedo. We essentially focus on the area around Huygens landing site, and we characterize the differences between the bright and dark zones.

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112.03 – Mapping the Atmospheric and Surface Properties of Titan by the Massive Inversion of Cassini/VIMS Spectra

Since the beginning of the Cassini mission, the imaging spectrometer VIMS has acquired ~40000 hyperspectral images of Titan containing several millions of spectra. Such a huge amount of data cannot be analyzed with a radiative transfer solver like SHDOM because of computational limits. Nevertheless, such a solver is the most suited tool to extract simultaneous information of the atmosphere and the surface of Titan from VIMS datacubes. We have developed a method of analyzing VIMS data that consents to use the power of a RT model without the inconvenience of long computational times, by the creation of look-up tables for different values of the RT model's parameters (geometry of the observation, surface albedo, aerosols opacity). We employ up-to-date information on gaseous spectral coefficients, aerosols' optical properties and Titan's climatology. These look-up tables, appropriately interpolated, are then used to minimize the observations and create simultaneous maps of aerosols opacity and of surface albedo (at the wavelengths of Titan's spectral windows). This method lowers the computational time by a factor of several thousands and thus, for the first time, a truly massive treatment of VIMS data. In this paper we present the results of our method applied to the area of the Huygens landing site and their comparison with the results of other Cassini instruments. We also show the retrieved maps of a region observed multiple times at different Cassini flybys with different observational conditions, as the T13/T17 mosaic of the Atzlan area. The perspectives for atmospheric and surface seasonal monitoring are highlighted.

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112.04 – The interaction of benzene and ethylene under Titan surface conditions

Previously, we have reported the discovery and characterization of a new co-crystal formed from benzene and ethane (Vu et al. 2014 J. Phys Chem. A 118, 4087; Cable et al. 2014 GRL 41, doi:10.1002/2014GL060531). This co-crystal would be thermodynamically stable on Titan's surface, and forms easily from the interaction of liquid ethane and solid benzene, as well as from the evaporation of benzene saturated solutions of ethane. These results imply that the benzene-ethane co-crystal may be an important component of Titan's evaporate deposits. The formation of these kinds of organic co-crystals may influence evaporite characteristics, such as particle size and infrared spectral properties.

Here, we report our most recent experiments exploring the interaction between benzene and ethylene. Ethylene has been detected in Titan's atmosphere, and some photochemical models predict a significant flux to the surface. We performed experiments examining the interaction of liquid ethylene with solid benzene under Titan-like conditions (90-150 K and 1 bar N₂), using micro-Raman spectroscopy and optical microscopy. We will present Raman spectra and vibrational analyses of the interaction, and implications for Titan's surface chemistry and evolution.

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112.05 – The methane distribution on Titan: high resolution spectroscopy in the near-IR with Keck NIRSPEC/AO

The distribution of methane on Titan is a diagnostic of regional scale meteorology and large scale atmospheric circulation. The observed formation of clouds and the transport of heat through the atmosphere both depend on spatial and temporal variations in methane humidity. We have performed observations to measure the the distribution on methane Titan using high spectral resolution near-IR (H-band) observations made with NIRSPEC, with adaptive optics, at Keck Observatory in July 2014. This work builds on previous attempts at this measurement with improvement in the observing protocol and data reduction, together with increased integration times. Radiative transfer models using line-by-line calculation of methane opacities from the HITRAN2012 database are used to retrieve methane abundances. We will describe analysis of the reduced observations, which show latitudinal spatial variation in the region the spectrum that is thought to be sensitive to methane abundance. Quantifying the methane abundance variation requires models that include the spatial variation in surface albedo and meridional haze gradient; we will describe (currently preliminary) analysis of the the methane distribution and uncertainties in the retrieval.

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112.06 – Ground Based Monitoring of Cloud Activity on Titan

We will report on the latest results of an on-going ground based monitoring campaign of Saturn's moon Titan using the SINFONI (Spectrograph for INtegral Field Observations in the Near Infrared) instrument on the Very Large Telescope (VLT). Presently, much is still unknown about the complex and dynamic hydrologic system of Titan as observations have yet to be made through an entire Titan year (29.7 Earth years). Because of the limited ability to observe Titan with Cassini, a combined ground and spaced-based approach provides a steady cadence of observation throughout the duration of a Titan year. We will present the results of observations to date using the adaptive optics (AO) mode (weather dependent) of SINFONI. We have been regularly observing Titan since April 2014 for the purpose of monitoring and identifying clouds and have also been in collaboration with the Cassini team that has concurrent ISS observations and historical VIMS observations of clouds. Our discussion will focus on the various algorithms and approaches used for cloud identification and analysis. Currently, we are entering into a very interesting time for clouds and Titan hydrology as Saturn moves into north polar summer for the first time since Cassini entered the Saturnian system. The increased insolation that this will bring to the north, where the majority of the liquid methane lakes reside, will give us our first observations of the potentially complex interplay between surface liquid and atmospheric conditions. By carefully monitoring and characterizing clouds (size, optical depth, altitude, etc.) we will also be able to derive constraints that can help to guide and validate GCMs. Since the beginning of our observations, no clouds have been observed through ground based observations, while Cassini has only observed a single cloud event in the north polar region over Ligeia Mare. We will provide an update on the latest results of our cloud monitoring campaign and discuss how this atmospheric inactivity and the frequency and characteristics of future cloud outbursts enhances our current understanding of Titan's hydrologic system.

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112.07 – Frozen Hydrocarbon Ponds on Titan: Implications for Titan's Lakes and Seas

Cassini Imaging Science Subsystem (ISS) observations have detected widespread darkening of Titan's surface believed to be the result of rainfall: in 2005 at Arrakis Planitia, near Titan's south pole (Turtle et al., 2009, GRL 36, L02204), and in 2009 in Titan's tropics (Turtle et al., 2011, Science 331, 1414–1417). Cassini Visual and Infrared Mapping Spectrometer (VIMS) and ISS observations revealed that, following the tropics storm, the albedo of the wetted surfaces increased, beyond even their original albedo, then slowly faded back to a pre-rain brightness over ~10 months (Barnes et al., 2013, Planet. Sci. 2, 1). Herein we report on combined analysis of Cassini VIMS, Synthetic Aperture Radar (SAR), and ISS observations of Arrakis Planitia acquired in the years following the 2005 precipitation event. The low-albedo surface (observed in 2005 ISS images) correlates with local topography (inferred from 2008 SAR data), consistent with a liquid that has pooled on the surface. Like the equatorial event, the low-albedo surface at Arrakis Planitia is observed in VIMS data acquired from 2007 to 2009 to increase in albedo. Unlike the tropics event, however, four years after the initial precipitation event (more than 2 years after the increased albedo was first observed), these south-polar regions were still bright compared to their pre-precipitation albedo. The combined results support the hypothesis that hydrocarbons rained onto Titan's surface and subsequently froze. Furthermore, because Titan's lakes and seas are almost certainly liquid, our results imply that some mechanism is preventing Titan's lakes and seas from freezing – one obvious hypothesis is that Titan's lakes and seas differ in composition from Titan's presumed methane-rich rain (likely the result of the concentration of minor constituents).

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112.08 – The Flushing of Ligeia: Composition variations in a simple hydrological model of Titan's Seas

I use a simple box model to explore possible differences in the liquid composition of Titan's seas. Major variations in the abundance of involatile ethane, somewhat analogous to salinity in terrestrial waters, arise from the hydrological cycle, which introduces more “fresh” methane rainfall at the highest latitudes in summer. The observed composition of Ligeia Mare, flushed by methane rainfall and exporting its solutes to Kraken via a narrow labyrinth of channels, may have a methane-rich (>80%) composition, well out of thermodynamic equilibrium with the atmosphere, whereas the basins of Kraken are relatively well mixed and will have an ethane-dominated (60%) composition. These variations, analogous to Earth's salinity gradient between the Black Sea and the Mediterranean, may be detectable with Cassini measurements and are important for future exploration.

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112.09 – The Depth, Composition, and Sea State of Titan's Mare

On August 21st, 2014, the Cassini spacecraft will perform its 104th flyby of Titan. The T104 fly-by will present a unique opportunity to sound the depth of Titan's largest sea - Kraken Mare, and characterize the sea state of both Kraken and Ligeia Mare. Based on the recent May 2013 (T91) nadir observations of Ligeia Mare, which were used to construct a bathymetric profile and determined the sea's loss tangent, we expect to detect echoes from both the surface and seafloor of Kraken with the opportunity to derive the depth and composition of this sea. In addition, the T104 observations will be interpreted in the context of wave activity. On Earth, it is rare to observe a body of water whose surface is not disturbed by some form of wave activity. On Titan, Cassini observations through the end of its Equinox Mission in Dec. 2010 showed no indication of waves. These observations are intriguing given the predominance of aeolian features at equatorial latitudes and have been attributed to the light winds predicted during the Titan winter. More recently, however, the previous series of upper limits and non-detections are giving way to indications that the expected freshening of winds in northern summer may be causing sporadic ruffling of the sea surfaces. Specifically, apparent sunglints offset from the geometric specular point has been observed by VIMS in Punga Mare and a transient radar signature, known as Titan's “Magic Island”, has been observed over the surface of Ligeia Mare. The T104 observation will be acquired at an incidence angle that will either confirm or deny the Magic Island's transient nature.

We will present a summary of the discoveries made during the T104 flyby, which represents one of the most exciting Titan observations of the Cassini mission and has the potential to significantly enhance our understanding of Titan's methane cycle. The discussion will address the total volume of liquid hydrocarbon contained in Titan's lakes and seas, the sea state of the Mare as Saturn approaches northern summer, and address the origin of a recent transient feature (the Magic Island) observed in Ligeia Mare in July 2013.

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Contributing team(s): Cassini Radar Science Team

113 – Sun-grazing Comet ISON

113.01 – Coma Chemistry of Sun-grazing Comets

The recent apparition of comet C/2012 S1 (ISON), and its disruption during perihelion passage, has motivated numerous observations of the associated variations in the gas and dust composition. More generally, comet ISON has regenerated interest in the physics and chemistry of Sun-grazing comets. Chemical models of cometary comae have typically always been developed to model comets at about 1 AU and beyond [1]. Apart from one early coma chemistry model [2], which calculated the coma chemistry of a comet at 0.125 AU with assumed single-fluid physics, there have been no detailed studies of coma chemistry at the small heliocentric distances experienced by comet ISON and other Sun-grazing comets. In this contribution we will discuss the various physical and chemical processes that have to be considered when modeling the comae of Sun-grazing comets. We will present comet models in which the physical and chemical structures of the multi-fluid flow are calculated self-consistently [3] as a function of decreasing heliocentric distance.

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113.02 – Gas Distributions in Comet ISON's Coma: Concurrent Integral-Field Spectroscopy and Narrow-band Imaging.

At a solar distance of 0.44 AU, Oort cloud comet C/2012 S1 (ISON) exhibited an outburst phase that was observed by small telescopes at the McDonald Observatory. In conjunction with narrow-band (14Å) imaging over a wide-field, an image-slicer spectrograph (R~20,000) simultaneously measured the spatial distribution of ISON's coma over a 1.6 x 2.7 arcminute field made up of 246 individual spectra. More than fifty emission lines from C², NH², CO, H₂O⁺ and Na were observed within a single Echelle order spanning 5868Å to 5930Å. Spatial reconstructions of these species reveal that ISON's coma was quite elongated several thousand km along the axis perpendicular to its motion. The ion tail appeared distinctly broader than the neutral Na tail, providing strong evidence that Na in the coma did not originate by dissociative recombination of a sodium bearing molecular ion. Production rates increased from $1.6 \pm 0.3 \times 10^{23}$ to $5.8 \pm 1 \times 10^{23}$ Na atoms/s within 24 hours, outgassing much less than comparable comets relative to ISON's water production. The anti-sunward Na tail was imaged >10⁶ km from the nucleus. Its distribution indicates origins both near the nucleus and in the dust tail, with the ratio of these Na sources varying on hourly timescales due to outburst activity.

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113.03D – Model Interpretation of Measured Water Rotational Temperatures and Column Abundances in the Coma of Comet C/2012 S1 (ISON)

While Comet ISON did not live up to its expectations in term of spectacle for the public, the large scientific interest for this comet led to an important global observational effort. Water rotational temperatures and column densities at several distances from the nucleus projected on the sky plane for observations on November 15 to 18, and November 22 by CSHELL at NASA IRTF. The first set of observations, while the comet was at 0.53 AU from the Sun, showed a slow drop in both rotational temperature and column abundance, with a strong asymmetry in the continuum anti-sunward. Also, the rotational temperature and column abundance profiles appear to be poorly correlated suggesting that an extended source of water plays a critical part in the coma of comet ISON.

Following the work applied to Comet 73P/Schwassmann-Wachmann 3 –B (SW3) from Fougere et al. (2012), we analyze the results of the measurements of comet ISON using the Direct Simulation Monte-Carlo model from Tenishev et al. (2008, 2011) with the use of sublimating “dirty” icy grains taking into account the electron-H₂O collision heating and

atmospheric seeing. Starting with a 1D model, we give constraints on the different parameters used in the simulation. Then, we extend to a 2D model in order to explain the day/night asymmetry observed.

While comet ISON was a very different comet than SW3, the inclusion of icy grains and electron-H₂O collision heating to the model also considerably improves the agreement between model and observations. The different geometry and spatial resolution of these new observations with respect to the measurements of SW3 from Bonev et al. (2008) enabled us to explore the competition between heating and cooling processes at a different spatial scale that was done in previous work.

Acknowledgements:

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Tenishev et al. 2008 *ApJ* 685:659, and 2011 *ApJ* 732:104

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114 – Exoplanet Eclipses and Phase Curves from Kepler

114.01 – Studying Atmosphere-Dominated Kepler Phase Curves

We identify three Kepler transiting planet systems, Kepler-7b, Kepler-12b, and Kepler-41b, whose orbital phase-folded light curves are completely dominated by atmospheric processes including thermal emission and reflected light, while the impact of other processes, beaming (Doppler boosting) and tidal ellipsoidal distortion, is negligible. Therefore, these systems allow a direct view of their atmospheres, in visible light, without being hampered by the approximations used in the inclusion of both atmospheric and non-atmospheric processes while modeling the phase curve shape. We model Kepler-12b and Kepler-41b atmosphere based on their Kepler phase curve, while the modeling of Kepler-7b was already presented elsewhere. We confirm Kepler-12b and Kepler-41b show a westward phase shift between the brightest region on the planetary surface and the substellar point, similar to Kepler-7b. We find that reflective clouds located on the west side of the substellar point can best explain the phase shift. The identification of a bright-spot shift in all three systems we studied suggests it occurs also in other phase curves, where both atmospheric and non-atmospheric effects are present and where accounting for it can present a degeneracy in the model. Finally, the relatively large albedo measured for these three transiting planets suggests that the photometric modulations induced by reflected light in non-transiting but otherwise similar planets can be used to detect them, although their mass is too small to show a signal from non-atmospheric processes.

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114.02 – A Study of Kepler Phase Curves and Secondary Eclipses

We study phase curves and secondary eclipses of Kepler planets. Our sample consists of confirmed planets with $R_p > 4 R_e$, $P < 10d$, and $V_{mag} < 15$. Our analysis models the ellipsoidal, Doppler, and phase curve variations in the light curves as well as their secondary eclipses. From this we constrain the temperatures and albedos of these planets. Our results confirm and in most cases improve parameters derived by previous studies. We present results for Kepler 1b-8b, 12b-15b, 17b, 40b, 41b, 43b, 44b, 76b, 77b, and 412b derived in a consistent manner. All of the planets studied have geometric albedos less than .33, and half have geometric albedos less than .2. This work was supported in part by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G. This paper includes data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission Directorate. The data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX13AC07G and by other grants and contracts.

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114.03 – Statistical Eclipses of Close-in Kepler Sub-Saturns

We present a method to detect small atmospheric signals in Kepler's planet candidate light curves by averaging light curves for multiple candidates with similar orbital and physical characteristics. Our statistical method allows us to

measure unbiased physical properties of Kepler's planet candidates, even for candidates whose individual signal-to-noise precludes the detection of their secondary eclipse. For a group of 31 close-in sub-Saturn ($R < 6$ Earth radii) planet candidates, we find an average geometric albedo of 0.22 ± 0.06 if the eclipses are due to reflected light alone. Including a thermal emission model does not change the geometric albedo appreciably, assuming the Bond albedo is $2/3$ of the geometric albedo. This result suggests that sub-Saturns are typically less reflective than the highly reflective Kepler-10b and Kepler-78b. Our result also suggests that hot Neptune-like planets are more reflective than the typical hot Jupiters.

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115 – Titan 4: Surface Geology

115.01D – Is Titan's Dune Orientation Controlled by Tropical Methane Storms?

Titan's equatorial regions are covered by eastward oriented linear dunes. This direction is opposite to mean surface winds simulated by Global Climate Models (GCMs) at these latitudes, oriented westward as trade winds on Earth [1, 2]. Here, we propose that Titan's dune orientation is actually determined by equinoctial tropical methane storms producing a coupling with superrotation and dune formation. Using meso-scale simulations of convective methane clouds [3, 4] with a GCM wind profile featuring the superrotation [5, 6], we show that Titan's storms should produce fast eastward gust fronts above the surface. Such gusts dominate the aeolian transport. Using GCM wind roses and analogies with terrestrial dune fields [7], we show that Titan's dune growth occurs eastward under these conditions. Finally, this scenario combining global circulation winds and methane storms can explain other major features of Titan's dunes (i.e. divergence from the equator, size and spacing).

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115.02 – Production Mechanisms for the Sand on Titan and the Prospects for a Global Sand Sea

With ~15% of its surface covered by sand seas, Titan turns out to be the Arrakis of the solar system. How the sand particles that make up the dunes are created, however, remains an outstanding question. Titan's haze particles are organic in composition as required by spectral analysis of dunes, however they have diameters of ~1 μ m, and are 10,000,000 times too small by mass to directly represent the ~200- μ m sand particles. In addition to previous suggestions that sand could come from sintering of sand particles or by burial, lithification, and subsequent erosion (more like typical sands on Earth), we suggest two new mechanisms for production of sand in association with Titan's liquid reservoirs. Dissolution and reprecipitation as evaporite forms the gypsum dunes of White Sands, NM, USA on Earth, and could play a role on Titan as well. Alternatively, haze particles in the lakes and seas could aggregate into larger particles via flocculation, a mechanism seen to occur on Earth in Morocco. Each of these sand particle production ideas has associated predictions that can be tested by future observations. The lack of evident sand sources in VIMS data implies that Titan's sand seas may be old and their continuous interconnectedness across the Dark Equatorial Belt implies that all of the equatorial dunefields may represent a single compositionally uniform sand sea. We will present possibilities for sands from this sea to bridge the large gap across Xanadu, including barchan chains and fluvial transport.

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115.03 – Fluvial Erosion of Craters on Titan

There are few identifiable impact craters on Titan, especially near the polar regions. One explanation for this observation is that the craters are being destroyed through hydrological processes, such as weathering, fluvial incision and deposition. In this work, we use a landscape evolution model to determine whether or not this is a viable mechanism for crater destruction on Titan. We find that fluvial degradation can modify craters to the point where they would be unrecognizable by an orbiting spacecraft such as Cassini, given enough time and a large enough weathering rate. It can also remove central peaks and fill in central pits, possibly explaining their absence in Titan craters. If fluvial degradation is the dominant mechanism destroying craters on Titan, then the 80 km diameter crater Soi is on average twice as old as the similarly sized crater Sinlap, and the 40 km diameter crater on Shikoku Facula is on average five times as old as the similarly sized crater Momoy. There has likely been some infilling by sand in these craters, so these age differences represent upper limits. Nonetheless, since all of these craters are located in Titan's extensive sand seas, the difference in depths suggests there is a range of crater ages on the surface of Titan.

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115.04 – Fluvial Erosion and Transportation of an Impact Regolith Layer: Implications for Titan

Large regions of Titan appear to be eroded cratered terrain. If this is correct, then Titan's surface could have been characterized by a regolith hundreds of meters thick with abundant unconsolidated debris in the size range that could be fluvially transported and serving as tools for bedrock incision. We utilized a variant on our Landform Evolution Model, originally developed to understand fluvial erosion on Mars, to study this issue. We see two end-member results. Slopes covered with coarse grained material develop a drainage network that essentially becomes stabilized after a sufficient time. They become paved with gravel that can only be eroded very slowly, if at all, after some degree of erosion. Simulations with finer sediment (for example with the maximum grain size only 16 mm) the flow can transport a good bit of sediment throughout the simulation, and drainage basins are initially created, but the topography evolves into a gentle slope of parallel drainage. For gravel channel systems under high sediment transport situations, there is no downstream concavity - the channels are essentially uniform in slope so that no drainage basins form. However, for coarser sediment we are near the threshold of motion near the end of the simulation, and channel gradients decrease downstream, implying a well-developed drainage network will form. However, if boulders are intermixed with the fines (which is reasonable), upland surfaces could eventually become mantled with a pavement of coarse debris after differential removal of transportable sediment, thus limiting net erosion unless a weathering (rock-disintegrating) process occurs on Titan. Titan's fluvial networks could have been quickly established, then become somewhat impervious to further landscape evolution even if the precipitation rates and intensities persisted for long times.

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115.05D – GCM Simulations of Titan's Paleoclimate

The hemispheric asymmetry observed in the distribution of Titan's lakes and seas has been suggested to be the result of asymmetric seasonal forcing, where a relative moistening of the north occurs in the current epoch due to its longer and less intense summers. General circulation models (GCMs) of present-day Titan have also shown that the atmosphere transports methane away from the equator. In this work, we use a Titan GCM to investigate the effects that changes in Titan's effective orbital parameters have had on its climate in recent geologic history. The simulations show that the climate is relatively insensitive to changes in orbital parameters, with persistently dry low latitudes and wet polar regions. The amount of surface methane that builds up over either pole depends on the insolation distribution, confirming the influence of orbital forcing on the distribution of surface liquids. The evolution of the orbital forcing implies that the surface reservoir must be transported on timescales of ~30 kyr, in which case the asymmetry reverses with a period of ~125 kyr. Otherwise, the orbital forcing is insufficient for generating the observed dichotomy.

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200 – Comet Dust, Tails, Trails, and Oddballs

200.01 – Gradients in dust chemical composition in protoplanetary disks: analogies with the Solar System

Clues to planet-forming processes are provided by the properties of the dust grains in protoplanetary disks and in cometary nuclei in our own Solar System. We present a compositional analysis of the 10 μ m and 20 μ m silicate emission features for young protoplanetary disks around FGKM stars. We find an increase in the crystallinity levels towards larger radii, such that the median crystalline mass fraction is higher in the outer cold disk region compared to the inner warm parts of the disk. For nearly 80% of the disks, the mass fraction of small ISM-like dust grains is negligible (< 5%) in the outer cold disk region. The median crystalline mass fraction in disks around late-type stars is found to be a factor of \sim 2 higher than the median for the higher mass FGK type stars. The relatively high abundance of crystalline silicates in the outer cold regions of protoplanetary disks provides an interesting analogy to comets. In this context, we will discuss the applicability of the various mechanisms that have been proposed for comets on the formation and the outward transport of high-temperature material. A (weak) anti-correlation between the X-ray emission strength and the extent of crystallinity in the disk is observed, suggesting X-rays to be an important dust amorphization agent in these disks. This work has highlighted the ubiquity of Solar System like chemical signatures in young protoplanetary disks, and suggests that protoplanets that form closer to a low-mass star can have a different chemical composition from those that formed farther away.

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200.02 – C/2013 P2 Pan STARRS - The Manx Comet

On Aug 4, 2013 an apparently asteroidal object was discovered by the Pan STARRS1 (PS1) survey telescope on Haleakala at magnitude $g \sim 20.4$ (corresponding to a nucleus radius between 1.4-2.9 km for albedos between 0.25-0.04). PS1 pre-recovery images taken on July 26 and on Aug. 3 allowed a good orbit to be determined. The orbit looks like that of a long-period comet with a semi major axis of 2720 AU and an eccentricity of 0.999. Shortly following the discovery, reports from small telescopes came in that there was low level activity associated with this object (at $r = 3.45$ AU), and the object was designated P/2013 P2 (Pan STARRS). The activity was not seen in images obtained with PS1, the Faulkes N telescope or the CFHT 3.6m, however the object was passing through a region of significant nebulosity. Deep images obtained on the CFHT on Aug. 8 and follow up images obtained with the Gemini North 8m telescope on Sep. 9 showed a very faint tail extending a few arcsec to PA=45 deg (inconsistent with the earlier reports). The object was observed using several facilities up until solar conjunction, and again after perihelion (Feb. 17, 2014) in March, with little increase in activity. A search of the NEOWISE archives show no detection during the cryogenic and immediate pos-cryogenic phases, so we can only place an upper limit on the nucleus size from these data. An object on a long-period comet orbit at this heliocentric distance typically should be very active, and our team hypothesized that this could either be a nearly-extinct comet or possibly inner solar system material ejected to the outer solar system during planet migration as predicted by various dynamical models. To distinguish between these scenarios, we obtained both optical and near-IR spectra of P/2013 P2 on 2014 May 7 and 21, when the object was at $r=2.97$ and 2.99 AU, respectively. Initial reductions show no emission lines. We will report on our spectra and imaging data, and discuss the implications for the origin of this object. This work was supported in part by the NASA Astrobiology Institute.

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200.03 – Discovery of the Fast Spinning Main Belt Comet (62412) 2000 SY178

The outer main belt asteroid (62412) 2000 SY178 exhibited a faint tail in images taken during our deep survey for objects beyond the Kuiper Belt with the Dark Energy Camera (DECam) on the CTIO 4 meter telescope. The orbit of 62412 suggests it is the first known active asteroid in the Hygiea family. Follow-up observations at the Magellan telescope found 62412 has a neutral color consistent with C-type asteroids. Time-resolved observations from Magellan show 62412 has a very fast rotation period of about 3.33 hours from a double-peaked light curve. The peak-to-peak amplitude of 0.45 magnitudes suggests 62412 is an elongated object with an a to b axial ratio greater than 1.51. We identify 62412 as the fastest known rotator of the Hygiea family and the nearby Themis family of similar composition, which contains several known main belt comets. The activity on 62412 is seen over 1 year after perihelion passage in its 5.6 year orbit. Because 62412 has the highest perihelion and one of the most circular orbits known for any main belt comet, the activity may not be caused by ice sublimation alone. We believe the rapid rotation of 62412 is part of the reason for the observed activity and suggest it has caused the shape and thus surface to shift, exposing ices that may then sublimate away. This is different than previous explanations of main belt comet activity such as an impact exposing buried ice. Assuming 62412 is a strength-less rubble pile near the critical period for rotational fission, we find the density of 62412 must be greater than 2200 kg/m³. This density is significantly higher than for comets thought to be from the Kuiper Belt or Oort Cloud. Thus MBCs are not related to the objects in these more distant reservoirs, which

must have formed in very different environments. This work is now in press at the *Astronomical Journal*.

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200.04 – Rotational Disruption of Comets with Parabolic Orbits

One of the most fundamental problems in planetary science is the natural lifetime of comets, which is limited by several processes, most notably by spontaneous disruption of the nucleus. While the underlying mechanism is uncertain, rapid rotation is often suspected. To address this problem, I derived the probability of rotational disruption, and investigated it for comets with parabolic orbits as a function of perihelion distance and nucleus size for a range of input parameters. The disruption probability is defined as the ratio of expected change in the rotation rate to the allowable span of the rotation rate, the latter being limited by the critical rotation rate (prograde and retrograde), which I adopted from Davidsson (2001, *Icarus* 149, 375). The expected change in the rotation rate, resulting from the action of torques generated by mass loss, is calculated following the standard approach (e.g. Drahus et al. 2011, *ApJL* 734, L4, and ref. therein), but taking into account the suspected decrease of the net torque with an increasing active fraction of the nucleus (Jewitt 1997, *EM&P* 79, 35; Samarasinha & Mueller 2013, *ApJL* 775, L10). The sublimation flux is obtained from the standard energy balance equation (e.g. Cowan & A'Hearn 1979, *M&P* 21, 155), but I also take into account extinction of sunlight in the dust coma. I find that close to the Sun coma transmission steeply decreases with a decreasing heliocentric distance, resulting in the sublimation flux at a remarkably constant level, and also that coma transmission decreases with an increasing nucleus size, both properties being critically important in the calculation of sublimation flux for large sungrazers. The obtained rotational-disruption probability features several interesting properties. It has a well-defined regime occupied by smaller comets closely approaching the Sun, for which rotational disruption is unavoidable regardless of the original rotation state. Moreover, the probability function offers a very close match to the empirical survival cutoff for long-period comets with perihelia of less than 0.5 AU (Bortle 1991, *ICQ* 13, 89), independently suggesting that rotational disruption is the primary mechanism responsible for the destruction of comets.

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200.05D – A Novel, Sublimation-Driven YORP-like Effect, and The Formation of Dust Striae in Cometary Tails

The dust tails of some great comets exhibit linear dust features that align with the Sun (striae). Striae are thought to form from icy chunks of dust ejected from the nucleus that are delayed in time before fragmenting [1]. Models show that striae formation is best fit through a mechanism of continuous fragmentation [2], but the physical mechanism responsible for this delayed fragmentation is unknown. We propose that striae form through a novel rotational fragmentation mechanism driven by the sublimation of volatile ices present in the ejected chunk.

We note that sublimating gas molecules scatter off of the surface of a non-specular material similarly to photons (i.e. Lambertian scattering), however gas molecules carry significantly more momentum. By comparing the momentum flux from a sublimating gas with solar radiation pressure, we are able to scale the YORP timescale [3] to derive its sublimation-driven equivalent. We find that this Sublimative YORP-like timescale is significantly shorter than the YORP timescales by 4-5 orders of magnitude for H₂O sublimation.

We apply this mechanism to Comet West, which exhibited prominent striae in its dust tail. For ejected dust clumps to drift behind the nucleus to form the observed dust striae near 0.4 AU, [1] estimated the β -parameter of the chunks (ratio of solar radiation to solar gravitational forces) to be between 0.6 and 2.4. We equate this to a new parameter β_{sub} (the ratio of dynamic sublimation to solar gravitational forces), which corresponds to icy chunks with radii of 5-20 cm, consistent with chunks ejected from Comet Wild 2 [4]. The sublimation-driven YORP timescales for chunks of this size is 1-3 hours, which allows for a cascade of rotational spin-up and fragmentation of daughter chunks to occur within the ~50-85 hour delay [1] between chunk ejection and striae formation. Thus, Comet West's dust tail striae are consistent with this novel rotational fragmentation mechanism, which is driven by the sublimation of volatile ices.

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[3] Jacobsen et al. (2014) *MNRASL* 439, L95-L99

[4] Kelley et al. (2013) *Icarus* 222, 634-652

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200.06 – Observations of Comet P/2003 T12 = 2012 A3 (SOHO) at large phase angle in STEREO-B

Comet P/2003 T12 = 2012 A3 (SOHO) was observed by the satellite STEREO-B during the period 2012 January 13-27.

During its apparition, it ventured into the highest phase angle ever observed for a comet, and the forward-scattering enhancement in brightness was marked, as large as ≈ 8.5 mag. Therefore, it provided a precious opportunity to examine the compound Henyey-Greenstein (HG) comet-dust light-scattering model and it also offered valuable polarization data under an unprecedented observing geometry. Our analysis reveals that the compound HG model fits the observations very well until the phase angle exceeds $\approx 173^\circ$, where the brightness surge of the comet was obviously steeper than the prediction by the model. We have found that the reason for the greater steepness cannot be explained by contaminations from the proximal tail. Instead, the model of Mie spheres with radii greater than $1 \mu\text{m}$, having a power-law distribution of power index ≈ 3 , matches the observation very well, providing a best-fitting complex refractive index $\tilde{m} = 1.38 + i 0.006$. The dust size was found to be consistent with the analysis of the comet's syndyne lines. The debiased polarization of the coma was ≈ 0 per cent in the phase angle range from 172.9° to 177.6° . No convincing evidence of temporal variation of the polarization was detected.

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200.07 – 209P/LINEAR: a peacefully demising comet?

Comet 209P/LINEAR made one of the closest cometary approaches to the Earth in May 2014. It is also responsible for the Camelopardalid meteor outburst which occurred on May 24, 2014. Here we report the optical/infrared observations of 209P/LINEAR and radar observations of the meteor outburst. Continuous monitoring of 209P/LINEAR with the XOSS facilities from Feb to May 2014 reveals the lowest perihelion dust production level of any comet on record, with $A_f \rho \ll 1$ cm. Spectroscopic observation with Gemini GMOS-N at T0-27 days also reveals very low gas emission rates of 8×10^{22} mol/s for CN, $< 3 \times 10^{22}$ mol/s for C₂, and $< 2 \times 10^{23}$ mol/s for C₃. Infrared imaging with the Gemini Flamingos-2 revealed an anti-solar fan-like tail that cannot be explained by viewing geometry. At the Earth, the Canadian Meteor Orbit Radar (CMOR) observed 105 multi-station Camelopardalid meteor echoes during 0 - 24 h UT May 24, showing a mass distribution index of $s = 1.86 \pm 0.02$, appropriate to meteors of magnitude $\sim 6-7$. We also identified 63 overdense meteor trails in CMOR data which showed a mass distribution index of $s = 2.12 \pm 0.02$, appropriate to meteors of magnitude $\sim > 4$. The large difference in the mass index in different magnitude ranges indicates that the Camelopardalid meteoroids do not follow power law distribution at mm-sizes. Considering that the outburst was caused by direct encounters with multiple dust trails released in the 1800s and 1900s, the low visual/radar flux of the outburst ($\sim 0.02 \text{ hr}^{-1} \text{ km}^{-2}$ from IMO visual data; $\sim 0.06 \text{ hr}^{-1} \text{ km}^{-2}$ from CMOR data) may indicate that P/LINEAR has been largely inactive in the past few centuries, supporting the idea that the comet is currently transitioning into a dormant/extinct comet.

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200.08 – Extended Solar System Structures Observed by WISE

Extended structures associated with recent asteroid collisions and comets were detected by the Infrared Astronomical Satellite, which conducted the first survey of the thermal emission of the sky in 1983. Twenty-seven years later, the Wide-field Infrared Survey Explorer (WISE), conducted a more sensitive survey of the sky at wavelengths spanning the shorter IRAS bandpasses and detected many of these same structures. Initial identifications include asteroid dust bands associated with collisions giving rise to the Karin and Beagle clusters within the Koronis and Themis asteroid families, respectively. An additional pair of bands is associated with the collision giving rise to the Veritas asteroid family. Comet trails associated with short-period comets have also been observed. Type 2 trails, detected by IRAS and possibly associated with asteroid collisions within the past few thousand years, have yet to be identified. Because WISE is significantly more sensitive than IRAS in the mid-infrared, it has detected some trails extending much further over their orbits and will greatly expand the catalog of trails detected in addition to those observed by IRAS and Spitzer (the latter by targeted observations). WISE and the yet more sensitive NEOCAM survey telescope will provide important insights into the recent collisional history of the asteroid belt and the nature and evolution of comets.

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200.09D – Studying Short-Period Comets and Long-Period Comets Detected by WISE/NEOWISE

The Wide-field Infrared Survey Explorer (WISE) mission surveyed the sky in four infrared wavelength bands (3.4, 4.6, 12 and 22-micron) between January 2010 and February 2011 [1, 2]. During the mission, WISE serendipitously observed 160 comets, including 21 newly discovered objects. About 89 of the comets observed by WISE displayed a significant dust tail in the 12 and 22-micron (thermal emission) bands, showing a wide range of activity levels and dust morphology. Since the observed objects are a mix of both long-period comets (LPCs) and short-period comets (SPCs), differences in their

activity can be used to better understand the thermal evolution that each of these populations has undergone. For the comets that displayed a significant dust tail, we have estimated the sizes and ages of the particles using dynamical models based on the Finson-Probstein method [3, 4]. For a selection of 40 comets, we have then compared these models to the data using a novel tail-fitting method that allows the best-fit model to be chosen analytically rather than subjectively. For comets that were observed multiple times by WISE, the dust tail particle properties were estimated separately, and then compared. We find that the dust tails of both LPCs and SPCs are primarily comprised of ~mm to cm sized particles, which were the result of emission that occurred several months to several years prior to the observations. The LPCs nearly all have strong dust emission close to the comet's perihelion distance, and the SPCs mostly have strong dust emission close to perihelion, but some have strong dust emission well before perihelion.

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201 – Exoplanet Orbital Dynamics and the Future

201.01D – Extraterrestrial Planet Formation in the Time Domain

We present a detailed analysis of the first real-time detection of a planetary collision outside the solar system, observed with Spitzer at 3.6 and 4.5 μ m around a 35-Myr-old solar analog star. The collision is indicated by a substantial brightening in the debris disk around the star, after which the output showed significant quasi-periodic variations on monthly timescales, on top of a decay over a year. This event appears to arise from an impact between planetesimals or planet embryos, which produced a dense cloud of dust possibly condensed from silica-rich vapor. An overview of the infrared monitoring of other similar systems, most of which are in the age range of terrestrial planet formation, suggests that such variations may be common in extreme debris disks around solar-like stars.

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201.02 – Binary Planets

Can a bound pair of similar mass terrestrial planets exist? We are interested here in bodies with a mass ratio of $\sim 3:1$ or less (so Pluto/Charon or Earth/Moon do not qualify) and we do not regard the absence of any such discoveries in the Kepler data set to be significant since the tidal decay and merger of a close binary is prohibitively fast well inside of 1AU. SPH simulations of equal mass “Earths” were carried out to seek an answer to this question, assuming encounters that were only slightly more energetic than parabolic (zero energy). We were interested in whether the collision or near collision of two similar mass bodies would lead to a binary in which the two bodies remain largely intact, effectively a tidal capture hypothesis though with the tidal distortion being very large. Necessarily, the angular momentum of such an encounter will lead to bodies separated by only a few planetary radii if capture occurs. Consistent with previous work, mostly by Canup, we find that most impacts are disruptive, leading to a dominant mass body surrounded by a disk from which a secondary forms whose mass is small compared to the primary, hence not a binary planet by our adopted definition. However, larger impact parameter “kissing” collisions were found to produce binaries because the dissipation upon first encounter was sufficient to provide a bound orbit that was then rung down by tides to an end state where the planets are only a few planetary radii apart. The long computational times for these simulation make it difficult to fully map the phase space of encounters for which this outcome is likely but the indications are that the probability is not vanishingly small and since planetary encounters are a plausible part of planet formation, we expect binary planets to exist and be a non-negligible fraction of the larger orbital radius exoplanets awaiting discovery.

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201.03 – Constraints on Exomoon Formation

It has been widely accepted that the Earth's moon formed by a giant impact during the late stage of the planetary formation process. The giant impact led to the formation of a debris disk around the Earth from which the Moon accreted. This type of satellite formation is considered to be common not only in the solar system (e.g., the Pluto-Charon system) but also in extrasolar systems (e.g. Ogihara & Ida 2009). However, no detailed research has been conducted on impact-induced exomoon formation. Wada et al. (2006) suggest that a vapor-rich disk is dynamically unstable and that it may not be suitable for moon formation. If this is the case, the mass and composition of a planet may affect the satellite formation process. Here, we show results from giant impact simulations of planets with various masses and compositions. We use the model suggested by Nakajima & Stevenson (2014) to estimate the vapor mass fractions of the disks. We find that the more massive and the more ice-rich the planet is, the higher the vapor mass fraction of the disk becomes. This indicates there is an upper limit of the planetary mass to form an impact-induced moon and the limit depends on the planetary composition. This upper limit is a few Earth masses for a rocky planet, and about an Earth mass for an icy planet. These results are consistent with the models that Earth's and Pluto's satellites formed by impacts. Although no exomoon has been detected yet, our model may be used to predict whether an observed terrestrial exoplanet could potentially have one or multiple impact-induced exomoons.

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201.04 – Detection and Characterization of Non-Transiting Planets from Transit Timing Variations

The Transit Timing Variations (TTVs) can be used as a diagnostic of gravitational interactions between planets in a multi-planet system. Here we conduct a photo-dynamical analysis of several Kepler Objects of Interest (KOIs) that exhibit significant TTVs. We show that KOI-142, KOI-227 and KOI-319 are (at least) two planet systems. KOI-142.01's TTVs uniquely detect a non-transiting companion with a mass 0.63 that of Jupiter. KOI-142.01's mass inferred from the TTVs is consistent with the measured transit depth, suggesting a Neptune-class planet. The orbital period ratio 2.03 indicates that the two planets are just wide of the 2:1 resonance. For KOI-319 and KOI-884, the observed TTVs of the inner transiting planet are used to detect an outer non-transiting planet. The outer planet in KOI-884 is 2.6 Jupiter masses and has the orbital period just narrow of the 3:1 resonance with the inner planet (orbital period ratio 2.93). The distribution of parameters inferred from KOI-319.01's TTVs is bimodal with either a 1.6 Neptune-mass planet wide of the 5:3 resonance (period 80.1 d) or a Saturn-mass planet wide of the 7:3 resonance (period 109.2 d). The radial velocity measurements can be used in this case to determine which of these parameter modes is correct. We discuss how the orbital architecture of KOI-142, KOI-227 and KOI-319 systems constrains their formation.

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201.05 – Compositional Constraints on the Best-Characterized Rocky Exoplanet, Kepler-36 b

Kepler-36 is an extreme planetary system, consisting of two transiting sub-Neptune-size planets orbiting around a sub-giant star with periods of 13.84 and 16.24 days. Mutual gravitational interactions between the two planets perturb the planets' transit times, allowing the planets' masses to be measured. Despite the similarity of their masses and orbital radii, the planets show a stark contrast in their mean densities: The inner planet (Kepler-36 b) is more than eight times as dense as its outer companion planet (Kepler-36 c). We perform a photo-dynamical analysis of the Kepler-36 system based on more than three years of Kepler photometry. With N-body integrations of initial conditions sampled from the photo-dynamical fits, we further refine the properties of the system by ruling out solutions that show large scale instability within 5 billion days. Ultimately, we measure the planets' masses with 4.2% precision and the planets' radii with 1.8% precision. Kepler-36 b is the rocky exoplanet with the most precisely measured mass and radius. Kepler-36 b's mass and radius are consistent with an Earth-like composition, whereas an iron-enhanced Mercury-like composition is ruled out.

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201.06 – Characterizing Low-Mass Planets in Kepler's Multi-Planet Systems with Transit Timing

The Kepler mission has revealed an abundance of planets in a regime of mass and size that is absent from the Solar System. This includes systems of high multiplicity within 1 AU, where low-mass volatile-rich planets have been observed in compact orbital configurations. Smaller, rocky planets have also been observed in such systems. The existing sample of characterized planets on the mass-radius diagram shows no abrupt transition from rocky planets to those that must be volatile-rich, but characteristic trends are beginning to emerge. More precise characterizations of planets by mass, radius, and incident flux will aid in revealing fundamental properties of a common class of exoplanets.

There is a small sample of exoplanets with known masses and radii, mostly hot jupiters whose radii are known from transit depths, and whose masses are determined from radial velocity spectroscopy (RV). In the absence of mass determinations via RV observations, transit timing variations (TTVs) offer a chance to probe perturbations between planets that pass close to one another or are near resonance, and hence dynamical fits to observed transit times can be used to measure planetary masses and orbital parameters. Such modelling with Kepler data probes planetary masses over orbital periods ranging from ~5-100 days, complementing the sample of RV detections. Furthermore, in select cases, dynamical fits to observed TTVs can tightly constrain the orbital eccentricity vectors, which can, alongside the transit light curve, tightly constrain the density and radius of the host star, and hence reduce the uncertainty on planetary radius.

TTV studies have revealed a class of low-mass low-density objects with a substantial mass fraction in the form of a voluminous H-rich atmosphere. To these we add precise mass measurements of the outer planets of Kepler-33, a compact system with five known transiting planets, three of which show detectable transit timing variations. These results will be placed in the context of other mass-radius measurements for planets of similar size and orbital periods to provide a summary of our knowledge to date.

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201.07 – The potential of GPI extreme AO system to image and characterize exoplanets and asteroids

The Gemini Planet Imager (GPI) is a next-generation adaptive optics coronagraph designed for direct imaging and spectroscopy of extrasolar planets, polarimetry of circumstellar disks and solar system planets. It is the first such facility-class instrument deployed on a 8-m telescope, designed to achieve contrast levels of up to 10^7 .

On the first commissioning observations (2013B), we achieved an estimated H band Strehl ratio of 0.89 and a 5-sigma contrast of 10^6 at 0.75 arcseconds. Observations of Beta Pictoris (Macintosh et al. PNAS 2014) clearly detect the planet, Beta Pictoris b, in a single 60-second exposure with minimal post-processing. These observations were taken covering the H-band (1.65 μ m).

A H-band spectrum of Beta Pic b presented in Chilcote et al. (2014) with a resolving power of ~ 45 and demonstrates the distinctive triangular shape of a cool substellar object with low surface gravity leading to an effective temperature of 1650 ± 50 K and a surface gravity of $\log(g) = 4.0 \pm 0.25$ (cgs units).

We will also present the analysis of observations of (2) Pallas observed in direct imaging (without coronagraph) on March 22 2014 in Y, J, H, and K1 filters (from 0.95 to 2.19 μ m) spectroscopically with a resolution varying from 34 to 70. The 540-km asteroid is well resolved and irregular. An ellipse of 540 ± 9 mas and 470 ± 9 mas fits its silhouette. The surface of the asteroid is mostly featureless but small differences of colors is currently being analyzed. No moons with a diameter larger than 2 km and at least 480 km from Pallas were detected on these observations.

These results show the power of a dedicated extreme AO with high-contrast imager, low resolution spectrograph and polarizer. A 600-star survey of young nearby stars led by B. Macintosh will begin in 2014B to produce a sample of directly imaged planets that spans a broad range of temperatures, ages, and masses and probes the range of semi-major-axes and stellar ages inaccessible to Doppler and transit surveys. Similarly a program to map ~ 30 -40 large main-belt asteroids and search for companions around them will be initiated in 2015A.

This work is funded by NASA NNX14AJ80G

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Contributing team(s): Gemini Planet Imager Science Team

201.08 – Exoplanet Frequency from Kepler, and Implications for AFTA

Using my estimate of the frequency of exoplanets as functions of planet radius and period, based on data from the Kepler mission, I estimate the yield of new planets that might be discovered by the WFIRST-AFTA direct-imaging coronagraph instrument.

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202 – Education

202.01 – NASA's Big Events: A Framework for Public Engagement

Through the education and communication programs in its Science Mission Directorate (SMD), NASA supports many nation-wide and international public engagement programs aimed at increasing public interest and scientific literacy in

space and Earth science. These programs key off of celestial and space mission events as well as historical dates and celebrations and achieve enormous reach (10's to 100's of millions annually) and impact through the involvement of numerous partners and networks of partners including NASA Field Centers and space missions, museums and science centers, schools and school districts, broadcast media, community groups, professional societies, and amateur astronomers. A summary of recent Big Events includes the Transit of Venus, the launches of LADEE and MAVEN, the MSL/Curiosity landing on Mars, and the arrival of Comet ISON. Through this presentation, we will discuss the strategies employed by NASA to stimulate public interest on large scales and preview upcoming NASA Big Events.

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202.02 – Preliminary Results from a Survey of DPS Scientist's Attitudes, Activities and Needs in Education and Public Outreach

The NASA SMD Planetary Sciences Forum, in partnership with the AAS DPS Education officer has conducted a semi-structured series of interviews with two-dozen DPS members to ascertain: the nature E/PO activities pursued by scientists, what resources and professional development opportunities are needed by scientists, how to increase the impact of scientists' E/PO efforts, scientists' concerns and questions regarding E/PO, and what we can do to identify opportunities to address these issues, both from the SMD and DPS perspectives. Members were contacted by phone, and responded to a loose script of questions over a time span of 20 to 90 minutes, depending on the individual. Members were chosen to represent a variety of career experience, home institutions and affiliations, and level of involvement with E/PO. Questions included: What is your level of involvement in E/PO? What sort of professional development or resources would you like to have to increase the efficiency of your E/PO efforts? What barriers to E/PO involvement have you encountered? How do you use social media in your E/PO efforts, if at all? What are your motivations for involvement in E/PO? etc. Our results are consistent with previous research conducted regarding this issue, but they do offer insight specific to the nature of DPS members and their views about E/PO. We will present a subset of these results, the opportunities they present, and the responses of both the PS Forum and the DPS. Based on this survey, the SMD PS Forum was able to identify specific new resources needed by scientists, and therefore developed the brief-one page guides, "The Quick Introduction to Education and Public Outreach," and "Making the Most of Your E/PO Time – Increasing Your Efficiency and Impact." Further resources and professional development opportunities will be developed as the data continue to be reviewed. This data collection effort is ongoing. If you would like to become involved, contact Jennifer Grier, jgrier@psi.edu.

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202.03 – Introducing Slide Sets for the Introductory Astronomy Instructor

The NASA Science Mission Directorate (SMD) Science Education and Public Outreach (E/PO) community and Forums work together to bring the cutting-edge discoveries of NASA Astrophysics and Planetary Science missions to the introductory astronomy college classroom. These mission- and grant-based E/PO programs are uniquely poised to foster collaboration between scientists with content expertise and educators with pedagogy expertise. We present two new opportunities for college instructors to bring the latest NASA discoveries in Space Science into their classrooms. In an effort to keep the astronomy classroom apprised of the fast moving field of planetary science, the Division of Planetary Sciences (DPS) has developed "DPS Discoveries", which are short, topical presentations that can be incorporated into college lectures. The slide sets are targeted at the Introductory Astronomy undergraduate level. Each slide set consists of three slides that cover a description of the discovery, a discussion of the underlying science, and a presentation of the big picture implications of the discovery, with a fourth slide that includes links to associated press releases, images, and primary sources. Topics span all subdisciplines of planetary science, and sets are available in Farsi and Spanish. The NASA SMD Planetary Science Forum has recently partnered with the DPS to continue producing the Discovery slides and connect them to NASA mission science. <http://dps.aas.org/education/dpsdisc> Similarly, the NASA SMD Astrophysics Forum is coordinating the development of a series of slide sets to help Astronomy 101 instructors incorporate new discoveries in their classrooms. The "Astro 101 slide sets" are presentations 5-7 slides in length on a new development or discovery from a NASA Astrophysics mission relevant to topics in introductory astronomy courses. We intend for these slide sets to help Astronomy 101 instructors include new developments (not yet in their textbooks) into the broader context of the course. <http://www.astrosociety.org/education/astronomy-resource-guides/>

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202.04 – Citizen Science in Planetary Sciences: Intersection of Scientific Research and Amateur Networks

The Pro-Am Collaborative Astronomy (PACA) project evolved from the observational campaign of C/2012 S1 or C/ISON in 2013. Following the success of the professional-amateur astronomer collaboration in scientific research via social media, it is now implemented in other comet observing campaigns. While PACA identifies a consistent collaborative approach to pro-am collaborations, given the volume of data generated for each campaign, new ways of rapid data analysis, mining access and storage are needed. Several interesting results emerged from the synergistic inclusion of both social media and amateur astronomers:

- (1) the establishment of a network of astronomers and related professionals, that can be galvanized into action on short notice to support observing campaigns;
- (2) assist in various science investigations pertinent to the campaign;
- (3) provide an alert-sounding mechanism should the need arise;
- (4) immediate outreach and dissemination of results via our media/blogger members;
- (5) provide a forum for discussions between the imagers and modelers to help strategize the observing campaign for maximum benefit.

In 2014, two new comet observing campaigns involving pro-am collaborations have been initiated: (1) C/2013 A1 (C/SidingSpring) and (2) 67P/Churyumov-Gerasimenko (CG), target for ESA/Rosetta mission. The evolving need for individual customized observing campaigns has been incorporated into the evolution of PACA portal that currently is focused on comets: from supporting observing campaigns of current comets, legacy data, historical comets; interconnected with social media and a set of shareable documents addressing observational strategies; consistent standards for data; data access, use, and storage, to align with the needs of professional observers. The integration of science, observations by professional and amateur astronomers, and various social media provides a dynamic and evolving collaborative partnership between professional and amateur astronomers. The empowerment of amateur astronomers vis-à-vis their partnerships with the professional scientists creates a new demographic of data scientists, enabling citizen science of the integrated data from both the professional and amateur communities.

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202.05 – Using Mars Rover Missions as a Vehicle for Introducing Space Science and Engineering in Grades 3-8

The Mars Rover Celebration and Mars Rover Curriculum (MRC) for grades 3-8 are centered around an open-ended, student-led collaborative project to design a mission to Mars. This curriculum incorporates up-to-date SMD education resources and science and mission data relating to NASA's explorations of Mars. The MRC focuses on the adventure of learning and discovery, asking participating teams to propose their own scientific mission to Mars, design a rover to carry it out, and present a mock-up at an open house. The curriculum is structured to be inquiry-based throughout. The "students choose the mission" structure is highly engaging. The latter half of the curriculum presents the Engineering Design Process and walks the students through the steps of designing and engineering a spacecraft/rover to meet the mission objectives chosen by the students. Students are introduced to engineering using the design-project approach. The six-week project period culminates in a public celebration at which students present their missions to members of the community including undergraduate and graduate students in science, engineering, and education fields; university faculty in these fields; and professionals from associated industries.

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202.06 – Using the Planetary Science Institute's Meteorite Mini-Kits to Address the Nature of Science

Hands-on learning allows students to understand science concepts by directly observing and experiencing the topics they are studying. The Planetary Science Institute (PSI) has created instructional rock kits that have been introduced to elementary and middle school teachers in Tucson, in our professional development workshops. PSI provides teachers with supporting material and training so that they can use the kits as tools for students' hands-on learning. Use of these kits provides an important experience with natural materials that is essential to instruction in Earth and Space Science. With a stronger knowledge of science content and of how science is actually conducted, the workshops and kits have instilled greater confidence in teachers' ability to teach science content.

The Next Generation Science Standards (NGSS) Performance Expectations includes: "What makes up our solar system?" NGSS emphasizes the Crosscutting Concepts—Patterns; Scale, Portion, and Quantity; and Systems and System Models. NGSS also states that the Nature of Science (NOS) should be an "essential part" of science education. NOS topics include understanding that scientific investigations use a variety of methods, that scientific knowledge is based on empirical evidence, that scientific explanations are open to revision in light of new evidence, and an understanding of the nature of scientific models.

Addressing a need expressed by teachers for borrowing kits less expensive than our \$2000 option, we created a Meteorite Mini-Kit. Each Mini-Kit contains eight rocks: an iron-bearing chondrite, a sliced chondrite (showing iron and chondrules), a tektite, a common Tucson rock, a river-polished rock, pumice, a small iron, and a rounded obsidian rock (false tektite). Also included in the Mini-Kits are magnets and a magnifier. The kits cost \$40 to \$50, depending on the sizes of the chondrites. A teacher can check out a classroom set of these which contains either 10 or 20 Mini-Kits. Each kit includes a description of the rocks as well as suggestions for using them in the classroom. Our presentation will highlight their use in various venues.

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202.07 – The Art Of Planetary Science: An Exhibition – Bringing Together The Art And Science Communities To Engage The Public

The University of Arizona's Lunar and Planetary Laboratory (LPL) presents the 2nd Annual The Art of Planetary Science: An Exhibition (TAPS) on 17-19 October 2014. This art exhibition and competition features artwork inspired by planetary science, alongside works created from scientific data. It is designed to connect the local art and science communities of Tucson, and engage the public together in celebration of the beauty and elegance of the universe. The exhibition is organized by a team of volunteer graduate students, with the help of LPL's Space Imaging Center, and support from the LPL administration. Last year's inaugural event featured over 150 works of art from 70 artists and scientists. A variety of mediums were represented, including paintings, photography, digital prints, sculpture, glasswork, textiles, film, and written word. Over 300 guests attended the opening. Art submission and event attendance are free, and open to anyone.

The primary goal of the event is to present a different side of science to the public. Too often, the public sees science as dull or beyond their grasp. This event provides scientists the opportunity to demonstrate the beauty that they find in their science, by creating art out of their scientific data. These works utilized, for example, equations, simulations, visual representations of spacecraft data, and images of extra-terrestrial material samples. Viewing these works alongside more traditional artwork inspired by those same scientific ideas provided the audience a more complex, multifaceted view of the content that would not be possible viewing either alone. The event also provides a way to reach out specifically to the adult community. Most science outreach is targeted towards engaging children in STEM fields. While this is vital for the long term, adults have more immediate control over the perception of science and public policy that provides funding and research opportunities to scientists. We hope this event raises awareness of the value and importance of planetary science, and paves the way for future art and science collaboration and engagement.

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202.08 – Investigating Undergraduate Students' Conceptions of Radiation

Radiation is an essential topic to the physical sciences yet is often misunderstood by the general public. The last time most people have formal instruction about radiation is as students in high school and this knowledge will be carried into adulthood. Peoples' conceptions of radiation influence their attitude towards research regarding radiation, radioactivity, and other work where radiation is prevalent. In order to understand students' ideas about radiation after having left high school, we collected science surveys from nearly 12,000 undergraduates enrolled in introductory science courses over a span of 25 years. This research investigates the relationship between students' conceptions of radiation and students' personal beliefs and academic field of study.

Our results show that many students in the sample were unable to adequately describe radiation. Responses were typically vague, brief, and emotionally driven. Students' field of study was found to significantly correlate with their conceptions. Students pursuing STEM majors were 60% more likely to describe radiation as an emission and/or form of energy and cited atomic or radioactive sources of radiation twice as often as non-STEM students. Additionally, students' personal beliefs also appear to relate to their conceptions of radiation. The most prominent misconception shown was that radiation is a generically harmful substance, which was found to be consistent throughout the duration of the study. In particular, non-science majors in our sample had higher rates of misconceptions, often generalized the idea of radiation into a broad singular topic, and had difficulty properly identifying sources.

Generalized ideas of radiation and the inability to properly recognize sources of radiation may contribute to the prevalent misconception that radiation is an inexplicably dangerous substance. A basic understanding of both electromagnetic and particulate radiation and the existence of radiation at various energy levels may substantially deter fear-based generalizations and increase students' abilities to make rational decisions when encountering various types of radiation in daily life.

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Contributing team(s): Collaborations of Astronomy Teaching Scholars (CATS), Steward Observatory, University of Arizona

202.09 – Where Non-Science Majors Get Information about Science and How They Rate that Information

College non-science major courses represent one of the last science courses many students will ever take. We report on a study of 400 undergraduate non-majors students enrolled in introductory astronomy courses at the University of Arizona to gain insight into where they get their information about science and their perception of that information. Students completed an online survey during the 2013-2014 school year. In addition to demographic information, students reported where they obtained information about science when they want to know something both for their own knowledge as well as information for a course assignment. They reported their interest in different science topics, rated the reliability of different sources of information, and reported how important science was to their life, including their future career choice.

Overall, students reported getting information from a variety of online sources when looking up a topic for their own knowledge, including internet searches (71%), Wikipedia (46%), and online science sites (e.g. NASA) (45%). When asked where they got information for course assignments, most reported from assigned readings (82%) but a large percentage still reported getting information from online sources such as internet searches (60%), Wikipedia (30%) and online science sites (e.g. NASA) (20%). Overall, students rated professors/teachers and textbooks at the most reliable sources of scientific information and rated social media sites, blogs and Wikipedia as the least reliable sources of scientific information. Additionally, friends and family members were rated as less reliable sources of scientific information than similar information found on multiple websites. Students' interest in science and self-reported knowledge in science was positively correlated. There was a significant positive correlation between those who reported that they liked science and felt that science was important to their future career. Overall, our results are giving us insights into how our non-science majors get and evaluate scientific information.

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203 – Mars Surface and Interior

203.01 – Curiosity Overview of a Two-Year Odyssey

The Mars Science Laboratory rover, Curiosity, has been exploring the floor of Gale Crater for well over a Mars year and has now entered its extended mission. Major milestones have been met and exceeded, especially having addressed its prime scientific objective through exploring Yellowknife Bay, an ancient fluvial environment in Gale Crater, and determining that it could have supported microbial life. The mission has accomplished many first-time planetary activities, such as measurements new to planetary science (Laser Induced Breakdown Spectroscopy, X-ray Diffraction), measurements of the high-energy radiation flux at the surface, radiogenic and cosmogenic isotope age dating of rocks, and detection of martian organic carbon. In addition, many measurements have provided a significant refinement to those of previous missions such as atmospheric isotopic measurements relevant to atmospheric loss, methane content of the atmosphere, and the daily and seasonal change in atmospheric temperature and pressure. Curiosity has left its landing ellipse and is progressing toward the base of Mt. Sharp. The rover has had the opportunity to make additional measurements of fluvial sediments, including extensive remote and contact measurements, and analysis of a drilled samples. A summary of two Earth years of major findings of Curiosity, their implications, and more recent results (potentially including comet Siding Spring) will be presented at the meeting.

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Contributing team(s): MSL Science Team

203.02 – Recent Highlights of ChemCam's exploration of Gale Crater

ChemCam has been exploring Gale Crater and documenting the chemistry along our traverse to Mount Sharp. More than 160,000 LIBS spectra and 2,000 images have been returned to Earth from locations along the 9 km route. Key discoveries documented by ChemCam along the traverse since leaving the Yellow Knife Bay drilling location include: 1) abundant alkali feldspar present in conglomerates and float rocks; 2) MnO present at up to several wt. % in specific coatings and in the Kimberly outcrop; its presence suggests highly oxidized fluids existed during emplacement; 3) fluorine present in key lithologies; the associated chemistry indicates the occurrence of fluor-apatites in igneous rocks and micas in conglomerates; 4) Cap rocks showing a wide range of compositions that span the compositions of outcrops seen at previous locations (e.g. "Shaler", "Point Lake"); 5) a pair of iron meteorites, "Lebanon" and "Littleton"; 6) Chlorine-bearing soils in "Hidden Valley" and corresponding light toned outcrops and 7) an assessment of coatings in

Gale that indicate alteration rates are generally slower than rates of aeolian abrasion. The talk will also include discussion of most recent results and their implications for fluvial processes at Gale.

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Contributing team(s): The MSL Science Team

203.03 – Recurring Slope Lineae (RSL) and Future Exploration of Mars and Europa

Recurring slope lineae (RSL) are narrow (<5 m), dark markings on steep (25°-40°) slopes that incrementally grow during warm seasons over low-albedo surfaces, fade when inactive, and recur over multiple Mars years. RSL often follow small gullies, but no topographic changes (with one exception) have been detected via 30 cm/pixel images from MRO/HiRISE. Mid-latitude RSL appear and lengthen in the late spring through summer favoring equator-facing slopes. RSL also occur in equatorial regions of Mars, especially in the deep canyons of Valles Marineris; some of these lineae are over 1 km long, again usually following pristine gullies. The fans on which many RSL terminate have distinctive color and spectral properties, but lack water absorption bands in MRO/CRISM. RSL are active at places with peak surface temperatures >250 K, but we do not know what time of day they are active. Laboratory experiments show that water or brines darken basaltic soils but produce weak water absorption bands after partial dehydration during the low-humidity middle afternoon conditions when MRO observes.

The primary question is whether RSL are really due to water at or near the surface. All observations can be explained in this way, and no entirely dry model has been offered, but there is no direct detection of water. If they are due to water, where does the water come from and how is it replenished each year? Multiple hypotheses exist.

RSL may be evidence for seepage of water today, and may mark the most promising sites to search for extraterrestrial life. There are 2 key unknowns: (1) Does the water originate from the subsurface where microbes would be protected from radiation, or does it have an atmospheric origin and is only skin deep? (2) Is the water too salty for life as we know it? RSL occur on steep, rocky slopes on which landing is dangerous, but several concepts for surface exploration of RSL were presented in <http://www.lpi.usra.edu/meetings/marsconcepts2012/>. Landing in RSL sites will require additional expenses for planetary protection. For these reasons, it is important to learn as much as possible about RSL from orbital observations.

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Contributing team(s): HiRISE team, CRISM team

203.04 – Comparing Central Pit Craters on Mars, Ganymede, Mercury, and the Moon

Central pit craters (CPC) display a central depression either directly on the crater floor (“floor pit”) or atop a central peak (“summit pit”). They are distinct from pitted floor material and peak ring structures and are commonly attributed to removal of target volatiles during crater formation. CPC are common on Mars, Ganymede, and Callisto but also have been reported on Mercury and the Moon, indicating that target volatiles are not the only contributor to their formation. This study compares the morphometric characteristics of CPC on volatile-richer (Ganymede, Mars) and volatile-poorer (Mercury, Moon) bodies to better constrain formation of these features. Our databases of CPC on Mars (1692 craters) and Ganymede (471 craters) are compared with data for Mercury (27 craters) and the Moon (47 craters) by Xiao and colleagues (Xiao and Komatsu, 2013; Xiao et al., 2014). Central pits are divided into floor pit or summit pit based on morphologic appearance and (if available) topographic data, diameters of craters and pits are measured, and geographic distributions are determined. Current results are: (1) Many fewer CPC occur on Mercury and the Moon compared to Ganymede and Mars; (2) No strong correlation of CPC distribution with specific latitude or geologic units is seen for any of the four bodies; (3) CPC occur over the narrowest diameter range (16.0-33.0 km) for Mercury and over the largest diameter range (12.0-143.8 km) for Ganymede; (4) No summit pit craters are identified on Ganymede and no floor pit craters are reported for Mercury; (5) Floor pit craters on Ganymede and Mars can be divided into those with and without an elevated rim around the pit and terrain characteristics influence rimmed vs non-rimmed pit distribution on Mars; (6) Median pit-to-crater diameter (Dp/Dc) values for floor pit craters are largest for volatile-rich Ganymede (0.20) and smallest for volatile-poor Moon (0.12); (7) Median Dp/Dc values for summit pit craters are identical for Mars

and Mercury (0.12) and smallest for the Moon (0.08); (8) Median Dp/Dc value for the Moon's floor pit craters is identical to that of summit pit craters on Mercury and Mars (0.12).

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203.05 – Distribution and Compositional Constraints on Subsurface Ice in Arcadia Planitia, Mars

Knowledge of the present-day quantity and distribution of water ice on Mars can help to understand past Martian climates, and also has implications for future human exploration. Within the northern mid-latitudes, there are many geomorphological features such as ice-exposing impacts (Dundas et al., 2014) and expanded secondary craters (Viola et al., 2014) that are indicative of widespread ice.

Impact crater morphology can reveal subsurface structure, such as when terraces form in layered target material (Ormö et al., 2013). We create Digital Terrain Models (DTMs) using the Mars Reconnaissance Orbiter's HiRISE (High Resolution Imaging Science Experiment) stereo image pairs to measure terrace depths within craters (and thus the depths to the boundary of the subsurface layer). Radar sounding from the SHARAD instrument, also on the Mars Reconnaissance Orbiter, provides an independent mechanism for probing the subsurface and shows an extensive subsurface reflector in Arcadia Planitia (180-225E, 38-50N). Assuming the change in material strengths responsible for the terraces is the same dielectric interface that causes the radar reflectors, combining the terrace depths with radar delay times allows us to determine the radar wave velocity (and thus dielectric constant) of the layer of material between the surface and subsurface reflector.

We present results from combining these observational datasets to map the distribution and constrain the dielectric constant of this widespread layer. Preliminary results suggest this decameters-thick layer is relatively pure excess (higher water ice abundances than can fit into the pore spaces of the regolith) ice. We compare our dielectric constant calculations with a 3-component dielectric mixing model to put limits on the porosity and purity of the ice. Understanding the conditions that emplaced and preserved this ice layer is important to improving our understanding of the Martian climate system.

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203.06 – Ground Ice on Mars: Numerical Modelling of a Terraced Crater in Arcadia Planitia

Simple craters are small impact structures, characterized by a bowl shape close to a parabola. Any departure from the canonical shape provides insight into subsurface target properties. Terraced craters are suggested to develop as a consequence of layers within the target having different strengths, with weak material overlying strong. For a population of terraced craters in Arcadia Planitia, the weak material is thought to be ice based on comparisons of SHARAD measurements of dielectric transitions and terrace depths [1].

In this work we will present the preliminary results of the numerical investigation of one of the dozens of terraced craters mapped in Arcadia Planitia [1]. This crater is located at 46.58°N, 194.85°E and has a floor terrace (thought to be the ice-rock interface) at ~40 m depth with an additional, smaller wall-terrace (likely from additional structure within the ice) at ~17 m depth.

Numerical modelling is performed through the iSALE shock physics code. Initially developed by [2], the code has been enhanced through modifications which include an elasto-plastic constitutive model, fragmentation models, various equations of state (EoS), multiple materials, and a novel porosity compaction model, called α - β model [3, 4]. In addition, the code is well tested against laboratory experiments at low and high strain-rates [4] and other hydrocodes [5].

We aim to compare the crater shape seen in the HiRISE stereo DTM with the simulations, in order to derive the best model setup, confirm remote sensing data, and lastly validate the target input parameters needed for the formation of this multi-terrace (dubbed 'bullseye') crater. We modelled the terraced crater by considering a 50 m-diameter basaltic projectile impacting at 7 km/s into a layered target made up of a 40 m ice layer on top of a basaltic crust.

[1] Bramson et al: 8th Int Conf Mars, #1042, 2014

[2] Amsden et al: Los Alamos Nat Lab, Report LA-8095, 1980

[3] Collins et al: Meteorit & Planet Sci 39, 217-231, 2004

[4] Wünnemann et al: Icarus 180, 514-527, 2006

[5] Pierazzo et al: Meteorit & Planet Sci 43, 1917-1938, 2008

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203.07 – Reinterpreting the Impact Craters of the North Polar Layered Deposits, Mars

The North Polar Layered Deposits (NPLD) of Mars contain a complex stratigraphy that has been proposed to contain a record of eccentricity- and obliquity-forced climatic variations. Obtaining the age of the surface of the overlying residual cap will allow for more stringent constraints on overall NPLD age and accumulation rates. This work utilizes a crater population previously identified on the NPLD (Banks et al. 2010). We expanded the High Resolution Imaging Science Experiment (HiRISE) image coverage of these impact craters to refine their diameter measurements and use the new crater production function reported by Daubar et al. (2013) to interpret their population statistics. Eighty-five impact sites have been measured in our study, which represents a statistically complete catalog of craters >30m in diameter on the North Pole residual cap. The largest crater in the region of interest is ~350m in diameter. These craters exhibit a range of degradation states, from having a depth/diameter ratio typical of fresh simple craters and a well defined rim to “ghost” craters where only a degraded rim remains, leading us to conclude that they are predominantly primary impacts. Several impact sites are comprised of clusters of impact craters, identified because all the impact structures were within a few crater diameters of each other. These were included in the population statistics as a single impact with an effective diameter of $(\sum D^3)^{1/3}$. Using a differential size-frequency distribution plot, we found the isochron from Daubar et al. (2013) that best fit the data was ~900yr, a significant revision downward from the Banks et al. (2010) interpretation of a maximum age of ~20Kyr. The diameters of small impact craters on Mars are affected by the material strength of the target material, and this icy target differs from regolith or bedrock. To evaluate the resulting difference between observed NPLD craters and the craters used to calculate the production function, we used PI group scaling. Accounting for these target material differences further reduces the crater retention age of this surface by a factor of two.

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203.08 – The current impactor flux on Mars and its seasonal variation

We calculate the current impactor flux on Mars and its variation over the Martian year, using the available data on the orbital distribution of known Mars-crossing minor planets. To mitigate the problem of observational incompleteness, we adopt the orbital distribution of the nearly complete set of bright (absolute magnitude $H < 16$) Mars-crossers as the intrinsic orbital distribution of the impactor population, and we use this distribution to generate a large number of clones to simulate the impact flux. We use the Öpik-Wetherill formulation for calculating collision probabilities. Our study pays careful attention to the effects of the non-uniform distribution of the perihelion longitudes (owed to planetary secular perturbations) and the non-uniform distribution of impact velocities. We find that these previously neglected non-uniformities have a significant effect on the mean annual impact flux as well as its seasonal variation. The impact flux peaks when Mars is at aphelion. The near-alignment of Mars' eccentricity vector with the mean direction of the eccentricity vector distribution of Mars-crossers causes the mean annual impact flux as well as the amplitude of the seasonal variation to be significantly lower than the estimate based on a uniform random distribution of perihelion longitudes of Mars-crossers. Extrapolation of our results to a de-biased population model of fainter (smaller) Mars-crossers provides theoretical predictions that can be tested with observational data of impacts that is becoming available from spacecraft currently in orbit about Mars.

This research was supported by NSF grant #AST-1312498.

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203.09 – Probing Mars' interior using seismic signals from small high-frequency meteorite impacts

In 2016 NASA will launch the InSight Discovery-class mission to Mars. This is the first geophysics-led planetary mission and will provide a wealth of new information about Mars' interior and sub-surface. Instruments include two seismometers, a heat probe, and environmental sensors. Science return from the seismometers will critically depend on the occurrence of natural seismic sources, of which meteorite impacts will play a key role. Seismic recording of impact events will also allow the current cratering rate to be estimated, providing important new constraints on crater-based chronologies.

In a recent study it was found that large globally detectable events require impacts to produce craters of order 100m in diameter (Teanby and Wookey, 2011). Such events are rare and only a few such events are predicted during the InSight mission. Here we extend this study to consider the much more frequent smaller events. While not producing as much seismic energy, these small events are much more numerous, as evidenced by recent observations of over 200 new impact craters (Daubar et al, 2013). Therefore, the probability of a small impact happening close to the InSight landing site is much higher. Importantly, these local events will not suffer as much crustal attenuation as distant events so may in

fact be more detectable. They will also have a much higher frequency content, providing important information on the Mars' crustal structure.

We calculate the seismic amplitudes from small impacts using ray tracing calibrated by impacts recorded on the Earth and Moon, allowing us to determine the number of events that will be detectable with InSight's seismometers. In particular, we focus on the short period seismometer, which is ideally suited to studying their higher frequency content. Daubar, I. J.; McEwen, A. S.; Byrne, S.; Kennedy, M. R. & Ivanov, B. (2013), 'The current martian cratering rate', *Icarus* 225, 506-516.

Teanby, N. A. & Wookey, J. (2011), 'Seismic detection of meteorite impacts on Mars', *Phys. Earth Planet. Int.* 186, 70-80.

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204 – Exoplanet Observations and Models

204.01 – Clouds and Atmospheric Dynamics in Ultracool Atmospheres: HST, Spitzer, and LBT Rotational Mapping of Exoplanets and Brown Dwarfs

Condensate clouds have a fundamental impact on the physical and thermal structures of photospheres of directly imaged exoplanets, brown dwarfs, and hot transiting exoplanets, but the details of cloud formation and evolution are not well understood.

Rotational phase mapping of ultracool atmospheres provides exciting new insights into the physical and chemical properties of condensate clouds.

Here I will summarize results from ongoing HST, Spitzer, and LBT rotational mapping projects, which provide very high quality spectrally and temporally resolved data of rotating brown dwarfs, and time-resolved photometry on directly imaged exoplanets. The multi-wavelength observations simultaneously probe clouds at multiple atmospheric depths. Finally, I will show first results from our Spitzer Cycle-9 Exploration Science program Extrasolar Storms that uses multi-epoch observations of complete rotations to study the evolution of cloud coverage in brown dwarf photospheres, thus providing detailed views of atmospheric dynamics in these ultracool atmospheres.

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204.02 – The Debris Structures of HD 95086 – A Young Analog of HR 8799

HD 95086 is a young early-type star that hosts a 5 Jupiter mass planet at the projected distance of 56 AU, revealed by direct imaging. It also has a large infrared excess, indicative of a massive debris disk. The disk was marginally resolved by Herschel and found to be inclined at 25 degrees from face-on. Here we report a tentative detection of the 69 μm crystalline forsterite feature in the Spitzer/MIPS-SED data, and we present detailed analysis of the disk SED and re-analysis of the resolved images. Our results suggest that the debris structure around HD 95086 is very similar to that of HR 8799: a warm (~ 175 K) belt, a cold (~ 55 K) disk, and an extended disk halo (up to ~ 800 AU). We compare the properties of these three components in debris structures, and suggest that HD 95086 is a young analog of HR 8799.

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204.03 – The Planetary System of HD 95086—A Young Analog of HR 8799?

HD 95086 is a 17 Myr old system containing debris structures similar to HR 8799-- a warm (~ 175 K) belt, a cold (~ 55 K) disk, and an extended disk halo (up to ~ 800 AU). A 5 ± 2 Jupiter-mass (M_J) planet (HD 95086b) has been discovered just interior to the cold disk at 61.5 AU (Rameau et al. 2013). Could this system host four massive planets between its warm and cold disks as seen in HR 8799? We explore the possible planetary configurations present in HD 95086 using numerical simulations and dynamical stability considerations. We find that equal-mass four-planet configurations, with each planet of mass $\sim 5 M_J$ are near the edge of dynamical stability for timescales of the age of the system. Dynamical stability increases for lower planet multiplicity or lower planet masses (within the range of estimates of the mass of HD 95086b). As a prediction for use in direct imaging campaigns, we also report estimates of planet spacings as a function of planet mass and multiplicity that are likely to be stable over the age of the system.

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204.04 – Titan Reveals Transit Spectra of a Definitely Hazy World

Hazes dramatically influence exoplanet observations by obscuring deeper atmospheric layers. This effect is especially pronounced in transit spectroscopy, which probes large pathlengths through an exoplanet atmosphere as it crosses the disk of its host star. While hazes are proposed to explain observed featureless transit spectra, it is difficult to make inferences from the observations because of the need to disentangle effects of noise, gas absorption, and haze extinction. Here, we turn to Titan, an extremely well studied world with a hazy atmosphere, to better understand how high altitude hazes can impact exoplanet transit observations. We use solar occultation observations from the Visual and Infrared Mapping Spectrometer (VIMS) aboard NASA's Cassini spacecraft to generate transit spectra. Our approach exploits symmetry between occultations and transits, producing transit radius spectra that inherently include the effects of haze multiple scattering, refraction, and gas absorption. The data, which span 0.88–5 microns at a resolution of 12–18 nm, show strong methane absorption features, and weaker features due to other gases, including acetylene and carbon monoxide. Unlike the usual assumption made when modeling and interpreting transit observations of potentially hazy worlds, the slope set by haze in our spectra is neither flat nor has a pure Rayleigh slope, and creates a variation in transit height whose magnitude is comparable to those from the strongest gaseous absorption features. We use a simple model of haze extinction to explore how Titan's haze affects its transit spectrum, and demonstrate how high altitude hazes can severely limit the atmospheric depths probed by transit spectra, bounding our observations to pressures smaller than 0.1–10 mbar, depending on wavelength. Overall, these new data challenge our understanding of how hazes influence exoplanet transit observations, and provide a means of testing proposed approaches for exoplanet characterization. Additionally, our findings will help with the interpretation of future exoplanet observations, especially since the VIMS instrument overlaps in wavelength with several instruments that will launch with NASA's James Webb Space Telescope.

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204.05D – Refracted and Forward Scattered Light in Transmission Spectra and Transit Light Curves

I present a model for exoplanet transit transmission spectroscopy that includes refraction and forward scattering. The model combines an existing radiative transfer code with a backwards Monte Carlo model that traces photon paths through an atmosphere, tracking changes in trajectory due to refraction and scattering events. Refraction sets an in-transit limit on the pressures that can be probed. This limit can greatly reduce the detectability of absorption features, especially for biosignatures and habitability markers. For Earth-like planets orbiting Sun-like stars this can result in as much as a 15-fold increase in exposure time required to detect certain features. However, because of their close-in geometry, potentially habitable planets orbiting M dwarf stars are relatively unaffected. Additionally, I find that despite the refraction limit, oxygen dimer molecules could be detectable for Earth-like planets and could be used as a probe of atmospheric pressure. The inclusion of forward scattering increases the observed in-transit flux by up to 1 scale height compared to standard models that treat scattering as extinction. This is because forward scattered photons have a high probability of remaining in the beam to a distant observer. This effect is strongest for very close-in planets, such as Hot Jupiters or terrestrial planets orbiting brown dwarfs, resulting in more detectable absorption features. Refraction and scattering can lead to an increase in the out-of-transit flux with a peak brightness just outside of transit. The detection of refracted light could be indicative of a haze-free atmosphere because the out-of-transit light is transmitted through layers with pressures greater than those at which haze layers typically form. In contrast, a detection of scattered light would strongly suggest the presence of aerosols in an atmosphere, and could provide upper limits on particle sizes and constraints on composition. Refracted light is detectable with JWST (for Jovians) and E-ELT (for terrestrial planets) for planets with temperatures <600 K, while scattered light is most detectable for hotter planets with temperatures >800 K.

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204.06 – The Thermal Emission and Albedo of Super-Earths with Flat Transmission Spectra

Vast resources have been dedicated to characterizing the handful of planets with radii between Earth's and Neptune's that are accessible to current telescopes. Observations of their transmission spectra have been inconclusive and do not constrain the atmospheric composition. Here, we present a path forward for understanding this class of small planets: by understanding the thermal emission and reflectivity of small planets, we can break these degeneracies and constrain the atmospheric composition.

Of the ~four small planets studied to date, all have radii in the near-IR consistent with being constant in wavelength. This suggests either that these planets all have higher mean molecular weight atmospheres than expected for hydrogen-dominated bulk compositions, or that the atmospheres of small planets are consistently enshrouded in thick hazes and clouds. For the particularly well-studied planet GJ 1214b, the measurements made using HST/WFC3 can rule out atmospheres with high mean molecular weights, leaving clouds as the sole explanation for the flat transmission spectrum. We showed in Morley et al. 2013 that these clouds and hazes can be made of salts and sulfides, which condense in the upper atmosphere of a cool H-rich atmosphere like GJ 1214b, or made of photochemical hazes such as soots, which result from methane photodissociation and subsequent carbon chemistry. Here, we explore how clouds thick enough to obscure the transmission spectrum change both thermal emission spectra and albedo spectra. These observations are complementary to transmission spectra measurements. Thermal emission probes deeper layers of the atmosphere, potentially below the high haze layer obscuring the transmission spectra; albedo spectra probe reflected starlight largely from the cloud particles themselves. Crucially, these complementary observations of planets with flat transmission spectra may allow us to break the degeneracies between cloud materials, cloud height and longitude, and bulk composition of the atmosphere. We make predictions for the observability of known planets for current and future telescopes.

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204.07 – Escaping hydrogen from HD209458b

Recent modeling of the atmosphere of HD209458b has been used to interpret the Lyman- γ line and other observations during transits. In this presentation, we model the hydrogen exosphere of the short period, Hot Jupiter planet to investigate the dynamics of the extended hydrogen cloud and to determine the observability of the solar ionization and acceleration on the escaping hydrogen.

Koskinen et al (2010) used a hydrostatic density profile in the thermosphere combined with the Voigt profile to estimate the Lyman- γ transit depths for an array of model parameters. A detailed photochemical-dynamical model of the thermosphere was developed by Koskinen et al (2013a) and used to again estimate model parameters to fit not only the Lyman- γ transits, but also the transits in the O I, C II and Si III lines (Koskinen et al, 2013b).

Recently, Bourrier et al (2013) modeled the escape of hydrogen from the extended atmospheres of HD209458b and HD189733b and used the results to interpret Lyman- γ observations. They included acceleration of hydrogen by stellar radiation pressure to obtain the high velocity tails in the escaping velocity distribution, arguing that the observations are explained by high velocity gas in the system, while Voigt broadening is negligible.

In this work we connect a free molecular flow (FMF) model, similar to Bourrier et al (2013), to the results of Koskinen et al (2013b) to simulate the extended atmosphere of HD209458b. We include ionization and radiation pressure in the extended atmosphere along with self-shielding due to the extended atmosphere and thermosphere. The extended atmosphere and absorption rates are iteratively computed to obtain a consistent solution. In this manner, we can interpret the importance of the various physical processes by comparing the simulated line profiles, consisting of velocity and natural broadening, to observations (Koskinen et al, 2010). Furthermore, the transit depths of this model can be used to re-evaluate the atmospheric model parameters to determine if they need to be adjusted due to the existence of the extended hydrogen atmosphere.

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204.08 – H γ Absorption by Hot Jupiter Atmospheres

While the investigation of the hydrogen content of Hot Jupiter outflows is primarily done through observed Lyman- γ absorption during transit. The observation by Jensen et al. of H γ absorption by the atmospheres of HD189733b and HD209458b offers a complementary probe of the hydrogen content of hot Jupiter atmospheres. Motivated by this observation, we have developed a model of a hydrostatic atmosphere in thermal and photoionization equilibrium in order to better understand the HD189733b detection. The n=2 level population is calculated by balancing collisional and radiative processes. The H γ absorption signal is primarily due to metastable 2s hydrogen found in the neutral atomic layer where its abundance varies slowly with radius despite the total hydrogen abundance decreasing exponentially. The 2s hydrogen is primarily formed through collisional excitation from the ground state and is subsequently destroyed by collisional transitions to the 2p state followed by rapid radiative de-excitation. With an enhanced ionization rate, the model can approximately reproduce the HD189733b H γ transit depths.

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204.09D – Quantifying Angular Momentum in Planetary Systems and Host Stars

For decades it has been known that the spin angular momentum of early-type stars may be related to the stellar mass by the empirically derived power law $J \propto M^?$. Late-type stars, however, break the power law with a significantly smaller value of $?$. In particular, the Sun's spin angular momentum is consistent with the late-type break, whereas the total angular momentum of the Solar System falls near an extension of the early-type power law for single stars. We examine existing stellar inertial models, use them to approximate the spin angular momentum of host stars of newly discovered planetary systems, and calculate the orbital angular momentum of their planets from available observational data. Ratios of planetary to total system angular momentum are also presented. Results are discussed in the context of star and planet formation.

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205 – Moon/Mercury Surface

205.01 – Estimating the Sizes of Late Veneer Impactors from Impact-Induced Mixing on Mercury

The abundance of highly siderophile elements in the mantles of Earth, the Moon, and Mars argues for the late accretion of compositionally diverse planetesimals. This would introduce chemical heterogeneity in the mantles of the terrestrial planets on a length scale controlled by planetesimal size. The approximate sizes of these late arriving projectiles is an important control on the final angular momenta, eccentricities, and inclinations of the terrestrial planets, but current estimates suggest either (i) meter-scale bodies or (ii) large objects with diameters on the order of thousands of km. Compositionally distinct provinces implanted by large late veneer impactors are most likely preserved in bodies whose subsequent geodynamic evolution is limited. The planet Mercury may have avoided intensive mixing by vigorous solid-state convection during much of its history; therefore, its subsequent bombardment may have excavated evidence of mantle heterogeneity introduced by the late veneer. Here, we use a 3-D global Monte Carlo model of impact cratering, excavation, and ejecta deposition to show that evidence of mantle heterogeneity can be preserved in the ejecta blankets of crust-penetrating impacts. We develop a test statistic that allows for the distinction between large and small subsurface provinces. Analysis of ejecta blanket compositions in Mercury's ancient, heavily cratered terrains, which can be undertaken using MESSENGER data, along with our model results can help discern between predominantly large or small late veneer objects.

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205.02 – Hollow Promises: A Window into Mercury's Surface Mineralogy

Early in its orbital operations at Mercury, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft's Mercury Dual-Imaging System (MDIS) began imaging "hollows" on the walls, rims, floors, and central peaks of impact craters. Hollows are shallow, irregular, rimless, flat-floored depressions, often with bright interiors and halos, are fresh in appearance, and have less steeply sloped spectral reflectance with wavelength than typical for Mercury. MDIS wide-angle camera (WAC) images obtained with eight narrow-band color filters from 433.2 nm to 996.2 nm of hollows in the craters Dominici (center latitude 1.38°N, longitude 323.5°E, ~20 km diameter), Hopper (12.4°S, 304.1°E, ~35 km), and Mistral (4.7°N, 305.4°E, ~100 km) have sufficient spatial resolution and repeatable color sets to examine spectral reflectance properties. The reflectance data, expressed as I/F , where I is light reflected from Mercury's surface and F is incident sunlight, were corrected for global geometric effects. Hollows on the south crater wall and rim of Dominici have well-defined depressions and halos that are a factor of ~1.4 brighter across the spectral range measured than those in the crater center. Hollows in the center of Dominici are factor of ~1.2 brighter than those in Hopper and Mistral. Eight color sets of Dominici show evidence for a spectral absorption feature centered near 700 nm in the hollows terrain. Three color sets of Hopper hollows show a spectral absorption feature diminished in depth compared to that for the Dominici hollows; the Mistral hollows show no discernible spectral absorption in two color sets. The reflectance differences are likely due to relative age of the hollows. At Dominici, we postulate that the hollows on the southern wall and rim were exposed to the local environment through a process of slumping of overlying material; it is likely that fresh material susceptible to hollow formation is regularly exposed. Local and global processes darken the hollows and diminish the spectral absorption feature. From laboratory reflectance studies of temperature effects on spectral properties of sulfides, these observations suggest that the hollows mineralogy incorporates low-density MgS.

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205.03 – Mid-infrared emission spectroscopy of meteorite NWA 7325: Identifying the mineralogy with a non-destructive, remote-sensing technique

A polished chip of the Northwest Africa 7325 meteorite, a highly reduced, ungrouped achondrite [1-4], was analyzed using an FTIR spectrometer modified for emission measurements. The chip was roughly triangular in shape with side lengths of ~12, 12, and 16 mm. Radiance data were collected at 2 cm⁻¹ spectral sampling from ~2000 – 230 cm⁻¹ (~5 – 44 microns) in a nitrogen-purged atmosphere while the sample was maintained at approximately 70 degrees C. The radiance curves were processed to retrieve emissivity spectra of the meteorite interior. Using a spectral library of 47 different rock-forming minerals, including a range of feldspar, pyroxene, and olivine compositions, and other mineral classes, the meteorite data were spectrally unmixed in order to determine the mineralogic composition of the meteorite chip. The results indicate that the meteorite sample consists of ~77 vol. % anorthite, ~13 vol. % diopside, and ~8 vol. % forsterite. These spectral unmixing results coincide well with the mineral compositions and their modal abundances determined in other petrologic studies [1-4]. These spectral analyses and the determined minerals and modal abundances will help identify the parent body of NWA 7325, so far proposed to be either Mercury [1] or a ureilite-like asteroid [4,5].

[1] Irving, A. et al., LPSC 44, abs. 2164 (2013)

[2] Bischoff, A. et al., EPSC 8, abs. 427 (2013)

[3] Morlok, A. et al., EPSC 8, abs. 114 (2013)

[4] Goodrich, C.A. et al., LPSC 45, abs. 1246 (2014)

[5] Kita, N. et al., LPSC 45, abs. 1455 (2014)

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205.04 – Mare Imbrium Regolith and Rock Information Retrieved from Imaging Spectrometer and Panorama Cameras onboard the Yutu Rover of Chang'E 3 Mission

The Chang'E 3 mission successfully landed on the Mare Imbrium region on December 14, 2013 and deployed the Yutu Rover to roam near the Chang'E A Crater. Although the rover roamed just over 100 meters before its premature failure, its onboard visible and near-infrared (VisNIR) imaging spectrometer was able to collect 4 spectra at 4 different sites which are the first in-situ lunar surface spectra ever taken. The onboard panorama cameras (PCAM) also photographed large amount of surface features since the Apollo era and some images have clearly shown the lunar opposition effect. The VisNIR spectrometer spans the wavelength from 450 to 2395 nm with a step of 5 nm. By performing radiometric and photometric calibrations, the absolute reflectance are obtained and it is found that the in-situ spectra are much brighter than that of the same area measured by the M3 instrument. The in-situ spectra also have a much deeper 1 μm absorption feature than that of the M3 spectra measured remotely. We conjecture that such differences are caused by the fact that the lander's descent engines must have blown away the top-most layers which are much more mature than the exposed underlying layers. A comparison of the continuum-removed in-situ spectra with that of the mineral spectral library gives the concentrations of major lunar rock-forming minerals including olivine, pyroxenes and plagioclase at these 4 different sites. The phase curve retrieved from the PCAM shows a strong opposition surge below 10-deg phase angle and the phase reddening effect. We attempt to retrieve the regolith physical properties using both the Hapke and Shkuratov photometric models. At a close distance the PCAM also captured high resolution images of a 4-meter across boulder at the edge of the Chang'E A Crater. Centimeter-sized bright clasts on its surface may indicate its basaltic nature. By comparing the VisNIR spectra of its nearby regoliths with that of the Apollo samples, we believe this boulder belongs to a different rock type from the Apollo rocks. Finally we make a rough estimation of the formation age of the crater. This work is supported by National Natural Science Foundation of China through grants 41071229 and 41276180.

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205.05 – Thermoelastic Grain-Scale Stresses on Airless Bodies and Implications for Rock Breakdown

Thermomechanical breakdown of rocks is thought to be an active process in the solar system, especially on airless bodies that experience large diurnal temperature changes and/or have high thermal cycling rates. Researchers have suggested it may operate on (among others) the Moon, Mercury, Eros, and Phaethon, however the extent of the damage produced as a result is unknown. Propagation of microcracks occurs due to stresses from expansion/contraction caused by changes in temperature, and mismatches in elastic behavior of adjacent mineral grains. Historically, spatiotemporal temperature gradients have been used as proxies for thermal stress. Here we link surface temperatures and spatiotemporal temperature gradients to actual stresses near rock surfaces in order to better judge the efficacy of thermal weathering on different planetary bodies.

In this study, we model the thermoelastic behavior of microstructures on airless body surfaces. We impose solar and

conductive fluxes on a microstructure over one solar day, and solve the heat and displacement equations. The microstructures are grids of hexagonal grains that are assigned properties of plagioclase and pyroxene. Results indicate that lunar surfaces experience a diurnal maximum stress of 150 MPa while under tension, comparable to typical strengths of rocks. Examination of the microstructures during this state reveals that maximum stresses are concentrated along surface-parallel boundaries between mineral types, suggesting that temperature and rock heterogeneity dominate thermoelastic behavior. Examination of microstructures over time reveals an anti-correlation between high stresses and large spatiotemporal temperature gradients, indicating that they are not an effective proxy for stress. Model runs done for arbitrary solar system bodies with varying rotation period and solar distance indicate that bodies that rotate slowly and/or are close to the sun are subjected to the highest stresses.

We will present results of thermoelastic stresses induced in microstructures of varying composition, on a variety of airless bodies. This work represents the first step in quantifying the contribution of thermal stress weathering to regolith production rates on these bodies.

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205.06 – The gravity signature of mantle uplift from impact modeling craters on the Moon

NASA's dual Gravity Recovery and Interior Laboratory (GRAIL) spacecraft have globally mapped the lunar gravity field at unprecedented resolution; this has enabled the study of lunar impact craters of all sizes and ages. Soderblom et al. [2014, LPSC abstract #1777] calculated the residual Bouguer anomalies for ~2700 craters 27-184 km in diameter (D). They found that the residual central Bouguer anomaly of craters smaller than D~100 km is essentially zero, that there is a transition for D~100–150 km, and that craters larger than 184 km have a positive residual Bouguer anomaly that increases with increasing crater size. We use the iSALE shock physics hydrocode to model crater formation, including the effects of porosity and dilatancy (shear bulking). We use strength parameters of gabbroic anorthosite for a 35-km-thick crust, and dunite for the mantle. Our dunite impactors range in size from 6–30 km, which produce craters 86–450 km in diameter. We calculate the Bouguer gravity anomaly due solely to mantle uplift. We eliminate the effects of pressure and temperature on density by setting the output densities from the simulations to 2550 kg/m³ if they are below the cutoff value of 3000 kg/m³, and 3220 kg/m³ if they are above. We compare our modeling results to gravity data from GRAIL. We find that the crater size at which mantle uplift dominates the crater gravity occurs at a crater diameter that is close to the complex crater to peak-ring basin transition. This is in agreement with the observed trend reported by Soderblom et al. [2014, LPSC abstract #1777].

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205.07 – Re-examining the main asteroid belt as the primary source of ancient lunar craters.

We use a Monte Carlo code called the Cratered Terrain Evolution Model (CTEM) to investigate the hypothesis that the ancient lunar highlands were bombarded by a population with the same size-frequency distribution as the main asteroid belt.

Our code has been calibrated by a human crater counter so that it can produce simulated terrains that may be compared directly with observational counts of the lunar highlands craters. We also take advantage of recent advances in understanding the scaling relationships between impactor size and final crater size for basin-sized impact craters in order to use large impact basins as a constraint on the ancient impactor population of the Moon. We find that matching the observed number of lunar highlands craters of ~100 km diameter requires that the total number of impacting asteroids Dⁱ > 10 km be no fewer than 4 per million km². However, this required mass of impactors has < 1 % chance of producing only a single basin larger than the 1200 km Imbrium basin; instead, these simulations are likely to produce more large basins than are observed on the Moon. This difficulty in reproducing the lunar highlands cratering record with a main asteroid belt SFD arises because the main belt is relatively abundant in the objects that produce these "megabasins" that are larger than Imbrium. These results suggest that the lunar highlands were unlikely to have been bombarded by a population whose size-frequency distribution resembles that of the currently observed main asteroid belt. We suggest that the population of impactors that cratered the lunar highlands had a somewhat similar size-frequency distribution as the modern main asteroid belt, reflecting a similar rocky composition and collisional history, but had a smaller ratio of objects capable of producing megabasins compared to objects capable of producing ~100 km craters.

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209 – Comets Posters

209.01 – Distant Coma Composition of Comet 67P/Churyumov-Gerasimenko as Observed from Rosetta/VIRTIS

Since July 2014, the Visual IR Thermal Imaging Spectrometer (VIRTIS) onboard the ESA's Rosetta spacecraft has intensively observed comet 67P/Churyumov-Gerasimenko. VIRTIS is composed of two channels, –M for mapping and –H for high resolution, working in the 0.25-5 microns and 2-5 microns wavelength domains, respectively. In addition to nucleus mapping observations, limb observations were carried out to obtain spectra of the coma, and to detect fluorescence emissions of gas phase species. In particular, H₂O, CO₂, CO and organics have strong vibrational bands in the 2.5-5 microns range. We will present the first VIRTIS results concerning gas activity and composition, and the VIRTIS capabilities to detect minor coma species.

The authors acknowledge funding from French and Italian Space Agencies.

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209.02 – Comet 67P: surface temperature maps as derived by Rosetta/VIRTIS in the early Mapping phase

We show spatially-resolved temperature maps of comet 67P/Churyumov-Gerasimenko, main target of the ESA Rosetta spacecraft, as obtained from infrared hyperspectral images acquired by the VIRTIS imaging spectrometer onboard the Rosetta Orbiter in the early Mapping phase carried out in August 2014.

VIRTIS infrared spectra in the range longward of about 4 μm are affected by the thermal emission of the comet, hence the measured radiance in that spectral region can be used to determine surface temperatures and spectral emissivities by means of temperature-retrieval algorithms.

The VIRTIS instrument onboard Rosetta is not sensitive to physical temperatures on the nightside of the comet, where the signal is considerably low. Typically, ~170 K is the minimum temperature that allows one to retrieve surface temperatures while preserving small formal errors (<1 K on retrieved temperatures). On the other hand, for a given local solar time (LST), the maximum temperature depends on the solar incidence angle and on surface properties such as thermal inertia and albedo.

Here we show surface temperature maps of comet 67P at a spatial resolution of 20-25 m/px, and under variable phase angles, illumination conditions, and heliocentric distances (spanning the range from 3.62 to 3.45 AU). We focus both on regional maps and on peculiar sites of interest seen at the local scale, with a special emphasis on the expected location of the landing site.

The availability of spatially-resolved, accurate temperature observations, significantly spaced out in local solar time, provides clues to the physical structure of specific surface units, which complements the mineralogical investigation based on imaging spectroscopy data collected at shorter wavelengths.

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Contributing team(s): Rosetta/VIRTIS Team

209.03 – COSIMA - Cometary Dust Analysis in the inner coma of Comet 67P/Churyumov-Gerasimenko

After a long journey through the inner solar system, ESA's corner stone mission ROSETTA has arrived at comet 67P/Churyumov-Gerasimenko. COSIMA or the COmetary Secondary Ion Mass Analyzer onboard ROSETTA is a secondary ion mass spectrometer focussing on in-situ measurements of the composition of cometary grains collected near the nucleus and inner coma. High resolution mass spectra will contain ions of complex mixtures of mineral compounds and organic molecules as well as molecular fragments representing the elements and molecules on the surface of the cometary grains. We will report on our envisaged in-situ analysis goals of cometary grains as captured, imaged and analysed by COSIMA.

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209.04 – Comet 67P/CG: Preliminary Shape and Topography from SPC

During the last weeks of July, the ROSETTA spacecraft made its final approach to comet 67P/Churyumov-Gerasimenko, revealing a two lobed object that would be a challenge to model. The first real rotation "movies", taken between August 1 and 4 and another set from August 8 allowed a group working at the Laboratoire d'Astrophysique de Marseille (LAM), to construct a first crude full-resolution shape model, building on earlier work on approach images also performed at LAM. During the next weeks and months, higher and higher resolution images became available at a variety of illuminations and viewing geometries, allowing the refinement of the shape and the construction of surface topography to sub-meter scale. We present a potpourri of preliminary results from this most intriguing object.

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209.05 – Expected constraints on the outer solar system formation conditions from the Rosetta-ROSINA measurements

Formation scenarios of the protosolar nebula invoke two main reservoirs of ices that took part in the production of icy planetesimals. The first reservoir, located within the inner region of the protosolar nebula, contains ices (dominated by H₂O, CO, CO₂, CH₄, N₂ and NH₃) originating from the ISM, which, due to their near solar vicinity, were initially vaporized. With time, the decrease of temperature and pressure allowed the water in this reservoir to condense at ~150 K in the form of crystalline ice. It is postulated that a substantial fraction of the volatile species were trapped as clathrates during this condensation phase as long as free water ice was available and there was enough time to overcome the slow kinetics of clathration. On the other hand, the remaining volatiles that were not enclathrated (due to the lack of available water ice or a low kinetics of clathration) probably formed pure condensates at lower temperatures in this part of the nebula. The second reservoir, located at larger heliocentric distances, is composed of ices originating from the ISM that did not vaporize when entering into the disk. In this reservoir, water ice was essentially in the amorphous form and the other volatiles remained trapped in the amorphous matrix. The location of the boundary between these two reservoirs is loosely constrained and may vary between 5 and 30 AU from the Sun, depending on the postulated nebula's thermodynamic conditions. The uncertainty in the distance of the boundary implies that comets may have formed from amorphous ice as well as from crystalline ices and/or clathrates. Here we review the key in situ measurements that are within the capabilities of the ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) instrument aboard the Rosetta spacecraft during its approach of comet 67P/Churyumov-Gerasimenko. These key measurements may allow disentangling between the different formation scenarios.

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209.06 – Three-dimensional kinetic modeling of the near coma of comet 67P/Churyumov-Gerasimenko

Rosetta is the first mission that escorts a comet along its way through the Solar system for an extended amount of time. As a result, the target of the mission, comet 67P/Churyumov-Gerasimenko, becomes an object of the increased scientific interest. Interpretation of the already obtained observations as well as planning of the new measurements requires detailed modeling of the coma constrained by physical quantities measured by the instruments onboard the spacecraft.

The primary difficulties of such modeling are the kinetic nature of the dusty gas flow in the coma as well as the complexity of the nucleus shape as shown by the recent Rosetta images.

Here we present the first results of the fully three-dimensional simulation of the near coma of comet 67P/Churyumov-Gerasimenko performed with our Adaptive Mesh Particle Simulator (AMPS) code. The simulation is performed using a realistic nucleus shape model based on Rosetta observations for modeling the coma and calculation of the synthetic images.

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209.07 – The Comet Radar Explorer Mission

Missions to cometary nuclei have revealed major geological surprises: (1) Global scale layers – do these persist through to the interior? Are they a record of primary accretion? (2) Smooth regions – are they landslides originating on the surface? Are they cryovolcanic? (3) Pits – are they impact craters or sublimation pits, or rooted in the interior? Unambiguous answers to these and other questions can be obtained by high definition 3D radar reflection imaging (RRI) of internal structure. RRI can answer many of the great unknowns in planetary science: How do primitive bodies accrete? Are cometary nuclei mostly ice? What drives their spectacular activity and evolution? The Comet Radar Explorer (CORE) mission will image the detailed internal structure of the nucleus of 10P/Tempel 2. This ~16 x 8 x 7 km Jupiter Family Comet (JFC), or its parent body, originated in the outer planets region possibly millions of years before planet formation. CORE arrives post-perihelion and observes the comet's waning activity from safe distance. Once the nucleus is largely dormant, the spacecraft enters a ~20-km dedicated Radar Mapping Orbit (RMO). The exacting design of the RRI experiment and the precise navigation of RMO will achieve a highly focused 3D radar reflection image of internal structure, to tens of meters resolution, and tomographic images of velocity and attenuation to hundreds of meters resolution, tied to the gravity model and shape. Visible imagers will produce maps of the surface morphology, albedo, color, texture, and photometric response, and images for navigation and shape determination. The cameras will also monitor the structure and dynamics of the coma, and its dusty jets, allowing their correlation in 3D with deep interior structures and surface features. Repeated global high-resolution thermal images will probe the near-surface layers heated by the Sun. Derived maps of thermal inertia will be correlated with the radar boundary response, and photometry and texture, probing surface materials attainable by future robotic excavation missions. Thermal images will reveal areas of sublimation cooling around vents and pits, and the secular response of the outer meters as the nucleus moves farther from the Sun.

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209.08 – Results from the Worldwide Coma Morphology Campaign for Comet ISON (C/2012 S1)

Comet ISON (C/2012 S1) was predicted to be a bright comet in late 2013 because of its extremely small perihelion distance of 2.7 solar radii. In anticipation of the likely bonanza of scientific results, we coordinated a worldwide campaign (<http://www.psi.edu/ison>) to obtain both dust and gas images of the comet. During the campaign, we have received many hundreds of images primarily from amateur astronomers but also from a number of professionals. Comet ISON showed dust structure in its coma at large heliocentric distances before water became the primary sublimating gas. The Hubble Space Telescope (HST) observed a dust feature in the coma at a heliocentric distance of

4.15 AU in April 2013 (Li et al. 2013, ApJL, 779, article id. L3). The enhancement of continuum images taken by team members Nick Howes and Ernesto Guido at the 2-m Liverpool Telescope in May 2013 at different multiple epochs clearly showed the same dust feature (e.g., <http://remanzacco.blogspot.com/2013/05/comet-c2012-s1-ison-update-may-20-2013.html>).

During the northern-hemisphere summer, the solar elongation of ISON became too small for ground-based observations. The comet was again observable starting in August 2013 as the solar elongation started to increase. These observations, at much smaller heliocentric distances than those described earlier, did not show the same dust feature. No unambiguous dust or gas features were seen until about two weeks prior to the perihelion and the comet's demise (i.e., until mid November 2013). Based on the observations taken more than two weeks prior to the perihelion, we place upper limits on the radial extent of any possible dust feature. This and other results based on the coma morphology campaign will be discussed at the DPS 2014 meeting. The results from the analysis will be published in the future and will include the entire campaign.

We thank many amateur and professional observers who contributed to this effort and all observers will be individually acknowledged in the future publication.

We thank the NASA PAST Program for supporting the analysis of observations.

* The ISON Coma Morphology Team is comprised of many Professional and Amateur Astronomers.

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209.09 – Water and a deep search for HDO in the inner coma of C/2012 S1 (ISON) at 0.53 and 0.35 AU from the Sun

We report high-resolution (R ~ 25,000), long-slit spectroscopy of water and a search for HDO in comet C/2012 S1 (ISON). The data presented utilized the CSHELL instrument on the NASA Infrared Telescope Facility, Maunakea, HI. We extracted spatial profiles of water gas rotational temperature and molecular column abundance observed pre-perihelion at heliocentric distances of 0.53 and 0.35 AU. The comet was highly variable with gas productivity changing on time scales over hours and days. Variations in measured spatial distributions of rotational temperature reflect the competition between heating and cooling processes in the coma, and also provide insight about the prevalent mechanism(s) of releasing gas-phase H₂O. The gas spatial profiles, characterized by a well-defined single peak, suggest that the comet was likely ejecting icy material continuously, which sublimated in the coma and heated the ambient gas – augmenting fast H-atoms produced by H₂O photolysis. However, given possible viewing geometries, we note that we cannot eliminate the possibility of a split nucleus suggested by Boehnhardt et al. (2013, CBET 3731). We also report a sensitive search for HDO in the coma performed on 16, 18, and 22 November 2013 and discuss the challenges in determining accurate abundance ratios for a highly variable comet. The implications for the origins of comet C/2012 S1 (ISON) will be discussed.

This work is supported by NSF (AAG) and NASA's Programs in Planetary Astronomy, Planetary Atmospheres, and Astrobiology.

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209.10 – Water Ice in the Comae of Comets C/2013 A1 (Siding Spring) and C/2012 S1 (ISON)

Comet C/2013 A1 (Siding Spring) passes Mars with a closest approach distance of about 138,000 km on 2014 October 19. This short distance gives our Mars-orbiting spacecraft the opportunity to observe a comet under conditions similar to a flyby mission, never before accomplished for a dynamically new comet. Hubble Space Telescope WFC3 observations of the comet in 2013 October, 4.6 AU from the Sun, revealed an inner coma with an optical spectral slope of ~3%/100 nm (Li et al., in preparation). The near-neutral slope is bluer than most observations of comet comae, which suggests the presence of water ice. Subsequent HST observations showed a coma that reddened as the comet's heliocentric distance decreased to 3.3 AU. On 2014 January 26, we observed comet Siding Spring with the NASA IRTF SpeX instrument, when the comet was at a heliocentric distance of 3.7 AU. Our 1 to 2.5- μ m, low-resolution spectrum of the comet has a subtle 2.0- μ m absorption feature, possibly indicating the presence of water ice. We model our spectrum using the approaches of Hapke (1993) and Protopapa et al. (2014, Icarus 238, 191). Our best-fit model suggests a coma of water-ice grains with a radius near 0.5 μ m, and an areal fraction of about 5%. We present our SpeX spectrum and best-fit model of the comet. In light of the modeling results, we consider the temporal and spatial color variations in the coma of comet Siding Spring, as well as similar HST observations of comet C/2012 S1 (ISON) from Li et al. (2013, ApJL 779, L3).

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209.11 – Radio OH Observations of Recent Bright Comets from Arecibo

We obtained OH spectra of recent comets with the Arecibo 305m radiotelescope. C/2012 X1 LINEAR was observed between 03 November 2013 and 13 January 2014, C/2014 E2 Jacques on 14 dates between 10 May and 31 July 2014, and C/2012 K1 PANSTARRS on 12 dates between 16 June and 23 August 2014. Spectra at 1667 and 1665 MHz (18cm wavelength) were obtained with an on-sky beam size of 2.9 arcminutes, mapping 7 positions of the OH within 4 arcminutes of the nucleus when the coma is sufficiently large. Radio OH spectra are seen via a π -doublet, with the excitation of the lines depending on the heliocentric velocity of the comet. We interpret the spectra via a Monte Carlo model, taking into account the OH inversion predictions of Despois et al. (1981) or Schleicher & A'Hearn (1988). In highly productive comets, high densities thermalize the lines, reducing the line strength near the nucleus. Models of mapping observations can directly constrain the radius within which quenching is active, and thus yield a more accurate estimate of the gas production rate, while radio observations at high spectral resolution place excellent constraints on the gas outflow velocity whether or not the coma is resolved. We present gas production rates, quenching radius estimates and outflow velocities for comets C/2012 X1 LINEAR, C/2014 E2 Jacques and C/2012 K1 PANSTARRS. Near its noteworthy sungrazing perihelion, comet C/2012 S1 ISON presented too small a gas coma for mapping observations, so we present only estimated gas production rates and outflow velocities for these unresolved observations.

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209.12 – The Production and Release of Volatiles in Comets

Recent observations of comets with high-resolution infrared spectroscopy have enabled the opportunity to study the spatial distributions of volatile species in the comae of comets providing information on how volatiles are stored and released from cometary nuclei. The spatial distributions of H₂O, HCN, C₂H₆, C₂H₂, CH₃OH, H₂CO, CH₄, CO, OCS, NH₃, NH₂, CN and dust can be measured in sufficiently bright comets at infrared wavelengths. Here we focus on a chemically diverse sample of comets that combine high signal-to-noise spectra with high spatial resolution. In particular, we compare the spatial distribution of volatiles in recently observed comets 73P/Schwassmann-Wachmann 3, 103P/Hartley 2, C/2007 N3 Lulin and C/2012 S1 ISON. Spatial distributions of unidentified emission features are also determined and compared to the spatial distributions of known volatiles in order to reveal characteristics that can lead to their identification. This work was supported by the NASA Planetary Atmospheres and Planetary Astronomy Programs, and also partially supported by the MEXT Supported Program for the Strategic Research Foundation at Private Universities, 2014 – 2018.

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209.13 – The Chemical Composition of Comet C/2012 S1 (ISON) between 1.2 and 0.35 AU of the Sun

The apparition of dynamically new, sun-grazing C/2012 S1 (ISON) [1] generated considerable ground- and space-based interest, and provided the rare opportunity to conduct compositional studies to heliocentric distances (R_h) well within 1 AU. We report gas production rates and molecular abundances from high-resolution ($\sim 25,000$) spectra on four dates (UT 2013 Oct 22, 24, 25, and Nov 7) using NIRSPEC [2] at Keck 2, and on six dates (Nov 15 through 19, and Nov 22) using CSHELL [3] at the NASA-IRTF. This permitted measuring volatile abundances over a wide range in R_h . NIRSPEC is cross-dispersed and so allows simultaneous measure of trace species together with H₂O, thereby avoiding most sources of systematic uncertainty, for example those associated with differences in slit losses and flux calibration among echelle orders. CSHELL has limited spectral coverage per setting, however the IRTF is unique among ground-based IR observatories in allowing daytime observations. This permitted compositional measurements of ISON to a minimum solar elongation angle of 20 degrees.

A suite of molecules (H₂O, CO, H₂CO, CH₃OH, C₂H₆, C₂H₂, CH₄, HCN, NH₃) and radicals (OH, NH₂) were targeted and detected. Our serial measurements allowed a search for potential changes in molecular abundances relative to H₂O. Those of some species (CO, C₂H₆, CH₃OH, CH₄) remained relatively constant with R_h , while others (e.g., H₂CO, HCN) increased in abundance with decreasing R_h , for example as could result from potential compositional heterogeneity in the nucleus and/or release from increasingly heated grains in the coma. Results from our serial measurements of ISON will be presented and discussed.

References: [1] Nevski V. and Novichonok A. (2012) CBET 3238. [2] McLean, I. S., et al. (1998) Proc. SPIE 3354, 566–578. [3] Tokunaga A, et al. (1990) Proc. SPIE, 1235, 131–143.

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209.14 – High-Dispersion Spectroscopic Observations of Comet C/2012 S1 (ISON) with the Subaru Telescope

Comet C/2012 S1 (ISON) was one of the Oort cloud comets and dynamically new. This comet was broken at its perihelion passage on UT 2013 November 28.1 (at $R_h \sim 17$ solar radius).

We observed the comet C/2012 S1 (ISON) on UT 2013 November 15 with the High Dispersion Spectrograph (HDS) mounted on the Subaru Telescope atop Mauna Kea, Hawaii. Its heliocentric and geocentric distances were 0.601 and 0.898 AU, respectively. We selected the slit size of $0''.5 \times 9''.0$ on the sky to achieve the spectral resolution of $R = 72,000$ from 550 to 830 nm. The total exposure time of comet C/2012 S1 (ISON) was 1200 seconds. We detected many emission lines caused from radicals (e.g., CN, C₂, NH₂), ions (H₂O⁺), atoms ([OI] and Na I) and also many unidentified lines in the spectra.

We report the (1) the ortho-to-para abundance ratios (OPRs) of water and ammonia estimated from the high-dispersion spectra of H₂O⁺ and NH₂, (2) the green-to-red line ratio of forbidden oxygen emissions, (3) the isotopic ratios of C₂ (the carbon isotopic ratio from Swan band) and CN (the carbon and nitrogen isotopic ratios from red band), (4) the sodium-to-continuum ratio of comet C/2012 S1 (ISON).

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209.15 – The Puzzle of HCN in Comets: Is it both a Product and a Primary Species?

Hydrogen cyanide has long been regarded as a primary volatile in comets, stemming from its presence in dense molecular cloud cores and its supposed storage in the cometary nucleus. Here, we examine the observational evidence for and against that hypothesis, and argue that HCN may also result from near-nucleus chemical reactions in the coma. The distinction (product vs. primary species) is important for multiple reasons:

1. HCN is often used as a proxy for water when the dominant species (H₂O) is not available for simultaneous measurement, as at radio wavelengths.
2. HCN is one of the few volatile carriers of nitrogen accessible to remote sensing. If HCN is mainly a product species, its precursor becomes the more important metric for compiling a taxonomic classification based on nitrogen chemistry.
3. The stereoisomer HNC is now confirmed as a product species. Could reaction of a primary precursor (X-CN) with a hydrocarbon co-produce both HNC and HCN?
4. The production rate for CN greatly exceeds that of HCN in some comets, demonstrating the presence of another (more important) precursor of CN.

Several puzzling lines of evidence raise issues about the origin of HCN:

- a. The production rates of HCN measured through rotational (radio) and vibrational (infrared) spectroscopy agree in some comets - in others the infrared rate exceeds the radio rate substantially.
- b. With its strong dipole moment and H-bonding character, HCN should be linked more strongly in the nuclear ice to other molecules with similar properties (H₂O, CH₃OH), but instead its spatial release in some comets seems strongly coupled to volatiles that lack a dipole moment and thus do not form H-bonds (methane, ethane).
- c. The nucleus-centered rotational temperatures measured for H₂O and other species (C₂H₆, CH₃OH) usually agree within error, but those for HCN are often slightly smaller.
- d. In comet ISON, ALMA maps of HCN and the dust continuum show a slight displacement (~ 80 km) in the centroids.

We will discuss these points, and suggest ways to test the primary and product origins of cometary HCN.

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209.16 – High Resolution Near-Infrared Spectroscopy of Comet C/2013 R1 (Lovejoy) using WINERED at Koyama Astronomical Observatory

High resolution near-infrared spectroscopic observations of comet C/2013 R1 (Lovejoy) using the WINERED ($R \sim 3 \times 10^4$) spectrometer on the 1.3-m Araki telescope at Koyama Astronomical Observatory were carried out on UT 2013 November 30. The comet was at 0.91 AU from the Sun and 0.49 AU from the Earth at the observations. This comet was

considered to originate in the Oort cloud and became bright in visible from October to December 2013. The newly developed instrument, WINERED, was a cross-dispersed Echelle spectrometer that can cover the wavelength range from 0.9 to 1.3 microns simultaneously. Many emission lines were recorded in the high signal-to-noise ratio spectra of comet Lovejoy. We report the line assignment of the detected emission lines and present our preliminary analysis for CN Red-band system.

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209.17 – The Spatial Distributions of Daughter Species in Comet C/2013 R1 (Lovejoy)

The spatial distributions of molecules in cometary comae are important to understand the chemical reactions in the coma and the original materials in the cometary nucleus.

We performed low-dispersion optical spectroscopic observations of C/2013 R1 (Lovejoy) with two instruments and telescopes. One is the FOCAS (R~1,000 with a slit size of 0".5 x 360", observational date was 2013 October 31st) mounted on the 8-m Subaru Telescope and the other is a compact low-resolution spectrograph (R~500, a slit size of 10" x 600", observational date were 2013 November 7th and 28th) mounted on a 28-cm Schmidt-Cassegrain telescope. We detected some daughter species (CN, C3, C2, NH2) and oxygen atoms.

We develop a three-generation Haser model to reproduce the spatial distributions of the observed species. Although the simple Haser model is generally used for such studies, we could not reproduce spatial distributions of C2 with the simple Haser model (Naka et al., 2013). We will present the lifetimes of observed species based on our three-generation Haser model and discuss the chemical reactions in the cometary coma of comet C/2013 R1 (Lovejoy).

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209.18 – Synergy Between Astrochemical Models and Cometary Taxonomies of Parent Volatiles

The principal output in taxonomic studies of cometary primary (parent) volatiles is the suite of "mixing ratios" between observed species. These ratios relate the abundances of different molecules (CH₄/C₂H₂/C₂H₆/H₂CO/CH₃OH/H₂O, etc.) or isotopologues (HDO/H₂O, CH₃D/CH₄, etc.). Infrared and radio observations have found strong evidence that mixing ratios vary substantially among comets. However, we still face serious uncertainties in decoding the cosmogonic significance of the measured abundances. The observed composition of comets may be an end product of a variety of processes, including chemical evolution in the protoplanetary disk, dynamical evolution in the young solar system, and (perhaps) thermal evolution during successive perihelion passages. Improved understanding of their relative importance requires additional sensitive measurements and a comprehensive synergy with astrochemical models. These models find that protoplanetary disks can be divided into three distinct regions: (1) a cold midplane, where ices freeze to dust grains; (2) a warm molecular layer, where ices sublimate and are processed via gas-phase reactions; and (3) a hot disk atmosphere containing predominantly atoms and atomic ions. Material from the different layers can be mixed by transport processes.

We will show how this synergy is being realized via close collaboration between modeling and observing teams. The goal is a deeper insight into the processes preceding comet formation that may have influenced the composition - what chemical reaction pathways dominated the synthesis of cometary compounds? What processes in the protoplanetary disk have left strong signatures in cometary ices? Can models provide testable predictions for the chemical diversity observed among comets? Addressing these questions, we will show initial comparisons between relative abundances for several cometary volatiles and those predicted for the midplane of the protoplanetary disk where comets formed. We will also discuss how models link observations of volatiles in comets with studies of protoplanetary disks around solar type stars.

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209.19 – Study of the Comet C/2013 A1 (Siding Spring)

The comet called C/2013 A1 (SIDING SPRING) was discovered on January 3, 2013 in Australia. In January 28/2014, NASA announced that is preparing for the close encounter that will happen between the comet C/2013 A1 and Mars on October 19-2014. The Mission called "MAVEN" will insert in Mars orbit on september 21—2014. The comet will pass just 138,000 kilometers far from the surface of Mars. The probability that the comet collides with Mars is small but the dust particles emitted by the comet can cause damage to spacecrafts and probes that are in orbit around that planet. NASA is making preparations to take all precautions. If the comet is quite active, there will be almost no time to take security measures with Mars orbiters. For that reason NASA is already ahead of the facts. According to scientists of the "JET PROPULSION LABORATORY-JPL", dust particles spewing from the comet may be traveling at 56 km / sec in relation to the orbiters, fifty times faster than the speed of a bullet. From our Observatory, located in Pasto-Colombia, we captured several pictures, videos and astrometry data during several days. The pictures of the asteroid were captured with the following equipment: CGE PRO 1400 CELESTRON (f/11 Schmidt-Cassegrain Telescope) and STL-1001 SBIG camera. Astrometry was carried out, and we calculated the orbital elements.

Summary And Conclusions: We obtained the following orbital parameters: eccentricity = 1.0003983, orbital inclination = 129.03078 deg, longitude of the ascending node = 300.99538 deg, argument of perihelion = 2.42310 deg, perihelion distance = 1.40023196 A.U. The parameters were calculated based on 20 observations (Jan 21 to April 02) with mean residual = 0.334 arcseconds.

We also obtained the light curve of the body with our data (January to November/2014)

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209.20 – Coma Morphology of Recent Comets: C/ISON (2012 S1), C/Pan-STARRS (2012 K1), C/Jacques (2014 E2), and C/Siding Spring (2013 A1)

We will present preliminary results from recent and upcoming imaging campaigns of four comets using Lowell Observatory's 4.3-m Discovery Channel Telescope, 42-in Hall Telescope, and/or 31-in telescope:

1. Observations of C/ISON (2012 S1) were carried out from January through November 2013. A small, sunward fan was detected in dust images acquired in March, April, May, and September. Two faint CN features approximately orthogonal to the tail appeared on November 1 and were visible until our final night of data on November 12. This significantly predates their first reported appearance in broadband images on November 14 (Boehnhard et al., CBET 3715; Ye et al., CBET 3718) and suggests that the features were not caused by a catastrophic disruption of the nucleus at that time.
2. We observed C/Pan-STARRS (2012 K1) regularly from October 2013 through June 2014 when it entered solar conjunction. Enhanced CN images in May and June 2014 exhibited a side-on pinwheel morphology that varied from night to night; similar morphology was not seen in concurrent dust images. Analysis of the rotation period is underway.
3. C/Jacques (2014 E2) was observed in April, May, and August 2014, and additional observations are scheduled through September 2014. After enhancement of the August images, Jacques exhibited two side-on CN corkscrews roughly orthogonal to the tail. The CN morphology was different from night to night but did not vary noticeably during ~1 hr of observations on a given night. Jacques also exhibited a smaller sunward dust feature in August that did not appear to vary during the observations. We will combine these data with our scheduled observations to investigate periodicity and compare the spatial distribution of multiple gas species.
4. Observations of C/Siding Spring (2013 A1) are scheduled around its close approach to Mars on October 19, 2014. This work is supported by NASA's Planetary Astronomy Program grants NNX09AB51G and NNX11AD95G.

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209.21 – The TRAPPIST comet survey in 2014

TRAPPIST (TRAnsiting Planets and Planetesimals Small Telescope) is a 60-cm robotic telescope that has been installed in June 2010 at the ESO La Silla Observatory [1]. Operated from Liège (Belgium) it is devoted to the detection and characterisation of exoplanets and to the study of comets and other small bodies in the Solar System.

A set of narrowband cometary filters designed by the NASA for the Hale-Bopp Observing Campaign [2] is permanently mounted on the telescope along with classic Johnson-Cousins filters. We describe here the hardware and the goals of the project. For relatively bright comets ($V < 12$) we measure several times a week the gaseous production rates (using a

Haser model) and the spatial distribution of several species among which OH, NH, CN, C2 and C3 as well as ions like CO⁺. The dust production rates (Afrho) and color of the dust are determined through four dust continuum bands from the UV to the red (UC, BC, GC, RC filters). We will present the dust and gas production rates of the brightest comets observed in 2014: C/2012 K1 (PANSTARRS), C/2014 E2 (Jacques), C/2013 A1 (Siding Springs) and C/2013 V5 (Oukaimeden). Each of these comets have been observed at least once a week for several weeks to several months. Light curves with respect to the heliocentric distance will be presented and discussed.

[1] Jehin et al., *The Messenger*, 145, 2-6, 2011.

[2] Farnham et al., *Icarus*, 147, 180-204, 2000.

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209.22 – Impact-Induced Shock-Stress Effects in Cometary Analogue Olivine, Pyroxene, Carbonate and Serpentine Minerals

The primary goal of the Stardust mission was to collect dust particles as the spacecraft flew past Comet 81P/Wild 2. The morphologies of several returned grains of forsterite and enstatite suggest that they have experienced shock effects due to collisions (Jacobs et al. *MAPS* 44, 2009; Keller et al., *GCA* 72, 2008; Tomeoka et al, *MAPS* 43, 2008). Because the particles were collected at an encounter speed of ~6 km/s, it was natural to question whether the collection process itself generated those microstructural shock features or if they were sustained prior to their capture in the aerogel. Analyses of the grains suggest the latter, namely, that the particles had undergone high-velocity impacts sometime before their capture.

With this in mind, unshocked minerals were impacted with the vertical gun in the NASA Johnson Space Center Experimental Impact Laboratory at 2.0 – 2.8 km/s, speeds that a typical comet might experience during its tenure in the Kuiper Belt (Stern 2002). Targets included minerals found in cometary dust and asteroids, including magnesium-rich pyroxenes (enstatite and diopside), magnesium-rich olivine (forsterite), carbonates (magnesite and siderite), and serpentine. Projectiles were Al₂O₃ spheres. Transmission electron microscope (TEM) imaging of experimentally shocked forsterite and enstatite samples reveal morphologies and densities of planar dislocations similar to those of the Stardust samples. Comparisons between TEM images of the Stardust grains and those of the experimentally shocked minerals will be presented.

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209.23 – Visible and Infrared Study of Comet 2P/Encke's Nucleus During Its 2013 Apparition

The 2013 apparition of comet 2P/Encke provided an opportunity to study the comet while it was relatively close to Earth (0.48 AU on October 17, the closest pass until 2030). We initiated a multiwavelength observing campaign for September and October with the goal of further characterizing the physical, thermal, and rotational properties of 2P's nucleus. Spectral observations were timed to coincide with an equator-on view of the nucleus, a rarely-seen vantage point compared to previous data (e.g. [1,2,3,4]). The spectra span both Wien-side thermal emission and reflected sunlight, covering 0.7 to 2.5 μm, and sample all of the nucleus's rotational longitudes. They were obtained using the SpeX instrument at the NASA Infrared Telescope Facility (IRTF). We will present results on thermal inertia and albedo from a preliminary analysis of these data. Visible observations over the past 13 years have shown that the rotation period of 2P's nucleus increases by ~4 minutes per orbit [5,6], and that the light curve has a two-humped shape but that the humps have quite different amplitudes (e.g. [7]). Thus the equator-on view gave us the chance to further investigate 2P's rotation state and shape. We used the CSUSB Murillo Family Observatory 0.5-meter telescope [8], the NOAO Kitt Peak 2.1-meter telescope, and the MORIS instrument at NASA/IRTF to obtain R-band, time-series photometry of the nucleus. We will present new, preliminary constraints on the secular changes in the nucleus's spin state and on the nucleus's shape based on these new data. We thank the allocation committees of the IRTF and NOAO telescopes for granting the time used for this project. References: [1] Y. R. Fernandez et al. 2000, *Icarus* 147, 145. [2] M. S. Kelley et al. 2006, *ApJ* 651, 1256. [3] Y. R. Fernandez et al. 2008, 40th Meeting of the DPS, #16.24. [4] P. Abell et al. 2009, 41st Meeting of the DPS, #20.02. [5] B. E. A. Mueller et al. 2008, 40th Meeting of the DPS, #16.25. [6] N. H. Samarasinha and B. E. A. Mueller 2013, *ApJ* 775, L10. [7] Y. R. Fernandez et al. 2005, *Icarus* 175, 194. [8] L. M. Woodney et al. 2013, 45th Meeting of the DPS, #413.25.

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209.24 – Radar images of Comet 209P/LINEAR: Constraints on shape and rotation

Comet 209P/LINEAR passed within 0.06 AU from Earth 23-27 May 2014, and we obtained images of the nucleus using the Arecibo and Goldstone planetary radar systems. The Arecibo images range from 75-m to 15-m resolution, and reveal an elongated nucleus about 2.5x3km in size. We did not detect evidence of large (few cm) grains in the coma, which have been detected in several other comets (e.g. Harmon et al. 2011). These images alone may not be sufficient to determine a detailed shape model, but they do constrain the size and rotation characteristics. Hergenrother observed the comet using the 1.8m VATT telescope and finds the rotation rate to be either 10.9 or 21.9 hours, however the radar data rule out the longer period. The highest resolution (15m) images show unusual surface features, unlike radar images of similar-sized asteroids. The six comet nuclei imaged by spacecraft to date, show great diversity in surface structure, texture and distribution of volatiles. More examples are needed in order to understand the formation and evolution of comets. Interpretation of the radar surface features of 209P/LINEAR and comparison to other comet nuclei will be presented.

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209.25 – Visible lightcurve observations of comet 46P/Wirtanen from 2014

Comet 46P/Wirtanen was observed at the Kitt Peak 2.1m telescope April 6-10 and May 4-7, 2014 to derive a precise rotation period to be compared with previous and future determinations. The comet will have a close approach to Earth in 2018 and these observations were the only opportunity to observe the comet when the flux was still dominated by the nucleus rather than the coma. The ultimate goal of these observations is to derive changes in the rotation period to test whether the changes are really independent of the active fraction as seen for four other comets (Samarasinha and Mueller 2013, ApJL 775, article id. L10). Establishing such a correlation will enable the prediction of rotational changes for other comets as well. It will also have far reaching implications for nuclear activity and its characteristics.

46P/Wirtanen is likely to be a hyperactive comet like 103P/Hartley 2 and our observations together with those from the close approach in 2018 will provide an excellent opportunity to compare the rotational properties of these two comets.

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209.26 – The Photometric lightcurve of Comet 1P/Halley

Comet 1P/Halley is considered an important object for a number of reasons. Not only is it the first-identified and brightest periodic comet, being the only periodic comet visible to the naked eye at every apparition, but in 1986 Halley became the first comet to be imaged by fly-by spacecraft. The NASA-funded International Halley Watch (IHW) directly supported the spacecraft by providing narrowband filters for groundbased photometric observations, and until the arrival of Hale-Bopp (1995 O1), Halley was the subject of the largest groundbased observational campaign in history. Following considerable controversy regarding its rotation period, it was eventually determined to be in complex rotation -- the first comet to be so identified. While the overall brightness variations of the coma repeated with a period of about 7.4 days, the detailed period and shape of the lightcurve constantly evolved. The determination of the specific characteristics of each of the two components of its non-principal axis rotational state has remained elusive.

To resolve this situation we have now incorporated all of the narrowband photometry, taken by 21 telescopes from around the world and submitted to the IHW archive, to create the most complete homogeneous lightcurve possible. Using measurements of three gas species and the dust, the lightcurve was investigated and found to alternate between a double- and triple-peaked shape, with no single feature being present throughout the entire duration of our dataset (316 days). The apparent period as a function of time was extracted and seen to vary in a step-wise manner between 7.27 and 7.60 days. Taken together, these results were used to produce a synthetic lightcurve revealing Halley's behavior even when no data were available. Details of this and other results, to be used to constrain future detailed modeling, will be presented.

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209.27 – Outflow Velocities of Dust as a Function of Time in the Coma of Comet 1P/Halley

We are presenting the measured sky-plane projected dust outflow velocity in the coma of Comet 1P/Halley. Based on dust features in 72 images taken from December 1985 to May 1986, it was possible to identify 21 unambiguous features. The images were obtained from the Small Bodies Node of the NASA Planetary Data System (PDS-SBN). They were originally taken from many different observatories during the International Halley Watch (IHW) initiative. The results for the projected outflow velocities will be presented as functions of both the heliocentric distance and the cometocentric distance.

We will show that there is a factor of two difference between the inbound and outbound mean projected outflow velocities of Comet 1P/Halley. For pre-perihelion, the average of the mean projected outflow velocity is approximately 0.09 km/s with a range of 0.04 to 0.17 km/s. In the post-perihelion time frame, the average of the mean projected outflow velocity is approximately 0.23 km/s with a range of 0.11 to 0.48 km/s.

There is clear evidence for acceleration of dust particles ejected from the nucleus as a function of cometocentric distance at each heliocentric distance. However, for a small fraction of dust features, we observe the opposite effect probably due to projection effects. This investigation is part of a broader study that will investigate the coma morphology and the lightcurve data to successfully develop a model to provide a self-consistent picture for the rotation and the activity of the comet.

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209.28 – Jet Morphology and Coma Analysis of 103P/Hartley 2: Temporal Evolution and Interspecies Comparisons

We present our results on an expanded study of the jet and coma behavior of comet 103P/Hartley 2 (a continuation of original results presented in Vaughan et al. 2012). We observed Hartley 2 pre- and post-perihelion in 2010 using the George and Cynthia Mitchell Spectrograph on the 2.7 m telescope at McDonald Observatory. Data for CN, C², C³, CH, and NH² were collected over six nights from 15 July to 10 November. The spectral data were used to create coma maps for each of the observed species, and the maps were processed using radial and azimuthal division techniques to create enhanced images of the coma to examine coma morphological features. To compliment the ongoing investigation of Hartley 2 as studied by the EPOXI flyby mission, we use findings from other researchers (Belton et al. 2012; Syal et al. 2012; Thomas et al. 2012) to identify dust jet locations on the nucleus and compare the computed jet directions to the radical densities in the coma at our observation times. We also calculate production rates and mixing ratios with water for suspected parent species. This work was funded by the National Science Foundation Graduate K-12 (GK-12) STEM Fellows program (Award No. DGE-0947419) and NASA's Planetary Atmospheres program (Award No. NNX14AH18G).

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209.29 – Development of the Deep Impact Ejecta Based on Early MRI Images

We analyze a sequence of the images acquired by the Deep Impact spacecraft High Resolution (HRI) and Medium Resolution (MRI) instruments during the first seconds after impact. These early images reflect the development of material excavation from the cometary nucleus, enabling a study of variations in the excavated material with time, and potentially allowing a peek into the nucleus' interior. Simply studying the brightness of the ejecta plume and its distribution as a function of height and time-after-impact could provide some insight into the characteristics of the ejecta. However, including the optical thickness of the ejecta offers an additional source of information through the resultant shadow on the surface of the nucleus, and brightness variations within it. Our goal was to reproduce both the distribution of brightness in the plume and in its shadow, thus constraining the characteristics of the ejecta. To achieve this, we used a 3D radiative transfer package HYPERION (<http://hyperion-rt.org>). The parameters of our dust modeling were composition, size distribution, and number density of particles at the base of the ejecta cone. Composition was created as a mixture of silicates, carbon and organics, ice, as well as voids to account for particle porosity. In our current modeling, we use the results of a parameter survey of dust characteristics reported previously, which was targeted to primarily simulating an HRI image taken at around 1 sec. In this survey, the best fit to Deep Impact data and excavated mass constraints showed a dust/ice mass ratio ≈ 1 , with some individual particle porosity necessary to retrieve a good fit (we checked individual particle density extremes of 0.4 g/cm³ and 1.75 g/cm³). Our current work explores the spatial distribution of dust within the ejecta plume and focuses on the changes in dust characteristics over time by analyzing and simulating a sequence of Medium Resolution (MRI) images, attempting to reveal the structure of the upper layers of the nucleus.

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209.30 – Naturally Occurring Outbursts at Comet Tempel 1

In the weeks leading up to closest approach with comet Tempel 1, the Deep Impact Flyby Spacecraft (DIF) observed 12 outbursts with its visual imagers. These outbursts varied in strength, were directional, and dissipated within hours. One outburst on 2 Jul 2005 was detected with DIF's infrared spectrometer, HRI-IR, in spectral scans acquired 0.5 hours before and 1.5 hours after the onset of the outburst. HRI-IR operates between 1.05 and 4.85 microns, which allows for the simultaneous detection of water vapor, water ice, organics, CO² and CO, provided that they are present in a sufficient quantity.

Water vapor and CO² emission bands were detected with a good signal to noise ratio, while there was no obvious detection of water ice, organics, or CO. A preliminary analysis reveals that the bulk abundance of water does not change within roughly 200 km of the nucleus as a result of the outburst. However, CO² shows an increase in abundance after the outburst. Interestingly, the magnitude of the increase in CO² appears to be dependent on aperture size, with larger apertures showing a greater increase, which is consistent with the CO² being released at the onset of the outburst. In addition, spatial variations in the distribution of water and CO² have been detected in smaller, spatially distributed apertures.

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209.31 – Demonstration of the Capabilities of CometCIEF: A Web-based Image Enhancement Facility to Enhance Images of Cometary Comae

Accurate identifications and measurements of spatial information related to coma structures of comets are an essential component of realistic quantitative interpretation of coma observations. For this purpose, there is a number of image enhancement techniques used by cometary scientists. Despite this, the wider applicability of many advanced enhancement techniques is limited due to the non-availability of relevant software as open source. We are making available a number of such techniques using a user-friendly web interface.

In this image enhancement facility available at <http://www.psi.edu/research/cometimen> one can upload a FITS format image of a cometary coma and digitally enhance it using an image enhancement technique of the user's choice. The user can then download the enhanced image as well as any associated images generated during the enhancement as FITS files for detailed analysis later at the user's institution. The available image enhancement techniques at the facility are:

- (a) division by azimuthal average,
- (b) division by azimuthal median,
- (c) azimuthal renormalization,
- (d) division by 1/? profile, where ? is the skyplane projected distance from the nucleus, and
- (e) radially variable spatial filtering.

The site provides documentation describing the above enhancement techniques as well as a tutorial showing the application of the enhancement techniques to actual cometary images and how the results may vary with different input parameters. In addition, the source codes as well as the executables are available for the user to download. To provide a secure facility, all the images uploaded by the users as well as the images created at the facility are deleted using a script that runs every hour.

At the Division for Planetary Sciences 2014 meeting, we will present a description of CometCIEF and its capabilities, as well as a live demonstration of the facility that includes a question-answer session.

Acknowledgements: We thank the NASA Planetary Atmospheres Program and the NASA Space Grant Program for supporting this work.

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209.32 – Dynamical Behavior of the Oort Cloud New Comets in Planetary Region

Nearly isotropic comets with very long orbital period are supposed to come from the Oort Cloud. Recent observational and theoretical studies have greatly unveiled the dynamical nature of this cloud and its evolutionally history, but many issues are yet to be known. Our goal is to precisely trace the dynamical evolution of the Oort Cloud new comets (OCNCs) produced in the evolving cloud, hopefully estimating the fraction of OCNCs embedded in the current populations of the small solar system bodies (SSSBs). We combine two models to follow the dynamical evolution of OCNCs beginning from their production until their ejection out of the solar system. The first model is a semi-analytical one about the OCNC production in an evolving comet cloud under the perturbation of the galactic tide and stellar encounters. The second

model numerically deals with planetary perturbation over OCNCs' dynamics in planetary region. The main results of the present study are: (1) Typical dynamical lifetime of OCNCs in our models turned out to be 10^7 years. Once entering into the planetary region, most OCNCs stay there just for this timespan, then get ejected out of the solar system on hyperbolic orbits. (2) While the average orbital inclination of OCNCs is small, the so-called "planet barrier" works effectively, preventing some OCNCs from penetrating into the terrestrial planetary zone.

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209.33 – Organic ices in the coma of comet C/2012 S1 (ISON) at heliocentric distances greater than 4 AU?

Comet C/2012 S1 (ISON) was monitored during its approach to the inner solar system, when the comet passed from a heliocentric distance of 6.0 to 4.3 AU. As many other Oort cloud comets at their first approach to the Sun, also comet ISON exhibited a systematic over population of grains in the inner part of the coma, as revealed by the β function (Tozzi et al., 2007, A&A 476, 979). So far this effect has been interpreted as due either to a short timescale variation of activity (outbursts), or long timescale variation of activity associated with very low escape velocity of the grains or with sublimating grains. In the presentation we will show that the most likely explanation of the phenomena is the sublimation of icy CO₂ grains. We will discuss also the implication of CO₂ production rates by this distributed source on the whole gas production rates of the comet at so large heliocentric distances.

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209.34 – Using an integral-field unit spectrograph to study radical species in cometary coma

We have observed several comets using an integral-field unit spectrograph (the George and Cynthia Mitchell Spectrograph) on the 2.7m Harlan J. Smith telescope at McDonald Observatory. Full-coma spectroscopic images were obtained for various radical species (C₂, C₃, CN, NH₂). Various coma enhancements were used to identify and characterize coma morphological features. The azimuthal average profiles and the Haser model were used to determine production rates and possible parent molecules. Here, we present the work completed to date, and we compare our results to other comet taxonomic surveys. This work was funded by the National Science Foundation Graduate K-12 (GK-12) STEM Fellows program (Award No. DGE-0947419), NASA's Planetary Atmospheres program (Award No. NNX14AH18G), and the Fund for Astrophysical Research, Inc.

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210 – Exoplanet Posters

210.01 – A Survey for Very Short-Period Planets in the Kepler Data

Most close-in gas giant exoplanets are unstable against tidal decay, and as these gas giants spiral inward and shed their atmospheres, their rocky and icy cores are stranded in orbits with periods as short as a few hours. Such fossil cores have been outside the main Kepler mission search parameters, but recently a few planets and a number more candidates with periods less than 1 day have been identified by different groups. We present the latest results from Superpig (the Short Period Planet Group) on identifying and characterizing such planets in the Kepler archive, combined with ground-based follow-up observations (RV and AO).

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210.02 – Upper Limits for Rings Around Exoplanets from Kepler Data

Rings have been found around all of the giant planets in our solar system, some more predominate than others, and now even around a dwarf planet, Centaur Chariklo. These ring systems in our solar system make it highly probable that exoplanets may have rings too. Barnes & Fortney (2004) considered using Kepler to detect rings around exoplanets, and they concluded that it is theoretically possible with favorable planetary geometries. However, Neptune-like rings are

undetectable. Using information obtained from the Kepler Archive we selected four candidates for which ring detectability is highest: KOI 289, 422, 490, and 1353. These targets were selected based on the following criteria: long orbital periods, high S/N ratio, and a Roche limit larger than $\approx 1.5R_p$.

The light curves of these four planets were analyzed not as a spherical body, but as a spherical body with a ringed system. None of the targets shows convincing evidence for the presence of rings. We therefore establish an upper limit for the characteristics of rings around each target planet, and explore the implications of finding rings around exoplanets.

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210.03 – Characterizing Extrasolar Planets from Transit Light Curves obtained at the Universidad de Monterrey Observatory

At the Universidad de Monterrey Observatory (MPC 720) we have been recording extrasolar planet transit light curves with telescopes of modest size and standard photometric filters since 2005. In our archives we have over 300 transits of over 70 known systems. Our goal is to combine individual transit light curves of the same system to increase the S/N of the data. We then analyze it together with the radial velocity information from the literature in order to confirm, improve or revise the main parameters that characterize the transiting system. It is important to continue observing these systems not only to improve and refine our understanding of them, but also to record any possible transient phenomenon (e.g. star spots) and monitor for possible period changes, as reflected in the mid-transit times, due to the gravitational influence of additional planets in the system.

In this presentation we report our first results from this project. We have successfully combined light curves for HAT-P-12 (5), HAT-P-13 (7), HAT-P-16 (4), HAT-P-23 (6), and WASP-10 (8) and have derived planet sizes (R_p/R_*), orbital distances (a/R_*) and orbital inclinations (i) for these systems. In most cases we confirm the parameters reported in the literature with similar uncertainties, validating our methodology. However, for HAT-P-12 we have decreased the uncertainties and derived a smaller inclination for the orbit ($87.9^\circ \pm 0.3^\circ$ vs $89.0^\circ \pm 0.4^\circ$). Also, for HAT-P-23, the only planet in our sample with a distinct non-circular orbit, we improved the uncertainties for the eccentricity (e) and the argument of periastron (ω) while deriving a $\sim 4\% \pm 1\%$ smaller planet size. From our mid-transit times and those of the literature we do not find any statistically significant deviations from a fixed orbital period for these systems, although it is known that HAT-P-13 has at least a second planet.

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210.04 – The San Pedro Mártir Transit Observations Program

In the framework of the TAOS-II project, aimed at the observation of small-size Kuiper Belt Object occultations, we present the first transit observation program carried on using the facilities of the San Pedro Mártir Observatory (Baja California, Mexico).

The involved telescopes consist in a traditional 84cm telescope, a robotic 1.5m, and a traditional 2.12m. The project consist in validating the possibility to use these facilities to observe known Hot Jupiters, in order to set up a follow-up strategy for specific TAOS-II alerts.

15 exoplanetary transits were successfully observed in 2014, in several photometric bands (U, V, R, r, and i).

We present a panoramic of the project and the results of the fit of first two objects, WASP-39 and WASP-43, which are also the subject of a manuscript in preparation.

Moreover, we are exploring 3D ray tracing models to model the system basing on our results, using the software SHAPE.

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210.05 – Using CLOUDY to investigate the physical characteristics in the vicinity of transiting hot Jupiters

Detecting and studying the magnetic fields of exoplanets will allow for the investigation of their interior structure, rotation period, atmospheric retention, moons, and habitability. In this study we simulate the plasma, chemistry, radiation transport, and dynamics of the plasma characteristics in the vicinity of the exoplanet using the code CLOUDY. We previously observed the primary transits of 18 exoplanets in the near-UV photometric band in an attempt to detect their magnetic fields and to search for a wavelength dependence in their planetary radii in order to constrain their atmospheric compositions (Turner et al. 2013, Pearson et al. 2014). It was postulated by Vidotto et al. (2011) that the magnetic fields of all our targets could be constrained if their near-UV light curves show an early ingress compared to their optical light curves, while their egress remains unattenuated. The early near-UV ingress is caused by the presence

of a bow shock in front of the planet formed by interactions between the stellar coronal material and the planet's magnetosphere. If the shocked material is sufficiently optically thick, it will absorb starlight and cause an early ingress in the near-UV light curve. We do not observe an early ingress in any of our targets, but determine upper limits on their magnetic field strengths. All our magnetic field upper limits are well below the predicted magnetic field strengths for hot Jupiters. Vidotto et al. (2011) originally predicted 69 planets should exhibit near-UV asymmetries and currently 19 of those show non-detections. Our result implies that hot Jupiters and hot Neptunes may have abnormally low magnetic field strengths. It may also indicate that the techniques outlined by Vidotto et al. (2011) can only be used in narrow-band spectroscopy and not broad-band photometry or that there is no absorbing species in our wavelength range. Using CLOUDY we have investigated whether there is an absorption species in the bow shock to cause an observable early ingress. All the non-detections in this study question the robustness of using near-UV asymmetries to detect and study exoplanet magnetic fields from the ground.

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210.06 – Exoplanet Observation from the Vatican Observatory

We report our spectroscopic investigation of the transiting hot Jupiter HD 189733b's atmospheric transmission and the first exoplanet transit taken with the Vatican Observatory 1.8m telescope on Mt. Graham using the medium resolution spectrograph VATTSpec. We reconfirm existing planet/star radius ratio measurements with 2675 individual channel measurements spanning ~400-900nm. We provide the first in depth look at the steps necessary for well-calibrated VATTSpec observations and provide advice for future observations with this instrument.

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210.07 – The Effect of Rotation Rate on Seasonally Migrating Tropical Precipitation Zones on Terrestrial Planets

In the Earth's atmosphere, tropical precipitation zones migrate seasonally but never extend beyond 30N, even in regions of large-scale monsoons. On Titan, however, seasonal, monsoon-like weather patterns regularly pump liquid methane to the poles. In this study, we argue that rotation rate is the main control on the seasonal extent of planetary monsoons, while surface thermal inertia plays a secondary role: i.e. the control is primarily dynamic rather than thermodynamic. Factors controlling the position and the sensitivity to energetic perturbations of the intertropical convergence zone (ITCZ) on Earth, a narrow latitudinal band where tropical precipitation is concentrated, have been widely investigated in the literature. Interestingly, while on Earth the ITCZ is limited to low latitudes, on Mars and Titan the ITCZ can migrate significantly off the equator into the summer hemisphere. Previous explanations for the ITCZ's larger migration on Mars and Titan compared to Earth emphasize the lower surface thermal inertias of those planets. Here, we study a wide range of atmospheric circulations with an idealized General Circulation Model (GCM), in which an atmospheric model with idealized physics is coupled to an aquaplanet slab ocean of fixed depth and the top-of-atmosphere insolation is varied seasonally. A broad range of circulation regimes is studied by changing the thermal inertia of the slab ocean and the planetary rotation, while keeping the seasonal cycle of insolation fixed and all other parameters Earth-like. We find that for rotation rates 1/8 that of Earth's and slower, essentially Titan-like rotation rates, Earth's ITCZ reaches the summer pole. At odds with previous explanations, we also find that decreasing the surface thermal inertia, to Titan's surface thermal inertia and smaller, does little to extend the ITCZ's summer migration off the equator. These results suggest that the ITCZ may be more controlled by dynamical mechanisms than previously thought. We explore such mechanisms within the framework of the momentum budget.

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210.08 – Hot Jupiter Radii: A Turbulent History

Many hot Jupiters, i.e. giant exoplanets with short orbital periods, are bloated, with radii that greatly exceed those of colder gas giants. In models that neglect atmospheric motion, the enhanced irradiation of hot Jupiters is insufficient to explain their large radii. However uneven surface irradiation drives atmospheric circulation. These atmospheric motions deposit heat at deeper layers than irradiation alone, and can explain their large radii. The specific dissipation mechanism for atmospheric circulation can involve a turbulent cascade and/or the driving of electric currents that undergo Ohmic dissipation. The "Mechanical Greenhouse" model (Youdin & Mitchell, 2010) showed that turbulence in hot Jupiter atmospheres does mechanical work against the stable stratification of upper radiative zones, thereby driving a heat flux deeper into the interior. This poster will describe the first efforts to include this turbulent heat flux in planetary structure models. The goal is to understand the effects of turbulent mixing on hot Jupiter radius evolution. To perform these calculations we modify the publicly available stellar structure code MESA. We show how the effects of turbulence can be included in MESA — and understood physically — as an effective dissipation profile. We compare the

radius evolution of hot Jupiters for different dissipation prescriptions, including our turbulent mixing model and others from the literature. We find that turbulent mixing is an energetically efficient way to explain the bloated radii of hot Jupiters.

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210.09 – Atmospheric Dynamics of Brown Dwarfs and Directly Imaged Giant Planets: Emergence of Zonal Jets and Eddies from Small-Scale Convective Perturbations

A variety of observations now provide evidence for vigorous motion in the atmospheres of brown dwarfs and directly imaged giant planets; these observations include spectral evidence for clouds, disequilibrium chemistry, lightcurve variability, and maps of surface patchiness. These observations raise major questions about the nature of the atmospheric circulation on these exotic worlds, which resemble high-heat-flux, high-gravity, rapidly rotating versions of Jupiter. Although brown dwarfs and directly imaged giant planets generally lack the strong external stellar irradiation that causes the atmospheric circulation on most solar system planets, the vigorous convection in their interiors will drive a wealth of waves and perhaps a coherent large-scale circulation in their overlying stably stratified atmospheres. Here, we investigate this process using state-of-the-art, global 3D simulations of the atmospheric circulation using the MITgcm. We parameterize convective perturbations near the radiative-convective boundary using a spatially and temporally random, isotropic, small-scale thermal forcing at the bottom of the domain. Radiation is parameterized with an idealized Newtonian cooling scheme. Clouds and condensates are neglected. Our simulations show that brown dwarfs can in many cases develop large-scale atmospheric circulations comprising banded flow patterns, zonal jets, turbulence, and in some cases stable vortices. We will describe how the amplitude, length scales, and fundamental nature of the circulation -- in particular, the tendency to favor zonal jets versus quasi-isotropic turbulence -- depends on the radiative time constant, the convective forcing amplitude and timescale, gravity, and other parameters. The simulations provide a foundation for understanding observed lightcurves and surface maps of brown dwarfs, and moreover illuminate the continuum of atmospheric-dynamics processes between brown dwarfs and Jupiter itself.

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210.10 – Spectroscopic analysis of the ν_{17} band of C^2H^5D at 770 - 850 cm^{-1}

To support planetary investigations of hydrocarbons, we analyzed the high resolution spectrum of C^2H^5D from 680 to 880 cm^{-1} in order to enable its detection in the atmospheres of Titan, Neptune and Uranus. Ethane, methane and acetylene are regarded as important organic molecules in the analysis of atmospheres and have been observed by ground based and satellite observations. The isotopes of ethane contain strong bands within the commonly viewed window of ethane's ν_9 band at 800 cm^{-1} . Detailed analyses of d^1 -ethane and ^{13}C -ethane provide unique insight into the isotopic fractionation and can be used to refine models of hydrocarbons in organic rich atmospheres. We present the analyses of the strong ν_{17} band of C^2H^5D at 805 cm^{-1} which lies within the often-measured "12 micron" window utilized by many present and past surveys of planetary atmospheres. Using the FTIR Bruker IFS 125HR at the Jet Propulsion Laboratory, the spectrum of 98% deuterium-enriched sample of C^2H^5D at high resolution (Resolving power $\sim 320,000$) was recorded at 130 K using a 0.20 m absorption cell. Over 10000 individual line frequencies and intensities were retrieved between 690 and 870 cm^{-1} . Improved quantum mechanical models permitted over 4700 quantum assignments to be determined for the ν_{17} band at 805 cm^{-1} , and the corresponding measured line positions were reproduced with a standard deviation of $4 \times 10^{-4} cm^{-1}$. We will describe the resulting linelist for the ν_{17} band of C^2H^5D that enable this species to be identified in planetary atmospheres.

Part of the research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, Connecticut College, and NASA Langley under contract with the National Aeronautics and Space Administration.

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210.11 – Equilibrium Chemistry Calculations for Model Hot-Jupiter Atmospheres

Every planet in our solar system has different elemental abundances from our sun's. It is thus necessary to explore a variety of elemental abundances when investigating exoplanet atmospheres. Composition is key to unraveling a planet's formation history and determines the radiative behavior of an atmosphere, including its spectrum (Moses et al. 2013).

We consider here two commonly discussed situations: $[C]/[O] > 1$ and 10x and 100x heavy-element enrichment. For planets above 1200 K, equilibrium chemistry is a valid starting point in atmospheric analysis. For HD 209458b, this assumption was verified by comparing the results of a robust kinetics code (non-ideal behavior) to the results of an equilibrium chemistry code (ideal behavior). Both codes output similar results for the dayside of the planet (Agundez et al. 2012). Using NASA's open-source Chemical Equilibrium Abundances code (McBride and Gordon 1996), we calculate the molecular abundances of species of interest across the dayside of model planets with a range of: elemental abundance profiles, degree of redistribution, relevant substellar temperatures, and pressures. We then explore the compositional gradient of each model planet atmosphere layer using synthetic abundance images of target spectroscopic species (water, methane, carbon monoxide). This work was supported by the NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program NNX13AF38G.

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210.12 – Observation and Analysis of Secondary Eclipses of WASP-32b

We report two Spitzer secondary eclipses of the exoplanet WASP-32b. Discovered by Maxted et al. (2010), this hot-Jupiter planet has a mass of 3.6 ± 0.07 M_J, a radius of 1.18 ± 0.07 R_J, and an orbital period of 2.71865 ± 0.00008 days around a G-type star. We observed two secondary eclipses in the 3.6 micron and 4.5 micron channels using the Spitzer Space Telescope in 2010 as a part of the Spitzer Exoplanet Target of Opportunity program (program 60003). We present eclipse-depth measurements, estimates of infrared brightness temperatures, and refinements of orbital parameters for WASP-32b from our eclipse measurements as well as amateur and professional data. Spitzer is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G. JB holds a NASA Earth and Space Science Fellowship.

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210.13 – Analysis of Secondary Eclipse Observations of Exoplanet WASP-34b

WASP-34b is a short-period exoplanet with a mass of 0.59 ± 0.01 Jupiter masses orbiting a sun-like star with a period of 4.3177 days and an eccentricity of 0.038 ± 0.012 (Smalley, 2010). We observed WASP-34b using the 3.6 and 4.5 micron channels of the Infrared Array Camera aboard the Spitzer Space Telescope in 2010 (Program 60003). We present eclipse-depth measurements, estimates of infrared brightness temperatures, and refine the orbit using our secondary eclipse measurements. Spitzer is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G. JB holds a NASA Earth and Space Science Fellowship.

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210.14 – Secondary Eclipse Observations of the Hot-Jupiter HAT-P-30-WASP-51b

HAT-P-30-WASP-51b is a hot-Jupiter planet that orbits an F star every 2.8106 days at a distance of 0.0419 AU. Using the Spitzer Space Telescope in 2012 (Spitzer Program Number 70084) we observed two secondary eclipses of the planet, one in the 3.6 micron channel on 3 January and one in the 4.5 micron channel on 17 January. We present eclipse-depth measurements, estimates of infrared brightness temperatures, We also refine its orbit using our own secondary eclipse measurements in combination with external radial-velocity and transit observations from both professional and amateur observers. Spitzer is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G.

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210.15 – The Dynamics of known Short-period Multi-planet Systems in the Presence of Outer Planets

Among the Kepler planet candidate sample, 23% of stellar hosts contain multiple transiting planet candidates (Burke et al. 2014). The false positive rate among the multi-candidate systems is expected to be very low, suggesting that the candidates in these systems are truly planets. The large abundance of these systems suggests that the formation of multi-planet systems at short orbital periods (the candidate period distribution peaks between 10 and 20 days) is a fundamental mode of planet formation. However, we do not understand what processes lead to the diversity of

planetary systems or whether the formation processes that give rise to Kepler multi-planet systems also permit the formation of distant planets akin to the Solar System. To this end, we explore the consequences that outer planets have on the stability and observability of known Kepler and Kepler-like multi-planet systems.

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210.16 – The dynamical structure of the HR8799 inner debris disk

The HR 8799 system, with its four giant planets and two debris belts, has an architecture closely mirroring that of our Solar System where the inner, warm asteroid belt and outer, cool Edgeworth-Kuiper belt bracket the giant planets. As such, it is a valuable laboratory for examining exoplanet dynamics and debris disc-exoplanet interactions. Whilst the outer debris belt of HR 8799 has been well resolved by previous observations, the spatial extent of the inner disc remains unknown, leaving a question mark over both the location of the planetesimals responsible for producing the belt's visible dust and the physical properties of those grains. We have performed the most extensive simulations to date of the inner, unresolved debris belt around HR 8799, using University of New South Wales's Katana supercomputing facility to follow the dynamical evolution of a model inner disc comprising 250,000 particles for a period of 100 million years. These simulations will (1) characterise the extent and structure of the inner disk in detail and (2) provide the first estimate of the small-body impact rate and water delivery prospects for possible (as-yet undetected) terrestrial planet(s) in the inner system.

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210.17 – The Arecibo Reconnaissance of Radio Emission from Nearby Extrasolar Planets

For several decades, it has been known that the Earth and Jupiter naturally generate radio emission from their magnetospheres, and that this radio emission serves as a probe of the magnetic field properties and plasma environments of these objects. In particular, the terrestrial auroral kilometric radiation, Jovian radio emission from decimetric through kilometric frequencies, and the Saturn kilometric radiation have been well studied through both remote sensing and in situ methods. At the more massive end of the continuum of substellar objects, brown dwarfs of spectral type as late as L3.5 have been shown to emit radio waves through the same mechanism that causes most of the radio emission from the magnetized Solar System planets.

During the course of our recent searches for radio emission from ultracool dwarfs, we investigated brown dwarfs of spectral types as late as T6.5 and pushed even farther down the intrinsic luminosity scale through the observation of the system of four planets around a young, A-type star, HR 8799. Our investigation was conducted with the 305-m Arecibo radio telescope, its 5 GHz receiver, and the fast-sampled, broadband Mock spectrometer. Although no radio emission was detected from the young, hot HR 8799 planets, we provide useful upper limits on their radio luminosities and magnetic field strengths. However, our surveys have detected radio emission from two cool brown dwarfs, which have temperatures comparable to those young planets: one of type T6 (~1050 K) and one of type T6.5 (~900 K; Route & Wolszczan 2012). These results imply that, for young, massive exoplanet systems, which, like the one around HR 8799, consist of planets at type-T brown dwarf luminosity-levels and temperatures, the detection of radio emission with instrumentation such as that currently available at Arecibo is entirely plausible. This strategy appears more promising than low frequency searches for radio emission from the old, low magnetic field exoplanets, which clearly require detection sensitivities that exceed the presently available ones by several orders of magnitude.

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210.18 – Pale Orange Dots: Hazy Archean Earth as an Analog for Hazy Earthlike Exoplanets

Of the four terrestrial worlds with significant atmospheres in our solar system – Venus, Earth, Mars, and Titan – two of these worlds are presently enshrouded by hazes, and observations suggest that hazy exoplanets are also common (Bean et al. 2010, Sing et al. 2011, Kreidberg et al 2014, Knutson et al. 2014). The early (Archean) Earth may have had a photochemical hydrocarbon haze similar to Titan's (Zerkle et al. 2012), with important climactic effects (Pavlov et al. 2001, Trainer et al. 2006, Haqq-Misra et al. 2008, Domagal-Goldman et al. 2008, Wolf and Toon 2012). Here, we considered Archean Earth as an analog for hazy Earthlike exoplanets and used a modified version of the 1-D photochemical code developed originally by Kasting et al. (1979) to generate model Archean atmospheres with fractal hydrocarbon haze particles. A 1-D line-by-line fully multiple scattering radiative transfer model (Meadows and Crisp 1996) was then used to generate synthetic spectra of early Earth with haze. We have used the resulting synthetic spectra to examine the effect of haze on the detectability of putative biosignatures and the Rayleigh scattering slope, which has been suggested as a means for constraining atmospheric pressure (Benneke and Seager 2012). We also examined haze's

impact on the spectral energy distribution reaching the planetary surface. Because the atmospheric pressure and haze particle composition of the Archean Earth are poorly constrained, and because exoplanets will occupy a range of parameter space, we tested the influence of atmospheric pressure and particle density on haze formation, and explored how various particle size distributions affect the spectrum. We find that haze strongly affects the spectral region of the Rayleigh slope, a change detectable at low spectral resolution that impacts the ability to constrain pressure with Rayleigh scattering. The spectral energy distribution at the surface is modulated by haze thickness and the assumed particle size distribution. For plausible haze parameters for early Earth and similar planets, the peak photon flux at the ground can shift to longer wavelengths, which may be important to biological processes.

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210.19 – Anti-Clockwork Planetary Systems: Long-Lived Chaotic Evolution of Mutually Inclined Exoplanets in Mean Motion Resonances

The orbital evolution of exoplanets in mean motion resonance and with mutual inclinations is often chaotic, with large amplitude variations of eccentricity (~0 up to 0.9) and inclination (~0 up to 170 degrees). Despite this strongly chaotic behavior, these systems can be stable for 10 Gyr. In cases that survive for only 0.1 to 1 Gyr, eccentricities can aperiodically reach values larger than 0.999 and inclinations larger than 179.9 degrees. Typically, the orbital behavior appears to switch between different modes, with the classic eccentricity-type resonance as one mode. Outside of that resonance, the motion cannot be easily characterized as eccentricity- and/or inclination-type, because both operate, with the conjunction longitude librating about specific directions. This phenomenon can affect Earth-mass planets in the habitable zone, potentially altering surface habitability. Planets with eccentricities that approach unity may be tidally circularized while the inclination is at any value, revealing a previously unknown process to produce misalignment between stellar spin axes and hot planets' orbital planes. Finally, we re-examine planet-planet scattering simulations and find they produce these types of systems with a frequency of order 0.5%. Giant planets exhibiting such behavior may be detectable by the GAIA spacecraft.

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210.20 – The NASA Exoplanet Exploration Program

The NASA Exoplanet Exploration Program (ExEP) is chartered to implement the NASA space science goals of detecting and characterizing exoplanets and to search for signs of life. The ExEP manages space missions, future studies, technology investments, and ground-based science that either enables future missions or completes mission science. The exoplanet science community is engaged by the Program through Science Definition Teams and through the Exoplanet Program Analysis Group. The ExEP includes the space science missions of Kepler, K2, and the proposed WFIRST-AFTA that includes dark energy science, a widefield infrared survey, a microlensing survey for outer-exoplanet demographics, and a coronagraph for direct imaging of cool outer gas- and ice-giants around nearby stars. Studies of probe-scale (medium class) missions for a coronagraph (internal occulter) and starshade (external occulter) explore the trades of cost and science and provide motivation for a technology investment program to enable consideration of missions at the next decadal survey for NASA Astrophysics. Program elements include follow-up observations using the Keck Observatory which contribute to the science yield of Kepler and K2, and include mid-infrared observations of exo-zodiacal dust by the Large Binocular Telescope Interferometer which provide parameters critical to the design and predicted science yield of the next generation of direct imaging missions. ExEP includes the NASA Exoplanet Science Institute which provides archives, tools, and professional education for the exoplanet community. Each of these program elements contribute to the goal of detecting and characterizing earth-like planets orbiting other stars, and seeks to respond to rapid evolution in this discovery-driven field and to ongoing programmatic challenges through engagement of the scientific and technical communities.

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210.21 – Geometric effects of Circumbinary Planets

The largest fraction of random observers will never see a planet transit. Multiple systems contain a planet orbiting two sun-like stars that orbit and eclipse each other, creating unique effects for the planet and its transits. In the case of a perfectly coplanar binary and planet system looked upon exactly edge on, there is a transit every time the planet comes by. In between, there are a wide variety of possibilities. To understand the complicated geometry, probability of transits,

and true frequency in these systems, determining bias in transits is essential. In looking at these possibilities, random observers from any location are considered for the most likely transits. We use three-body integration and we find the geometric probability depending on the number of random observations within a short interval in our model of transiting system. We will explore how these geometric effects vary as a function of binary and planetary orbital parameters, which will allow for a characterization of the unknown intrinsic properties of the circumbinary planet population.

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211 – Titan Posters

211.01 – Cassini UVIS Solar Zenith Angle Studies of Titan Dayglow Based on N₂ High Resolution Spectroscopy

The Cassini Ultraviolet Imaging Spectrograph (UVIS) observed photon emissions of Titan's day and night limb-airglow on multiple occasions, including during an eclipse observation. On one occasion the UVIS made a Solar Zenith Angle (SZA) study of the Titan limb dayglow (2011 DOY 171) from about 70 to 95 degrees SZA. The UV intensity variation observations of the N₂ photoelectron excited spectral features from the EUV (563-118.2 nm) and FUV (111.5-191.2nm) sub-systems followed a Chapman function. For other observations at night on the limb, the emission features are much weaker in intensity. Beyond 120 deg SZA, when the upper atmosphere of Titan below 1200 km is in total XUV darkness, there is an indication of weak and sporadic night side UV airglow emission excited by magnetosphere plasma collisions with ambient thermosphere gas, with similar N₂ excited features as above in the daylight or twilight glow over an extended altitude range. We have analyzed the UVIS airglow spectra with models based on high resolution laboratory electron impact induced fluorescence spectra. We have measured high-resolution (FWHM = 0.2 Å) extreme-ultraviolet (EUV, 800-1350 Å) laboratory emission spectra of molecular nitrogen excited by electron impact at 20 and 100 eV. Molecular emission was observed to vibrationally-excited ground state levels as high as v''=17, from the a 1^g, b 1^u, and b' 1^u+ excited valence states and the Rydberg series cⁿ+1 1^u+, c_n 1^u and o 1^u for n between 3 and 9. A total of 491 emission features were observed from N₂ electronic-vibrational transitions and atomic N I and N II multiplets. Their emission cross sections were measured. The blended molecular emission bands were disentangled with the aid of a model which solves the coupled-Schrodinger equation

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211.02 – Atmospheric Profiles of Titan's High-Altitude Haze: Cassini UVIS Stellar Occultation Measurements

We present retrievals of Titan haze profiles derived from Cassini UVIS stellar occultation observations of the upper atmosphere above 300 km. These measurements focus on the wavelength region in the far ultraviolet (FUV) between 1850-1900 Å, where absorption by other hydrocarbon species is minimal. While this work does not uniquely estimate haze particle absorptivity and number density separately, we provide robust estimates of the combined effects of these two physical parameters over multiple Titan flybys and for a range of latitudes. The results provide useful constraints for models of Titan haze formation throughout this region of the upper atmosphere.

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211.03 – The Effect of Saturn's Gravitational Tide on Superrotation in Titan's Atmosphere

The effect of Saturn's steady gravitational tide on superrotation in Titan's atmosphere is explored with an analytical model. A migrating, wavenumber-2 tide is established when the mean zonal wind in the atmosphere is non-zero. The properties of this tide and its effect on the zonal winds at low latitudes are estimated with the aid of a "superrotating beta-plane" approximation for the dynamics. Superposition of the two lowest symmetric modes forced by the tidal potential is found to produce significant zonal Reynolds stresses and mean-flow acceleration at low latitudes in the upper troposphere and stratosphere when the tidal vertical wind at the surface is zero. The possible relationship of these stresses to the "null wind zone" observed near 75 km altitude, and to the maintenance of the superrotation in general, will be discussed. This research has been supported by the NASA Planetary Atmospheres Program.

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211.04 – Temperature-dependent cross sections of benzene (C₆H₆) in the 7 – 15 μm region for Titan studies

Benzene is one of the terminal species produced by hydrocarbon photochemistry, as well as a precursor species for

polycyclic aromatic hydrocarbons (PAHs) on Titan. Benzene has already been detected in Titan's stratosphere, but existing laboratory measurements in nitrogen mixtures are either at room temperature or at low-resolution, which are not sufficient for the quantitative analysis of Titan observations from Cassini/CIRS. We have therefore undertaken a laboratory investigation of the temperature dependence of benzene absorption cross sections between 630 and 1540 cm^{-1} .

Multiple spectra of pure and N_2 -mixture samples of C_6H_6 have been recorded at 230 – 296 K using the high-resolution Fourier transform spectrometer (Bruker IFS-125HR) and two cold cells (80 cm and 2 cm path length) at JPL. From these FT-IR spectra, the benzene cross sections have been derived for a few combination and difference bands (e.g., $\nu_{17} - \nu_{20}$, $\nu_7 + \nu_{20}$, $\nu_4 + \nu_{11}$, etc.) as well as three strong fundamentals (ν_4 , ν_{13} , ν_{14}) out of seven in this region. We note that ν_4 band centered at 674 cm^{-1} is the strongest among all the benzene bands.

In addition, we have derived a HITRAN-format empirical 'pseudo-linelist' for benzene containing line positions, intensities, and effective lower state energies (analogous to true spectroscopic line parameters), by fitting simultaneously all the observed laboratory spectra (see <http://mark4sun.jpl.nasa.gov/data/spec/Pseudo/Readme> for details).

We will present preliminary results for the temperature-dependent cross sections of benzene. We also discuss their integrated intensities from the pseudoline intensities and compare them to those from earlier work.

[Research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.]

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211.05 – Nitrogen incorporation in Titan's tholins inferred from high resolution orbitrap mass spectrometry

Influx of solar photons and heavy charged particles from Saturn's magnetosphere on Titan's atmosphere - mainly comprised of methane and nitrogen - induce an intense organic photochemistry, which leads to the formation of a large amount of aerosols in suspension in the atmosphere. In order to infer the role of nitrogen in Titan's aerosol formation processes we produced laboratory analogs using the PAMPRE experiment [1]. In this work, we compare the composition of different analogs by using high resolution mass spectrometry and propose an additional study using gas-chromatography coupled to mass-spectrometry for a new kind of analog produced by polymerization of cryogenically trapped gaseous neutral species [2]. The comparison of these materials emphasizes the importance of ion chemistry processes for the inclusion of nitrogen in molecules constituting Titan's tholins. A statistical approach is also used for the treatment of high-resolution mass spectra of these highly complex organic materials. This method allows distinguishing molecular families that can be reconstructed by an ideal co-polymer [3]. We investigate several co-polymer reconstructions, and we suggest that a HCN (or CH_3CN) / C_2H_4 based co-polymer agrees well with the polymeric structure of tholins produced with 5% of methane in nitrogen.

[1] Szopa et al. PSS 54(4): 394-404 (2006)

[2] Gautier et al. Icarus 213(2): 625-635 (2011)

[3] Pernot et al. Analytical Chemistry 82(4): 1371-1380 (2010)

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211.06 – An updated photochemical model of the atmosphere of Titan for astrobiology

A new comprehensive Titan atmospheric model has been developed as part of the NASA Astrobiology Institute JPL-Titan team effort to understand the complexity of organic chemistry in the combined Titan atmosphere/surface system. The code is based on previous work (e.g., Allen et al., 1981; Yung et al., 1984) and has been improved to answer increasingly more complex questions on the chemical and dynamical processes responsible for the spatial and temporal distribution of chemical species in planetary atmospheres. The current reaction network consists of 1266 species and over 20,000 reactions including photolysis, neutral-neutral and ion-molecule reactions. We present preliminary results from the atmospheric simulation, focusing on the flux of molecular hydrogen in the lower atmosphere and the partitioning of carbon in the material settling to the surface, and the relative upper atmosphere/lower atmosphere source for this material

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211.07 – The Non-LTE Model of IR Emissions of Methane in the Titan's Atmosphere

Above about 400-450 km in Titan's atmosphere, the assumption of local thermodynamic equilibrium (LTE) breaks down for molecular vibrational levels of methane and various trace gases. Above this altitude non-LTE significantly impacts the formation of infrared ro-vibrational band emissions of these species observed in the limb viewing geometry. We present detailed model of the non-LTE in methane in the Titan's atmosphere based on a new extended database of the CH₄ spectroscopic parameters as well as on the revised system of collisional V-T and V-V exchange rates. We analyze for a number of atmospheric models the vibrational temperatures of various CH₄ levels and limb emissions, and compare them with those obtained for the HITRAN-2012 methane spectroscopic parameters. Implications for the non-LTE diagnostics of the Cassini CIRS and VIMS measurements are discussed.

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211.08 – Titan's Hydrocarbon Zoo: Detection of Propene and the Search for Structural Isomers

In the wake of the Voyager 1 encounter with Titan in 1980, several papers from the IRIS spectrometer team announced the detection of a plethora of molecular species in Titan's stratosphere. These included confirmation of the C₂H_x species ethane (C₂H₆), ethylene (C₂H₄) and acetylene (C₂H₂) – previously sighted by ground-based telescopes at lower resolution – and the new detections of propane (C₃H₈) and propyne (C₃H₄) (Maguire et al., *Nature*, 292, pp 683-686, 1981). Propene (C₃H₆) was the most prominent missing member of the C₃H_x family until its detection last year by Cassini CIRS, filling a gap in the molecular table (Nixon et al., *Ap. J. L.*, 776, L14, 2013). Of the C₄H_x family, only diacetylene is currently confirmed. As well as searching for heavier hydrocarbons, recent focus has been on the search for isomers of known molecules, including allene (C₃H₄) and cyclopropane (C₃H₆). Such detections would be of vital importance, since they help to elucidate the relative importance of various chemical pathways leading to large molecules. We will report on the abundance of propene from CIRS, and the on-going search for and upper limits of new species.

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Contributing team(s): Cassini CIRS Team

211.09 – Characteristics of the 5- μ m-bright spectral unit from spectral analysis of Tui Regio

Tui Regio, Titan's largest outcrop of 5- μ m-bright material, exhibits one of the few absorption features identified on Titan's surface McCord et al. (2008). In this work, we seek to constrain the formation mechanism for this spectral unit by characterizing the physical structure and optical properties of the surface. To do so, we explore the occurrence of this absorption feature in all available VIMS coverage of Tui Regio and investigate the depth of the absorption as a function of phase angle. With more thorough understanding of how the 4.92- μ m absorption feature works at Tui, we will be better able to compare it to other evaporitic material, especially the north polar deposits where VIMS observations are generally of different viewing geometries, and thus identify common characteristics of the 5- μ m-bright spectral unit.

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211.10 – Temporal changes of mid-latitude surface regions on Titan

The Cassini-Huygens instruments revealed that Titan, Saturn's largest moon, has a complex, dynamic and Earth-like surface. Understanding the distribution and interplay of geologic processes on Titan is important for constraining models of its interior, surface-atmospheric interactions, and climate evolution. Data from the remote sensing instruments have shown the presence of diverse terrains, suggesting exogenic and endogenic processes. However, interpretations of surface features need a precise knowledge of the contribution by the dense intervening atmosphere, especially the troposphere. Cassini's Visual and Infrared Mapping Spectrometer (VIMS) collects spectro-images within the so-called "methane windows" where the methane atmospheric absorption is weak, but non-negligible, permitting however a good perception of the surface. In order to make a good evaluation of the atmosphere and extract surface information we follow a method using a statistical tool and a Radiative transfer code with which we analyze regions of interest (i.e. regions of unknown origin), in order to monitor if their spectral behavior changes with time. These are cryovolcanic candidates and for comparison undifferentiated plains. We find that the cryovolcanic candidates Tui Regio and Sotra Patera change with time becoming darker and brighter respectively in terms of surface albedo while the plains

do not present any significant change. The surface brightening of Sotra supports a possible cryovolcanic rather than an exogenic origin. The unchanged surface behavior of the plains supports a sedimentary origin rather than cryovolcanic. Such a variety of geologic processes and their relationship to the methane cycle make Titan particularly significant in Solar System studies.

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211.11 – Titan's Haze Uncertainties and their Effects on Derived Surface Albedos

Methane photolysis in Titan's atmosphere produces a thick haze of organic compounds that obscures the planet's surface to most optical and near IR wavelengths. Derivations of surface reflectivity require an understanding the absorption and scattering effects of this haze. To this end, we have developed radiative transfer model using haze parameters derived from in situ Huygens/DISR measurements and data from the Cassini Visual and Infrared Mapping Spectrometer (VIMS). Radiative transfer calculations determine the surface albedo at the eight near-IR wavelengths where the atmosphere is transparent enough to view the surface. Analyses of the VIMS data from 2004, 2005, and 2007 demonstrate latitudinal changes in haze density consistent with the seasonal trans-hemispheric haze migration that had been observed previously. In addition, our analysis demonstrates positive correlations between the incidence/scattering angles and inferred haze density, indicating uncertainties in the haze parameters. This work will investigate the uncertainties due to single scattering albedo, phase function, and density of Titan's haze to infer the resultant uncertainties in the derived surface albedos.

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211.12 – Measurements of Dune Parameters on Titan Suggest Differences in Sand Availability

The equatorial region of Saturn's moon Titan has five large sand seas with dunes similar to large linear dunes on Earth. Cassini Radar SAR swaths have high enough resolution (300 m) to measure dune parameters such as width and spacing, which helps inform us about formation conditions and long-term evolution of the sand dunes. Previous measurements in locations scattered across Titan have revealed an average width of 1.3 km and spacing of 2.7 km, with variations by location. We have taken over 1200 new measurements of dune width and spacing in the T8 swath, a region on the leading hemisphere of Titan in the Belet Sand Sea, between -5 and -9 degrees latitude. We have also taken over 500 measurements in the T44 swath, located on the anti-Saturn hemisphere in the Shangri-La Sand Sea, between 0 and 20 degrees latitude. We correlated each group of 50 measurements with the average distance from the edge of the dune field to obtain an estimate of how position within a dune field affects dune parameters. We found that in general, the width and spacing of dunes decreases with distance from the edge of the dune field, consistent with similar measurements in sand seas on Earth. We suggest that this correlation is due to the lesser availability of sand at the edges of dune fields. These measurements and correlations could be helpful in determining differences in sand availability across different dune fields, and along the entire equatorial region of Titan.

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211.13 – Methane Line Intensities: Near and Far IR

Accurate knowledge of line intensities is crucial input for radiance calculations to interpret atmospheric observations of planets and moons. We have therefore undertaken extensive laboratory studies to measure the methane spectrum line-by-line in order to improve theoretical quantum mechanical modeling for molecular spectroscopy databases (e. g. HITRAN and GEISA) used by planetary astronomers. Preliminary results will be presented for selected ro-vibrational transitions in both the near-IR (1.66 and 2.2 – 2.4 microns) and the far-IR (80 – 120 microns) regions. For this, we have recorded high-resolution spectra (instrumental resolving power: 1,300,000 (NIR) and 10,000 (FIR)) with the Bruker 125HR Fourier transform spectrometer at JPL using isotopically-enriched ¹²CH₄ and ¹³CH₄, as well as normal methane samples. For the NIR wavelengths, three different absorption cells have been employed to achieve sample temperatures ranging from 78 K to 299 K: 1) a White cell set to a path length of 13.09 m for room temperature data, 2) a single-pass 0.2038 m cold cell and 3) a new coolable Herriott cell with a fixed 20.941 m optical path and configured for the first time to a FT-IR spectrometer. For the Far-IR, another coolable absorption chamber set to a 52 m optical path has been used. These new experiments and intensity measurements will be presented and discussed.

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211.14 – Mapping Titan’s Undifferentiated Plains (“Blandlands”) to infer their origin

The undifferentiated plains first mapped by Lopes et al. (2010, *Icarus*, 205) are vast expanses of terrains that appear bland in Cassini RADAR Synthetic Aperture Radar images, hence the designation “blandlands”. While the interpretation of several other geologic units on Titan, such as dunes and well-preserved impact craters, has been relatively straightforward, the origin of the “blandlands” has remained mysterious. SAR images show that the “blandlands” are mostly found at mid-latitudes and appear relatively featureless at radar wavelengths, with no significant topographic variations. Their gradational boundaries and paucity of features in SAR data make geologic interpretation particularly challenging. We have mapped the distribution of these terrains using SAR swaths up to T92 (July 2013), which cover > 50% of Titan’s surface. We compared SAR images with their de-noised counterparts, the topography using the SARTopo method (Stiles et al., 2009, *Icarus* 202) and, where possible, the response from radiometry. We examined and evaluated different formation mechanisms. Plains may be sedimentary in origin, resulting from fluvial or lacustrine deposition or accumulation of photolysis products created in the upper atmosphere. Alternatively, the plains may be cryovolcanic, consisting of overlapping flows of low relief, obscured by accumulation of sediments. In this paper, we use SAR, radiometry, and SARTopo data to examine the characteristics of the plains and compare them with other geologic units. The results from our analysis suggest that the sedimentary origin is the most likely, and that plain materials are similar or the same as dune materials. Plains occur mostly at mid-latitudes, while dunes occur mostly at low latitudes. This may be a result of wind patterns, decrease in sand supply, or changes in properties of sand, perhaps moisture content, all of which would inhibit the formation of large dunes.

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211.15 – Geomorphology of Afekan Crater, Titan: Terrain Relationships in Titan’s Blandlands

The enigmatic mid-latitude undifferentiated plains of Saturn’s moon Titan cover an estimated 29% of the surface of that world, making them one of the most important terrain units. Nicknamed “blandlands”, they appear nearly featureless to the Cassini spacecraft’s Visual and Infrared Mapping Spectrometer (VIMS), Imaging Science Subsystems (ISS) and Synthetic Aperture Radar (SAR) imaging. The possible origins and identity of the vast undifferentiated plains have ranged from thick organic photochemical deposits to cryovolcanic flood deposits of aqueous materials. To help constrain these possibilities, we selected the region around Afekan Crater for detailed geomorphological mapping. We defined and determined terrain units in ArcGIS primarily using SAR images and used the resulting contact and embayment relationships to determine a preliminary stratigraphy between the previously known units and the undifferentiated plains.

We find that although the plains are relatively featureless, they are not flat - some topographic variation is observed. Our work suggests Titan’s dunes embay the undifferentiated plains. This is consistent with dunes actively invading and depositing in the topographically low regions of the undifferentiated plains. Correlation of our defined undifferentiated plains regions with radiometric data is not consistent with large exposures of putative water-based cryovolcanic outflows, but is consistent with dune materials. The infrared reflectance obtained by Cassini VIMS and ISS show distinctive albedo differences between the dunes and undifferentiated plains materials. Combined, these results provide support that the undifferentiated plains are composed of organic materials, but that they are distinct from unmodified dune materials. Undifferentiated plains are found partially filling the interior of Afekan Crater, as well as in the presumed wind shadow of Afekan Crater, implying that plains material deposition happened after Afekan Crater was formed. Channels and other fluvial features are not abundant in the Afekan region at 300 m resolution, we interpret this to imply that the undifferentiated plains are porous, or that they only support sub-resolution channels and fluvial features.

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211.16 – Seasonal variations in Titan’s middle atmosphere of Titan during the northern spring derived from Cassini/CIRS observations

Spectra acquired at the limb and nadir of Titan in the 2009 – 2014 period by the Cassini/Composite Infrared Spectrometer (CIRS) were analyzed in order to monitor the seasonal evolution of the thermal, gas composition and aerosol spatial distributions. We are primarily interested here in the seasonal changes after the northern spring equinox, which occurred in August 2009. Data cover the 600-1500 cm⁻¹ spectral range and probe the 150-500 km range for the limb geometry viewing and the 100-200 km region for nadir geometry viewing.

We show that the retrieved temperature and mixing ratio latitude/pressure maps are compatible with a reversal of the global dynamics (with a downwelling branch at the South Pole and an upwelling branch at the North Pole) that is effective two years after the northern spring equinox, in agreement with the General Circulation Models predictions. Additionally, in February 2012, we observe an unexpected decrease of the temperature above the South pole around 400 km, while general circulation models predict a warming in this region due to adiabatic heating by the descending branch of the global circulation cell. Enrichment of molecules above the South pole is observed since June 2011 and is explained by the descending branch, bringing enriched air from higher altitude, where molecules are formed, to lower levels. Since November 2012, as the south autumn is progressing, the South pole temperature below 200 km is decreasing, reaching 120 K at 1 mbar (200 km) in May 2013. At that time, we retrieve benzene mixing ratio profiles above the south pole that are compatible with a condensation above 250 km. Benzene could therefore contribute to the cloud composition that is seen above the south pole in the visible range by the Cassini/ISS instrument.

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Contributing team(s): CIRS Team

211.17 – Examining the Exobase Approximation: DSMC models of Titan’s Thermosphere

Chamberlain (1963) developed a model for the exosphere using the so-called exobase approximation for planetary atmospheres. Below the exobase it is assumed that molecular collisions maintain a Maxwell Boltzmann distribution of velocities and above that altitude it is assumed that collisions are negligible. Therefore, the exobase altitude is often a critical parameter in models of the upper atmosphere because it is used to define the range of altitudes below which it is assumed that the atmosphere is in thermal equilibrium or above which collisions can be neglected. However, it is well understood that this transition occurs over a broad range of altitudes as described at Titan and Pluto (Tucker et al. 2013). Solar UV/EUV and energetic particles deposit energy in Titan’s upper thermosphere. To model the structure of the upper thermosphere it is critical to know whether this energy is thermalized and can be added assuming the gas is in thermal equilibrium, or whether stochastic effects are important. In addition, to model the exospheric density distribution on bodies like Titan it is also important to know whether molecular collisions can be neglected above some altitude. Here we examine the exobase approximation by using the Direct Simulation Monte Carlo (DSMC) technique that directly models molecular collisions (Bird 1994). The thermalization of energy inputted by magnetospheric ions into Titan’s thermosphere is modeled for two different considerations. In case 1 it is assumed that the energy deposited is thermalized by molecular conduction and it is added equally to all molecules when modeling the subsequent conduction and escape. Another set of simulations are used to test this assumption by adding the deposited energy to a fraction of suprathermal (>kT) molecules to model the subsequent thermalization. Finally, to examine the effects of collisions on an upward flux of suprathermal particles from the exobase we perform simulations with and without molecular collisions. The simulations of Titan’s upper atmosphere are compared to density data obtained during different Cassini flybys. Support grant NNH12ZDA001N from the NASA ROSES OPR Program.

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211.18 – The Effect of N² Photoabsorption Cross Section Resolution on C²H⁶ Production in Titan’s Ionosphere

Titan’s rich organic chemistry begins with the photochemistry of only two molecules: N² and CH⁴. The details on how

higher-order hydrocarbons and nitriles are formed from these molecules have key implications for both the structure and evolution of Titan's atmosphere, and for its surface-atmosphere interactions. Of high importance is the production of C^2H^6 , which is a sink for CH^4 , and a main component in the polar lakes. Results of photochemical models, though, may be sensitive to the choice of input parameters, such as the N^2 photoabsorption cross section resolution, as previously shown for nitrogen (Liang et al. (2007) *ApJL* 664, 115-118), and CH_4 (Lavvas et al. (2011) *Icarus* 213, 233-251). Here we investigate the possibility of the same effect on the production rates of C^2H^6 . We modeled production and loss rates, as well as mixing ratio and density profiles between an altitude of 600 and 1600 km for low and high resolution N^2 cross sections via a coupled ion-neutral-thermal model (De La Haye et al. (2008) *Icarus* 197, 110-136; Mandt et al. (2012) *JGR* 117, E10006). Our results show a clear impact of photoabsorption cross section resolution used on all neutral and ion species contributing to C^2H^6 production. The magnitude of the influence varies amongst species. Ethane production profiles exhibit a significant increase with better resolution; a factor of 1.2 between 750 and 950 km, and a factor of 1.1 in the total column-integrated production rate. These values are lower limits, as additional reactions involving C^2H^5 not included in the model may also contribute to the production rates. The clear effect on C^2H^6 (which is not a parent molecule, nor does it bear nitrogen) may have important implications for other molecules in Titan's atmosphere as well. The possible non-negligible impact of an isotope of nitrogen may argue for the inclusion of isotopes in photochemical models. For future analysis, development of a more efficient and streamlined model called Planet-INC is underway. This open source model is a high-performance probabilistic planetary model that includes detailed uncertainty analysis capabilities.

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211.19 – ALMA observations of Titan

We report submm observations of Titan performed with the ALMA interferometer from our cycle 0 data, centered around the rotational frequencies of HCN(4-3) and HNC(4-3), i.e. 354 and 362 GHz. The most extended configuration of the array in cycle 0 yielded disk-resolved emission spectra of Titan with an angular resolution of 0.54×0.42 arcsec. Titan's angular surface diameter was 0.77 arcsec.

Data were acquired in June-August 2012 near the greatest eastern and western elongations of Titan at a spectral resolution of 122 kHz ($\nu/d\nu = 3.10^6$).

We have obtained maps of several nitriles present in Titan's stratosphere: HCN, HC₃N, CH₃CN, HNC, DCN, and obtain the detection of the isotopes CH₃C¹³N and HCCC¹⁵N as well as line spectroscopic detection of C₂H₅CN.

This is a work in progress, maps of nitriles will be presented

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212 – Education Posters

212.01 – DPS Listing of Planetary Science Graduate Programs: A Resource for Students and Advisors

Last year we unveiled a new web page on the DPS Education site listing all the graduate programs we could find that can lead to a PhD with a planetary science focus. The list is meant to be a first-look point for undergraduate students and undergraduate advisors where they can find and compare programs across a set of very basic criteria, then follow links to the web sites of those programs for further information. We did this because the field of planetary science is incredibly diverse, typically is not a stand-alone department, and navigating all the possibilities can overwhelm even a determined undergraduate student—and even many advisors.

Over the past year we have striven to add programs as we are made aware of them, fill in missing information for known programs, and continually update the information we do have. In addition we have moved forward on plans to implement the most asked-for feature: filtered searching.

We present here the updated site and a preview of the transitional site needed before full filtered searching can be implemented. In addition we will present design notes for the full-featured version in order to elicit feedback from the community. Finally, we call upon those mentoring and advising undergraduates to use this resource, and program admission chairs to continue to review their entry and provide us with the most up-to-date information.

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212.02 – Guides, Tools, and Clearinghouses: A Presentation of Resources for Scientists Involved in Education and Public Outreach

The NASA Science Mission Directorate (SMD) Education Forums help scientists with their engagement in education and public outreach (E/PO) activities. The Forums provide professional development, resources, as well as opportunities to interact with the larger E/PO community. We have conducted both interviews and surveys of space scientists regarding their needs and attitudes about E/PO. The most recent of these was a series of semi-structured interviews with two-dozen DPS members, which allowed the Forums to identify those areas where new or additional resources and support are needed for scientists regarding their E/PO involvement. This poster will present key resources that scientists can use to learn more about the nature of E/PO, how to become involved, how to leverage their efforts, how to find effective and vetted demonstrations and activities, and where to go to make the most impact. The first two of an upcoming series of one-page guides includes “The Quick Introduction to Education and Public Outreach” as well as “Making the Most of Your E/PO Time – Increasing your Efficiency and Impact.” <http://smdepo.org/post/7202>. The Planetary Science Education and Public Outreach Resource Sampler offers a list of activities specifically selected for quick access and ease of use. These resources are organized by major science questions, and then by topics such as “Impacts in the Solar System,” “Windy Worlds,” and “Scale in the Solar System.” http://smdepo.org/data/uploads/PS_EPO_Resources_2.pdf Wavelength is a repository of resources for learning at all levels, from outreach programs and after school to formal K-college. All activities held within Wavelength have passed the NASA SMD peer-review for products, ensuring that each has sound content both in science and education. <http://nasawavelength.org>. The poster will also present the SMD Speaker’s Bureau, Community Workspace, and resources developed by partners, such as the AAS Ambassador Program’s MOOSE, Menu of Outreach Opportunities for Science Education <http://aas.org/outreach/moose-menu-outreach-opportunities-science-education>.

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212.03 – Soliciting Your Thoughts on Supporting Scientists in Education and Public Outreach Efforts

Over the past five years, the NASA Science Mission Directorate Education and Public Outreach (E/PO) Forums have worked with various professional organizations to solicit the needs of scientists and provide resources to support scientists who want to become engaged or are already engaged in education and public outreach activities. Most recently, we have partnered with the Division of Planetary Sciences of the AAS to interview scientists about their perceptions of E/PO and what tools and resources they need to become involved or support their engagements. Through these efforts, several resources have been developed and are currently being disseminated through our community workspace (smdepo.org), at professional meetings, and through our partners. We are interested in getting more feedback from the DPS membership on what you, scientists, want and need to support your work in education and public outreach. This poster will provide a place to engage in discussion with forum team members, leave feedback about what you want to see as next steps, and provide links to provide anonymous feedback and to sign up for an upcoming interview to give us more insight into how to support your work in education and public outreach. Contact Sanlyn Buxner (buxner@psi.edu) or Jennifer Grier (jgrier@psi.edu) to get more information about supporting scientists in E/PO activities or to give us feedback and ideas.

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212.04 – Online Workspace to Connect Scientists with NASA's Science E/PO Efforts and Practitioners

There is a growing awareness of the need for a scientifically literate public in light of challenges facing society today, and also a growing concern about the preparedness of our future workforce to meet those challenges. Federal priorities for science, technology, engineering, and math (STEM) education call for improvement of teacher training, increased youth and public engagement, greater involvement of underrepresented populations, and investment in undergraduate and graduate education. How can planetary scientists contribute to these priorities? How can they “make their work and findings comprehensible, appealing, and available to the public” as called for in the Planetary Decadal Survey?

NASA’s Science Mission Directorate (SMD) Education and Public Outreach (E/PO) workspace provides the SMD E/PO community of practice – scientists and educators funded to conduct SMD E/PO or those using NASA’s science discoveries in E/PO endeavors - with an online environment in which to communicate, collaborate, and coordinate activities, thus helping to increase effectiveness of E/PO efforts. The workspace offers interested scientists avenues to partner with

SMD E/PO practitioners and learn about E/PO projects and impacts, as well as to advertise their own efforts to reach a broader audience. Through the workspace, scientists can become aware of opportunities for involvement and explore resources to improve professional practice, including literature reviews of best practices for program impact, mechanisms for engaging diverse audiences, and large- and small-scale program evaluation. Scientists will find “how to” manuals for getting started and increasing impact with public presentations, classroom visits, and other audiences, as well as primers with activity ideas and resources that can augment E/PO interactions with different audiences. The poster will introduce the workspace to interested scientists and highlight pathways to resources of interest that can help scientists more effectively contribute to national STEM education priorities. Visitors are encouraged to explore the growing collection of resources at <http://smdepo.org>.

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212.05 – Providing Effective Professional Development for Teachers through the Lunar Workshops for Educators

In order to integrate current scientific discoveries in the classroom, K–12 teachers benefit from professional development and support. The Lunar Workshops for Educators is a series of weeklong workshops for grade 6–9 science teachers focused on lunar science and exploration, sponsored by the Lunar Reconnaissance Orbiter (LRO) and conducted by the LRO Education and Public Outreach (E/PO) Team. The Lunar Workshops for Educators, have provided this professional development for teachers for the last five years. Program evaluation includes pre- and post- content tests and surveys related to classroom practice, daily surveys, and follow-up surveys conducted during the academic year following the summer workshops to assess how the knowledge and skills learned at the workshop are being used in the classroom.

The evaluation of the workshop shows that the participants increased their overall knowledge of lunar science and exploration. Additionally, they gained knowledge about student misconceptions related to the Moon and ways to address those misconceptions. The workshops impacted the ways teachers taught about the Moon by providing them with resources to teach about the Moon and increased confidence in teaching about these topics. Participants reported ways that the workshop impacted their teaching practices beyond teaching about the Moon, encouraging them to include more inquiry and other teaching techniques demonstrated in the workshops in their science classes. Overall, the program evaluation has shown the Lunar Workshops for Educators are effective at increasing teachers’ knowledge about the Moon and use of inquiry-based teaching into their classrooms. Additionally, the program supports participant teachers in integrating current scientific discoveries into their classrooms.

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212.06 – Investigating Visitors' and Facilitators' Experiences at International Observe the Moon Night Events

International Observe the Moon Night (InOMN) is an annual event where people around the world are encouraged to look up at the Moon and share in the excitement of lunar science and exploration. The Lunar Reconnaissance Orbiter (LRO) leads the coordination of InOMN, with support from partner NASA mission and institution teams, including the Solar System Exploration Research Virtual Institute (SSERVI) and the Lunar Atmosphere and Dust Environment Explorer (LADEE). In 2013, InOMN was held on October 12th and a total of 521 unique events were registered on the InOMN website from around the world. These 521 events were held in 56 different countries, 46% of which were events in the United States. The InOMN evaluation was designed to characterize the overall participation of sites and visitors, characterize the types of visitors who attended, understand visitors’ intentions for attending an InOMN event, and understand how can facilitators be better supported for future events. Data was collected from event facilitators before and after the event and from visitors at the event. The follow-up facilitator survey was designed to understand to what extent the InOMN hosts were aware of the LRO mission and more generally understand how to support InOMN events in the future. Thirty-eight visitor surveys were collected and 186 facilitators completed follow-up surveys to give us an insight into both visitors’ and facilitators’ experiences.

Most of the visitors (67%) who responded to the surveys were new to InOMN and reported that they had not attended a previous InOMN event. As with the 2012 events, the findings from 2013 continue to support the findings that InOMN events are social experiences and that most visitors attend with other people. The majority of visitors attended in family groups (72%), and another 20% attended with groups of other individuals (friends or other groups) with only 7% attending by themselves. A majority of survey respondents were aware of the LRO mission and were knowledgeable about broad aspects of current lunar research. InOMN visitors were motivated to learn more about the Moon after

attending an InOMN event.

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212.07 – Communicating Science on YouTube and Beyond: OSIRIS-REx Presents 321Science!

NASA's OSIRIS-REx asteroid sample return mission launched *OSIRIS-REx Presents 321Science!*, a series of short videos, in December 2013 at youtube.com/osirisrex. A multi-disciplinary team of communicators, film and graphic arts students, teens, scientists, and engineers produces one video per month on a science and engineering topic related to the OSIRIS-REx mission. The format is designed to engage all members of the public, but especially younger audiences with the science and engineering of the mission. The videos serve as a resource for team members and others, complementing more traditional formats such as formal video interviews, mission animations, and hands-on activities. In creating this new form of OSIRIS-REx engagement, we developed *321Science!* as an umbrella program to encourage expansion of the concept and topics beyond the OSIRIS-REx mission through partnerships. Such an expansion strengthens and magnifies the reach of the OSIRIS-REx efforts.

321Science! has a detailed proposed schedule of video production through launch in 2016. Production plans are categorized to coincide with the course of the mission beginning with Learning the basics – about asteroids and the mission – and proceeding to Building the spacecraft, Run up to launch, Cruising to Bennu, Run up to rendezvous, Mapping Bennu, Sampling, Analyzing data, Cruising home and Returning and analyzing the sample. The video library will host a combination of videos on broad science topics and short specialized concepts with an average length of 2-3 minutes. Video production also takes into account external events, such as other missions' milestones, to draw attention to our videos. Production will remain flexible and responsive to audience interests and needs and to developments in the mission, science, and external events.

As of August 2014, *321Science!* videos have over 22,000 views. We use YouTube analytics to evaluate our success and we are investigating additional and more rigorous evaluation methods for future analysis.

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Contributing team(s): OSIRIS-REx Science Team, Members of the Target Audience

212.08 – A New Method to Retrieve the Orbital Parameters of the Galilean Satellites Using Small Telescopes: A Teaching Experiment

We show in this communication how it is possible to deduce the radius of the orbits of Galilean satellites around Jupiter using a small number of well-planned observations. This allows the instructor to propose a complete student activity that involves planning an observation, the observation itself, processing and analyzing the images and deduction of relevant magnitudes [1]. This work was performed in the Aula EspaZio Gela under the Master in Space Science and Technology [2].

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212.09 – Travelers In The Night

Travelers In The Night is an engaging and informative series of two minute radio programs about asteroids, comets, spacecraft, and other objects in space. The pieces are evergreen in that they are current but not dated. They are published on the Public Radio Exchange and carried by a number of radio stations. For teachers, students, and kids of all

ages, the script for each piece and the start of a path for further inquiry can be found on the website travelersinthenight.org. The Travelers InThe Night Pieces are written and produced by an observing member of the Catalina Sky Survey Team at the University of Arizona. DPS members are encouraged to submit program ideas which can be developed to feature their research efforts.

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212.10 – Scientific Tools and Techniques: An Innovative Introduction to Planetary Science / Astronomy for 9th Grade Students

Fernbank Science Center in Atlanta, GA (USA) offers instruction in planetary science and astronomy to gifted 9th grade students within a program called "Scientific Tools and Techniques" (STT). Although STT provides a semester long overview of all sciences, the planetary science / astronomy section is innovative since students have access to instruction in the Center's Zeiss planetarium and observatory, which includes a 0.9 m cassegrain telescope. The curriculum includes charting the positions of planets in planetarium the sky; telescopic observations of the Moon and planets; hands-on access to meteorites and tektites; and an introduction to planetary spectroscopy utilizing LPI furnished ALTA reflectance spectrometers. In addition, students have the opportunity to watch several full dome planetary themed planetarium presentations, including "Back to the Moon for Good" and "Ring World: Cassini at Saturn." An overview of NASA's planetary exploration efforts is also considered, with special emphasis on the new Orion / Space Launch System for human exploration of the solar system. A primary goal of our STT program is to not only engage but encourage students to pursue careers in the field of science, with the hope of inspiring future scientists / leaders in the field of planetary science.

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212.11 – Star Formation and Exoplanetary Systems in the National Science Olympiad Astronomy Event for High School Students

Science Olympiad is one of the nation's largest secondary school science competitions, reaching over 240,000 students on more than 6,000 teams. The competition covers various aspects of science and technology, exposing students to a variety of career options in STEM. 9 of Science Olympiad's 46 events (with 23 for both middle and high school) have a focus on Earth and Space Science, including process skills and knowledge of a variety of subjects, including: Astrophysics, Planetary Sciences, Oceanography, Meteorology, Remote Sensing, and Geologic Mapping, among others. The Astronomy event is held for students from 9th – 12th grade, and covers topics based upon stellar evolution and/or galactic astronomy. For the 2014-2015 competition season, Astronomy will focus on star formation and exoplanets in concert with stellar evolution, bringing recent and groundbreaking research to light for young potential astronomers and planetary scientists. The event tests students on their "understanding of the basic concepts of mathematics and physics relating to stellar evolution and star and planet formation," including qualitative responses, DS9 image analysis, and quantitative problem solving. We invite any members of the exoplanet and star formation communities that are interested in developing event materials to contact the National event supervisors, Donna Young (donna@aavso.org) and Tad Komacek (tkomacek@lpl.arizona.edu). We also encourage you to contact your local regional or state Science Olympiad tournament directors to help supervise events and run competitions in your area.

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212.12 – Using the Mars Student Imaging Project (MSIP) in a University Classroom

Many students enroll in an introductory astronomy course as a means to fulfill the science requirement for their general education classes. A common goal of these general education courses is to teach students about the nature and process of science. One of the best ways to learn this is by actually doing authentic scientific research. The Mars Student Imaging Project (MSIP) is a hands-on activity in which students conduct original research using images of Mars surface, and obtain a new image with the THEMIS camera. As a hands-on activity, the MSIP is an excellent addition to an introductory astronomy course as it allows students at all levels of scientific knowledge and ability to participate in making new discoveries and to make meaningful contributions to our understanding of Mars. In addition, students develop a much better understanding of the nature of science than they could through reading any textbook. The MSIP has been used in the Introductory Astronomy: The Solar System course at Concordia College for two years. The response from the students and faculty at our institution who have participated in MSIP has been very positive. We will provide helpful tips

on how to adapt this activity to the university environment including scheduling the various steps of the activity and creating university-level scaffolding activities.

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212.13 – From the Green Screen to the Classroom: Training Graduate Students to Communicate Science and Mathematics Effectively through the INSPIRE Program

Initiating New Science Partnerships in Rural Education (INSPIRE) is a five-year partnership between Mississippi State University and three school districts in Mississippi's Golden Triangle region. This fellowship program is designed to strengthen the communication and scientific reasoning skills of STEM graduate students by having them design and implement inquiry-based lessons which channel various aspects of their research in our partner classrooms. Fellows are encouraged to explore a diversity of approaches in classroom lesson design and to use various technologies in their lessons, including GIS, SkyMaster weather stations, Celestia, proscopes, benchtop SEM, and others. Prior to entering the classrooms for a full school year, Fellows go through an intense graduate-level training course and work directly with their partner teachers, the program coordinator, and participating faculty, to fold their lessons into the curricula of the classrooms to which they've been assigned. Here, we will discuss the various written, oral, and visual exercises that have been most effective for training our Fellows, including group discussions of education literature, role playing and team-building exercises, preparation of written lesson plans for dissemination to other teachers nationwide, the Presentation Boot Camp program, and production of videos made by the Fellows highlighting careers in STEM fields. We will also discuss the changes observed in Fellows' abilities to communicate science and mathematics over the course of their fellowship year. INSPIRE is funded by the NSF Graduate K-12 (GK-12) STEM Fellowship Program, award number DGE-0947419.

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212.14 – The Mixed Up Solar System: Professional Development for Secondary Science and Math Educators

The Hubble Education Team has developed the standards-based Mixed Up Solar System activity to provide middle and high school educators with the experience and tools for using real astronomical data in their classrooms.

The activity builds upon a table of characteristics of 16 selected objects (without identifying names) that are representative of the diversity of the solar system. Through a series of plotting exercises and analysis, participants explore individual characteristics and the trends that appear when comparing characteristics. Through the activity, participants discover similarities among certain solar system objects and begin to classify them accordingly. They discover that Pluto has much more in common with KBOs than rocky or giant planets and, in doing so, go beyond a mnemonic (MVEMJSUNP) to understand the true structure of the solar system.

During professional development workshops, the Hubble education team has worked through this exercise with more than 1000 educators. Evaluation results indicate that by experiencing this activity for themselves, educators gain a better appreciation for solar system science, an understanding of how to incorporate and scaffold real data into their classrooms, and they begin to think of adaptations for their students.

http://amazing-space.stsci.edu/eds/tools/type/classroom_activities.php.p=Teaching+tools%40%2Ceds%2Ctools%2C

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212.15 – Undergraduate Conceptions About What it Means to Study Something Scientifically

Non-science major students represent individuals who will become productive members of society in non-science fields including our business leaders, policy makers, and teachers. Their college non-major science courses are often the last formal instruction they will receive in science. As such, it is important to understand what students already know about science and provide instruction that is engaging and helps them gain a greater appreciation for doing science. We report on a study of almost 12,000 undergraduate students enrolled in introduction astronomy courses from 1989 – 2014, most of who were freshman or sophomore students. Almost every year during the 25 year period, students were asked to complete an in-class survey that included basic science content questions and attitude towards science questions. They were also asked to write a response to the question, "What does it mean to study something scientifically?"

Sixty-five percent of responses were meaningful and considered to be on target. In their responses 16% of students described science as a way of gaining knowledge or learning about something. Twenty three percent of respondents described science as using observations or experimentation and 10% described it as involving a hypothesis. Only 8% of respondents mentioned data analysis while 6% described using data or evidence. Four percent of respondents mentioned science was a way to solve problems and 4% described science as being systematic. Students who were

self-reported STEM majors (Pre-med, engineering, math, and science majors) more often mentioned that science is an empirical technique as well as the use of hypotheses in science STEM majors also mentioned data twice as often as non-STEM majors in their responses. Education majors, who made up 6% of the sample, had the least descriptive answers overall, and were the group who most often not include aspects that were essential to studying science. Gathering this information has helped characterize students' knowledge about science and make instruction to support their knowledge

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212.16 – Teaching Astronomy using a Flipped Classroom Model of Instruction

Astronomy: State of the Art is a MOOC specifically developed to study student participation in an online learning environment. The project aims to serve multiple audiences of learners. For this project we focused on college students who use the online environment for lectures and quizzes but whose classroom time is devoted to hands-on activities and group work; this is the “flipped classroom” model.

In spring 2014, Astronomy: State of the Art was co-convened with “The Physical Universe,” a Natural Sciences course taught at the University of Arizona that satisfies a General Education requirement for non-science majors. Using the same core material as Astronomy – State of the Art (with additional modules on the physics of radiation, atomic structure, energy, and gravity that are not necessary for the informal learners), the local course employed a “flipped” model where the students access lectures and podcasts online but are in a face-to-face classroom two times a week for labs and hands-on activities, lecture tutorials, group discussions, and other research-validated tools for enhancing learning. A flipped or hybrid model gives students flexibility, uses the online medium for the aspects of instruction where interaction with an instructor isn't required, and optimizes the scarce resource of time in a large classroom. Final student grades were closely related to their attendance, however, performance in this class was not correlated with completion of the online video lectures, even though the quizzes were closely tied to the content of these videos. The course will next be taught using Coursera which allow instructors to more closely examine the relationship between students use of course materials and understanding of course topics. The eventual goal is to recruit undergraduates from anywhere in the United States and award them transferrable credit for completing the class.

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212.17 – Using Exoplanet Models to Explore NGSS and the Nature of Science and as a Tool for Understanding the Scientific Results from NIRCam/JWST

Our Solar System is no longer unique. To date, about 1,800 planets are known to orbit over 1,100 other stars and nearly 50% are in multiple-planet systems. Planetary systems seem [to be] fairly common and astronomers are now finding Earth-sized planets in the Goldilocks Zone, suggesting there may be other habitable planets. To this end, characterizing the atmospheric chemistries of such planets is a major science goal of the NIRCam instrument on the James Webb Space Telescope.

For NIRCam's E/PO program with the Girl Scouts of the USA, we have produced scale models and associated activities to compare the size, scale, and dynamics of the Solar System with several exoplanet systems. Our models illustrate the techniques used to investigate these systems: radial velocity, transits, direct observations, and gravitational microlensing. By comparing and contrasting these models, we place our Solar System in a more cosmic context and enable discussion of current questions within the scientific community: How do planetary systems form and evolve? Is our present definition of a planet a good definition in the context of other planetary systems? Are there other planets/moons that might harbor life as we know it?

These models are appropriate for use in classrooms and conform to the Next Generation Science Standards (NGSS) through the Disciplinary Core Idea: Earth's Place in the Universe and Crosscutting Concepts—Patterns; Scale, Portion, and Quantity; and Systems and System Models. NGSS also states that the Nature of Science (NOS) should be an “essential part” of science education. NOS topics include, for example, understanding that scientific investigations use a variety of methods, that scientific knowledge is based on empirical evidence, that scientific explanations are open to revision in light of new evidence, and an understanding the nature of scientific models.

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212.18 – PDS and NASA Tournament Laboratory Project to Engage Citizen Scientists and to Provide New Access to Cassini Data

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5. Goddard Space Flight Center

The Planetary Data System (PDS), working with the NASA Tournament Lab (NTL) and TopCoder® , is using challenge-based competition to generate new applications that increase both access to planetary data and discoverability—allowing users to “mine” data, and thus, to make new discoveries from data already “on the ground”. The first challenge-based completion was an optimized database and API for comet data at the PDS Small Bodies Node (SBN) in 2012. Since start-up, the installation at SBN has been tweaked to provide access to the comet data holdings of the SBN, and has introduced new users and new developers to PDS data. A follow-on contest using Cassini images from the PDS Rings Discipline Node, was designed to challenge the competitors to create new, more transparent, agile tools for public access to NASA’s planetary data, where “public” includes citizen scientists and educators. The experience gained with the API at SBN was applied to establishing a second installation at the PDS Planetary Rings Node (Rings), to serve as the basis to develop similar access tools at Rings to make the growing archive of Cassini images available through the API. The Cassini-Rings project had as its goal to develop a crowd-sourcing project with eventual application across the PDS holdings. From the contest results, a preliminary algorithm can detect known satellites hidden in Saturn’s rings which should prove valuable to programmers. The contest approach is also of potential use to educators for exercises studying the solar system. The progress to date and results of this citizen-scientist project will be discussed.

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213 – Asteroids Physical Characterization Posters: NEAs

213.01 – A Digital Terrain Model of the NEAR-Shoemaker Landing Site on Asteroid (433) Eros

Stereophotogrammetry is a technique that has been used to determine the topography of many Solar System bodies [1]. Characterizing the terrain and elevation with images taken by the OSIRIS-REx CAMera Suite (OCAMS) is a requirement for the OSIRIS-REx Mission, which will survey and sample asteroid (101955) Bennu in 2019 [2]. Understanding the topography of the sample site will be of chief importance—the OSIRIS-REx Touch And Go Sample Acquisition Mechanism (TAGSAM) can only interface with terrain that meets specific slope and regolith aggregate-size thresholds.

To prepare for the OSIRIS-REx sampling event, we have carried out a proof of concept study using NEAR MSI optical images. In 2001 the NEAR-Shoemaker team successfully landed the spacecraft on asteroid (433) Eros after nearly a yearlong survey [3]. During the descent, MSI took several high-resolution images of the landing site. These images, as well as images of the landing site taken during Eros flyovers, have been combined into a stereo-set and processed using the commercial photogrammetry software package SOCET SET® distributed by BAE Systems, Inc [4]. SOCET SET® is a powerful photogrammetric toolbox capable of determining terrain from images taken at different resolutions using a suite of algorithms. In this work we report the results of this proof of concept study and show the Digital Terrain Model (DTM) we have derived for the NEAR-Shoemaker landing site.

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213.02 – Rapid Generation of Image Mosaics and Maps for the OSIRIS-REx Mission

The OSIRIS-REx mission will rely on image mosaics and maps of asteroid Bennu to support critical mission operations such as sample site selection and long-term science investigations. These mosaics and maps provide a convenient

method for visualizing the surface of Bennu and serve as the foundation for the geology maps required to carry out the science investigation for the mission. During proximity operations at Bennu, rapid turnaround of calibrated images into image mosaics and maps will be required to support mission planning and sample site selection. Updated operational and publication quality science maps will be needed as improved spacecraft information, photometric models, and shape models of Bennu become available. Quick turnaround image mosaics and map products will also support the public engagement activities of the mission.

Semi-automated image mosaic and map generation software is being developed based on the ISIS software package from the USGS. This software suite will consist of scripts, workflows and data quality checks that support automated control network development and image mosaic generation. Reprocessing capabilities will be incorporated in the software suite to support quick turnaround generation of updated image mosaics and maps resulting from new instrument calibration files, spacecraft trajectory and pointing kernels, photometric correction models and shape model information. Images from the NEAR-Shoemaker rendezvous mission to asteroid Eros provide a test dataset for verification and validation of the software. We present the results of our initial implementation of the system using MSI images of asteroid Eros.

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213.03 – Numerical Simulations of Spacecraft-Regolith Interactions on Asteroids

NASA's OSIRIS-REx mission will rendezvous in 2018 with the near-Earth asteroid (101955) Bennu and attempt to touch down and obtain a sample from its surface. The regolith surface's behavior in response to the spacecraft's intrusion is difficult to predict due to the asteroid's extremely low-gravity environment (on the order of 10 micro-g's.) We have been carrying out high-resolution ($N > 100,000$) numerical simulations of the intrusion of a realistic physical model of the sampling device into a bed of cm-size spherical particles to explore the relationship between the spacecraft's response and the dynamical behavior of the regolith. If the granular bed is too compliant, then the spacecraft may sink into the asteroid. If the granular bed is not compliant enough, then the spacecraft may not be able to obtain an appropriate sample. This is further complicated by the fact that the degree of compliance is also dependent on the material properties of the regolith surface (size distribution, local slope, friction coefficients, shape effects). The ultimate goal of this study is to construct a library of touchdown outcomes as a function of the potential observables (local slope, estimated maximum angle of repose, and to a limited extent particle size distribution). We study the effect of varying the regolith's material properties (cohesive, frictional, and dissipative parameters) in order to place limits on the range of possible outcomes. The library will be useful for sample-site selection based on available observables, and, upon sampling, may aid in interpreting the physical properties of the regolith (e.g., depth and density) by comparing measurements from on-board instruments with simulation data. Preliminary results show that grains with low coefficients of friction (smooth particles) provide little resistance and the spacecraft sinks into the asteroid. For high coefficients of friction (effectively mimicking grain angularity), the regolith is much less compliant, and the spacecraft is only able to penetrate the first few centimeters of the surface layer. This result suggests that for high grain angularity, the regolith directly underneath the sampler is able to shear thicken due to particle interlocking.

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213.04 – Crowd-sourcing Near-Earth Asteroid Science with the OSIRIS-REx *Target Asteroids!* Program

OSIRIS-REx *Target Asteroids!* is an award-winning citizen science project conducted as part of the Communications and Public Engagement program of the NASA OSIRIS-REx asteroid sample return mission. The project furthers the study of near-Earth asteroids (NEA) and promotes interest among the amateur astronomy community. The goal of *Target Asteroids!* is to expand the pool of observers who can contribute to the characterization of NEAs. We also seek to coordinate the observation of specific asteroids in order to maximize the usefulness of the data and to minimize duplication of effort.

Target Asteroids! was originally focused on a list of ~80 NEAs suitable for spacecraft sample return compiled by the OSIRIS-REx science team. The list was constrained to NEAs with absolute magnitude $H < 21.5$, perihelion distance > 0.8 AU, aphelion distance < 2.0 AU and inclination $< 8^\circ$. Since many sample return targets are beyond the reach of typical amateur telescopes (limiting magnitudes of ~14 to 20), the program was expanded to include other objects, namely asteroids that shed light on the properties of OSIRIS-REx target (101955) Bennu, bright NEAs making relatively close approaches to Earth and radar target NEAs. An introductory paper on the goals and methods of Target Asteroids! was published in the Minor Planet Bulletin (Hergenrother & Hill, Minor Planet Bulletin 40, 164-166, 2013).

Since 2012, over 100 participants with a wide range of instrumentation and experience from around the world have contributed photometry of 53 asteroids. While small telescope users cannot produce high S/N observations for faint objects, they do have the advantage of being able to make observations often. A large number of low S/N observations are useful if made over different observing geometries. Utilizing many photometric observations made at different times and phase angles, small telescope users can produce direct measurements of the phase function, absolute magnitude, broadband color, and rotation period of NEAs. These parameters can be used to make determinations of taxonomy, albedo, size and other physical parameters.

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Contributing team(s): Target Asteroids! participants

213.05 – Optimization of Sample Site Selection Imaging for OSIRIS-REx Using Asteroid Surface Analog Images

OSIRIS-REx will return a sample of regolith from the surface of asteroid 101955 Benu. The mission will obtain high resolution images of the asteroid in order to create detailed maps which will satisfy multiple mission objectives. To select a site, we must (i) identify hazards to the spacecraft and (ii) characterize a number of candidate sites to determine the optimal location for sampling. To further characterize the site, a long-term science campaign will be undertaken to constrain the geologic properties. To satisfy these objectives, the distribution and size of blocks at the sample site and backup sample site must be determined. This will be accomplished through the creation of rock size frequency distribution maps. The primary goal of this study is to optimize the creation of these map products by assessing techniques for counting blocks on small bodies, and assessing the methods of analysis of the resulting data. We have produced a series of simulated surfaces of Benu which have been imaged, and the images processed to simulate Polycam images during the Reconnaissance phase. These surface analog images allow us to explore a wide range of imaging conditions, both ideal and non-ideal. The images have been “degraded”, and are displayed as thumbnails representing the limits of Polycam resolution from an altitude of 225 meters. Specifically, this study addresses the mission requirement that the rock size frequency distribution of regolith grains < 2cm in longest dimension must be determined for the sample sites during Reconnaissance. To address this requirement, we focus on the range of available lighting angles. Varying illumination and phase angles in the simulated images, we can compare the size-frequency distributions calculated from the degraded images with the known size frequency distributions of the Benu simulant material, and thus determine the optimum lighting conditions for satisfying the 2 cm requirement.

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213.06 – Meteorite Source Regions as Revealed by the Near-Earth Object Population

Spectroscopic and taxonomic information is now available for 1000 near-Earth objects, having been obtained through both targeted surveys (e.g. [1], [2], [3]) or resulting from all-sky surveys (e.g. [4]). We determine their taxonomic types in the Bus-DeMeo system [5] [6] and subsequently examine meteorite correlations based on spectral analysis (e.g. [7],[8]). We correlate our spectral findings with the source region probabilities calculated using the methods of Bottke et al. [9]. In terms of taxonomy, very clear sources are indicated: Q-, Sq-, and S-types most strongly associated with ordinary chondrite meteorites show clear source signatures through the inner main-belt. V-types are relatively equally balanced between nu6 and 3:1 resonance sources, consistent with the orbital dispersion of the Vesta family. B- and C-types show distinct source region preferences for the outer belt and for Jupiter family comets. A Jupiter family comet source predominates for the D-type near-Earth objects, implying these “asteroidal” bodies may be extinct or dormant comets [10]. Similarly, near-Earth objects falling in the spectrally featureless “X-type” category also show a strong outer belt and Jupiter family comet source region preference. Finally the Xe-class near-Earth objects, which most closely match the spectral properties of enstatite achondrite (aubrite) meteorites seen in the Hungaria region[11], show a source region preference consistent with a Hungaria origin by entering near-Earth space through the Mars crossing and nu6 resonance pathways. This work supported by the National Science Foundation Grant 0907766 and NASA Grant NNX10AG27G.

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213.07 – The Taxonomic Distribution of Mission-Accessible Small Near-Earth Asteroids

Scientific interest in the near-Earth asteroid (NEA) population has grown in recent years, particularly with regards to characterizing the population of mission-accessible NEAs. Mission accessibility is defined by delta-v, the change in velocity required for a spacecraft to rendezvous with a celestial body. With current propulsion technology, spacecraft can reach NEAs whose orbits have delta-V < 7 km/s.

Across the entire NEA population, the smallest (d < 1 km) objects have not been well-studied, owing to the difficulty of observing them. These very small objects are often targets of opportunity, observable for only a short period of time after their discovery. Even at their brightest (V ~ 18), these asteroids are faint enough that they must be observed with large ground-based telescopes.

The Mission Accessible Near-Earth Object Survey (MANOS) began in August 2013 as a multi-year physical characterization survey that was awarded survey status by NOAO. MANOS will target several hundred mission-accessible NEOs across visible and near-infrared wavelengths, ultimately providing a comprehensive catalog of physical properties (astrometry, light curves, spectra).

Thirty-seven small, mission-accessible NEAs were observed between mid 2013 and mid 2014 using the Gemini Multi-Object Spectrograph at Gemini North & South observatories. Taxonomic classifications were obtained by fitting our spectra to the visible wavelength portions of the mean reflectance spectra of the Bus-DeMeo taxonomy (DeMeo et al 2009).

The smallest near-Earth asteroids are the likely progenitors of meteorites; we expect the observed fraction of ordinary chondrite meteorites to match that of their parent bodies, S-type asteroids. We present classifications for these objects as well as preliminary results for the distribution of taxa (as a proxy for composition) as a function of object size and compare to the observed fraction of ordinary chondrite meteorites.

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Contributing team(s): MANOS Team

213.08 – Rapid response near-infrared spectrophotometric characterization of Near Earth Objects

Small NEOs are, as a whole, poorly characterized, and we know nothing about the physical properties of the majority of all NEOs. The rate of NEO discoveries is increasing each year, and projects to determine the physical properties of NEOs are lagging behind. NEOs are faint, and generally even fainter by the time that follow-up characterizations can be made days or weeks later. There is a need for a high-throughput, high-efficiency physical characterization strategy in which hundreds of faint NEOs can be characterized each year. Broadband photometry in the near-infrared is sufficiently diagnostic to assign taxonomic types, and hence constrain both the individual and ensemble properties of NEOs. We will present results from our recently initiated program of rapid response near-infrared spectrophotometric characterization of NEOs. We are using UKIRT (on Mauna Kea) and the RATIR instrument on the 1.5m telescope at the San Pedro Martir Observatory (Mexico) to allow us to make observations most nights of the year in robotic/queue mode. This technique is powerful and fast. We have written automated software that allows us to observe NEOs very soon after discovery. Our targets are NEOs that are generally too faint for other characterization techniques. We are on pace to characterize hundreds of NEOs per year.

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213.09 – Near-Earth Asteroid Program at the Center for Solar System Studies

As of August 2014, the asteroid lightcurve database (LCDB; Warner et al., 2009) contains 611 near-Earth asteroids with statistically useful rotation rates, about 5% of all known NEAs. The LCDB also contains 48 NEAs that are known or suspected binary or multiple systems, 46 with approximate or known spin orientations, and 36 confirmed or suspected

tumblers (non-principal axis rotation). 131 NEAs have a rotation period of $P \approx 2$ h, and 116 with $P \approx 1$ h. While these counts are sufficient to make reasonable inferences about NEA rotation rate statistics, the significantly smaller sampling of binaries, tumblers, and known spin orientations in both the NEA and the general populations often leads to more questions than answers.

Starting in mid-2013, the Center for Solar System Studies (CS3) located in the Mojave Desert in Southern California began a concentrated campaign using up to nine robotic telescopes to find reliable rotation periods for as many NEAs as possible. We sometimes obtained multiple dense lightcurve sets to be used in lightcurve inversion modeling if the viewing aspect changed significantly over an apparition. We worked closely with the radar teams at Arecibo and Goldstone so that we could supplement their radar observations with dense lightcurves, which can lead to a successful determination of the spin orientation in less time than by either method alone.

We report on the results from the first year of our efforts, which includes lightcurves for 159 NEAs, about 63% of all NEA lightcurves reported in this time span. The CS3 lightcurves include 12 confirmed or suspected tumblers and three objects with $P \approx 0.12$ h.

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213.10 – Was the Chelyabinsk meteoroid a fragment of Potentially Hazardous Asteroid (86039) 1999 NC43?

We explored the compositional link between Chelyabinsk meteoroid and potentially hazardous asteroid (86039) 1999 NC43 to verify their presumed relation proposed by Borovička et al. (2013). This compositional link was proposed based on the Q-taxonomic classification of 1999 NC43 and LL5 ordinary chondrite composition of Chelyabinsk. Our analysis shows that while the Q-type classification of 1999 NC43 is accurate, assuming that all Q-types are LL chondrites is not. We note that not all ordinary chondrites fall under Q-taxonomic type and not all LL chondrites are Q-types.

Non-diagnostic spectral curve matching between laboratory spectra of Chelyabinsk and 1999 NC43 spectrum shows that the spectra do not match. Mineralogical analysis of Chelyabinsk (LL chondrite) and (8) Flora (the largest member of the presumed LL chondrite parent family) shows that their olivine and pyroxene chemistries are similar to LL chondrites. Similar analysis of 1999 NC43 shows that its olivine (Fa29) and pyroxene (Fs24) chemistries are more similar to L chondrites than LL chondrites. While some asteroid pairs show differences in spectral slope, there is no evidence for L and LL chondrite type objects fissioning out from the same parent body. Considering all these facts, we find the proposed link between the Chelyabinsk meteoroid and the asteroid 1999 NC43 to be unlikely.

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213.11 – Synoptic Observations for Physical Characterization of Fast Rotator NEOs

NEOs can be studied not only dynamically, to learn about their impact hazard, but also physically, to establish various properties important both to better address their potential hazard and also to understand what they can tell us about the origin of the solar system and its ongoing processes.

Taking advantage of the two-meter-class telescopes around Tucson, we plan to observe NEOs synoptically using telescopes at three different locations: VATT (Vatican Advanced Technology Telescope) at Mount Graham (longitude: -109.8719, latitude: 32.7016, elevation: 10469 feet), Bok 2.3 m at Kitt Peak (longitude: -111.6004, latitude: 31.9629, elevation: 6795 feet) and Kuiper 1.5-m at Mount Bigelow (longitude: -110.7345, latitude: 32.4165, elevation: 8235 feet). All three telescopes will aim simultaneously at the same object, each with a different instrument. The three telescopes will be part of the Arizona Robotic Telescope (ART) network, a University of Arizona initiative to provide near real-time observations of Target of Opportunity objects across the visible and near-infrared wavelengths. The VATT-4K optical imager mounted on the VATT has already been used for photometry. In the future we plan to utilize the BCSpec (Boller & Chivens Spectrograph) for visible spectroscopy on Bok 2.3 meter and a near-infrared instrument on Kuiper 1.5 meter. We report here the preliminary results of several NEOs whose rotation rate and color have been estimated using photometry with images recorded with VATT-4K. 2009 SQ104 has a rotation rate of 6.85 ± 0.03 h, 2014 AY28 has a rotation rate of 0.91 ± 0.02 h, 2014 EC of 0.54 ± 0.04 h, 2014 FA44 of 3.45 ± 0.05 h, and 2014 KS40 of 1.11 ± 0.06 h.

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213.12 – Spacewatch Taxonomic Photometry of Near-Earth Objects Detected by NEOWISE

We have performed a program of multiband photometry for carefully selected Near-Earth Objects (NEOs) having NEOWISE mission determined diameters (Mainzer et al. 2011 <http://adsabs.harvard.edu/abs/2011ApJ...743..156M>).

Standardized high precision V-band photometry of such objects establishes the albedo near the peak of incident solar flux, which reckons in modeling their thermal properties. These observations are valuable since the delivery of asteroids from the main belt to Earth-crossing orbits depends on albedo, size, & composition. Measurements of mineralogical classes by means of taxonomic photometry can thus help refine understanding of the filtering involved in asteroid transport.

Due to the faintness of the targets and time limitations, the program typically used BVRI photometry to classify the objects using Dandy et al. (2003). Although less accurate and potentially more ambiguous than the Bus-DeMeo or Tholen systems, it is significantly easier to obtain for faint asteroids but still allows sorting into major taxonomic groups. The poster presents results of the reductions to date, concentrating on four particular asteroids observed May 30-31, 2014 at the Steward 2.3 meter with full UBVRiz colors. Simultaneous ZY/JHK measurements were taken by UKIRT which will also be presented if available.

(36183) $V=19.18\pm0.05$, $U-B=0.41\pm0.05$, $B-V=0.86\pm0.05$, $V-R=0.50\pm0.05$, $V-I=0.85\pm0.04$ is consistent with an S type on the Dandy system.

(85628) $V=18.54\pm0.01$, $U-B=0.42\pm0.03$, $B-V=0.86\pm0.01$, $V-R=0.48\pm0.02$, $V-I=0.83\pm0.02$, consistent with an S type.

(85989) $V=17.46\pm0.06$, $U-B=0.40\pm0.08$, $B-V=0.75\pm0.08$, $V-R=0.49\pm0.08$, $V-I=0.80\pm0.06$ is consistent with an C type.

(162181) $V=18.59\pm0.01$, $U-B=0.44\pm0.02$, $B-V=0.88\pm0.01$, $V-R=0.48\pm0.01$, $V-I=0.87\pm0.01$, consistent with an S type.

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213.13 – Detectability of Boulders on Near-Earth Asteroids

Boulders are seen on spacecraft images of near-Earth asteroids Eros and Itokawa. Radar images often show bright pixels or groups of pixels that travel consistently across the surface as the object rotates, which may be indicative of similar boulders on other near-Earth asteroids. Examples of these bright pixels were found on radar observations of 2005 YU55 and 2006 VV2 (Benner et al. 2014). Nolan et al. (2013) also identify one large possible boulder on the surface of Bennu, target of the OSIRIS-REx sample return mission. We explore the detectability of boulders by adding synthetic features on asteroid models, and then simulating radar images. These synthetic features were added using BLENDER ver. 2.70, a free open-source 3-D animation suite. Starting with the shape model for Bennu (diameter ~500 m), spherical 'boulders' of 10 m, 20 m, and 40 m diameter were placed at latitudes between 0 and 90 deg. Simulated radar observations of these models indicated that spherical boulders smaller than 10 m may not be visible in observations but that larger ones should be readily seen. Boulders near the sub-Earth point can be hidden in the bright region near the leading edge, but as the asteroid's rotation moves them towards the terminator, they become visible again, with no significant dependence on the latitude of the boulder. These simulations suggest that we should detect large boulders under most circumstances in high-quality radar images, and we have a good estimate of the occurrence of such features on near-Earth objects. Results of these simulations will be presented.

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213.14 – Regolith Levitation on Small Fast Rotating Asteroids

A number of NEAs larger than few hundred meters are found with relatively high spin rates (from ~2.2 to less than 4 hr, depending on composition). On those bodies, local acceleration near their equator may be directed outwards, as in the case of the primaries of binary asteroids Didymos and 1996 FG3. They both are potential targets of future space missions. What are the effects of high spin states on regolith material at low asteroidal latitudes?

NEAs come from the asteroid belt and are believed to be mostly gravitational aggregates at $D > 0.5 - 1$ km due to their former collisional evolution history (Campo Bagatin et al, 2001). Once in the inner Solar System, NEAs may undergo spin up evolution through YORP causing their components to disperse, shed mass or fission and eventually form binary, multiple systems or asteroid pairs (Walsh et al, 2008, Jacobson and Scheers, 2010, Pravec et al, 2009 and 2010). The end state of those events is often an object spinning above any Chandrasekhar stability limit, kept together by friction (Holsapple, 2007) and sometimes characterized by an equatorial "bulge", as shown by radar images (Ostro et al, 2006). The centrifugal force acting on surface particles at equatorial latitudes may overcome the gravitational pull of the asteroid itself, and particles may leave its surface. Centrifugal is an apparent contact force, and as soon as particles lift off they mainly move under the gravitational field of the asteroid and the satellite, they may levitate for some time, land on the surface and repeat this cycle over and over.

We are studying the motion of particles in the 1 μ m to 10 cm range in the non-inertial reference frame of the rotating primary, accounting for centrifugal and Coriolis apparent forces as well as the gravitational fields of the primary, the

secondary, the Sun and the radiation forces by the Sun itself.
The main features of this effect are presented in the case of Didymos and 1996 FG3.

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213.15 – Radar observations and physical modeling of binary near-Earth asteroid (1862) Apollo T.F. Ford, L.A.M. Benner, M. Brozovic, C.B. Ledford, M.C. Nolan, J.D. Giorgini, S.J. Ostro, J.L. Margot.

Binary asteroid 1862 Apollo has an extensive observational history allowing many of its characteristics to be investigated. Apollo was one of the first objects to show evidence for the YORP effect (Kaasalainen et al. 2007, Nature 446, 420) and its mass has been estimated by detection of the Yarkovsky effect (Nugent et al. 2012, AJ 144, 60; Farnocchia et al. 2013, Icarus 224, 1). We observed Apollo at Arecibo and Goldstone from Oct. 29–Nov. 13, 2005, obtaining a series of echo power spectra and delay-Doppler images that achieved resolutions as high as 7.5 m/pixel. The Arecibo images show that Apollo is a binary system with a rounded primary that has two large protrusions about 120 deg apart in longitude. We used the Arecibo data and published lightcurves to estimate the primary's 3D shape. Our best fit has major axes of $\sim 1.8 \times 1.5 \times 1.3$ km and a volume of ~ 1.6 km³. The protrusions have lengths of ~ 300 and 200 m, are on the primary's equator, and give Apollo a distinctly different appearance from the primaries with equatorial ridges seen with other binary near-Earth asteroids. We estimated the pole by starting with the Kaasalainen et al. spin vector of ecliptic (longitude, latitude)=(50 deg, -71 deg) \pm 7 deg and letting it float. Our best fit has a pole within 11 deg of (longitude, latitude)=(71, -72). Convex models produced from inversion of lightcurves by Kaasalainen et al. and thermal infrared data by Rozitis et al. (2013, A&A 555, A20) are more oblate than our model, do not show protrusions, and have somewhat different pole directions. The Arecibo images reveal weak but persistent echoes from a satellite on Nov. 1 and 2 but cover only a fraction of its orbit. The images are insufficient to estimate the satellite's shape and yield a rough estimate for its long axis of 190 m. Preliminary fits give an orbital period of ~ 27.0 – 27.5 h and a semimajor axis of ~ 3.5 – 4.0 km, implying a mass of 2.8 – 3.9×10^{12} kg and a bulk density of 1.7 – 2.4 g/cm³. The density is consistent with estimates reported by Rozitis et al. and Farnocchia et al., providing the first independent test using a binary to estimate the density of near-Earth asteroid that has also been estimated through detection of the Yarkovsky effect.

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213.16 – Near-Infrared (2 – 4 μ m) spectroscopy of Near-Earth Asteroids: Searching for OH/H₂O on small planetary bodies

Near-Earth asteroids (NEAs) are not expected to have H₂O ice on their surfaces because; a) most accreted dry and therefore never contained H₂O, and b) their relatively high surface temperatures should drive rapid H₂O ice sublimation. However, OH/H₂O has been detected on other anhydrous inner solar system objects, including the Moon and Vesta. Possible sources for OH/H₂O in the inner Solar System might include production via solar wind interactions, carbonaceous chondrite or cometary impact delivery, or native OH/H₂O molecules bound to phyllosilicates. As these processes are active in near-Earth space, detectable levels of OH/H₂O might also be present on NEAs.

OH/H₂O can be detected by its spectral signature near 3- μ m absorption feature using near-infrared (2 – 4 μ m) spectroscopy from terrestrial infrared telescopes. This feature can be comprised of an OH absorption feature centered near 2.7 μ m and H₂O features near 2.9 and 3.1 μ m, or a blend of both, producing a relatively wide feature spanning 2.7 – 3.1 μ m. Analysis of the shape of the 3- μ m feature, coupled with the observed NEA orbital parameters and albedos, can help distinguish between the possible sources of OH/H₂O.

Here we present preliminary results of an ongoing observational program to measure spectra of NEAs in the 3- μ m region. We are using the SpeX instrument on NASA's Infrared Telescope Facility (IRTF) to measure spectra in from ~ 2 to 4 μ m. So far, we have 10 observations for 5 NEAs. 443 Eros has been observed twice: 1/09/2009, and 1/28/2012. 1036 Ganymed has been observed five times in 2011: 6/10, 7/4, 9/17, 9/27, and 10/19. 3122 Florence was observed 2010 August 5. (54789) 2001 MZ7 was observed on 2/1/2010. (96590) 1998 XB was observed on 2/15/2010 December. Rivkin et al. (2013; LPSC) reported detections of the 3- μ m feature on Ganymed and Eros with data taken in 2012. Data from our data of Ganymed, Eros, and 1998 XB is still in progress. Spectra of Florence and 2001 MZ7 appear to exhibit absorptions in the 3- μ m region. Our preliminary findings show that the 3- μ m feature is present on NEAs, and that this feature is not restricted to large airless bodies like the Moon and Vesta. Further studies are needed to determine the origin of the band.

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213.17 – Real-time Characterization of Near-Earth Objects: New Spectral Capabilities at the Magdalena Ridge Observatory 2.4-meter

Researchers at the Magdalena Ridge Observatory's (MRO) 2.4-meter telescope facility have been contributing to the Near-Earth Object (NEO) project by working in tandem with discovery survey programs since 2008 to provide real-time, rapid response astrometric and photometric characterization follow-up (i.e., lightcurves to deduce spin rates). We are now extending this to include rapid spectroscopic follow-up using the Magdalena Optical Spectroscopy System (MOSS). This R~300 visible wavelength spectrometer is permanently mounted at the Nasmyth port opposite the imager port (CCD camera) and is accessible in 30 seconds via repositioning of a tertiary mirror. A second spectroscopic capability is available via a simple filter wheel-mounted grating when MOSS is not in use. By having these instruments mounted (CCD, spectrometer, and stand alone grating) while performing our normal astrometric follow-up tasks, determination of rotation rates and spectral classification are possible as soon as an interesting target is identified, even within minutes of discovery.

We report on the first spectral characterization results of NEOs utilizing this new capability at MRO. In particular, we will present spectra for the Sq/Q-type asteroids 2010 XZ67 and 2000 DK79; and the more S-like 2012 HM. In addition, we will present the near simultaneous lightcurve and spectral observations of 2014 EC. The lightcurve observations reveal a period of 0.54 +/- 0.01 hours that hint at non-principle axis rotation. The MOSS-acquired spectra imply its spectral class is Sq/Q as well. A simple grating spectrum of this object was also obtained and was of sufficient quality to corroborate an Sq/Q classification. As an ancillary benefit, this demonstrates that the grating technique can be reliable for rough classification of targets-of-opportunity when it is the only instrumentation option available.

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213.18 – The Need for Speed in Near Earth Asteroid Characterization

The current discovery rate of Near Earth Asteroids (NEAs) is set to increase dramatically in the next few years from ~900/year to 2,000-3,000/year thanks to new surveys coming online and equipment upgrades to current ones. Despite this, the rate of characterization is expected to remain the same: ~100 spectra and a few dozen light curves per year. At this rate it will take up to a century to characterize just the NEA population with sizes above 100m. Characterization is crucial to science, space missions and planetary defense and cannot be left by the wayside. Herein we discuss the challenges of, and opportunities for, optimal NEA characterization. In particular we find that immediate follow-up (within days) of discovery is essential: A dedicated telescope (2-4m) could perform optical spectroscopy while a number of smaller telescopes would take light curves. Coordination could be performed by the Minor Planet Center as an extension of the services they provide through the NEO Confirmation Page.

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214 – Future Missions Posters

214.01 – A Broadband IR Compact High Resolution Spectrometer (BIRCHES) for a Lunar Water Distribution (LWaDi) Cubesat Mission

We are in the process of developing the BIRCH (Broadband IR for Cubesats with High Resolution) Spectrometer for characterization of a range of deep space targets. BIRCH is the first extremely compact Broadband IR spectrometer with high spectral resolution designed to measure water type and component distribution for a science-driven cubesat mission, such as the lunar orbital mission LWaDi (Lunar Water Distribution) designed to determine the systematics of lunar water and volatiles as a function of time of day, latitude, and terrain. The development of cubesat form factor instruments, such as BIRCH, capable of providing high priority science goals identified in the decadal survey is critical to achieve low cost planetary exploration promised by the cubesat paradigm by exploring volatile systems via orbiting or landed packages. On the Moon, as well as Mercury, Mars, and the asteroids, the source, distribution, and role of volatiles is a question of major importance, and has implications for formation processes, including interior structure, differentiation, and the origin of life in the early solar system. The form and distribution of water has implications for human exploration, resource exploitation, and sample curation. Recent lunar missions gave unanticipated evidence for the water from NIR instruments not optimized for finding it. Our instrument includes a compact broadband HgCdTe

detector with a linear variable filter and a compact cryocooler (for operation below 140K) attached to a compact optical system with 2 off-axis parabolic mirrors and variable field stop operating below 240K. Its 10 nm or better resolution and longer wavelength upper range (1.3 to 3.7 microns) are necessary to identify and separate features associated with water type (adsorbed, bound, ice) and components. Its 4-sided adjustable iris at the field stop enables a constant spot size (10 x 10 km) regardless of altitude. BIRCH will be able to provide systematic and extensive enough information to understand water's life cycle, temporal and spatial distribution and interactions as a function of lunar cycles, characteristic features, and regolith composition.

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214.02 – Solar System Science with HST and JWST: Connecting the Past, Present, and Future

NASA's Great Observatories have long provided solar system scientists with unique imaging and spectroscopic capabilities which have resulted in many important discoveries. As a successor to the Hubble Space Telescope (HST), the James Webb Space Telescope (JWST) will also make valuable contributions to solar system research. This poster summarizes some of HST's key past contributions to solar system science such as SL9, Pluto and its moons, and KBOs. Highlights of current HST solar system observing (e.g. Comet ISON) are presented; and finally, examples of future JWST observations are presented with an emphasis on how JWST will extend and improve on what HST has done.

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214.03 – The Space Launch System and the Proving Ground: Pathways to Mars

Introduction: The Space Launch System (SLS) is the most powerful rocket ever built and provides a critical heavy-lift launch capability. We focus on mission concepts relevant to NASA's Cislunar Proving Ground and the Global Exploration Roadmap (GER).

Asteroid Redirect Mission (ARM): ARM in part is a mission to the lunar vicinity. The ARM mission requirements result in system design based on a modified version of our 702 spacecraft. Including a NASA Docking System (NDS) on the Asteroid Redirect Vehicle allows for easier crewed exploration integration and execution.

Exploration Augmentation Module (EAM): Crew operations at a redirected asteroid could be significantly enhanced by providing additional systems and EVA capabilities beyond those available from the Orion only. An EAM located with the asteroid would improve the science and technical return of the mission while also increasing Orion capability through resource provision, abort location and safe haven for contingencies. The EAM could be repurposed as a cislunar exploration platform that advances scientific research, enables lunar surface exploration and provides a deep space vehicle assembly and servicing site. International Space Station (ISS) industry partners have been working for the past several years on concepts for using ISS development methods and assets to support a broad range of exploration missions.

Lunar Surface: The mission objectives are to provide lunar surface access for crew and cargo and to provide as much system reuse as possible. Subsequent missions to the surface can reuse the same lander and Lunar Transfer Vehicle.

Mars Vicinity: The International space community has declared that our unified horizon goal is for a human mission to Mars. Translunar infrastructure and heavy lift capability are key to this approach. The moons of Mars would provide an excellent stepping stone to the surface. As a "shake-down" cruise before landing, a mission to Deimos or Phobos would test all of the systems except those needed to get to the surface and back. This test would provide confidence for the in-space transportations and crew habitat systems.

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214.04 – The Planetary Data System— Archiving Planetary Data for the use of the Planetary Science Community

NASA's Planetary Data System (PDS) archives, curates, and distributes digital data from NASA's planetary missions. PDS provides the planetary science community convenient online access to data from NASA's missions so that they can continue to mine these rich data sets for new discoveries. The PDS is a federated system consisting of nodes for specific discipline areas ranging from planetary geology to space physics. Our federation includes an engineering node that provides systems engineering support to the entire PDS.

In order to adequately capture complete mission data sets containing not only raw and reduced instrument data, but also calibration and documentation and geometry data required to interpret and use these data sets both singly and together (data from multiple instruments, or from multiple missions), PDS personnel work with NASA missions from the initial AO through the end of mission to define, organize, and document the data. This process includes peer-review of data sets by members of the science community to ensure that the data sets are scientifically useful, effectively organized, and well documented. PDS makes the data in PDS easily searchable so that members of the planetary community can both query the archive to find data relevant to specific scientific investigations and easily retrieve the

data for analysis. To ensure long-term preservation of data and to make data sets more easily searchable with the new capabilities in Information Technology now available (and as existing technologies become obsolete), the PDS (together with the COSPAR sponsored IPDA) developed and deployed a new data archiving system known as PDS4, released in 2013. The LADEE, MAVEN, OSIRIS REx, InSight, and Mars2020 missions are using PDS4. ESA has adopted PDS4 for the upcoming BepiColumbo mission. The PDS is actively migrating existing data records into PDS4 and developing tools to aid data providers and users. The PDS is also incorporating challenge-based competitions to rapidly and economically develop new tools for both users and data providers.

Please visit our User Support Area at the meeting (Booth #114) if you have questions accessing our data sets or providing data to the PDS.

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214.05 – Monitoring of Comets and Extra-Solar Planets with ESA's Optical Ground Station

The ESA Optical Ground Station (OGS) is a 1-m telescope located at Teide Observatory, Tenerife, that was originally built for tests with laser link and space debris observations. In 2004, an additional instrument was commissioned at the OGS, which was specially developed for direct imaging and long-slit spectrometry of comets, and subsequently used for monitoring of long- and short period comets including 9P/Tempel during the Deep Impact encounter in 2005. The instrument is now being refurbished and reinstalled for long-term use at the OGS in support of comet and extra-solar planet research. The comet program focuses on the morphological and compositional coma evolution of targets from the various dynamical classes with the goal of establishing a statistically relevant classification scheme, which allows understanding the diversity and similarities of comets. The extra-solar planet program includes support of the CoRoT space mission observations. An overview of the telescope/instrument capabilities and a summary of the two main research projects will be given.

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214.06 – The Pan-STARRS discovery machine

The Pan-STARRS System has proven to be a remarkable machine for discovery. The PS1 Science Mission has drawn to a close, and the second Pan-STARRS survey, optimized for NEO's has begun. PS2 is in the commissioning stages and will eventually support NEO discovery as well.

The performance of the PS1 system, sky coverage, cadence, and data quality of the Pan-STARRS1 Surveys will be presented as well as progress in reprocessing of the data taken to date and the plans for the public release of all Pan-STARRS1 data products in the spring of 2015. Science results related to planetary studies and the dust will be presented.

The Pan-STARRS1 Surveys (PS1) have been made possible through contributions of the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max-Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, Queen's University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under Grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation under Grant No. AST-1238877, the University of Maryland, and Eotvos Lorand University (ELTE).

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214.07 – The OSIRIS-REx Mission Sample Site Selection Process

In September of 2016, the OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security, REgolith eXplorer) spacecraft will depart for asteroid (101955) Bennu, and in doing so, will turn an important corner in the exploration of the solar system. After arriving at Bennu in the fall of 2018, OSIRIS-REx will undertake a program of observations designed to select a site suitable for retrieving a sample that will be returned to the Earth in 2023. The third mission in NASA's New Frontiers program, OSIRIS-REx will return over 60 grams from Bennu's surface.

OSIRIS-REx is unique because the science team will have an operational role to play in preparing data products needed to select a sample site. These include products used to ensure flight system safety — topographic maps and shape models, temperature measurements, maps of hazards — as well as assessments of sampleability and science value. The timing and production of these will be presented, as will the high-level decision-making tools and processes for the interim and final site selection processes.

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214.08 – First Light with the EXES Instrument on SOFIA

The Echelon Cross Echelle Spectrograph (EXES) successfully carried out its first two flights with the Stratospheric Observatory for Infrared Astronomy (SOFIA) on the nights of April 7 and 9, 2014. EXES is a high-resolution ($R=100,000$) spectrograph that operates from 4.5 to 28.3 microns. Our commissioning targets included a mix of solar system and Galactic

objects which were selected to characterize the performance of EXES onboard SOFIA as well as to provide unique science data.

We present high-spectral resolution 2-D maps of Jupiter and Mars observed in the course of our commissioning. Among our scientific highlights, we detected and mapped the 28.3 micron $S(0)$ H₂ line across the disk of Jupiter and mapped key transitions of H₂O and HDO over the Martian disk. These spectral lines are unobservable from the ground due to low atmospheric transmission, showcasing the new scientific capabilities enabled by EXES on SOFIA. We discuss the performance and capabilities of EXES for future observations of comets, planets and extra-solar objects.

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214.09 – The Planetary Archive

We are building the first system that will allow efficient data mining in the astronomical archives for observations of Solar System Bodies. While the Virtual Observatory has enabled data-intensive research making use of large collections of observations across multiple archives, Planetary Science has largely been denied this opportunity: most astronomical data services are built based on sky positions, and moving objects are often filtered out.

To identify serendipitous observations of Solar System objects, we ingest the archive metadata. The coverage of each image in an archive is a volume in a 3D space (RA, Dec, time), which we can represent efficiently through a hierarchical triangular mesh (HTM) for the spatial dimensions, plus a contiguous time interval. In this space, an asteroid occupies a curve, which we determine by integrating its orbit into the past. Thus when an asteroid trajectory intercepts the volume of an archived image, we have a possible observation of that body. Our pipeline then looks in the archive's catalog for a source with the corresponding coordinates, to retrieve its photometry. All these matches are stored into a database, which can be queried by object identifier.

This database consists of archived observations of known Solar System objects. This means that it grows not only from the ingestion of new images, but also from the growth in the number of known objects. As new bodies are discovered, our pipeline can find archived observations where they could have been recorded, providing colors for these newly-found objects. This growth becomes more relevant with the new generation of wide-field surveys, particularly LSST.

We also present one use case of our prototype archive: after ingesting the metadata for SDSS, 2MASS and GALEX, we were able to identify serendipitous observations of Solar System bodies in these 3 archives. Cross-matching these occurrences provided us with colors from the UV to the IR, a much wider spectral range than that commonly used for asteroid taxonomy. We present here archive-derived spectrophotometry from searching for 440 thousand asteroids, from 0.3 to 3 μm . In the future we will expand to other archives, including HST, Spitzer, WISE and Pan-STARRS.

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214.10 – Results of the First Mars Organic Molecule Analyzer (MOMA) GC-MS Coupling

The Mars Organic Molecule Analyzer (MOMA) aboard the ExoMars rover will be a key analytical tool in providing chemical (molecular) information from the solid samples collected by the rover, with a particular focus on the characterization of the organic content. The core of the MOMA instrument is a gas chromatograph coupled with a mass

spectrometer (GC-MS) which provides the unique capability to characterize a broad range of compounds, including both of volatile and non-volatile species.

Samples will be crushed and deposited into sample cups seated in a rotating carousel. Soil samples will be analyzed either by UV laser desorption / ionization (LDI) or pyrolysis gas chromatography ion trap mass spectrometry (pyr-GC-ITMS).

The French GC brassboard was coupled to the US ion trap mass spectrometer brassboard in a flight-like configuration for several coupling campaigns. The MOMA GC setup is based on the SAM heritage design with a He reservoir and 4 separate analytical modules including traps, columns and Thermal Conductivity Detectors. Solid samples are sealed and heated in this setup using a manual tapping station, designed and built at MPS in Germany, for GC-MS analysis. The gaseous species eluting from the GC are then ionized by an electron impact ionization source in the MS chamber and analyzed by the linear ion trap mass spectrometer.

Volatile and non-volatile compounds were injected in the MOMA instrumental suite. Both of these compounds classes were detected by the TCD and by the MS. MS signal (total ion current) and single mass spectra by comparison with the NIST library, gave us an unambiguous confirmation of these identifications. The mass spectra arise from an average of 10 mass spectra averaged around a given time point in the total ion chromatogram.

Based on commercial instrument, the MOMA requirement for sensitivity in the GC-MS mode for organic molecules is 1 pmol. In this test, sensitivity was determined for the GC TCD and MS response to a dilution series containing isopropanol, hexane and benzene deposited onto silica beads in the MOMA oven. Generally, the MS was found to be 5 to 10 times more sensitive than the GC TCD for hexane and benzene respectively.

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Contributing team(s): MOMA Team

214.11 – Argus: A concept study for an Io observer mission from the 2014 NASA/JPL Planetary Science Summer School

Jupiter's moon Io is the ideal target to study extreme tidal heating and volcanism, two major processes shaping the formation and evolution of planetary bodies. In response to the 2009 New Frontiers Announcement of Opportunity, we propose an Io Observer mission concept named Argus (after the mythical watchman of Io). This concept was developed by the students of the August 2014 session of NASA's Planetary Science Summer School, together with the Jet Propulsion Laboratory's Team X.

The science objectives of our mission are: (1) study the physical process of tidal heating and its implications for habitability in the Solar System and beyond; (2) investigate active lava flows on Io as an analog for volcanism on early Earth; (3) analyze the interaction between Io and the Jovian system via material exchange and magnetospheric activity; (4) study Io's chemistry and geologic history to gain insight into the formation and evolution of the Galilean satellites. Our mission consists of a Jupiter-orbiting spacecraft performing ten close flybys of Io. The orbital inclination of ~31 degrees minimizes the total radiation dose received, at the cost of having to perform fast flybys (13 km/s).

The instrument payload includes: (1) IGLOO, a multi-band camera for regional (500 m/pixel) and high-resolution (50 m/pixel) imaging; (2) IoLA, a laser altimeter to measure the triaxial shape and diurnal tidal deformation, and topographic profiles of individual surface features; (3) IGNITERS, a thermal emission radiometer/spectrometer to map nighttime temperatures, thermal inertia, and characterize Io's atmosphere; (4) IoNIS, a near-infrared spectrometer to map global (10 km/pixel) and local (2 km/pixel) surface composition; (5) IoFLEX, a magnetometer and (6) IoPEX, a plasma particle analyzer to characterize the magnetic environment and understand the nature of Io's induced and possible intrinsic magnetic fields; (7) IRAGE, a gravity science experiment to probe Io's interior.

Our spacecraft design is powered by solar arrays rather than nuclear MMRTGs, as a result of a careful cost/trade analysis driven by our science objectives.

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Contributing team(s): JPL Team X

214.12 – Planetary Science with the Stratospheric Observatory for Infrared Astronomy

The Stratospheric Observatory for Infrared Astronomy (SOFIA) has executed the first two of its annual Cycles of guest investigator observing proposals. Proposals submitted for the third Cycle are under review. The planetary science community has made a significant showing in all proposal Cycles, comprising approximately 15% of Cycles 1 and 2. SOFIA offers observers access to the complete infrared spectrum, with much less atmospheric absorption than from even the finest ground-based telescope sites. New capabilities include high-resolution spectroscopy in the mid-infrared with the Echelon-Cross-Echelle Spectrograph (EXES), which allows, for example, spectroscopy of molecules from narrow stratospheric lines of planetary atmospheres, and imaging spectroscopy with the Field Imaging Far-Infrared Line Spectrometer (FIFI-LS), which allows simultaneous observation in 9 spatial pixels each of two far-infrared lines. Observations to date related to the solar system include comets ISON and PanSTARRS, main belt asteroids, Jupiter, Neptune, Europa, exoplanets, and debris disks. The poster will show science highlights, observatory capabilities, and proposal statistics.

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214.13 – Solar System Science with LSST

Inventorying the Solar System is one of the four key science drivers for the Large Synoptic Survey Telescope (LSST). LSST will survey over 20,000 square degrees with a rapid observational cadence, to typical limiting magnitudes of $r \sim 24.5$. Near the ecliptic, LSST will detect approximately 4000 moving objects per visit with its 9.6 square degree field of view. Automated software will link these individual detections into orbits; these orbits, as well as precisely calibrated astrometry (~ 50 mas) and photometry (~ 0.01 - 0.02 mag) in multiple bandpasses will be available as LSST data products. The result will be multi-color catalogs of hundreds of thousands of NEOs and Jupiter Trojans, millions of asteroids, tens of thousands of TNOs, as well as thousands of other objects such as comets and irregular satellites of the major planets.

The LSST catalogs will provide an order of magnitude larger sample sizes than currently exist for small body populations throughout the Solar System, generating new insights into Solar System evolution. Precision multi-color photometry will allow determination of lightcurves and colors for a significant fraction of the objects detected, providing constraints on the physical parameters of small bodies. Some examples of science enabled with this rich data set: A large sample of TNOs with highly accurate orbits (and well-understood sample characteristics) will allow much tighter constraints on planetary migration models. Large samples of comets (especially comets with perihelia beyond a few AU) will provide new constraints on the structure and mass of the Oort Cloud. Derivation of proper elements for Main Belt asteroids would greatly enlarge existing asteroid families, particularly at smaller sizes, and color information will facilitate further division. Using sparse lightcurve inversion, spin state and shape models could be derived for thousands of main belt asteroids.

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214.14 – LSST: Comprehensive NEO detection, characterization, and orbits

The Large Synoptic Survey Telescope (LSST) has Solar System mapping as one of its four key scientific design drivers, with emphasis on efficient Near-Earth Object (NEO) and Potentially Hazardous Asteroid (PHA) detection, orbit determination, and characterization. The baseline design satisfies strong constraints on the cadence of observations mandated by PHAs such as closely spaced pairs of observations to link different detections and short exposures to avoid trailing losses. Due to frequent repeat visits LSST will effectively provide its own follow-up to derive orbits for detected moving objects. We will describe detailed modeling of LSST operations, incorporating real historical weather and seeing data from Cerro Pachon in Chile, the LSST site, which shows that LSST using its baseline design cadence could find 90% of the PHAs with diameters larger than 250 m, and 75% of those greater than 140 m within ten years. However, simulations also show that LSST can reach the completeness of 90% of PHAs larger than 140m by optimizing observing cadence and extending the survey lifetime to 12 years. In addition to detecting and determining orbits for these PHAs, LSST will also provide valuable data on their physical characteristics through accurate color and variability measurements, which can be used to determine approximate taxonomical types, better size estimates by constraining albedos, rotation periods, and shape characteristics; thus constraining PHA properties relevant for risk mitigation strategies.

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Contributing team(s): LSST Collaboration

214.15 – Venus Atmosphere and Surface Explorer

Context

Venus is Earth's twin planet, but it is an evil twin! To understand how Venus went wrong, to understand the terrestrial planets in our Solar System, those around other stars, and the future of the Earth... we must understand Venus history, evolution and current processes. This requires entering the Venus atmosphere and examining its surface. Future missions will land on Venus, but they need better characterization of its atmosphere and of possible landing sites. VASE can build on discoveries from previous missions, on technical advances in the last decades and on improved balloon technology. The hybrid mission links together a single vertical profile with two weeks of temporal and longitudinal data on a global scale. We can investigate the linked surface and atmosphere processes. We will measure the noble gases which retain indicators of Venus formation; clouds, winds, and chemistry that drive the current Venus processes; and take descent images that extend the Magellan RADAR results to sub-1m resolution, providing ground truth for Magellan's global mapping and to characterize possible future landing sites.

Science Objectives

VASE will measure the complete inventory of atmospheric noble gas and light stable isotopes to constrain theories of planetary formation and evolution. It will take nested surface images on descent. It will provide the first complete atmospheric structure profile from clouds to surface of temperature, pressure and wind. VASE will measure with critical accuracy the trace and reactive gas composition profile from clouds to surface. VASE will map the surface emissivity along the surface below two balloon circumnavigations of Venus.

Mission

VASE is a hybrid Venus mission consisting of a large balloon and a small probe. It reaches Venus after a 4 month trip from Earth. The probe deploys from the entry vehicle and falls to surface in 1.5 hours. The balloon mission lasts 2 weeks, flying in the clouds at 55 km and circumnavigating Venus twice. The balloon communicates directly to Earth and serves as the telecom relay for the probe.

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Contributing team(s): VASE Team

214.16 – A Geophysical Laboratory for Rubble Pile Asteroids: The BASiX Mission

Small rubble pile asteroids exhibit a diverse range of evolutionary behaviors and morphologies, driven by an array of poorly understood geophysical effects. The complex ways that these bodies evolve belies their simple structure: gravitational aggregates of shattered primitive bodies. Their evolution can be dramatic, such as seen in the active asteroids P/2013 P5 and P/2013 R3, or may be subtly masked, such as in the tide-BYORP equilibria of singly-synchronous binary asteroids. Their evolutionary outcomes can defy the imagination, such as asteroid 1950 DA which is spinning faster than its gravitational attraction yet is held together by weak van der Waals forces (Rozitis et al. 2014), or present us with profound mysteries, such as how the Almahata Sitta meteorite could be comprised of such diverse components. Beyond these motivations, the study of rubble pile asteroid geophysics can shed insight into any solar system environment where gravitational aggregates interact in a micro-gravity setting, ranging from the protoplanetary disc to planetary ring systems. The broad study of the geophysics of aggregates in such micro-gravity environments is becoming both a unifying theme and emerging field of study.

Out of the many diverse and complex forms that rubble pile asteroids take on, the study of NEA binary asteroids can in particular be used to expose the geophysics of micro-gravity aggregates. Binaries are an expression of micro-gravity geophysics due to the manner in which they form and their continuing evolution. Due to our ability to visit, probe and interact with NEA, we can also turn them into geophysical laboratories.

This talk will introduce the science of the Binary Asteroid in-situ Explorer (BASiX) Discovery mission, which proposes to turn the primitive C-Type binary asteroid (175706) 1996 FG3 into such a geophysical laboratory. Exploring this body enables us to probe a broad range of rubble pile asteroid properties: internal tidal dissipation (through FG3's documented tide-BYORP equilibrium), the nature of surface heterogeneities on primitive bodies (well documented for FG3), the intrinsic seismic and strength properties of micro-gravity aggregates, and the processes that form and evolve such binaries.

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214.17 – Observing Solar System Targets with the James Webb Space Telescope

With its anticipated launch date in October 2018, the James Webb Space Telescope will tremendously advance astronomy in the near- and mid-infrared, offering sensitivity and spatial/spectral resolution greatly surpassing its predecessors. We have developed a white paper that explores observations of Solar System targets with JWST, with the goals of highlighting anticipated Solar System capabilities, motivation of potential observers, and encouragement of further interest and discussion. This paper presents the most current information available concerning JWST instrument properties and observing techniques relevant to planetary science. It also illustrates example observing scenarios for a

wide variety of Solar System objects, including the giant planets, Kuiper Belt objects, Europa, Titan, and more. We are also collaborating with a set of focus groups that have expanded upon this work, producing a series of further white papers dealing with individual subdisciplines. This work has been supported by NASA Grant NAG5-12457.

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214.18 – Kuiper: A Discovery-class Observatory for Giant Planets, Satellites, and Small Bodies

The recent Planetary Decadal identified important science goals for the study of the outer solar system. However, after the end of the Cassini and Juno missions in 2017, outer solar system science might face over a decade without new U.S. missions. The Survey thus noted the critical role that space-based telescopic observations, especially those enabling significant time-domain and target coverage, can play in advancing key planetary science questions. We propose a dedicated planetary space telescope, implementable in the Discovery program, to conduct three diverse investigations. Named after pioneering planetary astronomer Gerard P. Kuiper, the mission will address 9 of the 10 Decadal's Key Questions by studying 1) the giant planets, 2) their major satellites, and 3) the panoply of small bodies that populate the outer solar system. These three diverse investigations will enable significant advances in outer solar system science, through time-domain observations and substantial time on the targets. Advances in understanding the connections between weather and climate in giant planet atmospheres, as well as the interactions between giant planet atmospheres, satellites, and their external environments (e.g., auroral, solar wind, plumes, impacts), require consistent, well-calibrated, nearly-continuous observations spanning timescales from hours to years. Progress in understanding the ways that small outer solar system bodies can be used to understand the details of early giant planet migration requires compositional knowledge of statistically significant members of key dynamical populations. Observations with the required temporal coverage and fidelity needed to address these and many other important outer solar system Decadal science goals simply cannot be obtained from ground-based telescopes, or existing or planned space telescopes. Kuiper's combination of spatial resolution, spectral resolution, UV to near-IR coverage, and substantial time-domain sampling will offer an efficient, affordable, and highly relevant facility guaranteed to yield diverse, new insights and to inform planning of in situ missions for future decades.

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Contributing team(s): The Kuiper Team

214.19 – The NASA Infrared Telescope Facility (IRTF): Future Instrumentation and Upgrades

The NASA Infrared Telescope Facility (IRTF) is a 3.0-m infrared telescope located at an altitude of 4.2 km near the summit of Mauna Kea on the island of Hawaii. The IRTF was established by NASA to obtain solar system observations of interest to NASA. The funding for IRTF operations was renewed in May 2014 for another 5 years. We discuss new instrumentation and upgrades during this time period. Current instruments include: (1) SpeX, a 0.7-5 μ m moderate-resolution spectrograph and camera, (2) MORIS, a high-speed CCD imager attached to SpeX for simultaneous visible and near-infrared observations, and (3) CSHELL, a 1-5 μ m high-resolution spectrograph. Detector upgrades have recently been made to SpeX. We are also designing and constructing a new echelle spectrograph for 1-5 μ m. This instrument will be commissioned starting in early 2016. We also plan to restore to service our 8-25 μ m camera, MIRS. Our 1-5 μ m camera, NSFCAM, was lost due to a failure of the liquid nitrogen can that was caused by an ice plug. We can restore this instrument to service but no plans have been made yet. The IRTF supports remote observing from any site. This eliminates the need for travel to the observatory and short observing time slots can be supported. We also welcome onsite visiting astronomers. In the near future we plan to implement a low-order wave-front sensor to allow real-time focus and collimation of the telescope. This will greatly improve observational efficiency. In the longer term, we envision the construction of an adaptive optics system that is optimized for solar system observations. This instrument would use the restored NSFCAM, which has a circular variable filter allowing selection of any wavelength from 1-5 μ m. We welcome input for planetary science cases needing diffraction-limited imaging at 1-5 μ m. For further information on the IRTF and its instruments including visitor instruments, see: <http://irtfweb.ifa.hawaii.edu/>. We gratefully acknowledge the support of NASA contract NNH14CK55B, NASA Science Mission Directorate.

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214.20 – Response of Microchannel Plate (MCP) Detectors to MeV Electrons: Beamline tests in support of Juno, JUICE,

and Europa Mission UVS instrument investigations

The response of Microchannel Plate (MCP) detectors to far-UV photons is excellent. MCPs provide a photon-counting capability that is especially useful for high-quality stellar and solar occultation measurements. However, use of MCPs within the Jovian magnetosphere for UV measurements is hampered by their ~30% detection efficiency to energetic electrons and ~1% efficiency to γ -rays. High-Z shielding stops energetic electrons, but creates numerous secondary particles; γ -rays are the most important of these for MCPs. These detected particles are a noise background to the measured far-UV photon signal, and at particularly intense times their combination can approach detector global count rates of ~500 kHz when operating at nominal HV levels. To address the challenges presented by the intense radiation environment experienced during Europa encounters we performed electron beam radiation testing of the Juno-UVS flight spare cross-delay line (XDL) MCP in June 2012 at MIT's High Voltage Research Laboratory (HVRL), and again in Nov. 2013 adding an atomic-layer deposition (ALD) coated test-MCP, to measure the detection efficiency and pulse height distribution characteristics for energetic electrons and γ -rays. A key result from this UVS-dedicated SwRI IR&D project is a detailed characterization of our XDL's response to both particles (electrons and γ -rays) and photons as a function of HV level. These results provide confidence that good science data quality is achievable when operating at Europa closest approach and/or in orbit. Comparisons with in-flight data obtained with New Horizons Pluto-Alice MeV electron response measurements at Jupiter (Steffl et al., JGR, 2012), LRO-LAMP electron and proton event data, and Juno-UVS Earth proton-belt flyby data, and recent bench tests with radioactive sources at Sensor Sciences increase this confidence. We present a description of the test setup, quantitative results, and several lessons learned to help inform future beamline test experiments dedicated to instrument developments for NASA's next large mission to Europa and ESA's JUICE mission to Ganymede.

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214.21 – Focus Groups for Solar System Investigations with the JWST

The unprecedented sensitivity and angular resolution of the James Webb Space Telescope (JWST) will make it NASA's premier space-based facility for infrared astronomy. This 6.5-meter telescope, which is optimized for observations in the near and mid infrared, will be equipped with four state-of-the-art instruments that include imaging, spectroscopy, and coronagraphy. These instruments, along with the telescope's moving target capabilities, will enable the infrared study of solar system objects with unprecedented detail. A new white paper (Norwood et al., 2014) provides a general overview of JWST observatory and instrument capabilities for Solar System science, and updates and expands upon an earlier study by Lunine et al. (2010). In order to fully realize the potential of JWST for Solar System observations, we have recently organized 10 focus groups to explore various science use cases in more detail on topics including: Asteroids, Comets, Giant Planets, Mars, Near Earth Objects, Occultations, Rings, Satellites, Titan, and Trans-Neptunian Objects. The findings from these groups will help guide the project as it develops and implements planning tools, observing templates, the data pipeline and archives so that they enable a broad range of Solar System Science investigations. The purpose of this presentation is to raise awareness of the JWST Solar System planning, and to invite participation of DPS members with our Focus Groups and other pre-launch activities.

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214.22 – The Development and Field Testing of the Portable Acousto-optic Spectrometer for Astrobiology

The development of in situ instrumentation for the detection of biomarkers on planetary surfaces is critical for the search for evidence of present or past life in our solar system. In our earlier instrument development efforts we addressed this need through the development of a near-infrared point spectrometer intended for quick-look examinations of samples that could be subsequently analyzed with a laser desorption time-of-flight mass spectrometer. The point spectrometer utilized an acousto-optic tunable filter (AOTF) crystal as the wavelength selecting element. In

parallel with the aforementioned development efforts we identified the need for a portable version of the AOTF spectrometer that we could test and demonstrate in a range of field locations on Earth chosen to serve as terrestrial analogs for extreme environments elsewhere in the solar system. Here we describe the development and field testing of the Portable Acousto-optic Spectrometer for Astrobiology (PASA). We demonstrated this instrument in two very different cave environments, a predominantly gypsum and calcite cave in New Mexico and an actively forming cave rich in hydrated sulfates in Tabasco, Mexico. Both of these microbially active environments contain evidence of biologic alteration of minerals, which can be detected using IR spectroscopy. We will describe the instrument operations and present some data acquired with PASA to demonstrate its efficacy as a tool for biomarker detection on planetary surfaces. This work was supported by NASA's EPSCoR program through grant number NNX12AK77A.

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214.23 – PADME (Phobos And Deimos & Mars Environment): A Proposed NASA Discovery Mission

Ever the since their discovery in 1877 by American astronomer Asaph Hall, the two moons of Mars, Phobos and Deimos, have been enigmas. Spacecraft missions have revealed irregular-shaped small bodies with different densities, morphologies, and evolutionary histories. Spectral data suggest that they might be akin to D-type asteroids, although compositional interpretations of the spectra are ambiguous. The origin of Phobos and Deimos remains unknown. There are three prevailing hypotheses for their origin: 1) They are captured asteroids, possibly primitive D-type bodies from the outer main belt or beyond; 2) They are reaccreted impact ejecta from Mars; 3) They are remnants of Mars's formation. Each one of these hypotheses has radically different and important implications regarding the evolution of the solar system, and/or the formation and evolution of planets and satellites, including the delivery of water and organics to the inner solar system.

The Phobos And Deimos & Mars Environment (PADME) mission is a proposed NASA Discovery mission that will test these hypotheses, by investigating simultaneously the internal structure of Phobos and Deimos, and the composition and dynamics of their surface and near-surface materials.

PADME would launch in 2020 and reach Mars orbit in early 2021. PADME would then begin a series of slow and increasingly close flybys of Phobos first, then of Deimos. PADME would use the proven LADEE spacecraft and mature instrument systems to enable a low-cost and low risk approach to carrying out its investigation. In addition to achieving its scientific objectives, PADME would fill strategic knowledge gaps identified by NASA's SBAG and HEOMD for planning future, more ambitious robotic landed or sample return missions to Phobos and/or Deimos, and eventual human missions to Mars Orbit.

PADME would be built, managed, and operated by NASA Ames Research Center. Partners include the SETI Institute, NASA JPL, NASA GSFC, NASA JSC, NASA KSC, LASP, Cornell U., U. of Central Florida, U. of Maryland, U. of Virginia, Lowell Observatory, Royal Observatory of Belgium, Observatoire de la Cote d'Azur, and JAXA.

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Contributing team(s): PADME Team

214.24 – Orbiters for Callisto and Titan - the Affordable Options

Low cost missions to orbit the icy satellites of outer planets are possible. Recent studies by the "A Team" at the Jet Propulsion Laboratory have investigated possible configurations and costs of Callisto and Titan orbiters. The Callisto study was done as a demonstration that a scientifically valuable icy moon orbiter could be accomplished within the current Discovery mission cost cap. A solar-powered concept was defined, whose cost was estimated to be below the cost cap, including full reserves. The mission would operate from a low circular orbit (100 km altitude); would carry a medium-resolution visible imaging camera, a laser altimeter, and a magnetometer; and would use Ka-band tracking for gravity studies. The Titan orbiter study was done as part of a set of studies focused on decreasing the costs of several different types of Titan missions. The cost estimated for the orbiter was below the most recent New Frontiers cost cap. The mission would operate from a high circular orbit (1500 km altitude) to reduce atmospheric drag and would carry a medium-resolution infrared imaging camera and a mass spectrometer. Callisto's distance from Jupiter allows a lower cost orbiter than one for Ganymede or Europa. At Callisto's distance, the radiation environment is drastically more benign, decreasing the need for electronics hardening and/or radiation shielding and its associated mass. Being further from Jupiter's gravity well decreases the fuel needed for capture into a Jupiter orbit appropriate for an eventual capture by Callisto. Finally, its lower mass allows Callisto orbit insertion with less fuel than that needed for a similar maneuver at Ganymede. Although costing for the Titan orbiter mission assumed a normal propulsive capture into Saturn orbit, the great extent of Titan's relatively benign atmosphere should make it possible to aerocapture directly into Titan orbit from interplanetary cruise, at potentially lower cost.

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214.25 – Planetary Radar with the Green Bank Telescope

The large aperture and sensitive receivers of the National Radio Astronomy Observatory's Robert C. Byrd Green Bank Telescope (GBT) make it an attractive receiving station for bistatic radar experiments. Consequently, it has been used as a receive station for radar observations since its commissioning in 2001. The GBT is equipped with receivers for all common planetary radar transmitters at P, S, and X band, as well as for future radars at up to 86 GHz. We describe the technical capabilities of the GBT and its instrumentation in terms of its tracking and RF performance, the available radar backends, and select science results obtained through the use of the GBT.

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214.26 – Satellite Communications with NRAO Green Bank Antennas

The National Radio Astronomy Observatory's Green Bank facility has several medium and large antennas that are available for satellite communications. The 100 meter Robert C. Byrd Green Bank Telescope (GBT), the largest and most sensitive antenna on site, is capable of receiving signals at frequencies as high as 86 GHz. In addition to the GBT are the fully operational 43 meter, 20 meter, and 13.7 meter antennas, and three mothballed 26 meter antennas. A transmitter could be fitted to any of these antennas for spacecraft uplinks. We discuss the characteristics of these antennas and possible operational models for future planetary science mission support.

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214.27 – The Southern Argentine Agile Meteor Radar (SAAMER)

The Southern Argentina Agile Meteor Radar (SAAMER) is a new generation system deployed in Rio Grande, Tierra del Fuego, Argentina (53 S) in May 2008. SAAMER transmits 10 times more power than regular meteor radars, and uses a newly developed transmitting array, which focuses power upward instead of the traditional single-antenna-all-sky configuration. The system is configured such that the transmitter array can also be utilized as a receiver. The new design greatly increases the sensitivity of the radar enabling the detection of large number of particles at low zenith angles. The more concentrated transmitted power enables additional meteor studies besides those typical of these systems based on the detection of specular reflections, such as routine detections of head echoes and non-specular trails, previously only possible with High Power and Large Aperture radars. In August 2010, SAAMER was upgraded to a system capable to determine meteoroid orbital parameters. This was achieved by adding two remote receiving stations approximately 10 km away from the main site in near perpendicular directions. The upgrade significantly expands the science that is achieved with this new radar enabling us to study the orbital properties of the interplanetary dust environment. Because of the unique geographical location, SAAMER allows for additional inter-hemispheric comparison with measurements from Canadian Meteor Orbit Radar, which is geographically conjugate. Initial surveys show, for example, that SAAMER observes a very strong contribution of the South Toroidal Sporadic meteor source, of which limited observational data is available. In addition, SAAMER offers similar unique capabilities for meteor showers and streams studies given the range of ecliptic latitudes that the system enables detailed study of showers at high southern latitudes (e.g July Phoenicids or Puppids complex). Finally, SAAMER is ideal for the deployment of complementary instrumentation in both, permanent and campaign, operational mode. Results from various radar meteor investigations as well as radar/optical observation campaign will be presented in this paper.

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214.28 – Status of Radiative Transfer Model (RTM) development for the Northrop Grumman Venus Atmospheric Maneuverable Platform (VAMP) Technology Development Program

In support of the Northrop Grumman/L-Garde Venus Atmospheric Maneuverable Platform (VAMP) development, we are developing a multi-purpose radiative transfer model (RTM) for the applications of the Venus atmosphere. For the solar array sizing, spectral solar radiance calculations are needed and a Correlated-k method of spectral integration will be used. This method is relatively fast computationally and typical error of the method is within a few percent, sufficiently accurate for solar array sizing analyses. For sensor characterization or sensor performance study, details of an absorption line, e.g. the near-IR “atmospheric window” absorption lines, must be used and an equivalent line-by-line calculation will be performed. At the completion of the model a large data base of radiance profiles of different atmospheric conditions will be created. The database can also be used to support thermal radiation analysis for other sub-systems. In this poster, we present our current state of the RTM development and model validation development. Additionally, we will present some preliminary comparison of top-of-atmosphere solar radiance with Venus Express

VIRTIS measurements.

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300 – Mars Atmosphere 1

300.01 – Investigating the Effects of Water Ice Cloud Radiative Forcing on the Predicted Patterns and Strength of Dust Lifting on Mars

The dust cycle is critical for the current Mars climate system because airborne dust significantly influences the thermal and dynamical structure of the atmosphere. The atmospheric dust loading varies with season and exhibits variability on a range of spatial and temporal scales. Until recently, interactive dust cycle modeling studies that include the lifting, transport, and sedimentation of radiatively active dust have not included the formation or radiative effects of water ice clouds. While the simulated patterns of dust lifting and global dust loading from these investigations of the dust cycle in isolation reproduce some characteristics of the observed dust cycle, there are also marked differences between the predictions and the observations. Water ice clouds can influence when, where, and how much dust is lifted from the surface by altering the thermal structure of the atmosphere and the character and strength of the general circulation. Using an updated version of the NASA Ames Mars Global Climate Model (GCM), we show that including water ice cloud formation and their radiative effects affect the magnitude and spatial extent of dust lifting, particularly in the northern hemisphere during the pre- and post- winter solstitial seasons. Feedbacks between dust lifting, cloud formation, circulation intensification and further dust lifting are isolated and shown to be important for improving the behavior of the simulated dust cycle.

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300.02 – Climate Change on Mars: Cloud Greenhouse Effects in the Recent Past

The large variations in Mars' orbit parameters are known to be significant drivers of climate change. We present results from an updated version of the Ames GCM that shows at times of high obliquity it is possible that water ice clouds from a greatly intensified Martian hydrological cycle may have produced a greenhouse effect strong enough to raise global mean surface temperatures by several tens of degrees Kelvin. It is made possible by the ability of the Martian atmosphere to transport water to high altitudes where cold water ice clouds form, reduce the outgoing long wave radiation, and cause surface temperatures to rise to maintain global energy balance. Since Mars spends much of its time at high obliquity, these results suggest that Mars undergoes even more significant climate change due to orbital variations than previously thought.

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300.03 – Large-Scale Weather Disturbances in Mars' Southern Extratropics: Sway of the Great Impact Basins

The character of large-scale extratropical synoptic disturbances in Mars' southern hemisphere during late winter through early spring is investigated using a high-resolution version of the NASA Ames Mars global climate model (Mars GCM). This global circulation model imposes interactively lifted (and radiatively active) dust based on a threshold value of the instantaneous surface stress. Compared to observations, the model exhibits a reasonable "dust cycle" (i.e., globally averaged, a more dusty atmosphere during southern spring and summer occurs). In contrast to their northern-hemisphere counterparts, southern synoptic-period weather disturbances and accompanying frontal waves have smaller meridional and zonal scales, and are far less intense synoptically. Influences of the zonally asymmetric (i.e., east-west varying) topography on southern large-scale weather disturbances are examined. Simulations that adapt Mars' full topography compared to simulations that utilize synthetic topographies emulating essential large-scale features of the southern middle latitudes indicate that Mars' transient barotropic/baroclinic eddies are significantly influenced by the great impact basins of this hemisphere (e.g., Argyre and Hellas). In addition, the occurrence of a southern storm zone in late winter and early spring is keyed particularly to the western hemisphere via orographic influences arising from the Tharsis highlands, and the Argyre and Hellas impact basins. Geographically localized transient-wave activity diagnostics are constructed that illuminate fundamental differences amongst such simulations and these are described.

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300.04 – Mass Balance of Mars' South Polar Residual Cap

The mass balance of the CO₂ ice south polar residual cap (SPRC) of Mars is thought to be an indicator of Mars' climate stability. Observations of eroding pits combined with year-to-year fluctuations in extent of the cap have inspired attempts to detect any changes in Mars' atmospheric pressure that might arise from loss or gain of cap CO₂ ice [1,2]. The results have been ambiguous. Attempts to use imaging to measure mass balance have been limited in scope, and yielded large negative values, -20 to -34 km³/Mars yr [3,4]. We have greatly expanded the mapping of types of features in the SPRC, their erosion rates, and detection of limitations on the vertical changes in the RSPC over the last 7 – 22 Mars yr. We find a net volume balance of -7 to +3 km³ /Mars yr (~-0.05% to +0.02% of atmospheric mass/Mars yr). Combined with the apparent relative ages of different units within the cap, the climate fluctuations over the last 20 Mars years probably are different from changes recorded in thick unit deposition probably >100 Mars yr before present. Modest changes of dust loading for extended periods of time (Mars decades) might be important in the different ice depositional regimes.

[1] Haberle, R.M., Kahre, M.A. (2010) *Int. Jour. Mars Science and Exploration* 5, 68-75. [2] Haberle, R.M. et al. (2013) AGU Fall Meeting Abstracts, A1906. [3] Malin, M.C., et al. (2001) *Science* 294, 2146-2148. [4] Blackburn, D.G., et al. (2010) *Planetary and Space Science* 58, 780-791.

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300.05 – A Multi-Year Dust Devil Vortex Survey Using an Automated Search of Pressure Time-Series

Dust devils occur in arid climates on the Earth and ubiquitously on Mars, where they likely dominate the supply of atmospheric dust and influence climate. Martian dust devils have been studied with a combination of orbiting and landed spacecraft, while most studies of terrestrial dust devils have involved manned monitoring of field sites, which can be costly both in time and personnel. As an alternative approach, we describe a multi-year in-situ survey of terrestrial dust devils using pressure loggers deployed at El Dorado Playa in Nevada, USA, a site known for dust devil activity. Analogous to previous surveys for Martian dust devils, we conduct a post-hoc analysis of the barometric data to search for putative dust devil pressure dips using a new automated detection algorithm. We investigate the completeness and false positive rates of our new algorithm and conduct several statistically robust analyses of the resulting population of dips. We also investigate seasonal, annual, and spatial variability of the putative dust devil dips, possible correlations with precipitation, and the influence of sample size on the derived population statistics. Our results suggest that large numbers of dips (> 1,000) collected over multiple seasons are probably required for accurate assessment of the underlying dust devil population. Correlating long-term barometric time-series with other data streams (e.g., solar flux measurements from photovoltaic cells) can uniquely elucidate the natures and origins of dust devils, and accurately assessing their influence requires consideration of the full distribution of dust devil properties, rather than average values. For example, our results suggest the dust flux from the average terrestrial devil is nearly 1,000 times smaller than the (more representative) population-weighted average flux. If applicable to Martian dust devils, such corrections may help resolve purported discrepancies between the dust fluxes estimated from dust devil studies and those required to maintain the atmospheric dust concentration.

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300.06 – Investigating Dust-less Devils at Gale Crater

Understanding the frequency of and conditions that facilitate dust devil activity on Mars are key questions in determining whether convective vortices that lift dust are the main contributors to background dust opacity. Using pressure data from the Rover Environmental Monitoring Station (REMS) in Gale Crater, we detect approximately 200 convective vortices during the first 583 sols of the Mars Science Lab (MSL) mission. Most of these events do not have corresponding decreases in UV flux, which suggests that they are mainly dustless. Pressure drop magnitudes for the detections range from 0.31 – 2.86 pascals and 0.037 – 0.330% of ambient pressure. A rough approximation of the pressure drop required to lift dust can be made by assuming the vortices are in cyclostrophic balance (Sinclair, *J. Atmos. Sci.* 30, 1599, 1973) and that the tangential wind velocity threshold for particle lifting on Mars is between 12 and 40 m/s depending on particle size (Greeley et al., *JGR* 108, 5041, 2003). We estimate that under the right meteorological conditions at Gale Crater, the very smallest pressure drop that could lift particles is around ~2 pascals, suggesting that the majority of our detections are not strong enough for significant lifting. Further investigation of the local climate and drivers of convection within Gale Crater could explain why these vortices are relatively dustless and weak in magnitude.

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300.07 – Martian Dust Aerosol Size and Shape as Constrained by Phoenix Lander Polarimetry

Dust aerosol morphology is important to dust transport and the radiative heating of the Martian atmosphere. Previous analyses of Mars dust have shown that spherical particles are a bad analog for the dust, in terms of reproducing the distribution of scattered light. Parameterized scattering, based on laboratory observations of scattering by irregular dust particles, has been used for Viking, Pathfinder and Mars Exploration Rover data [Pollack et al., J. Geophys. Res. 100, 1995; Tomasko et al., J. Geophys. Res. 104, 1999; Lemmon et al., Science 306, 2004]. Analytical calculations have shown that cylinders are a better scattering analog than spheres [Wolff et al., J. Geophys. Res. 114, 2009]. Terrestrial studies have shown that a diverse assortment of triaxial ellipsoids is a good analog for dust aerosol [Bi et al., Applied Optics 48, 2009].

The Phoenix Lander operated in the Martian arctic for 5 months of 2008, around the northern summer solstice. During the mission atmospheric optical depth was tracked through direct solar imaging by the Surface Stereo Imager (SSI). For solar longitude (Ls) 78-95 and 140-149, small dust storms dominated the weather. Low-dust conditions (optical depths <0.4) dominated during Ls 95-140, with sporadic ice clouds becoming more common after Ls 108. The SSI also obtained occasional cross-sky photometric data through several filters from 440 to 1000 nm and cross-sky polarimetry at 750 nm wavelength. Radiative transfer models of the sky radiance distribution are consistent with dust aerosols in the same 1.3-1.6 micron range reported for models of observations from previous missions. Cylinders, triaxial ellipsoids, and the parametric model can fit sky radiances; spheres cannot. The observed linear polarization, which reached 4-5% and had a similar angular distribution to Rayleigh polarization, is similar to the triaxial ellipsoid model, but not spheres or cylinders. An extension to the parametric model using 7-10% Rayleigh scattering mixed with unpolarized scattering is also an adequate model.

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300.08 – A Mars Dust Model with Interactive Dynamics, Radiation, and Microphysics

Variability of the present day Martian climate is dominated by globally enveloping dust storms that recur with a frequency of approximately three years. Small-scale aeolian processes predictably generate local seasonal storms. However, factors that enhance local storm strength and grow local phenomenon to global scales are poorly understood. Research with Martian general circulation models (GCM) has recently demonstrated a strong correlation between dust storm generation, strength and long-term stability and the global distribution of dust reservoirs and their temporal permanence. Here we present results from the NCAR Mars Community Atmosphere Model (CAM) coupled with a fully interactive dust microphysics scheme. Dust devil lifting and saltation wind driven lifting are parameterized in the emission scheme. Mass is distributed into 20 size bins with a radius range of 0.1 to 8 microns. The initial radial size distribution is log-normal with a sigma value of 1.5. Dust is allowed to advect horizontally and is removed from the atmosphere by dry deposition. Dust also impacts the radiative heating rate, as do water clouds. The large number of dust bins allows for the opportunity to track the size distribution of dust deposits and investigate the long term stability of dust source regions as a function of particle size.

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300.09 – Detached Dust Layers in Regional and Global Dust Events on Mars

Throughout much of the year in Mars's tropics, the vertical distribution of dust has a local maximum in mass mixing ratio significantly above the inferred height of the planetary boundary layer: a feature known as a "detached dust layer." Detached dust layering also has been observed in the extratropics.

Modeling shows that dust-heated convective plumes within dust storms can rapidly transport dust vertically to altitudes of 40 km or more. These "rocket dust storm" plumes minimally mix with the surrounding environment, resulting in detached dust layers. Visible image climatology of dust storm activity argue against the "rocket dust storm" mechanism being dominant in northern spring and summer, when detached dust layer formation is common but tropical dust storm activity is rare.

Some detached dust layers undoubtedly form by the "rocket dust storm" mechanism, such as those during regional and global dust events, which reach altitudes of 45-75 km above the MOLA datum and have mass mixing ratios of 40-260 ppm, equivalent to well-mixed visible column opacities of 3.6-23. These layers are not just a phenomenological curiosity. The plumes that generate them could play a role in dust storm development analogous to convection in tropical cyclone activity on Earth: "the dusty hurricane" analogy.

Here I report on detached dust layers from one global dust event and five regional dust events observed by the Mars Climate Sounder on board Mars Reconnaissance Orbiter. I examine the history of detached dust layer activity during the dust events in the context of possible limb observations of deep convection as well as visible imaging of dust lifting activity.

Global dust events are associated with detached dust layers that are thicker and/or reach higher altitudes than in regional dust events. However, detached dust layers in these dust events do not originate from the tropics alone or have

a simple relationship with dust lifting activity, arguing against strong analogy with tropical cyclones. This work is supported by NASA's Mars Data Analysis Program, NNX14AM32G to Hampton University.

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301 – Exoplanet Theories and Predictions

301.01 – The Role of Hydrogen in Determining the Stability of CO₂ Atmospheres of Terrestrial Exoplanets Around M Dwarfs

The recent discovery of terrestrial worlds in the Habitable Zones of M Dwarfs necessitates a more intensive investigation of the properties of these planets. One major feature of certain M Dwarfs is their high fluxes of EUV radiation, which photolyzes CO₂, an important greenhouse gas that should be abundant on rocky worlds. This photolytic destruction of CO₂ can be countered by HO_x chemistry: photolysis of HO_x species by NUV radiation generates OH, which reacts with CO to regenerate CO₂. These processes are balanced around Sun-like stars such that Venus and Mars can maintain CO₂-dominated atmospheres. However, M Dwarfs tend to have much lower NUV/EUV flux ratios, which could prevent the formation of significant CO₂ atmospheres on any planets they may host. In this study, we evaluate the properties of CO₂ atmospheres surrounding an Earth-massed, Earth-sized exoplanet in orbit of an M Dwarf using a 1D photochemical kinetics model. We consider an atmosphere similar in composition to that of Mars, but scaled to have a surface pressure of 1 bar. We choose to focus on Mars-like atmospheres rather than Earth-like ones, as Earth's atmosphere has been altered through biological sources and sinks and the presence of a large liquid water ocean, which are not necessarily present on terrestrial exoplanets. Our preliminary results show that the hydrogen content of the atmosphere is crucial in determining the ratio of CO₂ to CO and O₂. In particular, for a H₂ mixing ratio identical to that of Mars (~20-30 ppm), a steady state atmosphere is reached after 10 Gyr consisting of ~85% CO₂, ~10% CO, and ~5% O₂, with an ozone mixing ratio of ~0.01 ppm. In the extreme case where all hydrogen is lost to space, an atmosphere consisting of ~64% CO₂, ~24% CO, and 12% O₂ results, while ozone levels reach ~10 ppm. Finally, for H₂ mixing ratios similar to that of Earth (~0.5 ppm) and no atmospheric escape, a 49% CO₂, 34% CO, 17% O₂, and 0.1 ppm O₃ atmosphere is possible. This not only points to the potential prevalence of abiotic O₂ and O₃ in M Dwarf exoplanet atmospheres, but also that hydrogen species, including H₂O, are essential in determining the global atmospheric makeup of these planets despite their relatively low concentrations.

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301.02 – Jupiter-like planets as dynamical barriers to inward-migrating super-Earths: a new understanding of the origin of Uranus and Neptune and predictions for extrasolar planetary systems

Planets of 1-4 times Earth's size on orbits shorter than 100 days exist around 30-50% of all Sun-like stars. These "hot super-Earths" (or "mini-Neptunes"), or their building blocks, might have formed on wider orbits and migrated inward due to interactions with the gaseous protoplanetary disk. The Solar System is statistically unusual in its lack of hot super-Earths. Here, we use a suite of dynamical simulations to show that gas-giant planets act as barriers to the inward migration of super-Earths initially placed on more distant orbits. Jupiter's early formation may have prevented Uranus and Neptune (and perhaps Saturn's core) from becoming hot super-Earths. It may actually have been crucial to the very formation of Uranus and Neptune. In fact, the large spin obliquities of these two planets argue that they experienced a stage of giant impacts from multi-Earth mass planetary embryos. We show that the dynamical barrier offered by Jupiter favors the mutual accretion of multiple migrating planetary embryos, favoring the formation of a few massive objects like Uranus and Neptune. Our model predicts that the populations of hot super-Earth systems and Jupiter-like planets should be anti-correlated: gas giants (especially if they form early) should be rare in systems with many hot super-Earths. Testing this prediction will constitute a crucial assessment of the validity of the migration hypothesis for the origin of close-in super-Earths.

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301.03D – Hot Jupiters from Coplanar High-eccentricity Migration

The question of what mechanism is responsible for delivering giant planets into short-periods orbits (<10 days), the so-called hot Jupiters (HJs), is one of the fundamental unresolved questions in planet formation. In this talk, I propose that most HJs are formed through the secular interaction of two planets in eccentric and nearly coplanar orbits and tidal dissipation due to the host star, mechanism which I term coplanar high-eccentricity migration (CHEM). I will show that the HJs formed by CHEM can well-reproduce the observed period distribution, as well as explain why most HJs have low stellar obliquities. I further provide with testable predictions regarding the properties (e.g., masses and orbital periods)

of the outer perturber and formation timescales in HJ systems.

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301.04 – Influence of Tidal Heating on the Internal and Orbital Evolution of Rocky Exoplanets

The thermal and magnetic evolution of terrestrial planets influences surface tectonics, outgassing rates, atmospheric composition, and magnetic shielding, all of which are important habitability factors. We model the influence of internal heating, generated by radioactive decay and tidal dissipation, and heat loss by melting on the thermal and magnetic histories of Earth-like exoplanets. Efficient heat transport can cool the core fast enough to drive thermal convection by a superadiabatic heat flow, compositional convection associated with the crystallization of the inner core, or both. Tidal dissipation drives orbital migration, which in turn influences the tidal heating rate. We couple thermal, magnetic, and orbital evolution models to explore how these feedbacks influence planetary habitability. We focus here on the habitable zone around M-stars where tidal heating is likely important and tidal locking is expected.

We identify habitability regimes where mantle cooling is efficient enough to maintain an Earth-like core dynamo and moderate volatile degassing rates, and regimes where the planet is not habitable due to either (i) a long lived magma ocean, (ii) a runaway greenhouse associated with rapid outgassing, or (iii) no magnetic field due to the suppression of convection in the core. The composition and surface tectonics of terrestrial exoplanets is unknown, but future observations of atmospheric composition and magnetic field cyclotron emissions can test these predictions.

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301.05 – Obliquity Evolution of an Early Venus

Stark differences in both atmospheric mass and rotation are apparent between the present-day Earth and neighboring Venus. These planets may have been more similar 4 Gyr ago when most of the carbon within Venus may have been in solid form, implying a low-mass atmosphere. As a result, Venus's rotation rate could have been much faster than at present due to the smaller cumulative effects of solid-body and atmospheric tides. We investigate how the obliquity of a hypothetical rapidly-rotating Early Venus would have evolved as compared to a Moonless Earth. As with our previous investigation [Lissauer, Barnes, & Chambers 2012], slow prograde rotation of our hypothesized Early Venus generally leads to larger variations in obliquity than does retrograde rotation. However, the variability of obliquity for retrograde rotations differs from the Moonless Earth and can change with the initial spin period. The implications for early habitability of extrasolar Venus analogs will also be discussed.

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301.06 – Optimal Planet Properties For Plate Tectonics Through Time And Space

Both the time and the location of planet formation shape a rocky planet's mass, interior composition and structure, and hence also its tectonic mode. The tectonic mode of a planet can vary between two end-member solutions, plate tectonics and stagnant lid convection, and does significantly impact outgassing and biogeochemical cycles on any rocky planet. Therefore, estimating how the tectonic mode of a planet is affected by a planet's age, mass, structure, and composition is a major step towards understanding habitability of exoplanets and geophysical false positives to biosignature gases.

We connect geophysics to astronomy in order to understand how we could identify and where we could find planet candidates with optimal conditions for plate tectonics. To achieve this goal, we use thermal evolution models, account for the current wide range of uncertainties, and simulate various alien planets. Based on our best model estimates, we predict that the ideal targets for plate tectonics are oxygen-dominated ($C/O < 1$) (solar system like) rocky planets of ~ 1 Earth mass with surface oceans, large metallic cores (\sim super-Mercury, rocky body densities of $\sim 7000 \text{ kg m}^{-3}$), and with small mantle concentrations of iron ($\sim 0\%$), water ($\sim 0\%$), and radiogenic isotopes (~ 10 times less than Earth). Super-Earths, undifferentiated planets, and especially hypothetical carbon planets, speculated to consist of SiC and C, are not optimal for the occurrence of plate tectonics.

These results put Earth close to an ideal compositional and structural configuration for plate tectonics. Moreover, the results indicate that plate tectonics might have never existed on planets formed soon after the Big Bang—but instead is favored on planets formed from an evolved interstellar medium enriched in iron but depleted in silicon, oxygen, and especially in Th, K, and U relative to iron. This possibly sets a belated Galactic start for complex Earth-like surface life if plate tectonics significantly impacts the build up and regulation of gases relevant for life.

This allows for the first time to discuss the tectonic mode of a rocky planet from a practical astrophysical perspective.

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301.07 – Groupies and Loners: The Population of Multi-planet Systems

Observational surveys with *Kepler* and other telescopes have shown that multi-planet systems are very numerous. Considering the secular dynamics of multi-planet systems provides substantial insight into the interactions between planets in those systems. Since the underlying secular structure of a multi-planet system (the secular eigenmodes) can be calculated using only the planets' masses and semi-major axes, one can elucidate the eccentricity and inclination behavior of planets in those systems even without knowing the planets' current eccentricities and inclinations. We have calculated both the eccentricity and inclination secular eigenmodes for the population of known multi-planet systems whose planets have well determined masses and periods. We will discuss the commonality of dynamically grouped planets ('groupies') vs dynamically uncoupled planets ('loners'), and compare to what would be expected from randomly generated systems with the same overall distribution of masses and semi-major axes. We will also discuss the occurrence of planets that strongly influence the behavior of other planets without being influenced by those others ('overlords'). Examples will be given and general trends will be discussed.

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301.08 – Kepler Circumbinary Planet KIC 9632895b: Implications of Planet's Orbital Inclination for its Origin and Formation

To date, there are eight published transiting circumbinary planets (CBPs) discovered by the Kepler space telescope. The transiting nature of these objects unambiguously confirms their presence as the third orbiting body. The detection of multiple transits in these systems points to the co-planarity of the planet-binary orbits. However, due to dynamical interactions, the orbit of a transiting CBP may develop slight inclination and the planet may not always transit. The planet KIC 9632895b is one of such CBPs. The photodynamical models predict the inclinations of the planet and binary oscillate with a period of approximately 100 years. In this rocking back and forth, the orbital inclination of the planet varies by a few degrees causing the planet to be outside the transit-visible window for more than about 90% of the times. An interesting implication of this finding is that because of the limitations in the duration of observations, for every CBP system that transits (similar to KIC 9632895), there are approximately 12 similar systems that do not transit (therefore, we do not see them). This occasional transit phenomenon has immediate implications for the formation, dynamical evolution, and population of CBPs. Combined with the fact that the majority of the currently known CBPs are close to the boundary of orbital stability, this suggests that, similar to planet formation around single stars, CBPs form in multiples and at large distances in the circumbinary disk. These planets may migrate through their interactions with the disk, and may be scattered into inclined orbits via planet-planet scattering. The fact that such CBPs transit their host binaries for only a certain amount of time strongly implies that many more CBPs may exist in each of these systems. I will discuss the KIC 9632895 system in detail with emphasis on the models of the formation, migration, and dynamical evolution of planets around binary stars.

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301.09 – Small, numerous and close-in: How occurrence rates of planets around lower-mass stars can constrain planet formation mechanisms.

The Kepler Space Telescope has observed stars from spectral type M to F, and differences in the distribution of planets between these types hold vital clues for unraveling the planet formation process. We present planet occurrence rates as a function of spectral type for planets of different sizes and orbital periods. We find that the distributions are significantly different: Occurrence rates increase towards lower-mass stars, the planet population is truncated at different distances from the star for different spectral types, and planets around smaller stars are systematically smaller.

These trends with stellar mass are linked to protoplanetary disk properties: The planet truncation radius matches the gas disk co-rotation radius, while smaller planets form in less massive disks around lower-mass stars. These results favor a hybrid formation and migration scenario where planetary building blocks migrate towards the disk inner edge and form planets that still reflect the initial disk mass.

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302 – Venus

302.01 – HST/STIS Observations of Venus' Dayside Atmosphere, from morning to noon

170-310 nm, high spectral (0.3 nm) and spatial (40-60 km/pixel) resolution observations of Venus' low latitude dayside atmosphere were obtained using Hubble's Space Telescope Imaging Spectrograph (HST/STIS), in order to measure the SO and SO₂ gas column density on Venus' morning quadrant between 20N and 40S latitude at an altitude of $\sim 75 \pm 2$ km, on three dates between late December 2010 and February 2011. These data provide the first direct and simultaneous measure of the SO and SO₂ gas column density variability within Venus' mesosphere as a function of both latitude and time of day. Our analysis indicates the cloud top gas densities vary strongly with latitude. On two of the 3 days of observing the gas densities are observed to peak at the equator, while the opposite trend is observed on the remaining date. On all dates, independent of the slope of the latitudinal gradient, a factor of $\sim 1.7 \pm 0.5$ enhancement in the SO₂ gas density near the terminator (i.e., at SZA $\sim 65 \pm 5^\circ$) is observed relative to the gas density detected at an equivalent latitude but smaller SZA. Using contemporaneously obtained Venus Express Monitoring Camera images, the significance of the HST inferred SO₂ and SO gas density latitudinal variability relative to the observed cloud top characteristics will be discussed. Likewise, how the HST results relate to the near terminator and average dayside the SO₂ and SO vertical volume mixing ratio (VMR) profiles inferred, respectively, from contemporaneously obtained Venus Express (VEx) Solar Occultation in the Infrared and sub-mm ground-based observations of Venus's dayside atmosphere will be discussed. Lastly, the significance of the HST results relative to SPICAV observations obtained throughout the lifetime of the VEx mission will be summarized. E.g., the average dayside SO₂ VMR inferred from the HST data is in the range of 42 ± 36 ppb, matching the average dayside VMR range derived from the SPICAV-UV data obtained during the entirety of 2011 (Jessup et al. 2014). These results suggest that HST data can be used to accurately document Venus' average dayside behavior within a single year, and may be used to monitor the average SO₂ gas density cloud top variance on a multi-year basis.

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302.02 – Photochemical Control of the Distribution of Venusian Water and Comparison to Venus Express SOIR Observations

We use the JPL/Caltech 1-D KINETICS photochemical model to solve the continuity diffusion equation for the atmospheric constituent abundances and total number density as a function of radial distance from the planet Venus. The photochemistry of the Venus atmosphere from 58 to 112 km is modeled using an updated and expanded chemical scheme (Zhang et al., 2010; 2012), guided by the results of recent observations. We mainly follow Zhang et al. (2010; 2012) to guide our choice of boundary conditions for 40 species. We fit the SOIR Venus Express results of 1 ppm at 70-90 km (Berteaux et al (2007) by modeling water from between 10 – 35 ppm at our 58 km lower boundary and using an SO₂ mixing ratio of 25 ppm as our nominal reference value. We then vary the SO₂ mixing ratio at the lower boundary between 5 and 75 ppm and find that it can control the water distribution at higher altitudes.

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302.03 – Laboratory Measurements of the Millimeter-Wavelength Sulfur Dioxide Absorption Spectrum under Simulated Venus Conditions

Over 130 laboratory measurements of the 2-4 millimeter wavelength opacity of sulfur dioxide in a carbon dioxide atmosphere under simulated conditions for the upper Venus troposphere (temperatures between 308-343 K and pressures between 0.03- 2 bar) have been made. These measurements along with the centimeter wavelength measurements by Steffes et al. (*Icarus*, 2014, in press) have been used to empirically assess existing formalisms for sulfur dioxide opacity in a carbon dioxide atmosphere (Fahd and Steffes *Icarus* **97**, 1992 and Suleiman et al. *JGR* **101**, E2 1996). The Van Vleck and Weisskopf Model (VWV) used by Fahd and Steffes with the JPL rotational line catalog (Pickett, et al. *JQSRT* **60**, 1998) was found to fit 85.88% of all 500 measurements within the 2-sigma uncertainty. This model was implemented in the new Georgia Tech Venus Radiative Transfer Model (GT-VRTM) which is capable of computing both disk-averaged and localized brightness temperatures of Venus. These are compared to observations. This work will improve retrievals of the atmospheric abundance of sulfur dioxide from observations of the Venus atmosphere.

This work was supported by the NASA Planetary Atmospheres Program under Grant NNX11AD66G.

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302.04 – Venus upper clouds and the UV-absorber from MESSENGER/MASCS observations

In June 2007, the MESSENGER spacecraft performed its second Venus flyby on its route to Mercury. The spacecraft's MASCS instrument (VIRS channel) acquired numerous spectra of the sunlight reflected from the equatorial region of the planet at wavelengths from the near ultraviolet (300nm) to the near infrared (1450 nm). In this work we present an analysis of the data and their spectral and spatial variability following the mission footprint on the Venus disk. In order to reproduce the observed reflectivity and obtain information on the upper clouds and the unknown UV absorber, we use the NEMESIS retrieval code, including SO₂, CO₂ and H₂O absorption together with absorption and scattering by mode-1, -2 and -3 cloud particles. This spectral range provides sensitivity to the uppermost cloud levels, above 60 km. Vertical profiles of the mode-1 and mode-2 particles have been retrieved along the equatorial region of Venus, with average retrieved sounding levels of 70 +/- 2 km at 1 micron, in good agreement with previous investigations. This spectral range is also very interesting because of the existence of a mysterious absorber in the blue and UV side of the reflected spectra, whose origin remains as one of the key questions about the Venus atmosphere. Here we report a comparison with some of the previously proposed absorbers: (1) sulfur-related compounds (amorphous and liquid sulfur, S₃, S₄, S₈, S₂O); (2) chlorine related species (Cl₂, FeCl₃); (3) organics (C₃O₂, Croconic acid). Preliminary results show that the first group provides better fits to the data, although combinations of the proposed agents might be required in order to produce better results. Acknowledgements: This work was supported by the Spanish MICIIN projects AYA2009-10701, AYA2012-38897-C02-01, and AYA2012-36666 with FEDER support, PRICIT-S2009/ESP-1496, Grupos Gobierno Vasco IT765-13, and UPV/EHU UFI11/55. S.P.-H. acknowledges support from the Jose Castillejo Program funded by Ministerio de Educación, Cultura y Deporte, Programa Nacional de Movilidad de Recursos Humanos del Plan Nacional de I-D+i 2008-2011.

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302.05 – Venus's Mysterious Oxygen Green Line: An Auroral Process?

Observations of nightglow (upper atmospheric emission from atoms and molecules on the nightside of a planet) allow for a multifaceted study of planetary atmospheres. Information on winds, chemistry, and solar effects is gained by observing temporal and spacial variation in nightglow intensity. One of the brightest nightglow features on Earth is the OI (1S) 557.7 nm line (oxygen green line). This emission is primarily due to photodissociation/transport but is also seen in the aurora as electron precipitation.

Unlike Earth, the Venusian green line is highly temporally variable. The chemistry and mechanisms responsible are still unknown. We observe the Venusian nightglow before and after solar flares, which produce large amounts of EUV emission, and coronal mass ejections (CMEs) impacts, which inject a large number of higher energy charged particles in the the Venusian atmosphere. We consistently detect green line emission after large charged particles injections from CMEs. However we do not detect

the OI (1D) red line at 630.0 nm, which is quenched below 150 km. We propose that the Venusian green line is an auroral-type emission due to electron precipitation and is occurring deep in the atmosphere, near 125 km.

To investigate how CMEs and solar flares effect the electron energy, flux, and density in the Venusian nightside atmosphere, we compare data taken by ASPERA and ELS onboard Venus Express (VEX) before and after solar storms.

We find that both electron energy and flux increase after CMEs, but only flux increases after solar flares. Additionally, the V1 ionospheric layer at 125 km increases in electron density while the V2 at 150 km decreases in density after CMEs but not after solar flares. We model the nightside Venusian ionosphere using the observed electron energy and fluxes from VEX in an effort to constrain the chemical processes and mechanisms responsible for green line emission. We will present the results of our ground-based observations and modeling.

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302.06 – Venus' thermospheric temperature field using a refraction model at terminator : comparison with 2012 transit observations using SDO/HMI, VEx/SPICAV/SOIR and NSO/DST/FIRS

The transit of Venus in June 2012 provided a unique case study of the Venus' atmosphere transiting in front of the Sun, while at the same time ESA's Venus Express orbiter observed the evening terminator at solar ingress and solar egress.

We report on mesospheric temperature at Venus' morning terminator using SDO/HMI aureole photometry and comparison with Venus Express. Close to ingress and egress phases, we have shown that the aureole photometry reflects the local density scale height and the altitude of the refracting layer (Tanga et al. 2012). The lightcurve of each spatially resolved aureole element is fit to a two-parameter model to constrain the meridional temperature gradient at terminator. Our measurements are in agreement with the VEx/SOIR temperatures obtained during orbit 2238 at evening terminator during solar ingress (46.75N - LST = 6.075PM) and solar egress (31.30N - LST = 6.047PM) captured from the Venus Express orbiter at the time Venus transited the Sun.

We also performed spectroscopy and polarimetry during the transit of Venus focusing on extracting signatures of CO₂ absorption. Observations were taken during the first half of the transit using the Facility InfraRed Spectropolarimeter (FIRS) on the Dunn Solar Telescope (DST). Although the predicted CO₂ transmission spectrum of Venus was not particularly strong at 1565 nm, this region of the H-band often used in magnetic field studies of the Sun's photosphere provides a particularly flat solar continuum with few atmospheric lines. Sun-subtracted Venus limb observations show intensity distribution of vibrational CO₂ bands 2v₁+2v₂+v₃ at 1.571 μ m and 141 v₁+4v₂+v₃ at 1.606 μ m.

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Contributing team(s): The EuroVenus consortium

302.07 – Thermal structure at the Venus terminator: Comparison of SOIR/Vex profiles with a radiative transfer model

The wavelength range probed by the SOIR instrument on board Venus Express - 2.2 to 4.3 μ m - allows a detailed chemical inventory of the Venus atmosphere [Bertaux et al., 2006; Vandaele et al., 2007]. The measurements all occur at the Venus terminator, on both the morning and evening sides, covering all latitudes from the North Pole to the South Pole. In particular CO₂ number density vertical profiles are obtained from 70 to 160 km. Temperature profiles are deduced from the CO₂ density profiles, using two different and independent techniques. The first one considers the hydrostatic law applied on the retrieved CO₂ density profiles, assuming a CO₂ mixing ratio vertical profile [Mahieux et al., 2010; 2012; 2014a]. The second one uses the ro-vibrational structure of the CO₂ lines [Mahieux et al., 2014b]. Results of both methods are in agreement within their error bars; the uncertainties are larger with the ro-vibrational method.

These temperature measurements show a striking permanent temperature minimum (at 125 km) and a weaker temperature maximum (over 100-115 km). The time variability of the CO₂ density profiles spans over two orders of magnitude, and a clear trend is seen with latitude. The temperature variations are also important, up to 80 K for a given pressure level, but the latitude variation are small [Mahieux et al., 2014a].

A 1D radiative transfer model has been developed to reproduce the SOIR terminator profiles, derived from the Mars thermosphere code used to simulate the atmospheric effects of Siding Springs coma on Mars atmosphere [Yelle et al., 2014]. This model has been improved to better account for the CO₂ and CO radiative heating and cooling processes which have to be considered in the dense atmosphere of Venus. Atmospheric diffusion of CO₂, CO and O is also considered. The preliminary results of the model and its comparison with the SOIR observations will be presented and discussed.

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302.08 – Three-dimensional thermal structure of the South Polar Vortex of Venus

We have analyzed thermal infrared images provided by the VIRTIS-M instrument aboard Venus Express (VEX) to obtain high resolution thermal maps of the Venus south polar region between 55 and 85 km altitudes. The maps investigate three different dynamical configurations of the polar vortex including its classical dipolar shape, a regularly oval shape and a transition shape between the different configurations of the vortex. We apply the atmospheric model described

by García Muñoz et al. (2013) and a variant of the retrieval algorithm detailed in Grassi et al. (2008) to obtain maps of temperature over the Venus south polar region in the quoted altitude range. These maps are discussed in terms of cloud motions and relative vorticity distribution obtained previously (Garate-Lopez et al. 2013). Temperature maps retrieved at 55 – 63 km show the same structures that are observed in the $\sim 5 \mu\text{m}$ radiance images. This altitude range coincides with the optimal expected values of the cloud top altitude at polar latitudes and magnitudes derived from the analysis of $\sim 5 \mu\text{m}$ images are measured at this altitude range. We also study the imprint of the vortex on the thermal field above the cloud level which extends up to 80 km. From the temperature maps, we also study the vertical stability of different atmospheric layers. The cold collar is clearly the most statically stable structure at polar latitudes, while the vortex and subpolar latitudes show lower stability values. Furthermore, the hot filaments present within the vortex at 55-63 km exhibit lower values of static stability than their immediate surroundings.

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Grassi, D. et al. *J. Geophys. Res.* 113, 1–12 (2008).

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302.09 – Results of the Venus Express Aerobraking Campaign

After a very successful mission orbiting Venus for more than 8 years, slowly the fuel is running out and the spacecraft will inevitably one day end up in the hot and acid atmosphere of the planet. Being near the end of the mission and in a position to accept some risk to the spacecraft we decided to take the opportunity to dip down deep into the atmosphere, to around 130 km, in a controlled manner, in order to make detailed in situ investigations of this for remote sensing instruments difficult to access region. The on board accelerometers gave direct measurements of the deceleration which in turn is directly proportional to the local atmospheric density. This provided an excellent way to study both the total density profile throughout the orbital arc in the atmosphere and small scale density variations in the region of the pericentre. The spacecraft behaved perfectly well throughout the whole campaign and provided a wealth of data both on the atmosphere and on the response of the spacecraft to the harsh environment with strong heat loads and some dynamic stress. At the time of the campaign the pericentre was located near the terminator at about 75 degrees Northern latitude. Aerobraking is a very efficient method of reducing the pericentre velocity and thereby reducing the apocentre altitude and the orbital period.

The so called "walk-in" phase started at an altitude of 190 km on 17 May and the campaign ended on 11 July, after having reached a lowest altitude of 129.2 km. Subsequently, a series of orbit control manoeuvres lifted up the pericentre to 460 km altitude and the science activities were resumed after a thorough check-out of the spacecraft. We have detected a highly variable atmosphere, both on a day to day basis and within the individual pericentre passes. The duration of each pass was approximately 100 s and the maximum dynamic pressure achieved was more than 0.75 N/m², probably a record for a spacecraft that continued its operation afterwards. The orbital period was reduced over the duration of the campaign changing from 24 hours to 22 hours 20 minutes.

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303 – Mars Atmosphere 2

303.01 – The Expected and the Unexpected: Seasonal Variation of Major and Minor Species in the Mars Atmosphere as Measured In Situ by *Curiosity*

The Sample Analysis at Mars (SAM) instrument on *Curiosity* has conducted a survey of major (CO₂) and minor (Ar, N₂, O₂) components of the Mars atmosphere over the course of a martian year in Gale Crater. Here we present the volume mixing ratios of these atmospheric species, which have been monitored as a function of season, temperature, and pressure, in conjunction with meteorological measurements conducted by the Mars Science Laboratory (MSL) rover environmental monitoring station (REMS). We will present data on the partial pressure and relative mixing ratio of CO₂, which shows a distinct trend with season as a result of transport to, and deposition at, the poles, coinciding with changes in local atmospheric pressure. This is the first comprehensive measurement of composition bridging several seasons that can link the pressure variation to changes in specific atmospheric mixing ratios. We will present results on

the $^{40}\text{Ar}/\text{N}_2$ ratio, which has remained constant throughout the year, as expected for non-condensable species. The measured ratio of $^{40}\text{Ar}/^{14}\text{N} \sim 0.5$ is significantly greater than that measured by the Viking Landers (VL), which were reported as $\text{Ar}/\text{N} = 0.3$ from the VL2 mass spectrometer and $\text{Ar}/\text{N} = 0.34$ from the gas chromatograph experiments. Finally, we will present data that shows a substantial variation in O_2 , relative to CO_2 and Ar, throughout the year. O_2 is thought to have a long photochemical lifetime, greater than 10 Mars years, and thus is expected to show a seasonal behavior identical to the other non-condensable inert gases such as Ar and N_2 . The SAM measurements of O_2/Ar , combined with frequent O_2 mixing ratio determinations via ChemCam Passive Sky Spectroscopy, show a clear decrease during the $\text{Ls} = 350^\circ$ to $\text{Ls} = 30^\circ$ period, and then a near-doubling of the mixing ratio during the $\text{Ls} = 50^\circ$ to $\text{Ls} = 130^\circ$ period. Possible mechanisms for the observed O_2 variation will be discussed.

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Contributing team(s): MSL Team

303.02 – Carbon Reservoir History of Mars Constrained by Atmospheric Isotope Signatures

The evolution of the atmosphere on Mars is one of the most intriguing problems in the exploration of the Solar System, and the climate of Mars may have evolved from a warmer, wetter early state to the cold, dry current state. Because CO_2 is the major constituent of Mars's atmosphere, its isotopic signatures offer a unique window to trace the evolution of climate on Mars. Here we use a box model to trace the evolution of the carbon reservoir and its iso-topic signature on Mars, with carbonate deposition and atmospheric escape as the two sinks and magmatic activity as the sole source. We derive new quantitative constraints on the amount of carbonate deposition and the atmospheric pressure of Mars through time, extending into the Noachian, ~ 3.8 Gyr before present. This determination is based on recent Mars Science Laboratory (MSL) isotopic measurements of Mars's atmosphere, recent orbiter, lander, and rover measurements of Mars's surface, and a newly identified mechanism (photodissociation of CO) that efficiently enriches the heavy carbon isotope. In particular, we find that escape via CO photodissociation on Mars has a fractionation factor of 0.6 and hence, photochemical escape processes can effectively enrich ^{13}C in the Mars's atmosphere during the Amazonian. As a result, modest carbonate deposition must have occurred early in Mars's history to compensate the enrichment effects of photochemical processes and also sputtering, even when volcanic outgassing up to 200 mbar occurred during the Hesperian. For a photochemical escape flux that scales as the square of the solar EUV flux or more, at least 0.1 bar of CO_2 must have been deposited as carbonates in the Noachian and Hesperian. More carbonate deposition would be required if carbonate deposition only occurred in the Noachian or with low fractionation factors.

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303.03 – Daily Variation of Isotope Ratios in Mars Atmospheric Carbon Dioxide

The atmosphere of Mars has been shown by ground based high-resolution infrared spectroscopy and in situ measurements with the Phoenix lander and Mars Science Laboratory Curiosity rover to be enriched in C and O heavy isotopes, consistent with preferential loss of light isotopes in eroding Mars' primordial atmosphere. The relative abundance of heavy isotopes, combined with contemporary measurements of loss rates to be obtained with MAVEN, will enable estimating the primordial atmospheric inventory on Mars. IR spectroscopy of Mars collected in May 2012 as well as in March and May of 2014 from the NASA IRTF has resolved transitions of all three singly-substituted minor isotopologues of carbon dioxide in addition to the normal isotope, enabling remote measurements of all the carbon and oxygen isotope ratios as a function of latitude, longitude, and time of day. Earlier measurements obtained in October 2007 demonstrated that the relative abundance of O-18 increased linearly with increasing surface temperature over a relatively warm early-afternoon temperature range, but did not extend far enough to inspect the effect of late-afternoon cooling. These results imply that isotopically enriched gas is sequestered overnight when surface temperature is minimum and desorbs through the course of the day as temperature increases. Current spectroscopic constants indicate that the peak isotopic enrichment could be significantly greater than what has been measured in situ, apparently due to sampling the atmosphere at different time of day and surface temperature. The observing runs in 2012 and 2014 measured O-18 enrichment at several local times in both morning and afternoon sectors as well as at the subsolar, equatorial, and anti-subsolar latitudes. The two runs in 2014 have additionally observed O-17 and C-13 transitions in the morning sector, from local dawn to noon. These observations include a limited sampling of measurements over Gale Crater, which can be compared with contemporary in situ measurements by the Curiosity

rover to investigate the degree of agreement between in situ and remote methods and potentially to calibrate the spectroscopic constants required to accurately evaluate isotope ratios all over Mars.

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303.04 – Revealing the water cycle on Mars via D/H isotopic measurements

Deuterium fractionation is a powerful metric revealing information about the cycle of water on Mars, and most importantly informing about its stability on short-term (diurnal) and long-term (seasonal) scales. The vapor pressures of HDO and H₂O differ significantly, making the condensation/sublimation cycle of the isotopologues strongly susceptible to the ambient temperature, saturation level and existence of condensation nuclei. Until recently, only isolated (in time and in space) measurements of D/H in the atmosphere were available, which were incorrectly assumed to be representative of the bulk atmosphere. Spatially resolved measurements of D/H at different times of day and seasons are necessary to disentangle local from global phenomena, and to possibly identify newly found sources of water on Mars.

We have addressed these concerns by acquiring full 2D maps of Mars for a broad range of seasons using high spectral resolution data at ground-based telescopes (Keck/NIRSPEC, VLT/CRIRES, NASA-IRTF/CSHELL). Our maps sample the full observable disk of Mars on 8 dates, spanning from late northern winter to late northern spring on Mars (Ls = 335°, 50°, 71°, 83°). The dates encompass the critical time as the northern polar cap sublimates and replenishes the atmosphere with water. By stepping the instrument's slit across the planet, we obtained full E-W and N-S coverage across the observable disk, allowing us to sample the short-term diurnal variations and the hemispheric seasonal effects. Our maps reveal significant diurnal and seasonal variability, together with a noticeable variation of the D/H ratio with topography (that we associate to the formation of clouds). We will present global maps of D/H acquired from 2008-2014, and will discuss possible scenarios to explain the observations.

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303.05 – An extremely high altitude plume seen at Mars morning terminator

We report the occurrence in March and April 2012 of two bright very high altitude plumes at the Martian terminator at 250 km or more above the surface, thus well into the ionosphere and bordering on the exosphere. They were located at about 195 deg West longitude and -45 deg latitude (at Terra Cimmeria) and lasted for about 10 days. The features showed day-to-day variability, and were seen at the morning terminator but not at the evening limb, which indicates rapid evolution in less than 10 hours and a cyclic behavior. Photometric measurements are used to explore two possible scenarios to explain their nature. If the phenomenon is due to suspended particles (dust, CO₂ or H₂O ice clouds) reflecting solar radiation, the mean size is about 0.1 microns with a nadir optical depth > 0.06. Alternatively, the plume could be auroral emission above a region with a strong magnetic anomaly and where aurora has previously been detected. Importantly, both explanations defy our current understanding of the Mars upper atmosphere.

Acknowledgements

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303.06 – Perturbation of the Mars atmosphere by Siding Spring

Comet C/2013 A1 (Siding Spring) will have a close encounter with Mars on October 19, 2014. Traveling on a highly inclined, 129 degree, hyperbolic orbit, this comet will encounter Mars with a relative velocity of 56 km/s and a close approach distance of roughly 130,000 km [JPL Small-Body Database]. The extended coma will impinge upon the upper atmosphere of Mars for about one hour. The flux of mass and energy incident upon the atmosphere will be considerable if the comet is active. This provides the opportunity to study the upper atmosphere of Mars at a unique time that could provide insight into physical processes that are difficult to investigate in normal circumstances. The physical consequences of the transit of a planet through a cometary coma have not previously been studied. Moreover, the near-collision with Siding Spring may affect the atmosphere so that the set of spacecraft currently investigating Mars may view a perturbed rather than normal atmosphere. Expected perturbations include elevated temperatures, compositional changes, and ionization. We will present calculations of atmospheric perturbations based on 1D aeronomical model and and a General Circulation model for the upper atmosphere.

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303.08 – Analysis and Modelling of HST Observations of the Martian Exosphere

We present modelling results of HST ACS/SBC images of martian hydrogen Lyman γ emission obtained in the far ultra-violet. These images of Mars were obtained during Fall 2007 and May 2014 and were synchronized with observations by SPICAM aboard Mars Express (MEX). The Fall 2007 HST images show a significant decrease in brightness within a period of just a month, a trend that was also observed by SPICAM. In this study we have attempted to determine the characteristics of the hydrogen exosphere of Mars: its temperature, number density with altitude, dependency with the sub-solar angle, etc. This analysis has allowed us to put constraints on the various thermal and non-thermal processes that could influence the escape flux of hydrogen atoms from the martian upper atmosphere. We have studied this upper atmosphere with a radiative transfer model developed by our group in combination with a Chamberlain model to simulate the Lyman γ emissions from the highly extended hydrogen exosphere. The HST images show the H emission profile upto high altitudes from outside the exosphere, while the in-situ spacecraft observations are more limited. Comparison of HST and MEX profiles will assist us in the future in analyzing data from MAVEN.

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303.09D – Simulated orbits of heavy planetary ions at Mars for different IMF configurations

We present simulated detections of O⁺, O₂⁺ and CO₂⁺ ions at Mars along a virtual orbit in the Mars space environment. Planetary pick-up ions are formed through the direct interaction of the solar wind with the neutral upper atmosphere, causing the newly created ions to be picked up and accelerated by the background convective electric field. Because previous missions such as Mars Global Surveyor (MGS) and Mars Express (MEX) have not been able to measure the interplanetary magnetic field (IMF) components simultaneously with plasma measurements, the response of heavy planetary pick-up ions to changes in the IMF has not been well characterized. Using a steady-state multi-species MHD model to provide the background electric and magnetic fields, the Mars Test Particle (MTP) simulation can trace each of these particles along field lines in near-Mars space and construct virtual ion detections from a spacecraft orbit. Specifically, we will present energy-time spectrograms and velocity space distributions (VSDs) for a selection of orbits during different IMF configurations and solar cycle conditions. These simulated orbits have broader implications for how to measure ion escape. Using individual particle traces, the origin and trajectories of different ion populations can be analyzed in order to assess how and where they contribute to the total atmospheric escape rate, which is a major objective of the upcoming MAVEN mission.

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304 – Assorted Small Bodies

304.01 – Wavelength Dependence of the Opposition Effect for Asteroids Steins and Lutetia: Analysis of the Rosetta OSIRIS Data

Rosetta OSIRIS optical system is equipped with a total of 25 medium and narrow-band filters which allow studying spectral dependence of photometric data obtained by this instrument. In this study we analyze the OSIRIS data for asteroids Steins and Lutetia at small phase angles to see how characteristics of their opposition effect depend on the wavelength and what mechanism can explain this dependence. For asteroid Steins, the data are available for the phase angles ranging from 0.36° up to 136° acquired with 9 filters that cover the wavelength range 295.9 – 631.6 nanometers; the images of asteroid Lutetia cover phase angles from 0.15° up to 156° in 16 filters in the range of wavelengths 269.3 – 989.3 nanometers. The data for Lutetia have a good coverage for phase angles smaller than 5° for three filters, whereas in the case of Steins only for the WAC filter 631.6 nm the angles smaller than 5° are covered. For other filters, a special interpolation procedure was performed; it is described in detail in La Forgia et al. (Mem. S.A.It. Suppl. Vol. 20, 15, 2012).

Both asteroids demonstrate significant brightness surge at small phase angles, however, its dependence on the wavelength is opposite: the sharpness of the surge increases with wavelength for asteroid Steins and decreases for asteroid Lutetia. The wavelength behavior of Steins' opposition effect is consistent with the coherent backscattering as the main mechanism that produces the opposition surge. However, the wavelength behavior of Lutetia's opposition surge cannot be explained either by coherent backscattering or by shadow hiding. We explore other opportunities to explain the specifics of the opposition effect for asteroid Lutetia. Particularly, we consider if the properties of individual particles can be responsible for the wavelength dependence of Lutetia's opposition effect.

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304.02 – Earth's Nearest Neighbors: Dynamical integrations of NEO-Earth approaches in support of MANOS

The Mission Accessible Near-Earth Object Survey (MANOS) began in August 2013 as a multi-year physical characterization survey that was awarded large survey status by NOAO. MANOS will target several hundred mission-accessible NEOs across visible and near-infrared wavelengths, ultimately providing a comprehensive catalog of physical properties (astrometry, light curves, spectra). In support of this telescopic survey, we are performing a suite of orbital integrations to investigate the dynamical evolution of the near-Earth asteroid population.

Using orbital information from the Lowell Observatory AstOrb database and the swift orbital integration package, we compute the orbital history of every known NEO from present day to five hundred thousand years in the past. This orbital history is used to identify the temporal evolution of each NEO's minimum orbital intersection distance (MOID) value, quantifying the physical distance between the orbits of a given NEO and that of a terrestrial planet. Due to the non-deterministic behavior of many NEO orbits beyond a few hundred years, these integrated MOIDs do not uniquely determine whether an NEO and a planet will actually encounter one another, but rather provide a probabilistic metric for the proximity in which two objects can encounter one another. Integrated MOIDs can be a useful tool for correlating measured physical properties with high probabilities of planetary encounters (e.g. Binzel et al. 2010, Nature 463, 331).

We will present the status of these orbital integrations. These integrations show a variety of dynamical histories, from objects that are stable over the integration limits to those that show chaotic behavior after approximately fifty to one hundred thousand years. These orbital integrations are being used to track the potentially hazardous object (PHA) population over time, to evaluate dynamical history for both specific objects and NEO sub-populations, and to estimate the evolution of NEO surface temperatures due to changing perihelion distances.

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304.03 – Where Did the Ureilite Parent Body Accrete? Constraints from Chemical and Isotopic Compositions

Almahata Sitta and other polymict ureilites contain a remarkable diversity of materials, including EH, EL, OC, R- and CB chondrites, in addition to the dominant ureilitic material [1]. These materials represent at least 6 different parent asteroids and a wide range of chemical and isotopic environments in the early Solar System. To understand the origin of this diversity it is critical to know where (heliocentric distance) the ureilite parent body (UPB) accreted. The chemical and isotopic compositions of ureilite precursors (inferred from the compositions of ureilites) can provide clues. Lithophile element ratios such as Si/Mg and Mn/Mg [2,3], and deficits in neutron-rich Cr, Ti and Ni isotopes [3], indicate that

ureilite precursors were similar to ordinary or enstatite chondrites (OC or EC), not carbonaceous chondrites (CC). In contrast, high carbon contents, carbon isotopes and oxygen isotopes suggest a genetic link to CC. This poses a conundrum considering the variation of asteroid types, which suggests that EC and OC dominate the inner asteroid belt and CC the outer belt. However, the CC-like oxygen isotopes of ureilites strongly suggest the effects of parent-body aqueous alteration [4,5], which clearly implies that the UPB accreted beyond the ice line. Lithophile element properties of ureilites compared with chondrites may not be a reliable indicator of location of accretion, because lithophile elements in chondrites are sited mainly in chondrules and the UPB accreted before most chondrules formed [6]. Ureilite Cr, Ti and Ni isotopes may indicate late introduction of the neutron rich isotopes of these elements to the CC-formation region [7]. We conclude that the UPB accreted in the outer belt, like CC. The UPB or one of its offspring must have migrated to the inner belt to acquire OC, EC and R-chondrite materials.

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304.04 – Physical Characteristics of Faint Meteors by Light Curve and High-resolution Observations

The physical structure of a meteoroid may be inferred from optical observations, particularly the light curve, of a meteor. For example: a classically shaped (late peaked) light curve is seen as evidence of a solid single body, whereas a symmetric light curve may indicate a dustball structure. High-resolution optical observations show how the meteoroid fragments: continuously, leaving a long wake, or discretely, leaving several distinct pieces. Calculating the orbit of the meteoroid using two station data then allows the object to be associated with asteroidal or cometary parent bodies. Optical observations thus provide simultaneous information on meteoroid structure, fragmentation mode, and origin. CAMO (the Canadian Automated Meteor Observatory) has been continuously collecting faint (masses < 10⁻⁴ kg) two station optical meteors with image-intensified narrow field (with a resolution of up to 3 meters per pixel) and wide field (26 by 19 degrees) cameras since 2010. The narrow field, telescopic cameras allow the meteor fragmentation to be studied using a pair of mirrors to track the meteor. The wide-field cameras provide the light curve and trajectory solution.

We present preliminary results from classifying light curves and high-resolution optical observations for 3000 faint meteors recorded since 2010. We find that most meteors (both asteroidal and cometary) show long trails, while meteors with short trails are the second most common morphology. It is expected that meteoroids that experience negligible fragmentation have the shortest trails, so our results imply that the majority of small meteoroids fragment during ablation. A surprising observation is that almost equal fractions of asteroidal and cometary meteors fragment (showing long trails), implying a similar structure for both types of meteoroids.

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304.05 – Measuring Fracture Properties of Meteorites: 3D Scans and Disruption Experiments.

The Arizona State University (ASU) Center for Meteorite Studies (CMS) houses over 30,000 specimens that represent almost every known meteorite type. A number of these are available for fragmentation experiments in small samples, but in most cases non-destructive experiments are desired in order to determine the fundamental mechanical properties of meteorites, and by extension, the Near-Earth Asteroids (NEAs) and other planetary bodies they derive from. We present results from an ongoing suite of measurements and experiments, featuring automated 3D topographic scans of a comprehensive suite of meteorites in the CMS collection, basic mechanical studies, and culminating in catastrophic fragmentation of four representative meteorites: Tamdakht (H5), Allende (CV3), Northwest Africa 869 (L3-6) and Chelyabinsk (LL5). Results will include high-resolution 3D color-shape models of meteorites, including specimens such as the 349g oriented and fusion crusted Martian (shergottite) Tissint, and the delicately fusion crusted and oriented 131g Whetstone Mountains (H5) ordinary chondrite. The 3D color-shape models will allow us to obtain basic physical properties (such as volume to derive density) and to derive fractal dimensions of fractured surfaces. Fractal dimension is closely related to the internal structural heterogeneity and fragmentation of the material, to macroscopic optical properties, and to rubble friction and cohesion. Freshly fractured surfaces of fragments that will result from catastrophic hypervelocity impact experiments will be subsequently scanned and analyzed in order to determine whether fractal dimension is preserved or if it changes with surface maturation.

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304.06 – Meteoroid Impacts: A Competitor for Yarkovsky and YORP

Meteoroids impacting an asteroid transfer linear and angular momentum to the larger body, which may change its orbit and its rotational state. The meteoroid environment of our Solar System may affect small (few meter sizes and smaller) asteroids at a level that is comparable to the Yarkovsky and Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effects. Asteroids orbiting on prograde orbits near the Earth encounter an anisotropic meteoroid environment, including a population of particles on retrograde orbits generally accepted to be material from long-period comets spiralling inwards under Poynting-Robertson drag. High relative speed (60 km/s) impacts by meteoroids provide a small effective drag force that decreases asteroid semimajor axes and which is independent of their rotation pole. This effect may exceed the Yarkovsky drift at sizes near and below one meter.

The momentum content of the meteoroids themselves is small enough to neglect, but it is the momentum transport by ejecta that increases the net effective force by two orders of magnitude for impacts into bare rock surfaces: this brings the effect to a level where it is of order that due to Yarkovsky, at least for small bodies. However, the above results are sensitive to the extrapolation of laboratory microcratering experiment results to real meteoroid-asteroid collisions and need further study.

Meteoroid impacts may also affect asteroid spins at a level comparable to that of YORP at sizes smaller than tens of meters. However, we conclude that recent measurements of the YORP effect have probably not been compromised, because of the targets' large sizes and because they are known or likely to be regolith-covered rather than bare rock, which decreases the efficiency of ejecta production. However, the effect of impacts increases sharply with decreasing size, and may be important for asteroids smaller than a few tens of meters in radius.

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304.07 – Phobos: Low Velocity Impacts

Mars's inner moon, Phobos, is located deep in the planet's gravity well and orbits far below the planet's synchronous orbit. Images of the surface of Phobos, in particular from Viking Orbiter 1, MGS, MRO, and MEX, reveal a rich collisional history, including fresh-looking impact craters and subdued older ones, very large impact structures (compared to the size of Phobos), such as Stickney, and much smaller ones.

Sources of impactors colliding with Phobos include a priori: A) Impactors from outside the martian system (asteroids, comets, and fragments thereof); B) Impactors from Mars itself (ejecta from large impacts on Mars); and C) Impactors from Mars orbit, including impact ejecta launched from Deimos and ejecta launched from, and reintercepted by, Phobos. In addition to individual craters on Phobos, the networks of grooves on this moon have also been attributed in part or in whole to impactors from some of these sources, particularly B.

We report the preliminary results of a systematic survey of the distribution, morphology, albedo, and color characteristics of fresh impact craters and associated ejecta deposits on Phobos. Considering that the different potential impactor sources listed above are expected to display distinct dominant compositions and different characteristic impact velocity regimes, we identify specific craters on Phobos that are more likely the result of low velocity impacts by impactors derived from Mars orbit than from any alternative sources. Our finding supports the hypothesis that the spectrally "Redder Unit" on Phobos may be a superficial veneer of accreted ejecta from Deimos, and that Phobos's bulk might be distinct in composition from Deimos.

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304.08 – PANDORA - Unlocking the mysteries of the Moons of Mars

After decades of intensive exploration of Mars, fundamental questions about the origin and evolution of the martian moons, Phobos and Deimos, remain unanswered. Their spectral characteristics are similar to C- or D-class asteroids, suggesting that they may have originated in the asteroid belt or outer solar system. Perhaps these ancient objects were captured separately, with orbits circularized by the action of gas drag in the solar nebula or early martian atmosphere, or maybe they are the fragments of a captured asteroid disrupted by impact. Various lines of evidence hint at other possibilities: one alternative is co-formation with Mars, in which case the moons contain primitive martian materials. Another is that they are re-accreted ejecta from a giant impact and contain material from the early martian crust. Thorough characterization of their global composition is required to determine their origins.

The Phobos ANd Deimos ORigin Assessment (PANDORA) mission, proposed in response to the 2014 NASA Discovery Announcement of Opportunity, will acquire new information needed to determine the provenance of the moons of

Mars. The mission design provides a powerful and robust framework for this investigation. PANDORA will travel to and successively orbit Phobos and Deimos to globally-map their chemical and mineral composition and further refine their shape and gravity. Geochemical data, acquired by nuclear- and infrared-spectroscopy, can distinguish between key origin hypotheses. High resolution imaging data will enable detailed geologic mapping and crater counting to determine the timing of major events and stratigraphy. Data acquired by the instrument suite will be used to characterize regolith properties, determine the nature of and relationship between "red" and "blue" units on Phobos, and determine how Phobos and Deimos are related. The information acquired by PANDORA can be compared with similar data sets for other solar system bodies, including Mars, Mercury, the Moon, Vesta and Ceres, as well as data from meteorite studies. Understanding the formation of the martian moons within this larger context will yield a better understanding of processes acting in the early solar system.

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304.09 – Periods, Poles, and Shapes of Irregular Satellites of Saturn from Lightcurves

The lightcurve-observation campaign of irregular (outer) moons of Saturn with the Cassini Imaging experiment is ongoing successfully. 21 rotation periods are now known, ranging from 5.5 h to ~3 d. The position of the Cassini spacecraft inside the orbits of the irregular moons allows observations from unusual geometries, especially at various phase angles and rapidly changing aspect angles. Many lightcurves are non-symmetric, and the large diversity of lightcurves for different objects indicates very different shapes. Lightcurves with three prominent maxima and minima are quite common, especially at phase angles higher than ~50°.

For several moons, recent observations from different viewing geometries provide the potential to reveal pole directions and convex-hull "photometric shapes". As seen from the poles, Ymir is now known to have a triangular shape with two about equally long sides and one shorter side. Its pole is approximately oriented antipodally to the major planets. Siarnaq data indicate that this moon has also a triangular cross-section, but with a very different pole direction and extreme seasons. Kiviuq's lightcurves show a very large amplitude even at low phase angles, suggesting a very elongated configuration with a ratio of the equatorial axes of about 3:1.

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305 – Laboratory Astrophysics

305.01 – The atomic branching ratios in the photodissociation N², CO, and CO² in the deep VUV from 11.50-15.15 eV is used to discuss the chemistry in comets, planetary atmospheres, protoplanetary disk, and dense molecular clouds.

The only pulsed molecular beam apparatus in the world with two tunable VUV lasers coupled to a time of flight mass spectrometer and a time-slice velocity imaging detector is used to determine the state of atomic products produced in the photodissociation of N², CO, and CO². This information is extremely important in modeling the chemistry in comets, planetary atmospheres, protoplanetary disk, and dense molecular clouds.

For N² reactions 2-4 are directly observed.

N² + h? ? N(⁴S) + N(⁴S) h? ? 9.76 eV (1)

? N(⁴S) + N(²D) h? ? 12.14 eV (2)

? N(⁴S) + N(²P) h? ? 13.34 eV (3)

? N(²D) + N(²D) h? ? 14.53 eV (4)

No evidence is found for the lowest energy channel that produces two N(⁴S) anywhere in this wavelength range.

The products from the photodissociation of CO between 12.361?13.180 eV are determined and discussed.

CO + h? ? C(³P^J) + O(³P^J) h? ? 11.09 eV (5)

? C(¹D) + O(³P^J) h? ? 12.35 eV (6)

? C(³P^J) + O(¹D) h? ? 13.06 eV (7)

In the photodissociation of CO² over the wavelength range from 94,000- 98,496 cm⁻¹ (11.655-12.212eV) and (13.540-13.678 eV) CO² reactions 8-15 occur.

CO² + h? ? (O³P^J) + CO(X¹?⁺) h? ? 5.45 eV (8)

? O(¹D) + CO(X¹?⁺) h? ? 7.42 eV (9)

? O(¹S) + CO(X¹?⁺) h? ? 9.64 eV (10)

? O(³P^J) + CO(a³?) h? ? 11.46 eV (11)

? O(¹D) + CO(a³?) h? ? 13.43 eV (12)

? O(³P_J) + CO(a¹Σ⁺) h? ? 12.31 eV (13)

? O(³P_J) + CO(d³Σ⁻) h? ? 12.97 eV (14)

? O(³P_J) + CO(e³Σ⁻) h? ? 13.35 eV (15)

The implications of these results to planetary science in terms of the chemical reactions of the long lived metastable N(²D), N(²P), O(¹D), O(¹S), and C(¹D) will be discussed.

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305.02 – VUV Spectroscopy of UV-Processed Planetary Ice Analogs

Far UV (120 - 200 nm) and Extreme UV (<120 nm) wavelength region enables spectral assignment of gas-phase atoms and molecules through their electronic absorption and emission characteristics. However, this wavelength region is also shown to reveal some important signatures of icy surfaces, especially by the Cassini UVIS instrument observations of the icy Saturnian satellites. However, carriers of spectral features between 180 and 200 nm that are not present in pure water-ice, have not been yet positively identified. One of the goals of our study is to identify the impurities in ices that could contribute to these features. Towards this goal we prepared several thin-film ices and subjected them to hydrogen-lamp (Lyman-alpha at 121.6 nm and Hydrogen continuum between 160 and 180 nm) photolysis. Such a photolysis of ice films is aimed to simulate atmosphere-less planetary icy surfaces processed by solar photons. We found that the spectral bands in the FUV are altered due to the formation of new species in the ice.

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305.03 – Micrometeorite Impact Effects on Comets and Asteroids: Temperature versus Spectral Variation

According to the Nice model, the placement of small bodies in the solar system were strongly affected 3.9 Ga ago. Collisions caused by this event would affect the surface properties of the remaining small bodies through shock deformation. Additionally, objects beyond Neptune are believed to have experienced significant collisional processing, including similar shock effects. When shocked, mineral absorption features can be shifted in wavelength and relative absorbance. The physical manifestations of shock effects include planar dislocations, phase changes, crystal deformation, and/or rupture. Room temperature experiments have revealed that the spectral effects of shock propagation are non-linearly related to the peak impact pressure of the experiment. Previous work by Grokhovsky with impact tests on Dronino and Chinga meteorites indicated that temperature has an effect on mineral impact strength, the mineral weakens with lower temperatures through the range of +25 C to -50 C [1]. Measuring differences, if any, in the effects of shock-deformation on absorption spectra is critical to measure as small bodies exist in cold temperatures. We will present our results from impacting enstatite and forsterite at the NASA/JSC Experimental Impact Laboratory at -10 and -50 degrees Celcius and highlight the differences relative to room temperature shocked spectra

Acknowledgements: Special thanks to the NASA EIL staff, F. Cardenas and R. Montes.

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305.04 – Identification of the UIR bands and their Relationship to Solar System Origins

Starlight undergoing multiple scattering processes within fluffy grains results in extinction, UV 2175A bump, DIBs and the UIR bands. Spectroscopic lab and DIB data has identified the highly fluorescent molecule Dipyrindyl Magnesium Tetrabenzoporphyrin (MgTBP). Reflection and Raman scattering experimental data will be presented which designates this molecule as the primary source for UIR signals. MgTBP sublimates at about 500°C. It is produced via high temperature

plasma synthesis within and subsequently ejected from comets which in turn are by-products of solar system-planetary development. Interstellar dust is the left-over refuse which implies prodigious solar system evolution in each galaxy
Fred M. Johnson, *Spectrochimica Acta Part A* 65 (2006) 1154-1179.

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306 – Moon/Mercury/Mars Exospheres

306.01D – Impacts of the Martian crustal magnetic fields on the thermosphere, ionosphere, and hot oxygen corona

A quantitative evaluation of the atmospheric loss at Mars is crucial to understanding the time-dependent inventory of water. Nonthermal mechanisms such as dissociative recombination of molecular ions result in the formation of the hot corona in the upper thermosphere and exosphere, where the escape of heavy neutral atoms occurs. Since Mars does not have an appreciable intrinsic magnetic field, its atmosphere is exposed to the direct interaction with the solar wind. The discovery of crustal magnetization at Mars by Mars Global Surveyor (MGS) shows that the crustal magnetic fields play a role in variation of the ionospheric content and the transport of ions in the upper atmosphere. These crustal magnetic fields may influence the production of hot oxygen atoms from dissociative recombination of O₂⁺, which is the dominant source of hot oxygen at the current epoch. In this study, we investigate the effects of the Martian crustal magnetic fields on the hot oxygen corona by examining the impacts on the horizontal and vertical structure of the ionosphere and the resulting loss rates of hot oxygen from the hot oxygen corona in the upper atmosphere. To describe the upper atmosphere self-consistently, our 3D Adaptive Mesh Particle Simulator (AMPS) is one-way coupled with the 3D Mars Global Ionosphere Thermosphere Model (M-GITM), a newly developed thermosphere/ionosphere model. The crustal magnetic fields are prescribed in new M-GITM simulations. Subsequently, the structure and spatial variation of the ionosphere and hot oxygen corona are compared to those simulated without the inclusion of the crustal fields. The coupled framework provides the macroscopic properties of the resulting hot oxygen corona and estimates the global oxygen loss rates for the conditions considered. These results are also important and are being used to contribute to the investigation of the solar wind interaction with the Martian upper atmosphere. This work has been supported by grant NNX09AL26G from the Mars Fundamental Research Program.

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306.02 – LADEE UVS Observations of Atoms and Dust in the Lunar Tail

The Lunar Atmosphere and Dust Environment Explorer (LADEE) was a lunar orbiter launched in September 2013 that investigated the composition and temporal variation of the tenuous lunar exosphere and dust environment. A major goal of the mission was to characterize the dust exosphere prior to future lunar exploration activities, which may alter the lunar environment. The Ultraviolet/Visible Spectrometer (UVS) onboard LADEE addresses this goal, utilizing two sets of optics: a limb-viewing telescope, and a solar-viewing telescope (Colaprete et al. 2014a). We report on spectroscopic (~280-820 nm) observations viewing down the lunar wake or along the 'lunar tail' from lunar orbit. Prior ground-based studies have observed the emission from neutral sodium atoms extended along the lunar tail, so often this region is referred to as the lunar sodium tail (e.g., Smith et al. 1999, Wilson et al. 1999).

UVS measurements were made on the dark side of the moon, with the UVS limb-viewing telescope pointed outward in the direction of the Moon's wake (almost anti-sun), during different lunar phases. These UVS observation activities sample a long column and allow the characterization of scattered light from dust and emission lines from atoms in the lunar tail (Colaprete et al. 2014b). Observations in this UVS configuration show the largest excess of scattered blue light in our data set, indicative of the presence of small dust grains in the tail. Once lofted (e.g., Stubbs et al. 2006), nanoparticles may become charged and picked up by the solar wind, similar to the phenomena witnessed above Enceladus's northern hemisphere (Farrell et al. 2012) or by the STEREO/WAVES instrument while close to Earth's orbit (Meyer-Vernet et al 2009). The UVS data show that small dust grains as well as atoms become entrained in the lunar tail.

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306.03 – Distribution of H₂ in the Lunar Exosphere from LAMP Observations

Hydrogen gas (H₂) has been detected in the Moon's exosphere. It was identified spectrally during the LCROSS impact plume (Gladstone et al., 2010). Then it was found in LAMP data from the nominal exosphere (Stern et al., 2013). We examine the distribution of H₂ in the lunar exosphere using a Monte Carlo model and data from the Lyman Alpha Mapping Project (LAMP) FUV imaging spectrograph onboard the Lunar Reconnaissance Orbiter (LRO). LAMP observations made in twilight, i.e., through illuminated exosphere, but with a footprint on the nightside of the Moon, are routinely made with LRO. However, during times when the beta angle of the orbit is close to beta=90°, a great portion of the nightside orbit is in the twilight viewing geometry. Using data from just behind the terminator on the post-dusk and pre-dawn sides, we compile a cumulative spectrum throughout LAMP's bandpass. A dawn/dusk asymmetry is detected in the H₂ abundance. Modeling is used to decipher the release mechanism and source distribution of diatomic hydrogen that best fits the observations. We examine the source rate and the total mass of the H₂ exosphere consistent with the observations.

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306.04 – Source and Distribution of Calcium in Mercury's Exosphere

Mercury is surrounded by a surface-bounded exosphere with six known components: H, He, Na, K, Ca, and Mg. Observations of the Ca exosphere by MESSENGER show a source concentrated on the dawn side that varies in a periodic way with that planet's true anomaly. The time variation in that Ca signal repeats every Mercury year (Burger et al., Icarus, 2014). We show that this pattern can be explained by impact vaporization by interplanetary dust. Our models of this scenario show that much of the seasonal variation in Ca is due to Mercury's substantial radial motion through the interplanetary dust cloud that results from Mercury's large orbital eccentricity (e=0.2). The seasonal Ca variation is enhanced further by Mercury's large orbital inclination (7° relative to the ecliptic), which causes additional periodic variations in the dust infall rate as Mercury's vertical motion carries it repeatedly across the dust-disk's midplane. However, an additional contribution near true anomaly 20° is required in addition to the contribution from the interplanetary dust disk. This anomaly is close to but not coincident with Mercury's true anomaly as it crosses comet 2P/Encke's orbital plane. The lack of exact correspondence may indicate the width of the potential stream or a previous cometary orbit. We note that the Encke meteor storms hit Earth at true anomaly angles ±20 degrees before and after where these two orbit planes cross. The temperature of the atomic calcium cannot be due to the impact vapor but must be imparted by an additional mechanism such as dissociation of a calcium-bearing molecule or ionization followed by recombination.

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400 – Asteroids: Dynamics and Collisions

400.01 – The Dynamical Evolution of the Inner Solar System in the Jumping-Jupiter Model

We investigate the dynamical evolution of the terrestrial planets and asteroid belt in the jumping-Jupiter model. Several simulations are performed starting with Jupiter and Saturn in the mutual 3:2 mean motion resonance. The instability of outer planets and subsequent encounters of Jupiter with an ice giant cause Jupiter to jump 0.3 AU inward in the semimajor axis. This affects the studied populations. The asteroid belt is represented by ~100,000 test particles that are initially distributed beyond 1.5 AU, including the stable orbital niches now populated by Hildas (3:2 resonance with Jupiter) and Trojans (1:1 resonance). Our results show that the primordial populations of Hildas and Trojans do not survive in the jumping-Jupiter model, thus supporting the idea that such populations must have been captured from elsewhere (e.g., from the outer disk of planetesimals). In particular, we investigate the possibility that (part of) the Hildas and Trojan populations was implanted from below 3.5 AU, and whether this could explain the presence of C-type asteroids among these groups. We also compare the final orbital structure of the simulated Main Belt with the current Main Belt for absolute magnitudes H < 9.7. The evolution of the terrestrial planets is simulated with a hybrid code, where the terrestrials perturb each other but do not affect the outer planets. Our results show that jumping Jupiter is capable of exciting the orbits of the terrestrial planets to values of eccentricity and inclination comparable with the current ones. This suggests that the partition of Angular Momentum Deficit among the terrestrial planets could have been caused by the secular coupling with Jupiter during the instability. The next step will be to combine the evolution of

the terrestrial planets with that of the Main Belt, and determine the impact rates of asteroids on the Moon and the terrestrial planets. This work can be important for our understanding of the Late Heavy Bombardment.

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400.02 – Origin of the Main-Belt Comets: Formed In-Situ or Interlopers from the Outer Solar System?

Since the discovery of the first main-belt comet (MBC), 133P/Elst-Pizarro, the dynamical origin of cometary objects in the asteroid belt has been the subject of great interest. The comet-like activity of MBCs appears to be driven by the sublimation of water ice, which is intriguing given studies showing that icy objects from the asteroid belt region could have been a significant primordial source of terrestrial water. However, while dynamical modeling of the first three known MBCs (Haghighipour, 2009, M&PS, 44, 1863-1869) favored in-situ formation as the most probable scenario for the origin of these objects, the possibility that MBCs could be interlopers from the outer solar system has never been definitively ruled out. The Tisserand parameter with respect to Jupiter, T_J , is commonly used to characterize the dynamical origin of a small solar system object. Asteroids believed to have formed in situ in the asteroid belt generally have $T_J > 3$ and comets which are presumed to have formed in the outer solar system generally have $T_J < 3$. All of the known MBCs have $T_J > 3$, suggesting that they formed in situ, but we are interested in investigating whether objects with $T_J < 3$ can in fact evolve onto stable main-belt orbits with $T_J > 3$. We have studied this issue by integrating the orbits of a large number of test particles with T_J values close to 3 ($2.8 < T_J < 3.2$) in order to observe what happens to particles close to the canonical $T_J = 3$ boundary between asteroids and comets. We confirm that $T_J = 3$ is not a hard boundary, as we find objects with $T_J < 3$ that are dynamically stable over timescales longer than typical cometary dynamical lifetimes, as well as objects with $T_J > 3$ that are dynamically unstable over typical cometary dynamical lifetimes. Intriguingly, we also find that a small fraction of particles with $T_J < 3$ do in fact evolve onto orbits similar to those of certain known MBCs, specifically those with large eccentricities or inclinations. This suggests that an outer solar system origin for those MBCs cannot be excluded. We will discuss the implications of these results for our understanding of the origin of the MBCs, as well as their utility as tracers of ice in the inner solar system.

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400.03 – The Origin of the Long-Lived Asteroids in the 2:1 Mean-Motion Resonance with Jupiter

We study the population of asteroids in the 2:1 mean-motion resonance with Jupiter. We first update this population on the basis of recent observational data from AstOrb, AstDyS and WISE. Using an N-body model of the long-term orbital evolution, we can distinguish 140 short-lived asteroids (“uninteresting”, c.f. Broz et al. 2005) and 230 long-lived. While a part of the long-lived asteroids slowly chaotically diffuses, the rest resides in two dynamically stable islands A and B (Nesvorný & Ferraz-Mello 1997) with an uneven population ratio $A/B = 11/113$. Moreover, the size-frequency distribution of the dynamically stable asteroids is steep with a cumulative slope ≈ 4.3 . We use the Boulder code (Morbidelli et al. 2009) and a modified Swift integrator (Levison & Duncan 1994) to perform simulations of both collisional and dynamical evolution in order to explain the origin of the long-lived asteroids. We argue that the origin might be related to the planetary migration for the following reasons: First, the intrinsic collisional probability on the main belt periphery is relatively low, so the size-frequency distribution may evolve on a 4 Gyr timescale and yet preserve its steepness. Additionally, the probability of a significant disruption event which could populate the resonance with fragments is only $\approx 10\%$ during 4 Gyr (for the parent body size of ≈ 100 km). Finally, the observed paucity in the highly inclined island A might be caused by a reconfiguration of the secondary and secular resonances overlapping the 2:1 resonance. We thus investigate a survival of primordial resonant asteroids and a capture of the population during the planetary migration in the two scenarios: with four giant planets only (“jumping Jupiter”) and with an escaping fifth giant planet (Nesvorný & Morbidelli 2012). The work of OC and MB has been supported by Charles University in Prague, project GA UK No. 1062214. The work of MB has been supported by the Grant Agency of the Czech Republic, grant no. 13-013085.

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400.04 – Possible Evidence for Two Subsequent Collisions on a Differentiated Parent Body, (135) Hertha

The Nysa-Polana complex is a group of low-inclination asteroid families in the inner main belt, bounded in semimajor axis by the ≈ 6 secular resonance and the Jupiter 3:1 mean motion resonance. This group is important as the most likely source region for the target of the OSIRIS-REx mission, (101955) Bennu; however, family membership in the region is complicated by the presence of several dynamically overlapping families with a range of surface reflectance properties. The large, S-type structure in the region (centered at proper elements $a = 2.4$ AU, $e = 0.18$, $\sin(i) = 0.042$) appears to be associated with parent body (135) Hertha. This family displays an a-e correlation with a slope of -0.57, consistent with

the ejection field of a collision with $v_{ej} = 250$ m/s and true anomaly in the range of 150 to 210 deg. This characterization of the ejection field places constraints on the semimajor axis dispersion of the original collision, which permits measurement of the dispersion due to the Yarkovsky effect, improving estimates of the family's age. Preliminary estimates yield an age of 240 ± 60 My; this roughly matches age measurements for the P/T extinction event on Earth (252 My).

Another, smaller structure overlaps the large Hertha family in proper orbital element space, and also appears to be associated with (135) Hertha. This structure differs from the larger one in SDSS a^* color, with reflectance properties more consistent with the X-type (135) Hertha than the surrounding S-type family. These objects form a distinct Yarkovsky "V" signature in a - H space, consistent with a recent collision with significantly less semimajor axis dispersion than the large family. These results have implications for the origin of this structure (second collision on (135) Hertha, core of the original large Hertha family, or unrelated neighboring collision), and the degree of differentiation of the parent body.

The Nysa-Polana complex also contains two additional families associated with (142) Polana and (495) Eulalia (Walsh et al. 2013). The Eulalia family shows structure that suggests either the presence of another separate family or a "wing" of the original family-forming collision.

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400.05 – In Search of the Source of Bennu, the OSIRIS-REx Sample Return Mission Target

(101955) Bennu, the target of NASA's OSIRIS-REx sample return mission, is a 0.5 km diameter low albedo B-type NEO. A plausible evolution scenario for Bennu is that (a) it migrated across the inner main belt from a low albedo family via Yarkovsky/YORP thermal forces/torques, (b) it reached a powerful resonance that took into the terrestrial planet region, and (c) planetary encounters and resonances took it to its current orbit. The source family of Bennu, however, is unknown, though it is needed to provide context for the interpretation of the retrieved carbonaceous chondrites.

Here we used a suite of numerical simulations to track (a)-(c) for test asteroids with a range of sizes evolving from the candidate low albedo families Clarissa, Erigone, Eulalia, New Polana, and Sulamitis. In particular, for (a), we employed a state of the art Yarkovsky/YORP evolution model that takes advantage of a new "stochastic YORP" mechanism describing how modest shape changes to asteroids, produced by a variety of processes, can cause an asteroid's spin rate but not its obliquity to undergo a random walk with time (see Statler 2009).

By following millions of test asteroids, we were able to reproduce, for the first time, the observed semimajor axis/size distribution of the ancient Eulalia family, whose parent disrupted ~ 830 ($+370$, -100) Ma, and the still older New Polana family, whose parent disrupted 1400 ± 150 Ma. Both parent bodies were 100-200 km in diameter. In comparison, the other families tested were relatively young (< 200 Ma). Given that Bennu-like objects take many hundreds of My to escape the main belt from all of the tested families, we predict Bennu came from Eulalia or New Polana. Next, by accounting for an extensive set of factors, we found that more than twice as many 0.5 km objects from New Polana reach Bennu's current orbit as those from the Eulalia family. Accordingly, we favor New Polana as Bennu's source by a 70 ($+8$, -4)% to 30 ($+4$, -8)% margin. Runs performed for (162173) 1999 JU₃, the 0.87 km Hayabusa 2 target, yield similar probabilities for each family.

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400.06 – A Look Inside Rotating Rubble-Pile Asteroids Spun to Disruption

Driven by the images obtained by different space missions to small asteroids, during the last few years different researchers have used self-gravitating granular mechanics codes for the simulation of small rubble-pile asteroids. One of the many topics of research has been the response of these bodies to rotational evolution due to YORP, specifically the deformation and ultimate disruption of small bodies due to elevated angular velocities.

In this research we use self-gravitating aggregates formed by thousands of spheres and a soft-sphere granular dynamics code to explore the effect of the variation of two parameters, friction angle and tensile strength, on their disruption process. The aggregates were slowly spun up to disruption controlling for friction angle, cohesion and global shape. How much each aggregate deformed before disruption was directly related to the angle of friction. The greater it was, the less the aggregate deformed before disruption. Cohesive forces controlled the mode of disruption and maximum spin rate, showing that the aggregates could disrupt by shedding particles or groups of particles from the equatorial

region. For high values of tensile strength, the pieces that detached from the initial aggregate were sizable enough for the disruption process to be seen as a fission. This implies that the change from shedding to fission is continuous and therefore, they should not be seen as different processes but just as two ends of the spectrum.

A closer look at the spherical aggregates showed that the reshaping of the bodies was not symmetrical. A granular aggregate cannot be completely homogeneous unless its particles are arranged in a crystalline structure, something we avoided. This resulted in an asymmetrically reshaped body, similar to that of 1999 KW4 (at times forming a binary system). For ellipsoidal aggregates, this meant the formation of tear-drop shapes and pairs. The failing of the granular structure is ultimately controlled by the inter-particle forces which in turn form force chains. How these force chains behave and change during reshaping and disruption will be explored during the conference.

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400.07 – Numerical Simulations of Microporous Body Disruptions: Comparison with Non-porous and Rubble-pile targets

In recent years, we have shown by numerical impact simulations that collisions and gravitational reaccumulation together can explain the formation of asteroid families and satellites (e.g. [1]). We also found that the presence of microporosity influences the outcome of a catastrophic disruption ([2], [3]). The size-frequency distributions (SFDs) resulting from the disruption of 100 km-diameter targets consisting of either monolithic non-porous basalt or non-porous basalt blocks held together by gravity (termed rubble piles by the investigators) has already been determined ([4], [5]). Using the same wide range of collision speeds, impact angles, and impactor sizes, we extended those studies to targets consisting of porous material represented by parameters for pumice. Dark-type asteroid families, such as C-type, are often considered to contain a high fraction of porosity (including microporosity). To determine the impact conditions for dark-type asteroid family formation, a comparison is needed between the actual family SFD and that of impact disruptions of porous bodies. Moreover, the comparison between the disruptions of non-porous, rubble-pile, and porous targets is important to assess the influence of various internal structures on the outcome. Our results show that in terms of largest remnants, in general, the outcomes for porous bodies are more similar to the ones for non-porous targets ([4]) than for rubble-pile targets ([5]). In particular, the latter targets are much weaker (the largest remnants are much smaller). We suspect that this is because the pressure-dependent shear strength between the individual components of the rubble pile is not properly modeled, which makes the body behave more like a fluid than an actual rubble pile. We will present our results and implications in terms of SFDs as well as ejection velocities over the entire considered parameter space. We will also check whether we find good agreement with existing dark-type asteroid families, allowing us to say something about their history.

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400.08D – Impact Simulations on the Rubble Pile Asteroid (2867) Steins

Images from the OSIRIS camera system on board the Rosetta spacecraft (Keller et al. 2010) has revealed several interesting features on asteroid (2867) Steins. Its macro porosity of 40%, together with the shape that looks remarkably like a YORP evolved body, both indicate a rubble pile structure. A large crater on the southern pole is evidence for collisional evolution of this rubble pile asteroid.

We have developed a new approach for simulating impacts on asteroid bodies that connects formation history to their collisional evolution. This is achieved by representing the interior as a 'rubble pile', created from the gravitational aggregation of spherical 'pebbles' that represent fragments from a major disruption event. These 'pebbles' follow a power law size function and constitute the building blocks of the rubble pile. This allows us to explicitly model the interior of rubble pile asteroids in hyper-velocity impact simulations in a more realistic way. We present preliminary results of a study validating our approach in a large series of simulated impacts on a typical small main belt rubble pile asteroid using the Smoothed Particle Hydrodynamics solver in Autodyn. We show that this approach allows us to explicitly follow the behavior of a single 'pebble', while preserving the expected properties of the bulk asteroid as known from observations and experiments (Holsapple 2009).

On the example of Steins, we use this model to investigate if surface features like the northern hill at 75/100 degrees lon/lat distance to the largest crater (Jorda et al. 2012), or the catena of depletion pits, can be explained by the displacement of large fragments in the interior of the asteroid during the impact. We do this by following the movement

of pebbles below the surface feature in simulations that recreate the shape of the impact crater.

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References: Keller et al., 2010, *Science*, 327(5962), pp. 190–193; Jorda et al., 2012, *Icarus*, vol. 221 (2) pp. 1089–1100; Holsapple, 2009, *PSS*, 57(2), 127–141.

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400.09 – Validating SESAME Equations of State for Use in Hydrocode Models of Small Solar System Bodies

Hydrodynamic models of small solar system body impacts, collisions, and hazard mitigation require material-specific equations of state (EOS's) in order to close the system of equations that comprise the model and accurately predict the response of such objects to shocks and other hydrodynamic phenomena. Current models approximate meteoritic and cometary materials using Earth-analogue EOS's, e.g., quartz, dunite, hydrated tuff, water ice, and numerical convolutions of analog EOS's. Earth-analogues are used because the formulation of a comprehensive equation of state requires a large amount of experimental data that is destructive to the often rare samples. Analogue EOS's can, however, perform very differently from the original material under shock loading. Some experimental data has become available over time for various meteorite types. Here we compare the available shock data for meteoritic materials to analogue EOS's available in the public Los Alamos National Laboratory SESAME EOS database to explore the applicability and limitations of these models.

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401 – Pluto 1: Mostly Atmosphere

401.01 – Evidence of Haze in Pluto's Lower Atmosphere in 2011

Based on stellar occultation observations since 1988, Pluto's lower atmosphere has been evolving (e.g., Elliot et al. 2007, *AJ*, 134, 1; Young et al. 2008, *AJ*, 136, 1757; Bosh et al. 2014, *Icarus*, in press). The structure of the lower atmosphere is likely due to a steep thermal gradient and/or extinction, the latter of which can be characterized as a dependence between observed occultation flux and wavelength. On 2011 June 23, a 13.64 *R*-magnitude star was occulted by Pluto as observed from multiple sites (Person et al. 2013, *AJ*, 146, 83). Observations made at NASA's 3-m Infrared Telescope Facility (IRTF) on Mauna Kea, Hawai'i, showed a full occultation of the star by Charon followed by an atmospheric graze by Pluto. Data were taken simultaneously in visible-wavelength images and low-resolution, near-infrared spectra. This unique, wavelength-resolved dataset serves as a test for atmospheric extinction.

The graze primarily probed Pluto's upper atmosphere. The upper atmosphere is typically defined to be above half-light level in occultation light curves (approximately three pressure scale heights above the surface), and the graze reached a minimum of roughly 0.35 flux. However, the light curve is well matched by an atmospheric model with a power-law thermal gradient, a clear upper atmosphere, and haze in the lower atmosphere. Furthermore, there is a negative dependence between flux and wavelength in the deepest part of the atmosphere probed by the graze, as well as in an emission spike. We find that a simple extinction model for spherical, micron-sized tholins matches the observed spectral trends (Gulbis et al. 2014, *Icarus*, in press). While the atmospheric fits cannot rule out a clear atmosphere having a steep thermal gradient at the bottom, the flux-wavelength dependence and the feasibility of our particle-scattering fits suggest that Pluto's lower atmosphere contained haze in 2011. These results provide an important link in monitoring Pluto's dynamic atmosphere, especially placed in context of the imminent arrival of the *New Horizons* spacecraft.

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401.02 – A Detailed Look at a Pluto Central Flash Occultation: Limits on Pluto's Haze Opacity, Oblateness and Surface Frost Pressure

We report a new analysis of occultation lightcurves observed in 2007 (from Mt John Observatory) and 2011 (from San Pedro Martir Observatory). In both cases, lightcurves were observed simultaneously in two wavelengths, and in the 2007 case, a double-peaked central flash was observed. In contrast to the wavelength-dependent opacities reported by

Elliot et al. (Nature 2003; 424:165) in 2002, we see no evidence for an opacity source in Pluto's atmosphere that has greater extinction at shorter wavelengths. From the separation of the peaks in the 2007 central flash lightcurves, we find the oblateness of Pluto's atmosphere (equatorial vs. polar radii of pressure contours near $R = 1215$ km) of 1.03 ± 0.002 . If this oblateness were caused solely by zonal winds, the wind speed at the equator would have to be 206 km/s; an alternative explanation is that the equatorial bulge is caused by warmer temperatures above the equator than the poles. Finally, the amplitudes of the central flash peaks are very sensitive to the surface pressure. If that pressure is driven by the vapor pressure of nitrogen ice, then the ice temperature of 42 ± 2 K reported by Tryka et al. (Icarus 1994; 212:513) is too high and produces central flash amplitudes that are much too bright. We find that the observed central flash peak amplitudes are consistent with nitrogen ice temperatures near 37 K, closer to the alpha-beta transition temperature (35.6 K) of nitrogen ice.

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401.03 – Keck/NIRSPEC High-Resolution Spectra of Pluto: A Search for Cold Gaseous CH⁴ Layer and Spatial Variation In CH⁴ Column Abundance

We obtained new observations of Pluto on 10 half nights between 2011 and 2014 using the NIRSPEC instrument on the Keck telescope. Our observations cover orders 43 through 50 (1510-1790 nm) at a resolving power of 35,000. Each order covers approximately 25 nm with similar sized spectral gaps between each order. Because we do not have continuous wavelength coverage, we selected wavelength regions that contain CH⁴ absorption lines that are highly sensitive to both column abundance and atmospheric temperature. In our range are several P, Q and R lines from the 2²3 band as well as Q-branches from 2²+3, 1+3, 3²+4 and 2¹. Our observations target 3 high priority longitudes. These longitudes covered the maximum CH⁴ frost (110-170°), minimum CH⁴ frost (220-280°, and New Horizons' encounter longitude) and pure CH⁴ frost (350-50°). All longitudes are from the current IAU system. By observing these longitudes we (i) establish a baseline for temporal change, (ii) search for spatial variability in gaseous CH⁴, and (iii) refine the vertical distribution of gaseous CH⁴. The average SNR in the grand average spectrum is 70 per resolution element. We examine the data as nightly average spectra and a run average spectrum and model these spectra using a combination of an atmospheric component and Hapke reflectance of Pluto and Charon's surface ice to define the continuum. We will present our findings at DPS. Funding for this work has been provided by NNX13AG06G and NNX11AG02G.

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401.04 – Gemini North/NIRI Spectra of Pluto and Charon: Simultaneous Analysis of the Surface and Atmosphere

We report on our analysis of blended Pluto and Charon spectra over the wavelength range 1.4 to 2.5 μ m as obtained by the NIRI instrument on Gemini North on June 25-28, 2004. The data have a resolving power ($\lambda/\Delta\lambda$) around 1500 and a SNR around 200 per pixel. The observed blended spectra are compared to models that combine absorption from the solid ice on the surface using Hapke theory, and absorption from the gaseous atmosphere. We assume the spectrum is a combination of several spatially separate spectral units: a CH⁴-rich ice unit, a volatile unit (an intimate mixture of N₂, CH⁴ and CO), and a Charon unit (H₂O, ammonia hydrate and kaolinite). We test for the presence of hydrocarbons (i.e. C₂H₆) and nitriles (i.e. HCN) and examine cases where additional ices are present as either pure separate spatial units, mixed with the CH⁴-rich unit or part of the volatile unit. We conclude that 2-4% of Pluto's surface is covered with pure-C₂H₆ ice and our identification of solid C₂H₆ is significantly strengthened when absorption due to gaseous CH⁴ is included. The inclusion of Pluto's atmosphere demonstrates that low-resolution, high-SNR observations are capable of detecting Pluto's atmosphere during a time when Pluto's atmosphere may have been undergoing rapid changes (1988-2002) and no high-resolution spectra were obtained. In particular, we identify features at 1.665 and 2.317 μ m as the Q-branch of the 2²3 and 3²+4 bands of gaseous CH⁴, respectively. The later band is also evident in many previously published spectra of Pluto. Our analysis finds it is unnecessary to include ¹³CO to explain the depth of the 2.405 μ m, which has been previously suggested to be a spectral blended with C₂H₆, but we cannot definitively rule out its presence.

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401.05 – Atmospheric CO on Pluto: Limits from Millimeter-wave Spectroscopy

Clearly detected as ice on Pluto's surface, CO should also be present in its atmosphere. Initial non-detections ([1], [2]) were recently followed by reported identifications in the near-IR ([3], hereafter L2011), and mm ([4], hereafter G2011),

which are strikingly different. From near-IR spectroscopy L2011 find CO at ~ 500 ppm for a 17 μ bar N₂ atmosphere, and show that this is compatible with the observed ratios of surface ices. For a ‘standard’ 100 K well-mixed atmospheric model with this CO abundance, the mm CO(2-1) emission line is ~ 60 mJy peak and ~ 1 MHz FWHM. In contrast, G2011 report the CO(2-1) line to be $\sim 591 \pm 110$ mJy peak, 10 \times stronger than expected. Their feature is also extremely narrow at 200 kHz FWHM; if it is CO from Pluto it must be significantly colder (30 to 50 K) than most atmospheric models predict. At this temperature, to fit the observed line flux density requires that the CO $\tau=1$ surface extends to ~ 5 -6 Pluto radii, implying that CO is much more abundant than N₂ in the upper atmosphere. Further, the G2011 feature exceeds by a factor of 4 the upper limit for the same CO line reported in [2], requiring a tremendous increase in CO abundance, through an unknown process, over just 10 years. To explore the CO abundance question further, we have reanalyzed our lower spectral resolution CO(2-1) observations from 2005 [5], and 2010 [6], and obtained new observations in 2013, with the Submillimeter Array (SMA). The two earlier data sets show no evidence for CO emission and are inconsistent with G2011, though only at ~ 3 - σ (combined). In 2013 we obtained ~ 17 hours on Pluto at a more appropriate 100-kHz resolution. These new data also fail to detect CO, reaching an rms of 82 mJy/channel, inconsistent with the G2011 results at >6 - σ (~ 10 - σ integrated). We present our analysis of the SMA observations and implications for CO in Pluto’s atmosphere, and make predictions for approved observations by ALMA slated for 2015. [1] Young et al. (2001), *Icarus* 153, 148-156. [2] Bockelée-Morvan et al. (2001), *A&A* 377, 343-353. [3] Lellouch et al. (2011) *A&A* 530, L4-L7. [4] Greaves, Helling, & Friberg (2011), *MNRAS* 414, 36-40. [5] Gurwell & Butler 2005, *BAAS*, 37, 743. [6] Gurwell, Butler & Moullet 2010, *BAAS*, 42, 1014.

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401.06 – Charge-Exchange X-rays: Limits on Pluto’s Atmospheric Escape Rate

Pluto is known to have an atmosphere, and current models postulate a majority N₂ composition with minor species CH₄, CO, and others with scale height ~ 3000 km and free escape of up to $\sim 10^{28}$ molecules s⁻¹. This is very similar to the physical situation of a variety of comets observed in the inner heliosphere. Following the discovery of X-rays from comets in 1996, their source was shown to be charge exchange between the escaping neutral molecules and highly ionized, minor-ion components of the solar wind. Some fraction of the highly charged ions produced is left in excited states, which de-excite via emission of X-ray photons. The emitted X-ray spectra are characteristic of the minor ion populations in the solar wind, themselves characteristic of the coronal temperature at the last collisions of that parcel of solar wind. X-ray emission from comet 9P/Tempel 1 was detected with Chandra when its total emission rate was $\sim 7 \times 10^{27}$ s⁻¹, and 2P/Encke has been observed by ROSAT in 1997 and Chandra in 2003 when its neutral gas emission rate was between 2×10^{27} and 10^{28} s⁻¹. These considerations suggest that Pluto might be a likely candidate for X-ray emission and that observations of this emission could provide a remote measurement of the atmospheric escape rate. The Chandra Advanced CCD Imaging Spectrometer-S (ACIS-S) provides the best chance for detecting such remote planetary emissions, with 0.5 x 0.5 arc second pixels, (or about 10 Pluto radii x 10 Pluto radii, roughly 12,000 km x 12,000 km, at Pluto’s current distance of 33 AU from the Sun), and 50 eV FWHM energy resolution at 0.3 - 2.0 keV where charge exchange x-ray photons are expected. An observation time of 35,000 seconds in February 2014, awarded for this observation during Chandra Guest Observer Cycle 15 did not provide a definitive detection of Pluto’s atmosphere in charge-exchange X-rays. We report here on details of the observations and implications for the current upper limits on the escape rate of Pluto’s upper atmosphere.

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401.07 – Pluto's Insolation History: Latitudinal Variations and Effects on Atmospheric Pressure

Since previous insolation modeling in the early 1990’s, new atmospheric pressure data, increased computational power, and the upcoming flyby of the Pluto system by NASA’s New Horizons spacecraft have generated new motivation and increased capabilities for the study of Pluto’s complex long-term (million-years) insolation history. The two primary topics of interest in studying Pluto’s insolation history are the variations in insolation patterns when integrated over different intervals and the evolution of diurnal insolation patterns over the last several decades. We find latitudinal dichotomies when comparing average insolation over timescales of days, decades, centuries, and millennia. Depending on the timescales of volatile migration, some consequences of these insolation patterns may be manifested in the surface features revealed by New Horizons. For any single rotation of Pluto there is a latitude that receives more insolation relative to the others. Often this is the sub-subsolar latitude but it can also be an arctic circle latitude when

near-polar regions of Pluto experience the "midnight sun". We define the amount of that greatest insolation value over the course of one rotation as the "maximum diurnal insolation" (MDI). We find that MDI is driven to its highest values when Pluto's obliquity creates a long arctic summer (or "midnight sun") beginning just after perihelion. Pluto's atmospheric pressure, as measured through stellar occultation observations during the past three decades, appears to correlate with Pluto's currently occurring midnight sun as quantified by the MDI parameter. If insolation (as parameterized by the MDI value) is the single dominant factor driving Pluto's atmospheric pressure, this "Midnight Sun Model" predicts that Pluto's maximum atmospheric pressure will be reached in 2017 followed by a steady decline. Pluto's maximum diurnal insolation value begins dropping after 2017 due to two factors: Pluto's sub-solar point becomes more equatorial (lessening the midnight sun effect) and the planet continues to recede toward aphelion. This work was supported in part by the NASA New Horizons mission to Pluto under SwRI Subcontract 299433Q.

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401.08 – The Influence of Topography on Volatile Transport

Topography can exert important influences on volatile transport on bodies, such as Pluto and Triton, with global atmospheres supported by vapor pressure equilibrium with volatile frost on the surface. First, because local energy balance depends on the illumination angle, volatile frost will preferentially sublime from (condense on) areas tilted towards (away from) the Sun, as has been previously modelled at small spatial scales [e.g. 1]. Topographic features can also cause a completely different kind of vertical volatile transport resulting from the decrease in atmospheric pressure with altitude. On Pluto and Triton the sublimation flux from a topographic feature approximately one km high is comparable to the seasonal or inter-hemispheric sublimation flux ($1 \text{ g/cm}^2/\text{year}$). To the extent that seasonal transport influences the distribution of volatile ices (and related characteristics such as albedo, emissivity, reflectance spectrum), topography-driven transport will exert a comparable influence around features a km or more above (or below) the global mean altitude of the frost deposits. This implies that in addition to there being a global "frost temperature" (defined by the temperature at which the frost vapor pressure equals the atmospheric pressure), there is a "frost altitude" (defined by the globally-averaged altitude of all the volatile frost). The sense of topography-driven volatile transport is to denude high areas. Consider two frost patches with equilibrium temperatures equal to the frost temperature, but at different altitudes. The high(low)-altitude patch is in contact with a lower(higher)-pressure atmosphere due to the $e^{(-z/H)}$ dependence of atmospheric pressure. If the high(low)-altitude patch is above(below) the frost altitude, frost will sublime from (condense on) the high (low) frost patch, resulting in net downhill transport. We present models for the combined effects of illumination and altitude on frost transport rates for simple topographic features and discuss how these may influence the appearance of Pluto's surface as it will be seen by the New Horizons spacecraft in July 2015. [1] Yelle (1992) *Science* 255, 1553-1555.

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401.09 – Escape Erosion and Relaxation of Craters on Pluto

Pluto and its satellites will be the most distant objects ever visited when NASA's New Horizons spacecraft conducts its intensive flyby to reconnoiter them in 2015. Craters on their surfaces have long been expected to provide a record of the size distribution of Trans-Neptunian Objects (TNOs) down to much smaller size scales than can be presently observed. However, Pluto's mainly-nitrogen atmosphere is expected to be undergoing hydrodynamic escape. The atmospheric mass lost to escape must be replenished by the sublimation of nitrogen ice and other volatiles from Pluto's surface. Over the age of the solar system, this requires up to several kilometers deep of nitrogen ice to have sublimated from the surface to maintain the current surface pressure. This is deeper than most expected craters on Pluto, so smaller craters observed by New Horizons may be very eroded by this process. In addition, pure nitrogen ice at Pluto's measured surface temperature of 35 K has a viscosity low enough that the largest craters Pluto could experience viscous relaxation, making them shallow enough to also experience significant escape erosion. As a result, the surface of Pluto may have considerably fewer craters than if there were no atmospheric escape, and could therefore look young, regardless of internal activity. Charon's water ice surface and lack of atmosphere should preserve craters much better than Pluto, and thus will provide a comparison point to estimate the long-term average erosion rate (and thus atmospheric escape rate) of Pluto.

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402 – Planetary Rings

402.01 – F Ring Core Stability: Corotation Resonance Plus Antiresonance

The decades-or-longer stability of the narrow F Ring core in a sea of orbital chaos appears to be due to an unusual combination of traditional corotation resonance and a novel kind of “antiresonance”. At a series of specific locations in the F Ring region, apse precession between synodic encounters with Prometheus allows semimajor axis perturbations to promptly cancel before significant orbital period changes can occur (Cuzzi et al. 2014, *Icarus* 232, 157-175). This cancellation fails for particles that encounter Prometheus when it is near its apoapse, especially during periods of antialignment of its apse with that of the F Ring. At these times, the strength of the semimajor axis perturbation is large (tens of km) and highly nonsinusoidal in encounter longitude, making it impossible to cancel promptly on a subsequent encounter and leading to chaotic orbital diffusion. Only particles that consistently encounter Prometheus away from its apoapse can use antiresonance to maintain stable orbits, implying that the true mean motion n_F of the stable core must be defined by a corotational resonance of the form $n_F = n_P - \beta P/m$, where (n_P , βP) are Prometheus’ mean motion and epicycle frequency. To test this hypothesis we used the fact that Cassini RSS occultations only sporadically detect a “massive” F Ring core, composed of several-cm-and-larger particles. We regressed the inertial longitudes of 24 Cassini RSS (and VGR) detections and 43 nondetections to a common epoch, using a comb of candidate n_P , and then folded them modulo the anticipated m -number of the corotational resonance (Prometheus $m=110$ outer CER), to see if clustering appears. We find the “true F Ring core” is actually arranged in a series of short longitudinal arcs separated by nearly empty longitudes, orbiting at a well determined semimajor axis of 140222.4km (from 2005-2012 at least). Small particles seen by imaging and stellar occultations spread quickly in azimuth and obscure this clumpy structure. Small chaotic variations in the mean motion and/or apse longitude of Prometheus quickly become manifest in the F Ring core, and we suggest that the core must adapt to these changes for the F Ring to maintain stability over timescales of decades and longer.

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402.02 – Investigating Non-icy Material Fraction from Microwave Emission

We will present calibrated, high- (~2000 km) and low- (~8000 km) resolution maps of Saturn’s rings at 2.2-cm wavelength acquired by the Cassini radar radiometer. Microwave emission is the ideal waveband for studying the scattering properties of cm-scale ring particles and for constraining the thermal emission from (possibly buried) non-icy ring contaminants, which, unlike water ice, behave as blackbodies at cm-wavelengths. While occultation observations are necessarily restricted to near-forward scattered light, scattered emission from Saturn (an extended source) can be viewed at a wide range of geometries. In order to successfully remove energy contributed by radar’s extensive side-lobes, we use an iterative self-calibration process. The current calibration reaches an RMS residual of 0.18 K (~ 2% ring brightness temperature). The observed microwave brightness temperature of Saturn’s rings is dominated by scattered Saturn emission and intrinsic thermal emission from the rings. We adopted a Monte Carlo multiple scattering model for the A, B and C rings that treats non-icy materials as inclusions in icy particles. Our results predict that the non-icy component of the C ring, assuming that contaminants behave with the dielectric properties of acidic rock, has a baseline volume fraction of ~2% throughout the entire C Ring with humps at the center and inner region that reach a maximum of ~7%. The implications of these results for the origin and evolution of the Saturn’s rings will be discussed. Furthermore, in optically thick B ring, the scattering properties of ring particles are altered by the closely packed effect. We employed a near-field Fresnel diffraction pattern for near field scattering events. Details on this near-field effect will be discussed.

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402.03 – Scattering by Gravitational Wakes in Saturn's A-Ring & Inference of Wake Sizes from Multiple Cassini Radio Occultations

Elongated and canted clusters of ring particles (gravitational wakes) are known to permeate the A- and B-Rings of Saturn. We constrain wake width W and height H , for given cant angle β , using multiple 3.6 cm- β Cassini radio occultations covering a range of ring opening angle B . We model the electromagnetic interaction problem as diffraction by randomly blocked screens constructed in the plane normal to the incidence direction (Marouf, DPS 1994, 1996, and 1997; Thomson and Marouf, *Icarus*, 2009). The screen’s transmittance is binary: the incident wave is either blocked or not blocked depending on the collective shadow area cast by the large particles and particle clusters. Wakes are modeled as monolayer of elliptical cylinders populated by random but uniform distribution of spherical particles. The cylinders can be immersed in a “halo” of loose spherical particles. Numerical simulations of diffraction patterns for a range of model parameters and viewing geometry reveal distinct diffracted cylindrical and spherical components. The first dominates at small scattering angles and originates from specific locations within the footprint of the spacecraft

antenna. The second dominates at larger angles and originates from the full footprint. Its angular spectrum is in good agreement with theoretical predictions based on multiple scattering by classical ring models (Marouf et al., Icarus, 1982, 1983). We interpret Cassini measurements in the light of the simulation results, assuming that the measured scattered signal spectra can be modeled as superposition of diffracted spherical and cylindrical components. We compute and remove contribution of the first component assuming Voyager-like size distributions (Zebker et al., Icarus, 1985). In most cases, a large residual spectral component is interpreted as contribution of cylindrical (wake) diffraction. Its angular width determines a characteristic cylindrical shadow width that depends on the wake (W, H) and the viewing geometry (θ , B). Self-consistent values of (W, H) are estimated using least-square fit to estimates from multiple occultations. Example results for observed scattering by A-Ring features suggest wakes that are few tens of meters wide and several meters thick.

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402.04 – Effects of Janus' orbit change every four years on Saturn's A ring

Every four years, Janus and Epimetheus change their orbits, because of their unique dynamical capture in horseshoe orbits (Yoder et al, 1983). Both Janus and Epimetheus drive strong density waves in the rings, but because of their configuration with variable orbits, their nearby resonance locations change every four years. As a result, the observed composite waves are driven by both satellites, each at two different semimajor axes at different times (Tiscareno et al, 2007). Moreover, the 7:6 Lindblad resonance with Janus controls the edge of the A ring, which is also affected by this dynamical behavior. We have examined a series of mosaics of the A ring edge derived from Cassini ISS images taken between 2005 and 2014, as well as large suite of occultation data. During the first period (2006 to 2009), when Janus was on its inner orbital leg, we have a regular 7-lobed pattern, with one minimum aligned with the orbital longitude of Janus, in agreement with the results obtained by Spitale and Porco (2009). Fits to the occultation data show a strong $m=7$ radial perturbation with an amplitude of 12.8 km, moving with Janus. During the second period (2010 to 2013), when Janus was on its outer orbital leg, we see a more irregular pattern with typically 5 or 6 lobes. We also see no obvious alignment with Janus. Individual distinctive features on the A edge appear to move at the keplerien rate over periods of several days. We will present a more complete analysis of these data and suggest a possible dynamical model for the behavior of the A ring edge after 2010.

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402.05 – Prometheus and the Keeler gap

Lindblad resonances with Saturn's satellites are located at many radii in the rings. While some cause density or bending waves, others hold gap edges from spreading, like the 2:1 resonance with Mimas located at the B-ring edge, the 7:6 resonance with Janus at the A-ring edge, and the 32:31 resonance with Prometheus at the inner edge of the Keeler gap. The latter is the case of study here.

Theoretically, the inner edge of the Keeler gap should have 32 regular sinusoidal lobes, where either the maximum or the minimum radius is expected to be aligned with Prometheus and rotating with its mean motion. We show that such is not the case. Fit of occultation data shows the presence of the 32:31 resonance, however, the fit residuals is as high as the amplitude of the resonance amplitude (about 2 km). Analysis of the ISS data, shows irregularities overlapping the lobes (Tiscareno et al. 2005, DPS), that follow Keplerian motion. These irregularities may be due to clumps of particles with different eccentricities than the rest of the edge particles. This phenomenon may be caused by the resonance, as it has not been observed at other circular edges where no resonance is present at their location. The ISS data also shows that the lobe's minimum/maximum is not perfectly aligned with the longitude of Prometheus, which may be due to libration about the centre of the resonance.

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402.06 – A new moon-induced structure

Cassini UVIS stellar occultations show prominent gaps within Saturn's ring located only a few km from the Encke and Keeler gap edges. These transparent regions feature sharp edges and measure a few km in radial width. Already the Voyager 2 PPS experiment registered such a gap near the inner Encke gap edge.

All gaps identified so far have been found exclusively downstream of the embedded moons Pan and Daphnis,

respectively. Interestingly, none has been observed at the inner Keeler gap edge, where temporal and spatial variability of the edge are still poorly understood and most likely driven by the Prometheus 32:31 ILR located nearby. There is evidence for a weak trend between radial width and relative azimuthal distance to the moon. Trends for features found near the inner and outer Encke gap edge are consistent with each other. Two occultations, one tracking and one double star occultation, allow to investigate spatial and temporal morphology of these gaps. Our preliminary results suggest that these structures are individual gaps with an aspect ratio of about 1:5 and may thus be about 10km long.

Embedded moons are known to create observable structures - gaps and kinematic wakes - in the surrounding ring. While Pan and Daphnis are massive enough to open a circumferential gap, smaller objects create the propeller features. These new results, however, reveal the existence of a previously unknown and unpredicted moon-associated structure. Its existence offers another avenue in searching for embedded objects, although our preliminary search did not produce examples apart from those reported here for Pan and Daphnis.

We acknowledge Tracy Becker for providing an initial list of positive detections. This work is supported by the Cassini project.

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402.07 – Modeling Diffraction Spikes to Characterize the Particle Size Distribution in Saturn’s A Ring

Stellar occultation data from Cassini’s Ultraviolet Imaging Spectrograph (UVIS) have revealed diffraction spikes near sharp edges in Saturn’s rings. The UVIS High Speed Photometer (HSP) observes these signals as photon counts surpassing measurements of the unocculted stellar signal in the ring gaps and in regions beyond the rings. In Saturn’s A ring, forward-scattered light can augment the direct stellar signal by up to 5%, and the signals typically extend tens of kilometers radially from the ring edge. The extent of the diffraction signals at the HSP wavelength of 150 nanometers indicates the presence of centimeter- and sub-centimeter-sized particles throughout the A ring. We reproduce the diffraction signals detected at the outer edge of the A ring and the edges of the Encke Gap and the Keeler Gap by modeling the particle populations at those edges with a power-law size distribution. We find centimeter-sized particles at the edges of the Encke Gap and millimeter-sized particles at the outer edge of the A ring. In addition to a decrease in particle size, we also find a steepening of the slope of the power-law size distribution with distance from Saturn. These constraints on the particle size distribution suggest that interparticle collisions caused by satellite perturbations in the region result in more shedding or fragmentation of particles in the outermost parts of the A ring.

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402.08 – An Unusual Feature in A-ring Janus Density Waves

We report on the results of approximately 110 stellar occultations by the A ring of Saturn as observed by the High Speed Photometer of the Cassini Ultraviolet Imaging Spectrograph between 19 May 2005 and 16 July 2014. A sharp, anomalously-dense feature is observed in 20 occultations by the Janus 4:3 spiral density wave and in 18 occultations by the Janus 5:4 spiral density wave between 9 Sept 2006 (Cassini rev 28) and 9 May 2007 (rev 44). We discuss the azimuthal extent of these features, their radial motion through the ring, and their morphology. We consider a possible connection with the January 2006 orbital swap of the Saturnian moons Janus and Epimetheus.

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402.09D – Results from a survey of the dynamics shaping Uranus’ Mab/?-ring system

Based on Hubble Space Telescope (HST) data, Showalter and Lissauer (2006) reported the discovery of two faint rings beyond Uranus’ main rings: the β - and γ - rings. They constitute Uranus’ outer ring system and are located beyond the β -ring but interior to the large classical moons. After co-adding a series of HST images, Showalter and Lissauer (2006) obtained radial profiles for both new rings. They discovered that the peak radial intensity of the β -ring aligns closely with the orbit of Mab. Along with numerous other observations, this points to the fact that the Mab/?-ring system is highly coupled.

The discovery of the β -ring has led to open questions about dust dynamics beyond Uranus’ main rings. Like Saturn’s E-ring, observations reveal that the β -ring is blue, indicative of a pre-dominance of sub-micron-sized particles (de Pater et al., 2006). The E-ring results from plumes on Enceladus’ south pole, however the origin of the β -ring remains a mystery. The latter is likely fed by ejecta from micro-meteorite impacts with Mab, much like Jupiter’s faint rings are regenerated by companion (small) moons (Burns et al., 1999). The β -ring’s steep size-distribution suggests that there is

an unknown mechanism at play that hides or removes large dust particles.

We present results from an investigation into the forces shaping the ρ -ring. To simulate the motion of dust in the Mab/ ρ -ring system, we developed a numerical toolbox (Dustsim; Kumar et al., 2015) that uses Tudat (Kumar et al., 2012). We performed integrations using Dustsim that included the effects of Uranus' gravity field, titled magnetic moment, solar radiation pressure, and collisions with a putative suite of large ρ -ring bodies, hypothesized as the cause of Mab's anomalous orbital motion (Kumar et al., 2014). Following on from previous studies (e.g., Sfair and Giuliatti Winter, 2009; Sfair and Giuliatti Winter, 2012), we present a survey of the expected lifetime of ρ -ring dust, as a function of particle size. Our results lay the basis for further research into the hypothesis that the blueness of the ρ -ring is a manifestation of size-based sorting, resulting from the natural environment.

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403 – Near-Earth Asteroid Dynamics

403.01 – NASA's Asteroid Redirect Mission: The Boulder Capture Option

NASA is examining two options for the Asteroid Redirect Mission (ARM), which will return asteroid material to a Lunar Distant Retrograde Orbit (LDRO) using a robotic solar-electric-propulsion spacecraft, called the Asteroid Redirect Vehicle (ARV). Once the ARV places the asteroid material into the LDRO, a piloted mission will rendezvous and dock with the ARV. After docking, astronauts will conduct two extravehicular activities (EVAs) to inspect and sample the asteroid material before returning to Earth. One option involves capturing an entire small (ρ 4–10 m diameter) near-Earth asteroid (NEA) inside a large inflatable bag. However, NASA is examining another option that entails retrieving a boulder (ρ 1–5 m) via robotic manipulators from the surface of a larger (ρ 100+ m) pre-characterized NEA. This option can leverage robotic mission data to help ensure success by targeting previously (or soon to be) well-characterized NEAs. For example, the data from the Hayabusa mission has been utilized to develop detailed mission designs that assess options and risks associated with proximity and surface operations. Hayabusa's target NEA, Itokawa, has been identified as a valid target and is known to possess hundreds of appropriately sized boulders on its surface. Further robotic characterization of additional NEAs (e.g., Bennu and 1999 JU3) by NASA's OSIRIS REx and JAXA's Hayabusa 2 missions is planned to begin in 2018.

The boulder option is an extremely large sample-return mission with the prospect of bringing back many tons of well-characterized asteroid material to the Earth-Moon system. The candidate boulder from the target NEA can be selected based on inputs from the world-wide science community, ensuring that the most scientifically interesting boulder be returned for subsequent sampling. This boulder option for NASA's ARM can leverage knowledge of previously characterized NEAs from prior robotic missions, which provides more certainty of the target NEA's physical characteristics and reduces mission risk. This increases the return on investment for NASA's future activities with respect to science, human exploration, resource utilization, and planetary defense.

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403.02 – Detecting NEO Impacts using the International Monitoring System

As part of the verification regime for the Comprehensive Nuclear Test Ban Treaty an International Monitoring System (IMS) consisting of seismic, hydroacoustic, infrasound and radionuclide technologies has been globally deployed beginning in the late 1990s. The infrasound network sub-component of the IMS consists of 47 active stations as of mid-2014. These microbarograph arrays detect coherent infrasonic signals from a range of sources including volcanoes, man-made explosions and bolides. Bolide detections from IMS stations have been reported since \sim 2000, but with the maturation of the network over the last several years the rate of detections has increased substantially. Presently the IMS performs semi-automated near real-time global event identification on timescales of 6-12 hours as well as analyst verified event identification having time lags of several weeks.

Here we report on infrasound events identified by the IMS between 2010-2014 which are likely bolide impacts. Identification in this context refers to an event being included in one of the event bulletins issued by the IMS. In this untargeted study we find that the IMS globally identifies approximately 16 events per year which are likely bolide impacts. Using data released since the beginning of 2014 of US Government sensor detections (as given at <http://neo.jpl.nasa.gov/fireballs/>) of fireballs we find in a complementary targeted survey that the current IMS system is able to identify \sim 25% of fireballs with $E > 0.1$ kT energy. Using all 16 US Government sensor fireballs listed as of July 31, 2014 we are able to detect infrasound from 75% of these events on at least one IMS station. The high ratio of detection/identification is a product of the stricter criteria adopted by the IMS for inclusion in an event bulletin as

compared to simple station detection.

We discuss energy comparisons between infrasound-estimated energies based on amplitudes and periods and estimates provided by US Government sensors. Specific impact events of interest will be discussed as well as the utility of the global IMS infrasound system for location and timing of future NEAs detected prior to impact.

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403.03 – Orbit Estimation for Late Warning Asteroid Impacts: The Case of 2014 AA

The possibility that newly-discovered asteroids could impact the Earth within days or weeks of their first detection raises a number of challenges, from tracking and orbit estimation, to prediction and hazard assessment, and even for public communication and disaster response. Here we focus on the astrodynamics problem of identifying and analyzing potential near-term situations requiring a rapid response, both in the observer community and in the orbit arena.

The observations for such cases will often include only an hour or so of tracking, leaving severe degeneracies in the orbit estimation. We get around this problem by exploring the poorly-constrained space of range and range rate to the observer, while the plane of sky position and motion is readily derived from the input observations. A raster scan in the two-dimensional range-range rate space allows us to identify regions in the space of possible orbits corresponding to collisions solutions. From this we can understand the possible impact times and locations, and even derive coarse estimates of impact probability.

As an example, we shall consider the case of 2014 AA. This very small asteroid (2-3 m diameter) was discovered early on the morning of January 1 by the Catalina Sky Survey operating near Tucson, Arizona. Immediate follow up provided almost 70 minutes of tracking, enough for us to predict a nearly certain impact. Indeed, infrasound observations indicate that the object entered the Earth's atmosphere over the Atlantic Ocean about 21 hours after discovery, consistent with the predictions from our technique.

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403.04 – Apophis: complex rotation and hazard assessment

(99942) Apophis is one of the most remarkable near-Earth asteroids in terms of impact hazard. In 2004 the probability of an impact in 2029 reached a peak of 2.7%. With the data available today we know that Apophis will pass Earth safely in 2029 at about 38,000 km. However, despite the availability of a well observed arc and three radar apparitions, the 2029 Earth encounter has such a strong scattering effect on the trajectory of Apophis that post-2029 predictions are only possible in a statistical sense and impacts in the following decades are hard to rule out.

To predict the future ephemerides of Apophis the dominant source of uncertainty is the Yarkovsky effect, a small nongravitational perturbation that arises from the anisotropic re-emission at thermal wavelengths of absorbed solar radiation. Modeling the Yarkovsky effect acting on an asteroid is generally challenging, as we need a good knowledge of the asteroid's physical model or observable deviations from a purely gravitational trajectory. A further complication comes from the complex rotation state of Apophis. We use the available information on the physical properties of Apophis, e.g., shape, size, thermal inertia, and rotation state, to estimate the Yarkovsky effect acting on Apophis by solving the nonlinear heat transfer equation on a finite-element mesh of facets model of the shape of Apophis.

We find that the Yarkovsky perturbation significantly affects the trajectory of Apophis despite the complex rotation. We analyze the implications on the hazard assessment by mapping the orbital uncertainty to the 2029 close approach and computing the keyholes, i.e., the locations at the 2029 Earth encounter leading to a resonant impact at a future close approach. Whereas collisions with Earth before 2060 are ruled out, impacts are still possible after 2060.

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403.05 – Properties of Earth's temporarily-captured flybys

In addition to the Moon, a population of small temporarily-captured NEOs is predicted to orbit the Earth. The definition of a natural Earth satellite is that it is on an elliptic geocentric orbit within 0.03 au from the Earth. The population is further divided into temporarily-captured orbiters (TCOs, or minimoons, making at least one full revolution around the Earth in a coordinate system co-rotating with the Sun) and temporarily-captured flybys (TCFs) which fail to make a full revolution, but are temporarily on an elliptic orbit around the Earth. Only one minimoon has been discovered to date, but it is expected that next generation surveys will be able to detect these objects regularly.

Granvik et al. (2012) performed an extensive analysis of the behaviour of these temporarily-captured objects. One of

the main results was that at any given moment there is at least one 1-meter-diameter minimoon in orbit around the Earth. However, the results of Granvik et al. (2012) raised questions considering the NES population such as the bimodality of the capture duration distribution and a distinctive lack of test particles within Earth's Hill sphere, which requires investigating the statistical properties also of the TCF population.

In this work we confirm the population characteristics for minimoons described by Granvik et al. (2012), and extend the analysis to TCFs. For the calculations we use a Bulirsch-Stoer integrator implemented in the OpenOrb software package (Granvik et al. 2009). We study, e.g., the capture statistics, residence-time distributions, and steady-state properties of TCFs. Our preliminary results indicate that TCFs may be suitable targets for asteroid-redirect missions. More detailed knowledge of the TCF population will also improve our understanding of the link between temporarily-captured objects and NEOs in general.

References: Granvik et al. (2009) *MPS* 44(12), 1853-1861; Granvik et al. (2012) *Icarus* 218, 262-277.

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403.06 – Depletion of the Near-Earth-Asteroid Population at Small Perihelion Distances

The majority of near-Earth objects (NEOs) eventually collide with the Sun. Recently it has also become evident that the intense thermal radiation close to the Sun is able to slowly erode asteroid surfaces. We show that this thermal fatigue has observable implications on a larger scale: population models describing NEO orbit and absolute magnitude distributions predict that there should be more objects on low-perihelion orbits than what is observed. This suggests that a significant fraction of all NEOs disrupt at small perihelion distances and can thus no longer be detected. The assumption that, on average, near-Earth asteroids disrupt at perihelion distances less than about 20 solar radii leads to a virtually perfect agreement between observations and theory that increasingly complicated NEO population models otherwise fail to achieve.

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403.07 – The population of small NEAs

Every two years I re-assess the completion of NEA surveys and from that estimate the size-frequency distribution of NEAs, from the largest (~10 km diameter) down to the smallest detected by surveys, only a few meters across. The number of large NEAs ($D > 1$ km) is by now well established at just under 1,000 objects, and not likely to be revised much. The greatest uncertainty lies in the smaller range, from ~100 m diameter down to about 10 m, below which bolide and meteor data yield more reliable numbers. Connecting the two in the mid-range has been a bit problematical. In this paper I will present new population estimates, concentrating in this size range, and propose a smoothed linkage between the survey estimated population at 100 m and above with the bolide estimated population at 10 m and smaller. I will also present an estimate of the population and survey completion of so-called ARM-target asteroids ($D \sim 10$ m, Earth encounter velocity < 2.6 km/sec, and MOID < 0.03 AU). I find that present ground-based surveys are surprisingly efficient detecting such objects, and that the 20 or so thus far found represent about 1% of the total population of a couple thousand. This result is consistent with the fact that of the 20 or so found, two are known to be re-discovered old rocket bodies, out of a total of about 100 such objects out there (we know the latter number because we put them there). Lastly, I will estimate the population expected of such low-v objects, based on diffusion from higher-v orbits and depletion by Earth collisions, to show that the ~2,000 population estimate is about what is expected in steady state. Larger populations could exist from time to time due to lunar ejecta launched into heliocentric orbits following major impact events on the moon. Such excesses would have a decay time scale of hundreds of thousands of years.

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403.08 – Rejuvenating NEOs: the Efficiency of Asteroid Resurfacing via Planetary Flybys

Laboratory measurements of meteorite reflectance spectra rarely match telescopic observations of asteroid reflectance spectra due to the space weathering process(es), which darkens and reddens asteroid surfaces on Myr timescales (e.g. Chapman 2004). While most main belt asteroids are weathered, a fraction of near-Earth asteroids appear unweathered (Q-types) – possibly the result of a previously unrecognized resurfacing mechanism associated with planetary encounters (Marchi et al. 2006; Binzel et al. 2010; Nesvorný et al. 2010; DeMeo et al. 2014). We hypothesize that tidal perturbations during planetary flybys trigger debris flows and are resurfacing these asteroids.

To characterize the efficiency of this tidal resurfacing process, we have developed an original numerical model for evaluating the stability of hill slopes on asteroids of arbitrary shape, density, and spin state during planetary flybys. We model the stability of asteroidal regolith using Mohr-Coulomb failure criterion (including cohesion), and track the stability of surface regolith against hill slope failure due to changing rotational, tidal, and gravitational forces through the flyby. This includes the change in rotation state of the asteroid due to tidal torques (Scheeres et al. 2000). Our Mohr-Coulomb approach is computationally simple, and allows for a much larger investigation of asteroid and flyby parameter space than comparable N-body or SPH models.

In this presentation, we will present preliminary results of this parameter space survey, in an effort to determine the efficiency of tidal resurfacing. We will also discuss the possibility of directly observing this process during the 2029 flyby of (99942) Apophis, and smaller (but more frequently encountered) asteroids like (367943) Duende. Future work will involve coupling this hill slope stability model with a 2D debris flow model. Understanding the efficiency of this process is critical for understanding the geophysics of small bodies, interpreting telescopic observations of asteroids during flybys, and constraining the still uncertain space weathering timescale.

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403.09 – The Nearest of the Near Earth Asteroids

While the orbits of many known near-Earth objects (NEOs) may cross that of Earth, very few NEOs actually approach near to Earth itself. In fact, the majority of NEOs spend most of their orbital periods in the asteroid belt beyond Mars. However, there is a subset of NEOs on orbits which allow for repeated close-encounters with Earth. These objects are locked in a co-orbital resonance with Earth, orbiting the sun in exactly one year. This unusual one-to-one resonance causes the NEOs to appear to be orbiting Earth and gives them their name; quasi-satellites.

Despite their close proximity to Earth, only recently have the first quasi-satellites of Earth been detected. These are the asteroids 2003 YN107, 2004 GU9, and 2006 FV35. We carried out N-body computer simulations of these asteroids as well as a larger theoretical population. We demonstrate that quasi-satellite asteroids always remain exceptionally close to Earth, typically just 20-60 times farther than the moon, and undergo two close-encounters with Earth each year. Furthermore, quasi-satellites that eventually escape the resonance can have extremely deep low-velocity close-encounters with Earth as they leave the resonance, some coming well inside the orbit of the moon.

When weak drag forces are included in the simulations quasi-satellite objects evolve onto more Earth-like orbits and spiral closer and closer to Earth. This dramatically reduces the relative velocity and distance of closest approach between Earth and the quasi-satellite object. Under the influence of weak drag quasi-satellites objects can develop effective encounter velocities of just a few hundred meters per second, often much less. These low encounter velocities lead to a strong enhancement in Earth's gravitationally enhanced impact cross-section compared to close-encounters of non-resonant objects with similar initial orbital elements.

This research is supported by NASA grant NNX14AN23G.

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404 – Pluto 2: Mostly Surface

404.01 – The Size of Pluto

The presence of a thin atmosphere around Pluto prevents the stellar occultation method from probing all the way down to the surface of Pluto. As such, the most accurate method for measuring the size of Pluto is fitting the mutual event photometry from 1985 to 1990. Previous fits solved for not only the size of Pluto, but also the size and orbit of Charon. Since that era, the size and orbit of Charon have been determined independently and more accurately via other means. Stellar occultation measurements have established the diameter of Charon as 1212 km, while the orbit of Charon has been determined via direct images obtained with the Hubble Space Telescope over a period of two decades. By imposing the known values for the size and orbit of Charon on the fits to the mutual event photometry, a new size for Pluto can be derived with considerably fewer free parameters. To perform this fit, the extensive set of mutual event photometry acquired at Mauna Kea Observatory was utilized. A fit to all the data yields a diameter for Pluto of 2317 km. To avoid the question of limb darkening on Pluto and the effect of albedo variation over the surface of Pluto, even fewer free parameters can be solved for by restricting attention to just the superior mutual events, during which Charon was behind Pluto. In this case the diameter of Pluto increases to 2379 km. Work is currently being done to determine how weighting of the data affects the result. The true value will become known in a few months when New Horizons flies past Pluto. These fits also show that there is still room for improvement in the orbit of Charon.

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404.02 – Impact and Cratering History of the Pluto System

The observational opportunity of the New Horizons spacecraft fly-through of the Pluto system in July 2015 requires a current understanding of the Kuiper belt dynamical sub-populations to accurately interpret the cratering history of the surfaces of Pluto and its satellites. We use an Opik-style collision probability code to compute impact rates and impact velocity distributions onto Pluto and its binary companion Charon from the Canada-France Ecliptic Plane Survey (CFEPS) model of classical and resonant Kuiper belt populations (Petit et al., 2011; Gladman et al., 2012) and the scattering model of Kaib et al. (2011) calibrated to Shankman et al. (2013). Due to the uncertainty in how the well-characterized size distribution for Kuiper belt objects (with diameter $d > 100$ km) connects to smaller objects, we compute cratering rates using three simple impactor size distribution extrapolations (a single power-law, a power-law with a knee, and a power-law with a divot) as well as the "curvy" impactor size distributions from Minton et al. (2012) and Schlichting et al. (2013). Current size distribution uncertainties cause absolute ages computed for Pluto surfaces to be entirely dependent on the extrapolation to small sizes and thus uncertain to a factor of approximately 6. We illustrate the relative importance of each Kuiper belt sub-population to Pluto's cratering rate, both now and integrated into the past, and provide crater retention ages for several cases. We find there is only a small chance a crater with diameter $D > 200$ km has been created on Pluto in the past 4 Gyr. The 2015 New Horizons fly-through coupled with telescope surveys that cover objects with diameters $d = 10$ -100 km should eventually drop current crater retention age uncertainties on Pluto to $< 30\%$. In addition, we compute the "disruption timescale" (to a factor of three accuracy) for Pluto's smaller satellites: Styx, Nix, Kerberos, and Hydra.

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404.03 – Medium-resolution ($R \sim 3800$) Near-infrared Spectrum of Charon from 1.47-2.38 μm

Spectra showing a clearly spatially separated Pluto and Charon were obtained using the Keck/OSIRIS instrument and adaptive optics from 2010 to 2013. Spectra were obtained in the near-infrared with the Hbb (1.47-1.80 μm) and Kbb (1.97-2.38 μm) filters with an average spectral resolution of 3800. A total of 39 Pluto/Charon spectra were obtained in the Hbb band and 45 Pluto/Charon spectra were obtained in the Kbb band. Preliminary analysis of averaging all individual Charon spectra in each band resulted in spectra with a signal-to-noise of ~ 25 per 0.2 nm in Hbb and ~ 27 per 0.25 nm in Kbb. This high-signal-to-noise, medium-spectral-resolution Charon spectrum will allow us to confirm or deny the presence of previously claimed ice species, undertake a search for ice species as yet undetected on the surface, and re-tool expectations for the New Horizons flyby of Charon in July 2015. This work was funded in part by NASA's Planetary Astronomy Program and by the NASA Earth and Space Science Fellowship Program.

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404.04 – New rotationally resolved spectra of Pluto-Charon from 350 - 900 nm

We are using the 11-meter Southern African Large Telescope (SALT) to acquire the first rotationally resolved visible spectra of Pluto-Charon in nearly 20 years. We use the Robert Sobie Spectrograph (RSS) to observe Pluto-Charon from 350 nm to 900 nm. At 500 nm, resolution is 0.05 nm ($R \sim 10,000$) and SNR per spectral resolution element is ~ 500 .

We planned observations for 13 dates during June - August 2014, spaced so as to evenly sample Pluto's 6.5-day rotational period. As of the abstract submission, we have 8 of these in hand, two of which sample the same hemisphere as the best planned color New Horizons image. We determined the surface reflectivity by comparing with the solar-type star HD 146233.

Our results will provide constraint on the composition and spatial distribution of material on Pluto's surface, enabling comparison to previous epochs and near-infrared results, and giving a present-day 'ground truth' ahead of New Horizons' July 2015 flyby. In addition, our data will allow us to search for new spectral features in the range 350 nm to 600 nm, at a sensitivity substantially higher than all previously published searches.

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404.05 – Diurnal and Seasonal Variations of Pluto's surface composition through Spitzer Space telescope eyes

NASA's New Horizons mission will encounter the Pluto system in July 2015. The payload of this mission has been designed to provide us with detailed knowledge on the physical and chemical characteristics of this icy world. From decades of ground-based visible and near-infrared (VNIR) observations we know that mixtures of CH₄, N₂ and CO, heterogeneously distributed, dominate Pluto's surface. However, this composition is changing with a timescale of only months to years. Even though this mission will provide a very precise snapshot of the Pluto system, continuous monitoring before and after encounter are needed to gain a better understanding of the long term evolution of Pluto's volatiles and atmosphere.

Here we present broadband photometry of the Pluto-Charon system obtained in 2004 with IRAC/Spitzer, during the cryogenic phase of the mission. These data were acquired at eight equally spaced sub-observer longitudes. Two distinct spectral behaviors are readily apparent from the study of the albedos at 3.6, 4.5, 5.8 and 8.0 μ m. Four longitudes show a lower albedo in channel-2 (4.5 μ m) and a higher albedo in channel-1 (3.6 μ m) suggesting a higher abundance of N₂ (~4.29 μ m) and/or CO (~4.68 μ m), and possibly CO₂ (~4.27 μ m) in these regions. This variability appears to be consistent with ground-based VNIR observations but the sparse 8-longitudes cadence precludes detailed comparison.

In 2014 we conducted a second IRAC/Spitzer observational campaign to obtain data at 18 equally spaced longitudes in channel-1 and 2. These observations resulted in higher density light-curves. Along with spatial variability, the two datasets enable us to investigate temporal changes over a decade timescale.

We show here a comparative study of the longitudinal variations of Pluto's surface composition at two different dates separated by ten years. We investigate whether these variations indicate secular volatile transport or whether they are due to spatial variations of ices with latitude (sub-observer latitude changed from 33° to 51° from 2004 to 2014, both on the Northern hemisphere). Finally, we discuss what these variations tell us regarding the large picture of Pluto's atmospheric and surface composition.

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404.06 – Continued Volatile Transport on Pluto: First Results from the 2014 Observing Season

With its high eccentricity and obliquity, Pluto should exhibit seasonal volatile transport on its surface. This transport should be detectable through changes in its historical rotational light curve, once all variations due to viewing geometry have been modelled. Observations of Pluto's light curve between 1950 and 1999 suggest a stable albedo pattern. Starting in the early part of this millennium, both new Hubble Space Telescope maps and light curve measurements obtained at JPL's Table Mountain Observatory show evidence of small changes in Pluto's distribution of surface albedo (Hicks et al. 2008, B.A.A.S. 40, 460.; Buie et al., 2010, Astron. J. 139, 1128). Supporting possible surface volatile transport is the doubling of Pluto's atmospheric pressure over the past two decades (Young et al., 2013, Ap. J. 766, L22). With the New Horizons spacecraft due to encounter Pluto in July 2015, close scrutiny of this dwarf ice planet has begun in earnest. Ground-based observations are especially critical for context and for a larger temporal excursion. Rotational light curves of Pluto have been created in two recent epochs: 2007-2008, and 2012-2014. Both light curves show a smaller amplitude than that expected for a static frost model based on albedo maps from the earliest HST images (Stern et al. 1997, Astron. J. 113, 827).

Observations of both Buie et al. (2010) and our own between 2007 and 2014 show that Pluto is becoming redder. This observation makes sense if nitrogen frost is being removed from the surface to uncover a red, photolyzed substrate of methane.

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404.07 – The methane–nitrogen mixing ratio across the surface of Pluto by means of a two-phase Hapke model

Modeling of Pluto's spectra by many groups (e.g., Douté et al., 1999; Olkin et al., 2007; Protopapa et al., 2008) employs pure methane and methane diluted at low concentrations in nitrogen. However, the coexistence of pure and diluted methane on Pluto's surface violates thermodynamic equilibrium: the methane-nitrogen binary phase diagram generated from X-ray diffraction studies by Prokhvatilov and Yantsevich (1983) indicates that at Pluto's surface temperature of about 40 K (Tryka et al., 1994) methane ice saturated with nitrogen and nitrogen ice saturated with

methane must coexist. New optical constants of methane diluted in nitrogen and nitrogen diluted in methane have been recently computed at temperatures between 40 and 90 K, in the wavelength range 0.8 – 2.5 micron at different mixing ratios (Protopapa et al., 2014). These laboratory measurements enable, for the first time, a proper characterization of Pluto's surface composition under conditions of thermodynamic equilibrium. A two-phase Hapke model of Pluto's near-infrared spectroscopic measurements and its implications for the methane-nitrogen mixing ratio across Pluto's surface will be discussed.

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404.08 – The Infrared Optical Constants of Ethane and Ethylene Ices: Relevance to Pluto and Triton

As New Horizons approaches the Pluto system, our research group is carrying out new infrared optical-constants measurements of hydrocarbons with an emphasis on temperatures below ~70 K. Our goal is to add to the relatively meager literature on this subject and to provide electronic versions of state-of-the-art data, since the abundances of such molecules cannot be deduced without accurate optical constants (n, k) and reference spectra. Ethane (C₂H₆) and ethylene (C₂H₄) are the subject of the present work. Photochemical models of the atmospheres of Pluto and Triton predict both of these molecules as abundant precipitating products (Krasnopolsky and Cruikshank, 1995, JGR 100, 21271-21286; Krasnopolsky and Cruikshank, 1999, JGR 104, 21979-21996), and the infrared reflectance features of both Pluto and Triton are well fit by laboratory spectra when pure, solid ethane is included as a component (Cruikshank et al., 2006, Bulletin of the AAS 38, 518). Here we present our recent measurements of near- and mid-infrared optical constants for ethane and ethylene in multiple ice phases and at multiple temperatures. We also report new measurements of the index of refraction of each ice at 670 nm. Comparisons are made to earlier work where possible. Electronic versions of our new results are available at <http://science.gsfc.nasa.gov/691/cosmicice/constants.html>.

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404.09 – Laboratory Investigations of Complex Refractory Organic Material Produced from Irradiation of Pluto Ice Analogs

Much of Pluto's surface consists of N₂ ice with smaller amounts of CH₄ and CO ices. Despite the low temperature (~45K), chemistry can be driven in the surface ices by radiation processing such as cosmic ray bombardment. When cosmic rays strike the surface, much of their energy is dispersed in the form of secondary electrons, which in turn drive much of the resulting chemical reactions. Laboratory experiments designed to simulate the conditions on these icy bodies may provide insight into this chemistry. Significant progress has been made in the laboratory toward understanding the smaller, simple compounds produced in the solid phase by radiation processing of (N₂, CH₄, CO) ices (Bohn et al. 1994; Moore & Hudson 2003; Hodyss et al. 2011; Kim and Kaiser 2012). Recently Materese et al. (2014) used a variety of techniques to better characterize the refractory materials produced from the UV photo-irradiation of N₂:CH₄:CO ices. However, because Pluto's atmosphere is optically thick to Lyman- γ UV radiation it is important to re-examine the results using an alternate radiation source. Our latest work has consisted of the analysis of refractory materials produced from the electron bombardment of low-temperature N₂-, CH₄-, and CO-containing ices (100:1:1). The ice mixture was chosen to be analogous to the known surface ices on Pluto and the radiation source was chosen to mimic the secondary electrons produced by cosmic rays bombardment. The residues were studied using multiple chemical techniques including, infrared (IR) spectroscopy, X-ray absorption near-edge structure (XANES) spectroscopy, and gas chromatography coupled with mass spectrometry (GC-MS). The organic residues produced in these experiments can be seen as an analog for the refractory component of the surface of Pluto, and are compared with the residues previously obtained from UV photo-irradiation. UV and near-IR spectroscopy of the surfaces of Pluto and Charon during the encounter with NASA's New Horizons spacecraft in 2015, will give the first close-up measurements of ices and their photoproducts. Laboratory measurements and experiments will provide a better context for the data returned by the spacecraft.

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405 – Active Icy Worlds

405.01 – Curtains for Enceladus

We have produced maps of fracture activity in Enceladus' south-polar region at five different times spanning about one

year in 2009 and 2010 using Cassini imaging data. In contrast to our prior work (Spitale and Porco 2007), where we triangulated the locations of eight prominent sources based on distant Cassini imaging observations, in this work we use more recent close-in imaging to characterize the activity in finer detail than possible in the earlier study. We apply a new approach that is more compatible with the geometry of the south-polar fractures than previous approaches (Spitale and Porco 2007, Porco et al. 2014) and which allows us to consider the entire range of activity detectable in the Cassini images. We note that many features in the high-resolution images that might otherwise be identified as discrete jets are fictitious, arising from the viewing geometry relative to continuous curtains of material emanating from the fractures. We find good agreement between average activity counts and the pattern of thermal anomalies seen by the Cassini Composite Infrared Spectrometer (Howett et al. 2011). The total length of active fracture at each mean anomaly is consistent with the variation of the material observed in the global plume by the Cassini Visual and Infrared Mapping Spectrometer (Hedman et al. 2013). Our results suggest that heating along the tiger stripes is significantly influenced by the cycle of fractures turning on and off, rather than solely by the magnitude of the material flux. We infer the presence of two unseen fractures parallel to Baghdad Sulcus that have become active as recently as 1000 years ago. Large fractures associated with Damascus, Baghdad, and Alexandria Sulci show no activity and may have recently become inactive. We note the sudden activation of three discrete jets on Baghdad Sulcus and place a lower bound of 120 m/s on the average particle velocities in two of those jets.

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405.02 – Enceladus' enigmatic heat flow

Enceladus' heat flow provides a fundamental constraint on its tidal dissipation mechanisms, orbital evolution, and the physical processes that generate the plumes. An initial estimate of this value, 5.8 ± 1.3 GW, was made by Spencer et al. (2006) using Cassini Composite Infrared Spectrometer (CIRS) 600 to 1100 cm^{-1} observations. This number was refined using 10 to 600 cm^{-1} CIRS observations to 15.8 ± 3.1 GW by Howett et al. (2011). However, recent reanalysis of high-spatial resolution 10 to 1100 cm^{-1} CIRS observations of Enceladus' active south polar region conducted by Spencer and Howett gives a heat flow of 4.64 ± 0.23 GW. Whilst all of these heat flow estimates are much larger than those expected in a steady state, 1.1 GW (Meyer and Wisdom, 2007), their obvious discrepancy is a puzzle. Was the passive emission component simply underestimated in the 15.8 GW determination, or is there significant between-stripe endogenic emission that is excluded in the most recent estimate, or is something else going on?

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405.03 – Possible evidence for a methane source in Enceladus' internal ocean

We investigated the possible formation of clathrate hydrates (hereafter clathrates) in Enceladus' putative internal ocean. We modeled this ocean as a terrestrial subglacial lake, with an initial composition matching the one of the plumes as determined by the Cassini-INMS mass spectrometer. We used a statistical thermodynamic model based on the description of the guest-clathrate interaction by a spherically averaged Kihara potential with a nominal set of potential parameters. We investigated the behavior of five detected volatile species prone to be trapped into clathrates: CO_2 , CO , CH_4 , N_2 and H_2S . Noble gases (Ar, Kr, Xe) were also considered in order to compare predictions with future measurements. Our calculations considered an ocean extending from 35 to 50 km under the ice layer, at a temperature value of 0°C . We found that the conditions for the formation of clathrates are met in the ocean. The exact structure of these clathrates (structure I or II) is not firmly determined as species known to form both are present. We found that CH_4 is very efficiently trapped into clathrate phase and its proportion among dissolved species always falls below plume levels. Additional tests considering different mixtures with more CH_4 do not solve this question as the efficiency of the trapping always bring CH_4 levels below the expected value. This points to an subsequent dissociation of clathrates or to an additional methane source in the ocean. The fate of the clathrates depends on their density: they can either ascend to the top of the ocean, possibly reaching a region of lower pressure where they dissociate, or sink to the bottom. We found that pressure above a 20km depth would allow for dissociation. The density of the clathrates depends on which structure is formed, but we determined that a proportion of partially-filled clathrate would ascend in all cases. To establish the link with a methane source, a study of the timescale of entrapping and transfer is needed. Especially, ascension from the bottom of the ocean could be slowed down by horizontal currents which are thought to be non-negligible at the scale of Enceladus.

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405.04 – Linking Europa’s Plume Activity to Tides, Tectonics, and Liquid Water

Much of the geologic activity preserved on Europa’s icy surface has been attributed to tidal deformation, mainly due to Europa’s eccentric orbit. Although the surface is geologically young, evidence of ongoing tidally-driven processes has been lacking. However, a recent observation of water vapor near Europa’s south pole suggests that it may be geologically active. Non-detections in previous and follow-up observations indicate a temporal variation in plume visibility and suggests a relationship to Europa’s tidal cycle. Similarly, the Cassini spacecraft has observed plumes emanating from the south pole of Saturn’s moon, Enceladus, and variability in the intensity of eruptions has been linked to its tidal cycle. The inference that a similar mechanism controls plumes at both Europa and Enceladus motivates further analysis of Europa’s plume behavior and the relationship between plumes, tides, and liquid water on these two satellites.

We determine the locations and orientations of hypothetical tidally-driven fractures that best match the temporal variability of the plumes observed at Europa. Specifically, we identify model faults that are in tension at the time in Europa’s orbit when a plume was detected and in compression at times when the plume was not detected. We find that tidal stress driven solely by eccentricity is incompatible with the observations unless additional mechanisms are controlling the eruption timing or restricting the longevity of the plumes. In contrast, the addition of obliquity tides, and corresponding precession of the spin pole, can generate a number of model faults that are consistent with the pattern of plume detections. The locations and orientations of the model faults are robust across a broad range of precession rates and spin pole directions. Analysis of the stress variations across model faults suggests that the plumes would be best observed earlier in Europa’s orbit. Our results indicate that Europa’s plumes, if confirmed, differ in many respects from the Enceladean plumes and that either active fractures or volatile sources are rare.

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405.05 – New Observations of Europa's Surface Composition: Discovery of an Anti-Jovian Salty Region

The surface composition of Europa is the best means available to probe its global chemical cycle and constrain the composition of its ocean. New observations of Europa's near-infrared reflectance spectra were obtained with the OSIRIS instrument on the Keck II telescope. Previous investigations of Europa's surface composition have mostly relied on Galileo NIMS infrared spectra; though NIMS measurements have high spatial resolution, they lack spectral resolution and span a limited spatial extent. Conversely, our observations comprise a near-global spectral map of Europa in the infrared H and K bands. At ~ 1 nm spectral resolution and ~ 100 km spatial resolution, these data reveal global distributions of key spectral features, enabling a more complete characterization of Europa's surface composition than previously possible.

Simple linear spectral modelling of these data reproduces the global abundance distributions of water ice and sulfuric acid hydrate. In addition, this modelling reveals a suggestively "salty" region on Europa's anti-Jovian hemisphere. This region is spectrally distinct from both the trailing hemisphere bullseye and the spectrum of pure water ice, and shows a direct spatial correlation to an anti-Jovian chaos unit. Similar chaos regions show enhancements of saltier spectra as well, though to a lesser degree.

We report three spectral end member regions on Europa's surface, represented by the trailing hemisphere bullseye, the leading hemisphere north polar "icy" region, and the anti-Jovian "salty" chaos unit. We present global compositional maps, and discuss the potential compositions of the three end member regions.

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405.06 – New constraints on the surface properties of Triton

Triton is one of the largest satellites of the solar system and was probably captured from the transneptunian population. The global composition, size and orbit of this object lead to the formation, as in the case of Pluto, of a thin N₂ rich atmosphere, with CH₄ and CO traces (Lellouch et al. 2011 Msngr145, Greaves et al. 2011 RAS 414). Sublimation of these species could lead to geographical and temporal chemical variation (Grundy et al. 2010 Icarus 205) as well as the formation of complex chemical compounds mainly formed from irradiation of N₂:CH₄:CO layers (Moore and Hudson 2003 Icarus 161). Quirico et al. (1999 Icarus 139), for instance, mentioned unidentified features possibly due to the presence of such material.

New observations have been obtained at the VLT-ESO with SINFONI and will be presented in order to comment on new constraints on the chemical and physical properties of the surface from H and K band spectroscopy at different longitudes.

Our analyses confirm the strong longitudinal variation of N₂ and CO species and indicate temporal variation too. Several

models based on the Hapke theory (1981) have also been tested in order to constrain the temperature, size, abundance and state of the major ices (N₂, CH₄, CO, CO₂ and H₂O) as well as an attempt to identify other species (NH₃, C₂H₂, C₂H₆).

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405.07 – Tidal Dissipation in the Oceans of Icy Satellites

Dissipation of tidal energy is an important mechanism for the evolution of outer solar system satellites, several of which are likely to contain subsurface oceans. We extend previous theoretical treatments for ocean tidal dissipation by taking into account the effects of ocean loading, self-attraction, and deformation of the solid regions. These effects modify both the forcing potential and the ocean thicknesses for which energy dissipation is resonantly enhanced, potentially resulting in orders of magnitude changes in the dissipated energy flux.

Assuming a Cassini state obliquity, Enceladus' dissipated energy flux due to the obliquity tide is smaller than the observed value by many orders of magnitude. On the other hand, the dissipated energy flux due to the resonant response to the eccentricity tide can be large enough to explain Enceladus' observed heat flow.

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405.08 – Impact Rates on Giant Planet Satellites: Checking Our Assumptions

The giant planets gravitationally scatter comets more often than they accrete them. Levison and Duncan (1997) and Levison et al. (2000) estimated that only about 2% of ecliptic comets struck a planet, with most ultimately being ejected into interstellar space by Jupiter. Impact rates on even the biggest moons are a factor of 10,000 smaller yet. Thus, even with fast computers and orbital integrators, determining impact rates on moons directly is impractical. A statistical approach is required. Shoemaker and Wolfe (1982) used Öpik's equations (Öpik 1951, Kessler 1981), which, for this application, give the impact probability of a small body with a satellite on a circular orbit in terms of the small body's planetocentric pericenter distance, orbital eccentricity (greater than 1 except for temporarily bound Shoemaker-Levy 9-like comets), and inclination. Zahnle et al. (1998, 2003) performed Monte Carlo simulations that implement Öpik's equations and tabulated impact rates for a wide variety of satellites. We have confirmed these results with a semi-analytic approach. However, both Zahnle et al. and we assume that the orbital distribution of ecliptic comets that cross the Hill sphere of a planet is isotropic in the frame of the planet. Isotropy is a reasonable approximation for the typical low-to-moderate heliocentric eccentricities and inclinations of ecliptic comets (Levison et al. 2000), but the magnitude of the error incurred by this assumption is unknown. We will present the results of orbital integrations in which we assume a distribution of heliocentric elements for a vast number of giant planet-crossing or -approaching comets and will follow their orbits through the planet's Hill sphere. We will compute impact rates with satellites and will compare our results with those assuming an isotropic distribution of impactors.

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405.09 – Towards a Unified Theory of Impacts and Crater Populations on Icy Satellites

We present our recent work to derive a unified, self-consistent model for the divergent crater populations seen on the Saturnian (and Galilean) satellites. We attack this problem from multiple fronts: modeling the flux of impactors, the resulting primary craters on the satellites' surfaces, modeling the production of ejecta fragments and their corresponding secondary craters, and correlation between the modeling and measured crater populations on the satellites.

Our recent work includes (i) quantifying the expected secondary populations, and (ii) extensive crater measurements against which to compare our models. For (i), we find that the interplay between v_{\min} (the min speed to make a crater), v_{esc} , surface gravity, and the inverse relationship between ejection speed and fragment size, result in different secondary crater populations on satellites. For (ii), we found that the escape speed on Mimas is so small that

secondaries may not form on that satellite, or if they do, they are too small to be seen at currently available image resolution. We are expanding our measurements on Rhea, on which we predict a measurable and significant secondary crater population. We will continue our measurements to include Tethys, Dione, Iapetus, and Hyperion, and will compare those with existing measurements of the icy Galilean satellites.

We find that the different combinations of impact speeds and surface gravities across the satellites, in conjunction with minimum (v_{\min}) and maximum (v_{esc}) speeds, produce a diverse set of outcomes between primary crater sizes and secondary crater production and distribution; the net effect is that a single impacting population (e.g. comets) can generate different crater populations. These predictions have been borne out by the crater measurements made to date. Thus it may not be necessary to appeal to multiple or time-dependent impacting populations to explain differences observed in the crater populations on the mid-sized Saturnian satellites, or the differences between the Saturnian satellites and Galilean satellites. This work is supported by a grant from the NASA CDAPS program.

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409 – Asteroid Physical Characterization 1: Close Encounters

409.01 – Goldstone and Arecibo Radar Images of Near-Earth Asteroid 2014 HQ124

2014 HQ124 was discovered by the NEOWISE mission on 2014 April 23, about six weeks before the asteroid approached within 0.0084 au on June 8. Prior to the encounter, A. K. Mainzer used NEOWISE data and a thermal model to estimate a diameter of 330 ± 90 m. The NEOWISE data and photometry obtained by J. T. Pollock yielded a rotation period of ~20 h and a lightcurve amplitude of 0.8 mag. The close approach, diameter, and slow rotation indicated that this object would provide an outstanding opportunity for radar imaging, characterization, and orbit refinement. We observed 2014 HQ124 on June 8 and 10 with at Goldstone, Arecibo, and the Very Long Baseline Array (VLBA). We conducted monostatic radar imaging at X-band (8560 MHz, 3.5 cm) with the 70 m DSS-14 antenna and at S-band (2380 MHz, 13 cm) with Arecibo; bistatic X-band imaging using DSS-14 to transmit and Arecibo and the 34 m DSS-13 antenna to receive; and S-band radar speckle observations to constrain the spin state using Arecibo to transmit and the Pie Town, Los Alamos, Ft. Davis, and Kitt Peak VLBA facilities to receive. Radar astrometry improved the orbit significantly and increased the interval of reliable orbit estimation by a factor of two to ~900 years. The images achieve a resolution of 3.75 m x 0.00625 Hz and provide some of the most detailed radar views obtained for any near-Earth object. 2014 HQ124 is elongated, angular, and bifurcated with a long axis of at least 400 m. The asteroid has a large concavity, possible ridges, and small-scale features including radar-bright spots that are candidates for boulders. The larger lobe has a narrow, sinuous, ~100-m-long radar-dark feature that may be a scarp or perhaps a fault. These observations were the first test of new data taking equipment at Arecibo that can acquire images at 3.75 m resolution, which is twice as fine as the highest range resolution that Arecibo can achieve with monostatic observations. Receiving echoes at Arecibo using transmissions from Goldstone also boosts the signal-to-noise ratio by a factor of five relative to monostatic Goldstone observations and is ideal for resolving very close and/or small near-Earth objects with slow spin states.

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409.02 – Radar-Derived Shape Model of Near-Earth Binary Asteroid System (285263) 1998 QE2

We report on shape modeling of binary asteroid 1998 QE2, a 3.2-km asteroid with a 800-m moon. We observed this asteroid with both Arecibo Observatory planetary radar (2380 MHz, 12.6 cm) and Goldstone Solar System Radar (8560 MHz, 3.5 cm) between May 31-Jun 9, 2013. The close approach on May 31, 2013 (0.039 au) presented an outstanding opportunity for radar delay-Doppler imaging with resolutions as fine as 7.5 m of both objects. The extensive radar dataset was used for shape modeling of both components. Our SHAPE 3D modeling software (Hudson, 1993 and Magri et al., 2007) uses a constrained, weighted least-squares minimization procedure to invert radar delay-Doppler images.

The rotation rate of the primary, 4.749 ± 0.002 h, was well constrained from optical lightcurves (P. Pravec, pers. comm.) and rotates prograde as determined from radar data. The primary is roughly spheroidal, showing prominent concavities and surface features, with effective diameter 3.2 ± 0.3 km.

The secondary is irregularly shaped, with an effective diameter of 800 ± 80 m and significant elongation. The radar data suggest it is tidally locked, with an orbital period of 31.31 ± 0.01 h hours and a semi-major orbital axis of 6.2 ± 0.1 km. The orbit is approximately circular ($e < 0.01$), which is typical of most near-Earth asteroid binary system orbits. We

estimate a preliminary density for the primary of $0.7 \pm 0.2 \text{ g/cm}^3$. The low density is consistent with a "rubble pile" structure.

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409.03 – The Smallest Binary Asteroid? The Discovery of Equal-Mass Binary 1994 CJ1

Arecibo S-band (12.6 cm, 2380 MHz) radar observations of asteroid 1994 CJ1 in late June/early July 2014 reveal two roughly equal-size bodies in mutual orbit. This is only the second such system identified in the near-Earth region following 69230 Hermes. The components of the 1994 CJ1 binary are, however, several times smaller than the components of the Hermes binary. At less than 150 meters in diameter, the components of 1994 CJ1 are comparable to the smallest primaries known, those of the 2003 SS84 and 2004 FG11 binary systems. The maximum range separation of the components is at least 525 meters, implying a mutual orbit at least 7 primary radii wide or twice as wide as the (scaled) Hermes system. An incomplete optical lightcurve suggests a mutual-orbit period of 30 hours and includes a partial eclipse/occultation event. Constraints on the physical parameters of the system will be presented.

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409.04 – Radar evidence for diverse shapes of the primaries among binary near-Earth asteroids

The Arecibo and Goldstone planetary radars have been exceptionally valuable instruments for the discovery of binary and triple asteroids in the near-Earth asteroid (NEA) population. To date, 34 out of 46 known binaries and two ternaries (~71% objects total) have been discovered by radar. One of the first discovered and most well studied binary systems is (66391) 1999 KW4 (Ostro et al., 2006). This was the first system with radar evidence for a prominent equatorial bulge, sloped hemispheres, and polar flattening. 1999 KW4 Alpha became a "canonical shape model" for many theoretical studies and numerical simulations on the nature of the binary systems. As the number of binaries detected by radar grew, evidence mounted that not all primaries look like 1999 KW4 Alpha. In fact, (276049) 2002 CE26 (Shepard et al., 2006) and (285263) 1998 QE2 (Springmann et al., 2014) have very rounded shapes without an obvious presence of equatorial ridges. Furthermore, (164121) 2003 YT1 (Nolan et al., in prep.), (1862) Apollo (Ford et al., in prep.), and (363599) 2006 VV2 all have irregular, moderately elongated shapes that show the presence of a bulge at only selected longitudes. All three objects also show elongations of 1.2-1.3, which is still smaller than the mean elongation of ~1.5 in the NEA radar sample. Nevertheless, numerous other primaries have KW4-like shapes such as (185851) 2000 DP107 (Naidu et al., 2011), (311066) 2004 DC (Taylor et al., 2008), and (175706) 1996 FG3 (Benner et al., in prep.). We estimate the abundance of KW4-like objects to be at least 40% of the multiple system population, based on the 41 radar-detected cases. Our results only give the lower bound because not all the dataset have the sufficient SNRs and/or the rotational coverage. Recent Goldstone delay-Doppler images of 2013 WT44 were obtained at nearly pole-on subradar latitude and clearly show evidence of an equatorial bulge, sloped hemispheres, and polar flattening. This has provided one of the strongest arguments to date that KW4-like shapes are real and that they are not artifacts of the shape modeling algorithms. This does not come as a surprise given that KW4-like shapes are strongly motivated by the physics of the rapidly rotating rubble pile.

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409.05 – Recent Radar Speckle Observations of Near-Earth Asteroids

Radar speckle tracking is an observational technique to constrain the spin state of a target object. When illuminated by a monochromatic radar beam, the target scatters light into regions of constructive and destructive interference - a speckle pattern. This pattern moves as the target rotates, with a speed and direction determined by the object's rotation rate

and spin vector. By tracking the motion of a radar speckle pattern between two or more receiving stations, we can constrain the spin state of the target.

First applied to measure the spin state of Mercury, since 2008 radar speckle tracking has become one of the standard techniques for radar observations of near-Earth asteroids. We transmit with either of the Arecibo and Goldstone planetary radars, receive with elements of the Very Long Baseline Array or of the Very Large Array, and measure the time lags between the speckle pattern as seen by each station. Starting with the first asteroid observed with speckle observations, 2008 EV5, this technique has allowed us to resolve ambiguities in asteroids' spin states that delay-Doppler radar imaging and lightcurve observations did not.

Recent radar speckle targets have included the near-Earth asteroids 1998 ML14, 2005 WK4, and 2014 HQ124. ML14 was observed with radar shortly after its discovery in 1998, but the earlier radar observations did not yield a unique pole direction constraint. HQ124 is a contact-binary object and was one of the best radar targets of 2014.

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409.06 – Recent Arecibo Radar Observations of Main-Belt Asteroids.

We recently observed main-belt asteroids 12 Victoria (Tholen S-class, Bus L-class), 246 Asporina (A-class), and 2035 Stearns with the S-band (12 cm) Arecibo radar. Signal-to-noise ratios for Asporina and Stearns were only strong enough for continuous-wave (CW) analysis. Signal-to-noise ratios for Victoria were high enough for delay-Doppler imaging. Stearns exhibited a high radar polarization ratio of unity, higher than any other main-belt E-class, but similar to near-Earth E-class asteroids [Benner et al. *Icarus* 198, 294-304, 2008; Shepard et al. *Icarus* 215, 547-551, 2011]. The A-class asteroids show spectral absorption features consistent with olivine and have been suggested as the source of pallasite meteorites or the rare brachinites [Cruikshank and Hartmann, *Science* 223, 281-283, 1984]. The radar cross-section measured for Asporina leads to a radar albedo estimate of 0.11, suggesting a low near-surface bulk density, and by inference, a low metal content. This suggests that the brachinites are a better analog for Asporina than the iron-rich pallasites. Victoria has been observed by radar in the past and the continuous-wave echoes suggest it has a large concavity or is a contact binary [Mitchell et al. *Icarus* 118, 105-131, 1995]. Our new imaging observations should determine which is more likely.

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410 – Origins of Planetary Systems 1

410.01 – From Dust to Protoplanets

To date, most simulations of planetary accretion have considered a single stage of growth such as dust coagulation, planetesimal formation, or oligarchic growth. However, these stages are likely to take place concurrently in different regions of a protoplanetary disk, and even at the same location in a disk. This can lead to interactions and feedbacks between the various growth stages, altering the outcome. Here I will present results of new simulations that model growth from micrometer-size dust grains up to planetary embryos throughout a protoplanetary disk, including potentially important physical processes such as radial drift, bouncing and fragmentation during collisions, and pebble accretion onto large bodies. I will also discuss the implications for giant-planet formation, dust retention in protoplanetary disks, and meteorite parent body ages and compositions.

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410.02 – The Formation of Terrestrial Planets from the Direct Accretion of Pebbles

A radical new scenario has recently been suggested for the formation of giant planet cores that reports to solve this long-standing problem. This scenario, known as pebble accretion, envisions: 1) Planetesimals form directly from millimeter- to meter-sized objects (the pebbles) that are concentrated by turbulent eddies and then gravitationally collapse to form 100 – 1000 km objects (Cuzzi+ 2008, *AJ* 687, 1432; Johansen+ 2007, *Nature* 448, 1022). 2) These planetesimals quickly sweep up the remaining pebbles because their capture cross sections are significantly enhanced

by aerodynamic drag (Lambrechts & Johansen 2012, A&A 544, A32; Ormel & Klahr (2010) A&A Volume 520, id.A43). Calculations show that a single 1000 km object embedded in a swarm of pebbles can grow to ~10 Earth-masses in less than 10,000 years. These short timescales present a problem in the terrestrial planet region because it took many tens of millions of years for the Earth to form (Touboul+ 2007, Nature 450, 1206). However, recent full-scale simulations of core formation have shown that the only way to grow a small number of giant planets in the Solar System is for the pebbles to form over a long period of time (Kretke & Levison 2014, AJ, submitted; Levison & Kretke in prep.) in a process we call 'Slow Pebble Accretion'. Thus, here we will present preliminary results of a study of slow pebble accretion in the terrestrial planet zone.

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410.03 – Growth properties of protoplanetary dust in a long-term microgravity experiment

In the very first steps of the formation of a new planetary system, dust agglomerates and grows inside the protoplanetary disk that rotates around the newly formed star. In this disk, collisions between the dust particles, induced by interactions with the surrounding gas, lead to sticking. Aggregates start growing until their sizes and relative velocities are high enough for collisions to result in bouncing or fragmentation.

As part of a series of microgravity experiments aiming at the investigation of the transitions between sticking, bouncing and fragmentation of colliding dust aggregates, the Suborbital Particle and Aggregation Experiment (SPACE) was designed, built and operated both at the drop tower in Bremen (August 2011) and on the REXUS 12 suborbital rocket (March 2012). The SPACE experiment allowed for the observation of collisions between aggregates of sizes of a few 100 μm that were composed of SiO₂, a commonly used protoplanetary dust analog material. At velocities below 10 cm/s, clusters composed of a high number of aggregates (more than 10⁴) formed and grew to sizes of up to 5 mm. The analysis of these collisions delivered valuable input to a current dust collision model, which maps the outcome of collisions depending on the aggregate sizes and their relative velocities. The sticking probability of sub-mm-sized dust aggregates could directly be measured during the suborbital rocket flight, over a velocity range covering the transition between the sticking and bouncing regimes.

In addition, the evolution of clusters formed from sub-mm-sized aggregates during the different experiments could be observed and some of their intrinsic properties derived. The measured characteristics were the cluster fractal dimensions, the tensile strength of their outer aggregate layer and the effective surface energy of their constituents. Threshold energies for cluster restructuring and fragmentation could also be determined. All these cluster properties are important input parameters for molecular dynamics or numerical simulations investigating the behavior of macroscopic clusters (>1 mm in size) in protoplanetary disks.

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410.04 – Microgravity collisions of dust aggregates as an analogue to early planetesimal formation

During the early stages of planet formation the dusty progenitors of planetesimals collided with each other continuously to form the seeds of planets. These collisions could result in growth or disruption depending on the individual impact velocities. Based on input from solar nebula models a laboratory-based microgravity dust collision experiment was developed for a drop tower at the Technische Universität Braunschweig, Germany. We collided 1.0 – 1.6 mm SiO₂ dust aggregates with clusters of these aggregates at a range of velocities and mass ratios to determine the thresholds between bouncing, sticking, and fragmentation. Presented here are the results of 264 microgravity collisions occurring at velocities of 1 – 160 cm/s with target-impactor mass ratios of 5:1 to 400:1. We also present the coefficient of restitution for low-velocity collisions and we find the specific collision energy of fragmentation Q^* for aggregates of this size. We find sticking occurs at mass ratios larger than 40:1, but only for low velocities ≥ 3 cm/s, clear boundaries exist for bouncing up to 30 cm/s, and fragmentation at ~ 50 cm/s and up, with total disruption occurring above 1 m/s.

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410.05 – Gravitational Instability in Planetesimal Disks

Gravitational instability (GI) has been proposed as a method of forming giant gas planets enhanced by disk thermodynamics in a protoplanetary disk (Boss, 1997, Science 276; Durisen et al., 2007, Protostars and Planets V) and as a method of forming planetesimals through the focusing of boulders by the interaction between solids and gases in a turbulent circumstellar disk (Johansen et al., 2007, Nature 448; Youdin & Goodman, 2005, Astrophys. J. 620). GI is mediated through a gaseous circumstellar disk in each each of these scenarios. We explore the possibility of GI occurring in a planetesimal disk devoid of gas. In this regime, mutual collisions between planetesimals are required to

dissipate their orbital shear and velocity dispersion enough for collapse to occur as described by the Toomre stability criterion (Toomre, 1964, *Astrophys. J.* 139; Toomre, 1981, *Structure and Evolution of Normal Galaxies*). How frequent must collisions be between planetesimals in a gravitationally stable planetesimal disk for GI to occur? Are there collisional rates where GI is postponed indefinitely in an equilibrium state between gravitational stirring and collisional cooling? We present 3D shearing sheet simulations using the REBOUND N-body code with the symplectic epicyclic integrator (Rein & Liu, 2011, *A&A* 537; Rein & Tremaine, 2011, *MNRAS* 415) in which the candidate collision rates are within a few orders of magnitude of the disk dynamical lifetime. Our simulations suggest that collisions rate directly controls disk cooling. The shape of the disk cooling curve is independent of the collision rate when scaled to the collision time.

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410.06 – Development of a Circum-Embryo Debris Disk Model Subject to Collisions from the Heliocentric Swarm

Collisionally generated debris disks have been extensively studied in the formation of various bodies in our solar system, yet planetary accretion models typically assume the evolving bodies are spherical objects. It is our goal to understand how the existence of debris disks may affect the growth rates of protoplanets in the early solar system. To do this we have constructed a model to calculate the surface mass density profile of a debris disk orbiting an actively accreting body subject to collisions with impactors from a heliocentric protoplanetary disk. Using the accretion history of a protoplanetary embryo, we solve for the collision environment of the body by calculating the rate at which material impacts the surface of the embryo. Including effects of gravitational focusing, we extrapolate this information as a function of distance from the embryo to find the amount of material passing through the region in which our disk exists. The probability a collision will occur between an impactor and the circum-embryo disk depends on the optical depth of the debris disk at the location of the collision. Given some initial surface mass density profile for the circum-embryo disk, our model calculates how mass within the disk is redistributed by these collisions. Collisions between impactors and material within the circum-embryo disk conserve angular momentum, energy, and mass. Additionally, this model is capable of evolving constant and variably viscous disks, calculating mass transfer within the disk due to the increasing mass of the parent body, and tracking the amount of material moving across the inside boundary of the disk. If the disk is chosen to extend to the surface of the parent body, this material accretes onto the body, increasing its mass, which in turn continues to affect the disk. Efforts to continue developing this model will include the effects of collisions between disk particles and satellite accretion beyond the Roche limit in order to more fully understand how circum-embryo debris disks may affect growth rates for protoplanets undergoing oligarchic growth.

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411 – Io, Jupiter's Volcanic Wonderland

411.01 – Constraining the volcanic contribution to Io's atmosphere with ALMA maps

Io's atmosphere, which requires a continuous replenishment, is mostly likely fed by volcanic plume outgassing and SO₂ frost sublimation, but the relative contributions of the different sources is still poorly understood. One way to retrace the atmospheric origin is to establish with good precision the location of the atmosphere.

We used the Atacama Large Millimeter Array (ALMA) to map simultaneously the distribution of SO₂, SO and KCl. The observations obtained, while achieving only a modest improvement in angular resolution (down to 0.45" in the longitudinal direction), are of much better quality than previous (sub)millimeter maps thanks to the high sensitivity of ALMA. The maps clearly demonstrate that each atmospheric component displays a strikingly different spatial distribution. SO₂, the main component, appears to be relatively spread out in a latitudinally-bound equatorial band, which is consistent both with previous HST observations and the hypothesis of a mainly sublimation-sustained bulk atmosphere on the day-side. On the other hand, KCl, for which we are presenting the first significant detection, is limited to small unresolved areas. This suggests it is only present in active volcanic plumes and quickly condenses once outside the plumes. Finally the SO distribution roughly traces the spread out distribution of SO₂, but its offset emission maximum is indicative of an additional distinct source.

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411.02 – Io's Primary Atmosphere In Eclipse: First Observations from Gemini-TEXES

Io's thin and spatially inhomogeneous SO₂ atmosphere is supported by a combination of direct volcanic injection and SO₂ frost sublimation off the surface. The relative roles and proportions that contribute to the overall atmosphere by these mechanisms have been a long-standing problem in studying Io's atmosphere and its interactions with the surface and plasma environment. A key observation is determining the behavior of Io's atmosphere going into and during eclipses by Jupiter, which helps separate the sublimation component of the atmosphere in vapor pressure equilibrium with the surface from the volcanic component. Until now, the neutral molecular primary SO₂ atmosphere has been difficult to observe during eclipses.

Here, we discuss high spectral and time resolution spectroscopy observations of Io's atmosphere as Io entered eclipse in November 2013 using the TEXES spectrometer at 19 μm on the Gemini telescope. The mid-IR spectra, which are the first ever observation of Io's bulk atmosphere going into and in eclipse show significant change in the absorption bands of SO₂. We will discuss the implications of these observations, and the apparent contradictory results compared to previous observations from HST-COS in the ultraviolet.

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411.03 – Simulations of the Effects of Jupiter's Plasma Torus on Io's Pele Plume

Io's plumes rise hundreds of kilometers above its surface and sublimation atmosphere, presenting large targets for incoming ions from Jupiter's plasma torus. The direct simulation Monte Carlo method is used to model the gas plume at Pele and its interaction with the Jovian plasma torus. Chemical reactions resulting from ion impacts in a plume change its composition and energy from the impacts changes the plume's structure (asymmetrically). The presence of non-condensable daughter species in a warmer plume canopy produces a more diffuse deposition ring on Io's surface, compared to simulations without plasma. Energized molecules also escape from the plume, forming a diffuse cloud of fast particles above the plume's canopy, which may function to resupply the plasma torus and which suggests a mechanism for lofting other species to very high altitudes.

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411.04 – Observations of Massive Volcanic Eruptions on the Jovian Moon Io in August 2013: A Template for Unravelling the Mysteries of Large Lava Flow Emplacement on the Terrestrial Planets

Flood basalt eruptions helped shape the surfaces of the terrestrial planets in the distant past, but little is understood about the mechanism of eruption and duration of events. However, highly-voluminous eruptions are taking place on Io. Only recently have multispectral data been obtained over a useful time period which allow detailed modelling of the evolution of individual eruption episodes, thus revealing the eruption style and effusion rate variability. Observations obtained with the near-infrared camera NIRC2 and the adaptive optics system on the 10-m Keck II telescope (Mauna Kea, HI) on 15 Aug 2013 revealed two large "outburst" eruptions [1]. Follow-up observations 5 and 7 days later showed that both had substantially faded. The most energetic eruption on 15 Aug 2013 was at Rarog Patera, at a location near 305°W, 42°S; the less energetic eruption occurred further south at ~310°W and ~57°S, close to Heno Patera. We note that a third outburst eruption (designated 201308C) was observed at ~224°W, ~29°N on 29 Aug 2013 with the Gemini N and IRTF telescopes [2], an unprecedented series of such events. Ionian outbursts are rare, transient, highly-voluminous volcanic eruptions of high-temperature silicate lava in lava fountains feeding fast-moving lava flows [3]. The modelling the time series data of the Heno and Rarog Paterae data allowed estimation of peak volumetric lava effusion rates, which approach 10⁵ m³/s. This rate is two orders of magnitude greater than that of the Mauna Loa, HI, 1984 eruption, one of the largest effusive eruptions of recent times. Temperatures determined from spectral data at 201308C suggest an ultramafic lava composition, although uncertainties are large [2]. The Rarog and Heno Patera 2013 eruptions each delivered 6-13 km³ of lava to the surface in ~1 week, suggesting flood basalts were erupted in similar short duration, high volume episodes. Part of this work was carried out at the Jet Propulsion Laboratory-California Institute of Technology, under contract to NASA. References: [1] de Pater, I., et al. (2014) *Icarus*, in press. [2] de Kleer, K., et al. (2014) *Icarus*, in press. [3] Davies, A. G. (1996) *Icarus*, 124 (1), 45-61.

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411.05D – Numerical simulations of convection and melt migration in Io's mantle

Io is the most volcanically active body in the solar system. The Laplace resonance with Europa and Ganymede maintains Io's high eccentricity, which leads to tidal heating in Io's mantle. The extensive volcanism on Io's surface and the detection of an induced magnetic field at Io [1] suggest that the tidal heating is so extreme that it partially melts Io's mantle. Previous modeling of convection in Io's mantle has shown that convection alone is not enough to produce the current observed high heat flux if Io is in thermal equilibrium [2]. However, if tidal heating partially melts Io's mantle, this magma will buoyantly rise through the solid grains and erupt to the surface carrying heat from the interior with it. This is known as the heat pipe mechanism of planetary heat loss. Io is currently the only body in our solar system losing heat mainly through this mechanism. However, it may have been relevant to other bodies in our solar system earlier in their history, and it could be relevant to extrasolar planets experiencing high internal heating rates. We study this process in the context of Io using the mantle convection code StagYY, which includes the formation, migration, and eruption of magma. Although previous studies of Io's mantle have considered melt migration [3] or convection [e.g. 4], this is the first study to consider both processes. We find that Io does have a partially molten mantle, and that it loses two orders of magnitude more heat through volcanic eruptions than through conduction through its stagnant lid, which exemplifies the heat pipe mechanism of heat loss. The rate of heat loss from the volcanic eruptions is on average equal to the tidal heating rate we assume, but it oscillates around this value, which suggests that measurements of Io's heat flux are not necessarily representative of its average heat loss over longer time scales.

[1] Khurana K. K. et al. (2011) *Science*, 332, 1186-1189. [2] Moore W. B. (2003) *J. Geophys. Res.*, 108, E8, 15-1. [3] Moore, W. B. (2001) *Icarus*, 154, 548-550. [4] Tackley, P. J. (2001) *Icarus*, 149, 79-93.

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411.06 – Temperature and Structure of Active Eruptions from a Handheld Camcorder

A commercial handheld digital camcorder can operate as a high-resolution, short-wavelength, low-cost thermal imaging system for monitoring active volcanoes, when calibrated against a laboratory heated rock of similar composition to the given eruptive material. We utilize this system to find full pixel brightness temperatures on centimeter scales at close but safe proximity to active lava flows. With it, observed temperatures of a Kilauea tube flow exposed in a skylight reached 1200 C, compared with pyrometer measurements of the same flow of 1165 C, both similar to reported eruption temperatures at that volcano. The lava lake at Erta Ale, Ethiopia had crack and fountain temperatures of 1175 C compared with previous pyrometer measurements of 1165 C. Temperature calibration of the vigorously active Marum lava lake in Vanuatu is underway, challenges being excessive levels of gas and distance from the eruption (300 m). Other aspects of the fine-scale structure of the eruptions are visible in the high-resolution temperature maps, such as flow banding within tubes, the thermal gradient away from cracks in lake surfaces, heat pathways through pahoehoe crust and temperature zoning in spatter and fountains. High-resolution measurements such as these reveal details of temperature, structure, and change over time at the rapidly evolving settings of active lava flows. These measurement capabilities are desirable for future instruments exploring bodies with active eruptions like Io, Enceladus and possibly Venus.

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412 – Mars Atmosphere Posters

412.01 – Atmospheric properties reconstruction from the Mars Science Laboratory Entry, Descent and Landing

The Mars Science Laboratory (MSL) landed on August 5, 2012 in Gale Crater on Mars (4.5 S, 137.4 E) [1]. The MSL entry vehicle measured accelerations and angular velocity during its descent through the Martian atmosphere using accelerometers and gyroscopes in an inertial measurement unit. We have applied smoothing techniques previously developed for the NASA Phoenix Mars mission [2] to these acceleration data. Smoothed accelerations were used in conjunction with the vehicle's aerodynamic database to reconstruct atmospheric density, pressure and temperature profiles to above 120 km altitude. The density profile was estimated using axial accelerations in the drag force equation. Corresponding pressure and temperature profiles were calculated using the hydrostatic equilibrium and ideal gas law, respectively.

In contrast to previous missions, MSL used a guided entry that resulted in periods of near-horizontal flight at approximately 20 km altitude [3], during which pressure could not be determined from hydrostatic equilibrium. Instead, atmospheric pressures at low altitudes were determined independently by the Mars Entry Atmospheric Data System (MEADS) [4]. These were used in conjunction with accelerometer-derived densities to extend the atmospheric

temperature profile through the period of near-horizontal flight.

Although the results present only a snapshot of the regional atmospheric conditions at the time of entry, descent and landing of MSL, they have excellent vertical resolution and vertical extent, thereby complementing orbital observations. We will present an overview of our atmospheric reconstruction process, the derived atmospheric profiles, and preliminary scientific interpretation of the atmospheric results.

References: [1] Vasavada, A.R. et al (2014), *JGR-Planets*, 119, 6, 1134-1161 [2] Withers, P. (2013) *Planet. & Space Sci.*, 79-80, 52-55, [3] Dutta, S. et al. (2013) *23rd AAS/AIAA Space Flight Mechanics Meeting*, AAS 13-309, [4] Schoenenberger, M. et al. (2013) *23rd AAS/AIAA Space Flight Mechanics Meeting*, AAS 13-306

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412.02 – Ice Cloud Optical Depth Retrievals from CRISM Multispectral Images

One set of data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on the Mars Reconnaissance Orbiter (MRO) is the multispectral survey that measured the visible-through-near-infrared reflectance of the entire planet of Mars at specific wavelengths. The spectral data from several sols were combined to create multi-spectral maps of Mars. In addition, these maps can be zonally averaged to create a latitude vs season image cube of Mars. All of these image cubes can be fit using a full radiative transfer modeling in order to retrieve ice cloud optical depth—as a map for one of the particular dates, or as a latitude vs season record.

To compare the data radiative transfer models, a measure of the actual surface reflectance is needed. There are several possible ways to model this, such as using a nearby region that is "close enough" or by looking at the same region at different times and assuming one of those is the actual surface reflectance. Neither of these is ideal for trying to process an entire map of data because aerosol clouds can be fairly extensive both spatially and temporally.

Another technique is to assume that the surface can be modeled as a linear combination of a limited set of intrinsic spectral endmembers. A combination of Principal Component Analysis (PCA) and Target Transformation (TT) has been used to recover just such a set of spectral endmember shapes. The coefficients in the linear combination then become additional fitting parameters in the radiative transfer modeling of each map point—all parameters are adjusted until the RMS error between the model and the data is minimized. Based on previous work, the PCA of martian spectral image cubes is relatively consistent regardless of season, implying the underlying, large-scale, intrinsic traits that dominate the data variance are relatively constant. These overall PCA results can then be used to create a single set of spectral endmembers that can be used for any of the data cubes.

Presented here are the results of this PCA/TT work to find the singular set of spectral endmembers and their use in recovering ice cloud optical depth from the MRO-CRISM multispectral image cubes.

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412.03 – Maps of [HDO]/[H₂O] on Mars near Northern Solstice (L_s = 87°) and mid-Summer (L_s = 141°) in 2014

We report maps of HDO and H₂O taken at seasonal points L_s = 87° (09 February 2014) and L_s = 141° (06 June 2014) using CSHELL at NASA's IRTF. For these observations, the entrance slit of the spectrometer was positioned N-S on Mars centered at the sub-Earth point. Multiple spectral lines were measured near 3.67 μm (HDO) and 3.29 μm (H₂O) with both settings also encompassing lines of carbon dioxide (CO₂) permitting the retrieval of accurate mixing ratios. Column densities were obtained by matching the observed spectral lines to those of a multi-layered, radiative transfer model. The model includes solar Fraunhofer lines, two-way transmission through Mars' atmosphere, thermal emission from Mars' surface and atmosphere, and a one-way transmission through the Earth's atmosphere. Latitudinal maps of HDO, H₂O, and their ratios were then constructed. The [HDO]/[H₂O] ratios have been found to be larger than those on Earth and they vary with both latitude and season. We will compare the recent measurements to previously taken measurements at L_s = 357°, 50°, and 72°. For the L_s = 357° and 50° observations, the ratio peaks near the sub-solar latitude ([HDO]/[H₂O] ~ 6.9 VSMOW) and decreases towards both the North and South polar-regions. For observations taken at seasonal points after L_s = 50°, column densities of both HDO and H₂O are greatest north of 60°N. Sunlight falls on the Northern Polar Cap causing vaporization and the isotopic composition of the water vapor in this region reflects the composition of the surface layer in the polar cap. Our results for H₂O column densities will be compared with TES results. The results for HDO and the [HDO]/[H₂O] ratios will be compared with model results.

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412.04 – A new search for active release of volcanic gases on Mars: Sensitive upper limits for OCS.

As part of our multi-species search for active release of volcanic gases on Mars, we looked for atmospheric carbonyl sulfide (OCS) in two successive Mars years (31 & 32), during Mars' late Northern Spring and mid Northern Summer seasons, between $L^S = 43^\circ$ and $L^S = 147^\circ$. The targeted volcanic districts, Tharsis and Syrtis Major, were observed during the two intervals, 14 Dec. 2011 to 6 Jan. 2012 on the first year, and 30 May 2014 to 16 June 2014 on the second year using the high resolution infrared spectrometer (CSHELL) on NASA's Infrared Telescope Facility (NASA/IRTF) atop Maunakea, Hawaii. On Earth, sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) are the main sulfur species released during volcanic outgassing. The two molecules have relatively short photochemical lifetimes on Mars, 2 years for SO_2 (Krasnopolsky, 1995; Nair et al., 1994) and 9 days for H_2S (Wong et al., 2003), and OCS is a byproduct of the photochemical cycle. With an 850 km spatial resolution on Mars, we positioned CSHELL's slit at the North-South central meridian of the planet above each volcanic region, and searched for OCS, both in its combination band ($\nu_2 + \nu_3$) at 3.42 μm and its fundamental band (ν_3) centered at 4.85 μm . OCS was not detected, and sensitive upper limits will be presented. The non-detection of measurable OCS quantities in the atmosphere of Mars indicates the absence of major volcanic outgassing, and provides limits for the level of current volcanic activity in the crust of Mars. Those limits will be discussed.

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412.05 – Laboratory measurement of temperature dependent ^{13}C and D kinetic isotope effect in the reaction of CH_4 oxidation by $O(1D)$

Martian atmospheric methane (CH_4) concentrations observed from satellite orbiter and Earth based telescopes have shown significant time and spatial variations. Recent MSL measurements observed very low methane concentrations (0.18 ± 0.67 ppbv). In order to reconcile these findings, a search of missing methane sinks is needed. In this study, we investigated the kinetic isotope effect (KIE) of methane oxidation reaction by $O(1D)$ as a function of temperature, which will provide an important constraint to the loss of methane. The KIE of major methane isotopologues ($^{13}CH_4$ and $^{12}CH_3D$) are measured as a function of temperature. The experiments were carried out by photolyzing a mixture of N_2O , isotope enriched methane, and He at 193 nm in a temperature controlled cell between 155 K and 300 K. The N_2O molecules were used as an $O(1D)$ source, while He was used to collisionally quench translationally hot $O(1D)$ radicals. The concentrations of all major methane isotopologues before and after photolysis were analyzed using a frequency stabilized cavity ringdown (FS-CRDS) spectrometer. The spectrometer employs coupling of two orthogonally polarized cw lasers into a ringdown cavity for simultaneous spectral measurements over the full wavelength range of 1.45 – 1.65 μm and is capable of measuring isotopes of methane of enriched samples to a very high precision ($D < 0.03\%$ and $^{13}C < 0.01\%$). We measured for the first time the D -KIE and ^{13}C -KIE at temperatures relative to the Martian conditions. Our measurements observed D -KIE(155 K) = 1.133(20), and ^{13}C -KIE(115 K) = 1.149(22).

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412.06 – O_2 abundance on Mars observed by Mars Express / SPICAM

Molecular oxygen is one of the primary products of photochemistry on Mars and knowledge of its distribution is critical to an understanding of current day photochemical and transport processes as well as an understanding of the chemical evolution and stability of the atmosphere. Up to now there have been relatively few measurements of O_2 densities on Mars and these have been either determinations of global average abundance from ground-based telescopic measurements or single point measurements by spacecraft. Information on geographic and temporal variations has been lacking. In order to remedy this situation we have developed a technique to infer the O_2 abundance from MEX/SPICAM UV occultation measurements that are dominated by the much stronger CO_2 absorption signatures. By carefully accounting for all systematic effects we are able to retrieve density profiles of O_2 over the 90-140 km range for most occultations. The derived mixing ratios show considerable variability from 1×10^3 to 5×10^3 . The lower end of this range is consistent with earlier measurements. The variations of the derived mole fractions with latitude, longitude, and season will be discussed.

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412.07 – Time Dependent Responses of the Martian Upper Atmosphere to the 2001 Global Dust Storm using Mars GITM Simulations

Various Mars spacecraft datasets reveal that the Martian thermosphere-ionosphere (~100-250 km) is significantly impacted by the occurrence of regional or global lower atmosphere dust storm events. For example, thermospheric responses during the regional MY23 Noachis storm (late 1997) during its onset phase include: (a) a factor of 3 enhancement of MGS Accelerometer mass densities at 130 km near 38 N latitude, (b) a factor of 2.5 enhancement of corresponding zonal winds near 120-130 km, and (c) the associated ~8 km rise in the height of the 1.26-nbar reference pressure level (Keating et al., 1998; Baird et al. 2007). These features correspond to a rapidly warming (and vertically expanding) lower atmosphere due to “dust-lifting latitude” aerosol heating, the resulting acceleration of global winds and amplification of tidal amplitudes throughout the atmosphere, and adiabatic warming arising from downwelling winds. Furthermore, during the 2001 MY25 global dust storm, MGS/ER photo-electron measurements at 400 km reveal that fluxes were enhanced, possibly related to long-lived changes in thermosphere-exosphere composition (Liemohn et al., 2012). These responses to dust events, and associated atmospheric feedbacks, provide excellent constraints for Mars GCMs. The recently developed and initially validated 3-D Mars Global Ionosphere-Thermosphere Model (M-GITM) (e.g. Bougher et al., 2014) is used to investigate these feedbacks and responses of the Mars thermosphere-ionosphere for the 2001 global dust storm. The M-GITM code simulates the conditions of the Martian atmosphere from the surface to the exosphere (~0-250 km), utilizing physical processes and subroutines largely taken from previous Mars GCMs. Empirical (time evolving) dust opacities are specified from MGS/TES datasets for MY25 (starting in July 2001). The time evolution of the resulting thermosphere and ionosphere fields is examined; comparisons with available MGS datasets are made.

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412.08 – HST Observations of the Martian Hydrogen and Oxygen Exosphere

HST observations of FUV emissions from the extended atomic H and O exosphere of Mars have been performed at several epochs now, and show pronounced changes with time with relevance to the escape rate of water from the upper atmosphere. In particular, large and rapid changes in the hydrogen exosphere were observed in Fall 2007, indicative of a possible seasonal dependence in the escape rate of water. This poster will present an overview of the different observations, and the schedule for new HST observations in Fall 2014. The new visits are being planned to study a) any seasonal changes in the H and O exospheres, and b) the influence of the close passage of Comet Siding Spring in Oct. 2014.

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412.09 – Parameter Study of Plasma-Induced Atmospheric Sputtering and Heating at Mars

Atoms and molecules in Mars' upper atmosphere are lost predominately through sputtering, caused by the impact of ions into the exosphere, dissociative recombination, and thermal escape. While all three processes are thought to occur on Mars, a detailed understanding must ascertain the relative importance of each process, due to time variations in pick-up and solar wind ions. In this project, using case studies of an oxygen atmosphere modeled with Direct Simulation Monte Carlo techniques, we have endeavored to categorize when the momentum transfer or thermal escape is more likely to occur. To do this, we vary the incident plasma flux and energy based on models of the interaction of the solar wind with the Martian atmosphere. We first repeat the heating and sputtering rates due to a flux of pick-up O⁺ examined previously (Johnson et al. 2000; Michael and Johnson 2005; Johnson et al 2013). We have used multiple examples of particle fluxes for various solar wind conditions, from steady solar wind conditions (Luhmann et al. 1992; Chaufray et al. 2007) to more extreme cases (Fang et al. 2013; Wang et al. 2014), which are thought to increase escape by several orders of magnitude. The goal is to explore the escape parameter space in preparation for the expected data from MAVEN on hot atoms and molecules in the Martian exosphere.

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413 – Mars Surface/Moon Posters

413.01 – A Physical Taxonomy of Martian Sand and Dust Grains at the Phoenix Landing Site

A quantitative taxonomy of martian sand and dust grains for soil samples at the Phoenix lander site has been developed from the mission's optical microscope data with a resolution of 4 μm per pixel. Approx. 3-4000 grains were analyzed for color, hue, size, shape, surface texture, aspect ratio, and optical properties. At least 26 types of sand and dust grains have been identified. Grain colors include black, brown, orange, red, white, and clear. Most grains are opaque, but many are translucent or transparent. Grain shapes range from botryoidal, blackberry-like, bead-like and rounded, to subrounded, elongate, angular, and highly irregular forms. Surface textures range from knobbly, rough, and multifaceted to smooth and polished. Surface reflectivity varied from dull to shiny to specularly reflective. Materials may include augite, pyroxenes, olivine, volcanic glass, hematite, other iron oxides, and salts.

Grain size of the sand has a modal value of $\sim 90 \mu\text{m}$, but there is no gradation into dust sizes, indicating a bimodal distribution of the samples. The dust was probably imported into the region from aeolian dust storms. This accords with a mineralogical dissimilarity between the sand and dust grain populations. The sand is dominated by black and brown grains; the dust is dominated by orange grains. The Phoenix site also has centimeter and larger stones in abundance that again have no apparent gradation into the sand size material. Thus, the Phoenix landing site soil appears multimodal. The soil appears to be magnetically susceptible, but it is unclear what the source of magnetism might be. Specific magnetic minerals were not identified in the samples with the possible exception of paramagnetic microbotryoidal hematite. The soil was nevertheless adhesive to the substrates and internally cohesive (forming spherical aggregates) owing to van der Waals forces and possibly salt/moisture bonding.

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413.02 – Geology of the Tyrrenus Mons Lava Flow Field, Mars

The ancient, eroded Martian volcano Tyrrenus Mons exhibits a central caldera complex, layered flank deposits dissected by radial valleys, and a 1000+ km-long flow field extending to the southwest toward Hellas Planitia. Past studies suggested an early phase of volcanism dominated by large explosive eruptions followed by subsequent effusive activity at the summit and to the southwest. As part of a new geologic mapping study of northeast Hellas, we are examining the volcanic landforms and geologic evolution of the Tyrrenus Mons flow field, including the timing and nature of fluvial activity and effects on volcanic units. New digital geologic mapping incorporates THEMIS IR (100 m/pixel) and CTX (5 m/pixel) images as well as constraints from MOLA topography.

Mapping results to-date include delineation of the boundaries of the flow field, identification and mapping of volcanic and erosional channels within the flow field, and mapping and analysis of lava flow lobes. THEMIS IR and CTX images allow improved discrimination of the numerous flow lobes that are observed in the flow field, including refinement of the margins of previously known flows and identification of additional and smaller lobes. A prominent sinuous rille extending from Tyrrenus Mons' summit caldera is a major feature that supplied lava to the flow field. Smaller volcanic channels are common throughout the flow field; some occur in segments along crests of local topographic highs and may delineate lava tubes. In addition to volcanic channels, the flow field surface is characterized by several types of erosional channels, including wide troughs with scour marks, elongate sinuous channels, and discontinuous chains of elongate pits and troughs. High-resolution images reveal the widespread and significant effects of fluvial activity in the region, and further mapping studies will examine spatial and temporal interactions between volcanism and fluvial processes.

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413.03 – Small-Scale Spectral and Color Analysis of Ritchey Crater Impact Materials

Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) analysis of Ritchey crater on Mars has allowed identification of the minerals uplifted from depth within its central peak as well as the dominant spectral signature of the crater fill materials which surround it. However, the 18m/px resolution of CRISM prevents full analysis of the nature of small-scale dykes, mega breccia blocks and finer scale crater-fill units. We extend our existing CRISM-based compositional mapping of the Ritchey crater interior to sub-CRISM pixel scales with the use of High Resolution Imaging Science Experiment (HiRISE) Color Ratio Products (CRPs). These CRPs are then compared to CRISM images; correlation between color ratio and CRISM spectral signature for a large bedrock unit is defined and used to suggest similar

composition for a smaller unit with the same color ratio. Megabreccia deposits, angular fragments of rock in excess of 1 meter in diameter within a finer grained matrix, are common at Ritchey. The dominant spectral signature from each megabreccia unit varies with location around Ritchey and appears to reflect the matrix composition (based on texture and albedo similarities to surrounding rocks) rather than clast composition. In cases where the breccia block size is large enough for CRISM analysis, many different mineral compositions are noted (low calcium pyroxene (LCP) olivine (OL), alteration products) depending on the location. All block compositions (as inferred from CRPs) are observed down to the limit of HiRISE resolution. We have found a variety of dyke compositions within our mapping area. Correlation between CRP color and CRISM spectra in this area suggest that large (~10 m wide) dykes within LCP-bearing bedrock close to the crater center tend to have similar composition to the host rock. Smaller dykes running non-parallel to the larger dykes are inferred to be OL-rich suggesting multiple phases of dyke formation within the Ritchey crater and its bedrock.

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413.04 – Active Mars Revealed through HiRISE DTMs and Orthoimages

Before the arrival of the Mars Reconnaissance Orbiter (MRO) with the High-Resolution Imaging Science Experiment (HiRISE), the amount of surface activity on Mars was not well known. HiRISE repeat imaging (often at ~30 cm/pixel), combined with the ability to take stereo images and generate high resolution Digital Terrain Models (DTMs) reveals the many types of surface processes that are currently active on Mars. Examples of active processes on Mars studied with HiRISE data include aeolian activity [Bridges et al., 2012, Nature 485; Chojnacki et al., 2014, Icarus 232], Recurring Slope Lineae (RSL) [McEwen et al., 2011, Science 333; 2014, Nature Geoscience 7], active gullies [Dundas et al., 2012, Icarus 220], polar processes [Hansen et al., 2011, Science 331; Portyankina et al. 2013, AGU], new impacts [Byrne et al., 2009, Science 325; Daubar et al., 2013, Icarus 225; Dundas et al., 2014, JGR 119], and north polar scarp avalanches [Russell et al., 2008, GRL 35, 2014, LPSC]. These studies utilize images from multiple Mars years and seasons. We generate animated gifs with sequences of orthorectified images to analyze temporal changes (see <http://www.uahirise.org/sim/>). HiRISE DTMs and orthoimages can be used to quantitatively map and record changes in geospatial software. More than 200 DTMs and 400 orthoimages are available through the Planetary Data System (see <http://uahirise.org/dtm>). Three-band color (blue-green, red, and near infrared) orthoimages are also available in many cases. The ability to monitor the surface of Mars at high spatial and temporal resolution provides insight into seasonal and annual changes, further increasing our understanding of Mars as an active planet.

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Contributing team(s): HiRISE Team

413.05 – Sulfate Mineral Formation from Acid-weathered Phyllosilicates: Implications for the Aqueous History of Mars

Phyllosilicates on Mars are common in Noachian terrains whereas sulfates are found in the younger Hesperian terrains and suggest alteration under more acidic conditions. Phyllosilicates that formed during the Noachian era would have been exposed to the prevailing acidic conditions during the Hesperian. The purpose of this project is to characterize the effects of acid-weathering on phyllosilicates to better understand the aqueous history of Mars. Nontronite, montmorillonite, and saponite were exposed to H²SO⁴ solutions at water-rock (WR) ratios of 50 and 25.

X-ray diffraction (XRD) patterns of all three acid-treated minerals showed progressive collapse of the phyllosilicate basal spacing with increasing acid concentration. Bassanite formed as an intermediate phase in weathered nontronite and montmorillonite from extracted interlayer Ca. The octahedral cation determined which sulfate formed at high acid concentration: rhomboclase from nontronite, alunogen from montmorillonite, hexahydrate and kieserite from saponite. Gypsum and anhydrite also formed as intermediate phases in nontronite treated at WR=25, showing a change in sulfate hydration state with changing acid concentration (i.e. water activity). Scanning electron microscopy analyses detected phases not identified by XRD. Al-sulfate was found in nontronite weathered at WR=25 and Ca-sulfate in weathered saponite. Near-infrared reflectance spectra of the weathered samples showed decreasing intensity of the hydration/hydroxylation bands and a change or disappearance of metal-OH bands indicating dehydration and dissociation of the interlayers and octahedral layers, respectively, with increased acid weathering.

Sulfate mineral formation from acid-weathered phyllosilicates may explain the presence of phyllosilicates and sulfates in close proximity to each other on Mars, such as in Gale Crater. The CheMin XRD instrument on *Curiosity* may find evidence for acid-weathered phyllosilicates in Mt. Sharp by comparing the 001 and 02l peak positions of phyllosilicate deposits to those from phyllosilicates associated with sulfates.

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413.06 – Predictions on the Deliquescence of Calcium Perchlorate at the MSL Landing Site

The Mars Science Laboratory (MSL) has now provided in-situ humidity measurements at Gale crater for more than a martian year. This data, along with the discovery of perchlorates at the equatorial landing site, can elucidate possible aqueous processes occurring on present-day Mars. Here we investigate salt deliquescence, the transition from a solid crystalline salt into an aqueous brine solution. Previous experimental constraints have demonstrated that calcium perchlorate can deliquesce under Mars-like conditions for extended periods of time. We use a heat and mass transfer model along with experimental constraints on deliquescence and the MSL humidity data to study brine stability in time and with depth. Our results indicate deliquescence of Calcium Perchlorate occurs primarily during the predawn hours with efflorescence occurring by early morning. Aqueous activity persists at depth for longer periods than on the surface; however, deliquescence begins later and ends later than on the surface. Such results help elucidate the water exchange processes between the lower atmosphere and regolith reservoirs active on Mars today and helps characterize the current martian habitability.

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413.07 – Implementation the NASA Planetary Data System PDS4 Providing Access to LADEE Data

The NASA Planetary Data System (PDS) is responsible for archiving all planetary data acquired by robotic missions, and observational campaigns with ground/space-based observatories. PDS has moved to version 4 of its archive system. PDS4 uses XML to enhance search and retrieval capabilities. Although the efforts are system wide, the Atmospheres Node has acted as the lead node and is presenting a preliminary users interface for retrieval of LADEE data. LADEE provides the first opportunity to test out the end-to-end process of archiving data from an active mission into the new PDS4 architecture. The limited number of instruments, with simple data structures, is an ideal test of PDS4. XML uses schema (analogous to blueprints) to control the structure of the corresponding XML labels. In the case of PDS4, these schemas allow management of the labels and their content by forcing validation dictated by the underlying Information Model (IM). The use of a central IM is a vast improvement over PDS3 because of the uniformity it provides across all nodes. PDS4 has implemented a product-centric approach for archiving data and supplemental documentation. Another major change involves the Central Registry, where all products are registered and accessible to search engines. Under PDS4, documents, data, and other ancillary data are all products that are registered in the system. Together with the XML implementation, the Registry allows the search routines to be more complex and inclusive than they have been in the past. For LADEE, the PDS nodes and LADEE instrument teams worked together to identify data products that LADEE would produce. Documentation describing instruments and data products were produced by the teams and peer reviewed by PDS. XML label templates were developed by the PDS and provided to the instrument teams to integrate into their pipelines. Data from the primary mission (100 days) have been certified and harvested into the registry and are accessible through the user interface. The LADEE implementation represents the first step toward modernization of the archive and should make the archive more usable for data providers and end-users alike. The poster provides a link to a PDS4 online tutorial.

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413.08 – Size-frequency Statistics of Boulders on the Moon – Characterizing the Surface Roughness of Ejecta Fields

Analyzing the size-frequency of boulders on the Moon provides an opportunity to study the geologic processes related to cratering and ballistic sedimentation. We will be integrating results from a series of boulder-count studies with Mini-RF data to recognize Mini-RF's ability to ascertain surface roughness and better understand how surface roughness information derived from radar data can provide insight into surface boulder distributions associated with km-scale fresh craters. Ultimately, Mini-RF could provide a resource to determining surface roughness characteristics and statistics without the need for manual boulder counting. This work will also provide valuable information in characterizing surface roughness for potential future landing sites. Here we attempt to characterize the surface roughness in areas surrounding three craters on the Moon: Kopff, Censorinus and Kirch E.

Boulder size-frequency distributions for the craters used in this study were determined by analyzing LROC NAC data in ArcMap. Using a specialized script in ArcMap, we are able to count and measure each boulder in the LROC NAC image. Limitations related to this technique are that it misses boulders that are in shadowed areas and boulders that are smaller in diameter than the 0.5 m resolution of the LROC NAC imagery.

Boulder counts were made in three areas surrounding each crater: immediately outside the crater wall, within the continuous ejecta, and within the discontinuous ejecta. We used estimates from Oberbeck et al. (1974) and Moore et al.

(1974) to infer the likely distance from the crater where ejecta will be deposited. In general, ejecta deposits within 1-2 crater radii are considered continuous ejecta and beyond this they are considered discontinuous ejecta. Published geologic maps of these craters were also used to better constrain areas that were within the continuous and discontinuous regions of ejecta. Preliminary results of this study will be discussed, showing how the size-frequency of boulders differs in each area of interest and how this relates to surface roughness characteristics shown in Mini-RF data.

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413.09 – Evidence for Recent Extension and Volcanism inside the Southern Margin of Mare Frigoris

We report the identification of possible recent volcanic activity inside the southern margin of Mare Frigoris. Evidence includes two elliptical constructs with associated dark flows found at 56.6° N, – 19.7° W, north of the La Condamine J impact crater. They were discovered on high resolution (0.5 m/pixel) LROC WAC and NAC imagery (e.g., M188379739R and M142393589L) by the first author while performing a systematic geologic overview of the area.

The constructs occur along a 3.2 km lineament trending southwest to northwest. The southwestern construct is the largest, measuring approximately 1.4 km in diameter by 65 m in height while the northeastern structure measures 1.2 km wide by 40 m high. The summits appear to be concave and contain well-defined pits 190 m and 120 m in diameter, respectively, each encircled by a deposit of raised material. Distinct dark deposits, exhibiting flow lobes, emanate from the pits. In addition, rubbly, flow-like dark deposits are found sporadically along the flanks of each feature.

We interpret these structures as low profile steep-sided volcanic domes. Hawke et al. (2014) discussed volcanic constructs in the eastern part of Mare Frigoris; however, the features described in this study appear to be significantly younger. The domes may represent upwelling along a localized rift. Continued extension on the flanks appears to have released discrete dark flows. Well-defined flows crossing the floors of summit pits appear to have flowed uphill. We suggest that the evacuation of the magma chambers beneath these flows caused subsidence, forming the pits and giving the illusion that the lava flowed up and over the rims. Although the age of these constructs and flows is unknown, the paucity of impact craters suggests that they are relatively young. These could represent very recent eruptions of evolved magma on the Moon, similar to those reported by Jolliff et al. (2011).

References: B. R. Hawke et al., 2014, LPSC, 45, 1318. Jolliff et al., 2012, Nature Geoscience, 4, 566-571.

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413.10 – Modeling the Provenance of Crater Ejecta

The cratering history of the Moon provides a way to study the violent early history of our early solar system. Nevertheless, we are still limited in our ability to interpret the lunar cratering history because the complex process of generation and subsequent transportation and destruction of impact melt products is relatively poorly understood. Here we describe a preliminary model for the transport of datable impact melt products by craters over Gy timescales on the lunar surface. We use a numerical model based on the Maxwell Z-model to model the exhumation and transport of ejecta material from within the excavation flow of a transient crater. We describe our algorithm for rapidly estimating the provenance of ejecta material for use in a Monte Carlo cratering code capable of simulating lunar cratering over Gy timescales.

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413.11 – Formation of Saturn's F ring by collision between rubble-pile satellites

Saturn's F ring is located just outside the Roche limit. This pure icy ring is radially narrow and is thought to be dynamically young. Two shepherding satellites, inner Pandora and outer Prometheus, confine and regulate its current dynamical evolution. The bulk density of these satellites is lower than that of rigid water ice, thus they are likely to be rubble-pile bodies. Crida & Charnoz (2012) showed that Saturn's inner major satellites are formed by spreading of ancient massive rings through the Roche limit using one-dimensional analytical model. Recently, we have performed N-body simulations of the evolution of circumplanetary particle disks initially confined within a planet's Roche limit, and showed that rubble-pile co-orbital satellites are often formed just outside the Roche limit (Hyodo et al, submitted). However, these co-orbital satellites are not always stable but can experience collisions between them. In addition, at radial locations barely outside the Roche limit, accretion efficiency is not 100%, and collision between aggregates can lead to complete or partial disruption (Karjalainen 2007, Hyodo & Ohtsuki 2014).

In the present work, we perform local N-body simulations in the Hill coordinate system and investigate collisional

disruption of rubble-pile satellites just outside the Roche limit corresponding to the location of Saturn's F ring. We find that in some cases, collision between two aggregates results in partial disruption such that the dispersed particles are distributed between the two remnant satellites with small radial extent. Our results suggest that the F ring is a relic of collisional disruption between rubble-pile satellites formed at the last stage of the formation of inner major satellites as the rings spread across the Roche limit.

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413.12 – Mapping and Analysis of 'Dunes' in the Ejecta Blankets of Fresh Lunar Craters

Lunar concentric 'dunes' are ridge-like features that appear in the ejecta blankets of fresh craters on the Moon. These 'dunes' are oriented roughly perpendicular to ejecta flow, and are found between ~1.2 to several crater radii. We have been mapping and measuring these features using the high-resolution images from the Lunar Reconnaissance Orbiter Camera (LROC). In our survey of the Moon we have so far found fifty-seven craters where the facies of the Lunar concentric 'dunes' can be seen, ranging in diameter from one to eleven kilometers, in both the mare and the highlands. We have created mosaics from high-resolution LROC Narrow Angle Camera (NAC) images for fourteen of these craters which allow us to examine the morphology of these dunes in detail. We note a general progression in dune morphology as distance from the crater increases (the following measurements are not standard from crater to crater and reflect the mapping results for crater Piton B): 'dunes' are most distinct between 1.5 to 3 crater radii from the crater center. Between 3 and 6 crater radii, dunes are commonly accompanied by a trough on the crater-facing side of the dune. As distance from the crater increases, dune morphology subsides and troughs become the most notable feature within the ejecta blanket. Using Lunar Orbiter Laser Altimeter (LOLA) data we are able to examine how the 'dunes' form in the context of local pre-existing slopes. These 'dunes' are known to form predominantly on level and crater facing slopes, however we have found at some highlands craters, like Stevinus A, that they can form on slopes facing away from the crater. We have observed a number of morphological features of the 'dunes' that do not seem to support the previously proposed ballistic impact sedimentation and erosion hypothesis for the formation of this facies. Thus we will need to formulate and test new hypotheses for how this interesting lunar facies forms.

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414 – Asteroid Observations and Modeling Posters

414.01 – The DECam NEO Survey: A sensitive, wide-field search for near-Earth asteroids

We report preliminary results from a survey for near-Earth asteroids with the Dark Energy Camera. DECam is a facility-class 520 Megapixel wide-field imager on the 4m Blanco telescope at Cerro Tololo Inter-american Observatory. It has a 3.2 square degree field of view, and a focal plane consisting of 62 2Kx4K red-optimized CCDs. In spite of its large number of pixels, DECam reads out in less than 30 seconds, making it possible to cover a large area of sky efficiently. Compared to the largest aperture of the currently most productive NEO searches, the Blanco has an aperture that is several times larger and a comparable field of view. Our goal is to measure the size distribution of NEOs well below 140m, and we have been allocated 30 nights through the NOAO Survey program to achieve it. Here we report on results from the first 10 nights of our survey.

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414.02 – The Mission Accessible Near-Earth Object Survey Public Database Development Effort

The Mission Accessible Near-Earth Object Survey (MANOS) began in August 2013 as a multi-year physical characterization survey that was awarded large survey status by NOAO. MANOS will target several hundred mission-accessible NEOs across visible and near-infrared wavelengths, ultimately providing a comprehensive catalog of physical properties (astrometry, light curves, spectra). The MANOS project will provide a resource that not only helps to manage our survey in a fully transparent, publicly accessible forum, but will also help to coordinate minor planet characterization efforts and target prioritization across multiple research groups. Working towards that goal, we are developing a portal for rapid, up to date, public dissemination of our data. Migrating the Lowell Astorb dataset to a SQL framework is a major step towards the modernization of the system and will make capable up-to-date deployment of data. This will further allow us to develop utilities of various complexity, such as a deltaV calculator, minor planet finder charts, and sophisticated ephemeris generation functions. We present the state of this effort and a preliminary timeline for functionality.

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Contributing team(s): MANOS

414.03 – Simulating the Performance of Ground-Based Optical Asteroid Surveys

We are developing a set of asteroid survey simulation tools in order to estimate the capability of existing and planned ground-based optical surveys, and to test a variety of possible survey cadences and strategies. The survey simulator is composed of several layers, including a model population of solar system objects and an orbital integrator, a site-specific atmospheric model (including inputs for seeing, haze and seasonal cloud cover), a model telescope (with a complete optical path to estimate throughput), a model camera (including FOV, pixel scale, and focal plane fill factor) and model source extraction and moving object detection layers with tunable detection requirements. We have also developed a flexible survey cadence planning tool to automatically generate nightly survey plans. Inputs to the cadence planner include camera properties (FOV, readout time), telescope limits (horizon, declination, hour angle, lunar and zenithal avoidance), preferred and restricted survey regions in RA/Dec, ecliptic, and Galactic coordinate systems, and recent coverage by other asteroid surveys. Simulated surveys are created for a subset of current and previous NEO surveys (LINEAR, Pan-STARRS and the three Catalina Sky Survey telescopes), and compared against the actual performance of these surveys in order to validate the model's performance. The simulator tracks objects within the FOV of any pointing that were not discovered (e.g. too few observations, too trailed, focal plane array gaps, too fast or slow), thus dividing the population into "discoverable" and "discovered" subsets, to inform possible survey design changes. Ongoing and future work includes generating a realistic "known" subset of the model NEO population, running multiple independent simulated surveys in coordinated and uncoordinated modes, and testing various cadences to find optimal strategies for detecting NEO sub-populations. These tools can also assist in quantifying the efficiency of novel yet unverified survey cadences (e.g. the baseline LSST cadence) that sparsely spread the observations required for detection over several days or weeks.

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414.04 – A new mechanism for the formation of regolith on asteroids

The soil of asteroids, like that of the Moon, and other rocky, airless bodies in the Solar System, is made of a layer of pebbles, sand, and dust called regolith.

Previous works suggested that the regolith on asteroids is made from material ejected from impacts and re-accumulated on the surface and from surface rocks that are broken down by micrometeoroid impacts. However, this regolith formation process has problems to explain the regolith on km-sized and smaller asteroids: it is known that impact fragments can reach escape velocities and breaks free from the gravitational forces of these small asteroids, indicating the impact mechanism is not the dominant process for regolith creation. Other studies also reveal that there is too much regolith on small asteroids' surfaces to have been deposited there solely by impacts over the millions of years of asteroids' evolution.

We proposed that another process is capable of gently breaking rocks at the surface of asteroids: thermal fatigue by temperature cycling. As asteroids spin about their rotation axes, their surfaces go in and out of shadow resulting in large surface temperature variations. The rapid heating and cooling creates thermal expansion and contraction in the asteroid material, initiating cracking and propagating existing cracks. As the process is repeated over and over, the crack damage increases with time, leading eventually to rock fragmentation (and production of new regolith).

To study this process, in the laboratory, we subjected meteorites, used as asteroid material analogs, to 37 days of thermal cycles similar to those occurring on asteroids. We measured cracks widening at an average rate of 0.5 mm/y. Some fragments were also produced, indicating meteorite fragmentation. To scale our results to asteroid lifetime, we incorporated our measurements into a fracture model and we deduced that thermal cycling is more efficient than micrometeorite bombardment at fragmenting rock over millions of years on asteroids (see Delbo et al. 2014. Nature 508, 233-236).

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414.05 – The Undiscovered Country: How Many Low-Delta-V Near-Earth Objects Remain to be Found?

Low delta-v near-Earth objects (NEOs) are of great interest as targets for science and human missions, for possible

retrieval to cis-lunar space and as potential resource targets for both exploration and commercial uses. This interest stems from the exponential nature of the rocket equation that imposes a harsh mass penalty on any mission to a higher delta-v. We have compared the known NEO population from the IAU Minor Planet Center (MPC) with the NEOSat-1 model residence times for the NEO population (Greenstreet & Gladman, 2012) to assess how many undiscovered NEOs there are as a function of H magnitude and delta-v. We find that the median of known NEOs is at lower delta-v (7.3 km/s) than the model population (9.8 km/s), suggesting a bias toward detecting lower delta-v NEOs. To the precision of our data, which is as low as 40% for the 300-500 m diameter (D) objects, the bulk of the larger D>300 m NEOs have been found from delta-v<10.3 km/s. However in the 50 < D < 300 m range there are tens of thousands of delta-v < 10.3 km/s to be found. We examine the total number of undiscovered NEOs as a function of delta-v and find that to find at least 100 now unknown NEOs requires a threshold delta-v of 5.7 km/s, while to find at least 1000 of them requires a threshold delta-v of 6.2 km/s. These numbers can be used to determine mission delta-v requirements for a given number of suitable targets, that will likely be restricted by other criteria (size, composition, spin state) to a few percent of the total population.

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414.06 – A 1-D Cryothermal Model of Ceres' Megaregolith: Predictions for Surface Vapor Flux, Subsurface Temperatures and Pore Ice Distribution

We have applied a self-consistent 1-D model for heat diffusion, vapor diffusion, and ice condensation/sublimation, and surface energy balance to investigate our hypothesis for the source of the recently observed water vapor around Ceres [1]. As described in a companion presentation [2], we find that the estimated global flux of 6 kg/s can be produced by steady-state sublimation of subsurface ice driven by the "geothermal" temperature gradient for a heat flux of 1 mW/m² - the value estimated for a chondritic abundance of heat-producing elements [3,4]. We will present a detailed description of our Ceres cryothermal diffusion model and comparisons with previous models. One key difference is the use of a new physics-based analytic model ('MaxRTCM') for calculating the thermal conductivity (Kth) of planetary regolith [5] that has been validated by comparisons to a wide range of laboratory data [6]. MaxRTCM predicts much lower Kth values in the upper regolith than those in previous work [3]. It also accounts for a process first modeled in a study of unstable equatorial ground ice on Mars [7,8], where vapor diffusing up from a receding ice table toward the surface can recondense at shallower depths - eventually forming a steady-state profile of pore ice volume fraction that increases with depth and maintains a constant flux of vapor at all depths [7]. Using MaxRTCM we calculate the corresponding Kth(z) profiles and will present predictions and implications of the resulting temperature profile in the upper few kilometers of Ceres' megaregolith.

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414.07 – DASTCOM5: A Portable and Current Database of Asteroid and Comet Orbit Solutions

A portable direct-access database containing all NASA/JPL asteroid and comet orbit solutions, with the software to access it, is available for download (<ftp://ssd.jpl.nasa.gov/pub/xfr/dastcom5.zip>; `unzip -ao dastcom5.zip`). DASTCOM5 contains the latest heliocentric IAU76/J2000 ecliptic osculating orbital elements for all known asteroids and comets as determined by a least-squares best-fit to ground-based optical, spacecraft, and radar astrometric measurements. Other physical, dynamical, and covariance parameters are included when known. A total of 142 parameters per object are supported within DASTCOM5. This information is suitable for initializing high-precision numerical integrations, assessing orbit geometry, computing trajectory uncertainties, visual magnitude, and summarizing physical characteristics of the body. The DASTCOM5 distribution is updated as often as hourly to include newly discovered objects or orbit solution updates. It includes an ASCII index of objects that supports look-ups based on name, current or past designation, SPK ID, MPC packed-designations, or record number. DASTCOM5 is the database used by the NASA/JPL Horizons ephemeris system. It is a subset exported from a larger MySQL-based relational Small-Body Database ("SBDB") maintained at JPL. The DASTCOM5 distribution is intended for programmers comfortable with UNIX/LINUX/MacOSX command-line usage who need to develop stand-alone applications. The goal of the implementation is to provide small, fast, portable, and flexibly programmatic access to JPL comet and asteroid orbit solutions. The supplied software library, examples, and application programs have been verified under gfortran, Lahey, Intel, and Sun 32/64-bit Linux/UNIX FORTRAN compilers. A command-line tool ("dxlook") is provided to enable database access from shell or script environments.

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414.08 – Electrostatically-driven Dust Motion near Itokawa

Electrostatically-dominated dust motion has been hypothesized to occur on the Moon and asteroids. In our previous work, we used a 1-dimensional plasma and gravity model to show that micron-sized dust grains could stably levitate above the surface of Itokawa. However, we have now implemented a 2-dimensional model that more accurately represents the irregular surface of Itokawa, including topographic details important for both gravitational and plasma dynamics. Using this state-of-the-art model, we have discovered equilibria about which dust grains may be able to levitate near the surface of the asteroid. Here, we show trajectories of dust grains about the equilibria. By studying the behavior of dust grains, we will assess whether the identified equilibria are numerical artifacts and, if not, determine the stability of the equilibria. Studying the dynamics of dust grains near the surface of Itokawa will allow us to assess the importance of electrostatically-dominated dust motion in the morphological evolution of this body.

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414.09 – The Catalina Sky Survey: Status, Discoveries and the Future

On 1 January 2014, the Catalina Sky Survey kicked off its year with the discovery of 2014 AA, a small Apollo-type NEO that entered the atmosphere over the mid-Atlantic ocean 21 hours after discovery. As of 12 August 2014, the Catalina Sky Survey (CSS) has discovered 5192 Near Earth Objects. Accounting for nearly two thirds of all NEO discoveries since 2005, and over 46% of all known NEOs, CSS has a long history of being an effective dedicated NEO survey, and pending upgrades will allow it to continue its productivity into the foreseeable future.

We present an overview of our facilities and equipment, the current status of survey operations, an overview of recent discoveries and discovery statistics, and the status of recent and pending upgrades to our instrumentation and equipment. The 1.0m follow-up telescope on Mt. Lemmon is now operational (MPC code I52) and providing asteroid astrometry. A new camera for the 1.5 m telescope (G96) will increase the field four times to 5 square degrees and may be operational by the end of the year. A similar camera for the Catalina Schmidt telescope (703) will follow with a 19.4 square degree field. These upgrades will substantially increase the NEO discovery rate from CSS. Additionally, software upgrades to accommodate the larger data flow are in process. Finally, we will discuss ways in which our data are being used for other purposes within the astronomical community, including the search for optical transients (Catalina Real-Time Transient Survey), and the public search for NEOs through the Asteroid Zoo program, developed by Planetary Resources, Inc. in collaboration with CSS and Zooniverse, under the auspices of NASA's Asteroid Grand Challenge initiative.

The Catalina Sky Survey is funded by NASA's Near Earth Objects Observation Program.

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414.10 – The LCOGT Near Earth Object (NEO) Follow-up Network

Las Cumbres Observatory Global Telescope (LCOGT) network is a planned homogeneous network of over 35 telescopes at 6 locations in the northern and southern hemispheres. This network is versatile and designed to respond rapidly to target of opportunity events and also to do long term monitoring of slowly changing astronomical phenomena. The global coverage of the network and the apertures of telescope available make LCOGT ideal for follow-up and characterization of Solar System objects (e.g. asteroids, Kuiper Belt Objects, comets, Near-Earth Objects (NEOs)) and ultimately for the discovery of new objects.

LCOGT has completed the first phase of the deployment with the installation and commissioning of nine 1-meter telescopes at McDonald Observatory (Texas), Cerro Tololo (Chile), SAAO (South Africa) and Siding Spring Observatory (Australia). The telescope network is now operating and observations are being executed remotely and robotically. I am using the LCOGT network to confirm newly detected NEO candidates produced by the major sky surveys such as Catalina Sky Survey (CSS), NEOWISE and PanSTARRS (PS1). Over 600 NEO candidates have been targeted so far this year with 250+ objects reported to the MPC, including 70 confirmed NEOs. An increasing amount of time is being spent to obtain follow-up astrometry and photometry for radar-targeted objects in order to improve the orbits and determine the rotation periods. This will be extended to obtain more light curves of other NEOs which could be Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) or Asteroid Retrieval Mission (ARM) targets. Recent results have included the first period determination for the Apollo 2002 NV16 and our first NEO spectrum from the FLOYDS spectrographs on the LCOGT 2m telescopes obtained for 2012 DA14 during the February 2013 closepass.

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414.11 – Spacewatch Observations of Asteroids and Comets Supporting the Large-Scale Surveys

We specialize in followup astrometry of Near-Earth Objects (NEOs) of high priority while they are faint, including recently discovered objects on the MPC's Confirmation Page, objects with potential close encounters with Earth, NEOs for which NEOWISE determined albedos and diameters, targets of radar, potential destinations for spacecraft, and special requests by the MPC or JPL. The present era of Spacewatch observations began on 2011 Oct 15 with a new imaging camera on our 1.8-meter telescope. From then, the MPC has been accepting an annual average of 8,492 lines of astrometry of 1,018 different NEOs from Spacewatch, including 177 different PHAs per year. Thus we observe half of all such objects that are observed by anyone in the same interval. We make twice as many measurements of PHAs while they are fainter than $V=22$ than the next most productive astrometry group. We have contributed to the removal of half of the objects that were retired from JPL's impact risk list. Per year we observe about 35 radar targets, 50 NEOs that were measured by NEOWISE, and 100 potential rendezvous destinations. We also average 400 observations of comets per year. Since 2004 we have increased our efficiency by a factor of six in terms of observations per unit personnel work year by means of new hardware, software, and the automation of the 0.9-m telescope. Last year we received a grant to upgrade our 0.9-m telescope and develop a public archive of image data dating back to 1990. New grants from the NEOO Program now support our use of telescopes larger than the 1.8-meter of Spacewatch and improvement of the efficiency of the Spacewatch 1.8-m. Support of Spacewatch was/is from JPL subcontract 100319 (2010-2011), NASA/NEOO grants NNG06GJ42G, NNX11AB52G, NNX12AG11G, NNX13AP99G, NNX14AL13G, and NNX14AL14G, the Lunar and Planetary Laboratory, Steward Observatory, the Brinson Foundation of Chicago, IL, the estates of R. S. Vail and R. L. Waland, and other private donors. We are also indebted to the MPC of the IAU for their web services.

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414.12 – Delivery of Organic Material and Water through Asteroid Impacts

Meteorites, specifically carbonaceous chondrites, are frequently invoked as the primary source of Earth's water and organic materials, crucial ingredients for the formation of life. We have started developing a dynamical model of the delivery of their parent bodies, primitive low-albedo asteroids, from the asteroid main belt to Earth and to other planetary surfaces.

Existing modeling work focuses on time-integrated delivery rates, which are dominated by the Solar System's turbulent youth. We, in turn, aim at calculating instantaneous delivery rates for comparison with instantaneous measurements. In doing so, we take direct account of the asteroid main belt's observed dynamical and physical structure. In particular, we use low albedo (as taken from the WISE catalog) as a proxy for primitive composition.

Our first goal is for our model to reproduce the measured rate of micro-meteorite impacts on Earth. We will then calculate improved delivery rates to Mars and other planetary surfaces within the Solar System.

Finally, we aim at applying our model to select exo-planetary systems. Far-IR observations of Vega and Fomalhaut reveal the presence of asteroid belts around these stars; dynamical calculations suggest that those are not a rare occurrence but should occur rather generically around the location of the frost line. In such planetary systems, asteroids could deliver water and organics to the habitable region. In this sense, our model should lead to the definition of benchmark observables for exoplanet studies using upcoming/proposed IR facilities such as SPICA, METIS, and JWST.

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414.13 – Effect of the gas drag on the planetesimals in a Transitional Disk

We study the effect of aerodynamic drag due to the gaseous component of a Transitional protoplanetary disk on planetesimals embedded in the disk itself.

We present a series of numerical simulations of the dynamics concerning the exterior planets and a discrete number of particles exterior to these, representing the solid component of the disk. Planets are arranged in a compact, multiresonant configuration as that proposed in the so-called Nice model. We model the gaseous component of the protoplanetary disk as both a minimum mass solar nebula and a viscous accretion disk model, both truncated out to a disc radius of approximately 20 AU, following recent observations.

We find that aerodynamic drag has important consequences on the early evolution of the compact Solar System. As pointed out previously by other authors, gas drag leads to planetesimal trapping in low order resonances, particularly for kilometer size bodies. In our case, since planetesimals are all located initially outwards of Neptune, these are trapped in outer resonances with such planet on typical timescales of a few million years. This effect leads to an accelerated migration scenario, with the system becoming dynamically unstable on a very short timescale, in comparison to gas free scenarios.

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414.14 – Evaluating Different Scenarios for the Formation and Early Evolution of the Asteroid Belt

The asteroid belt is dynamically excited, depleted in mass relative to the surface mass density of the rest of the Solar System, and contains numerous diverse taxonomic classes of asteroids that are partly, but not completely, radially mixed. In the 'classical' scenario of Solar System formation, the excitation, depletion and radial mixing of the asteroid belt is best explained by the effect of planetary embryos that are initially present in the primordial asteroid belt region [1-3]. In the more recent 'Grand Tack' scenario proposed by Walsh et al. [4], the early inward-then-outward migration of Jupiter in the gas disk initially depletes, then repopulates the asteroid belt with material scattered from both interior and exterior to Jupiter. Here we will examine in detail the model asteroid distributions resulting from these two scenarios for a range of parameters, and compare them to observational constraints on the current distribution of asteroids in the Solar System. We will also address the possible effects that late-stage planetesimal-driven migration and resonance-crossing of Jupiter and Saturn in the Nice Model [eg. 5,6] may have on the final asteroid distribution.

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414.15 – Light-Scattering Simulations of Space-Weathering Effects on Asteroid and Meteorite Spectra

Space weathering introduces changes to the reflectance spectra of asteroid surfaces. In silicate minerals, space weathering is known to darken the spectra, reduce the silicate absorption band depths, and increase the spectral positive slope in visual and near-infrared wavelengths (see, e.g., T. Kohout et al., *Icarus* 237, p. 72-83, 2014, and references therein).

The space-weathering process is believed to influence the spectra by generating small nanophase iron (npFe⁰) inclusions in the surface layers of mineral grains. The npFe⁰ inclusions are believed to be one to some tens of nanometers in size. This mechanism has been linked to the Moon and to a certain extent also to the silicate-rich S-complex asteroids and to the ordinary chondrite meteorites.

We will present light-scattering simulations that validate the space-weathering and npFe⁰ effects on the spectra of olivine. All the observed effects, i.e., the darkening and reddening of the spectra, as well as the decreasing of the 1- μ m absorption band, can be reproduced in the simulations. We use a radiative-transfer solution for a semi-infinite slab of olivine and compute the reflectance spectra over the wavelengths from 0.5 μ m to 2.5 μ m. Laboratory-measured, wavelength-dependent complex refractive indices of olivine are used in the model as input. To include the npFe⁰ in the host material, we use the Maxwell-Garnett effective-medium theory to model the effect of small Fe inclusions on the refractive index. The resulting spectra show all the observed space-weathering effects.

We will also improve the light-scattering model with exact scattering simulations (i.e., based on the *T*-matrix or volume-integral equation methods) to model the single scatterer, which can include npFe⁰ inclusions, together with a radiative-transfer approach that can use this computed single scatterer information as input (K. Muinonen, *Waves in Random Media* 14, p. 365, 2004). With this approach, we can avoid using the effective medium theory, and study the size effect of npFe⁰ inclusions more thoroughly.

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414.16 – The Stopping Power of Asteroidal Materials as High-Energy Charged Particle Shielding

Extended human missions in deep space face a challenging radiation environment from high-energy galactic cosmic rays and solar energetic particles generated by solar flares and related coronal mass ejections.

Shielding to attenuate these high-energy particles will require significant mass and volume, and would be extremely expensive launch from the surface of the earth. One possible solution could be the use of asteroidal resources as shielding for these high-energy particles. The effectiveness of shielding material for moderately relativistic charged particles is a function of the mean rate of energy loss, primarily to ionization and atomic excitation and is termed stopping power. In general, low atomic number elements are more effective per unit volume.

We have calculated the stopping power for the average compositions of all major meteorite groups and will compare these data with typical spacecraft materials.

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414.17 – Spacewatch Astrometry of Asteroids and Comets with the Bok 2.3-m and Mayall 4-m Telescopes.

We use the Bok 2.3-m and Mayall 4-m telescopes on Kitt Peak to improve knowledge of the orbits and magnitudes of high priority classes of Near Earth Objects (NEOs) and other small bodies in need of recovery that cannot be reached with the Spacewatch 0.9-m and 1.8-m telescopes. Targets include NEOs with potential close encounters with Earth (Virtual Impactors; VIs), future targets of radar, NEOs previously detected by NEOWISE with orbits or albedos suggesting potential for cometary activity, potential destinations for spacecraft, returning NEOs with hard-won albedos and diameters determined by NEOWISE, and faint Potentially Hazardous Asteroids (PHAs). Notable targets successfully recovered include the Earth Trojan 2010 TK7 and the faint almost-lost VI 2011 BY24 discovered by NEOWISE. Between 2010 June 6 and 2014 July 23 the MPC accepted 1316 lines of astrometry by us with these telescopes on 207 different NEOs including 84 PHAs. We made 343 observations of PHAs with $V \geq 22$. Our average arc extension on large PHAs (with $H \leq 17.75$) is 184 days, which is 2x longer than the next most effective observing station. Recently with all four telescopes Spacewatch has made 39% of all the observations of PHAs that were fainter than $V=22$ at the time of measurement. This count is twice that of the next most productive station in that measure. The faintest V magnitude we have observed so far is 24.4 and the smallest solar elongation angle at which we have observed is 46 degrees. Our work with the Mayall and Bok telescopes has been determined by the Minor Planet Center (MPC) to provide "dramatic improvement" to NEO orbits (T. Spahr, 2014 private communication). Support of Spacewatch was/is from JPL subcontract 100319 (2010-2011), NASA/NEO grants NNG06GJ42G, NNX11AB52G, NNX12AG11G, NNX13AP99G, NNX14AL13G, and NNX14AL14G, the Lunar and Planetary Laboratory, the Brinson Foundation of Chicago, IL, the estates of R. S. Vail and R. L. Waland, and other private donors. We are also indebted to the MPC for their web services and to NOAO/KPNO and Steward Observatory for telescope time.

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414.18 – Synthetic Tracking Observation of Near Earth Asteroids

The motion of a near Earth Asteroids (NEA) will often result in a streaked image on a typical 30sec CCD exposure. The fact that photons from the asteroid are spread over many pixels reduces both the sensitivity of the camera as well as astrometric accuracy of the measurement. Instead of taking a 30sec exposure, synthetic tracking takes multiple short (~0.5s) images where the NEA image is not streaked. A shift and add algorithm is used to generate an image of the NEA as if the telescope were tracking the moving object. This type of algorithm is sometimes called a multi-hypothesis velocity matched filter. While the improvement in sensitivity for detecting moving objects has been explored, it turns out there is an equally significant improvement in astrometric accuracy, when we looked at data from a high frame rate camera on the Palomar 5m telescope. As new NEO search telescopes/cameras become operational, the number of discoveries will increase beyond the ~1000/year. Most of these objects especially < 100m dia, will be lost almost immediately after discovery. An improvement in optical astrometry of 10~20 could enable improved orbits to where they could be found if they were to pass near the Earth by 4-6 years in the future. This paper discusses these two properties of synthetic tracking.

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414.19 – The Pan-STARRS search for Near Earth Objects

The two Pan-STARRS telescopes, located on Haleakala, Maui, Hawaii, are 1.8-meter diameter telescopes equipped with 1.4 Gigapixel cameras that deliver 7 square degree fields of view. The first of these telescopes, Pan-STARRS1 (PS1), is now conducting a dedicated survey for Near-Earth Objects. The second telescope, Pan-STARRS2 (PS2) is being commissioned. It will initially supplement the PS1 search by targeting Near Earth Objects (NEO) candidates from PS1. As its efficiency grows, PS2 also will search for NEOs, and will increase the sky coverage and cadence.

PS1 is cooperating with the G96 telescope of the Catalina Sky Survey in terms of field selection. Between declinations of -30 and +40 degrees, the telescopes alternate 1 hour-wide RA stripes each night. This strategy has led to increased productivity, and eliminated accidental repeats of fields. The PS1 survey area has been extended south to -47.5 degrees declination. The image quality in the deep south sky from Haleakala is good, and the new southern extension to the survey area has been very productive.

PS1 has discovered more than half of the larger NEOs and PHAs in 2014 to date, and has become the leading NEO discovery telescope. PS1 delivers excellent astrometry and photometry. PS1 continues to discover a significant number of large (> 1km) NEOs.

The present discovery rate of NEO candidates by PS1 is now overwhelming the external NEO followup resources. particularly for fainter NEOs. It has required that PS1 repeat fields to recover NEO candidates. As PS2 matures, and when G96 has its new camera, the combination of these three telescopes will facilitate a higher NEO discovery rate, and a

better census of the NEOs in the sky. This will in turn lead to a better understanding of the size and orbit distribution of NEOs. The Pan-STARRS NEO survey is also likely to discover asteroids suitable for the NASA asteroid retrieval mission.

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414.20 – Digital Tracking Observations Discover Asteroids Ten Times Fainter than Conventional Searches

Digital tracking is a method for asteroid searches that greatly increases the sensitivity of any telescope. While it is not original to us, we are the first to develop and use it to detect large numbers of new faint asteroids from the ground. We describe details of our implementation, challenges and their solutions, and the current state of our results. Digital tracking has the potential to revolutionize searches for faint moving objects, including Kuiper Belt objects, main belt asteroids, near-earth objects, and even anthropogenic space debris in low Earth orbit. Our results show that there are no serious obstacles to its large-scale implementation.

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415 – Asteroid Physical Characterization Posters: Main Belt

Reddy, Vishnu

415.01 – Did Ordinary Chondrite Impactors Deliver Olivine to Vesta?

Ground-based and Hubble Space Telescope observations of asteroid Vesta suggested the presence of olivine. However, subsequent analysis of data from NASA's Dawn mission proved that this "olivine-bearing unit", identified as Oppia crater and its ejecta blanket, was composed of HED impact melt rather than olivine. The lack of widespread olivine in the 19 km deep Rheasilvia basin on the South Pole suggests that the crust-mantle boundary was not breached during the formation of the basin, and that Vesta's crust is thicker than originally anticipated. Recently, local-scale olivine units have been reported in the walls and ejecta of two craters, Arruntia and Bellicia, located in the northern hemisphere of Vesta, 350-430 km from the Rheasilvia basin (Ammannito et al., 2013). These units were interpreted as exposed plutons by Clenet et al. (2014) rather than of mantle origin excavated during the formation of the Rheasilvia basin. We explored alternative sources for these olivine-rich units by reanalyzing the data published by Ammannito et al. (2013). Our mineralogical analysis gives olivine abundance between 70-80 vol.% consistent with those obtained previously (>60%). The pyroxene ferrosilite content and olivine abundance of the olivine-rich units are similar to ordinary chondrites. Meteoritic evidence suggests contamination of HEDs by several ordinary chondrite impactors including H, L and LL chondrites. This includes howardite JaH 556, which contains ~20 vol.% H chondrite material mixed with HED impact melt. Based on the non-diagnostic curve match and detailed mineralogical analysis using diagnostic spectral band parameters, we conclude that the olivine units in the northern hemisphere of Vesta could be explained by the delivery of exogenic H/L chondrite material rather than being a product of planetary differentiation.

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415.02 – Vesta's Pinaría Region: Lower Crustal Composition and Regolith Mixing from Early Vesta

A region in the southeastern quadrant of Vesta named Pinaría (0°-90° E long, 21°-66° S lat, in the Claudia coordinate system) is studied in the spectral range 0.44-3.5 μm and spatial resolution ~200-700 m/pixel using data returned from the Dawn mission's visible and infrared spectrometer (VIR). We examine spectra of the exposed wall of a portion of Matronalia Rupes, the partial rim of the 505 km diameter basin, Rheasilvia and compare band positions, strength and width to the plains north of the wall and the groove and ridge terrain on the floor of the basin. The band positions of the exposed scarp spectra in the 1- and 2- μm region are indicative of low calcium, low iron pyroxene found in diogenite meteorites which most likely originated at Vesta. The spectra of surrounding terrain contain additional pyroxenes as determined by wider absorption bands and longer wavelength of band minima. Some regions contain a larger eucritic component and is interpreted as a mixture of ancient crust and lower crustal, diogenitic material. These regions have relatively weaker or non-existent absorption bands at 2.8 μm that are related to OH-bearing minerals. Examination of the largest craters in this region show band parameter changes and overall reflectance variations between exposed crater walls and ponded material in the bottom of the craters. Interpretation of these spectra demonstrates mixing resulting from crater formation and ejecta blankets producing regolith. Mineralogical interpretation using higher spatial resolution, broad-band filter images from the Framing Camera will be compared with analysis of VIR spectra that extend

to longer wavelength and have higher spectral resolution.

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Contributing team(s): Dawn Science Team

415.03 – Exogenous Olivine on Vesta

Vesta has conserved an early status of planetary evolution, demonstrated by the global coverage of HED lithology on its surface. Being sufficiently large to retain some material from slow projectiles, but small enough to prevent its complete evaporation during the impacts, this unique environment is ideal for distinction and identification of exogenous material. In particular, the distribution, concentration, and geological context of olivine exposures are poorly consistent with a Vestan mantle origin. Similar arguments are valid for the areas of dark carbonaceous chondrite-like lithology, and a few other features with unusual visual spectral slopes. Most olivine is found close to the large impact craters Bellicia, Arruntia, and Pomponia in the northern hemisphere, whose ejecta sheet is characterized by a mixing trend from an HED lithology to S- or A-type asteroid material. The olivine has diagnostic significance for the extent and duration of differentiation during the early accretion of parent bodies in the asteroid region. Sources for exogenous olivine are available in Vesta's environment among A- and S-type asteroids. It is not clear, however, if it is derived mainly from achondritic or chondritic sources. On the other hand, the lack of evidence for Vesta's mantle material implies constraints on its inner structure, e.g. the depth of the crust.

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415.04 – New lightcurve of asteroid (216) Kleopatra to evaluate the shape model

Asteroid 216 Kleopatra is an M class asteroid in the Main Belt with an unusual shape model that looks like a dog bone. This model was created, from the radar data taken at Arecibo Observatory (Ostro et al. 1999). The discovery of satellites orbiting Kleopatra (Marchis et al. 2008) has led to determination of its mass and density (Descamps et al. 2011). New higher quality data were taken to improve upon the existing shape model. Radar images were obtained in November and December 2013, at Arecibo Observatory with resolution of 10.5 km per pixel. In addition, observations were made with the fully automated 20-inch telescope of the Murillo Family Observatory located on the CSUSB campus. The telescope was equipped with an Apogee U16M CCD camera with a 31 arcmin square field of view and BVR filters. Image data were acquired on 7 and 9 November, 2013 under mostly clear conditions and with 2x2 binning to a pixel scale of 0.9 arcseconds per pixel. These images were taken close in time to the radar observations in order to determine the rotational phase. These data also can be used to look for color changes with rotation. We used the lightcurve and the existing radar shape model to simulate the new radar observations. Although the model matches fairly well overall, it does not reproduce all of the features in the images, indicating that the model can be improved. Results of this analysis will be presented.

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415.05 – Updated Shape Model of 1627 Ivar from 2013 Observations

1627 Ivar is a near Earth asteroid with a taxonomic type of Sqw [1] and a rotation period of about 4.8 hours [2] and was the first asteroid to be imaged by radar in 1985. Its large size and close approach to Earth in 2013 (minimum distance 0.32 AU) provided an opportunity to observe the asteroid over many different viewing angles for an extended period of time. We are determining a new shape model of Ivar by combining delay-Doppler data and visible-wavelength lightcurves obtained in 2013 using the Arecibo Observatory's 2380 MHz radar and the 0.35m telescope at the Palmer Divide Station respectively. We have used the software SHAPE [3] to incorporate these recent radar and lightcurve datasets and in order to find the best shape model for Ivar that updates the results presented by Kaasalainen et al. [4], which was based solely on lightcurves. The software yields reasonable asteroid shapes by rejecting overly complex and

implausible shapes that may appear to fit the data. Using this updated shape model, future work will involve putting this shape model into the thermal-modeling code SHERMAN to create synthetic near-IR spectra that can be compared to our 2013 IRTF SpeX data that cover a wide range of Ivar's rotational longitudes and viewing geometries. We will thus learn more about the detailed regolith and surface properties of Ivar and how those properties compare to those of other S-complex asteroids. References: [1] DeMeo et al. 2009, *Icarus* 202, 160-180. [2] Ostro, S. J. et al. 1990, *Astron. J.*, 99, 2012-2018. [3] Magri, C. et al. 2011, *Icarus* 214, 210-227. [4] Kaasalainen, M. et al. 2004, *Icarus* 167, 178-196. We thank NSF (AST-1109855) and the CLASS SSERVI for their support of this work.

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415.06 – Colors and spin period distributions of sub-km main belt asteroids

The size dependency of space weathering on asteroid's surface and collisional lifetimes suggest that small asteroids are younger than large asteroids. Therefore, the studies of smaller asteroid provide us new information about asteroid composition on fresh surface and their collisional evolution. We performed a color observation using 4 filters and lightcurve observation using 2 filters on different nights, using the 8.2m Subaru telescope/Suprime-Cam, for investigating the color and spin period distributions of sub-km main-belt asteroids (MBAs) that could not be seen before by middle class telescopes. In a lightcurve observation on Sep. 2, 2002, we kept taking images of a single sky field at near the opposition and near the ecliptic plane. Taking advantage of the wide field view of Suprime-Cam, this observation was planned to obtain lightcurves of 100 asteroids at the same time. Actually, we detected 112 MBAs and obtained their lightcurves by using a modified GAIA-GBOT PIPELINE. For the period analysis, we defined a criterion for judging whether an obtained rotational period is robust or not. Although Dermawan et al. (2011) have suggested that there are many fast rotators (FR) in MBAs, we noticed that many MBAs have long spin periods. Therefore, we could determine the rotation period of only 22 asteroids. We found one FR candidate (P=2.02 hr). We could measure the B-R color of 16 asteroids among the 22 MBAs. We divided them into S-like and C-like asteroids by the B-R color. The average rotational periods of C-like and S-like asteroids are 4.3 hr and 7.6 hr, respectively. C-like asteroids seem to rotate faster than S-like ones. We carried out a multi-color survey on Aug. 9 and 10, 2004 and then detected 154 MBAs. We classified them into several taxonomic types. Then we noticed that there are only very few Q-type candidates (non-weathered S-type) unlike the near Earth asteroid (NEAs) population, in which Q-type is a main component. This may indicate that most of Q-type NEAs did not originate from Q-type MBAs. They are probably objects subjected to resurfacing process (by peeling surface regolith, the outer layer of asteroid changes from S-type to Q-type) due to the tidal effect during their planetary encounters.

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415.07 – Orbital Measurement of Bulk Carbon, Hydrogen, Oxygen, and Sulfur of Carbonaceous Asteroids via High Energy Resolution Gamma-Ray Spectroscopy

Various populations of low-albedo asteroids (C-complex, D, and P spectral types) dominate the outer Main Asteroid Belt, Hildas, and Trojan clouds and are thought to be related to carbonaceous meteorites. However, carbonaceous meteorites are themselves a diverse group and it remains unclear which types represent which asteroids or asteroid populations. A high-energy-resolution (HPGe) gamma-ray spectroscopy (GRS) experiment on an asteroid orbiter would be sensitive to many of the elements that differentiate carbonaceous chondrite subclasses from each other and from the ureilites, including H, C, O, and S, in the outer ~20-50 cm of the asteroid surface. We have therefore conducted new simulations of the performance of a GRS experiment in orbit around asteroids with carbonaceous chondritic compositions at levels of hydration ranging from CI-like (~17 wt% structural water) to CO-like (<2 wt% structural water). Cosmic-ray interactions with the asteroid surfaces were modeled using the MCNPX Monte-Carlo radiation transport code. A spacecraft background (based on a Dawn-like spacecraft model) was also modeled using MCNPX: this included background due to direct GCR/spacecraft interactions as well as background due to asteroidal neutron flux on the spacecraft. A Dawn-like mission scenario was modeled with the altitude equal to the asteroid radius for a 4.5-month low-orbit phase. The detector model was based on Mars Odyssey Gamma-Ray Spectrometer (MOGRS), the largest and most sensitive HPGe GRS flown to date. The spectra from

the MCNPX output were broadened to a resolution based on the in-flight performance of MOGRS, FWHM = 4.1 keV at 1332 keV.

Doppler broadening was also modeled where applicable. Line fluxes were then extracted from the combined background + asteroid spectrum and statistical uncertainties evaluated.

We find that within 4.5 months the GRS can measure H/Si, O/Si, C/Si, and S/Si with sufficient precision to distinguish OH-rich CI and CM chondrites from drier CO-like compositions, and Fe/Si and S/Si to distinguish chondrites from ureilites and other achondrites. Comparison with in-flight MOGRS count rates for Martian Fe, Si, S, K, and Cl will also be discussed.

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415.08 – Spectropolarimetry of X-type Asteroids to Constrain the Wavelength Dependence of Polarization

We present spectropolarimetric observations of four X-type asteroids: (87) Sylvia, (110) Lydia, (201) Penelope, and (359) Georgia, that were conducted using the SPOL polarimeter at the Bok 2.3-m and Kuiper 1.6-m telescopes. The primary goal of these observations is to improve our understanding of the wavelength dependence of polarization from light reflected off of asteroid regoliths. Initial work from Belskaya et al (2009) suggests that the wavelength dependence of asteroids is roughly linear. For the X-types, the slope of this wavelength dependence becomes more negative as phase angle increases. S-type and V-type asteroids behave similarly to the X-types with regard to wavelength dependence. However, it is still uncertain whether wavelength dependence is driven by variations in albedo or composition between that asteroid types. Our observations will be used to confirm a linear change in polarization with wavelength. From the observations, we can calculate the slope of the wavelength dependence (assuming linearity) and construct polarimetric phase curves (polarization vs. phase angle) in an attempt to discern whether albedo change or composition is responsible. Our results will also be compared to Belskaya et al. (2009) and to other taxonomic types we have surveyed previously.

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415.09 – Distributions of spin/shape parameters of asteroid families and targeted photometry by ProjectSoft robotic observatory

In our recent work (Hanus et al. 2013) we studied dynamics of asteroid families constrained by the distribution of pole latitudes vs semimajor axis. The model contained the following ingredients: (i) the Yarkovsky semimajor-axis drift, (ii) secular spin evolution due to the YORP effect, (iii) collisional reorientations, (iv) a simple treatment of spin-orbit resonances and (v) of mass shedding.

We suggest to use a different complementary approach, based on distribution functions of shape parameters. Based on ~1000 old and new convex-hull shape models, we construct the distributions of suitable quantities (ellipticity, normalized facet areas, etc.) and we discuss differences among asteroid populations. We also check for outlier points which may then serve as a possible identification of (large) interlopers among "real" family members.

This has also implications for SPH models of asteroid disruptions which can be possibly further constrained by the shape models of resulting fragments. Up to now, the observed size-frequency distribution and velocity field were used as constraints, sometimes allowing for a removal of interlopers (Michel et al. 2011).

We also describe ongoing observations by the ProjectSoft robotic observatory called "Blue Eye 600", which supports our efforts to complete the sample of shapes for a substantial fraction of (large) family members. Dense photometry is targeted in such a way to maximize a possibility to derive a new pole/shape model.

Other possible applications of the observatory include: (i) fast resolved observations of fireballs (thanks to a fast-motion capability, up to 90 degrees/second), or (ii) an automatic survey of a particular population of objects (MBAs, NEAs, variable stars, novae etc.)

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415.10 – Simulations of asteroid surfaces and interiors using geometric optics

We simulate electromagnetic scattering from a realistic model of an asteroid using an algorithm of geometric optics with Fresnelian reflection and refraction as well as diffuse scattering (Muinonen et al. 2009). The goal is to understand and constrain, which physical properties of the asteroid surface affect the radar parameters and how. The results show the simulated circular-polarization ratios and radar albedos compared to radar observations of asteroids.

Two types of diffuse media will be studied: the first one is a uniform, internal diffuse medium inside a host body, and the second one is an external layer on the surface. The host body is large relative to the size of the diffuse scatterers and the wavelength (3-70 cm). Previously, we have utilized spheres and aggregates of spheres of different sizes as the diffuse scatterers. Now, we move on to more complex shapes, i.e., Gaussian random particles that mimic irregular boulders of 10-80 cm in size.

In this study, we show how the type of the diffuse medium, including the mean free path or the optical thickness, affects the radar parameters. As for materials, we utilize the electric permittivities of solid and fractured rocks and ice. The applications of the study can be extended from asteroids also to comets and moons.

References:

Muinonen et al., Light scattering by Gaussian particles with internal inclusions and roughened surfaces using ray optics, *JQSRT* 110 (2009) 1628-1639.

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415.11 – Artificial size frequency distribution indices in laboratory experiments: Implications for understanding the evolution of Itokawa

Asteroid 25143 Itokawa is a near-Earth irregular asteroid 535 by 294 by 209 meters in size [1]. The surface topography can be divided into the smooth lowlands and the rocky highlands. The origins of these regions could be due to the surface flow of fines from high to low points of gravitational potential [2]. Previous block studies conducted by Michikami et al. [3] and Mazrouei et al. [4] reported average size frequency distribution (SFD) indices on blocks larger than 6 m in diameter to be -3.1 ± 0.1 and -3.5 ± 0.1 , respectively. Noviello et al. [5] reported preliminary results showing that blocks from 0.1 to 6 m in diameter had significantly lower SFD indices. They also reported that SFDs created from lowland image analyses consistently yield indices of around -2.71 ± 0.01 , while the SFDs from highland images yield indices of roughly -2.00 ± 0.01 at the same scale. There are a number of geologic processes that could be responsible for the observed differences in SFD indices between different topographical regions. To quantify the effects of seismic shaking on SFD indices, we conducted simple laboratory experiments. Blocks were placed in a bin and slowly covered with sand and gravel, and then subjected to periods of moderate shaking in 10-second increments. The same methods used in the observational study were then applied to the experimental blocks to quantify the change in SFD index as the blocks were first covered and subsequently revealed. The initial results are: 1) As blocks are covered, in general the indices decrease; 2) Seismic shaking restores the indices; and 3) Larger blocks reappear faster than smaller rocks after shaking. This has implications for interpreting results of block count studies (the Brazil nut effect [6]) and sample return missions, while also providing details about the physical expression of certain geologic processes on small bodies. [1] Fujiwara, A. et al., (2006) *Science*, 312, 1330-1334. [2] Miyamoto, H. et al., (2007) *Science*, 316, 1011-1014. [3] Michikami, T. et al., (2008) *Earth Planets Space*, 60, 13-20. [4] Mazrouei, S. et al., (2014) *Icarus* 229, 181-189. [5] Noviello, J. L. et al., (2014) *LPSC XLV*, Abstract #1587. [6] Asphaug, E., et al. (2001) *LPSC XXXII*, Abstract #1708.

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415.12 – Coherent Backscattering by Particulate Planetary Media of Nonspherical Particles

The so-called radiative-transfer coherent-backscattering method (RT-CB) has been put forward as a practical Monte Carlo method to compute multiple scattering in discrete random media mimicking planetary regoliths (K. Muinonen, *Waves in Random Media* 14, p. 365, 2004). In RT-CB, the interaction between the discrete scatterers takes place in the far-field approximation and the wave propagation faces exponential extinction. There is a significant constraint in the RT-CB method: it has to be assumed that the form of the scattering matrix is that of the spherical particle. We aim to extend the RT-CB method to nonspherical single particles showing significant depolarization characteristics. First, ensemble-averaged single-scattering albedos and phase matrices of nonspherical particles are matched using a phenomenological radiative-transfer model within a microscopic volume element. Second, the phenomenological single-particle model is incorporated into the Monte Carlo RT-CB method. In the ray tracing, the electromagnetic phases within the microscopic volume elements are omitted as having negligible lengths, whereas the phases are duly accounted for in the paths between two or more microscopic volume elements. We assess the computational feasibility of the extended RT-CB method and show preliminary results for particulate media mimicking planetary regoliths. The present work can be utilized in the interpretation of astronomical observations of asteroids and other planetary objects. In particular, the work sheds light on the depolarization characteristics of planetary regoliths at small phase angles near opposition. The research has been partially funded by the ERC Advanced Grant No 320773 entitled "Scattering and Absorption of Electromagnetic Waves in Particulate Media" (SAEMPL), by the Academy of Finland (contract 257966), NASA Outer Planets Research Program (contract NNX10AP93G), and NASA Lunar Advanced Science and Exploration Research Program (contract NNX11AB25G).

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415.13 – The Rotational Properties of Multi-tailed Asteroid P/2013 P5

To date, there are twelve known celestial bodies in the Solar System, labeled Main Belt Comets (e.g. Hsieh & Jewitt, 2006) or Active Asteroids (Jewitt, 2012) that exhibit both asteroid and comet-like properties. Among them is P/2013 P5, a comet-asteroid transition object discovered by PAN-STARRS in August 2013. Observations made with the Hubble Space Telescope in September 2013 revealed that P/2013 P5 appears to have six comet-like dust tails. Jewitt et al. (2013) concluded that this extraordinary structure and activity cannot be explained by traditional near-surface ice sublimation or collision events ejecting particles from the asteroid's surface. Instead, the most likely explanation is that this unusual object has been spun-up by YORP torques to a critical limit that has resulted in the rotational disruption of the asteroid causing the unique six-tail structure. This interpretation predicts that the nucleus of this comet-like asteroid should be in rapid rotation. In November 2013, broadband photometry of P/2013 P5 was obtained with Lowell Observatory's 4-meter Discovery Channel Telescope using the Large Monolithic Imager to investigate the possibility of rapid rotation. On chip optimal aperture photometry was performed on P/2013 P5. At an apparent magnitude $V=22.5$ magnitude, we found no significant variability in the light curve at the level of 0.15 magnitudes. General morphology changes in the nucleus-coma system of the asteroid were also investigated. We will present our analysis of this search for variability in both time and spatially across the coma relative to the object's center of brightness.

Hsieh, H. H., & Jewitt, D. 2006, *Science*, 312, 561

Jewitt, D. 2012, *AJ*, 143, 66

Jewitt, D.C., Agarwal, J., Weaver, H., Mutchler, M., & Larson, S. 2013, *ApL*, 778

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415.14 – The color-magnitude distribution of small Jupiter Trojans

The Jupiter Trojans constitute a population of minor bodies that are situated in a 1:1 mean motion resonance with Jupiter and are concentrated in two swarms centered about the L4 and L5 Lagrangian points. Current theories of Solar System evolution describe a scenario in which the Trojans originated in a region beyond the primordial orbit of Neptune. It is hypothesized that during a subsequent period of chaotic dynamical disruptions in the outer Solar System, the primordial trans-Neptunian planetesimals were disrupted, and a fraction of them were scattered inwards and captured by Jupiter as Trojan asteroids, while the remaining objects were thrown outwards to larger heliocentric distances and eventually formed the Kuiper belt. If this is the case, a detailed study of the characteristics of Trojans may shed light on the relationships between the Trojans and other minor body populations in the outer Solar System, and more broadly, constrain models of late Solar System evolution. Several past studies of Trojans have revealed significant bimodalities with respect to various spectroscopic and photometric quantities, indicating the existence of two groupings among the Trojans – the so-called red and less-red sub-populations. In a previous work, we used primarily photometric data from the Sloan Digital Sky Survey to categorize several hundred Trojans with absolute magnitudes in the range $H < 12.3$ into the two sub-populations. We demonstrated that the magnitude distributions of the color sub-populations are distinct to a high confidence level, suggesting that the red and less-red Trojans were formed in different locations and/or experienced different evolutionary histories. Most notably, we found that the discrepancy between the two color-magnitude distributions is concentrated at the faint end. Here, we present the results of a follow-up study, in which we analyze color measurements of a large number of small Trojans collected using the Suprime-Cam instrument on the Subaru telescope. The new data extend the known color-magnitude distributions of the Trojan sub-populations to smaller sizes, where the effects of current collisional evolution become significant.

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415.15 – Picking Sides: Classifying Jupiter's Greeks and Trojans

The L4 and L5 Lagrange points of Jupiter are populated with thousands of known, and possibly hundreds of thousands of unknown, Greek and Trojan Asteroids. As a robust, intermediate population, these objects represent a crucial dynamical group for testing the viability of various Solar System formation models and mechanisms. A detailed examination of these two camps is therefore necessary for fully understanding Solar System formation. We have collected hundreds of visible photometric observations for 110 of the brightest ($H \lesssim 10.0$) members from both camps using several different observatories in both hemispheres in an effort to precisely classify these objects in a way readily comparable both to the Main Belt population as well as to populations of icy bodies further out in the Solar System. Here we present the full results of our photometric survey and analysis. These data also allow for a visible wavelength

comparison between the two camps as well a search for a similar visible color bimodality in the populations as has been suggested by some Infrared spectroscopic observations. Ultimately such information will help us better understand this very important group of objects and how they came to reside in their current orbits. This in-turn will provide insight into the very formation of the Solar System.

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415.16 – An Experimental Path to Constraining the Origins of the Jupiter Trojans Using Observations, Theoretical Predictions, and Laboratory Simulants

Hypotheses based on recent dynamical models (*e.g.* the Nice Model) shape our current understanding of solar system evolution, suggesting radical rearrangement in the first hundreds of millions of years of its history, changing the orbital distances of Jupiter, Saturn, and a large number of small bodies. The goal of this work is to build a methodology to concretely tie individual solar system bodies to dynamical models using observables, providing evidence for their origins and evolutionary pathways. Ultimately, one could imagine identifying a set of chemical or mineralogical signatures that could quantitatively and predictably measure the radial distance at which icy and rocky bodies first accreted. The target of the work presented here is the Jupiter Trojan asteroids, predicted by the Nice Model to have initially formed in the Kuiper belt and later been scattered inward to co-orbit with Jupiter.

Here we present our strategy which is fourfold: (1) Generate predictions about the mineralogical, chemical, and isotopic compositions of materials accreted in the early solar system as a function of distance from the Sun. (2) Use temperature and irradiation to simulate evolutionary processing of ices and silicates, and measure the alteration in spectral properties from the UV to mid-IR. (3) Characterize simulants to search for potential fingerprints of origin and processing pathways, and (4) Use telescopic observations to increase our knowledge of the Trojan asteroids, collecting data on populations and using spectroscopy to constrain their compositions. In addition to the overall strategy, we will present preliminary results on compositional modeling, observations, and the synthesis, processing, and characterization of laboratory simulants including ices and silicates.

This work has been supported by the Keck Institute for Space Studies (KISS). The research described here was carried out at the Jet Propulsion Laboratory, Caltech, under a contract with the National Aeronautics and Space Administration (NASA) and at the Caltech Division of Geological and Planetary Sciences.

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415.17 – Triggering Comet-Like Activities of Main Belt Comets

Main-belt comets (MBCs) have attracted a great deal of interest since their identification as a new class of bodies by Hsieh and Jewitt in 2006. Much of this interest is due to the implication that MBC activity is driven by the sublimation of volatile material (presumed to be water ice) presenting these bodies as probable candidates for the delivery of a significant fraction of the Earth's water. Results of the studies of the dynamics of these bodies suggest that MBCs were formed in-situ as the remnants of the break-up of large icy asteroids. Simulations also show that collisions among MBCs and small objects could have played an important role in triggering the cometary activity of these bodies. Such collisions might have exposed sub-surface water ice which sublimated and created thin atmospheres and tails around MBCs. Earlier dynamical studies established collision statistics of km-sized objects such as main belt comet (MBC) candidates with m-sized boulders in the asteroid belt (Haghighipour 2010). In order to drive the effort of understanding the nature of the activation of MBCs, we have investigated these collision processes by simulating the impacts in detail using a smoothed particle hydrodynamics (SPH) approach that includes material strength and fracture models. We have carried out simulations for a range of collision velocities and angles, allowing m-sized impactors to erode enough of an MBC's surface to trigger its activation. We present the results of our simulations and discuss their implications for the origin of MBCs.

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416 – Venus Posters

416.01 – Mars and Venus Ionospheres: Similarities and Differences Related to Solar Wind Interaction

The Pioneer Venus Orbiter (PVO) provided a fairly comprehensive picture of the Venus ionosphere above ~150km at a

time of moderate to high solar activity. PVO observations included ionospheric density morphology and related velocities and magnetic fields, and suggested a nominal picture of a robust ionospheric obstacle affected by solar wind erosion

at the top. In the coming months MAVEN will similarly probe the Martian ionosphere to ~150km, obtaining analogous in-situ measurements. Mars, with its more extended upper atmosphere and crustal magnetic fields, is known from Mars Global Surveyor (MGS) to exhibit a relatively complicated ionosphere interaction that is some mixture of a Venus-like and magnetosphere-like state.

BATS-R-US MHD models of the solar wind interactions with Mars and Venus allow investigations of the related ionospheric details within the framework of fluid treatments with basic CO₂ atmosphere photochemistry, including the underlying physics. In this study we compare multispecies single fluid model results for Mars and Venus for both solar maximum and minimum EUV conditions, and in the case of Mars, for several strong crustal field local times and interplanetary field orientations. These comparisons bring out some of the similarities and differences that may be observed as MAVEN data accumulate. Among the expectations from the models are features associated with the Mars crustal magnetic fields, including structured outflows and complicated dynamics in some localized areas. The results can help guide the analysis and interpretation of the new MAVEN measurements toward obtaining a more complete picture of Terrestrial planet differences and similarities.

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416.02 – Characterization of the lower layer in the dayside Venus ionosphere

The dayside Venus ionosphere consists of two layers: the V2 layer at 141 km, produced by solar extreme ultraviolet (EUV) photons, and the V1 layer at 127 km, produced by solar soft X-rays. The influence of solar zenith angle (SZA) and solar irradiance has been well characterized for the V2 layer, but not the V1 layer, where previous efforts were limited by data scarcity and incomplete SZA coverage. Here we use over 200 radio occultation profiles from Venus Express to characterize how the V1 peak altitude, peak density, and morphology respond to changes in SZA and solar activity. The V1 and V2 peak altitudes do not vary with SZA, and both peak electron densities vary with SZA in a Chapman-like manner. These results imply that the thermal structures of the atmosphere and ionosphere between 141 km and 127 km vary little with SZA. Also, the V1 peak density increases more with solar activity than the V2 peak density and the V1 morphology can change much more than the V2 morphology. These results are due to the soft X-ray flux increasing relative to the EUV flux as solar activity increases.

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416.03 – A Unique Approach for Studying Venus's Atmosphere: Technology Development for the Venus Atmospheric Maneuverable Platform (VAMP)

We are investigating a novel, reduced-risk approach to long-duration upper atmosphere exploration of Venus. The Venus Atmospheric Maneuverable Platform (VAMP) concept is a semi-buoyant plane with a science payload that can perform in situ measurements of Venus's atmosphere. VAMP is also capable of revisiting scientifically interesting locations. Designed with a low ballistic coefficient, VAMP deploys in space and enters Venus's atmosphere without an aeroshell. Once in the atmosphere, it can engage in a variety of science campaigns while varying its altitude between 50 and 68 km as it circumnavigates Venus. During daytime, VAMP will be able to make continuous science measurements at a range of latitudes, longitudes, and altitudes, while at night the vehicle will descend to a fully-buoyant, lower-power state, capable of performing modest science measurements at the float altitude. Near the end of VAMP's mission life, the vehicle may attempt an end-of-life trajectory into higher latitudes or descend to lower altitudes. This presentation focuses on the technology roadmap that will allow the vehicle to accomplish these science measurements. The roadmap is driven by high priority science measurements and the technology needed to implement VAMP's main mission phases: deployment, entry into Venus's atmosphere, and the transition to flight and science flight performance. The roadmap includes materials tests, platform aerodynamic characterization, various subscale and full-scale packaging and deployment tests, and a full-scale suborbital flight and is being produced with extensive science community interaction to define the science measurements that would be uniquely possible with this new science platform.

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416.04 – Observations of Venus at 1-meter wavelength

Radio wavelength observations of Venus (including from the Magellan spacecraft) have been a powerful method of probing its surface and atmosphere since the 1950's. The emission is generally understood to come from a combination

of emission and absorption in the subsurface, surface, and atmosphere at cm and shorter wavelengths [1]. There is, however, a long-standing mystery regarding the long wavelength emission from Venus. First discovered at wavelengths of 50 cm and greater [2], the effect was later confirmed to extend to wavelengths as short as 13 cm [1,3]. The brightness temperatures are depressed significantly (~50 K around 10-20 cm, increasing to as much as 200 K around 1 m) from what one would expect from a "normal" surface (e.g., similar to the Moon or Earth) [1-3].

No simple surface and subsurface model of Venus can reproduce these large depressions in the long wavelength emission [1-3]. Simple atmospheric and ionospheric models fail similarly. In an attempt to constrain the brightness temperature spectrum more fully, new observations have been made at wavelengths that cover the range 60 cm to 1.3 m at the Very Large Array, using the newly available low-band receiving systems there [4]. The new observations were made over a very wide wavelength range and at several Venus phases, with that wide parameter space coverage potentially allowing us to pinpoint the cause of the phenomenon. The observations and potential interpretations will be presented and discussed.

[1] Butler et al. 2001, *Icarus*, 154, 226. [2] Schloerb et al. 1976, *Icarus*, 29, 329; Muhleman et al. 1973, *ApJ*, 183, 1081; Condon et al. 1973, *ApJ*, 183, 1075; Kuzmin 1965, *Radiophysicis*. [3] Butler & Sault 2003, *IAUSS*, 1E, 17B. [4] Intema et al. 2014, *BASI*, 1.

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417 – Planetary Rings Posters

417.01 – Propellers in Saturn A and B rings

Propellers are gravitational signatures of small embedded moonlets within Saturn's rings. Even if the objects are too small to be directly observed, each body creates a much larger "S" shaped undulation on the rings. In this paper we present new results about by now classical A ring propellers and more enigmatic B ring population. In 2008 we obtained a UVIS occultation of the largest A ring propeller Bleriot. Utilizing Cassini ISS images we obtain Bleriot orbit and demonstrate that UVIS occultation did cut across Bleriot about 100km downstream from the center. The occultation itself shows a prominent partial gap and higher density outer flanking wakes, while their orientation is consistent with a downstream cut. Using simple model of the induced moonlet wakes we obtain that the size of the embedded body is about 400m, consistent with other estimates. While in the UVIS occultation the partial gap is more prominent than the flanking wakes, the features mostly seen in Bleriot images are actually flanking wakes. This result has been confirmed in another UVIS occultation from 2012.

One of the most interesting aspects of the A ring propellers are their wanderings, or longitudinal deviations from a pure circular orbit. We numerically investigated the possibility of simple moon driven librations. We adopted HNbody numerical integrator and checked for possible influence of Saturnian satellites. We found that some of A ring propellers indeed respond to the satellites. Earhart and Sikorsky are strongly perturbed by 415:416 and 293:294 mean longitude resonances with Pan and propellers close to the Keeler gap are all perturbed by Daphnis.

While the A ring propellers are not far from the Roche zone limit, propellers within the B ring come as a surprise. Simple expectation has been that the strong shear rate in the inner rings would tear bodies apart, which in turn requires stronger evidence for the B ring propellers. In B ring we discovered 12 propellers in 21 ISS NAC images (both lit and unlit geometry) and we found a propeller signature in one UVIS beta Centauri Rev96 occultation at $r=94,958\text{km}$.

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417.02 – Incomplete cooling down of Saturn's A ring at solar equinox: Implication for seasonal thermal inertia and internal structure of ring particles

At the solar equinox in August 2009, the Composite Infrared Spectrometer (CIRS) onboard Cassini showed the lowest temperatures of Saturn's rings ever observed. The equinox temperature of Saturn's A ring is found to be much higher than model predictions regardless of ring structure assumed as long as only the flux from Saturn is taken into account. This temperature anomaly is likely to indicate incomplete cooling down of ring particles at the equinox, and this fact allows us to estimate the ring particle size and the seasonal thermal inertia. We first assume that the internal density and the thermal inertia of a ring particle are uniform in depth. In the model, we use the analytic expression of Froidevaux (1981) for the seasonal solar flux variation and the time dependence is taken into account by solving the thermal diffusion equation. Model fits show that the particle size is about 1 m. The seasonal thermal inertia is found to be as high as 30-40 in MKS units in the middle A ring whereas it is as low as 10 in MKS units or as the diurnal thermal

inertia in the inner A ring and outermost A ring. An additional model, in which a particle has a high-density core covered by a fluffy regolith layer, showed that the size of core radius is about 90 % of the particle radius for the middle A ring and is much less in the outer and inner A ring. This indicates that the radial gradient of the internal mean density of particles exists across the A ring. We discuss possible origins of the density gradient.

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417.03 – Chaotic dynamics outside Saturn’s main rings: The case of Atlas

We revisit in detail the dynamics of Atlas. From a fit to new Cassini ISS astrometric observations spanning February 2004 to August 2013, we estimate $GM_{\text{Atlas}} = 0.384 \pm 0.001 \times 10^{-3} \text{ km}^3 \text{ s}^{-2}$, a value 13% smaller than the previously published estimate but with an order of magnitude reduction in the uncertainty. Our numerically-derived orbit shows that Atlas is currently librating in both a 54:53 corotation eccentricity resonance (CER) and a 54:53 Lindblad eccentricity resonance (LER) with Prometheus.

We demonstrate that the orbit of Atlas is chaotic, with a Lyapunov time of order 10 years, as a direct consequence of the coupled resonant interaction (CER/LER) with Prometheus. The interactions between the two resonances is investigated using the CoraLin analytical model (El Moutamid et al., 2014), showing that the chaotic zone fills almost all the corotation site occupied by the satellite’s orbit. Four 70 :67 apse-type mean motion resonances with Pandora are also overlapping, but these resonances have a much weaker effect on Atlas.

We estimate the capture probabilities of Atlas into resonances with Prometheus as the orbits expand through tidal effects, and discuss the implications for the orbital evolution.

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417.05 – Towards an Understanding of Thermal Throughput across Saturn's Rings with Cassini CIRS

One of the more striking aspects of Saturn's main ring system is its aspect ratio. Although it spans over 270,000 km from ansa to ansa, its thickness normal to the ring plane is less than a million times its breadth. Hence, studies of the rings' structure tend to focus on radial and azimuthal features. And yet in the thermal infrared the finite vertical thickness of the main rings is clearly manifest as temperature differences between that face of the rings under direct solar illumination (the lit face) and the opposite (unlit) face as derived from observations with Cassini's Composite Infrared Spectrometer (CIRS). The ultimate goal of this work is to understand these lit/unlit temperature differentials and their variation with radius and optical depth in order to infer information about the main rings' structure and dynamics in this third dimension.

As previous work has shown (Spilker et al., 2006), the thermal flux from the rings observed by CIRS is a function of observing geometry. To control for these variations, we designed paired observations of the lit and unlit sides of the rings where observing variables such as the emission, phase and local hour angles were as similar as possible to facilitate direct comparison between lit and unlit observations. Initial results show that, as expected, virtually no temperature differential exists across the optically thin C ring and Cassini Division. Temperature differentials are greatest in the optically thick B ring. The A ring, which is of intermediate optical depth, has temperature differentials that are intermediate between the other regimes. The B ring exhibits the largest spread in temperature differentials. The lit/unlit temperature differential in the B1 ring region is comparable to that of the A ring, while the B3 region, the most optically thick portion of the B ring, has a temperature differential that is several times higher. This presentation is a progress report on our analysis of such observations and our plans for future work.

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417.07 – Spoke Formation in Saturn's Ring: The Collisional Cascade Model

The mysterious wedge-shaped spokes in Saturn's main rings have defied explanation ever since their discovery during the Voyager flybys of the early 1980s. No earlier model can explain the three disparate timescales over which spokes evolve: i) the 10-minute formation time for a new spoke, ii) the hour-long period over which a spoke's radial edge remains active, and iii) the day-long timescale over which the magnetic longitude of earlier spoke activity is preferentially

repopulated with subsequent spokes. This and other observations of ongoing spoke formation can be understood in the context of a Collisional Cascade model in which a hail of rapidly-moving submicron dust grains rain down upon more massive ring particles. Tiny ~ 0.1 micron grains leave the ring plane en masse from the site of an initial disturbance (likely a meteoroid impact) and are accelerated by the magnetic field to high speeds relative to more massive ring particles. When the dust returns to the ring plane -nearly simultaneously over a large radial range - they strike fluffy dust-coated ring particles at km/s speeds, freeing both visible 0.5 micron spoke particles and additional submicron debris. Differences between the motions of the 0.1 micron dust grains and the much larger ring particles provides a potent free energy source that powers spoke formation. The onset of this hail of tiny energetic impactors can account for the observed rapid formation of spokes and, as the hail continues to fall, for the hour-long active periods over which some spoke edges remains nearly radial. The hour-long timescale is controlled by differences in initial launch velocities and different grain charge-to-mass ratios which strongly affect vertical motions. Additional tiny grains liberated in the first hailstorm go on to continue the cascade, returning to strike the same magnetic longitude in the ring hours to days later and stirring up more micron-sized spoke particles. This continuing cascade nicely accounts for the observed propensity of spokes to recur in certain magnetic longitudes.

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417.08 – Gravitational Accretion of Particles onto Moonlets in Saturn’s Rings

Detailed observations of shapes and densities of small satellites in Saturn’s system have been carried out by the Cassini spacecraft, and the results suggest that they were formed by gravitational accretion (Porco et al. 2007). Observations of Saturn’s rings by Cassini also revealed the existence of boulders and moonlets that are much larger than the background particles. Most of them were inferred from observations of propeller structures found in the A ring (e.g., Tiscareno et al. 2006; Sremcevic et al. 2007). On the other hand, the existence of boulders in the C ring has also been recently suggested from the observations of transparent holes by the Cassini Ultraviolet Imaging Spectrograph (Baillie et al. 2013). These observations combined with theoretical modeling would lead to constraints on the origin and evolution of the ring-satellite system. In the present work, using local N-body simulation, we examine gravitational accretion of ring particles onto moonlets in Saturn’s rings (Ohtsuki, Yasui, Daisaka 2013; Yasui, Ohtsuki, Daisaka, submitted). We examine in detail how the degree of gravitational accretion of ring particles onto moonlets depends on the radial distance from Saturn. We also examine the process of particle accretion onto a moonlet, and investigate effects of various parameters, such as the ring thickness, on the accretion process. Based on our numerical results, we will discuss their implications for the origin and evolution of small moons in Saturn’s rings. Our results suggest that large boulders recently inferred from observations of transparent holes in the C ring are not formed locally by gravitational accretion, while propeller moonlets in the A ring would be gravitational aggregates formed by particle accretion onto dense cores.

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417.09 – Extracting the Radial Profile of Saturn's Phoebe Ring

Saturn is famous for its dramatic main rings. Less well known is that two orders of magnitude further away from the planet, Saturn also hosts the solar system’s largest known circumplanetary ring. This Phoebe ring is likely sourced by collisions with Saturn’s largest irregular satellite Phoebe, and presents an important opportunity to learn more generally about the collisional evolution of this distant population of irregular satellites. Debris from such collisions is likely ultimately responsible for the dramatic two-faced coloration of the odd moon Iapetus.

We present results from recent observations with the Cassini spacecraft (in orbit about Saturn) in scattered optical light. Using a novel observational technique that exploits the moving shadow cast by Saturn, we have been able to clearly extract the exceedingly faint Phoebe ring signal (line-of-sight optical depth $\sim 10^{-9}$, surface brightness ~ 27 mag/arcsec²). Additionally, we present reconstructed radial profiles over the broad range of distances from Saturn spanned by our observations.

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417.10 – Study of the F ring core at high and low resolutions with Cassini ISS

Saturn’s F ring evolution is still a mystery since its discovery by Pioneer 11. This ring is unique by its changing appearance, its spiral shape, its shepherd satellites Prometheus and Pandora, its ephemeral satellites, and its chaotic behavior. We focus here on the brightest and central region of the F ring called the core. Using Voyager data, the core

was primarily believed to be one of the four strands of the F ring (Murray et al., 1997, *Icarus*, vol.129, p.304–316). However, the core is very different from the other strands, because we have demonstrated previously that the core reconnects on itself over 360 degrees, while the strands don't (Charnoz et al. 2005, *Science*, vol.310, p.1300-1304). Indeed, the strands originate from the core and are connected between themselves in a single feature that is a spiral, as explained in our previous works (Charnoz et al. 2005, *Science*, vol.310, p.1300-1304, Deau, 2007, PhD thesis University Paris 7 Denis Diderot). Our present study focuses on the F ring core. We have established a protocol (Deau, 2007, PhD thesis University Paris 7 Denis Diderot) to calculate the radial width and the radial local variations of the core using a Gaussian model. We use this method on Cassini ISS data to derive azimuthal profiles of core's radial width and local kicks. Our study shows that the F ring core is very stable on a scale of several months, as suggested by the recent chaos theory of Cuzzi et al. (2014, *Icarus*, vol.232, p.157-175), while the spiral has a much smaller timescale, i.e. the order of a few weeks.

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418 – Outer Solar System Satellites Posters

418.01 – Cassini VIMS Measurements of Thermal Emission from the Tiger Stripes on Enceladus

The 3 to 5 μm sensitivity of the Cassini VIMS instrument detects the rising, short-wavelength edge Planck thermal radiation from the highest temperature ($T \sim 200$ K) component of the active fissures at the south pole of Enceladus. The tiger stripe fissures are heated by the escaping warm water vapor that forms the plumes. During an extremely low 7 km altitude pass through the plumes in 2012, Goguen et al. (2013) used VIMS in the high-speed occultation mode to measure the temperature and width of an active site along the Baghdad fissure. In this presentation, we will give an overview of some of the other VIMS measurements of thermal emission from the tiger stripes and compare the emission from different active locations at different times for data that is already archived in the Planetary Data System.

Goguen, J.D., et al. (2013). The Temperature and Width of an Active Fissure on Enceladus Measured with Cassini VIMS during the 14 April 2012 South Pole Flyover. *Icarus* 226,1128-1137.

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Contributing team(s): Cassini VIMS Team

418.02 – A Passive Probe for Subsurface Oceans and Liquid Water in Jupiter's Icy Moons

We present a method for passive detection of subsurface oceans and liquid water in Jovian icy moons using Jupiter's decametric radio emission (DAM). The DAM flux density exceeds 3,000 times the galactic background in the neighborhood of the Jovian icy moons, providing a signal that could be used for passive radio sounding. An instrument located between the icy moon and Jupiter could sample the DAM emission along with its echoes reflected in the ice layer of the target moon. Cross-correlating the direct emission with the echoes would provide a measurement of the subsurface ocean depth along with the dielectric properties of the ice shell. The technique is complementary to ice penetrating radar measurements in that it works best where interference due to Jupiter's strong decametric emission is the strongest.

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418.03 – The Tidal Perturbations of the Galilean Satellites

To support the Juno mission currently enroute to Jupiter and preproject studies for the Europa Clipper mission, we developed new ephemerides for the Jovian satellites (the Galileans and four inner moons). The ephemerides are based on orbits that were determined by fitting a data set that included Earth-based astrometry from 1891 through 2013, Galilean satellite mutual events from 1973 through 2009, Galilean satellite eclipse timings from 1878 to 2013, and data acquired by the Pioneer, Voyager, Ulysses, Cassini, Galileo, and New Horizons spacecraft. As a part of the data fit we also redetermined the Jovian system gravity parameters and the spacecraft trajectories to be consistent with the satellite orbits. The dynamical model for the satellite orbits did not include tidal perturbations. Lainey et al. (2009 *Nature* 459, 957) determined tidal parameters for Jupiter and Io from a fit of the Galilean satellite orbits to Earth-based astrometry from 1891 to 2007 and mutual events from 1973 to 2003; he estimated only the satellite states and the tidal parameters. Subsequent to our ephemeris development, we activated the tide model and repeated our orbit analysis adding the determination of the tidal parameters. We found that if we omitted the spacecraft data and estimated only satellite states and tidal parameters, we obtained results similar to Lainey. However, when we included the spacecraft data in the fit, the tidal acceleration on Io was smaller but still caused a positive secular acceleration. The remaining task is to

discriminate between the effects of the tide raised on Jupiter by Io and that raised on Io by Jupiter.

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418.04 – The influence of variations in Jupiter's plasma environment on the Europa interaction

We present a multidisciplinary study of the influence of variations in Jupiter's corotational plasma environment on the details of the Europa interaction and the production of Europa's sputtered atmosphere. We build upon the measurements of the Voyager and Galileo spacecraft with updated models of the Jovian plasma environment and its interaction with Europa. We specifically discuss how plasma perturbations affect the accuracy with which Europa's induction signature can be extracted from measurements and the resulting fidelity of any quantities obtained related to ocean depth and salinity.

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418.05 – What causes an icy fault to slip? Investigating the depth and frictional conditions for tidally driven Coulomb failure along major strike-slip faults of Europa and Ganymede

The surfaces of Europa and Ganymede display strike-slip fractures, presumably arising from a combination of global and local stress sources. To better understand the role of tidal stress sources and implications for strike-slip faulting on these icy bodies, we investigate the relationship between shear and normal stresses at several major fault zones: Agenor Linea, Rhadamanthys Linea, Agave/Asterius Lineae, and Astypalaea Linea (on Europa), and Dardanus Sulcus (on Ganymede). Assuming tidal diurnal and non-synchronous rotation (NSR) stresses as plausible mechanisms for strike-slip tectonism, here we investigate the mechanics of Coulomb shear failure. We consider a range of friction coefficients ($\mu_f = 0.2 - 0.6$) and fault depths (0 – 6 km) to evaluate how failure predictions vary between the satellites and as a function of depth, ice friction, geographic location, and fault geometry. Assuming present-day orbital eccentricities, our results indicate that the conditions for failure at depth are not met for any of the fault systems if subject to diurnal stresses only. Alternatively, models that include both diurnal and NSR stresses readily generate stress magnitudes that could permit shear failure. On Europa, shear failure is easily activated and failure extends to depths ranging from 3 – 6 km when a low coefficient of friction ($\mu_f = 0.2$) is assumed. On Ganymede, failure is limited to even shallower depths (< 2 km). A high coefficient of friction ($\mu_f = 0.6$) limits failure depths to < 3 km on Europa faults and discourages strike-slip faulting completely on Ganymede. Based on these results, we infer that the conditions for shear failure are potentially met along at least these five studied systems, and possibly others in the outer solar system, if NSR is adopted as a driving stress mechanism and the coefficient of friction is low.

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418.06 – High spatial and spectral resolution near-infrared mapping of Europa with ESO/VLT/ SINFONI

Europa is a major exobiological target of interest owing to the possibility of a sub-surface briny ocean deeply buried under a water ice dominated crust several km thick (Dalton et al., 2010). The upcoming ESA L-class mission JUICE to the Jupiter system and its ambitious payload will address this question, in particular through compositional remote sensing in the near-infrared (MAJIS) and visible (MAJIS and JANUS) wavelength range.

In order to improve our knowledge mainly acquired by the instrument NIMS on the Galileo spacecraft, we have started a compositional mapping campaign of the icy moons using adaptive optics on ground-based observations from the Very Large Telescope (VLT) in Chile. Thanks to five nights of observation on the integral field spectrograph SINFONI, we have obtained spatially resolved spectra of nearly the entire surface of Europa, with a spectral resolution of 0.5 nm in the wavelength range 1.48–2.42 μm for a pixel scale of 12.5 by 25 m.a.s, equivalent to 35 by 70 km on Europa's surface. In this wavelength range, the spectra are generally dominated by crystalline and amorphous water-ice absorption features, but the distorted and asymmetric aspect of the 2.0 μm water-ice band on Europa's leading side confirms the presence of non-ice minerals such as sulfuric acid hydrate (Carlson et al., 2005) and magnesium sulfates such as epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$) (Brown et al., 2013).

Our first analysis reveals that the maps of the ice-water bands at 1.65 μm and 2.0 μm are, as expected, dominated by the leading/trailing effect, but also well correlated to well-identified geological structures as Pwyll Crater and Tara Regio. Global maps of relevant spectral parameters will be presented so as to showcase the spectral inhomogeneity of the surface of Europa for both major and minor signatures. No narrow signature, which could indicate the presence of

material of exobiological interest, has been so far detected in this complex data set. By the time of the meeting, we will however continue to search for such feature. Finally, linear and nonlinear mixing of icy and non-icy materials will be performed for selected areas.

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418.07 – The long-period librations of large synchronous icy moons

A moon in synchronous rotation has longitudinal librations because of its non-spherical mass distribution and its elliptical orbit around the planet. We study the long-period librations of the Galilean satellites and Titan and include deformation effects and the existence of a subsurface ocean. We take into account the fact that the orbit is not keplerian and has other periodicities than the main period of orbital motion around Jupiter or Saturn due to perturbations by the Sun, other planets and moons. An orbital theory is used to compute the orbital perturbations due to these other bodies. For Titan we also take into account the large atmospheric torque at the semi-annual period of Saturn around the Sun.

We numerically evaluate the amplitude and phase of the long-period librations for many interior structure models of the icy moons constrained by the mass, radius and gravity field.

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418.08 – Mapping the Topography of Europa: The Galileo-Clipper Story

The renewed effort to return to Europa for global mapping and landing site selection raises the question: What do we know about Europa topography and how do we know it? The question relates to geologic questions of feature formation, to the issue of ice shell thickness, mechanical strength, and internal activity, and to landing hazards. Our topographic data base for Europa is sparse indeed (no global map is possible), but we are not without hope. Two prime methods have been employed in our mapping program are stereo image and shape-from-shading (PC) slope analyses. On Europa, we are fortunate that many PC-DEM areas are also controlled by stereo-DEMs, mitigating the long-wavelength uncertainties in the PC data. Due to the Galileo antenna malfunction, mapping is limited to no more than 20% of the surface, far less than for any of the inner planets. Thirty-seven individual mapping sites have been identified, scattered across the globe, and all have now been mapped. Excellent stereo mapping is possible at all Sun angles, if resolution is below ~350 m. PC mapping is possible at Sun angles greater than ~60 degrees, if emission angles are less than ~40 degrees. The only extended contiguous areas of topographic mapping larger than 150 km across are the two narrow REGMAP mapping mosaics extending pole-to-pole along longitudes 85 and 240 W. These are PC-only and subject to long-wavelength uncertainties and errors, especially in the north/south where oblique imaging produces layover. Key findings include the mean slopes of individual terrain types (Schenk, 2009), topography across chaos (Schenk and Pappalardo, 2004), topography of craters and inferences for ice shell thickness (Schenk, 2002; Schenk and Turtle, 2009), among others. A key discovery, despite the limited data, is that European terrains rarely have topographic amplitude greater than 250 meters, but that regionally Europa has imprinted on it topographic amplitudes of +/- 1 km, in the form of raised plateaus and bowed-down arcuate troughs. Such amplitudes imply that the ice shell is capable of supporting relief and is not extremely thin.

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418.09 – Reassessing the Crater Distributions on Ganymede and Callisto: Results from Voyager and Galileo, and an Outlook to ESA's JUICE Mission to Jupiter

Crater distributions and origin of potential impactors on the Galilean satellites has been an issue of controversial debate. In this work, we review the current knowledge of the cratering record on Ganymede and Callisto and present strategies for further studies using images from ESA's JUICE mission to Jupiter. Crater distributions in densely cratered units on these two satellites show a complex shape between 20 m and 200 km crater diameter, similar to lunar highland distributions implying impacts of members of a collisionally evolved projectile family. Also, the complex shape predominantly indicates production distributions. No evidence for apex-antapex asymmetries in crater frequency was found, therefore the majority of projectiles (a) preferentially impacted from planetocentric orbits, or (b) the satellites were rotating non-synchronously during a time of heavy bombardment. The currently available imaging data are insufficient to investigate in detail significant changes in the shape of crater distributions with time. Clusters of secondary craters are well mappable and excluded from crater counts, lack of sufficient image coverage at high resolution, however, in many cases impedes the identification of source craters. ESA's future JUICE mission will study Ganymede as the first icy satellite in the outer Solar system from an orbit under stable viewing conditions. Measurements of crater distributions can be carried out based on global geologic mapping at highest spatial resolutions (10s of meters down to 3 m/pxl).

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418.10 – Thermal conductivity and radiation processing of Mimas and Tethys leading hemisphere anomalies

Analysis of Cassini spectroscopy and photometry data revealed an anomalous region present on the leading edge of the Saturnian icy moons Mimas and Tethys. A lens shaped feature centered on the equator of the leading hemisphere of both Mimas and Tethys was seen clearly as a low IR/UV ratio compared to the surrounding surface [Schenk et al., 2011]. Additionally, a region of roughly the morphology exhibited an increased thermal conductivity [Howett et al., 2012]. The anomalous region closely matches the expected deposition profile of high energy ($\sim >1$ MeV) electrons traveling opposite to the thermal plasma [Paranicas et al., 2012]. It is thought that these electrons can explain the optical feature through increased scattering at UV wavelengths due to a higher concentration of light scattering defects in the icy regolith grains, as well as explain the increased thermal conductivity by increasing the effective contact area between adjacent ice grains through sintering. These hypotheses were tested by applying published heat flow models for porous regoliths to estimate relative grain properties necessary to explain the thermal conductivity differences, comparing the defect creation rate vs. optical depth, and applying numerical simulations to determine sintering effects in the porous water-ice regolith. The time-scale for the cementation to increase sufficiently is then compared with estimates of the regolith gardening rate to determine whether a steady state is maintained.

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418.11 – Interplanetary Exchange Of Meteoritic Material: From Europa to the Earth

We study the dynamics of high-speed ejecta launched to interplanetary space from the Jovian satellite Europa, possibly as a result of a giant impact.

In particular we consider this as a mechanism for the exchange of crustal material between Europa and other Solar System bodies, a process of possible astrobiological importance. Numerical simulations of a large collection of test particles, taken to represent the different conditions of ejected debris, are carried out for 3,000 yr using the Mercury 6.5 code. We concentrate on debris ejected with such velocity that it escapes from Europa's gravitational influence and several ejection velocities are considered.

We find that particles ejected from Europa's surface with speeds greater than ~ 10.10 km/s, approximately 5 times the satellite's escape velocity, are able to overcome the gravitational influence of Jupiter and are captured in heliocentric orbits or escape from the Solar System. For suitable conditions, particles reach orbits with perihelia smaller than 1 AU, where in principle they could collide with Earth. We consider this as a mechanism for exchange of crustal material between Europa and other solar system bodies. On the basis of our results, and estimations of the number of particles ejected following a giant impact, we estimate the collision probability of such ejecta with other bodies in the Solar System.

We find, ejection velocities from Europa greater than about 10 km/s are required to allow particles to reach Earth crossing orbits within just 3,000 yr.

Our results suggest that interplanetary exchange between Earth and Europa is possible. Our probability estimation indicates 50 collisions (giant impacts) on Europa Surface to have an impact with Earth.

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418.12 – Possible astrometric determination of tidal dissipation within Uranus from a future space mission

Tidal dissipation is the main actor of orbit migration among satellite systems. Recent work suggests possibly strong tidal dissipation within icy giant planets (Remus et al. 2013), with important consequences on satellite orbital evolution. Here we focus on the possible determination of tidal dissipation within Uranus using astrometric observations from ground and space. Besides regular observation campaigns from the Earth, simulations of observations from a future space probe around the Uranian system is considered. Constraints on the Uranian tidal ratio k_2/Q as a function of astrometric accuracy and time span is assessed.

This work is partly supported by EMERGENCE-UPMC grant (contract number: EME0911) and by the EC's 7th Framework Programme (FP7/2008-2017) under grant agreement n. 263466.

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418.13 – A Timeline of Volcanic Activity on Io in 2013-14 with Near-Infrared Surface Maps

From rapidly varying volcanic activity to plumes and new surface deposits, Io presents a constantly changing target. We have been monitoring Io in the near-infrared with adaptive optics imaging at the Keck and Gemini N telescopes and in disk-integrated spectroscopy at NASA's IRTF. We present imaging data from ~40 nights in 2013 and 2014, including timelines of thermal emission at specific volcanic sites. We show surface maps of Io in 2013 and 2014 with nearly complete longitudinal coverage, displayed for comparison between years. These maps are produced from Keck imaging data at multiple wavelengths between 2 and 5 microns, and include the first map presented in the new Br β filter for Keck's NIRC2 imager. This filter falls in the middle of an SO₂ ice absorption band at 4.05 microns, and thus probes the distribution of SO₂ ice on Io's surface while simultaneously being at a long enough wavelength to clearly show the distribution of thermal emission from volcanic hot spots.

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418.14 – Amorphous and Crystalline H₂O ice at Rhea's Inktomi Crater

We present the analysis of Cassini spectral data from spectral mapping of Saturnian icy moons Dione and Rhea, to investigate possible effects of impact crater formation on the relative abundances of crystalline and amorphous water ice in the moons' ice crusts. Both moons display morphologically young ray craters as well as older craters. Possible changes in ice properties due to crater formation are conjectured to be more visible in younger craters, and as such Rhea's well imaged ray crater Inktomi is analysed, as are older craters for comparison. We used data from Cassini's Visual and Infrared Mapping Spectrometer (VIMS). For each pixel in the VIMS maps, spectral data were extracted in the near-infrared range (1.75 μ m < λ < 2.45 μ m). Analysis was begun by fitting a single Gaussian to the peak in absorption at 2.0 μ m, which was then subtracted from the data, leaving residuals with a minimum on either side of the original 2.0- μ m band. The spectra of the individual spatial pixels were then clustered by the differences between these minima, which are sensitive to changes in both ice grain size and crystallinity. This yielded preliminary maps which approximated the physical characteristics of the landscape and were used to identify candidates for further analysis. Spectra were then clustered by the properties of the 1.5- μ m band, to divide the map into regions based on inferred grain size. For each region, the predicted differences in minima from the Gaussian residuals, over a range of crystallinities, were calculated based on the found grain sizes. This model was used to find the crystallinity of each pixel via grain size and characteristics of the residual function. Preliminary results show a greater degree of crystallization of young crater interiors, particularly in Rhea's ray crater Inktomi, where ice showed crystalline ice abundances between 33% and 61%. These patterns in ice crystallization are possibly attributable to increased heat generated during crater formation.

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418.15 – Large Binocular Telescope Adaptive Optics Mid-infrared Spectroscopy of Thermal Radiation from an Eruption near Io's Gish Bar Patera

This contribution reports mid-infrared low-resolution spectroscopy (2.8 - 4.2 μ m; R~120) of Jupiter's satellite Io obtained with the grism-equipped Large Binocular Telescope Mid-Infrared Camera (LMIRcam). LMIRcam operates behind the Large Binocular Telescope Interferometer (LBTI). For these observations, obtained 22OCT2014UT1200, only one of the two LBT 8.4-meter primaries was in operation, limiting the adaptive optics corrected PSF to a FWHM of 0.1" at L'-band (3.8 μ m) corresponding to approximately 10 resolution elements across the 1.02" disk presented by Io at the time. The visible hemisphere of Io contained one dominant hotspot at a longitude of ~95 W. The latitude and longitude of this hotspot is consistent with Gish Bar Patera. The LMIRcam slit is oriented in azimuth such that dispersion is in the altitude direction. At the time of observation the altitude direction was approximately 20 degrees from the direction of Io's north pole, thus the slit's long direction was oriented largely along a line of constant latitude with the hotspot centered on the slit capturing the spectrum of the hotspot as well as reflected/emitted light from the disk of Io at similar latitude.

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418.16 – Laboratory Infrared Spectroscopy to Identify New Compounds on Icy Moon Surfaces

We are exploring the value of mid-infrared spectroscopy for identifying non-H₂O constituents of icy moon surfaces. Recently we reported evidence for a new emissivity feature identified on Iapetus using Cassini's Composite Infrared Spectrometer [1]. This 11.7 μ m feature is consistent with emissivity minima (transparency features) of very fine-grained silicates. Its position and shape may be diagnostic of silicate type, but most lab data at these wavelengths have been acquired using coarser grains and/or at Earth surface pressures and temperatures. Infrared spectra can change substantially under low-temperature, vacuum conditions [e.g., 2,3].

We prepared sieved (<0.4 mm) and very fine-grained (few μm) powders of six different silicates and measured their VNIR (0.35-2.5 μm) reflectance spectra under ambient air, and mid-IR (1.2-20 μm) spectra in a purged N₂ glovebox. All silicates exhibited mid-IR transparency features (and loss of other features) in micronized form that were not observed for the coarser grain sizes. Muscovite, a phyllosilicate mineral possibly similar to those tentatively identified on Europa [4], provided the closest match to Iapetus in the mid-IR--although clear VNIR features of muscovite have not been identified on Iapetus [5]--and therefore we measured muscovite across the same wavelength range under Iapetus-like conditions ($T=125\text{ K}$, $P<3\times 10^{-8}\text{ torr}$). We will report on our ongoing analysis and plans for additional future measurements in JPL's Icy Worlds Simulation Lab.

[1] Young, C.L., et al. (2014), Workshop on the Habitability of Icy Worlds, Abstract #4038.

[2] Logan, L.M., et al. (1973), *J. Geophys. Res.*, 78(23), 4983-5003.

[3] Donaldson Hanna, K.L., et al. (2012), *J. Geophys. Res.*, 117, E00H05.

[4] Shirley, J.H., et al. (2013), AGU Fall Meeting, Abstract #P54A-07.

[5] Clark, R.N., et al. (2012), *Icarus*, 218, 831-860.

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418.17 – Multi-Wavelength Near Infrared Observations of Marum and Yasur Volcanoes, Vanuatu

To help understand and test models of thermal emission from planetary volcanoes, we obtained in May 2014 a variety of near-infrared observations of the very active Marum lava lake on Ambrym, Vanuatu, as well as the Strombolian activity at Yasur on Tanna. Our observations include high resolution images and movies made with standard and modified cameras and camcorders. In addition, to test the planetary emission models, which typically rely on multi-wavelength observations, we developed a small inexpensive prototype imager named "Kerby", which consists of three simultaneously active near-infrared cameras operating at 0.860, 0.775, and 0.675 microns, as well as a fourth visible wavelength RGB camera. This prototype is based on the Raspberry Pi and Pi-NoIR cameras. It can record full high definition video, and is light enough to be carried by backpack and run from batteries. To date we have concentrated on the analysis of the Marum data. During our observations of the 40 m diameter lava lake, convection was so vigorous that areas of thin crust formed only intermittently and persisted for tens of seconds to a few minutes at most. The convection pattern primarily consisted of two upwelling centers located about 8 m in from the margins on opposite sides of the lake. Horizontal velocities away from the upwelling centers were approximately 4 m/s. A hot bright margin roughly 0.4 m wide frequently formed around parts of the lake perimeter. We are in the process of establishing the absolute photometry calibration to obtain temperatures, temperature distributions, and magma cooling rates.

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418.18 – High Resolution Imaging of Io's Volcanoes with LBTI

The Large Binocular Telescope (LBT), located on Mount Graham in eastern Arizona, employs two 8.4 meter mirrors with a 14.4 center-to-center separation on a common mount. Coherent combination of these two AO-corrected apertures via the LBT Interferometer (LBTI) produces Fizeau interferometric images with spatial resolution consistent with the diffraction limit of the 22.8-meter aperture. In particular LBTI resolves thermal signatures (i.e., features observed at M-band) on the surface of Io down to ~ 150 kilometers; a two-fold improvement over what has previously been possible from the ground. We show images collected with LBTI on December 24, 2013, in which Loki's shape is clearly resolved and at least fourteen additional volcanic hot spots are detected.

We analyze three locations in the LBTI data: emission features within Loki Patera, the area near Rarog and Heno Patarae, and a hot spot seen in the Colchis Regio.

For Loki Patera, we interpret spatially resolved variation in the emission within that region. With M-band resolution that is comparable to what has previously been achievable only at K-band, we compare localized emission features with what has been seen in earlier observations at shorter wavelengths.

Thermal emission from activity at Rarog and Heno Patarae is well resolved in these images, while a third hot-spot in the nearby Lerna Regio is also clearly resolved. This area is of special interest since it was the site of two high-effusion outbursts on August 15th, 2013 [de Pater et al. (2014) *Icarus*].

Lastly, we explore a hot-spot seen in the Colchis Regio that may be a remnant of a violent outburst detected on August 29th, 2013 [de Kleer et al. (2014) *Icarus*].

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418.19 – Characterization of Callisto's O² Atmosphere with HST

We report detection of FUV atomic oxygen emissions from Callisto's atmosphere, based on complete analysis of data from the highly sensitive Hubble Space Telescope Cosmic Origins Spectrograph. We observed an emission brightness of ~ 3 R in the O I 1356 Å doublet on Callisto's leading / Jupiter-facing quadrant. Limits to the (O I 1356 Å)/(O I 1304 Å) emission ratio favor emission by dissociative excitation of O², suggesting that O² is the dominant atmospheric component rather than other possible oxygen-bearing alternatives. Photo-electrons, rather than magnetospheric electrons, are the most likely source of the dissociative excitation. This detection yields an O² column density of $\sim 4 \times 10^{15}$ cm⁻² on the leading / Jupiter facing hemisphere, which implies that Callisto's atmosphere is collisional and is the fourth-densest satellite atmosphere in the Solar System, in addition to being the second-densest O²-rich collisional atmosphere in the Solar System, after Earth. Longitudinal variations in published densities of ionospheric electrons suggest that O² densities in Callisto's leading hemisphere, which we did not observe, may be an order of magnitude greater. We also detected an extended corona of O I 1304 Å emission around Callisto, with a brightness of ~ 1 R to ~ 4 R.

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418.20 – Astrometry of natural satellites: improving the dynamics of Mars, Jupiter and Saturn with old observations

A new astrometric reduction of old photographic plates, benefiting from modern technologies such as sub-micrometric scanners associated with a reduction using accurate catalogues (UCAC at the present time and GAIA in a near future), provides improved knowledge of the orbital motion of planetary satellites.

In the framework of an international collaboration first, and in the FP7 ESPaCE european project afterward, U.S. Naval Observatory plates were digitized with the new generation DAMIAN scanning machine of the Royal Observatory of Belgium. The procedure was applied to a few hundred photographic plates of the Martian satellites covering the years 1967-1997, of the Galilean satellites covering the years 1967-1998, and of the major Saturnian satellites covering the years 1974-1998. We provide results with an accuracy better than 60 mas in (RA,Dec) positions of the Martian satellites, better than 70 mas in (RA,Dec) positions of the Galilean moons, and better than 100 mas in (RA,Dec) positions of the major Saturnian moons. Since the positions of the planets may be deduced from the observed (RA,Dec) positions of their satellites, we can also assess the accuracy of the ephemerides of Mars, Jupiter and Saturn.

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418.21 – Spectral Properties of Tethys and Mimas

Although, water ice is spectrally dominant everywhere on the surfaces of Tethys and Mimas, distinct spectral variations could be detected, which are either correlated to the surface geology and/or the interaction with the space environment. In addition, Tethys shows further spectral variations, whose origin cannot be fully explained as a result of these processes. The abundance of water ice on the satellites' surfaces usually follows the visible surface albedo as seen on many satellites. In case of Mimas and Tethys, the lowest abundance of water ice could be measured on their trailing hemispheres, which is also known from Dione and Rhea (1-3) and fits to the influence of magnetospheric particles impacting the surface material here. On Tethys, however, two relatively narrow N/S-trending bands characterized by larger ice particle sizes of water ice separate the Saturn-facing and the anti-Saturnian hemisphere of Tethys. So far, larger ice particles are usually associated to geologically young and/or less weathered portions of the surfaces on the icy Saturnian satellites (2,3). No indication, however, could be found that support these assumptions as a origin for these bands. Possibly, on Tethys the observed variations are more complex due to the influence of fine particles from the E-ring coating the surface or the bands are a remnant of past surface properties, which changed due to a global event like the Odysseus impact [4]. Spectral properties of Tethys also disfavor a relation between the Odysseus impact event and the formation of Ithaca Chasma, the extended graben system [4].

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418.22 – Effect of Microstructure on Spontaneous Polarization in Amorphous Solid Water (ASW) Films C. Bu[a], J. Shi[b] and R. A. Baragiola[a] [a]University of Virginia, Charlottesville, VA 22904 [b]Syracuse University, Syracuse, NY 13244

Introduction: Water ice is abundant on many planetary bodies within the outer solar system. We report on the spontaneous polarization and thermal relaxation of ASW films formed at 10 - 110 K and provide evidence for the essential role of porosity [1].

Experiments: Experiments were performed in an ultra-high vacuum system. ASW films were deposited from a collimated vapor beam or from a diffuse background water vapor onto a liquid-He cooled, gold-coated quartz crystal microbalance (QCM). The porosity was calculated by combining the measurements obtained from the QCM and UV reflectance [2]. The surface potential was determined using a Kelvin probe.

Results: We focused on observations pertaining to the porosity: 1) the surface potential experiences an abrupt change of -0.25 V relative to the substrate during deposition of the first ~ 5 monolayers and subsequently increases linearly with thickness; 2) the surface potential magnitude decreases with the incidence angle; 3) the surface potential decreases with temperature after a lag of ~ 4 K above the deposition temperature; it decreases more slowly in films with larger incidence angle; 4) for charged films with different pre-annealing temperatures, the ratios of surface potential to fluence remain roughly constant with temperature before discharged; 5) the surface potential decreases with time at a constant annealing temperature.

Conclusions: These observations suggest that the polarization is governed by the relaxation of the micropore structure rather than changes in intrinsic dielectric behavior of the water network [3]. We propose that the observed surface potential results from a fraction of aligned water dipoles on the internal surface area of the pores. Depolarization occurs during the collapse of the pores, resulting in the decrease of the surface potential.

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419 – Pluto Posters

419.01 – Coordinated Occultation Observations for Pluto, Nix, and Quaoar in July 2014

We observed Pluto, its moon Nix, and Quaoar during a predicted series of occultations in July 2014 with the 1-m telescope of the Mt. John University Observatory in New Zealand. The observations were based on new USNO photometry. We successfully detected occultations by Pluto of an $R=18$ mag star on 23 July (14:23:30 \pm 00:00:10 UTC to 14:25:30 \pm 00:00:10 UTC), with a drop of 5%, and of an $R=17$ star on 24 July (11:41:30 \pm 00:00:10 UTC to 11:43:30 \pm 00:00:10 UTC), with a drop of 3%, both with 20 s exposures with our frame-transfer POETS. Since Pluto had a geocentric velocity of 22.51 km/s on 23 July and 22.35 km/s on 24 July, these intervals yield limits on the chord lengths (surface + lower atmosphere) of 2700 ± 130 km and 2640 ± 250 km respectively, indicating that the events were near central, and provide astrometric data. Our coordinated observations with the 4-m AAT in Australia on 23 July and the 6.5-m Magellan/Clay, the 4.1-m SOAR, the 2.5-m DuPont, the 0.6-m SARA South, and the 0.45-m Cerro Calán telescopes in Chile on July 27 and 31, which would have provided higher-cadence observations for studies of Pluto's atmosphere, were largely foiled by clouds.

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419.02 – Predicted Atmospheric Temperature Retrievals for the New Horizons Encounter with Pluto.

The New Horizons spacecraft will flyby Pluto this July. Three opportunities for observing the temperature vs. height will present themselves: A radio occultation of radio signals transmitted from Earth to the Radio Science Experiment (REX) instrument, a stellar occultation of a background star as seen by Alice, and a stellar occultation of the Sun as seen by Alice. The temperature vs. height profiles will be generated using the Pluto version of the Massachusetts Institute of

Technology general circulation model, which now includes radiative-convective forcing from the Strobel et al. (1996) model, a multilayer subsurface, and a volatile cycle. The simulations begin in the year 1986 and end at the date of the New Horizons encounter. The Pluto conditions that will be discussed are (1) a surface albedo pattern taken from Buie et al. (2010), (2) a "best case" surface N₂ ice distribution and temperature from the Hansen and Paige (1996) model, (3) a configuration where there is initially no surface N₂ ice, and (4) a configuration where there is effectively infinitely deep surface N₂ ice.

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419.03 – Highly fractionated mass loss from the atmosphere of Pluto

Molecules can escape readily from the atmosphere of Pluto. Under the framework of hydrodynamic approximation, it was generally accepted that the process produced rather small isotopic fractionation. Here, we show that the escape highly fractionates the isotopic composition of nitrogen. The process preferentially selects lighter species, with an escape probability a factor of ~3 higher for the lighter isotopologue. The validity of the approach may be testable if the isotopic composition of the outer most regions can be measured. The property of the selection can significantly modify the isotopic composition of the atmosphere, leaving the present-day atmosphere isotopically heavier than the ancient one. This also impacts the current view of the evolution of planetary atmospheres. Venus, for example, may not need that much mass loss, in order to explain the current D/H ratio.

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419.04 – Spectroscopy of Pluto at six longitudes, 380-930 nm

We have obtained spectra of the Pluto-Charon pair (unresolved) in the wavelength range 380-930 nm with resolution ~450 at six roughly equally spaced longitudes. The data were taken in May and June, 2014, with the 4.2-m Isaac Newton Telescope at Roque de Los Muchachos Observatory in the Canary Islands, using the ACAM (auxiliary-port camera) in spectrometer mode, and using two solar analog stars. The new spectra clearly show absorption bands of solid CH₄ at 620, 728, and 850-910 nm, which were known from earlier work. The 620-nm CH₄ band is intrinsically very weak, and its appearance indicates a long optical pathlength through the ice. This is especially true if it arises from CH₄ dissolved in N₂ ice. Earlier work (Owen et al. Science 261, 745, 1993) on the near-infrared spectrum of Pluto (1-2.5 μm) has shown that the CH₄ bands are shifted to shorter wavelengths because the CH₄ occurs as a solute in beta-phase crystalline N₂. The optical pathlength through the N₂ crystals must be on the order of several cm to produce the N₂ band observed at 2.15 μm. The new spectra exhibit a pronounced red slope across the entire wavelength range; the slope is variable with longitude, and differs in a small but significant way from that measured at comparable longitudes by Grundy & Fink (Icarus 124, 329, 1996) in their 15-year study of Pluto's spectrum (500-1000 nm). The new spectra will provide an independent means for calibrating the color filter bands on the Multispectral Visible Imaging Camera (MVIC) (Reuter et al. Space Sci. Rev. 140, 129, 2008) on the New Horizons spacecraft, which will encounter the Pluto-Charon system in mid-2015. They will also form the basis of modeling the spectrum of Pluto at different longitudes to help establish the nature of the non-ice component(s) of Pluto's surface. It is presumed that the non-ice component is the source of the yellow-red coloration of Pluto, which is known to be variable across the surface.

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419.05 – Resolved photometry and a solar phase curve for Pluto and Charon from New Horizons LORRI.

During its eighth annual checkout, the New Horizons spacecraft's LOng Range Reconnaissance Imager (LORRI, Cheng, A. F. et al. (2008) Space Sci Rev, 140, 189–215, DOI: 10.1007/s11214-007-9271-6) snapped 15 series of five optical navigation images of Pluto and Charon. These images, taken over the course of a single 6.38-day revolution/rotation of the system between 2014-07-19 and 2014-07-26 represent a continuation and expansion of last year's campaign to provide the first Pluto and Charon solar phase curves beyond the ground-based limit of 2 degrees (Zangari et al 2013, DPS 45, # 303.08). Since July 2013, Pluto and Charon have become brighter and more-clearly separated as the Pluto-spacecraft distance has halved from 5.9 AU to 2.8 AU, and the solar phase angle has increased from 10.9 to 13.0 degrees. We will present individual light curves and solar phase curves as well as comparisons to previous measurements. Follow-up observations will be continued in January 2015.

This work has been funded by NASA's New Horizons mission to Pluto.

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419.06 – What the Surfaces of Pluto and Charon Can Teach Us about Their Orbital and Interior Evolution

Pluto and Charon currently orbit in a mutually synchronous state with zero orbital eccentricity. This configuration means that the direction of, and distance between, each body remains the same throughout each orbit, limiting current diurnal tidal deformation. In order to achieve this state, however, both Pluto and Charon would have experienced tidal heating and stress. For each body, the extent of tidal activity is controlled by the orbital evolution of the system and by its interior structure and rheology. Unfortunately, there are few constraints on the evolution of the Pluto-Charon system or on the interiors of Pluto and

Charon. Therefore, in anticipation of the New Horizon's flyby of the system, we determine the conditions under which Charon could have experienced tidally-driven geologic activity and the extent to which observations could be used to constrain Charon's internal structure and orbital evolution. Using plausible interior structure models that include an ocean layer, we find that tidally-driven tensile fractures would likely have formed on Charon if its eccentricity were of order 0.01, especially if Charon were orbiting closer to Pluto than at present. Such fractures could display a variety of azimuths near the equator and near the poles, with the range of azimuths in a given region dependent on longitude. In contrast, east-west-trending fractures should dominate at mid-latitudes. The fracture patterns we predict indicate that Charon's geologic record could provide constraints on the thickness and viscosity of Charon's ice shell at the time of fracture formation. Furthermore, we explore the response of Pluto, which would have been affected by Charon's supposed orbital evolution, under the assumption that its interior was similar in structure to Charon's interior.

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419.07 – The Internal Structures of Pluto and Charon, and Can *New Horizons* Tell?

The fly-through of the Pluto-Charon system by *New Horizons* offers the first opportunity to determine both the total system mass and the individual masses of Pluto and Charon by direct Doppler tracking. Simulations indicate potential accuracies of order 0.1%, a substantial improvement in precision (especially for Charon). This will put to rest a long-standing limitation on modeling and understanding Pluto and Charon's internal structure and evolution. It is notable, based on the recent astrometry, that the "density gap" between Pluto and Charon appears to be narrowing. At the 3 σ level and considering crustal porosity, this gap could be zero. If Pluto and Charon were actually close in density, it could change our view as to how the binary formed. Refinement at the next level – determining Pluto's or Charon's internal structure, specifically their degree of differentiation (and presence or absence of oceans) – will not be trivial. *New Horizons* will not pass close enough to either to measure degree-2 gravity (nor was this an original mission objective), but shape determination from imaging offers the possibility of determining differentiation state. For this to succeed, however, Pluto or Charon must be in hydrostatic equilibrium. For such models, the differences between the lengths of the principal axes of their figures are predicted to be <1 km, and the differences between differentiated and undifferentiated models smaller still. But, either Pluto or Charon may retain fossil figures from earlier in their mutual tidal evolution. These fossil figures should be larger (more biaxial for Pluto, more triaxial for Charon), and will provide important clues to thermal and structural evolution. For Pluto we predict a flattening >1% (radii differences >10 km) for a strengthless icy lithosphere and an unrelaxed rock core. For a fully relaxed core, we predict a >2-3 km fossil bulge supported by icy lithospheric strength, unless impacts have allowed the ice shell to relax. These values do not depend on the presence or absence of an internal ocean. Despinning may be corroborated by characteristic tectonics and tectonic patterns.

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Contributing team(s): New Horizons Science Team

419.08 – Upper limit on dust in the Pluto system

On UT 31 July 2014, we observed an appulse between Pluto and a bright star ($R \sim 11.3$) from three telescope sites in Chile: Las Campanas (the 6.5-m Clay and the 2.5-m du Pont telescopes), La Silla (the 2.2-m MPI/ESO telescope), and CTIO/Cerro Pachon (the 4.1-m SOAR, the 1.3-m SMARTS, and the 0.6-m SARA-S telescopes). In Arizona, we also observed with the 4.3-m Discovery Channel Telescope. The Clay observations of this appulse (see also M.J. Person et al., this conference) have the potential to have the highest SNR of any event, although they were plagued by variable clouds. We analyze the seven light curves for constraints on dust and debris in the Pluto system, and we compare these results to previous work (e.g. Zangari et al. 2013, Throop et al. 2014).

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419.09 – Atmospheric state of Pluto from the 31 July 2014 stellar occultation

On 31 July 2014 (UT), while observing a potential Pluto occultation ($m=12$, unfortunately obscured by clouds), we imaged a fortuitous occultation by Pluto of a small companion star ($m=15$) several minutes before the main event (and before the clouds came in) with the 6.5-m Clay telescope at Magellan. The main star's resulting light curve (essentially flat until the weather intervened) was one of the highest signal-to-noise light curves yet obtained from a Pluto occultation observation. It will be analyzed for possible signatures of dust in the Pluto system (see Levine et al., this meeting). Given the lower signal to noise ratio provided by the secondary star, careful calibration is needed to analyze the atmospheric occultation itself. Several other attempts at observing Pluto occultations in July 2014 were unfortunately clouded out (see Levine et al., Pasachoff et al., this meeting).

Using precise astrometry obtained with the 2.5-m DuPont telescope and the 4.3-m Discovery Channel telescope before and after the event, while Pluto and the stars were well-separated, we are able to constrain the closest approach distance of the secondary star occultation event. Using the photometry from these same images, we are also able to characterize the relative brightness of both stars in relation to Pluto (taking care to account for the light from Charon as well). With these two constraints we can analyze the atmospheric signature of the occultation, and provide a current (July 2014) estimate of Pluto's changing atmospheric diameter. Initial results indicate no large changes in the atmospheric scale height; complete results from the final analysis will be presented with this work.

This work was supported in part by NASA Planetary Astronomy grants to MIT (NNX10AB27G) and Williams College (NNX12AJ29G), as well as grants from USRA (#8500-98-003) and Ames Research (#NAS2-97-01) to Lowell Observatory. P.R. acknowledges support from FONDECYT through grant 1120299.

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419.10 – Possible formation of organic aerosol formation in Pluto's atmosphere

Titan, Pluto, and Triton are the outer solar system bodies with nitrogen dominant atmospheres. Trace amount of gaseous methane and carbon monoxide are present, but with different CH₄/CO ratios. Considering the organic haze production in Titan's ionosphere, similar haze generation could occur in Pluto's thin atmosphere. However, the CH₄/CO ratios are substantially different in those bodies. Thus, it is not clear if similar haze formation could occur in Pluto's atmosphere as well. We have experimentally investigated the production rates of organic haze analogues in simulated atmospheres of Titan/Pluto/Triton from EUV-VUV radiation. In this study, we focus on their dependence on the CH₄/CO ratios and UV irradiation wavelengths between 50 – 150 nm. Our experimental results indicate that EUV photochemistry of a N₂/CO gas mixture can initiate the formation of aerosols even without CH₄. Progressive CH₄ addition to the N₂/CO gas mixture generally increases the solid production rates. However, noticeable stepwise increase at CH₄/CO ratio of $\sim 0.1-0.2$ was observed under our experimental conditions. A simulated Pluto gas mixture, N₂/CH₄/CO (= 90/9/1), was irradiated at 60 nm to accumulate Pluto aerosol analogue. It shows significant difference in spectroscopic feature from Titan's N₂-CH₄ UV aerosol analogue. Pale yellowish solid sample is relatively transparent in visible, and demonstrates a prominent aliphatic CH bonds at 3.4 μm . Our results imply that EUV-VUV photochemistry in Pluto's atmosphere may generate organic aerosol layers. However, the presence of CO could result in haze particles with very different chemical/optical properties from those in Titan. The New Horizon mission would reveal the detailed in 2015.

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420 – Origins of Planetary Systems Posters

420.01 – Stop hitting yourself: did most terrestrial impactors originate from the terrestrial planets?

Although the asteroid belt is the main source of impactors in the inner solar system today, it contains only 0.0006 Earth mass, or 0.05 Lunar mass. While the asteroid belt would have been more massive when it formed, it is unlikely to have had greater than 0.5 Lunar mass since the formation of Jupiter and the dissipation of the solar nebula. By comparison, giant impacts onto the terrestrial planets typically release debris equal to several per cent of the planets mass. The Moon-forming impact on Earth and the dichotomy forming impact on Mars, to consider but two of these major events, released 1.3 and 0.3 Lunar mass in debris respectively, many times the mass of the present day asteroid belt. This escaping impact debris is less long lived than the main asteroid belt, as it is injected on unstable, planet-crossing orbits, but this same factor also increases the impact probability with the terrestrial planets and asteroids. We show that as a result terrestrial ejecta played a major role in the impact history of the early inner solar system, and we expect the same is also likely to be true in other planetary systems.

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420.02 – Growth of Planetary Embryos During the Oligarchic Growth Stage

Here we update the classic model of oligarchic growth to include mass conservation. Planetesimals from the swarm are accreted onto embryos, decreasing the surface mass density of the planetesimal swarm. Therefore, the surface mass density of the planetesimal swarm can be described as the total initial surface mass density minus the surface mass density of the material accreting onto the surface of the embryo. However, since the surface mass density decreases, the average spacing between planetesimals must change as well. Therefore, the parameter for characteristic spacing between planetesimals, b , must also change. Using the isolation mass of an embryo, we approximate the final value of b to be about 10. We confirm that the eccentricity of a planetary embryo changes as a function of the mass of the growing embryo during oligarchic growth. We incorporate the changing eccentricity, surface mass density, and characteristic spacing of embryos into a model that describes the growth of a planetary embryo with mass conservation.

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420.03 – Experimental studies of low-velocity collisions in protoplanetary disks and planetary rings

Particle size evolution in protoplanetary disks and planetary ring systems can be driven by collisions at relatively low velocities (<1 m/s). Collisions between centimeter-sized objects may result in particle growth by accretion, rebounding, or the production of additional smaller particles. The outcomes of these collisions are dependent on factors such as collisional energy, particle size, and particle morphology. We present the results of a sequence of laboratory experiments designed to explore collisions over a range of these parameters. Collisions take place within a vacuum chamber that is placed in our 0.8-sec drop tower apparatus. Initial experiments utilize a variety of impacting spheres, including glass, Teflon, aluminum, and brass, as well as chalk clumps. These spheres are either used in their natural state or are “mantled” - coated with a few-mm thick layer of chalk. A high-speed, high-resolution video camera is used to record the motion of the colliding bodies. These videos are then processed so that particle speeds, coefficients of restitution, and collisional outcomes can be obtained. Impact velocities range from about 20-60 cm/s, and we observe that mantling of particles significantly reduces their coefficients of restitution. These results will contribute to an empirical model of collisional outcomes that can help refine our understanding of proto-planetesimal collisional growth and planetary ring collisional evolution.

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420.04 – Planetesimal-driven migration of the outer planets in presence of a self-gravitating planetesimal disk.

We study the effect of a massive planetesimal disk on the dynamical stability of the outer planets in the solar system assuming, as has been suggested in the Nice 2 model, that these were initially locked in a compact and multiresonant configuration as a result of gas-driven migration in a protoplanetary disk. The gravitational interaction among all bodies in our simulations is included self-consistently using the Mercury6.5 code. Several initial multiresonant configurations and planetesimal disk models are considered. Under such conditions a strong dynamical instability, manifested as a rapid giant planet migration and planetesimal disk dispersal, develops on a timescale of less than 40 Myr in most cases. Dynamical disk heating due to the gravitational interactions among planetesimals leads to

more frequent interactions between the planetesimals and the ice giants Uranus and Neptune, in comparison to models in which planetesimal-planetesimal interactions are neglected.

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420.05 – Solar nebula constraints derived from the masses and formation times of Earth, Mars, Jupiter and Saturn

Terrestrial planets accreted from the late-stage collisional evolution of planetary embryos (roughly Mars-sized) and leftover planetesimals (Chambers 2013). Since the timescale to produce Earth-like analogues is on the order of ~ 100 My, the solar nebula gas would have dissipated by then. On the other hand, Hf-W chronology yields a short accretion timescale for Mars ~ 9 My (Dauphas and Pourmand 2011), which is similar to the gas dissipation time (Haisch et al. 2011). The Grand-Tack model proposes that Jupiter and Saturn migrated inward until Saturn was caught in a 2:3 mean motion resonance then migrated outward, truncating the disk in the process and accounting for Mars' orbit, accretion timescale, and small mass (Walsh et al. 2011). However, in order to power the migration of the giant planets this model assumes the presence of a massive (compared to Jupiter) viscously evolving gas disk. This means that the giant planets themselves would not have completed their growth. Thus, the Grand-Tack model provides an explanation for the small mass of Mars at the cost of ignoring the resulting problematic large mass of Saturn. Here we fix the locations and masses of Jupiter and Saturn and develop a model in which the depleted region is due to three key mechanisms: one, removal of collisional fragments by gas drag; two, coalescence of planetary embryos by sweeping secular resonances during gas disk dispersal; three, removal of planetary embryos by Type I tidal interaction with the gas disk. We use analytical and numerical N-body results to evaluate the consequences of the above processes for the disk of solids. We focus on the variables controlling the extent of the depleted region. We stress that the static giant planets nevertheless play a determining role: first, by filtering-out outer disk planetesimal fragments that would otherwise replenish the inner disk; second, by increasing the (phased) eccentricities of planetary embryos thereby allowing larger objects to form; third, by opening gaps in the gas disk and thus setting the boundary conditions for the Type I tidal interaction of the planetary embryos with the nebula gas. In particular, the embryo's Type I migration depends on the location of Jupiter.

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420.06 – Planet Formation in Stellar Binaries: How Disk Gravity Can Lower the Fragmentation Barrier

Binary star systems present a challenge to current theories of planet formation. Perturbations from the companion star dynamically excite the protoplanetary disk, which can lead to destructive collisions between planetesimals, and prevent growth from 1 km to 100 km sized planetesimals. Despite this apparent barrier to coagulation, planets have been discovered within several small-separation (<20 AU), eccentric ($e^b \sim 0.4$) binaries, such as alpha Cen and gamma Cep. We address this problem by analytically exploring planetesimal dynamics under the simultaneous action of (1) binary perturbation, (2) gas drag (which tends to align planetesimal orbits), and (3), the gravity of an eccentric protoplanetary disk. We then use our dynamical solutions to assess the outcomes of planetesimal collisions (growth, destruction, erosion) for a variety of disk models. We find that planets in small-separation binaries can form at their present locations if the primordial protoplanetary disks were massive ($>0.01M^{\odot}$) and not very eccentric (eccentricity of order several per cent at the location of planet). This constraint on the disk mass is compatible with the high masses of the giant planets in known gamma Cep-like binaries, which require a large mass reservoir for their formation. We show that for these massive disks, disk gravity is dominant over the gravity of the binary companion at the location of the observed planets. Therefore, planetesimal growth is highly sensitive to disk properties. The requirement of low disk eccentricity is in line with the recent hydrodynamic simulations that tend to show gaseous disks in eccentric binaries developing very low eccentricity, at the level of a few percent. A massive purely axisymmetric disk makes for a friendlier environment for planetesimal growth by driving rapid apsidal precession of planetesimals, and averaging out the eccentricity excitation from the binary companion. When the protoplanetary disk is eccentric we find that the most favorable conditions for planetesimal growth emerge when the disk is non-precessing and is apsidally aligned with the orbit of the binary.

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421 – TNOs and Centaurs Posters

421.01 – The IMACS Occultation Survey: I. Pilot Study

We report the results of a pilot study, searching for occultations of background stars by small (sub-km) Kuiper belt

objects (KBOs). Our study is ground-based, using the Inamori Magellan Areal Camera and Spectrograph (IMACS) instrument on the 6.5m Magellan Baade telescope, at Las Campanas Observatory in Chile. We implemented a novel shutterless continuous readout mode on the IMACS instrument, with custom-made aperture masks, permitting simultaneous high-speed (36 Hz) photometry for numerous stars, while minimizing the effects of stellar crowding and sky background. Observing in the southern hemisphere allows us to target the intersection of the ecliptic and galactic planes, where hundreds of stars can be monitored with a single field of view. We observed for a total of ~28 hours spread over eight nights, obtaining ~11,000 star-hours of light curves with per-point SNR > 10. This represents an order of magnitude increase in star-hours compared to the previous best ground-based survey by Bianco et al. (2009). Our results allow us to place strong constraints on the surface density of sub-km objects in the Kuiper-Belt, as well as to complement the HST FGS results of Schlichting et al. (2009, 2012).

Author(s): Matthew J. Holman¹, Matthew J. Payne¹, Charles Alcock¹, Hilke Schlichting², David Osip³, Federica Bianco⁴, Brian McLeod¹, Ruth Murray-Clay¹, Paul Nulsen¹, Pavlos Protopapas¹, Ian Thompson³, Greg Burley³, Christoph Birk³
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421.02 – The IMACS Occultation Survey: II. An Extended Campaign

We report the results of our extended campaign to search for occultations of background stars by small (sub-km) Kuiper belt objects (KBOs) using the IMACS instrument on the Magellan Telescope. Previously, we implemented a novel shutterless continuous readout mode on the IMACS instrument, able to obtain high-speed photometry on multiple stars, simultaneously generating light curves for all targets with a 40 Hz cadence. Following our pilot study, we extended our observational campaign, improving our target selection methodology such that we can now simultaneously monitor thousands of stars in a crowded field-of-view. We were granted ~60 hrs observing time on Magellan in 2014, allowing us to increase our observational data set by almost an order of magnitude, giving us ~60,000 star-hours of light curves with per-point SNR > 10. We expect that these observations will result in the first ground-based detections of occultations by sub-km objects in the Kuiper-Belt, allowing us to verify and improve upon the sky plane density of sub-km diameter KBOs implied by the HST FGS detections reported by Schlichting et al. (2009, 2012).

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421.03 – The Whipple Mission: Exploring the Kuiper Belt and the Oort Cloud

Whipple will characterize the small body populations of the Kuiper Belt and the Oort Cloud with a blind occultation survey, detecting objects when they briefly (~1 second) interrupt the light from background stars, allowing the detection of much more distant and/or smaller objects than can be seen in reflected sunlight. Whipple will reach much deeper into the unexplored frontier of the outer solar system than any other mission, current or proposed. Whipple will look back to the dawn of the solar system by discovering its most remote bodies where primordial processes left their imprint.

Specifically, Whipple will monitor large numbers of stars at high cadences (~12,000 stars at 20 Hz to examine Kuiper Belt events; as many as ~36,000 stars at 5 Hz to explore deep into the Oort Cloud, where events are less frequent). Analysis of the detected events will allow us to determine the size spectrum of bodies in the Kuiper Belt with radii as small as ~1 km. This will allow the testing of models of the growth and later collisional erosion of planetesimals in the early solar system. Whipple will explore the Oort Cloud, detecting objects as far out as ~10,000 AU. This will be the first direct exploration of the Oort Cloud since the original hypothesis of 1950.

Whipple is a Discovery class mission that will be proposed to NASA in response to the 2014 Announcement of Opportunity. The mission is being developed jointly by the Smithsonian Astrophysical Observatory, Jet Propulsion Laboratories, and Ball Aerospace & Technologies, with telescope optics from L-3 Integrated Optical Systems.

Author(s): Charles Alcock¹, Michael Brown², Tom Gauron¹, Cate Heneghan², Matthew Holman¹, Almus Kenter¹, Ralph Kraft¹, John Livingston², Stephen Murray³, Ruth Murray-Clay¹, Paul Nulsen¹, Matthew Payne¹, Hilke Schlichting⁴, Amy Trangsrud², Jan Vrtilik¹, Michael Werner²

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421.04 – Thermal and Electron Irradiation Processing of Outer Solar System Ice Simulants: Chemical and Spectroscopic Laboratory Characterization

Our team is examining the effects of energetic radiation and thermal cycling on pure and mixed solar system ices under ultra-high vacuum conditions. These ices are being examined in search of markers that are unique to a specific thermal or radiation history, with specific interest in simulating histories believed to be relevant to Jupiter Trojan asteroids and Kuiper Belt Objects. A key telescopic observation of the Trojan asteroids is that they have a bimodal distribution of spectral slopes in the visible and near infrared regions. One population exhibits very red spectral slopes, while the other moderately red slopes. This distribution may point to differing formation locations and dynamical histories between the two populations.

The ices are deposited on a cryogenic stage at temperatures appropriate to outer solar system objects. Of specific interest are water, methanol, hydrogen sulfide, and ammonia, which are simple ice constituents that together contain the most common reactive elements found in ices. Electron irradiation has been conducted, with plans to irradiate with other particle sources as well. The ices are examined by reflectance spectroscopy in the visible through mid infrared while a quadrupole mass spectrometer monitors the vacuum chamber background for any desorbed or sputtered neutral products. All mixtures analyzed thus far have shown the appearance of new bands and disappearance of others during irradiation and formation of a residue that did not sublime upon heating to 300 Kelvin.

This work has been supported by the Keck Institute for Space Studies (KISS). The research described here was carried out at the Jet Propulsion Laboratory, Caltech, under a contract with the National Aeronautics and Space Administration (NASA) and at the Caltech Division of Geological and Planetary Sciences.

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421.05 – Probing the transneptunian disk with MIOSOTYS

MIOSOTYS (Multi-object Instrument for Occultations in the SOLar system and Transitory Systems) is a multi-fiber positioner coupled with a fast photometry camera. This is a visitor instrument mounted on the 193 cm telescope at the Observatoire de Haute-Provence, France. Our immediate goal is to characterize the spatial distribution and extension of the Kuiper Belt, and the physical size distribution of Trans-Neptunian objects (TNOs).

We present the observation campaigns during 2010-2012, objectives and observing strategy. We report the detection of potential candidates for occultation events of TNOs. We will discuss more specifically the method used to process the data and the modelling of diffraction patterns.

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421.06 – Refining the Search for Suitable KBOs: Calibration of the HST/ACS Wide Field Camera Ramp Filters.

After the New Horizons flyby of Pluto, the spacecraft will travel on to fly by one or more KBO objects. These are yet to be determined; searches are currently underway to locate suitable candidates. Once some candidates are identified, further observations are likely in order to decide on the actual targets; e.g., spectra or narrow-band observations vs. rotational phase to determine the presence of frozen volatiles. With its wide field, clear and broad band B and I filters, and its suite of medium band filters (9% FWHM), the ACS WFC camera on board HST is useful for searches over the CCD wavelength range. Moreover, its suite of narrow band (2%) ramp filters, which are also distributed over this wavelength range, are potentially useful for identifying the signature of spectral features, such as solid methane bands, for KBOs as dim as $V = +25$. However, the transmission of these ramp filters is uncertain since it was never calibrated. We report the calibration of 9 ACS/WFC ramp filters at 15 selected central wavelengths. A comparison of the calibrated transmissions to the existing uncalibrated ramp filters is presented. Corrective flats have been submitted for insertion into the ACS data reduction pipeline.

This program was supported through HST-AR-10981.01-A.

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421.07 – Centaur size distribution with DECam

We present the results of the 2014 centaur search campaign on the Dark Energy Camera (DECam) in Tololo, Chile. This is the largest debiased Centaur survey to date, measuring for the first time the size distribution of small Centaurs (1-10km) and the first time the sizes of planetesimals from which the entire Solar System formed are directly detected.

The theoretical model for the coagulation and collisional evolution of the outer solar system proposed in Schlichting et al. 2013 predicts a steep rise in the size distribution of TNOs smaller than 10km. These objects are below the detection limit of current TNO surveys but feasible for the Centaur population. By constraining the number of Centaurs and this

feature in their size distribution we can confirm the collisional evolution of the Solar System and estimate the rate at which material is being transferred from the outer to the inner Solar System. If the shallow power law behavior from the TNO size distribution at ~40km can be extrapolated to 1km, the size of the Jupiter Family of Comets (JFC), there would not be enough small TNOs to supply the JFC population (Volk & Malhotra, 2008), debunking the link between TNOs and JFCs.

We also obtain the colors of small Centaurs and TNOs, providing a signature of collisional evolution by measuring if there is in fact a relationship between color and size. If objects smaller than the break in the TNO size distribution are being ground down by collisions then their surfaces should be fresh, and then appear bluer in the optical than larger TNOs that are not experiencing collisions.

Author(s): Cesar Fuentes^{1, 2}, David E. Trilling³, Hilke Schlichting⁴

Institution(s): 1. *Universidad de Chile, Santiago, Chile.* 2. *CTIO, La Serena, Chile.* 3. *Northern Arizona University, Flagstaff, AZ.* 4. *MIT, Cambridge, MA.*

421.08 – Infrared Observations of Minor Planets in the Outer Solar System

Most minor planets in the Solar System reside in stable regions, and the flux of objects out of any of these regions is particularly informative in understanding the evolution of the Solar System. It is generally believed that Centaurs are derived from the trans-Neptunian object (TNO) population, and that the Jupiter-family comet (JFC) population is derived from the Centaurs. This progression is described dynamically, and there is little concrete evidence to date of how the physical properties of TNOs, Centaurs, and JFCs relate. We are searching for evidence of this relationship through comparing the mean albedos of members of these populations, with the expectation that smaller semi-major axes would lead to increased radiolysis rates and therefore lower albedos. The albedos of minor planets are accessible through infrared observations with space telescopes. We use results from the literature, works in progress, and our own measurements using data from the Wide-field Infrared Survey Explorer (WISE), and have a total sample size of around 150 objects. We will present our statistical results on the mean albedos in the TNO, Centaur, and JFC populations together with our analysis of the observation biases inherent in individual and combined surveys. We will present our conclusions about the TNO/Centaur/JFC evolution based on our results.

Author(s): Ryan Blackman^{1, 2}, David Trilling², Michael Mommert², Brian Burt³, Eric MacLennan⁴

Institution(s): 1. *Yale University, New Haven, CT.* 2. *Northern Arizona University, Flagstaff, AZ.* 3. *Massachusetts Institute of Technology, Cambridge, MA.* 4. *University of Tennessee at Knoxville, Knoxville, TN.*

421.09 – Rotational properties of the binary and non-binary populations in the Trans-Neptunian belt

An exhaustive study about short-term variability as well as derived properties from lightcurves allowed us to draw some conclusions for the Trans-Neptunian belt binary population. Based on Maxwellian fit distributions of the spin rate, we suggested that the binary population rotates slower than the non-binary one. This slowing-down can be attributed to tidal effects between the satellite and the primary, as expected. We showed that no system in this work is tidally locked, but the primary despinning process may have already affected the primary rate (as well as the satellite rotational rate). We used the Gladman et al. (1996) formula to compute the time required to tidally lock the systems, but this formula is based on several assumptions and approximations that do not always hold. The computed times are reasonable in most cases and confirm that none of the systems is tidally locked, assuming that the satellite densities are low and have a high rigidity or have a higher dissipation than usually assumed.

The rotational properties of small bodies provide information about important physical properties, such as shape, density, and cohesion (Pravec & Harris 2000; Holsapple 2001, 2004; Thirouin et al. 2010, 2012). For binaries it is also possible to derive several physical parameters of the system components, such as diameters of the primary/secondary and albedo under some assumptions. We compare our results as well as our technique for deriving this information from the lightcurve with other methods, such as: i) thermal or thermophysical modeling, ii) from the mutual orbit of the binary component, iii) from direct imaging or iv) from stellar occultation by Trans-Neptunian Objects (TNOs).

Finally, by studying the specific angular momentum of the sample, we proposed possible formation models for several binary TNOs. In several cases, we obtained hints of the formation mechanism from the angular momentum, but for other cases we do not have enough information about the systems to favor or discard a formation model.

Author(s): Audrey Thirouin^{1, 2}, Keith S. Noll³, Jose Luis Ortiz Moreno¹, Nicolas Morales¹

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421.10 – Status of the Transneptunian Automated Occultation Survey (TAOS II)

TAOS II is a next generation occultation survey with the goal of measuring the size distribution of the small objects (diameters between 0.5 and 30 km) in the Kuiper Belt. The project is a collaboration between the Academia Sinica Institute of Astronomy and Astrophysics, the Universidad Nacional Autónoma de México, and the Harvard-Smithsonian

Center for Astrophysics, The survey will operate three 1.3 m telescopes at San Pedro Martir Observatory in Baja California, Mexico. Each telescope will be equipped with a custom camera comprising a focal plane array of CMOS imagers. Each camera will be capable of reading out image data from 10,000 stars at a cadence of 20 Hz. All telescopes will monitor the same set of stars simultaneously to search for coincident occultation events while minimizing the false positive rate. This poster describes the project and reports on the progress of the development of the survey infrastructure.

Author(s): Mauricio Reyes-Ruiz¹

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Contributing team(s): TAOS II team

422 – Jovian Planets Posters

422.01 – Precision Pointing Reconstruction and Geometric Metadata Generation for Cassini Images

Analysis of optical remote sensing (ORS) data from the Cassini spacecraft is a complicated and labor-intensive process. First, small errors in Cassini's pointing information (up to ~40 pixels for the Imaging Science Subsystem Narrow Angle Camera) must be corrected so that the line of sight vector for each pixel is known. This process involves matching the image contents with known features such as stars, ring edges, or moon limbs. Second, metadata for each pixel must be computed. Depending on the object under observation, this metadata may include lighting geometry, moon or planet latitude and longitude, and/or ring radius and longitude. Both steps require mastering the SPICE toolkit, a highly capable piece of software with a steep learning curve. Only after these steps are completed can the actual scientific investigation begin.

We are embarking on a three-year project to perform these steps for all 300,000+ Cassini ISS images as well as images taken by the VIMS, UVIS, and CIRS instruments. The result will be a series of SPICE kernels that include accurate pointing information and a series of backplanes that include precomputed metadata for each pixel. All data will be made public through the PDS Rings Node (<http://www.pds-rings.seti.org>). We expect this project to dramatically decrease the time required for scientists to analyze Cassini data. In this poster we discuss the project, our current status, and our plans for the next three years.

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422.02 – Jupiter's polar auroral dynamics

The morphology of Jupiter's ultraviolet aurora is commonly described in terms of components located inside (poleward of) or outside (equatorward of) the main oval emission. These components may also be discriminated by their temporal behaviour, where the narrowest parts of the main "oval" remain relatively stable over time periods of several hours, and the satellite footprints show large variability with timescales of minutes. Inside the main emission the so-called polar aurora, presumably corresponding to the polar cap mixing open and closed magnetic field lines, is characterized by rapid motions taking the form of swirls, giving rise to the "swirl region" and by intermittent brightenings in the "active region". Coarse analysis of these motions suggests that they are too fast to respond to an equatorial magnetospheric forcing. Instead, they appear to be related to processes taking place in or above the ionosphere where distances travelled by plasma waves match those of the subtended auroral emission. Here, we present a preliminary improved analysis of the auroral motion in the polar region based on the application of an iterative "Advection Corrected Correlation Image Velocimetry" (ACCIV) method (Asay-Davis et al., 2009). This method allows one to build velocity fields quantifying local and overall auroral motions which may then be used to constrain their origin.

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Contributing team(s): Laboratoire de Physique Atmosphérique et Planétaire

422.03 – Search for Satellite Effects on Saturn's Auroras in Cassini UVIS Data

The Cassini UVIS has been obtaining Saturn auroral images since 2004. We have previously reported instances when the main auroral oval brightened briefly in a quasi-periodic fashion near the sub-Mimas longitude. Here we examine the large set of auroral images obtained from close range and high sub-spacecraft latitudes. We will plot the brightness of the individual auroral measurements as a function of local time, and as a function of the location of Mimas and other moons to test for any correlations.

Author(s): Wayne R. Pryor¹, Larry Esposito², Alain Jouchoux², Denis Grodent³, Jacques Gustin³, Aikaterini Radioti³

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Liege, Belgium.

Contributing team(s): Cassini UVIS Team

422.04 – Jupiter's Great Red Spot and Ammonium Hydrosulfide

The color and composition of Jupiter's Great Red Spot (GRS) have been studied for over a century, and numerous explanations have been offered for this feature's origin and properties. Since ammonium hydrosulfide (NH₄SH) is thought to be a component of Jupiter's clouds, and since sulfur chemistry is a rich source of colors, we have initiated a laboratory research program to study this ionic solid and a complementary program of GRS telescopic observations. Our initial experiments have investigated whether NH₄SH or its radiation-chemical products might contribute to the spectrum of the GRS. This DPS presentation will cover some of our new results on the thermal and radiolytic stability of NH₄SH, along with new infrared and mass spectral measurements. Support by NASA's Planetary Atmospheres and Outer Planets Research programs is acknowledged.

Author(s): Reggie L. Hudson¹, Mark J. Loeffler¹, Nancy J. Chanover², Amy A. Simon¹

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422.05 – New evidence for chemical depletion of ammonia in the 1 to 2 bar region of Jupiter's atmosphere

It has long been known that the vertical profile of ammonia within Jupiter's cloud layers is not well-described by a simple equilibrium profile, with saturated vapor above the cloud base and the well-mixed deep abundance below the cloud base. An additional depletion of ammonia by a factor of 4-10 is required by global microwave spectra at $p < 6$ bar [e.g., 1]. Dynamical effects, ranging from cloud layer circulation between belts and zones [2] to molecular differentiation following convective activity [3] might be sufficient to explain the global microwave data.

However, in situ cloud density measurements by the Galileo Probe [4] suggest a large gap in our understanding of cloud chemistry in Jupiter, especially when combined with other tracers such as volatile mixing ratios [5] and static stability [6]. Using the "fresh clouds" method of modeling cloud density [7], and assuming that cloud-forming advection was weak at all levels in the probe site, we find that NH₄SH formation cannot explain cloud densities between 1 and 1.4 bar in situ.

The composition of additional chemical species, or adsorption of ammonia on other ices, are candidate processes that strongly require further laboratory study of the H₂O-NH₃-H₂S volatile system at temperatures of 150 to 300 K [1].

Spectral features near 3 microns suggest widespread NH₄SH in the visible cloud decks of Jupiter [8], but additional species may also contribute to absorption at these wavelengths. Infrared spectroscopy at high angular resolution in the future---performed by Juno, JWST, or 30-m class ground-based telescopes---may be able to observe ammonia depletion mechanisms in action.

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422.06 – Tracking Jupiter's Quasi-Quadrennial Oscillation and Mid-Latitude Zonal Waves: Initial Results

We report on initial results of a long term observational study to track the temporal and 3-dimensional evolution of the Quasi-Quadrennial Oscillation (QO) and the propagation and evolution of mid-latitude zonal waves in Jupiter's stratosphere. These wave-driven phenomena affect variations in Jupiter's vertical and horizontal temperature field, which can be inferred by measuring methane emission in the thermal infrared at 1245 cm⁻¹. Using TEXES, the Texas Echelon cross-dispersed Echelle Spectrograph, mounted on the NASA Infrared Telescope Facility we observed high-spectral resolution (R=75,000) scan maps of Jupiter's mid-latitudes in January and October 2012, February 2013, and February 2014. These initial datasets were taken using several different observing strategies in an attempt to optimize efficiency and mapping accuracy in preparation for our prime study period (2014-2019). We will present the zonally averaged inferred thermal structure over $\pm 30^\circ$ latitude and between 10 and 0.01 mbar, showing the QO's

downward progression along with inferred 3-dimensional thermal maps (latitude, longitude, pressure) displaying a multitude of vertically isolated waves and eddies. These results set the stage for an unprecedented dataset that will: 1) significantly improve the determination of the period and vertical descent velocity of Jupiter's QJO and map its 3-dimensional spatial structure; 2) measure the zonal wavenumbers, vertical wavelengths, zonal group velocities and lifetimes of transient mid-latitude waves that are impossible to obtain from historic mid-infrared imaging datasets due to their lack of vertical resolution; and 3) record the thermal state of Jupiter's stratosphere in detail prior to, during, and after Juno's prime mission to assist in analysis of Juno Mission observations from the Waves, JIRAM, and UVS instruments.

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422.07 – Numerical modeling of planetary-scale waves on Jupiter

The atmosphere of Jupiter has multiple alternating east-wind wind jets with different cloud morphologies some of which can be explained by the presence of atmospheric waves. One jet feature observed by Cassini and HST at 30N, called the Jovian Ribbon for its similarity to Saturn's Ribbon, displays chaotic cloud morphology caused by multiple wave components with dominating planetary scale wave-numbers ranging from 13 to 30. Both the cloud morphology and the dominant wave numbers observed change as a function of time and correlate to changes in the jet's speed. The average speed of the westward jet where this Jovian Ribbon is found is small compared to other notable jets that display wave behavior, namely the high velocity eastward jets at 7N (hot spots) and 7S (chevrons). We present the results of numerical simulations that show how attributes like jet speed, location, vertical shear and other background properties of the atmosphere (e.g. static stability) contribute to the development and evolution of wave structures in jets similar to those observed. Additionally, we explore the effects of local convective events and other atmospheric disturbances such as spots, on the morphology of these jets and waves.

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422.08 – Moment of inertia of Jupiter from the measurement of its spin-pole precession rate using Juno's radio-science data

Numerical simulations have been performed to assess the accuracy with which the precession rate of Jupiter's pole of rotation can be measured by Juno. These simulations extend those published by Helled et al., [2011] by separating the effects of precession from Lense-Thirring effect and by quantifying the impact of the variation in tracking duration. Using the JPL Orbit Determination Program, we carried out a detailed and realistic variance/covariance analysis based on simulated Ka-band Doppler measurements from the Juno mission. We account here for a large number (>300) of parameters that will affect the orbital motion of Juno, including Jupiter's mass parameter (GM) and gravity field coefficients through degree 12, as well as several non-gravitational acceleration parameters (solar pressure, Jupiter infrared radiation, outgassing) and of course the Jupiter orientation parameters.

The analysis shows that the precession rate of Jupiter's pole can be estimated with accuracy better than 0.1%. Accounting for the lack of knowledge in the different parameters relating the pole precession rate and the normalized polar moment of inertia (NPMOI) of Jupiter, we show that the accuracy of the NPMOI inferred from the precession rate is better than 0.1%, and 50 times better than inferred from the Lense-Thirring. Such a strong improvement in the precision of the NPMOI determination should also tighten the constraints on the interior structure of Jupiter, especially the core size and mass, which are key parameters to distinguish among competing scenarios of formation and evolution of the giant planet.

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422.09 – Some Properties of Saturnian Equatorial and Temperate Belts at the 2009 Equinox

The special processing was made for more than 600 zonal spectra obtained by scanning of Saturn's disk during the equinox-2009. A comparative study of the optical characteristics of the southern and northern temperate latitudes and equatorial belt have shown some hemispheric differences in the methane absorption behavior. In the equatorial zone we have usually observed decrease in the intensity of the methane absorption compared to temperate latitudes. But the correct estimation of this difference may be done only at the equinox when the ring influence is minimal. In 2009

the methane absorption on equator is 21-24 per cent less than on temperate latitudes and it may be considered as true value of that difference. The CH₄ absorption bands variations at middle latitudes show some of the specific features. In particular, the absorption band of 725 nm in the southern hemisphere is not different from that in the northern hemisphere. However, other bands, centered at 619, 678, 702 and 787 nm, are some less in the S-hemisphere than in the N-hemisphere. This difference grows with the bands weakening. During the preceding equinox in 1995 similar asymmetry was expressed more strongly and also with the absorption depression at southern hemisphere. These differences are considered as related to the vertical inhomogeneity of the cloud layer, increased the upper boundary of the clouds in the equatorial belt, and seasonal changes in the radiation regime hemispheres of Saturn. The results of this work will be published in «Solar System Research».

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422.10 – Metric Observations of Saturn with the Giant Meterwave Radio Telescope

We used the Giant Meterwave Radio Telescope (Pune, India) to observe Saturn at three wavelengths in the metric domain – 0.49 m (610 MHz), 1.28 m (235 MHz), and 2.0 m (150 MHz) – with the aim of constraining the deep atmospheric ammonia and water vapor concentrations around 10-20 kbar. We have obtained a clean detection at 0.49 m, with a disk brightness temperature of 216 ± 23 K, and no significant emission outside the disk, thus confirming model predictions about the weakness of synchrotron radiation by magnetospheric electrons. The initial measurements at the longer wavelengths were affected by strong ionospheric scintillation and RFI interferences. These measurements have been repeated and are expected to help reducing the initial error bars. We will discuss the constraints resulting from these observations on Saturn's deep atmospheric composition.

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422.11 – The Anticyclonic Eye of the Storm: Evolution of Saturn's Great Storm Region and Associated Anticyclone as seen by Cassini/VIMS

A massive storm system erupted in Saturn's northern hemisphere in late 2010, ultimately sweeping clean the cloudy region previously occupied by the long-lived (> 5 years) String of Pearls feature. This latitude band has remained relatively cloud free (5- μ m bright) ever since, but for a massive anticyclonic oval storm system. We have observed this persistent feature with Cassini/VIMS over several years and find that it has oscillated latitudinally north and south in this stormy region. It was centered at 35.9° planetocentric latitude in May 2011, drifting northward to 37.8° in 2012, hovering around 37° through much of 2013, then settling southward to ~35.9° in 2014. It periodically bumps up against the dark band above it, even interacting with it in Aug. 2013. We measure a prograde drift speed of ~22 m/s in 2012, increasing as much as 60% as it drifted northward in 2013, then finally relaxing back to a more moderate ~15 m/s in July 2014 as the oval sagged southward, all consistent with the Voyager wind profile for these latitudes. The feature has evolved in morphology as well. It spanned 4.9° x 3.18° in 2011. By 2012-2013 it had elongated zonally and contracted latitudinally to span on average ~7.3° x ~2.9°, contracting further to an average ~5.5° x 2.9°. The oval has varied in terms of cloudiness, being ~90% 5- μ m dark (obscured) in 2011, whereas by 2013 it was mostly bright (clear) with a thin dark edge, resembling a smoke ring. It is currently about half obscured and half bright. Since 2012, the storm latitude of ~33 - 38° N itself has remained remarkably clear, being much more 5- μ m intense than anything on the planet. Preliminary results indicate however that it has begun to dim. Between early 2012 and 2014 it has steadily diminished in brightness relative to the nearby clouds above it by ~46%. We are continuing to monitor the evolution of this storm region and the related anticyclone over time with Cassini/VIMS.

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422.12 – Long-Term Variability of Saturn's Clouds at 5.1-5.2 micron

We report the results of long-term studies of thermal emission from the atmosphere of Saturn using ground-based imaging in Saturn's atmospheric window between 5.1 and 5.2 microns. These images have revealed a detailed cloud structure representing variations of cloud opacity around Saturn's 2-3 bar pressure region that we have tracked since 1995. Since that time, the zonal-mean narrow, dark bands have remained constant and are correlated with variations of zonal jets. We have identified long-term variations in the cloud opacity that do appear to be correlated with seasonal changes, with a decrease of zonal-mean cloud opacity strongly correlated with seasonal changes in insolation. Substantial perturbations to the atmosphere in the northern hemisphere from the great storm of 2010-2011 have led to significant perturbations of the deep cloud field detected at 5.1 μ m. The clouding over of the central storm track during early 2011 was followed by a central clearing and clouding over of regions to its north and south. This process made the

storm latitude the clearest atmospheric region (i.e. the brightest at 5.1 μm) ever detected. It is gradually returning to its pre-storm state, but at a very slow rate and remains the clearest region on the planet.

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422.13 – Discrete Clouds on Uranus and Neptune: Investigating Formation Mechanisms

We investigate several possible mechanisms for producing discrete cloud in the upper tropospheres and lower stratospheres of Uranus and Neptune. Mechanisms include the rising convective thermals, upwelling associated with global Hadley-like circulations, and ascent associated with vortex dynamics. Each is evaluated in context of observed cloud features and accompanying heights inferred from radiative transfer analysis of IR spectra. Implications for heat transport and circulations are considered.

Observations made using ground based adaptive optics and the HST reveal discrete features in the upper tropospheres of Uranus and Neptune. For Neptune, some of these features appear to be forming in the lower stratosphere, far above the adiabatic mixing layer. For both planets, the number and spatial extent of features observed in recent years is greater than observed during the Voyager flybys. What mechanisms can produce these features, and what explains the temporal variation?

The thermodynamics of rising parcels are analyzed to show what conditions would be necessary to convectively raise aerosols to the observed heights. Vortex dynamics and the possible role of ortho-para conversion are discussed.

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422.14 – Investigating the Increasing Inventory of Observed Clouds and Dark Spots on Uranus and Neptune through Computational Simulation

The years of observations since the Voyager II encounters have revealed a growing variety of observable features in the atmospheres of Uranus and Neptune. Clouds have been observed in the form of hazy bands, orographic vortex companions, regional groupings, and isolated features. Many clouds are dominated by methane, but some appear to be deeper and likely formed of other ices. Dark spots may be steady in latitude or drift meridionally; they may have a steady shape or morph in an oscillatory fashion; they may have constant companion clouds, intermittent companion clouds, or no apparent associated clouds at all. Clouds and spots have appeared at more latitudes and altitudes, although there still are some regions that have remained largely free of these features. Many of these features, even the most prominent, appear and then disappear over a few months or a few years, although a few have persisted for a decade or more. In some cases, the unsteadiness may be linked to seasonal changes; in others, it appears to be more circumstantial.

The variety of features reflects a high degree of dynamic activity in these atmospheres, connected by common underlying physics. Using the EPIC General Circulation Model, an effort is underway to distinguish what changes in atmospheric conditions lead to these different types of vortices and clouds. For example, simulations has shown that the likelihood of companion cloud formation is unsurprisingly sensitive to the global methane humidity; more surprisingly, the level of humidity and cloud formation can significantly influence the drift rate of the vortex. Through the numerical parametric investigation of these atmospheric conditions, this study aims to understand some of the key causes for the growing taxonomy of visible features in the Ice Giant atmospheres.

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422.15 – Thermal Evolution of the Inhomogeneous Jovian Planets: The Effects of Helium Phase Separation

We compute evolutionary models of Jupiter and Saturn including the effects of helium phase separation in the deep interior. The aim is to simultaneously match each planet's present-day luminosity and surface helium abundance, which are at odds with homogeneous, adiabatic thermal evolution. The calculations are carried out using the open source MESA code, extended to include a modern phase diagram for hydrogen/helium mixtures at high pressures and a self-consistent radiative atmosphere grid for each planet. We find that if He redistribution proceeds much faster than a convective circulation time, then the composition gradient established between one and a few Mbar stabilizes the fluid against convection. In this region the heat is transported less efficiently by overstable double-diffusive convection, which we implement following recent 3D hydrodynamics simulations of the instability. The onset and evolution of this

superadiabatic barrier region between the hot, He-rich inner adiabat and the cool, He-depleted outer adiabat bears directly on the cooling histories, especially that of Saturn. The upcoming measurement of Saturn's atmospheric He abundance expected of Cassini will place constraints on both the extent of the convectively stable region in Saturn and the general H/He phase diagram which informs the thermal evolution of all giant planets. We discuss implications for the dynamo within each planet, and ring seismology for Saturn.

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422.16 – Direct Wind Measurements in Io's Atmosphere

Io's atmosphere, which is mainly composed of SO₂ along with other minor species, is known to present a highly heterogeneous spatial distribution. Ionian atmospheric dynamic models argue that winds are expected to flow from high-density to low-density regions, which, in the context of a sublimation-sustained atmosphere, would correspond to a wind pattern flowing outward from the sub-solar point. Until now, only one direct wind measurement was available, and was at odds with the model predictions. With the Atacama Large Millimeter Array (ALMA), observations were taken with a spatial resolution of 0.86", 0.46", allowing one to resolve Io's disk (~1.15"). ALMA, located in Chili on the Chajnantor plateau, is the world's most sensitive (sub) millimeter interferometer thanks to its large collective area and its high altitude and dry site. Two observations of a strong SO₂ transition were taken one Io day apart. Doppler-shift mapping was performed on the SO₂ emission line to measure the line-of-sight projected winds on the leading hemisphere. Our main conclusion is that the global wind pattern, with projected winds moving from the eastern limb to the western, does not match the models. Once Io's rotational velocity is accounted for, the derived wind velocities are relatively small compared to the previous direct wind observation.

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422.17 – Photochemistry in Saturn's Ring-Shadowed Atmosphere: Modeling of Key Molecules and Observations of Dust Content

Cassini has been orbiting Saturn for over ten years now. During this epoch, the ring shadow has moved from covering a large portion of the northern hemisphere to covering a large swath south of the equator and continues to move southward. At Saturn Orbit Insertion in 2004, the ring plane was inclined by ~24 degrees relative to the Sun-Saturn vector. The projection of the B-ring onto Saturn reached as far as 40N along the central meridian (~52N at the terminator). At its maximum extent, the ring shadow can reach as far as 48N/S (~58N/S at the terminator). The net effect is that the intensity of both ultraviolet and visible sunlight penetrating into any particular latitude will vary depending on both Saturn's axis relative to the Sun and the optical thickness of each ring system. In essence, the rings act like venetian blinds.

Our previous work [1] examined the variation of the solar flux as a function of solar inclination, i.e. ~8 year season at Saturn. Here, we report on the impact of the oscillating ring shadow on the photolysis and production rates of hydrocarbons in Saturn's stratosphere and upper troposphere, including acetylene, ethane, propane, and benzene. Beginning with methane, we investigate the impact on production and loss rates of the long-lived photochemical products leading to haze formation are examined at several latitudes over a Saturn year. Similarly, we assess its impact on phosphine abundance, a disequilibrium species whose presence in the upper troposphere is a tracer of convective processes in the deep atmosphere.

We will also present our ongoing analysis of Cassini's CIRS, UVIS, and VIMS datasets that provide an estimate of the evolving haze content of the northern hemisphere and we will begin to assess the implications for dynamical mixing. In particular, we will examine how the now famous hexagonal jet stream acts like a barrier to transport, isolating Saturn's north polar region from outside transport of photochemically-generated molecules and haze.

[1] Edgington, S.G., et al., 2012. Photochemistry in Saturn's Ring Shadowed Atmosphere: Modeling, Observations, and Preliminary Analysis. *Bull. American. Astron. Soc.*, 38, 499 (#11.23).

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422.18 – Modeling Neptune's Upper Troposphere and Stratosphere from Keck Spectra

More than three decades after Voyager 2 left Neptune, the structure and variability of aerosols in Neptune's upper troposphere and stratosphere remain enigmatic. Bands of discrete, bright clouds dominate the appearance of Neptune in the near infrared, but they are not the only aerosols that must be present in the upper atmosphere. Many studies

indicate a global cloud layer is present at 2-4 bars. Thermochemical equilibrium models argue for a series of thick global cloud decks in Neptune's troposphere; hence the 2-4 bar cloud layer was originally presupposed to be spatially uniform and optically thick, and was tentatively identified as hydrogen sulfide ice. However, other results suggest this cloud may be optically thin (Sromovsky et al. 2001), spatially variable (Irwin et al. 2011) or may not exist at all, with the tropospheric opacity instead arising from vertically extended haze (Karkoschka and Tomasko 2011). At higher altitudes, some — but not all — models include an optically thin methane haze at 1-2 bar, and one or more optically thin stratospheric haze layers, formed by the settling of photochemically-produced hydrocarbons.

Derivation of Neptune's aerosol structure from observations depends on one's assumptions for the vertical temperature and methane mixing ratio profiles, which are uncertain. The picture is further complicated by evidence that these atmospheric properties likely vary with latitude (e.g., Conrath et al. 1998, Karkoschka and Tomasko 2011). We describe our recent efforts to constrain the aerosol structure of Neptune using data from the Keck OSIRIS integral field spectrograph and a Markov chain Monte Carlo algorithm, focusing on regions free of discrete bright clouds. We will discuss the variability of this background aerosol structure with latitude, considering the effects of compositional and thermal variations. We will address our ability to place constraints on the composition and temperature as well as the properties of the aerosols.

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422.19 – Optical and Near-IR Spectral Comparison with Chromophore Candidates in the Jovian Atmosphere

Large atmospheric features, such as the belts, zones, and storms that make up Jupiter's atmosphere remain colored by an unidentified chemical compound (or set of compounds). Optical reflectance spectra of Jupiter's atmosphere in the literature show few spectral features in the blue (shortwards of 500 nm), unlike the red portion of the spectrum which is dominated by the methane absorption spectrum. The prevailing spectral slope and dearth of molecular absorption features in the blue are attributed to absorption by coloring compounds, or chromophores, in the upper Jovian atmosphere. While both organic and inorganic candidate compounds have been proposed, few laboratory studies have been conducted at temperatures and pressures appropriate for local Jupiter conditions to determine the identity of the chromophores responsible for coloring these large atmospheric features such as Jupiter's Great Red Spot. In this study, we analyzed ground-based optical spectra and near-IR spectral image cubes of Jupiter for comparison with laboratory data of a potential chromophore compound. Optical spectra (~330-450 nm in the blue, ~570-690 nm in the red) were obtained between December 2013 and February 2014 with the Dual Imaging Spectrograph, mounted on the Astrophysical Research Consortium 3.5-meter telescope at Apache Point Observatory. Near-infrared (1.25-2.5 μ m) spectra of various locations in Jupiter's atmosphere were obtained from spectral image cubes taken with the New Horizons Linear Etalon Imaging Spectral Array during the early 2007 Jupiter flyby. The combination of these two data sets allowed us to identify specific regions in the Jovian atmosphere with distinct coloration. We compare these ground- and space-based observations to laboratory spectra from the Cosmic Ice Laboratory at NASA's Goddard Space Flight Center. Thin films of NH₄SH were exposed to varying amounts of ionizing radiation at Jovian temperature conditions, thereby enabling us to evaluate NH₄SH as a candidate chromophore material. This work was supported by NASA's Outer Planets Research Program through grant number NNX12AJ14G.

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422.20 – Computation of Concentric Shell Particle Scattering Effects in Jovian Clouds

From analysis of NIMS and ISO spectra of Jupiter Sromovsky and Fry (2010, Icarus 210, 211-229; 2010, Icarus 210, 230-257) concluded that both NH₃ and NH₄SH were present near the visible cloud tops, probably in the form of composite particles. Composite particles were also suggested from analysis of VIMS spectra of Saturn's Great Storm of 2010-2011 by Sromovsky et al. (2013, Icarus 226, 402-418), in this case concentric shells of H₂O, NH₄SH, and NH₃. These results and suggestions that coatings of various materials might be capable of hiding NH₃ spectral features on Jupiter, such as by Atreya et al. (2005, Planet. Space Sci. 53, 498-507), have raised interest in and a need for modeling of scattering properties of complex composite particles. Since many of the particle sizes inferred for composite particles are below or close to the range near 1 μ m where particle shape has less impact on near IR spectral features (Clapp and Miller, 1993, Icarus 105, 529-536), concentric shell codes have considerable relevance to modeling of composite particles. Here we report on two codes: one fast code (Toon and Ackerman, 1981, Applied Optics 20, No. 20, 3657-3660) that is capable of handling a core and shell of different materials, and a slower code (Pena and Pal, 2009, Computer Physics Comm., 180, 2348-2354) that can handle an arbitrary number of layers. Typical times to calculate a phase function for a wide size distribution (gamma distribution with normalized variance of 0.1) for the faster core/shell code are about 0.75 seconds per wavelength. The newer slower, but more versatile, code runs about 10X slower, and will typically double or triple the execution time of our multiple scattering code when it is incorporated. Optimizing

integration over particle size distributions to achieve suitable accuracy can minimize computational costs; we have therefore determined a rule for the number of intervals in the size distribution. Sample calculations will be presented to show effects of alteration of spectral features by coatings and effects of the order of condensation for the same volume fractions. This work was supported by NASA Jupiter Data Analysis Program grant NNX09AE07G and Outer Planets Research program grant NNX11AM58G.

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422.21 – The Chemistry of Ethene in the Storm Beacon Region on Saturn

The immense tropospheric storm that erupted in Saturn's northern spring hemisphere was first observed on 5th December 2010 (Sanchez-Lavega et al. 2011, Nature 475, 71), and displayed typical storm signatures such as lightning activity and clouds (e.g., Fischer et al. 2011, Nature 475, 75). However, Cassini/CIRS also observed an unexpected stratospheric response consisting of elevated temperatures and molecular abundances, which has come to be known as the 'beacon' region (Fletcher et al. 2011, Science 332, 1413). Most significantly the abundance of ethene (C₂H₄; also called ethylene) was observed to have increased by a factor of ~100 in the stratospheric beacon region in May 2011, compared with photochemical models and observations from the same latitude before the storm (Hesman et al. 2012, ApJ. 760, 24). Our project seeks to replicate the abundances of C₂H₄ and other hydrocarbons observed in the Cassini/CIRS beacon data through photochemical modeling. The KINETICS code (Allen et al. 1981, JGR 86, 3617) has been used to solve the 1-D continuity equations for stratospheric hydrocarbon and oxygen species, assuming the "Model C" chemical reaction list of Moses et al. (2005; JGR 110, E08001), and time-variable beacon temperatures, retrieved from the Cassini/CIRS data by Fletcher et al. (2012; Icarus 221, 560). The models predict a greatly increased C₂H₄ abundance in the high-temperature beacon regions, with a distinct mixing-ratio peak near 1 mbar. This increase is the result of a highly temperature-dependent reaction that produces C₂H₄. No such increases were seen in the model for other major hydrocarbons such as C₂H₂ and C₂H₆. The predicted C₂H₄ emission from our models still falls short of reproducing the observed beacon emission for May 2011, but the multiplicative factor required to scale the model profile to reproduce the CIRS emission has been reduced to a factor of ~5 from the previous factor of ~100. The important chemical production and loss mechanisms for C₂H₄ that control its behavior in the beacon region will be discussed.

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422.22 – Numerical Modeling of Saturn's Northern Hexagon as a Meandering Shallow Jet

Voyager flybys of Saturn in 1980-81 revealed a circumpolar hexagonal cloud morphology at 78 degree N planetographic latitude centered at the planet's north pole. This feature has been called Saturn's hexagon. Space- and ground-based observations have revealed the following characteristics of the hexagon; (1) an eastward atmospheric jetstream flows along the outline of the hexagon; (2) there are no large vortices associated with the wavenumber-6 system; (3) it propagates slowly in the System III reference frame, and (4) it has persisted for at least one Saturnian year (~29.5 Earth years) surviving seasonal changes.

Previous numerical models and laboratory experiments have shown that a hexagonal morphology can be reproduced and maintained by six interlocking pairs of cyclones and anticyclones that form a vortex-street; however, those models necessarily have intense closed-streamline vortices and fast drift rates, which are unlike the observed characteristics of the hexagon on Saturn. We present an alternative to the vortex-street model of the Saturnian hexagon, in which we demonstrate that a jetstream that is confined in altitude above the water condensation level at 10 bar develops a meandering morphology through shear instability, and reproduces the vortex-less flow pattern and a slow propagation rate.

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422.23 – JunoCam: Outreach and Science Opportunities

JunoCam is a visible imager on the Juno spacecraft en route to Jupiter. Although the primary role of the camera is for

outreach, science objectives will be addressed too. JunoCam is a wide angle camera (58 deg field of view) with 4 color filters: red, green and blue (RGB) and methane at 889 nm.

Juno's elliptical polar orbit will offer unique views of Jupiter's polar regions with a spatial scale of ~50 km/pixel. The polar vortex, polar cloud morphology, and winds will be investigated. RGB color mages of the aurora will be acquired. Stereo images and images taken with the methane filter will allow us to estimate cloudtop heights. Resolution exceeds that of Cassini about an hour from closest approach and at closest approach images will have a spatial scale of ~3 km/pixel.

JunoCam is a push-frame imager on a rotating spacecraft. The use of time-delayed integration takes advantage of the spacecraft spin to build up signal. JunoCam will acquire limb-to-limb views of Jupiter during a spacecraft rotation, and has the possibility of acquiring images of the rings from in-between Jupiter and the inner edge of the rings. Galilean satellite views will be fairly distant but some images will be acquired. Outer irregular satellites and small ring moons Metis and Adrastea will also be imaged.

The theme of our outreach is "science in a fish bowl", with an invitation to the science community and the public to participate. Amateur astronomers will supply their ground-based images for planning, so that we can predict when prominent atmospheric features will be visible. With the aid of professional astronomers observing at infrared wavelengths, we'll predict when hot spots will be visible to JunoCam. Amateur image processing enthusiasts are onboard to create image products. Many of the earth flyby image products from Juno's earth gravity assist were processed by amateurs.

Between the planning and products will be the decision-making on what images to take when and why. We invite our colleagues to propose science questions for JunoCam to address, and to be part of the participatory process of deciding how to use our resources and scientifically analyze the data.

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422.24 – Wave-Driven Compositional Effects in the Upper Atmospheres of Giant Planets

Atmospheric waves are commonly detected in the upper atmospheres of most solar system planets. Energy and momentum transport by waves have been studied by a number of research groups. Here we present a theoretical investigation of the effect that atmospheric gravity waves have on the composition of the upper atmospheres of Jupiter and Saturn. This work considers the combined effect of enhanced atmospheric mixing, perturbed chemical equilibrium, and wave-induced escape fluxes for individual neutral and ionized upper-atmospheric species. Numerical results are presented for a set of wave parameters compatible with existing observational constraints from the Galileo and the Cassini missions.

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422.25 – A Study of Cyclones and Anti-Cyclones in Jupiter's North Tropical Zone, 2003-2013

We have examined ground and space-based data from Jupiter's Northern Equatorial Belt and North Tropical Zone to characterize drift rates and statistics of cyclones and anti-cyclones. Ground-based positional data on the storms comes from the JUPOS database, maintained by the JUPOS team. Over 2,000 observations of 80 storms in the 2003-2013 time period were used to characterize trends in both latitudinal and longitudinal position, and velocity over time. We found that after the year of 2009, the dark storms in the 15-16N latitude band were forming further south than before. We hypothesize that small changes in the differential zonal wind caused this new, southerly zone to be favored. Because these storms form in an area of lower zonal wind speed, they also drift at a slower velocity relative to system III. Additionally, By comparing our analysis of JUPOS observations to Hubble and Cassini measurements of wind speed, we were able to characterize the relationship between storm size and storm velocity and a fraction of the zonal flow, and build an empirical model useful for predicting jovian storms in the future.

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422.26 – Numerical Simulations of Jupiter's Moist Convection Layer: Structure and Dynamics in Statistically Steady States

A series of long-term numerical simulations of moist convection in Jupiter's atmosphere are performed to investigate idealized characteristics of vertical structures of multi-composition clouds and convective motions associated with them, varying the deep abundances of condensible gases and the time constant of the auto-conversion process that is one of the most questionable parameters in the cloud microphysical parameterization. The simulations are conducted using a two-dimensional cloud resolving model that explicitly represents convective motion and microphysics of the three cloud components, H₂O, NH₃, and NH₄SH. The results generally represent the following characteristics qualitatively similar to

those found in Sugiyama et al (2011); stable layers associated with condensation and chemical reaction will behave as dynamical and compositional boundaries, intense cumulonimbus clouds develop with distinct temporal intermittency, and the active transport associated with the cumulonimbus clouds results in an establishment of the mean vertical profiles of condensates and condensable gases that are distinctly different from the hitherto accepted three-layered structure. Our results also demonstrate that the period of the intermittent cloud activity is roughly proportional to the deep abundance of H₂O gas. The moist convection layer becomes potentially unstable with respect to an air parcel rising from below the H₂O lifting condensation level (LCL) well before the development of cumulonimbus clouds. The instability accumulates until an appropriate trigger is provided by the H₂O condensate that falls down through the H₂O LCL; the H₂O condensate drives a downward flow below the H₂O LCL by latent cooling associated with re-evaporation of the condensate, and the returning updrafts carry moist air from below to the moist convection layer. The active cloud development is terminated when the instability is completely exhausted. The period of the intermittency is roughly equal to the time obtained by dividing the mean temperature increase caused by active cumulonimbus development, by the rate of body cooling.

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422.27 – Numerical Simulations of Saturn's Polar Cyclones

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Cassini mission to Saturn has revealed evidences of a warm core cyclone centered on each of the poles of the planet. The morphology of the clouds in these cyclones resembles that of a terrestrial hurricane. The formation and maintenance mechanisms of these large polar cyclones are yet to be explained. Scott (2011, *Astrophys. Geophys. Fluid Dyn*) proposed that cyclonic vortices beta-drifting poleward can result in a polar cyclone, and demonstrated that beta-drifting cyclonic vortices can indeed cause accumulation of cyclonic vorticity at the pole using a 1-layer quasi-geostrophic model.

The objectives of our project is to test Scott's hypothesis using a 1.5-layer shallow-water model and many-layer primitive equations model. We use the Explicit Planetary Isentropic Coordinate (EPIC) model (Dowling et al. 1998, 2004, *Icarus*) to perform direct numerical simulations of Saturn's polar atmosphere. To date, our project has focused on modifying the model to construct a polar rectangular model grid in order to avoid the problem of polar singularity associated with the conventional latitude-longitude grids employed in many general circulation models. We present our preliminary simulations, which show beta-drifting cyclones cause a poleward flux of cyclonic vorticity, which is consistent with Scott's results.

Our study is partially supported by NASA Outer Planets Research Grant NNX12AR38G and NSF Astronomy and Astrophysics Grant 1212216 to KMS.

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500 – Asteroid Physical Characterization 2: Vesta and Ceres

500.01 – Eight is enough: Identification of additional Vestoids via NIR spectral and mineralogical characterization

We present initial results of a large-scale effort to constrain the basaltic asteroid population in the main asteroid belt. Our main goal is to study potential Vestoids, which are defined as the group of asteroids most likely to be ejected fragments from (4) Vesta. Through the combination of ground-based near-infrared spectral observations, WISE-derived

albedos, Vp-type taxonomies, and orbital elements (a,e,i), this work aims to better constrain the Vestoid population by studying a sample of ~125 candidate asteroids. A second part of this effort involves characterizing ~15 outer main belt asteroids to search for basaltic objects. Surface mineralogical characterizations derived from NIR spectra are a vital tool to confirm the basaltic nature of Vp-type asteroids due to ambiguities and misclassifications in taxonomies. Criteria for classification as a Vestoid includes the presence of the deep 0.9- and 1.9- μ m pyroxene absorption features, derived spectral band parameters that are consistent with those of basaltic achondrites, and estimates of average surface pyroxene chemistries consistent with those of the HED meteorites derived from (4) Vesta. NIR spectral observations of 8 Vp-type asteroids were obtained at the NASA Infrared Telescope Facility (IRTF), Mauna Kea, Hawai'i, on January 14, 2013 UT, utilizing SpeX in low-resolution prism mode. All eight asteroids exhibit orbital elements, taxonomies, and albedos that identify them as candidate Vestoids. They include (3867) Shiretoko, (5235) Jean-Loup, (5560) Amytis, (6331) 1992 FZ1, (6976) Kanatsu, (17469) 1991 BT, (29796) 1999 CW77, and (30872) 1992 EM17. Analysis indicates that all eight asteroids are likely Vestoids based on the criteria described above. (3867) Shiretoko has a surface mineralogy consistent with the eucrites while the remaining seven asteroids have surface mineralogies consistent with the howardites. The dominance of howarditic compositions among the Vestoids we studied is consistent with a collisional origin from (4) Vesta, which predicts a more howarditic composition rather than pure eucrites or diogenites. This work is supported by NASA Planetary Astronomy Program grant NNX14AJ37G.

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500.02 – Modal mineralogy of Vesta

The surface composition of Vesta is constrained using spectral data gathered by the visible and near-infrared imaging spectrometer VIR onboard NASA/Dawn. To derive new constraints on the surface composition of this asteroid, we applied a scattering model to VIR reflectance spectra. This model was first successfully tested by properly reproducing the characteristics of several HED meteorites spectra. Abundance estimates of end-members in HEDs are accurate to within 15–25% for the analyzed samples, while the estimated particle sizes are within the intervals of actual sizes. The modeling technique was then applied to the VIR data to retrieve the modal mineralogy of selected terrains of Vesta. Major expected minerals (Low-Calcium Pyroxene, High-Calcium Pyroxene, plagioclase and olivine) can provide satisfactory fits with overall residuals $\leq 1\%$. The modal mineralogy of terrains exhibiting the strongest LCP signatures is well representative of those of diogenites. Modeling results demonstrate that coarse-grained olivine (a few hundred μ m in size) is likely to be present in all major units of Vesta, with inferred abundance ranging from 10% to 20%. A bimodal distribution in grain size with relatively coarse grain for olivine and fine grains (typically smaller than 100 μ m) for the other components is derived. This is similar to the lithologic size distribution of HEDs, in particular howardites containing olivine-bearing melt. In addition, there is a good agreement between the modal mineralogy of this type of HED and Vesta. The relatively uniform derived modal mineralogy of different units confirms that major homogenization occurred with time, possibly explaining the lack of specific olivine enrichment in Rheasilvia. This study provides strong support for the vestan origin of HEDs by clarifying the relationship between HEDs and the different geological units on Vesta. Howardites containing olivine-bearing melt, although rare in the HED collections, are the closest petrological analogs of today Vesta surface material; hence further studies on evolutionary processes on Vesta should focus on this class of HED meteorites.

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500.03 – Vesta Is Not an Intact Protoplanet

Asteroid 4 Vesta has been identified as the likely source of howardite, eucrite, and diogenite (HED) basaltic achondrite meteorites, whose parent body differentiated and started solidifying within 3 Ma after the condensation of the Ca-Al-rich inclusions (CAIs). The formation of Jupiter and the disk-driven migration of the giant planets also occurred during this period; thus it was expected that Vesta could provide an intact record of large-scale early episodes of planetary migration and bombardment as in the proposed Jovian Early Bombardment and the "Grand Tack" scenarios. However, the results of the Dawn mission detailing Vesta's mass, volume, density, and surface characteristics provide challenges for modeling the structure and evolution of this asteroid. All proposed models for the generation of the HEDs require the presence of a substantial olivine-rich mantle. But recent work on the depth of excavation of the large basins at the south pole of Vesta suggests that because there is not abundant mantle olivine visible on Vesta or in the Vestoid family asteroids, the crust of Vesta must be at least 80 km thick. Such a thick crust is radically at odds with previous models; should it exist, it ought to manifest itself in other ways such as Vesta's density structure and bulk chemical composition. However, we find that no Vesta model of iron core, olivine-rich mantle, and HED crust can match the joint constraints of (a) Vesta's density as derived from the gravity field observed by Dawn; (b) the observed depletion of sodium and potassium and trace element enrichments of the HED meteorites; and (c) the absence of exposed olivine on Vesta's surface, among Vestoid asteroids, or in our collection of basaltic meteorites. Either Vesta was subjected to a

radical change in composition, presumably due to the intense collisional environment where and when it formed, or the asteroid we see today is in fact a reaccretion of material formed elsewhere from now-destroyed protoplanetary parent bodies. We conclude that Vesta is not a remnant protoplanet but a radically altered, chemically stripped and possibly reaccreted body.

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500.04 – A Rough Surface Model to Explain Surface Temperatures on Vesta

We modeled the spatially resolved temperature of the surface of Vesta controlling for high resolution topography, Bond albedo and 1D thermal conduction. We determined a systematic difference between the temperatures measured by the Visual and Infrared spectrometer (VIR) and computer models.

We analyzed a highly degraded crater that shows negligible variations in regolith gardening and albedo. Using this crater, where the only variation in temperature is based upon illumination conditions, we were able to calculate a correction factor, and ultimately identify a thermal model based on surface roughness. This requires that the grains are small enough to be illuminated individually but large enough that they do not thermally equilibrate.

We will present a "rough-surface" thermal model that takes into account how irregular grains create sub-pixel variations in the thermal spectrum and describes the effect this has on the observed surface temperatures of Vesta. We have applied this method to the VIR observations of Vesta, which produced a high level of agreement between the model and the observations.

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500.05 – A Brief History of Ceres

Available observations and thermal simulations suggest that Ceres is a warm icy body differentiated in a rocky core and icy shell. Combining geophysical tools developed for icy satellite modeling and hydrogeochemistry modeling, we derive interior and geological evolution scenarios for a variety of assumptions on the asteroid's accretional environment. Key events include (1) the early differentiation of a rocky core accompanied by a phase of intensive hydration in high pH environment. These conditions are favorable to the production of brucite and carbonates, as well as the redistribution of certain elements, e.g., potassium, from the rock to the aqueous phase; (2) an episode of partial dehydration of the core leading to the release of warm water at the base of the icy shell and further rock leaching; (3) efficient convection, including a phase in the mobile-lid regime that could have been responsible for the recent emplacement of Ceres' surface; (4) a possible late phase of rehydration.

It is important to keep in mind that Ceres is a small object ($R < 475$ km)

whose main present-day heat source is limited to decay of long-lived radioisotopes. Hence it is unlikely, from a basic thermal standpoint, that this object could maintain endogenic activity at present. However, we will also report on a scenario in which potassium-40 has been extensively leached from the rock and is now concentrated in thick salt cumulates at the interface between the rocky core and shell, as was proposed for Europa (Prieto-Ballesteros and Kargel (2005) *Icarus* 173, 212). Low salt thermal conductivity combined with potassium-40 abundance may lead to partial melting. Whether or not this warm layer at the base of the icy shell can promote a late phase of activity will be evaluated and presented at the meeting.

We will compare the implications of these models against other models for the emplacement of Ceres' surface. Global geological and compositional mapping by the Dawn spacecraft will be our primary source of information on Ceres' origin and evolution.

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500.06 – The Case of the Missing Ceres Family

Most of the largest asteroids in the main belt are associated with an impact-generated dynamical family. The Vesta family dominates the inner asteroid belt with its numbers, and was a critical piece of evidence in tying the HED meteorites to Vesta. In addition to Vesta (the third-largest asteroid), Pallas (the second-largest asteroid), Hygiea (the fourth-largest asteroid), and the largest S-class asteroid, 15 Eunomia, all have dynamical families. It is curious that the very largest body in the asteroid belt, Ceres, is missing from this list of parents. The most recent dynamical family studies show Ceres to be unassociated with a family of any size. This alone is perhaps not sufficient to draw any conclusion, but motivates us towards the considerations we make here. We use relevant published works to demonstrate that Ceres' collisional history very likely includes large enough impacts to create a family, that a Ceres family would be found if extant, and that a Ceres family would not be easily erased once created if it is like the rocky bodies comprising "typical" asteroid families. There is observational and model evidence that Ceres is a differentiated body, with an icy mantle atop a rocky core. However, the surface of Ceres is too warm to maintain ice for significantly long periods of time (save very near the poles), and the retreat of ice does not effectively halt until it reaches a depth of rough order 100-1000 m (depending upon latitude and surface temperature) beneath an insulating lag deposit. What if a family-forming impact primarily or solely liberated icy material from the postulated icy mantle? To first order, an icy Ceres family is subject to the same sublimation rates as Ceres itself. Can its members have simply sublimed away? An order-of-magnitude argument shows that sublimation may have been a powerful force in erasing an icy Ceres family, this simplified model very likely understates the case for sublimation. We will show that the lack of a family has implications for Ceres' internal structure, and further hope to encourage research beyond the scope of this work – geodynamical, chemical and collisional modeling – that can provide additional firm constraints.

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500.07 – The potential of continuum slopes in the near-IR spectrum for the analysis of the surface of Ceres

Carry et al. (2012) recently reported that spectral slopes for Ceres (determined from the J, H, K bands using the HST and Keck) showed no spatial variation and they suggested a globally uniform composition of phyllosilicates and carbonates on the surface. However, recently observed venting from Ceres, albedo variations on the surface, laboratory data for terrestrial phyllosilicates, phyllosilicate/carbonate mixtures, phyllosilicates heated to 500-1100°C, and meteorites (Ostrowski et al., 2011), suggest that the surface should not be uniform but that variations in hydration and thermal alteration should be expected. Dawn's encounter with Ceres offers an opportunity to look for variations at a surface resolution far superior to these remote observations. Of particular interest would be the relationship between composition and surface topography, particularly craters and potential cryptovolcanoes, which are probably associated with dark spots on Ceres from which the venting appears to be coming. Also of interest will be compositional variations that can be related to stratigraphy or levels of alteration as this might be indicative of surface alteration sequence and thus primary, and therefore possibly mantle, compositions.

Carry B. et al., 2012. The remarkable surface homogeneity of the Dawn mission target (1) Ceres. *Icarus* 217, 20–26.

Ostrowski D.R. et al., 2011. IRTF spectra for 17 asteroids from the C and X complexes: A discussion of continuum slopes and their relationships to C chondrites and phyllosilicates. *Icarus* 212, 682-696.

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500.08 – Core Cracking and Hydrothermal Circulation Profoundly Affect Ceres' Geophysical Evolution

The dwarf planet (1)Ceres is about to be visited by the Dawn spacecraft [1]. In addition to a recent report of water vapor emission [2], observations and models of Ceres suggest that its evolution was shaped by interactions between liquid water and silicate rock [3,4].

Hydrothermal processes in a heated core require both fractured rock and liquid. Using a new core cracking model coupled to a thermal evolution code [5], we find volumes of fractured rock always large enough for significant interaction to occur. Therefore, liquid persistence is key. It is favored by antifreezes such as ammonia [4], by silicate dehydration which releases liquid, and by hydrothermal circulation itself, which enhances heat transport into the hydrosphere. The heating effect from silicate hydration seems minor. Hydrothermal circulation can profoundly affect Ceres' evolution: it prevents core dehydration via "temperature resets", global cooling events lasting ~50 Myr, followed by ~1 Gyr periods during which Ceres' interior is nearly isothermal and its hydrosphere largely liquid.

Whether Ceres has experienced such extensive hydrothermalism may be determined through examination of its present-day structure. A large, fully hydrated core (radius 420 km) suggests that extensive hydrothermal circulation prevented core dehydration. A small, dry core (radius 350 km) suggests early dehydration from short-lived radionuclides, with shallow hydrothermalism at best. Intermediate structures with a partially dehydrated core seem ambiguous, compatible both with late partial dehydration without hydrothermal circulation, and with early dehydration with extensive hydrothermal circulation. Thus, gravity measurements by the Dawn orbiter [1] could help discriminate between scenarios for Ceres' evolution.

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500.09 – An Icy Regolith Model that Predicts the Estimated Source Flux of H₂O on Ceres

Recent observations of the asteroid Ceres made in the far infrared indicate that the body is outgassing water vapor at a rate of approximately 6 kg/s [1]. We find that a model for the flux of vapor from a partially ice-saturated regolith on Ceres, driven outward by the geothermal gradient for an assumed heat flux of ~1 mW/m², can produce a comparable global flux of H₂O vapor.

Our model is based on previous theoretical work related to deep equatorial ground ice on Mars [4] that demonstrated how an assumed initially pore-filling subsurface ice layer would retreat when near-surface conditions made the ground ice no longer stable. Mellon [4], and Clifford [5], pointed out that once the ice table (the shallowest depth with a non-zero volume fraction of pore ice) retreated below a certain depth, the linear gradient of vapor density established by diffusion of vapor to the surface would necessarily go through the supersaturated regime of its phase diagram and therefore recondense as pore ice, an effect not considered in previous work [6]. Once this occurs, a steady-state profile of ice volume fraction, $f_{ice}(z)$, develops, with net mass loss only occurring from the retreating pore-filling ice layer. The rate of vapor flux to the surface is then determined only by the vapor density and temperature gradient at the ice table depth (z_0). We use an analytic physical model for regolith thermal conductivity [7,8] and a range of assumed values for the crustal heat flux to calculate the temperature gradient at z_0 , then integrate over all latitudes where surface ice is unstable to find the resulting global vapor flux.

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501 – Origins of Planetary Systems 2

501.01 – The Dispersal of Protoplanetary Disks - Impact on Planetary Architectures

Gas-rich dust disks around young stars provide the raw material to build up planets. Thus, the timescale over which they disperse and the physical mechanisms driving their dispersal are crucial to understand the origin of planetary systems. I will highlight key theoretical advances and observations that have revolutionized our understanding of protoplanetary disk dispersal in the past few years. I will also show how planetary system architectures are shaped by disk dispersal.

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501.02 – Primordial Excitation Of Spin-Orbit Misalignments Through Gravitational And Magnetic Star-Disk Interactions

Observational characterization of short-period, transiting exoplanets has revealed that a substantial fraction of such planets follow orbits that are inclined with respect to the spin axes of their host stars. Furthermore, the magnitude of spin-orbit misalignments is correlated with stellar effective temperature, with stars hotter than ~6250K displaying greater misalignments. These observations challenge the conventional idea that short-period planets arrived at their close-in orbits via smooth migration through a protoplanetary disk. However, recent work, both theoretical and observational, has suggested that the gravitational influence of a massive, distant companion star can torque the natal disk out of alignment, resulting in orbital obliquity. Here, we will discuss the consequences of magnetic disk-star coupling within the framework of the disk-torquing mechanism and show that the correlation between stellar effective temperature and orbital misalignment arises naturally. As such, our results are fully consistent with disk-driven migration as a dominant transport mechanism for close-in planets.

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501.03D – Angular Momentum Transport in Circumplanetary Disks

The Galilean satellites likely formed in a late-stage accretion disk that persisted around Jupiter after it was fully formed. The structure of this disk is highly dependent on its ability to transport angular momentum. Uncertainty in the level of angular momentum transport has led to competing theories of circumplanetary disk structure. Despite success in other astrophysical contexts, recent studies indicate that the conditions were not suitable for magnetorotational instabilities to develop in circumplanetary disks. However, it has been suggested that baroclinic instabilities can generate turbulence and provide the necessary transport of angular momentum. We present a 1+1D numerical model of the circumplanetary accretion disk that surrounded Jupiter during the epoch of regular satellite formation. An analysis of the radial entropy gradient in this model indicates that baroclinic instabilities can not only develop but persist throughout the majority of the disk. Furthermore, we find evidence for a two-component, gas-starved disk which may help to reconcile the differences in current competing theories of circumplanetary disk structure.

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501.04 – Detailed opacity model of viscously evolved protoplanetary disks: trapping planetary cores.

In order to constrain the favorable conditions for planetary formation, we have designed a hydrodynamical numerical model for the spreading of protoplanetary disks based on a self-consistent coupling between the disk thermodynamics, photosphere geometry and dynamics (Baillié & Charnoz., 2014, ApJ 786, 35). We retrieved the recurrent observational properties of protoplanetary disks around young Classical T Tauri type stars. One of the novelty of our approach lies in the proper treatment of the disk geometry, leading to the presence of non-irradiated zones. In addition, we show the importance of the physical composition of the disk: using a full-opacity model, our disk temperature takes into account the various changes of states experienced by the different components of our gas-dust disk. This is crucial for estimating the resonant torques that a potential planet would experience in an evolved disk: these corotation and Lindblad torques are very sensitive to the discontinuities in surface-mass density and temperature gradients. From these torques, we show that there are some preferential zones for planetary embryos to accumulate and some regions could be totally depleted in planetary cores.

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501.05 – Hydrodynamic Stability Criteria for Vertically Stratified Protoplanetary Disks

Whenever a vertically stratified circumstellar disk has a radial entropy gradient, the balance of forces in the radial and vertical directions implies that the unperturbed orbit frequency is a function of both radius and height above the midplane of the disk. This vertical shear in the orbit frequency can produce baroclinic instabilities that result in slanted convection in the r - z plane, vertical corrugations of the disk midplane, and outward angular momentum transport with an effective α of 0.001 (Nelson et al., MNRAS 435, 2610-2632, (2013)). It is difficult to derive a rigorous dispersion relation for this instability due to the inseparable nature of the r and z -dependence of the problem. Previously published stability criteria are limited to small vertical scales because they assume the vertical component of the star's gravity to be independent of z . This limitation can be overcome if one assumes that the vertical structure near the disk midplane is nearly adiabatic, so that the anelastic approximation is valid. For this case, the problem can be reduced to a set of three evolution equations for the z -component of the angular momentum, the potential temperature, and the component of vorticity due to motions in the r - z plane. This reduced dynamical system has a Hamiltonian structure that allows one to readily derive a Liapunov functional that governs the linear and nonlinear stability of the problem. The stability criterion reduces to a statement about the relative slopes in the r - z plane of the surfaces of constant angular momentum and constant potential temperature in the unperturbed disk. This stability condition is analogous to the criterion for symmetric baroclinic instabilities in planetary atmospheres. Support from NASA's Origins of Solar Systems program is gratefully acknowledged.

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501.06 – Terrestrial Planet Formation in the Presence of Migrating Super-Earths

Super-Earths with orbital periods less than 100 days are extremely abundant around Sun-like stars. It is unlikely that these planets formed at their current locations. Rather, they likely formed at large distances from the star and subsequently migrated inward. In this work we use N-body simulations to study the effect of super-Earths on the accretion of rocky planets. In our simulations, one or more super-Earths migrates inward through a disk of Moon-size to Mars-size protoplanetary embryos and much smaller planetesimals embedded in a gaseous disk. In order to qualitatively cover possible scenarios of type-I migration for super-Earths, we have performed simulations considering many different migration speeds and configurations for these bodies. Fast-migrating super-Earths, where super-Earth's

migration is comparable to the traditional type-I isothermal regime ($\tau_{\text{mig}} \approx 0.01-0.1$ Myr), only have a modest effect on the protoplanetary embryos and planetesimals. Sufficient material survives to form rocky, Earth-like planets on orbits exterior to the super-Earths'. In contrast, slowly-migrating super-Earths shepherd rocky material interior to their orbits and strongly deplete the terrestrial planet-forming zone. In this situation any Earth-sized planets in the habitable zone are extremely volatile-rich and are therefore probably not Earth-like.

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501.07 – Co-Accretion of Jupiter's Core and Gaseous Envelope

We simulate the formation of Jupiter by core-nucleated accretion, aided by the presence of an envelope of gas captured from the solar nebula. An initial Ceres-sized seed body is introduced into a swarm of small planetesimals whose radii range from 0.015 to 50 km, with initial surface density 10 g/cm² at 5.2 AU. The simulation uses a multi-zone code spanning ~ 1 AU in heliocentric distance. The swarm evolves by accretion with fragmentation, gravitational stirring, and drag-induced migration of planetesimals. Runaway growth of the seed allows its perturbations to prevent the emergence of rival bodies, and a single core dominates the region around its orbit, yielding an Earth-mass core in ~ 0.1 My. Without an envelope, growth of a bare core stalls at ~ 4 Earth masses (about half the isolation mass) due to local depletion of the swarm and clearing of a gap by shepherding. However, an Earth-mass core can capture gas from the nebula. We compute the structure of the gaseous envelope self-consistently with energy input from infalling planetesimals and opacity due to dust supplied by their ablation, including settling and coagulation. The core's cross-section for accretion of planetesimals is substantially enhanced by the envelope, allowing the core to attain a larger mass in a shorter time. The mass of the envelope also becomes significant, increasing the gravitational reach of the growing planet. At 1.3 My the core reaches ~ 8 Earth masses with an envelope of about 4 Earth masses. At this point the rate of gas accretion substantially exceeds that of solids; further growth is dominated by capture of gas. A detailed description of our methodology and results through 0.4 My is presented by D'Angelo et al., *Icarus* 241, 298 (2014). Supported by NASA OPR.

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501.08 – Forming Inner Ice-Rich Moons at Saturn from a Massive Early Ring

Saturn's rings are 90 to 95% water ice. As a group, Saturn's moons interior to and including Tethys are also about 90% ice. The small inner moons (interior to and including Janus) are dynamically young with histories tied to that of the rings (e.g., Goldreich & Tremaine 1982; Esposito 1986). Charnoz et al. (2010) showed that ring material viscously spreading outward across the Roche limit can produce these small moons and their observed mass vs. distance relationship within the last 10^7 years.

Canup (2010) proposed that at the end of Saturn's formation, tidal stripping from a differentiated Titan-sized moon as it spiraled into Saturn could have produced a massive $10^{24} - 10^{25}$ g initial ice ring, and that Mimas, Enceladus and Tethys could have been similarly spawned from this primordial ring as it viscously evolved. Charnoz et al. (2011) considered a massive ice-rock ring and a tidal dissipation factor for Saturn of $Q \approx 10^3$, and found that satellites out to Rhea could be spawned from such a ring. However the likelihood of such a small value for Q is debated. In addition, capture into mutual mean motion resonances and resulting eccentricity growth (not included in the Charnoz et al. model) could lead to orbital destabilization as the moons tidally expand over large distances (Peale & Canup 2014).

Here we consider a dissipation factor for Saturn $Q \approx 10^4 - 10^5$ and investigate whether Mimas, Enceladus and Tethys could have been spawned from a massive initial ice ring. In this scenario, the rock in these moons would be delivered by material from outside the rings, e.g. by heliocentric impactors during the LHB (Canup 2013). We have expanded a numerical model developed to study the accretion of Earth's Moon (Salmon and Canup 2012, 2014), which couples an analytic Roche-interior disk model to the N-body code SyMBA for material exterior to the Roche limit, so that we can directly track the accretion and mutual interactions of growing satellites (including mean-motion resonances) as well as their tidal interaction with the planet. Implications for the origin and early dynamical evolution of Saturn's inner moons will be discussed.

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501.09 – On an impact origin of Phobos-Deimos

Phobos and Deimos are the only example of terrestrial satellites other than our Moon, and their origin could provide constraints on Mars' accretion. These tiny moons are also potential targets for robotic and manned exploration. Remarkably little is known about how Phobos and Deimos formed. A frequently cited idea is that the moons were

carbonaceous asteroids captured intact into Mars orbit. However, intact capture appears inconsistent with their nearly circular orbits, which instead imply formation from a disk (e.g., Burns 1992; Peale 2007; Rosenblatt 2011). A natural way to form a disk is through a large, oblique impact. The difference in formation timescales for Mars (~1 to 10 Myr; Nimmo & Kleine 2007) vs. the Earth (~ 50 to 100 Myr; Touboul et al. 2007) suggests that Mars did not experience the protracted phase of giant impacts that Earth did. However, Mars' rotation rate implies that it experienced at least one large impact at the end of its accretion by an object containing a few percent of Mars' mass (e.g., Dones & Tremaine 1993). While an impact origin of Phobos-Deimos has been proposed (Craddock 2011), its viability has not been assessed with direct impact simulations.

We have performed an initial series of such simulations, and these suggest that an impact consistent with Mars' day produces a disk with orders-of-magnitude more mass than in Phobos and Deimos. A key distinction from an impact-generated protolunar disk is that at Mars, tidal interaction with the planet causes most moons to spiral inward toward the planet and be lost. For a disk that is initially entirely within Mars' Roche limit (located at about 3 Mars radii), all moons may well be lost (Rosenblatt & Charnoz 2012). However we find initial disks that are more radially extended, with outer edges comparable to the inferred formation distances of Phobos and Deimos (between about 5.5 and 7 Mars radii). In this case, Phobos and Deimos could accrete from the outer disk and survive, while their more massive primordial inner companions evolve inward and are accreted by Mars.

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502 – Icy Satellites Potpourri

502.01 – Distribution of CO² ice and evidence for near-surface layers on the large Uranian satellites

We are investigating the distribution of CO² ice on the surfaces of Ariel, Umbriel, Titania, and Oberon in order to constrain the origin of this volatile. Our preferred hypothesis is that charged particles trapped in Uranus' magnetosphere bombard the surfaces of these moons, driving a radiolytic production cycle of CO². We have collected near-infrared (NIR) spectra (~0.8 – 2.5 μm) using IRTF/SpEx to expand on data presented in Grundy et al. (2006), which are also included in our analysis. Statistical analysis of the CO² bands present in these spectra indicates that CO² preferentially accumulates on the moons' trailing hemispheres and decreases in abundance with increasing distance from Uranus. Our best fit numerical models include particulate mixtures of H²O ice and amorphous C, mixed with up to 27% CO² ice on Ariel (5 – 50 μm grain sizes for all three constituents).

We are also using NIR photometry (~3.1 – 9.5 μm) collected by Spitzer/IRAC to investigate the distribution of CO² ice on these moons. The CO² asymmetric stretch fundamental (centered near 4.27 μm) is coincident with IRAC channel 2 (centered near 4.5 μm, pass band width of 0.87 μm). Consequently, bodies with detectable levels of CO² should exhibit a reduction in geometric albedo in channel 2 relative to channels 1 and 3. Our photometric results indicate that each moon exhibits a reduction in geometric albedo from channel 1 to 2, but they also exhibit a reduction in geometric albedo from channel 2 to 3, which is inconsistent with the presence of CO² ice. Numerical modeling of our IRAC results indicates that the surfaces of these moons are dominated by small H²O ice grains, mixed with only minor amounts of CO² (0.5 – 2 μm grain sizes).

In summary, our band area analysis indicates that there is a statistically significant accumulation of CO² on the trailing hemispheres of all four of these moons. The disparity between our SpeX and IRAC numerical models suggests that we are probing distinct layers in the near-surfaces of these moons. Thus, the CO² ice detected using SpeX might be retained beneath a veneer of H²O ice that is opaque over IRAC wavelengths.

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502.02 – Temperature maps of Saturn's satellites retrieved from Cassini-VIMS observations

The spectral position of the 3.6 μm continuum peak measured on Cassini-VIMS reflectance spectra is used to infer the temperature of the regolith particles covering the surfaces of Saturn's icy satellites. Laboratory measurements by Clark et al. (2012) have shown that 3.6 μm peak for pure crystalline water ice particles shifts towards shorter wavelengths when the sample is cooled, moving from about 3.65 μm at T=123 K to about 3.55 μm at T=88 K. A similar trend is observed also in the imaginary part (k) of the refractive index of water ice when the sample is cooled from T=140 K to 20 K (Mastrapa et al., 2009). Since water ice is the dominant endmember on Saturn's satellites surfaces (Clark and Owensby, 1981; Clark et al., 1984; Filacchione et al., 2012), the measurement of the wavelength at which the 3.6 μm reflectance peak occurs can be considered as a temperature indicator. We report on our temperature maps of Mimas,

Enceladus, Tethys, Dione and Rhea derived by applying this method to Cassini-VIMS data taken at spatial resolution of 20-40 km/pixel. These maps allow us to correlate the temperature distribution with solar illumination conditions and with geological features. On average Enceladus' mid-latitudes regions appear at $T < 100$ K while the south pole tiger-stripes active area shows a thermal emission at $T > 115$ K. Tethys' and Mimas' equatorial lenses show significant thermal anomalies: despite the fact that these features have low visible albedo they appear colder than the surrounding mid-latitude regions as a consequence of a much higher thermal inertia. On Mimas, the floor of Herschel crater appears warmer ($T > 115$ K) than the adjacent equatorial lens area ($T < 110$ K). Finally, the analysis of Dione shows that the temperature across the bright wispy terrains is lower than the nearby low albedo areas.

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502.03 – Spectroscopic Variation of Water Ice Abundance Across Mimas and Tethys' Surface

We present results from our ongoing work mapping the variation of the main water ice absorption bands across Mimas and Tethys' surfaces using Cassini-VIMS cubes acquired in the IR range (0.8–5.1 μ m).

Mimas and Tethys are Enceladus' orbital neighbours, lying inside and outside Enceladus' orbit respectively. It is therefore likely that Mimas and Tethys surfaces interact with icy particles from the E-ring, resulting in a spectral, color modification.

For all pixels in the selected VIMS cubes, we measured the band depths for water-ice absorptions at 1.25, 1.5 and 2.02 μ m and the height of the 3.6 μ m reflection peak, whose value relates to grain size. To characterize the global variation of water-ice band depths across Mimas and Tethys, we divided the surface into a $1^\circ \times 1^\circ$ grid and then averaged the band depths and peak values inside each square cell.

The most prominent feature on Mimas surface is the crater Herschel with a diameter of 130 km, one-third of the satellite's one. Mimas has the most uniform surface among Saturn's principal satellites, with its trailing side just 10% brighter and redder than the leading one. The uniformity of Mimas extends on spectral appearance too. The 1.52 and 2.02 μ m H₂O-ice absorption bands are $\sim 10\%$ deeper on trailing hemisphere.

On Tethys' leading hemisphere a 400 km in diameter crater, Odysseus, is present. Its dimension represents $\sim 40\%$ of Tethys diameter.

For both moons we find that large geologic features, such as the Odysseus and Herschel impact basin, do not correlate with water ice's abundance variation.

For Tethys, we found a quite uniform surface on both hemispheres. The only deviation from this pattern shows up on the trailing hemisphere, where we notice two north-oriented, dark areas around 225° and 315° . For Mimas the selected dataset covers just the leading hemisphere and a portion of the trailing side. From the analysis, the two hemispheres appear to be quite similar in water ice abundance, the trailing portion having water ice absorption bands lightly more suppressed than the leading side.

No correlation with the visible-color/thermal anomaly features has yet been found.

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502.04D – Transport of Ice on the Surface of Iapetus

The global black-and-white dichotomy as well as the dark floors and rims of equatorial craters on the Saturnian moon Iapetus can be explained by ice migration driven by a thermal feedback [1]. All icy moons in the Jovian and Saturnian systems are - with the exception of Titan - airless bodies. Yet it is unique, how these two types of surface features on Iapetus look. A physical model of the processes of absorption, sublimation and deposition was developed and a computational model that simulates ice migration of volatiles under these circumstances derived. The model tessellates the surfaces of an airless body into triangles of equal size that can each have different surface properties. These properties evolve while the model simulates a long-term development. A rate network of net migration is calculated from sublimation and redeposition under the assumptions of

- a slowly rotating body
- undisturbed ballistic molecular trajectories
- isotropic emission
- Maxwellian speed distribution
- high sticking coefficients of the surfaces.

The assumptions (b.) to (e.) are equally valid for all bigger outer solar system icy moons (except Titan). The very first assumption however is not equally valid throughout the moons of the outer solar system. Callisto being in many regards similar to Iapetus still has a five times higher rotation rate. So global effects depending on slow rotation are more profound on Iapetus. The computer model is complemented by a model for local ice migration from craters.

First results show, that the global timescale of albedo change in our model is of the same order of magnitude as in the supporting material to [1] with a tendency towards slightly faster (~ 2 Gyr instead of ~ 2.4 Gyr) darkening compared to the "Model B". The time rate of local crater darkening rates lies between the global darkening rate and rate of the opposing brightening effect as estimated in [2] to (? between 10 and 100 MYr).

[1] Formation of Iapetus' Extreme Albedo Dichotomy by Exogenically Triggered Thermal Ice Migration, John R. Spencer, Tilmann Denk, *Science* 22, Vol. 327, January 2010.

[2] Iapetus: Unique Surface Properties and a Global Color Dichotomy from Cassini Imaging T. Denk et al., *Science* 22, Vol. 327, January 2010.

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502.05 – Modeling of Sublimation-Driven Erosion and Ice Pinnacle Formation on Callisto

Most of the areas observed at high resolution on the Galilean satellite Callisto have a morphology that implies sublimation-driven landform modification and mass wasting is at work [Moore et al., 1999]. These areas comprise rolling dark plains with interspersed bright pinnacles. Howard and Moore [2008], using the MARSSIM landform evolution model, simulated evolution of this landscape as a combination of bedrock volatile sublimation, mass wasting of the dark, non-coherent residue, and redeposition of ice at high-elevation cold traps sheltered from thermal re-radiation to form the pinnacles.

The goal of our study is to further investigate the details of pinnacle formation by refining this model, and by constraining values for the variable environmental parameters within the model such that they are consistent with the current understanding of Callisto's surface environment. We present the results of the updated model and our experimentation with varying key parameters.

Our refinement of the model has caused us to revise the result of Howard and Moore [2008] that the pinnacles represent an ice cover of several tens to hundreds of meters. Instead, our results indicate an ice coverage reaching several meters at most, a figure that is consistent with the prediction of Moore et al. [2004]. We have also modified the model such that ice contained within the pinnacles is now subject to sublimation itself.

Using Fick's Law to solve for the diffusive transport rate between a volatile table and an atmosphere [Moore et al., 1996], we have determined that the loss rate of H₂O ice from the volatile-refractory bedrock through sublimation is too slow ($\sim 10^{-20}$ kg m⁻² s⁻¹) to account for the formation of the ice pinnacles, and that a volatile mixture that contains H₂O ice is necessary to facilitate its loss. We find that CO₂ hydrate fulfills this role well: loss rates of CO₂?6H₂O ($\sim 10^{-10}$ kg m⁻² s⁻¹) are sufficient to produce deposited ice thicknesses reaching several meters, with the volatile CO₂ resulting from dissociation remaining in the tenuous atmosphere [Carlson, 1999; Liang et al., 2005].

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502.06 – Space Weathering on Icy Satellites in the Outer Solar System

Space weathering produces well-known optical effects in silicate minerals in the inner Solar System, for example, on the Moon. Space weathering from solar wind and UV is expected to be weaker in the outer Solar System simply because intensities are lower. However, cosmic rays from inner to outer solar system would be similar to first order. Similarly with micrometeoroid bombardment. That, combined with the much higher volatility of icy surfaces means there is the potential for space weathering on icy outer Solar System surfaces to show optical effects. The Cassini spacecraft orbiting Saturn is providing evidence for space weathering on icy bodies. The Cassini VIMS instrument has spatially mapped satellite surfaces and the rings from .35-5 microns and the UVIS instrument from 0.1 to 0.2 microns. These data have sampled a complex mixing space between H₂O ice and non-ice components and they show some common spectral properties. Similarly, spectra of the icy Galilean satellites and satellites in the Uranian system have some commonality in spectral properties with those in the Saturn system. The UV absorber is spectrally similar on many surfaces. VIMS has identified CO₂, H₂ and trace organics in varying abundances on Saturn's satellites. We postulate that through the spatial relationships of some of these compounds that they are created and destroyed through space weathering effects. For example, the trapped H₂ and CO₂ observed by VIMS in regions with high concentrations of dark material may in part be space weathering products from the destruction of H₂O and organic molecules. The dark material, particularly on Iapetus which has the highest concentration in the Saturn system, is well matched by space-weathered silicates in the .4-2.6 micron range, and the spectral shapes closely match those of the most mature lunar soils, another indicator of space weathered material.

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502.07 – Time-varying Geometric Orbital Elements of Saturn's Moons

The orbital elements of Saturn's moons are a moving target. Not only do they change with time due to gravitational interactions among the moons, but the familiar osculating elements are often not physically meaningful because of Saturn's large oblateness. Starting with numerical orbit integrations constrained by ground-based and spacecraft observations (e.g., Jacobson et al. 2008, AJ), we express the orbits of Saturn's moons in terms of the physically meaningful "epicyclic elements" derived in several papers by Borderies (Rappaport) and Longaretti, obtaining them from the Cartesian position and velocity at each moment in time via the algorithm of Renner and Sicardy (2006, CeMDA). Our purpose is twofold: Firstly, Saturn's rings respond to myriad resonances with the moons, and the location and phase of those resonances depend on each moon's mean motion, argument of pericenter, etc. By obtaining time series for these quantities in forms that directly reflect the motion of the perturbers as seen by the rings, we enable more precise study of ring resonances. Resonances due to Mimas, Janus, and Epimetheus, and perhaps also Prometheus and Pandora, change with time in such a way as to result in observable effects in spiral waves and edge locations (e.g., Tiscareno et al. 2006, ApJL; Spitale and Porco 2009, AJ). Secondly, by means of Fourier analysis and wavelet analysis, we investigate the frequencies that govern the evolution of the geometric orbital elements, and even how those frequencies themselves may change with time, thus casting light on the interactions among moons, as well as on the relation between orbital and rotational motion.

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502.08 – Spectrophotometric Properties of Thermally Anomalous Terrain on Mimas

Cassini's Composite InfraRed Spectrometer (CIRS) maps of thermal emission from Mimas reveal a V-shaped boundary, centered at 0° N and 180° W, which divides relatively warm daytime temperatures from an anomalously cooler region at low to mid-latitudes on the moon's leading hemisphere (Howett et al. 2011, Icarus 216, 221-226). This cooler region is also warmer at night, indicating that it has high thermal inertia, and also coincides in shape and location with that of high-energy electron deposition from Saturn's magnetosphere (Roussos et al. 2007, JGRA 112, A06214; Schenk et al. 2011, Icarus 211, 740-757). Global IR/UV color ratio maps assembled from Cassini Imaging Science Subsystem (ISS) images show a lens-shaped region of relatively blue terrain also centered on Mimas' leading hemisphere (Schenk et al. 2011), coinciding in shape and location with the region of high thermal inertia. We present results of our analysis of Cassini ISS CL1 UV3 and IR3 filter (centered at 338 and 930 nm, respectively) images using the Hapke (2008, Icarus 195, 918-926) photometric model. We investigate whether the photometric properties of surface particles are consistent with the conclusion by Howett et al. (2011) that their high thermal inertia is produced by sintering processes due to bombardment by high energy electrons. The non-thermally anomalous surface on Mimas' trailing hemisphere exhibits a strong opposition effect, consistent with the presence of a more complex microtexture due to preferential bombardment by E ring particles. This work is supported by the NASA Cassini Data Analysis and Participating Scientists Program.

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502.09 – Coherent Backscattering Effect in Saturnian vs. Uranian Satellites: Observations and Enhanced MSTM Modeling

We continue our campaign to extract spectra and measure absorption band parameters from Cassini Visual & Infrared Mapping Spectrometer (VIMS) and ground-based near-infrared observations of saturnian and uranian icy satellites. We compare these spectra to numerical models to study the coherent backscattering effect (CBE; constructive interference of radiation) that should significantly alter the interpretation of spacecraft spectra obtained at solar phase angles $\theta < 2$ degrees. To quantify CBE, we extract VIMS spectra for different θ from the same location on the icy satellite surface, ideally within +/- 1-2 degrees in subspacecraft latitude and longitude. Using 2013-2014 calibration updates for VIMS, we present groups of VIMS spectra (pairs or trios) for 3 saturnian moons that most closely fit these ideal criteria. We also show models of the light-scattering characteristics of icy surfaces using a new version of the Multiple Sphere T-Matrix (MSTM) code (Mackowski, D., 2014, in Proceedings of the Workshop "Scattering by aggregates (on surfaces)", Bremen, Germany, 24 - 25. March 2014, p. 6-9). This code, called MSTM4, allows users to build large, thick slabs of dozens of thousands of spheres to model planetary regolith more accurately. The results clearly indicate the influence of CBE on the spectra and show significant dependence on the size of particles and their packing. To extend the low phase angle coverage of Cassini VIMS data and examine CBE on darker surfaces, we also compare to spectra of several uranian satellites (Titania, Oberon Ariel) acquired using Triplespec (R~3500) at Apache Point Observatory, New Mexico. Synthesizing such results will ultimately place limits on the size and packing fraction of icy satellite regolith particles and aid in interpretations of the structure, composition, and evolution of icy satellites.

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cubes appear courtesy of the Cassini VIMS team and the PDS.

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503 – Asteroid Physical Characterization 3: NEAs, Active Asteroids, and Simulations

503.01 – The Physical, Geological, and Dynamical Nature of Asteroid (101955) Bennu - Target of OSIRIS-REx

OSIRIS-REx will survey asteroid (101955) Bennu to understand its properties, assess its resource potential, refine the impact hazard, and return a sample to Earth. This mission launches in 2016.

Bennu is different from all other near-Earth asteroids previously visited by spacecraft. (433) Eros, target of the NEAR-Shoemaker mission, and (25143) Itokawa, target of Hayabusa, are both high-albedo, S-type asteroids with irregular shapes. In contrast, Bennu has a low albedo, is a B-type asteroid, and has a distinct spheroidal shape. While Eros and Itokawa are similar to ordinary chondrites, Bennu is likely related to carbonaceous chondrites, meteorites that record the history of volatiles and organic compounds in the early Solar System.

We performed an extensive campaign to determine the properties of Bennu. This investigation provides information on the orbit, shape, mass, rotation state, radar response, photometric, spectroscopic, thermal, regolith, and environmental properties of Bennu. Combining these data with cosmochemical and dynamical models yields a hypothetical timeline for Bennu's formation and evolution. Bennu is an ancient object that has witnessed over 4.5 Gyr of Solar System history. Its chemistry and mineralogy were established within the first 10 Myr of the Solar System. It likely originated as a discrete asteroid in the main belt ~0.7 – 2 Gyr ago as a fragment from the catastrophic disruption of a large, carbonaceous asteroid. It was delivered to near-Earth space via a combination of Yarkovsky-induced drift and interaction with giant-planet resonances. During its journey, YORP processes and planetary encounters modified Bennu's spin state, potentially reshaping and resurfacing the asteroid.

Bennu is a Potentially Hazardous Asteroid with an ~1-in-2700 chance of impacting the Earth in the late 22nd century. It will most likely end its dynamical life by falling into the Sun. The highest probability for a planetary impact is with Venus, followed by the Earth. There is a chance that Bennu will be ejected from the inner Solar System after a close encounter with Jupiter. OSIRIS-REx will return samples from this intriguing asteroid in September 2023.

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Contributing team(s): OSIRIS-REx Team

503.02D – Bidirectional Reflectance Distribution Functions For the OSIRIS-REx Target Asteroid (101955) Bennu

We used ground-based photometric phase curve data of asteroid (101955) Bennu and low phase-angle (proxy) data from asteroid (253) Mathilde to fit precise Modified Minnaert, Modified Lommel-Seeliger, and (RObotic Lunar Orbiter) ROLO photometric models that capture the light scattering properties of the surface and subsequently allow us to calculate the geometric albedo, phase integral, and spherical Bond albedo for this asteroid. Radiance Factor functions (RADFs) are used to model the disk-resolved brightness of Bennu. Our geometric albedo values of 0.047, 0.047, and 0.048 for the Modified Minnaert, Modified Lommel-Seeliger, and ROLO models, respectively, are consistent with the geometric albedo of 0.030-0.045 computed by Hergenrother et al. (2013), using IAU H-G photometric system. Also, our spherical Bond albedo values of 0.016, 0.015, and 0.015 for the Minnaert model, Lommel-Seeliger, and ROLO models, respectively, are consistent with the value of 0.017 presented by Emery et al. (2014).

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503.03 – Numerical Simulations of Granular Processes

Spacecraft images and indirect observations including thermal inertia measurements indicate most small bodies have surface regolith. Evidence of granular flow is also apparent in the images. This material motion occurs in very low gravity, therefore in a completely different gravitational environment than on the Earth. Understanding and modeling these motions can aid in the interpretation of imaged surface features that may exhibit signatures of constituent material properties. Also, upcoming sample-return missions to small bodies, and possible future manned missions, will involve interaction with the surface regolith, so it is important to develop tools to predict the surface response. We have

added new capabilities to the parallelized N-body gravity tree code pkdgrav [1,2] that permit the simulation of granular dynamics, including multi-contact physics and friction forces, using the soft-sphere discrete-element method [3]. The numerical approach has been validated through comparison with laboratory experiments (e.g., [3,4]). Ongoing and recently completed projects include: impacts into granular materials using different projectile shapes [5]; possible tidal resurfacing of asteroid Apophis during its 2029 encounter [6]; the Brazil-nut effect in low gravity [7]; and avalanche modeling.

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References: [1] Richardson, D.C. et al. 2000, *Icarus* 143, 45; [2] Stadel, J. 2001, Ph.D. Thesis, U Washington; [3] Schwartz, S.R. et al. 2012, *Gran. Matt.* 14, 363. [4] Schwartz, S.R. et al. 2013, *Icarus* 226, 67; [5] Schwartz, S.R. et al. 2014, *P&SS*, 10.1016/j.pss.2014.07.013; [6] Yu, Y. et al. 2014, *Icarus*, 10.1016/j.icarus.2014.07.027; [7] Matsumura, S. et al. 2014, *MNRAS*, 10.1093/mnras/stu1388.

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503.04 – Tidal Disruption Revisited - Creating Bifurcated Shapes Among Rubble Pile Asteroids

We revisit the tidal disruption of rubble pile asteroids encountering terrestrial planets. The rubble pile structure of the asteroid is modeled with spherical particles that interact with full "soft-sphere" descriptions of the particles interactions - including static, sliding, and rolling friction. Using friction parameters that have matched the behavior of irregularly shaped gravel particles dynamically evolving [1], we have run a suite of tidal disruption simulations to compare with previous simulations that used more simplistic particle interactions. We find that the soft-sphere description of the asteroids's mechanics is very important and dramatically change the dynamics of the disruption, particularly the resulting shapes of remnants. Here we find many elongated and bifurcated shapes, reminiscent of some of the irregularly shaped bodies recently imaged with delay-doppler radar.

[1] Yu, Y. et al. 2014, *Icarus*, 10.1016/j.icarus.2014.07.027

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503.05 – The Effect of Shape Model Uncertainty on the Geophysical Predictions of Binary Asteroids

Recent work by Jacobson and Scheeres (*ApJ* Vol. 736, L19) have shown that for a binary asteroid system in and equilibrium between tides and the binary YORP effect, the ratio Q/k can be determined, where Q is the tidal dissipation number and k is the tidal Love number. In their work, the value for B (the binary YORP coefficient) was that computed by McMahon and Scheeres (*Icarus* Vol. 209, pp 494-509, 2010) for binary asteroid 1999 KW4. Using this value, it was shown that the geophysical parameters Q/k can be estimated. Furthermore, we can similarly compute Q based on the relationship between Q and k (where Q is the rigidity parameter), as discussed by Scheerich et al (*ACM*, Niigata, Japan, 2012, No. 1667, id.6123). These geophysical predictions, however, depend directly on the value of the binary YORP coefficient used, which is uncertain due to the limited shape model accuracy.

In this study, we analyze the effect of shape model uncertainty on the predictions of Q/k and Q . The 1999 KW4 secondary shape model is stochastically perturbed based on the radar observation accuracy (Ostro et al, *Science* Vol. 314, pp 1276-1280, 2006). Furthermore the detail of the topography is varied by adding more vertices to create a higher resolution shape model. For each newly perturbed shape model, the binary YORP coefficient is computed using our most advanced modeling software, and is used to derive new values for the geophysical parameter relationships. Furthermore we compute the B for a variety of known asteroid shape models as investigated by McMahon and Scheeres (44th AAS DPS, Reno, NV, 2012. Abstract No. 105.08). The results give effective error bounds on the Q/k (and derived Q) predictions based on the shape model uncertainties.

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503.06D – Observations of Asteroid 2577 Litva with Analysis of Physical Properties Through Bayesian Inference Based Modeling

Observations of asteroid 2577 Litva, a known multiple system, were taken from Robinson Observatory at the University of Central Florida spanning several weeks from late 2013 to early 2014. This work outlines a modified Bayesian Inference methodology for determining periodicities within the data as well as correcting for orbital effects with pole determination, and compares our results with previously published works. For the primary object, Litva, we find the most probable period to be $2.812186 \pm 5 \times 10^{-6}$ hours, the most probable for the pole direction to be at $26.96 \pm 2, 298.8 \pm 11$ degrees latitude and longitude. The secondary system does not appear to eclipse the primary object, most likely due orbital geometries. For the third object we find the most probable rotation period to be 5.68389 ± 0.0005 hours. We discuss how to extend this work to determine the direction of the rotation axis for the third body, as well as the pole direction for the eclipsing satellite. This methodology is a novel tool for generating probability distributions for each measured quantity handling low signal-to-noise observations, working with widely spaced data, and detecting periodicities.

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503.07 – Active Asteroids P/2013 P5 and P/2013 R3

Active asteroids (a.k.a. main-belt comets) possess the dynamical character of asteroids but exhibit evidence for mass loss, giving them a comet-like appearance. About 16 members of this newly-recognized group are currently known. Scientific interest lies in understanding the mechanisms responsible for the mass loss. Examples of impact, sublimation and thermal disintegration have been identified, and it seems clear that still other mechanisms exist. We are investigating these objects using high resolution observations from the Hubble Space Telescope, supplemented by observations from the Keck and other ground-based telescopes.

Two exciting new objects show properties consistent with mass loss caused by rotational instability. P/2013 P5 shows a unique multiple dust tail system (dust mass of order 10^5 kg), produced by irregular ejection over 8 months. This is inconsistent with an impact origin and unlike activity seen in any ice-driven comet. The inner belt orbit ($a = 2.189$ AU) and S-type optical colors additionally suggest a metamorphosed composition incompatible with the survival of water ice. We suggest that P5 is shedding mass through local avalanche instabilities caused by a presumed rapid spin. The small size (radius < 240 m) renders P5 potentially susceptible to spin-up by radiation torques.

P/2013 R3 is a dust-shrouded, multiple object in the outer asteroid belt ($a = 3.033$ AU) that is disintegrating in real-time. Ten distinct components have been detected, the largest four having radii up to 200 m. The velocity dispersion amongst fragments is 0.2 to 0.5 m/s, comparable to the gravitational escape speeds of the largest components. The dust mass is of order 10^8 kg, about 1000 times larger than in P5. Keck spectra set a limit to gas production near 1 kg/s. We suggest that R3 has experienced a rotational breakup, more severe than that of P5, in which the nucleus has disintegrated into component pieces. We are tracking the components to determine their dynamics and to search for evidence of rapid rotation.

Astrophysical Journal, 2013, 778:L21. Extraordinary Multi-Tailed Main-Belt Comet P/2013 P5.

Astrophysical Journal, 2014, 784:L8. Disintegrating Asteroid P/2013 R3.

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503.08 – Constraints on the Physical Properties of Main Belt Comet P/2013 R3 from its Breakup Event

Main belt comet P/2013 R3 recently experienced a breakup, probably due to rotational disruption. From October through December 2013 its small components, with effective radii of 0.2-0.5 km, were observed to be escaping with a dispersion velocity of 0.2-0.5 m/s (Jewitt et al., *Apj Letters* 784, L8, 2014). This study develops and applies a technique for constraining the physical properties of the proto-body. The proto-body is assumed to be a uniformly rotating biaxial ellipsoid. To model this breakup event, we develop a combined analysis for the failure condition of the proto-body during its structural breakup phase and of the mutual orbit dynamics of the small components during its dynamics phase. To model the structural breakup phase we use structural analysis. Since a uniformly rotating ellipsoid with cohesion may fail across the central cross section first, we apply the Davidsson method (Davidsson, *Icarus* 149, 375-383, 2001) that considered the failure condition to be characterized by the yield condition of the averaged stress over the cross section. For the dynamics phase, we consider the energy conservation during this event. Calculation of the total energy requires consideration of the shape change due to the breakup phase, and we derive it without approximation (Scheeres, *CMDA* 89, 127-140, 2004). These phases can be combined based on the assumption that the initial spin period is equal to the spin period when the proto-body starts the structural breakup phase. Given a proto-body with a

bulk density ranging from 1000 kg/m³ to 1500 kg/m³ (a typical range of bulk density for C-type asteroids), we obtain possible values of the cohesion (40 - 210 Pa) and the initial spin state (0.48 - 1.9 hr). We conclude that although the proto-body could have been a rubble pile, it was likely spinning beyond its gravitational binding limit and would have needed cohesive strength to hold itself together. If additional observations of P/2013 R3 are carried out, the present technique will be able to provide more precise estimates of its internal structure. This study was published in the *Astrophysical Journal Letters* (Hirabayashi et al., *Apj Letters* 789, L2, 2014).

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503.09 – The Mission Accessible Near-Earth Object Survey (MANOS): Project Overview

The Mission Accessible Near-Earth Object Survey (MANOS) began in August 2013 as a multi-year physical characterization survey that was awarded survey status by NOAO. MANOS will target several hundred mission-accessible NEOs across visible and near-infrared wavelengths, ultimately providing a comprehensive catalog of physical properties (astrometry, light curves, spectra). Particular focus is paid to sub-km NEOs, for which little data currently exists. These small bodies are essential to understanding the link between meteorites and asteroids, pose the most immediate impact hazard to the Earth, and are highly relevant to a variety of planetary mission scenarios. Accessing these targets is enabled through a combination of classical, queue, and target-of-opportunity observations carried out at 1- to 8-meter class facilities in both the northern and southern hemispheres. The MANOS observing strategy is specifically designed to rapidly characterize newly discovered NEOs before they fade beyond observational limits.

MANOS will provide major advances in our understanding of the NEO population as a whole and for specific objects of interest. Here we present an overview of the survey, progress to date, and early science highlights including: (1) an estimate of the taxonomic distribution of spectral types for NEOs smaller than ~100 meters, (2) the distribution of rotational properties for approximately 100 previously unstudied objects, (3) models for the dynamical evolution of the overall NEO population over the past 0.5 Myr, and (4) progress in developing a new set of online tools at asteroid.lowell.edu that will enable near realtime public dissemination of our data while providing a portal to facilitate coordination efforts within the small body observer community.

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504 – Origins of Planetary Systems 3

504.01 – Evolution of the proto-lunar disk and the origin of the Moon's material

The Earth's Moon is thought to have accreted from an impact generated disk. Whereas many works have studied the impact itself, the evolution of the disk that gave birth to the Moon is largely unknown and in particular its dynamical evolution and cooling timescale. These are important parameters as they control the onset of the gravitational instability that triggers satellite formation. In particular, the chemical and isotopic composition of the Earth's moon is thought to be largely inherited from the protolunar disk (formed after an impact on the proto-earth). However, for the moon to form, the disk must cool down first. During this cooling phase, major dynamical, chemical and isotopic restructuring may happen in the disk, and thus, the material that will get ultimately incorporated in the protomoon may be largely different from the average composition of the Earth or its impactor.

We have developed a viscous model of a two-phase protolunar disk, including phase transition, gravitational instability and Kelvin Helmholtz instability (KH) to investigate the evolution of this disk on several 10⁴ years, from the impact up to its ultimate cooling and assembling into a protomoon. We show that the protolunar disk forms rapidly a dense and compact disk below 2 earth radii, with a high density. This high density promotes long cooling timescales, about 10⁴ to 10⁵ years. During this phase the material hasenough time to equilibrate isotopically. In addition if the disk is turbulent then the gas phase is very mobile an cand efficiently separate from the liquid phase and lead to an incomplete condensation of the disk material, which is a good candidate to explain the today moon devolatilisation with respect to Earth material. Extension of this work to the formation of Ice giant planet's satellites will be also presented.

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504.02 – Comparing Accretion Histories of Earth, Mars, and Theia Analogs

The canonical scenario for the formation of the Moon predicts that a Mars-mass impactor collided with the proto-Earth in a glancing collision that threw material into orbit around the Earth. However, such a scenario results in a Moon largely composed of material from the impactor rather than the proto-Earth. Since meteorites from Mars and the asteroid belt have markedly different oxygen isotope abundance ratios than Earth, this Moon origin scenario appears at odds with the nearly identical oxygen isotope signatures of lunar and terrestrial rocks. Here we test the possibility that the proto-Earth and Theia (the lunar impactor) had similar enough accretion histories before their collision to yield a moon with nearly identical oxygen isotope abundances to the Earth. To do this, we perform many numerical models of the final giant impact phase of terrestrial planet formation. In these models, we impose primordial distributions of oxygen isotopes that are tuned to yield final $\delta^{17}\text{O}$ differences between fully formed Earth and Mars analogs that match the observed differences between the two planets. Using these distributions, we can then build a hypothetical distribution of $\delta^{17}\text{O}$ values for Theia analogs that can be used to assess the probability that Theia had a similar accretion feeding zone to the Earth.

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504.03 – Accretion and Core-Mantle Differentiation of the Earth and Other Terrestrial Planets

Using a multi-stage core-mantle differentiation model that incorporates over 250 Grand Tack N-body simulations, we have studied the growth of the Earth's mantle and core as well as those of Mars, Venus and the embryos, which impacted the Earth (i.e. the proto-lunar impactor Theia). The Grand Tack is the terrestrial planet formation scenario that most successfully matches dynamic and simple compositional constraints. During this scenario, Jupiter and Saturn migrate inwards and then outwards through the inner Solar System. The Earth grows due to the accretion of planetesimals and embryos from throughout the inner disk and from a disk of planetesimals exterior to Jupiter and Saturn, which are scattered inward by their migration. The core-mantle differentiation model uses chemical mass balance and metal-silicate element partitioning data to determine the mantle and core compositions as the Earth grows. Treating the initial oxidation state of the original bodies as free parameters, taking the composition of the Earth's primitive mantle as a constraint, and assuming that the non-volatile elements are present in Solar System (CI) relative abundances, we use least squares refinement to fit the metal-silicate equilibration pressure, the disequilibrium fraction of projectile cores and 4 parameters defining an initial oxidation gradient in the inner Solar System. Consistent with the Grand Tack scenario's explanation of the C-type asteroids originating from the outer Solar System, water is delivered from only these bodies.

We find that that the accreting Earth evolves in time—accreting increasingly oxidized material and changing the oxidation state of the Earth's mantle, and that the metal-silicate equilibration pressures are about 60-70% of the core-mantle boundary pressures and nearly all of the metal in each projectile core equilibrates with the some portion of the planet's silicate mantle. The best fits are found when the planetesimals and embryos closest to the Sun are highly reduced and those further out are increasingly oxidized. Venus is found to be very similar to the Earth, and the FeO content of the Martian mantle depends critically on the location of the original location of its stranded embryo nucleus.

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504.04 – Ceres: Its Origin and Predicted Bulk Chemical Composition

I explore the formation of Ceres in the framework of the Modern Laplacian theory of Solar System origin (MLT; Prentice 2006 PASA 23 1; 2008 LPSC, abs.1945.pdf). I suggest that all MB asteroids condensed within a gas ring cast off from the equator of the contracting protosolar cloud (PSC) near to the mean present orbit of Ceres. According to the MLT, the shedding of gas rings started at the orbit of Quaoar and comes about through supersonic turbulent stress due to powerful convective motions in the cloud. If the PSC contracts uniformly, the gas ring mean orbital radii R_n ($n = 0, 1, 2, \dots$) form a geometric sequence and their temperatures T_n scale nearly as $T_n \sim A/R_n$. The values of the mean ratio R_n/R_{n+1} and the constant A depend on the controlling parameters of the PSC. These are chosen so that the mean ratio $\langle R_n/R_{n+1} \rangle$ matches the observed mean planetary spacing and that the metal mass fraction ~ 0.71 of the condensate at Mercury's orbit yields a planet of mean density 5.43 g/cc. For Mercury, $T_n = 1638$ K and the gas pressure on the gas ring

mean orbit is 18 kPa.

For Ceres, $T_n = 272$ K and the gas pressure is 8.9 Pa. The condensate consists mostly of Mg-silicates & SiO₂ (mass fraction 0.394), magnetite (0.181), (Fe-Ni-Co)S (0.191), and brucite (0.127). The RTP mean density is 3.391 g/cc. If short-lived radionuclides cause dehydration of the rock and separation of rocks & metals to form a central core, the RTP density of the core is 3.662 g/cc and the mass fractions of separated water and NaCl are 0.04182 and 0.00153. All MB asteroids may initially have been ocean worlds. As T_n exceeds the brine freezing temperature 271 K, the water mantles remain liquid. Collisions between the asteroid embryos dislodge water from the smaller ones, so creating a liquid torus on the gas ring mean orbit. This water is then accreted by the largest embryos. A 4-zone model for Ceres (c) with mean density 2.08 g/cc has a rock (and inner metal) core of mass 0.732Mc, overlain by a 2.5 km thick salt layer and an outer pure ice mantle of mass 0.258 Mc. The MOI factor of this model is 0.295. Perhaps Dawn will find the surface of Ceres to be very flat, though roughened through aeons of impacts, with fresh craters having bright floors and ejecta.

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504.05 – Linking the formation of comets to their activity

Over the past years, several models of the formation of planetesimals have been developed. As the physical processes underlying these models are all well known, the resulting model planetesimals possess distinguishable physical properties. One of these properties is the tensile strength, which obtains values from <1 Pa to >1 kPa for the various formation models. Under the assumption that comets are leftover planetesimals, which never underwent excessive thermal or impact alterations, only those formation model that predict tensile strengths <1 Pa can account for the observed dust activity of comets. This means that comets most likely formed by dust and ice coagulation into cm-sized aggregates, which then underwent spatial concentration by, e.g., the streaming instability until they collapsed due to gravitational instability. This latter process is so gentle that the required low tensile strengths result.

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504.06 – Pebbles as Clues to Comet Formation

When the EPOXI spacecraft flew by Comet 103P/Hartley 2, it observed large particles floating around the comet nucleus (A' Hearn et al. 2011, *Science* 32, 6036). These particles are likely low-density, centimeter- to decimeter-sized ice balls (Kelley et al. 2013, *Icarus* 222, 2). While the nature of these particles remains somewhat mysterious, it is possible that they are giving us important information about the earliest stages of our Solar System's formation. Recent advancements in planet formation theory suggest that the initial planetesimals (or cometesimals) may grow directly from the gravitational collapse of aerodynamically concentrated small particles, often referred to as "pebbles" (Cuzzi et al. 2008, *AJ* 687, 1432, Johansen et al. 2007, *Nature* 448, 1022). Here we discuss the possibility that the observed particles are indicative of the pebbles from which the initial cometary bodies formed, and how we can use this idea to learn about protoplanetary disks and the early processes involved in planet formation. This work is supported by the Goddard Center for Astrobiology (a NASA Astrobiology Institute).

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504.07 – Global Evolution of Solids in the Nebula: Implications for Outer Solar System Composition

Observational constraints such as the the formation ages of primitive meteorites, and the duration of evolving "dusty-gas" protoplanetary nebulae has increasingly led us away from the oversimplified view that planetary formation occurs in a "minimum mass" nebula where the local temperature uniquely determines the chemistry through some invariable "cosmic abundance" in favor of a more dynamic picture in which mass concentration and composition evolves both locally and globally. Grain growth into larger aggregates can lead to radially inward drift of material over large distances. As migrating material moves from cooler to warmer regions, it may encounter an evaporation front (EF) where it may lose some or all of its "volatile" while passing through it. As more and more migrating material passes through an EF, the process of evaporation, diffusion and recondensation can lead to a systematic enhancement in the volatile species outside the EF. In a turbulent nebula, this can further lead to the enhancement of the outer regions of the disk through the diffusion of small grains that have been enriched in, or condensed from the volatile. The extent to which the outer regions can be enhanced compositionally depends on the strength of the turbulence. On the other hand, the amount of mass concentration that can occur outside an EF can vary from a factor of a few to over an order of magnitude depending on nebula conditions (e.g., larger enhancements can occur if a pressure bump or dead zone is present).

Here we perform simulations using our global nebula evolution code (e.g., Estrada and Cuzzi, 2014) to determine the

extent to which mass concentration can be enhanced outside a water-ice EF, and examine the implications for the compositional enhancement of the outer solar system. In particular, we wish to provide some insight for the existence of objects such as TNO 2002UX25 whose large size coupled with low density argues against macroporosity as a viable explanation for its low density (Brown, 2013).

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504.08D – The formation of Uranus and Neptune on the CO iceline

The formation mechanisms of the ice giants Uranus and Neptune, and the origin of their elemental and isotopic compositions, have long been debated. The density of solids in the outer protosolar nebula is too low to explain their formation, and spectroscopic observations show that both planets are highly enriched in carbon, very poor in nitrogen, and the ices from which they originally formed might had deuterium-to-hydrogen ratios lower than the predicted cometary value, unexplained properties observed in no other planets. Here we show that all these properties can be explained naturally if Uranus and Neptune both formed at the carbon monoxide iceline. Due to the diffusive redistribution of vapors, this outer region of the protosolar nebula intrinsically has enough surface density to form both planets from carbon-rich solids but nitrogen-depleted gas, in abundances consistent with their observed values. Water rich interiors originating mostly from transformed CO ices reconcile the D/H value of Uranus and Neptune's building blocks with the cometary value. Finally, Our scenario generalizes a well known hypothesis that Jupiter formed on an iceline (water snowline) for the two ice giants, and might be a first step towards generalizing this mechanism for other giant planets.

[1] Ali-Dib, M.; Mousis, O.; Petit, J.-M.; Lunine, J. I. *The Astrophysical Journal* (2014a, in press). arXiv:1407.2568

[2] Ali-Dib, M.; Mousis, O.; Petit, J.-M.; Lunine, J. I. *The Astrophysical Journal*, Volume 785, Issue 2, article id. 125, 7 pp. (2014b).

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504.09 – Overcoming the Meter Barrier and The Formation of Systems with Tightly-packed Inner Planets (STIPs)

The Kepler space mission has revealed numerous planetary types and systems, shaping our understanding of planet formation. Among the quickly-growing data is a subclass of multi-planet configurations referred to as Systems with Tightly-packed Inner Planets (STIPs). Their large abundance (>10% of stars) suggests that they are one of the principal outcomes of planet formation. The prototype STIP is Kepler-11, which hosts six known transiting planets, five of which have measured masses in the super-Earth and mini-Neptune regimes. The known planetary orbits in this system are spaced between $a=0.09$ and 0.47 AU, with small eccentricities and mutual inclinations. The lack of low-order mean motion resonances among planets in STIPs suggests that migration may have not played a dominant role in placing all of these planets on short orbital periods. While the formation of massive planetary systems on the hot side of the water ice line may be difficult to reconcile under the current paradigm of planet formation, we must explore whether many STIP planets formed by and large in situ. We discuss an overlooked mechanism that may allow the in situ formation of planetary systems on very short orbital periods. As solids spiral inward due to aerodynamic drag, they will enter disk regions that are characterized by high temperatures, densities, and pressures. High partial pressures of rock vapor can reduce net evaporation of incoming material, which could promote collisions between partially molten solids, allowing rapid growth and overcoming the classic meter barrier.

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505 – Uranus, Neptune, and Giant Planet Interiors from Juno and Cassini

505.01 – Ten years of Cassini Discoveries in the Saturn System and More Excitement to Come

Cassini's findings have revolutionized our understanding of Saturn, its complex rings, the amazing assortment of moons and the planet's dynamic magnetic environment. The robotic spacecraft arrived in 2004 after a 7-year flight from Earth, dropped a parachuted probe named Huygens to study the atmosphere and surface of Saturn's big moon Titan, and commenced making astonishing discoveries that continue today. Icy jets shoot from the tiny moon Enceladus; Titan's hydrocarbon lakes and seas are dominated by liquid ethane and methane, and complex pre-biotic chemicals form in the

atmosphere and rain to the surface; 3-dimensional structures rise above Saturn's rings, and a giant Saturn storm circled the entire planet. Cassini's findings at Saturn have also fundamentally altered many of our concepts of how planets form around stars.

The Solstice Mission continues to provide fundamental new science as Cassini observes seasonal and temporal changes, and addresses new questions that have arisen during the mission thus far. Cassini is now 4 years into its 7-year Solstice Mission. The mission's grand finale occurs in 2017, with 22 inclined orbits between the innermost D ring and the upper portions of Saturn's atmosphere, enabling unique gravity and magnetic field measurements of the planet, unprecedented determination of the ring mass, some of the highest resolution measurements of the rings and Saturn, and in situ observations in a completely new region around the planet. Highlights from 10 years of Cassini's ambitious inquiry at Saturn will be presented along with the remarkable science that will be collected in the next three years.

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505.02 – Inversion of Jupiter and Saturn gravity field into the atmospheric circulation on these planets - using the gravity measurements by Juno and Cassini and an adjoint based dynamical model

In approximately two years Juno and Cassini will both perform close flybys of Jupiter and Saturn respectively, obtaining a high precision gravity spectrum for these planets. This data can be used to estimate the depth of the observed flows on these planets. Here we use a hierarchy of dynamical models in order to relate the three dimensional flow to perturbations of the density field, and therefore to the gravity field. The models are set up to allow either zonal flow only, or a full horizontal flow in both zonal and meridional directions based on the observed cloud-level winds. In addition, dynamical perturbations resulting from the non-spherical shape of the planets are accounted for. In order to invert the gravity field to be measured by Juno and Cassini into the 3D circulation, an adjoint inverse model is constructed for the dynamical model, thus allowing backward integration of the dynamical model. This tool can be used for examination of various scenarios, including cases in which the depth of the winds depends on latitudinal position. We show that given the expected sensitivities of Juno and Cassini, it is possible to use the gravity measurements to derive the depth of the winds, both on Jupiter and Saturn. This holds for a large range of zonal wind possible penetration depths, from ~100km to ~10000km, and for winds depth that vary with latitude. This method proves to be useful also when incorporating the full horizontal flow, and thus taking into account gravity perturbations that vary with longitude. We show that our adjoint based inversion method allows not only to estimate the depth of the circulation, but allows via iterations with the spacecraft trajectory estimation model to improve the inferred gravity field.

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505.03 – Validity of the "Laplace Swindle" in Calculation of Giant-Planet Gravity Fields

Jupiter and Saturn have large rotation-induced distortions, providing an opportunity to constrain interior structure via precise measurement of external gravity. Anticipated high-precision gravity measurements close to the surfaces of Jupiter (Juno spacecraft) and Saturn (Cassini spacecraft), possibly detecting zonal harmonics to J10 and beyond, will place unprecedented requirements on gravitational modeling via the theory of figures (TOF). It is not widely appreciated that the traditional TOF employs a formally nonconvergent expansion attributed to Laplace. This suspect expansion is intimately related to the standard zonal harmonic (J-coefficient) expansion of the external gravity potential. It can be shown (Hubbard, Schubert, Kong, and Zhang: Icarus, in press) that both Jupiter and Saturn are in the domain where Laplace's "swindle" works exactly, or at least as well as necessary. More highly-distorted objects such as rapidly spinning asteroids may not be in this domain, however. I present a numerical test for the validity and precision of TOF via polar "audit points". I extend the audit-point test to objects rotating differentially on cylinders, obtaining zonal harmonics to J20 and beyond. Models with only low-order differential rotation do not exhibit dramatic effects in the shape of the zonal harmonic spectrum. However, a model with Jupiter-like zonal winds exhibits a break in the zonal harmonic spectrum above about J10, and generally follows the more shallow Kaula power rule at higher orders. This confirms an earlier result obtained by a different method (Hubbard: Icarus 137, 357-359, 1999).

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505.04 – Saturn Ring Seismology: Evidence for Stable Stratification in the Deep Interior of Saturn

Seismology allows for direct observational constraints on the interior structures of stars and planets. Recent observations of Saturn's ring system have revealed the presence of density waves within the rings excited by oscillation

modes within Saturn, allowing for precise measurements of a limited set of the planet's mode frequencies. We construct interior structure models of Saturn, compute the corresponding mode frequencies, and compare them with the observed mode frequencies. The fundamental mode frequencies of our models match the observed frequencies (of the largest amplitude waves) to an accuracy of roughly one percent, confirming that these waves are indeed excited by Saturn's f-modes. The presence of the lower amplitude waves (finely split in frequency from the f-modes) can only be reproduced in models containing gravity modes that propagate in a stably stratified region of the planet. The stable stratification must exist deep within the planet near the large density gradients between the core and envelope. Our models cannot easily reproduce the observed fine splitting of the $m=-3$ modes, suggesting that additional effects (e.g., significant latitudinal differential rotation) may be important.

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505.05 – Unusual activity in the atmosphere of Uranus in 2014

Uranus continues to evolve as it progresses through the post-equinoctial season. Images taken on 5 and 6 August 2014 at the 10-m Keck 2 telescope show significant atmospheric activity in the planet's northern (currently sun-facing) hemisphere. Although Keck's adaptive optics system was underperforming (resulting in artifacts and some blurring), many discrete features were visible on the planet at H (1.6 microns) and K' (2.2 microns). Many of these features reached altitudes above the 1-bar level, as evidenced by their detection at K'. One feature breaks the record as the brightest ever detected on Uranus at K', producing 30% of the total light reflected by the planet in that filter, compared to 12% for the previous record in 2005 (Sromovsky et al., *Icarus* 192, 558-575, 2007). The 2014 feature's morphology was similar at both K' and H, suggestive of an underlying vortex (e.g., Hammel et al., *Icarus* 201, 257-271, 2009). However, the feature's brightest region in K' is not particularly bright in H; i.e., although it is relatively high in altitude, it does not have a high optical depth. The total light fraction at H is only 2-3%, compared to the 4-5% found for the 2005 feature. Thus, its visible-wavelength contrast may be low; this could explain why there have been no amateur follow-up detections as of this writing. The new images also reveal development of a long-expected north polar haze as well as polar cloud features. Interestingly, some discrete polar features were visible through the polar haze. This may indicate that the northern polar haze is not yet at an optical depth comparable to that of the fully-formed southern polar haze seen in pre-equinoctial years. Acknowledgements: the data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among Caltech, University of California and NASA, and was made possible by the generous financial support of the W.M. Keck Foundation. The authors acknowledge the significant cultural role of Mauna Kea's summit, and extend thanks to those of Hawaiian ancestry on whose sacred mountain we are privileged to be guests.

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505.06 – Uranus' Southern Circulation Revealed by Voyager-2 Images: Asymmetric, Unique, Unexpected

The southern half of Uranus' southern hemisphere of Uranus has been exceptionally bland. Only a single discrete feature was detected in Voyager-2 images, and none has been seen in thousands of HST and ground-based images since. All other observed regions on Uranus and jovian planets have many features that defined circulation patterns of the jovian planets, but the circulation of Uranus south of -45 deg latitude has been unknown.

We performed a reanalysis of Voyager images of Uranus that revealed dozens of discrete features instead of the single feature known before. We improved flatfielding, pad-pixel treatment, and nonlinearity correction. We greatly decreased noise by averaging up to 1600 images. The result is a rotational profile without major gaps.

Uranus' high southern latitudes are exceptional in several aspects: 1) The rotational profile has sharp kinks while it is smooth elsewhere on the ice giants. This puts current ideas of a simple Hadley cell on each hemisphere into question. 2) The rotational profile has a large north-south asymmetry, an order of magnitude larger than elsewhere on the jovian planets. 3) Between -68 and -59 deg latitude, the rotational shear is some 30 times lower than at other latitudes. Here, wind speeds around 200 m/s are regular to the 0.1 m/s level. 4) The South Pole had a spot off center rotating 5 h faster than the interior, which has not been observed elsewhere on jovian planets. 5) Uranus revealed spirals winding around the whole planet more than once that indicate very regular meridional motions, to the 2 cm/s level. 6) The latitude at -84 deg was featureless even at a signal-to-noise ratio of 55,000, one of the blandest zones in nature.

Some features show significant evolution within the 5-week observing period providing constraints on dynamics.

Features also show distinct spectral characteristics in the 8-filter data set providing constraints on the physical nature of features and their altitude. We have the data to understand Uranus' unique southern hemisphere. More can be done in the future than during the past 28 years of the data's existence.

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505.07 – Models for Temperature and Composition in Uranus from Spitzer, Herschel and Ground-Based Infrared through Millimeter Observations

Photometric and spectroscopic observations of Uranus in the thermal infrared were combined to create self-consistent models of its global-mean temperature profile and vertical distribution of gases. These were derived from a suite of observations from Spitzer and Herschel, together with ground-based observations from UKIRT, CSO, Gemini, VLT and Subaru. Observations of the collision-induced absorption and quadrupoles of H₂ have constrained the temperature structure for pressures of nearly 2 bars down to 0.1 millibars. We coupled the vertical distribution of CH₄ in the stratosphere of Uranus with models for the vertical mixing in such a way to be consistent with the mixing ratios of hydrocarbons. Spitzer and Herschel data constrain the abundances of CH₃, CH₄, C₂H₂, C₂H₆, C₃H₄, C₄H₂, H₂O and CO₂. The Spitzer IRS data, in concert with photochemical models, show that the homopause is at much higher atmospheric pressures than for the other outer planets, with the predominant trace constituents for pressures lower than 30 μ bar being H₂O and CO₂. The ratio of the oxygen-bearing molecules is consistent with exogenic origins in KBOs or comets. At millimeter wavelengths, there is evidence that an additional opacity source is required besides the H₂ collision-induced absorption and the NH₃ absorption needed to match the microwave spectrum; this can reasonably (but not uniquely) be attributed to H₂S. This model is of ‘programmatic’ interest because it serves as a standard calibration source; the cross-comparison of its spectrum with model spectra for Mars and Neptune shows consistency to within 3%. Near equinox, the IRS spectra at different longitudes showed rotationally variable stratospheric emission that is consistent with a temperature anomaly \sim 10 K near \sim 0.1-0.2 mbar. Spatial variability of tropospheric temperatures observed in ground-based observations from 2006 to 2011 is generally consistent with Voyager infrared (IRIS) results.

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505.08 – Time variability of Neptune’s horizontal and vertical cloud structure revealed by VLT/SINFONI and Gemini/NIFS from 2009 to 2013

New observations of Neptune’s clouds in the near infrared were acquired in October 2013 with SINFONI on ESO’s Very Large Telescope (VLT) in Chile. SINFONI is an Integral Field Unit spectrometer returning a 64x64 pixel image with 2048 wavelengths. Image cubes in the J-band (1.1 – 1.41 micron) and H-band (1.43 – 1.87 micron) were obtained at spatial resolutions of 0.1” and 0.025” per pixel, while SINFONI’s adaptive optics provided an effective resolution of approximately 0.1”. Image cubes were obtained at the start and end of three successive nights to monitor the temporal development of discrete clouds both at short timescales (i.e. during a single night) as well as over the longer period of the three-day observing run. These observations were compared with similar H-band observations obtained in September 2009 with the NIFS Integral Field Unit spectrometer on the Gemini-North telescope in Hawaii and previously reported by Irwin et al., *Icarus* 216, 141-158, 2011.

We find both similarities and differences between these observations, spaced by four years. The same overall cloud structure is seen with high, bright clouds visible at mid-latitudes (20-40°N, S); with slightly lower transient clouds at the equator; together with small discrete clouds seen circling the pole at a latitude of approximately 60°S. However, while discrete clouds were visible at this latitude at both the main cloud deck level (at 2-3 bars) and in the upper troposphere (100-500mb) in 2009, no clear deep, discrete circumpolar clouds were visible in 2013. The nature of these deep circumpolar discrete clouds is intriguing. While it is possible that in 2013 these deeper clouds were masked by faster moving, overlying features, we consider that it is unlikely that this should have happened in 2013, but not in 2009 when the upper cloud activity was generally similar. Hence, these observations may have detected a real temporal variation in the occurrence of Neptune’s deep clouds, pointing to underlying variability in the convective activity at the pressure of the main cloud deck at 2-3 bars near Neptune’s south pole.

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505.09 – A Deep-Seated Ocean in Uranus and Neptune

Recent phase diagram data (Bali et al, 2013) suggest that the hydrogen-helium adiabat for Uranus and Neptune crosses the condensation curve for water twice: First, high up, for the usual water clouds, and second, deep down (but way above the putative superionic phase, which this paper is not concerned with). This deeper crossing, at pressure of a few GPa, will be a discontinuity in density with a water saturated hydrogen-helium mixture above and a hydrogen-saturated weakly ionic water layer below. No other choice is plausible given the need to satisfy the mean density and gravity of these planets, though many of the details are uncertain. The fundamental origin of this phenomenon lies in the well-known increased ionicity of water with pressure, which is antagonistic for any non-polar species, notably hydrogen, all noble gases, and methane. But hydrogen, being most dominant, determines the location of phase separation and all the other species will then partition so that the atmosphere will be mildly enriched in helium, for example (relative to solar hydrogen/helium), a prediction that is not violated by current data. Importantly, this ocean surface removes much of the present ambiguity of interior models (which do not at present make any attempt to understand how the water is distributed based on thermodynamic constraints). It also removes some ambiguity in thermal evolution models, since the cooling in the outer regions over billions of years will be accompanied by precipitation of water and latent heat release. The deep interior of the planet is likely not participating much in the cooling, and the dynamo magnetic field is sustained by a quite low heat flux (as scaling laws permit.) The difference between Uranus and Neptune in heat flow is primarily a consequence of initial conditions and not a direct outcome of these considerations. Exoplanets including subNeptunes will be strongly affected by the considerations described here.

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506 – Asteroid Physical Characterization 4: Colors and Composition

506.01 – Space Weathering in Olivine and the Mineralogy of (Some) M-Class Asteroids

One aspect of space weathering of airless bodies is the production of nanophase iron (npFeO) from Fe bearing silicate minerals. The combined effects of low oxygen fugacity and solar-wind implanted H tend to result in strongly-reduced surfaces that can be chemically activated by heating due to micrometeorite impacts. The mineral kinetics of olivine makes it particularly vulnerable to reduction, decomposition, and npFeO production. Kohout et al. has recently developed a new method of controlled npFeO production on olivine powder grains that mimics the essential features of this weathering process and was developed to quantitatively evaluate spectral changes related to space weathering and presence of npFeO. Compared to fresh olivine the treated samples exhibit spectral characteristics of space weathering including spectral darkening, shallowing and attenuation of 1 μm olivine absorption band, and reddening. The attenuation of the 1 μm band significantly shrinks the band FWHM and shifts the much reduced band center to shorter wavelengths around 0.95 μm . These spectral changes are related to increasing amounts of npFeO and the disruption of the crystal structure of the parent olivine.

Significantly, the darkened, reddened, and band attenuated olivine spectra are a close match to a number of M-class asteroids. What is particularly interesting is the match with the weak absorption band near 0.95 μm seen in many M-class asteroids (i.e. 16 Psyche, 22 Kalliope, 55 Pandora to name a few). One of the major issues in asteroid science is the relative scarcity of olivine asteroids (the "Great Dunite Shortage" coined by Bell et al in Asteroids II). One possibility worth further study is that asteroidal olivine may be hidden by the relative ease with which it weathers. The surface chemical and micrometeorite environment in the asteroid belt may produce over time a spectrum for an olivine-rich surface that is remarkably similar to that of an M-class asteroid.

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506.02 – Can We Distinguish Between Shock-Darkened and Space-Weathered Asteroids?

Both lunar-type space weathering and impact shock-darkening are capable of significant darkening of asteroid spectra. Thus, question arises – are we able to distinguish between these processes from asteroid reflectance spectra? The Chelyabinsk meteorite represents unique opportunity with delivery of large amount of meteorite material of various shock levels. The basic three lithologies include (1) slightly shocked light-colored lithology, (2) partly molten shock-darkened dark-colored lithology, and (3) entirely molten impact melt lithology. In order to compare shock effects to space weathering, the light-colored lithology was subjected to simulated space weathering and the spectral changes were compared to mixtures of the light-colored and shocked materials. Results indicate that shocked material shows no significant spectral slope change while both 1 and 2 μm bands are progressively reduced with a nearly constant depth ratio. In contrast, the space weathering causes a strong increase in spectral slope. Also, the ratio of 2 μm band depth to 1 μm band depth is progressively increasing with amount of space weathering, most likely due to higher resistance of

pyroxene to space weathering compared to olivine. This is also seen in the principal component space by DeMeo et al. 2009. Fresh light-colored lithology plots into Q-type field. Both space-weathered and shocked materials show reduction in PC1' component related to decrease in 1 μm band depth. However, the addition of shocked material causes also significant reduction in PC2' component related to decrease in 2 μm band depth and transition from the Q-type field across alpha line into C/X complex. In contrast space-weathered material shows smaller PC2' component changes and moves along alpha line towards S-type field. Thus, 1 and 2 μm band depth ratio or PC2'/PC1' ratio together with spectral slope may be indicator of shock darkening vs. space weathering in (ordinary chondrite) asteroid spectra.

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506.03 – New Results on Hydration in M-Type Asteroids

The M-type asteroids are a taxonomic group considered to be a candidate source of iron meteorites due to spectral and albedo similarities; however, because the spectra of M-type asteroids lack strong diagnostic absorption features in the near-infrared (NIR), their composition is difficult to constrain. High-resolution NIR spectroscopy and radar studies have shown that a metallic interpretation is unlikely to be valid for the majority of M-types. Many show weak absorption features attributed to mafic silicates (Hardersen et al. 2005, 2011; Ockert-Bell et al. 2010; Fornasier et al. 2010). Radar results show evidence for elevated metal content on the surfaces of most M-type asteroids, but few are likely to be entirely metal (Shepard et al. 2010). Surprisingly, spectrophotometric studies in the 3- μm region have indicated that hydrated minerals are relatively common among the M-type population, confounding interpretations of M-types as highly thermally processed (Rivkin et al. 1995, 2000). The shape of the 3- μm band, diagnostic of hydrated and hydroxylated minerals, is relevant to an asteroid's thermal history (Rivkin et al. 2002, Takir & Emery 2012). To characterize this region, we have conducted a 2 – 4 μm spectroscopic study of six M-type asteroids using SpeX at NASA's Infrared Telescope Facility. In its LXD mode, SpeX allows us to investigate the 3- μm band at spectral resolutions unavailable during previously published studies. We report the presence of a 3- μm feature on all six asteroids, indicating hydrated minerals on the asteroids' surfaces. We have also detected rotational variability of the 3- μm feature in asteroid (216) Kleopatra, which, interestingly, had been interpreted as "dry" in previous work (Rivkin et al. 2000). On all of our target asteroids, the 3- μm band depths are < 10%, and there is apparent variation in the shape of the feature among them. We discuss the impact of our results on interpretations of M-type asteroid composition.

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506.04 – The Surface Composition of the Asteroid (21) Lutetia From HST/STIS Observations in the Near Ultraviolet

The asteroid (21) Lutetia, is one of the largest in the main belt, with dimensions of 121x101x75 km along its principal axes of inertia. On July 10, 2010, four years before its arrival at comet 67P/Churyumov-Gerasimenko, ESA's Rosetta spacecraft passed within 3168 +/- 7.5 km of Lutetia's surface. However, even after the Rosetta flyby, fundamental uncertainties remain about the composition of Lutetia's surface. The primary reason for this is that from visible to millimeter wavelengths, Lutetia's reflectance spectrum is almost completely devoid of absorption features and contains nothing that can uniquely constrain its surface composition. The scientific literature is now split with about half advocating an enstatite chondrite composition and half a carbonaceous chondrite composition. Although these materials look similar in the visible/IR, they have markedly different appearances in the NUV. We acquired spectra of the northern hemisphere of (21) Lutetia from 180-570 nm over four consecutive orbits of HST on March 23, 2014. We present results from these observations and explain how they constrain Lutetia's surface composition.

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506.05 – Pyroxene Spectroscopy: Remote Characterization of Composition, Structure and Thermal History

Pyroxene is one of the most commonly used minerals for remote analysis of mineralogy and composition of planetary bodies. This is in part due to the prevalence of pyroxene on the surfaces of objects in the inner solar system. Pyroxene also exhibits a distinctive spectrum that is highly sensitive to its specific composition, structure, and cation site occupancy. Cation ordering, which is partially a result of the cooling history of a pyroxene, affects the strengths of

absorptions caused by Fe²⁺ in the M1 and M2 cation sites, which in turn affects the relative band 1 and band 2 areas. Terrestrial pyroxenes are generally quite well-ordered, as many have been exposed to and held for long times at temperatures warm enough to allow cations to exchange between the M1 and M2 sites. Extraterrestrial pyroxenes have been exposed to a vast array of cooling regimes, including flash heating and cooling in the protoplanetary disk, impact brecciation and melting, and more traditional igneous processes.

To push pyroxene spectroscopy beyond simple mineral identification and develop it as a tool for characterizing the thermal history of a body, we have been working to characterize and document the crystal chemistry, structure, and site occupancies of a suite of 91 synthetic pyroxenes. This is accomplished by measuring single-crystal XRD, Attenuated Total Reflectance (ATR) and electron probe microanalysis (EMP), variable-temperature Mössbauer and Raman spectra. For each of the samples, visible-far IR spectra have also been collected. We will present the results of this integrated study, focusing on how the crystal structure, composition and site occupancy in pyroxenes is reflected in their visible-infrared spectra and how they can be used to evaluate the thermal history of asteroids and the Moon.

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506.06 – Medium Rare or Well Done? Asteroid Melting in the Hungaria Region

The Hungaria region is located interior to the Main Belt and contains ~12,000 small asteroids (D <11 km). The region is inhabited by the Hungaria family of mainly Xe-type asteroids, which comprises a significant fraction of the regional population. However, this family is situated among a spectrally diverse asteroid background. Among the asteroids with semi-major axes interior to the Main Belt (e.g., Hungarias, Mars-crossers, and near-Earth asteroids), only Hungarias are located in relatively stable orbital space. Therefore, these objects may represent the closest remaining reservoir of the material that accreted to form the terrestrial planets. Deciphering the mineralogy of the Hungaria asteroids may place constraints on the nature of this material.

Partially-melted or differentiated bodies that originated in the terrestrial planet region were either accreted or scattered out of this region early in solar system history. We hypothesize that planetesimals in the inner part of the solar nebula (terrestrial planet region) underwent significant melting - the Hungaria region should retain this petrologically-evolved material. We test this hypothesis by performing detailed spectral band parameter analyses on Hungaria asteroid spectra and on primitive achondrite meteorite spectra obtained from the RELAB database.

Through an ongoing near-infrared survey of Hungaria asteroids at the IRTF and TNG telescopes we have acquired a spectral sample of 36 objects (32 background, 4 family). Preliminary results indicate a compositionally diverse background population dominated by S- and S-subtypes (23 out of 32). Band parameter analyses of 19 of these S-types show that two main meteorite groups appear to be represented, unmelted ordinary chondrites; and partially-melted primitive achondrite meteorites acapulcoites/lodranites. Furthermore, three of four family members are X-types, likely consistent with the largest collisional fragment 434 Hungaria. Xe-subtypes in the Hungaria region are thought to be related to fully-melted enstatite achondrite meteorites (i.e., aubrites). These spectral comparisons suggest that at least some objects in the Hungaria region have experienced low- to high-degrees of petrologic evolution.

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506.07 – Mineralogy of dark asteroids: Detection of phyllosilicate features in the mid-infrared

Dark asteroids (C- and related types) have been shown to have phyllosilicates on their surfaces by the presence of the 0.7- μ m charge transfer band in the visible/near-infrared (VIS/NIR) spectral region (e.g. [1], [2]). Observations of asteroids in the 2.5-5- μ m have also indicated the presence of water [3, 4] and phyllosilicates [5, 6]. Phyllosilicates also have spectral features in the 8-30- μ m [7]. The results of a coordinated spectral-mineralogical study of aqueously altered meteorites [8] can be used to both remotely identify the presence of aqueous alteration and determine the degree of alteration on asteroids. Two main regions have strong features related to the mineralogy and degree of alteration: the 10-13- μ m and the 16-25- μ m region. Alteration features change continuously in these regions between less (~60%) and highly (~90%) altered meteorites. These features have been identified in the spectra of some dark asteroids [8, 9, 10]. Additionally, no trends are found between 0.7- μ m charge transfer band and degree of alteration. While all meteorites with a 0.7- μ m band have phyllosilicates, the absence of a 0.7- μ m band is not indicative of the absence of alteration. Altered meteorites always exhibit MIR features that are directly related to their degree of alteration whether or not they have a 0.7- μ m band. Here, we present preliminary results of a survey of archived Spitzer Space Telescope data of asteroids in the 10-13- μ m region and the 16-25- μ m region (where data is available) including comparisons to published

VIS/NIR spectra of the same dark asteroids without VIS/NIR features. Possible effects in comparing laboratory measurements of meteorite powders under ambient conditions to telescopic spectra of asteroid regoliths are considered.

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506.08 – The Colors of Hilda Group Asteroids: Complications For Use in Testing Dynamical Models

Hilda group asteroids are in a stable 3:2 resonance with Jupiter which may have been reshaped by giant planet migration in the early epochs of solar system formation. Although the population is currently dynamically stable, the dynamics of this population suggest at minimum an inward migration of Jupiter by ~ 0.4 AU (Franklin et al. 2004, *AJ*, 128, 1391). As this population of objects is relatively isolated, compositional types can be used to test dynamical models such as the Grand Tack and Nice Model which suggest that objects of outer solar system (beyond Saturn) origin would be found in the Hilda population. We have undertaken a multi-year observational program at the 2.3-m Bok Telescope to obtain compositional types for a large sample of Hilda group asteroids. With a preliminary sample of ~ 400 objects from our observations and the literature, we find complications for direct compositional tests of the giant planet migration models. Specifically, we find that the two dynamical families within the Hilda group, Schubart and Hilda, have disparate dynamical ages (1.7 ± 0.7 Gyr vs > 4 Gyr ; Broz & Vokrouhlicky 2008, *MNRAS*, 390, 715) but similar colors not seen elsewhere in the Hilda group population. This suggests dynamical family members should be removed from samples when using Hilda group asteroid compositions as a test of giant planet migration models. This research was supported by an appointment to the NASA Postdoctoral Program at Goddard Space Flight Center, administered by Oak Ridge Associated Universities through a contract with NASA. This work also funded by NASA Planetary Astronomy Grant NNX13AJ11G.

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506.09 – Shape and Size of Patroclus and Menoetius from a Stellar Occultation

We will present results of a stellar occultation by the Jupiter Trojan asteroid, Patroclus and its nearly equal size moon, Menoetius. The occultation was observed widely across the United States on 2013 Oct 21 UT. Eleven sites out of 36 successfully recorded an occultation. Seven chords across Patroclus yielded an elliptical limb fit of 124.6 km by 98.2 km. There were six chords across Menoetius that yielded an elliptical limb fit of 117.2 km by 93.0 km. There were three sites that got chords on both objects. At the time of the occultation we measured a separation of 0.247 arcsec and a position angle for Menoetius of 265.7 deg measured eastward from J2000 North. More surprisingly, there were two sites that should have seen an occultation by Menoetius but instead never saw the star disappear. These two non-detections indicate the presence of a large void on the southern limb of the satellite. The observations are consistent with a large impact basin centered on the rotation pole. The depth of the projected crater profile is roughly 15 km, measured from the elliptical limb profile. The inferred diameter of the crater would be about 85 km. Combining this occultation data with previous lightcurve data, the axial ratios (ignoring the mass void) of both objects is 1.26:1.19:1 indicative of a mostly oblate ellipsoid with a slight asymmetry in its equatorial projection. These results are consistent with a fully tidally evolved system with the mass void or putative crater in a position consistent with principal axis rotation that is itself consistent with the largely oblate shape. Note: the location for IOTA listed in the affiliations is not correct (but was required to be entered) as there is no location for this global virtual organization. This research is funded, in part, by NSF AST-1212159.

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507 – TNOs and Centaurs: Populations and Dynamics

507.01 – OSSOS: The Outer Solar System Origins Survey

We present the first detection set from the Outer Solar System Origins Survey (OSSOS) which is a mammoth 560-hour CFHT Large Program over 4 years (finishing January 2017). This is likely to be the largest Kuiper Belt survey before LSST comes on line (in terms of the number of precise transneptunian object (TNO) orbits it provides).

OSSOS studies gradually-slewing 21-square degree blocks of sky that are repeatedly imaged in many dark runs over two semesters. This strategy is designed to detect and track TNOs in order to provide extremely high-quality orbits in a short amount of time; in 16-18 month arcs we are obtaining fractional semimajor axis uncertainties in the range 0.01-0.1% and accuracies in the libration amplitudes of resonant objects better than 10 degrees, due to mean astrometric residuals routinely being of order 50-100 milliarcseconds.

This talk will present the survey design and full detection sample for objects observed in the first half of 2013 and 2014. We will report how adding these detections to those from the Canada-France Ecliptic Plane Survey (CFEPS) modifies conclusions about the orbital and size distribution of main classical Kuiper Belt, as well as other non-resonant sub-populations. In particular, because OSSOS is sensitive to, and has detected objects, from 8 AU to beyond 60 AU, we will report on how the combined distance and magnitude distribution impact discussions of the absolute magnitude distribution of outer Solar System objects.

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Contributing team(s): OSSOS Collaboration

507.02 – Preliminary models of the resonant trans-Neptunian populations from the Outer Solar System Origins Survey

The dynamical history of the solar system's giant planets left its signature in the orbital distribution trans-Neptunian objects (TNOs). In particular, the population of resonant TNOs is crucial to understanding Neptune's orbital evolution in the early solar system. Resonant TNOs are subject to complicated detection biases, so estimating the intrinsic resonant TNO population from observations requires a well-characterized survey. We present preliminary models and population estimates for the resonant TNOs based on detections from the first 25% of the Outer Solar System Origins Survey (OSSOS, see abstract by Gladman et al). We discuss small improvements that need to be made to the Canada-France Ecliptic Plane Survey models for the 3:2, 2:1, and 5:2 resonances (Gladman et al 2012) in order to match the full data set. We will discuss some puzzles in the orbital distributions inside of these resonances which appear to be increasingly statistically significant. We demonstrate improvements in the 3:2 resonance mode that will be possible with future OSSOS observations which are expected to increase the total number of well-characterized 3:2 objects by a factor of a few over the Canada-France Ecliptic Plane Survey. The improved resonance models from OSSOS will be a useful lever arm on the processes by which the resonances were filled.

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507.03 – The Effect of Dwarf Planets on the Dynamics of the Kuiper Belt

With the use of N-body and steady potential simulation, we have explored the dynamical effect of dwarf planets and large minor bodies of the outer solar system, in the currently well known objects (cometary nuclei) of the Kuiper Belt. To this purpose we have employed the Mercury 6.2 code to conduct the simulations including all the known large bodies in the Kuiper belt, and a simpler steady potential to perform a statistical analysis on the number and orbital characteristics of a dwarf planet hypothetical system in the KB. We present preliminary results of studies on the chaotic nature with different diagnostic tools. We find that, although small, the effect produced by the presence of dwarf planets on the classical KB bodies, might be significant in the long-term evolution, even producing the onset of chaos for some regions of the phase space in the KB classic objects.

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507.04 – The 5:1 Neptune Resonance: Dynamics and Population

Based on 4 objects detected with semi-major axes near the 5:1 external resonance with Neptune, we estimate a substantial and previously unrecognized population of objects, perhaps more significant than the 3:2 (Plutino) resonance population. These external resonances are largely unexplored in both observations and dynamical

simulations. However, understanding the characteristics and trapping history for objects in these populations is critical for constraining the dynamical history of the solar system. The 4 objects detected in the Canada-France Ecliptic Plane Survey (CFEPS) were classified using dynamical integrations. Three are resonant, and the last appears to be a resonant drop-off. The 3 objects are taken to be representative of the steady-state population, so by using these detections and the CFEPS characterization (pointings and detection limits) we calculate a population estimate for this resonance at $\sim 3000(+5000 - 2000)$ with $H_g < 8$. This is at least as large as the Plutinos (3:2 resonance) at 90% confidence. The small number of detected objects results in such a large population estimate due to the numerous biases against detecting objects with semimajor axes at 88AU. Based on the dynamical behavior of the known objects, the trapping mechanism for the 5:1 resonance appears to be resonance sticking from the scattering objects. The long resonance lifetimes of some dynamical clones suggests that a steady state population could be maintained through periodic sticking.

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507.05 – All Bright Cold Classical KBOs are Binary

When sorted by absolute magnitude as seen in ground based observations, an extremely high fraction of the brightest Cold Classical (CC) Kuiper Belt objects (KBO) are, in fact resolved as binaries when observed at higher angular resolution. Of the 22 CCs brighter than $H=6.1$ observed by HST, 16 have been found to be binary yielding a binary fraction of $73 \pm 10\%$. When low inclination interlopers from the hot population and close binaries are considered, this very high fraction is consistent with 100% of bright CCs being binary. At fainter absolute magnitudes, this fraction drops to $\sim 20\%$. Such a situation is a natural outcome of a broken size distribution with a steep drop-off in the number of CCs with individual component diameters larger than 150 km (for an assumed albedo of 0.15). A sharp cutoff in the size distribution for CCs is consistent with formation models that suggest that most planetesimals form at a preferred modal size of order 100 km.

The very high fraction of binaries among the largest CCs also serves to limit the separation distribution of KBO binaries. At most, 27% of the brightest CCs are possible unresolved binaries. The apparent power law distribution of binary separation must cut off near the current observational limits of HST (~ 1800 km at 43 AU). It is worth noting, however, that this observation does not constrain how many components of resolved binaries may themselves be unresolved multiples like 47171 1999 TC36.

Finally, it is important to point out that, when sorted by the size of the primary rather than absolute magnitude of the unresolved pair, the fraction of binaries is relatively constant with size (Nesvorny et al. 2011, AJ 141, 159) eliminating observational bias as cause of the pile up of binaries among the brightest Cold Classical Kuiper Belt objects. The very high fraction of binaries among the brightest CCs appears to be an effect of the underlying CC size distribution.

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507.06 – Towards a Model of the Trans-Neptunian Binary Population

The trends of binary properties across all classes of trans-Neptunian Objects and all size and separation regimes provide important constraints on the dynamical environment and history of the outer Solar System. To date, no population model has been developed, tested, and published that simultaneously considers binary mutual orbit distributions, component size ratios, photometric colors, and conditional occurrence frequency depending on primary size and host population. Here I present the first efforts to develop such a model, and apply it to existing catalogs of trans-Neptunian binaries to extract new estimates of the characteristics of this valuable population.

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507.07 – A Precise Description of the Hot Classical Belt from the High Latitude Ecliptic Survey

The Canada-France Ecliptic Plane Survey (CFEPS) determined the orbital structure of the Cold classical belt, a component restricted to the semimajor-axis range between the 3:2 and 2:1 mean motion resonances with Neptune. It also showed that the high-inclination component of the inner, main and outer belt form a continuous population, but failed to constrain the inclination distribution itself.

The High Latitude survey (HiLat) covered 600 sq.deg. from 15 to 90 deg. ecliptic latitude to address this question. We find that the Brown-like gaussian inclination distribution for each survey separately requires incompatible width of the distribution. Rather, it appears that a gaussian centered on a high (10 to 15 deg.) latitude, $\{it \ `a \ la\}$ Gulbis et al. (2010) provides a better match to the observations. We also confirm that the resonant populations have an inclination distribution compatible with a common origin with the Hot component. The hot component itself comes from a

constraint q range ($35 < q < 41$ AU) slightly larger than what some researchers associated with the scattered disk. This enlarged q range places constraints on the eccentricity reached by Neptune in its early history and the duration of this phase.

With this more accurate orbital distribution and a refined modelling of the surveys, we present new population estimates of the various populations.

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Contributing team(s): CFHT QSO Team

507.08D – On the high inclination KBOs common dynamical formation

The Kuiper belt is a dynamically intriguing region. Different "classes" of objects can be defined, according to their orbital properties. These are: the classic belt (with the subclasses of cold & hot objects), resonant objects, scattered disk and extended scattered disk. In this work, we seek to investigate possible common origins, during the orbital conformation of the giant planets, for the formation of classes of objects with moderate or high inclination. Interesting results were obtained for the hot objects of the Kuiper belt and the objects belonging to the extended scattered disk. The general mechanism found for the formation of these objects can be summarized as: (i) scattering phase due to the interaction with the giant planets, during the LHB; (ii) capture into mean motion resonances (MMR) with Neptune; (iii) capture into Kozai

resonance/mode; (iv) escape FROM both resonances into a mode known as "hibernation mode", in which the object has low eccentricity and high inclination; (v) fossilization in an orbit outside the resonant semi-major axis due to residual migration of Neptune. The results show good consistency between known objects with the model of dynamical formation.

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507.09 – Sedna, 2012 VP113 and the Inner Oort Cloud Population

The Inner Oort Cloud objects are the most distant solar system population observed. Sedna and our recent discovery 2012 VP113 are defining members of this class both with perihelia greater than 75 Astronomical Units (AU). It is not clear how the Inner Oort Cloud objects formed, however all formation scenarios invoke the action of significant mass in the formation stages of our solar system. We are conducting an ongoing survey for Inner Oort Cloud objects using the Dark Energy Camera (DECam) on the Cerro Tololo 4-m telescope. The goal of our survey is to find more Inner Oort Cloud objects so that fundamental constraints can be placed on the Inner Oort Cloud formation scenarios, and thus the events that took place in our early solar system.

With its 3 square degree field of view, DECam has the largest sky coverage of any 4-m class telescope or greater. The DECam/CTIO 4-m instrument combination is uniquely suited to detect Inner Oort Cloud objects which are both faint due to their extreme distance and rare in the sky. In the first data from our survey we discovered Inner Oort Cloud Object 2012 VP113 with a perihelion of 80 AU, the first solar system object found with a perihelion well beyond 50 AU since Sedna's discovery about a decade ago. We find the following about the Inner Oort Cloud objects: (1) there appears to be a paucity of Inner Oort Cloud objects with perihelia less than 75 AU, (2) the total number and mass of the Inner Oort Cloud could exceed that of the Kuiper Belt, and (3) there is a clustering of the argument of perihelion of the Inner Oort Cloud objects and extreme Kuiper Belt Objects which is consistent with the action of a super earth mass body at hundreds of AU. We present the latest results from our ongoing survey of the outer solar system.

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508 – Saturn Poles and Stratosphere

508.01 – Dynamics of Saturn's Polar Regions

In this study we analyze the horizontal velocity fields of Saturn's North and South Polar regions, including the hexagonal wave and its jet. The studied regions cover 30° in latitude going from 60° to 90° in both hemispheres. Using an automated two dimensional brightness correlation we create 2D zonal and meridional wind maps and zonal wind profiles for both polar regions, obtaining information on the horizontal velocity field up to 89.9° latitude in the north

polar region and -89.5° latitude in the south. The eastward jet in the north polar region has its peak of velocity at higher latitudes (closer to the pole) than that in the south polar region, and this could be one of the reasons for the formation of the hexagonal wave in the north. An anticyclone (South Polar Vortex) is observed in the south polar region, just outside the eastward jet and impinging on it, similar to the NPS anticyclone (north Polar Vortex observed in Voyager time). However, it does not excite a wave, showing that these anticyclones are not the cause of the formation of the hexagonal feature. We also deduce vorticity maps and analyze the stability of the zonal jets, finding potential instability at the flanks of the eastward jets. Finally, we study the transfer of momentum from the turbulent motion to the westward jets in these regions.

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508.03 – Analysis of Saturn's Polar Vortices with Cassini ISS Images

We present new analyses of Saturn's north pole using high-resolution images captured in late 2012 by the Cassini spacecraft's Imaging Science Subsystem (ISS) camera. The new images reveal the presence of an intense cyclonic vortex centered at the north pole. In the red, green and near-IR methane continuum wavelengths, the north polar region exhibits a spiraling cloud morphology extending from 89 degree N to 85 degree N latitude, with a 4700 km radius. Images captured in the methane absorption bands, which sense upper tropospheric haze, show an approximately circular hole in the haze extending up to 1.5 degree latitude away from the pole. The spiraling morphology and the "eye"-like hole at the center are reminiscent of a terrestrial tropical cyclone. In the System III reference frame (rotation period of 10h39m22.4s, Seidelmann et al 2007), the eastward wind speed increases to about 140 m/s at 89 degree N planetocentric latitude. The vorticity peaks at the pole at $(6.5 \pm 1.5) \times 10^{-4} \text{ s}^{-1}$, and decreases to $(1.3 \pm 1.2) \times 10^{-4} \text{ s}^{-1}$ at 89 degree N. In addition, we present new analysis of Saturn's south polar vortex using images captured in January 2007 to compare its cloud morphology to the north pole. The south-polar images reveal an eye-like hole similar to that over the north pole; however, the reflectivity of the upper tropospheric haze is significantly higher over the south pole in 2007 than the north pole in 2012, perhaps exhibiting seasonal difference.

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508.04D – Polar Vortices in Shallow Water Simulations of Gas Giants

Jupiter, Saturn and Neptune each exhibit unique polar atmospheric behavior. Assuming these flows are due to shallow dynamics, we explore the parameter space potentially responsible for the difference between each planet's polar features. The best observations have come from the Cassini mission to Saturn. Among many discoveries, a massive, warm and cyclonic vortex has been observed on each pole. The South Polar Vortex (SPV), specifically, has the highest measured temperatures on Saturn, a double eyewall, deep eye and a rapid cyclonic jet with the second highest windspeeds observed on the planet. Numerous small, vortical, and potentially convective systems are embedded within the large-scale flow of the SPV. Given these observations, we explore one potential mechanism of polar vortex maintenance: up-scale, poleward vorticity flux due to vortical hot towers (VHTs). Large GCMs cannot yet resolve local deep convection in the weather layer. Using a reduced gravity shallow water model on a polar beta plane, we represent convective towers with mass-flux driven vortex pairs and allow them to move freely. We show that there exist multiple regimes of polar flow, and that small and/or quickly rotating planets with sufficient total energy favor a polar cyclone in our simulations.

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508.05 – Saturn's Tropospheric Temperatures and Para-Hydrogen Distribution from Ten Years of Cassini Observations

Cassini/CIRS observations of Saturn's 10-1400 cm^{-1} spectrum have been inverted to construct a global record of tropospheric temperature and para-hydrogen variability over the ten-year span of the Cassini mission. The data record the slow reversal of seasonal asymmetries in tropospheric conditions from northern winter (2004, $L_s=293$), through northern spring equinox (2009, $L_s=0$) to the present day (2014, $L_s=60$). Mid-latitude tropospheric temperatures have cooled by approximately 4-6 K in the south and warmed by 2-4 K in the north, with the seasonal contrast decreasing with depth. CIRS detected the north polar minimum 100-mbar temperatures 6-8 years after winter solstice, whereas the south polar maximum occurred 1-2 years after summer solstice, consistent with the lag times predicted by radiative equilibrium models. Warm polar cyclones and the northern hexagon persist throughout the mission, suggesting that they are permanent features of Saturn's tropospheric circulation. The 200-mbar thermal enhancement ("knee") that was strongest in the summer but weak or absent in winter in 2004-2006 (Fletcher et al., 2007, Icarus 189, p.457-478) has now shifted northward and is present globally in 2014, suggestive of radiative heating in Saturn's tropospheric haze layer. Saturn's para-H₂ fraction, which serves as a tracer of both tropospheric mixing and the efficiency of

re-equilibration between the ortho- and para-hydrogen states, is slowly altering: super-equilibrium conditions (para-H₂ fraction exceeding equilibrium expectations and suggestive of subsiding airmasses) that dominated the southern summer hemisphere are now weakening, whereas the sub-equilibrium conditions (suggestive of uplift) of the northern winter are being replaced by equilibrium or super-equilibrium conditions in spring. The thermal 'knee' and the para-H₂ distribution are tracking both the increased spring illumination and the increasing tropospheric haze opacity of the springtime hemisphere observed via colour changes in visible light, suggesting a close connection between the tropospheric temperatures, para-H₂ and haze characteristics.

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508.06 – Atmospheric Structure in Saturn's Equatorial Region from Cassini Radio Occultations: 2005-2012

We present results from 19 radio-occultation soundings obtained over 2005-2012 at latitudes 10 S to 8 N and pressure levels from 0.1 mbar down to 1-2 bar. The retrieved temperatures and associated zonal winds derived from the gradient-wind relation exhibit a vertical undulatory zonal-mean structure of warmer and colder anomalies and westerly and easterly wind shear, respectively, that is associated with Saturn's equatorial oscillation. The long time span also reveals the descending pattern of this structure. For the equatorial oscillations observed in Earth's middle atmosphere, this descent is associated with the damping of a combination of vertically propagating waves having easterly and westerly phase velocities, which deposit zonal momentum into the background flow.

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508.07 – Evolution of Stratospheric Chemistry in the Saturn Storm Beacon

The colossal northern-hemisphere storm that erupted on Saturn in December 2010 triggered significant changes in stratospheric temperatures and species abundances that have persisted for several years (e.g., Fletcher et al. 2011, 2012; Hesman et al. 2012). These stratospheric regions have been dubbed "beacons" due to their prominent infrared-emission signatures; the two beacon regions that were initially present merged in April 2011 to form a single anticyclonic vortex (Fletcher et al. 2012). We model the expected photochemical evolution of the stratospheric constituents in the beacons from the initial storm onset through the merger and on out to March 2012. The results are compared with Cassini/CIRS spectra from May 2011. We find that C₂H₂, C₂H₆, and C₃H₈ remain unaffected by the increased stratospheric temperatures in the model, whereas the shorter-lived C₃H₄ abundance decreases slightly, and the C₂H₄ abundance increases significantly, most notably in a secondary mixing-ratio peak located near the 1 mbar level. The C₄H₂ abundance in the model decreases by a factor of a few in the 0.01-10 mbar region but has a significant increase in the 10-30 mbar region due to evaporation of the previously condensed phase. The column abundances of C₆H₆ and H₂O above ~30 mbar also increase due to evaporation (significantly, for the case of water). Model-data comparisons show that the models underpredict the abundance of C₂H_x species by a factor of 2-5 in the beacon center for the May 2011 date, suggesting that other processes not considered by the 1-D models, such as downwelling winds in the vortex, are affecting the species profiles. If we assume that the temperature increase in the beacon vortex is due to adiabatic compression from subsidence, we can estimate the necessary wind speeds. Adding such winds to the model does increase the C₂H_x abundances slightly, but not to the extent needed. We will discuss these issues and the general chemical behavior of stratospheric species in the beacon region.

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508.08D – 2D-photochemical modeling of Saturn's stratosphere: hydrocarbon and water distributions

Saturn's axial tilt of 27° produces seasons in a similar way as on Earth. The seasonal forcing over Saturn's 30 years period influences the production/loss of the major atmospheric absorbers and coolants through photochemistry, and influences therefore Saturn's stratospheric temperatures. We have developed a 2D time-dependent photochemical model of Saturn's atmosphere [Hue et al., in prep.], coupled to a radiative-climate model [Greathouse et al., 2008] to study seasonal effects on its atmospheric composition. Cassini spacecraft has revealed that the distribution of hydrocarbons in Saturn's stratosphere [Guerlet et al., 2009] differs from pure photochemical predictions, i.e. without meridional transport [Moses et al., 2005]. Differences between the observed distribution of hydrocarbons and

2D-photochemical predictions are likely to be an indicator of dynamical forcing.

Disentangling the origin of water in the stratosphere of this planet has been a long-term issue. Due to Saturn's cold tropopause trap, which acts as a transport barrier, the water vapor observed by the Infrared Space Observatory (ISO) [Feuchtgruber et al., 1997] has an external origin. Three external sources have been identified: (i) permanent flux from interplanetary dust particles, (ii) local sources from planetary environments (rings, satellites), (iii) large cometary impacts, similar to Shoemaker-Levy 9 on Jupiter. Previous observations of Saturn with Herschel's Hsso program [Hartogh et al., 2009] led to the detection of a water torus around Saturn [Hartogh et al., 2011], fed by Enceladus' geysers. A substantial fraction of this torus is predicted to be a local source of water for Saturn's and its satellites, as it will spread in this system [Cassidy et al., 2010]. Using the new 2D-photochemical model, we test here the validity of Enceladus' torus as the source of Saturn's stratospheric water.

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508.09 – An exploration of Saturn's stratospheric dynamics through Global Climate Modeling

A decade of Cassini observations has yielded a new vision on the dynamical phenomena in Saturn's troposphere and stratosphere. Several puzzling signatures (equatorial oscillations with a period of about half a Saturn year, interhemispheric circulations affecting the hydrocarbons' distribution, including possible effects of rings shadowing, sudden warming associated with the powerful 2010 Great White Spot) cannot be explained by current photochemical and radiative models, which do not include dynamics. We therefore suspect that 1. the observed anomalies arise from large-scale dynamical circulations and 2. those large-scale dynamical motions are driven by atmospheric waves, eddies, and convection, in other words fundamental mechanisms giving birth to, e.g., the Quasi-Biennial Oscillation and Brewer-Dobson circulation in the Earth's middle atmosphere. We explore the plausibility of this scenario using our new Global Climate Modeling (GCM) for Saturn. To build this model, we firstly formulated dedicated physical parameterizations for Saturn's atmosphere, with a particular emphasis on radiative computations (using a correlated-k radiative transfer model, with radiative species and spectral discretization tailored for Saturn) aimed at both efficiency and accuracy, and validated them against existing Cassini observations. A second step consisted in coupling this radiative model to an hydrodynamical solver to predict the three-dimensional evolution of Saturn's tropospheric and stratospheric flow. We will provide an analysis of the first results of those dynamical simulations, with a focus on the development of baroclinic and barotropic instability, on eddy vs. mean flow interactions, and how this could relate to the enigmatic signatures observed by Cassini. Preliminary high-resolution simulations with a new icosahedral dynamical solver adapted to high-performance computing will also be analyzed. Perspectives are twofold: firstly, broadening our fundamental knowledge of atmospheric waves and instabilities; secondly, provide the community with a "gas giant GCM" capable to interpret past and future observations of gas giants inside and outside our Solar System.

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509 – Asteroid Physical Characterization 5

509.01 – Current and Future Space-Based Mid-Infrared Surveys for Minor Planets

Mid-infrared surveys provide an efficient means of discovering asteroids and measuring their diameters; albedos can be determined with the addition of optical data. We describe the past results and current performance of the NEOWISE project, which has discovered >34,000 asteroids using 3.4, 4.6, 12 and 22 micron channels, and place NEOWISE in context with the existing and future suite of near-Earth object (NEO) surveys. Future prospects for space-based discovery and characterization of NEOs using thermal infrared (IR) wavelengths are enabled by the recent development

of megapixel 10 micron detectors capable of operating at 35 – 40 K. These new detector arrays will allow a future NEO survey mission to operate for many years, given a suitable thermal environment that allows for passive cooling. In order to investigate the optimal location for such a mission, we performed detailed simulations of an advanced IR survey's performance, showing that a telescope located at the Earth-Sun L1 Lagrange point will discover more NEOs larger than 140 m in diameter than a telescope in a Venus-like orbit.

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509.02 – Near-Infrared Albedos of Main Belt Asteroids and Families from NEOWISE

We present new results from revised thermal models of Main Belt asteroids in the NEOWISE dataset, focusing on the 3.4- and 4.6-micron albedos of asteroids and asteroid families. We show that the Main Belt is well described by three unique 3.4-micron albedo groups, tracing to the C-complex, S-complex, and K-type asteroids. Among large asteroid families, the Eos family shows a reflectance behavior that is unique in the Main Belt, matching the K-type albedo group. This work is described in detail in a recently published article in the *Astrophysical Journal*.

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509.03 – Near-Earth asteroid surface thermal inertias with NEOWISE

NEOWISE, the asteroid discovery and characterization mission that employs the Wide-field Infrared Survey Explorer (WISE) spacecraft, has observed over 150,000 minor planets, and continues to observe near-Earth asteroids daily. Several of these asteroids have also been observed by radar, and shapes and spin states have been derived from those observations. Thermophysical modeling combines these 3-D asteroid shapes, a model of heat transport, and infrared observations to determine the surface thermal inertia of an asteroid.

We present thermal inertia measurements derived using the NEOWISE dataset. These measurements can inform regolith composition and density, which can then be linked to collisional history and dynamical evolution. Measurements of heat capacity and thermal conductivity (components of thermal inertia), can refine predictions of the Yarkovsky drift, a non-gravitational force that can alter asteroid orbits.

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509.04 – Binary Candidates and Fractions in the Jovian Trojan and Hilda Populations from NEOWISE Lightcurves

Objects in orbital resonance with Jupiter, particularly Jovian Trojans (hereafter, Trojans) and Hildas, are some of the most diagnostic and accessible small body populations for constraining planetary migration patterns since their capture and physical state must be explained by dynamical evolution models. Different solar system formation models (e.g., gentle vs. rapid giant planet migration) predict different formation locations and dynamical histories for Trojans (and Hildas, which are likely fed from the Trojan region). Different dynamical environments can also produce different binary fractions as a function of separation between the two components. In order to explore whether the dynamical environment during early solar system evolution was mild or turbulent by helping discern which binary formation mechanism dominated for Trojans and Hildas, we searched the Trojan and Hilda thermal rotational lightcurves cataloged by NEOWISE for anomalously large lightcurve amplitudes indicative of close or contact binaries. These tight binary candidates are in need of dense follow-up observations to confirm their binarity. We also compared binary fractions between various Trojan subpopulations and for Trojans versus Hildas. We present binary fractions corrected for sampling and sensitivity biases and for survey efficiency at detecting tight binaries.

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509.05 – Thermal Inertias of Main-Belt Asteroids from Wise Thermal Infrared Data

By means of a modified thermophysical model (TPM) that takes into account asteroid shape and pole uncertainties, we analyze the thermal infrared data acquired by the NASA's Wide-field Infrared Survey Explorer (WISE) of about 300 asteroids with derived convex shape models. We adopt convex shape models from the DAMIT database (Durech et al., 2010, A&A 513, A46) and present new determinations based on optical disk-integrated photometry and the lightcurve inversion method (Kaasalainen & Torppa, 2001, *Icarus* 153, 37). This work more than double the number of asteroids

with determined thermophysical properties. We also discuss cases in which shape uncertainties prevent the determination of reliable thermophysical properties. This is per-se a novel result, as the effect of shape has been often neglected in thermophysical modeling of asteroids.

We also present the main results of the statistical study of derived thermophysical parameters within the whole population of MBAs and within few asteroid families. The thermal inertia increases with decreasing size, but a large range of thermal inertia values is observed within the similar size ranges between $D \sim 10$ -100 km. Surprisingly, we derive low ($< 20 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$) thermal inertia values for several asteroids with sizes $D > 10$ km, indicating a very fine and mature regolith on these small bodies.

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509.06 – Shape-Based Thermal Modeling of Three Near-Earth Asteroids

Infrared observations of an asteroid can be used to estimate its size, albedo, thermal inertia, and other physical properties. However, these estimates are often based on thermal models that assume a spherical shape. Detailed shape information is only available for a small fraction of known asteroids, so making simplifying assumptions about the shape is often unavoidable. Nevertheless, it is important to quantify the errors that can arise from applying spherical thermal models to non-spherical asteroids. Here, we consider three near-Earth asteroids for which detailed radar- and lightcurve-based shape models are available: (4769) Castalia, (8567) 1996 HW1, and (162421) 2000 ET70. All three have substantial concavities: Castalia and 1996 HW1 are elongated contact binaries, and 2000 ET70 is a spheroidal object with large ridges. We observed these asteroids from the NASA InfraRed Telescope Facility (IRTF), each at multiple phase angles, as part of our campaign to obtain both radar observations and infrared spectroscopy of near-Earth asteroids. With our shape-based thermophysical model, SHERMAN, we show the range of variations in the asteroids' infrared spectra due to changes in rotation phase and viewing geometry. We also compare the thermal properties derived using the asteroids' true shapes to the thermal properties and sizes that would be derived from applying spherical thermal models to the same observations.

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509.07 – Estimating Asteroid Thermal Inertia from Multi-epoch Observations

Granular material, or regolith, is observed to be ubiquitous on asteroid surfaces. To date, two feasible mechanisms of regolith generation have been proposed: recurrent impacts and thermal fracturing. By combining thermal infrared observations and a thermophysical model (TPM), the thermal inertia of an asteroid surface can be used to infer its physical properties, including the average regolith grain size. With the regolith properties of a large population of diverse asteroids (i.e. different spectral class, size, rotation period etc.), information regarding the details of regolith generation can be inferred.

Traditional thermal inertia determination methods use a TPM with a previously derived asteroid shape model and spin axis for constraining the observed surface temperature distribution. TPMs invoke the heat diffusion equation to calculate surface temperatures for a rotating asteroid. An asteroid spin axis provide the boundary condition needed to calculate the surface energy balance in a TPM. However the limited amount of objects with a shape model and thermal infrared observations inhibit the number of thermal inertias that can potentially be calculated. Here, a technique using WISE (12 & 22 μm) observations taken before or after opposition is employed to derive thermal inertias of asteroids without using a shape model. By gathering thermal infrared data at multiple viewing geometries the temperature distribution, thus thermal inertia, is constrained.

We first demonstrate the validity of this method on objects with a previously determined shape model and spin axis from the DAMIT website. Our analyses show that not knowing an asteroid's shape does not significantly affect the resulting thermal inertia estimates. Additionally, we apply our TPM to WISE multi-epoch thermal observations to place estimates for the thermal inertia for more than 100 objects. The set of objects used samples many sizes, spectral classes and rotation periods, which may be important factors in the generation of regolith. We search for and quantify

dependencies on these physical properties with our preliminary thermal inertia estimates.

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509.08 – Detection of cohesive forces in the rubble-pile asteroid (29075) 1950 DA

The physical behavior of rubble-pile asteroids has traditionally been described using only gravitational and frictional forces within a granular material. Cohesive forces in the form of small van der Waals forces between constituent grains have recently been predicted to be important for small rubble-pile asteroids (less than 10 kilometers in size), and could potentially explain how small fast spinning asteroids remain intact. It is possible to infer the existence of cohesive forces within a rubble-pile asteroid by determining if it has insufficient self-gravity, dictated by its bulk density, to prevent rotational breakup by centrifugal forces. The kilometer-sized and potentially-hazardous asteroid (29075) 1950 DA is one of the largest known candidates for being held together by cohesive forces, as it has a rotation period of 2.1216 h that is just beyond the critical spin limit of 2.2 h estimated for a cohesionless asteroid. Using the Advanced Thermophysical Model (or ATPM), in combination with the radar shape model, WISE thermal-infrared data, and Yarkovsky orbital drift measurement, we determined the thermal inertia, bulk density, and cohesive strength of (29075) 1950 DA (Rozitis et al., 2014, *Nature*, 512, 174-176). The thermal inertia value is remarkably low at $24 \pm 20/-14$ SI units, which gives a corresponding bulk density of 1.7 ± 0.7 g/cm³ in the Yarkovsky orbital drift analysis. This bulk density is typical of a rubble-pile asteroid, and a minimum cohesive strength of $64 \pm 12/-20$ Pa is therefore required to prevent surface mass shedding and structural failure by centrifugal forces. This strength is comparable to, though somewhat less than, the cohesive forces found between the grains of lunar regolith. Finally, as (29075) 1950 DA has a 1 in 19,800 chance of impacting the Earth in 2880, and has the potential to disrupt like main-belt comet P/2013 R3, it raises new implications for impact mitigation against fast spinning rubble-pile asteroids.

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509.09 – Precessing Asteroids from Radius Vector Models?

Examining a sample of asteroids (the first 99) for which radius vector models have been constructed from mostly lightcurves, located on a web site where such models are listed (<http://astro.troja.mff.cuni.cz/projects/damit>; see Durech et al. (2010), DAMIT: a database of asteroid models, *A&A*, 513, A46), we fit their surfaces as triaxial ellipsoids and provide their three dimensions. In the process we also derive an Euler angular offset ψ between each model's spin axis and its axis of maximum moment of inertia assuming a uniform distribution of mass. Most ψ 's conform to a chi-squared distribution having a maximum at 3° and a mean at 5° , and with the square root of the variance being 3° . However, seven models produce $\psi > 20^\circ$, which we interpret as indicating possibly strong precessors, tumblers, or due to incorrect models: asteroids (68), (89), (125), (162), (167), (222), and (230). Nine others produce an excess over the distribution at $12^\circ < \psi < 16^\circ$: asteroids (2), (5), (37), (38), (79), (115), (157), (174), and (178). We initially interpret these as perhaps more legitimate precessors. However a calculation of the probability of an impact sufficient to change the angular momentum of the asteroid implied by ψ during the damping time to return to rotation about the small axis is vanishingly small (less than 1 in 10000) for the 8 out of 16 asteroids with absolute dimensions. The most likely resolution, then, is that the rotational pole for the 16 asteroid models with high ψ needs to be adjusted by ψ degrees.

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509.10 – Asteroid shapes and spins reveal a preferred erosional state of maximum surface stability

Over the past decade, it has been recognized that when asteroid spin states and body elongations are examined together, these bodies appear to be clustered in regions whereby internal stresses are minimized. However, no viable compositional or internal mechanism has been found to adequately explain this observation.

We have recently completed a study that investigated the shape, gravity, and spin of thirty publicly available small-body datasets, looking for common properties and trends. Eight shape models derived from spacecraft optical data were used; of 4 asteroids, 2 comet nuclei, and the 2 martian moons. Twenty-two shape models derived from Arecibo and Goldstone planetary radar data were used; of 1 Main Belt and 21 near-Earth asteroids. These shape models were selected based upon the degree of surface coverage obtained ($> 65\%$ preferred); the shape model resolution achieved (> 1000 polyhedron facets preferred); and the degree to which the body has been characterized in the scientific literature.

This study shows that asteroid shape, gravity, and spin combine to gradually drive the asteroid's surface towards a condition of minimum topographic variation, low slopes, and low surface erosion rates. Of the 30 bodies investigated, 50% reside within this 'zone of surface stability', and when asteroid light-curve estimates are included, roughly 75% of

1300 well observed asteroids reside within this zone. Our findings indicate that when surface erosion and regolith migration are taken into consideration, asteroid bodies naturally tend to erode towards a state of maximum surface stability, with erosion rates increasing dramatically as one deviates from this state. This region of maximum surface stability also coincides with a state of maximum internal stability, as previously observed.

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509.11 – Physical properties of asteroids derived from a novel approach to modeling of optical lightcurves and WISE thermal infrared data

Convex shape models and spin vectors of asteroids are now routinely derived from their disk-integrated lightcurves by the lightcurve inversion method of Kaasalainen et al. (2001, *Icarus* 153, 37). These shape models can be then used in combination with thermal infrared data and a thermophysical model to derive other physical parameters - size, albedo, macroscopic roughness and thermal inertia of the surface. In this classical two-step approach, the shape and spin parameters are kept fixed during the thermophysical modeling when the emitted thermal flux is computed from the surface temperature, which is computed by solving a 1-D heat diffusion equation in sub-surface layers. A novel method of simultaneous inversion of optical and infrared data was presented by Durech et al. (2012, LPI Contribution No. 1667, id.6118). The new algorithm uses the same convex shape representation as the lightcurve inversion but optimizes all relevant physical parameters simultaneously (including the shape, size, rotation vector, thermal inertia, albedo, surface roughness, etc.), which leads to a better fit to the thermal data and a reliable estimation of model uncertainties. We applied this method to selected asteroids using their optical lightcurves from archives and thermal infrared data observed by the Wide-field Infrared Survey Explorer (WISE) satellite. We will (i) show several examples of how well our model fits both optical and infrared data, (ii) discuss the uncertainty of derived parameters (namely the thermal inertia), (iii) compare results obtained with the two-step approach with those obtained by our method, (iv) discuss the advantages of this simultaneous approach with respect to the classical two-step approach, and (v) advertise the possibility to use this approach to tens of thousands asteroids for which enough WISE and optical data exist.

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509.12 – Spin Axis Distribution of the Hungaria Asteroids via Lightcurve Inversion

Since 2005, we have conducted a dedicated campaign to obtain dense lightcurves of members of the Hungaria asteroid population. As a result, the number of Hungarias in the asteroid lightcurve database (LCDB; Warner et al., 2009; *Icarus* 202, 134-146) with a statistically valid rotation rate rose from less than 50 to almost 300. The particular value of the Hungarias is that they are smallest and closest-to-sun main belt objects that can be studied with modest-sized telescopes. As such, they are more likely subject to YORP-altered spin states. We have previously verified highly-evolved rotation rates (Warner et al., 2009; *Icarus* 204, 172-182). This study takes the next step of tracing the evolution of spin orientations. We combined the dense lightcurves from our campaign with so-called “sparse data” from the NEA surveys to model the spin axis orientation using lightcurve inversion methods (see works by Kaasalainen, Torppa, Durech, and Hanus). Because high-dispersion sparse data are of little use for low amplitude objects, we limited the Hungarias to be modeled to those with a maximum amplitude of $A \leq 0.15$ mag, an LCDB reliability code of $U \leq 2$, the period in the LCDB summary was unambiguous, and the asteroid did not show signs of tumbling (non-principal axis rotation). The result as of mid-August 2014 was a list of 231 Hungaria candidates for modeling. Using a bank of five independent desktop computers and customized software, we first determined the likely sidereal period of the asteroid. That period was then used for a spin axis (pole) search involving 315 discrete longitude-latitude pairs. We report on the results of our searches, including weighting solutions when a unique solution was not found (often the case in lightcurve inversion), and how the results compare to similar studies using a more general asteroid population. BDW and AWH acknowledge funding from NASA NNX13AP56G and NSF grant AST-1210099. RDS acknowledges NASA grant NNX13AP56G and the Planetary Society Shoemaker NEO grant.

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510 – TNOs and Centaurs: Characterization

510.01 – Volatile Loss and Classification of Kuiper Belt Objects

Some of the largest Kuiper Belt Objects (KBOs) appear to have retained volatiles which affect their spectra, thermal energy balance, and atmospheres. Schaller & Brown (2007) (SB) estimated atmospheric escape rates from KBOs using Jeans escape from the surface, which they suggested gives a lower limit to the net atmospheric loss, and Levi & Podolak (2009) (LP) used a hydrodynamic model driven by the surface temperature. Based on recent molecular kinetic simulations, the SB escape rates are not necessarily lower limits and can be hugely in error, while the LP rates are valid only for KBOs with very small Jeans parameters (Volkov et al., 2011a,b). In addition, unless the atmosphere is thin or the body very small, escape can be driven primarily by the UV/EUV radiation absorbed in the upper atmosphere. Here we estimate the N₂ loss from several KBOs, guided by recent molecular kinetic simulations that include thermal energy balance at the surface and heating of the upper atmosphere by UV/EUV irradiance. For the latter effect, we extrapolate simulations of escape from Pluto (Erwin et al., 2013; Zhu et al. 2014) using an energy limited escape model, which we have recently validated via molecular kinetic simulations (Johnson et al., 2013). In this way, we improve on current estimates of atmospheric retention and use the results to interpret the spectral differences observed. The longer-term goal is to connect detailed atmospheric loss mechanisms with a model for volatile transport (e.g., Young, 2014) in order to better describe recent KBO observations.

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510.02 – Irradiation chemistry in the outer solar system

The dark, reddish tinged surfaces of icy bodies in the outer solar are usually attributed to the long term irradiation of simple hydrocarbons such as methane leading to the loss of hydrogen and the production of long carbon chains. While methane is stable and detected on the most massive bodies in the Kuiper belt, evidence of active irradiation chemistry is scant except for the presence of ethane on methane-rich Makemake and possible detections of ethane on more methane-poor Pluto and Quaoar. We have obtained deep high signal-to-noise spectra of Makemake from 1.5 to 2.5 microns in an attempt to trace the radiation chemistry in the outer solar system beyond the initial ethane formation. We present the first astrophysical detections of solid ethylene, acetylene, and possibly propane -- all expected products of the continued irradiation of methane, and use these species to map the chemical pathway from methane to long-chain hydrocarbons.

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510.03 – Methane and Nitrogen Abundances on the Icy Dwarf Planet Makemake

We present an optical spectrum of the icy dwarf planet Makemake from the MMT 6.5 meter telescope and Red Channel Spectrograph (6250 - 9800 angstroms; 3.5 angstroms per pixel; exposure time 7h 30m) on Mt. Hopkins, AZ. In addition, we present laboratory transmission spectra over similar wavelengths of methane-nitrogen ice mixtures from the Astrophysical Ice Laboratory in the Department of Physics and Astronomy at Northern Arizona University. By anchoring our analysis with the methane-nitrogen phase diagram of Prokhvatilov and Yantsevich (1983, *Sov. J. Low Temp. Phys.*, 9, 94), and comparing methane bands in our Makemake spectrum and methane bands in our laboratory spectra, we are able to make the first quantitative estimate of Makemake's methane and nitrogen abundances. We compare Makemake's abundances with our previously derived abundances for Triton, Pluto, and Eris (see Tegler et al., 2012, *ApJ*, 751, 76). We gratefully acknowledge support from the NASA Solar Systems Observations and Solar System Workings programs. We thank Steward Observatory for the consistent allocation of telescope time.

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510.04 – A New, Longitudinally Resolved, Spectroscopic Characterization of Quaoar's Surface

(50000) Quaoar, one of the largest Trans-neptunian objects, is comparable in size to Pluto's moon Charon. However, while Charon's surface is rich almost exclusively in H₂O ice, Quaoar's surface is characterized by ices of CH₄, N₂, as well as C₂H₆, a product of irradiation of CH₄ (Dalle Ore et al. 2009). Because of its distance from the Sun, Quaoar is expected

to have preserved, to a degree, its original composition, however, its relatively small size did not make it a prime candidate for presence of volatile ices in the study by Schaller and Brown (2007). Furthermore, based on the Brown et al. (2011) study its red coloration points to CH_3OH as the ice which, when irradiated, might have produced the red material.

We present new visible to near-infrared (0.3-2.48 μm) spectro-photometric data obtained with the XSHOOTER (Vernet et al. 2011) instrument at the VLT-ESO facility at four different longitudes on the surface of Quaoar. The data are complemented by previously published photometric observations obtained in the near-infrared (3.6, 4.5 μm) with the Spitzer Space Telescope, which provide an extra set of constraints in the model calculation process in spite of the different observing times that preclude establishing the spatial consistency between the two sets.

For each of the four spectra we perform spectral modeling of the entire wavelength range -from 0.3 to 4.5 μm - by means of a code based on the Shkuratov radiative transfer formulation of the slab model. We obtain spatially resolved compositional information for the surface of Quaoar supporting the presence of CH_4 and C_2H_6 , as previously reported, along with evidence for N_2 and NH_3OH . The albedo at the two Spitzer bands indicates the likely presence of CO and CO_2 . CH_3OH , predicted on the basis of Quaoar's coloration (Brown et al. 2011), is not found at any of the four longitudes, implying that the presence of this ice is a sufficient, but not necessary condition for reddening of TNO surfaces. Other ices, in particular CH_4 (Brunetto et al. 2006), have been shown to be plausible precursors for reddening of TNO surfaces.

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510.05 – A new look at the visible color correlations of Centaurs and KBOs: what's there and what we may be missing.

Broadband surface colors of Centaurs and KBOs are usually seen as a mere rough approximation of their reflectivity spectra. Whereas JHK colors are not the best proxy for the near-IR spectra with possible presence of absorption features of several ices, BVRI colors have shown to be so when it comes to visible spectra.

We have compiled a data-set of visible colors available in the literature for 369 objects and analyzed their color vs. color correlations and their color vs. orbital parameters correlations, both globally and by dynamical family.

In this work we present the first study on: i) the “degradation” of the detectable strength of a correlation as a function of data error-bars, ii) the “risk” of missing-out existing correlations due to low sampling, iii) the sample-sizes required to “warrant” detection at a given significance level, iv) the use of partial correlations to disentangle complex mutual correlations, and v) the high sensitivity of the so-called “reddening line” to the central wavelength of similar filters at different telescopes.

We will discuss, in particular: a) how data error-bars impose a limit on the detectable correlations regardless of sample size and, therefore, once that limit is achieved it is important to diminish the error-bars but pointless to enlarge the sampling with the same or larger errors; b) how almost all families still require larger samplings to “ensure” the detection of correlations stronger than ± 0.5 , i.e. correlations that may “explain” $\sim 25\%$ or more of the color variability; and c) how it is statistically equivalent to use any of the different “flavors” of orbital excitation or collisional velocity parameters regarding the famous color-inclination correlation among Classical KBOs, whereas the inclination and Tisserand parameter relative to Neptune cannot be separated from one another.

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510.06 – TNOs as probes of planet building: the Plutino size- & colour-distributions

Planetesimals are the building blocks of giant planet cores; some are preserved as large transneptunian objects (TNOs). Previous work concluded steep power-law size-distributions for TNOs of diameters > 100 km. Recent results claim a dramatic roll-over or divot (sudden drop in number of objects at a transition size) in the size-distribution of Neptunian Trojans and scattering TNOs, with a significant lack of intermediate-size $D < 100$ km planetesimals. One theoretical explanation is that planetesimals were born big, skipping the intermediate sizes, contrary to the expectation of bottom-up planetesimal formation.

Using the Canada-France-Hawaii Telescope, our 32 sq.deg. survey, near $\text{RA} = 2$ hr with limiting magnitude $m_r = 24.6$, detected and tracked 77 TNOs and Centaurs for up to 28 months, providing both the high-quality orbits and the quantitative detection efficiency needed for precise modelling. We used the 18 Plutinos (3:2 Neptunian resonance) from our survey to constrain the size- and orbital-distribution model of this population. We show that the Plutino

size-distribution cannot continue as a rising power-law past $H_r \approx 8.3$ ($D \approx 100$ km); a sharp dramatic change must occur near this point. A single power-law is rejectable at >99% confidence; a double power law cannot be rejected outright, but appears to be an uncomfortable match to the available data. A divot, with the parameters found independently for scattering TNOs by Shankman et al. (2013, ApJ vol 764), provides an excellent match; the best match, found from an extensive parameter search, comes with only slightly different parameters; this size-distribution also satisfies the known Neptunian Trojan data.

Both large TNOs and small nearby Centaurs are known to feature a bimodal colour-distribution; however, recent work (Peixinho et al. 2012, A&A vol 546) has suggested that intermediate-size TNOs may not show bimodality. We present g-r photometric colours for our Plutino sample, obtained with the Gemini North telescope in 2013-2014. This telescopically-expensive endeavour has provided us with unique insight into the colour-distribution of the physically smallest Plutinos.

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510.07 – The synchronous rotations of Eris/Dysnomia and Orcus/Vanth binary systems

We have measured the rotation periods of the Eris/Dysnomia and Orcus/Vanth binary systems using long-term observations obtained with the SMARTS 1.3m telescope at Cerro Tololo, combined with incidental observations obtained by the La Silla – QUEST survey on the ESO 1.0-m Schmidt at La Silla, and using historical observations of Eris published by others. We find that both binary systems are synchronous, with the dominant periodicity in their light curves matching their mutual orbit periods (9.54 and 15.774 days, respectively). For Orcus/Vanth, the reflected light from both bodies contributes to the signal. The measured periodicity could be due to the rotation of Orcus or Vanth separately, but it is most likely the system is doubly synchronous. For Eris/Dysnomia, only Eris is bright enough to contribute significantly to the observations. The conclusion is therefore unambiguous that Eris is synchronously rotating with the orbit of Dysnomia. This is surprising given that Eris is 500 times brighter than Dysnomia, and likely to be 100 to 10000 times more massive (assuming an albedo > 5% for Dysnomia). If Dysnomia has migrated outward from Eris owing to long-term tidal interactions, the time for Eris to slow from an initially fast rotation (period < 1 day) to a synchronous one is longer than the age of the solar system. We discuss the constraints these observations place on the relative albedos, masses, and internal composition of the two binary systems.

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510.08 – New Horizons: Long-Range Kuiper Belt Targets Observed by the Hubble Space Telescope

We will report on Hubble Space Telescope (HST) observations of three Kuiper Belt Objects (KBOs), discovered in our dedicated ground-based search campaign, that are candidates for long-range observations from the New Horizons spacecraft: 2011 JY31, 2011 HZ102, and 2013 LU35. Astrometry with HST enables both current and future critical accuracy improvements for orbit precision, required for possible New Horizons observations, beyond what can be obtained from the ground. Photometric colors of all three objects are red, typical of the Cold Classical dynamical population within which they reside; they are also the faintest KBOs to have had their colors measured. None are observed to be binary with HST above separations of ~ 0.02 arcsec (~ 700 km at 44 AU) and $\theta \approx 0.5$.

This research is based in part on ground-based data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan, and on data gathered with the 6.5 meter Magellan Telescopes located at Las Campanas Observatory, Chile. Space-based observations were made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

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510.09 – The Use of Stellar Occultations to Study Trans-Neptunian Objects

The physical parameters of the Trans-Neptunian Objects (TNO's) such as size, shape, density, presence of atmosphere, and rings, provide important information on their formation and evolution. At more than 30 Astronomical Units (AU) from the Sun, those objects receive low solar radiation and have low mutual collisions velocities so they can be considered as remnants of the primordial outer Solar System. Besides that, information on TNO's is of great relevance

when trying to establish a general formation scenario for the recently discovered planetary systems. The problem is that such bodies have a diameter smaller than 2300 km (Eris, one of the largest TNO, has 2326 km) and, when viewed from Earth, they usually subtend angles smaller than 50 milli-arcseconds, preventing direct imaging. One method to obtain very accurate information on the TNO's is the stellar occultation technique. Sizes at kilometer accuracies and pressure at nanobar levels can be achieved with this method, as well as detection of ring systems. Shape, density, albedo and other physical parameters can also be derived from this technique.

Since 2010, we observed stellar occultations of several TNO's (Eris, Makemake, 2003VS2, Quaoar, Ixion, Varuna, 2002KX14, and 2003AZ84) besides some other occultations by Pluto and Charon, and by the largest Centaur known to date, Chariklo. We also predicted future events in 2014 and 2015 for 40 TNO's and Centaurs. On this work, we present the process of our campaigns – predictions, follow ups, world wide cooperation, post-occultation data analysis –, the new results obtained from recent stellar occultations of TNO's, and the expectations of improvements after GAIA.

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511 – Jupiter and Saturn Atmospheric Structure and Clouds

511.01 – Progress in Studying Radiation Energy Budgets of Jupiter, Saturn, and Titan

Expanding on our previous studies (Li et al., 2010, 2011, 2012) of exploring the global energy budgets of Jupiter, Saturn, and Titan, we present new investigations based on the long-term Cassini multi-instrument (CIRS, ISS, and VIMS) observations. We first discuss the preliminary results about the global-average albedo and hence the absorbed solar energy of Jupiter in the Cassini epoch (2000-01). Jupiter's global energy budget in the Cassini epoch is estimated by combining the current measurements of absorbed solar energy and the previous measurements of emitted thermal energy (Li et al., 2012). We also present the preliminary study of the relationship between the 2010 giant storm and the global energy budget on Saturn. Finally, we present our investigation of the temporal variation of Titan's emitted thermal energy from 2004 to 2013, which suggests a dramatic change.

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Contributing team(s): Cassini CIRS, ISS, and VIMS teams

511.02 – Cloud structure of Jupiter's troposphere from Cassini VIMS

Cassini VIMS 4.5-5.1 μ m thermal emission spectra were used to study the composition and cloud structure of Jupiter's middle troposphere during the 2000/2001 flyby. The radiance observed varies considerably across the planet (a factor of 50 between the warm North Equatorial Belt and the cool Equatorial Zone) but the spectral shape remains constant, suggesting the presence of a spectrally flat, spatially inhomogeneous cloud deck. Spectra were analysed using the NEMESIS radiative transfer code and retrieval algorithm. Both night- and day-side nadir spectra could be well reproduced using a model with a single, compact, grey cloud deck. For hotter spectra, this grey cloud could be located as deep as 3.0 bar, but the cooler spectra required the cloud deck to be at pressures of 1.2 bar or less. At these pressures, the clouds are expected to be NH₄SH or NH₃, but the single-scattering albedos of pure ices of NH₃ or NH₄SH produce spectral features that are incompatible with the VIMS data. These spectral signatures may be masked by complex rimming/coating processes, and/or by the presence of multiple cloud decks. Retrievals show that the cloud optical thickness varies significantly with latitude and longitude. The North Equatorial Belt contains discrete cloud-free "hot-spots" whose radiance is twice as bright as the coolest parts of the belt. The turbulent region in the wake of the Great Red Spot (GRS) has the thickest clouds of the South Equatorial Belt; these begin to thin out on the opposite hemisphere, 180° away from the GRS. The relatively low spectral resolution and model degeneracies mean that no variability could be detected (or ruled out) in the gaseous species (NH₃, PH₃ and other disequilibrium species). A limb darkening analysis was carried out using the nightside observations. Extreme inhomogeneity within latitude circles meant that simultaneous retrievals at different emission angles were not possible. However, forward modelling was used to show that highly scattering particles are required to produce results consistent with the data. Acceptable fits were obtained using cloud particles with high single-scatter albedos ($\tau > 0.85$) and low asymmetry parameters ($g < 0.75$).

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511.03 – Longitude-resolved VLA Radio Maps of Jupiter

Visible light and 5-micron infrared images of Jupiter reveal the familiar zone-belt structure, where the brown belts appear as warm regions at 5 μm . As clouds are a major source of opacity at this wavelength, the high 5 μm temperatures are indicative of no or relatively thin cloud decks so that deeper warmer layers are probed. In the mid-eighties microwave images at 1 – 6 cm showed a similar zone-belt structure, where deeper warmer layers were probed in the belts, due to a lower NH_3 abundance in the belts than in the zones. Conventional radio interferometric images are integrated over many hours to meet the required sensitivity and to use Earth rotation synthesis to achieve good sampling of the Fourier plane. Consequently, any potential structure in longitude is smeared out in such maps. In 2004, we published an innovative technique to synthesize together many hours of radio data to produce a longitude-resolved map [1]. This map showed the hot spots on Jupiter very clearly, and we showed that the NH_3 gas abundance must be depleted significantly down to several bars in these hot spots.

This past year we embarked on a program to map Jupiter at multiple wavelengths with the much-improved (order of magnitude in sensitivity) VLA. In this talk we will present our first maps of Jupiter in the X (3.6 cm) and Ku (2 cm) bands. These maps will be compared with maps produced by the amateur community at optical wavelengths, with similar resolution, and radiative transfer calculations of a select number of features will be presented.

[1] Sault, R.J., C. Engel, and I. de Pater, 2004. Longitude-resolved Imaging of Jupiter at $\lambda=2$ cm. *Icarus*, 168, 336-343.

Author(s): Imke de Pater¹, R. J. Sault³, Bryan Butler², David deBoer¹

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511.04 – The Latitudinal Variation of Jupiter's Deep Cloud Structure

In March 2014, we used NIRSPEC on the Keck telescope to spectrally resolve line profiles of CH_3D and other molecules on Jupiter in order to derive the pressure of the line formation region in the 5-micron window. The slit was aligned north/south on the Central Meridian of Jupiter. Two slit positions ensured pole to pole coverage. Deuterated methane is a good choice for studying cloud structure because methane and its isotopologues do not condense on Jupiter. Variations in CH_3D line shape with position on Jupiter are therefore ONLY due to cloud structure rather than due to changes in gas mole fraction. The profile of the CH_3D lines is very broad in Hot Spots in the North and South Equatorial Belts due to collisions with up to 8 bars of H_2 , where unit optical depth due to collision-induced H_2 opacity occurs. The extreme width of these CH_3D features implies that Hot Spots do not have significant cloud opacity where water is expected to condense. In Jupiter's zones, the line profiles are substantially narrower than in Hot Spots, but they are broader than would be expected if they were formed in a column above an opaque cloud at 0.7 bars (NH_3) or 2 bars (NH_4SH). Once we have established a cloud structure, gas mole fractions may then be retrieved. Strong and weak H_2O absorption features were detected at the same time as CH_3D , which provides independent evidence that we are sounding deep in Jupiter's atmosphere. These data will allow us to retrieve NH_3 , PH_3 , and gaseous H_2O as a function of latitude from pole to pole on Jupiter. This technique can be applied to study the deep cloud structure anywhere on Jupiter whether or not upper level clouds are present.

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511.05 – Why is the Great Red Spot Red? The Exogenic, Photolytic Origin of the UV/Blue-Absorbing Chromophores of Jupiter's Great Red Spot as Determined by Spectral Analysis of Cassini/VIMS Observations using New Laboratory Optical Coefficients

For centuries, a major question for Jupiter has been: Why is the Great Red Spot red? In particular, two major theories have been proposed: (1) that the coloring is due to photolytic processes in the upper cloud layer, or (2) it is due to the upwelling of red materials processed relatively deep within the troposphere. Utilizing indices of refraction for red chromophores generated by the photolysis of ammonia and acetylene in the laboratory, we present results of a spectral analysis of the core of Jupiter's Great Red Spot (GRS) as observed by the visual channel of the Cassini/Visual Infrared Mapping Spectrometer (VIMS). Consistent with the physical origin of such laboratory-generated chromophores in Jupiter – i.e., by solar-driven UV photolysis within the upper levels of the GRS structure near ~ 0.3 bar – our spectral modeling yields satisfactory results for such Mie scattering chromophores only when they are confined to the upper ~ 100 mbar of the GRS. Beneath this reddish upper cloud layer, our models indicate that the remainder of the GRS cloud – assumed to extend down to at least the ammonia condensation level near 0.6 bar – must be relatively spectrally bright throughout the UV-red spectrum; that is, they must be predominantly a whitish or grey color at depth. Thus, our 0.35-1.0 micron spectral models of the GRS are inconsistent with an endogenic origin of the reddish coloring originating in the depths of Jupiter, but are consistent with a photolytic origin due to the photolysis of ammonia and acetylene in the upper troposphere.

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511.06 – Jovian Mid-Infrared Aurora: Retrospective Analysis of Variability and Cassini Flyby Measurements in Preparation for Juno

With the approaching arrival of the Juno mission at Jupiter it is important to look at the current knowledge of Jovian phenomena that can or cannot be further studied from orbital spacecraft. It is also important to retrospectively investigate previously acquired data using current improved methods and capabilities. The thermal (mid-) infrared aurora from Jupiter's polar regions has been studied extensively from ground-based observatories as well as by Voyager IRIS and Cassini CIRS during Jupiter flybys. We report on a reexamination and re-analysis of hydrocarbon emission spectra from the polar regions of Jupiter obtained using ground based infrared heterodyne spectroscopy (IRHS) and Cassini CIRS Fourier transform spectroscopy (FTS) during the flyby of Jupiter in 2000-2001. Measurements with IRHS have been made over 30 years, primarily of ethane near 12 micrometer wavelength. IRHS provides fully resolved individual spectral lines whose shape yields unique information on variability of temperature and abundance. CIRS data, at lower spectral resolution, explores extended spatial distributions and covers a broad spectral region that includes auroral response of ethane as well as several other hydrocarbons in the 8–13 micrometer wavelength region (methane, ethylene, and acetylene). These spectra are radiometrically calibrated and can serve as a sensitive thermometer of the Jovian atmosphere. Recently improved analysis techniques show detailed spatial enhancements of the primary hydrocarbons in northern latitudes. Temporal changes of the ethane line emission over three solar cycles and comparison of retrievals from ethane data taken contemporaneously during the Cassini flyby by both techniques will be compared and results discussed. Juno does not have instrumentation in this spectral region and this work provides complementary information and diagnostics for studying Jovian aurora and magnetosphere in a spectral region and altitude range not directly probed by Juno.

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511.07 – Saturn's Zonal Winds at Cloud Level between 2004-2013 from Cassini ISS Images

We examine images of Saturn returned by Cassini orbiter's Imaging Science Subsystem (ISS) camera between 2004 to 2013 to analyze the temporal evolution of the zonal mean wind speed as a function of latitude. Our study primarily examines the images captured in the 752-nm continuum band using the CB2 filter. Images captured using the CB2 filter sense the upper troposphere of Saturn between 350 mbar and 500 mbar (Pérez-Hoyos and Sánchez-Lavega, 2006; Sánchez-Lavega et al, 2006; García-Melendo et al, 2009). We measure the wind speed using a two-dimensional Correlation Imaging Velocimetry (CIV) technique. The wind vectors are computed using pairs of images separated in time by up to two planetary rotations, and binned in latitude to determine the zonal mean wind profile, which typically covers a limited range of latitude. To achieve pole-to-pole coverage, we systematically merge all the wind measurements during each of the calendar years in order to compile a yearly, near-global record of Saturn's zonal wind structure. Using our wind measurements, we analyze the temporal evolution of the zonal wind. We specifically focus on changes in the wind profile after the 2009 equinox; we predict that changes in the insolation pattern caused by the shifting ring shadows affect the horizontal temperature gradient, and change the zonal mean wind through the thermal wind relationship. Furthermore, we also extend the zonal wind analysis by Sayanagi et al (2013), who detected changes in the zonal wind related to the Great Storm of 2010-2011, to study the subsequent evolution of the region affected by the storm. We compare our results with previously published zonal wind profiles obtained from Voyager 1 and 2 (Sánchez-Lavega et al, 2000) and Cassini (García-Melendo et al, 2011).

Our study is supported by the Cassini Project, and our investigation is funded by NASA Outer Planets Research Program grant NNX12AR38G and NSF Astronomy and Astrophysics grant 1212216 to KMS.

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511.08 – The variability of Saturn's thermosphere from Cassini/UVIS occultations

We present temperature and density profiles that we retrieved from 17 stellar occultations obtained by the Cassini UVIS instrument. These results complement our previous analysis of 15 solar occultations by Saturn's upper atmosphere. We find that the exospheric temperature ranges from 370 K to 550 K, in agreement with our previous results. The temperature appears to increase with latitude from the equator to the poles by 100 – 150 K, a trend that is also evident in the pressure level altitudes that we derive from the data. We also find evidence for the expansion of the thermosphere by about 500 km between 2005 and 2011 at low to mid northern latitudes. This expansion is probably caused by significant warming of the lower thermosphere that anti-correlates with solar activity. We also present a comparison of our results with the newly available reanalysis of the Voyager UVS results (Vervack and Moses, 2014), and

discuss the results in the context of energy deposition and dynamics in Saturn's upper atmosphere.

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511.09 – Vertical structure of Saturn lightning storms and storm-related dark ovals

In Cassini ISS images of Saturn during 2004-2006 Dyudina et al. (2007, *Icarus* 190, 545-555) identified four cases in which bright cloud features near 35° S were correlated with thunderstorm activity, inferred from SED events detected by the Radio and Plasma Wave Science instrument. The bright features left behind remnant dark ovals that reached full contrast within about a week. Baines et al. (2009, *Plan. & Space Sci.* 57, 1650-1658) investigated similar radio-correlated storms, using 2008 VIMS spectra. Noting that the dark ovals were about 20% less reflective than surrounding clouds over a wide spectral range, they suggested that the cloud particles might contain a broadband absorber that was produced by lightning-induced chemistry at the 10-20 bar water cloud level and convected up to the visible cloud level. Another possibility is that lower optical depths cause the ovals to be less reflective than the surrounding clouds. We carried out quantitative radiative transfer calculations to evaluate these alternatives, and also derived cloud models for the active region that is the presumed source of lightning. The main result for the dark ovals is that we can obtain good fits with typical condensates in vertically thin cloud layers, but can also obtain good fits with deep clouds of composite particles containing a sooty core within a shell of $n=1.4+0i$ material. However, unlike Saturn's Great Storm of 2010-2011 (Sromovsky et al. 2013, *Icarus*), neither the bright clouds nor the dark ovals show the significant 3-micron absorption that would be expected if NH₃, NH₄SH, or H₂O were lofted to upper cloud level. This missing absorption tends to favor models in which the upper cloud layer (near 250 mbar) is comprised of conservative (non-absorbing) particles and physically thin, in which case the dark oval spectra can be explained by a reduced upper cloud opacity (by ~50%) relative to surrounding clouds, and raises the possibility that the upper cloud features might be generated by waves rather than by convection all the way up to the visible cloud level.

This research was supported by grant NNX11AM58G from NASA's Outer Planets Research Program.

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512 – Jupiter and Saturn Composition

512.01 – Saturn's Helium Abundance from Cassini VIMS Stellar Occultations and CIRS Limb Temperature Profiles

We have used Saturn stellar occultations as observed by Cassini VIMS, in concert with Saturn limb temperature profiles derived from Cassini CIRS data to determine the Helium abundance in Saturn's atmosphere near a few mbars. This quantity is long sought, as indication of the internal evolution that Saturn has undergone. Additionally, previous attempts to determine this quantity have produced inconsistent results ranging from He/H₂=0.03±0.02 using Voyager IRIS and RSS (Conrath et al., 1984) to He/H₂=0.13±0.02 using only Voyager IRIS (Conrath & Gautier, 2000) with a similar result being found by Orton and Ingersoll (1980) using Pioneer IRR and RSS (He/H₂=0.11±0.04). These discordant results motivate us to try yet another approach to yield this quantity, in this case using the Cassini VIMS stellar occultations to yield a profile of atmospheric density, and nearly co-located Cassini CIRS limb profiles to yield atmospheric temperature. Combining the two results then yields the mean molecular weight and thus the He/H₂ mixing ratio.

We reported preliminary values from an occultation from the 151st Cassini orbit at DPS in 2011 (He/H₂=0.14±0.05), but have since identified errors in that analysis that have caused us to revisit the problem. Additionally, that occultation occurred near the large Saturn northern hemisphere storm, with significant longitudinal temperature gradients present. The longitudinal separation between the CIRS and VIMS footprints could have skewed the results. In this report, we will discuss our latest results with the algorithm errors corrected, and using data from an occultation of Betelgeuse on the 161st Cassini orbit. These data have the best S/N of all stellar occultations caught by Cassini VIMS to date, and the combination of the VIMS/CIRS data doesn't suffer from problems due to proximity to the storm and its associated spatial gradients in temperature.

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512.02 – Abundances of Elements in Jupiter's Atmosphere

As measured by the Galileo mission, Jupiter's atmosphere is enriched (relative to H and a protosolar composition) in Ar, Kr, Xe, C, N, S and P, by a similar factor of 3 [1]; it is depleted in He, Ne and O. Fractionation of Ar from H requires

temperatures < 35 K [2], but multiple theories exist invoking trapping of species in ices, in principle explaining these enrichments [3-5]. He is depleted by 18%, and Ne by 88% [1]. At the ~1 Mbar level in Jupiter's atmosphere, where H transitions to a metallic state, He droplets can form that precipitate to Jupiter's core; Ne, but not Ar, is expected to dissolve into these droplets, explaining the depletion of both He and Ne [6]. The factor-of-2 depletion of O is currently unexplained but is attributed to meteorological effects [7]. The Juno mission en route to Jupiter will measure the global abundance of O [8].

We present a model for the enrichments of Ar, Kr, Xe, C, N, S and P. Our model [8] builds on that of [5] in which Jupiter accretes nebular gas depleted in H by photoevaporation. Our model improvements allow enrichments with less mass loss, and explain how water vapor can be produced at $T < 35$ K, necessary for trapping of Ar and other species. We predict that Jupiter accreted with a factor-of-3 enrichment of O, but was then sequestered into Jupiter's core along with He and Ne, potentially explaining its factor-of-2 depletion.

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512.03 – New Insights on Jupiter's Deep Water Abundance from Disequilibrium Species

The bulk water abundance on Jupiter potentially constrains the planet's formation conditions. We aim to improve the chemical constraints on Jupiter's deep water abundance in this paper. The eddy diffusion coefficient is used to model vertical mixing in planetary atmosphere, and based on laboratory studies dedicated to turbulent rotating convection, we propose a new formulation of eddy diffusion coefficient. The new formulation predicts a smooth transition from slow rotation regime (near the equator) to the rapid rotation regime (near the pole). We estimate an uncertainty for newly derived coefficient of less than 25%, which is much better than the one order of magnitude uncertainty used in the literature. We then reevaluate the water constraint provided by CO, using the newer eddy diffusion coefficient. We considered two updated CO kinetic models, one model constrains the water enrichment (relative to solar) between 0.1 and 0.75, while the other one constrains the water enrichment between 7 and 23. This difference calls for a better assessment of CO kinetic models.

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