# Habitable Worlds 2021 Workshop
# Open Engagement Abstracts

| # | Title | Abstract | Authors |
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| 8 | Rocky Worlds and their Siblings | We live in a system with multiple rocky planets, but only Earth hosts intelligent life. How did Earth and Venus become twice as large as Mercury and Mars? Did Jupiter help or hinder the growth of the terrestrial planets? Multi-planet systems are natural laboratories that will help us answer these questions. I am leading a NASA Key Strategic Mission Support Survey to measure the composition diversity in a magnitude-limited sample of multi-planet systems. I will discuss my team's recent mass measurements, including characterizations of rocky planets and discoveries of distant Jovian companions, and highlight future opportunities for characterizing rocky planets and their siblings. | L. Weiss;<br><br>Institute for Astronomy, University of Hawai'i at Manoa, Honolulu, HI |
| 10 | Exploring Biogenic Dispersion Inside Star Clusters with System Dynamic Modeling | The discovery of a growing number of exoplanets and even extrasolar systems supports the scientific consensus that it is possible to find other signs of life in the universe. The present work proposes an explicit mechanism inspired by the dynamics of biological dispersion, widely used in ecology and epidemiology, to study the dispersion of biogenic units, interpreted as complex organic molecules, between rocky or water exoplanets (habitats) located inside star clusters. The results of the dynamic simulation suggest that for clusters with populations lower than 4 $M_{\oplus}$/ly3 it is not possible to obtain biogenic worlds after 5 Gyr. Above this population size, biogenic dispersion seems to follow a power law, the larger the density of worlds lesser will be the impact rate (β-0.46) value to obtain at least one viable biogenic Carrier habitat after 5 Gyr. Finally, when we investigate scenarios by varying β, a well-defined set of density intervals can be defined in accordance to its characteristic β value, suggesting that biogenic dispersion has a behavior of “minimal infective dose” of “minimal biogenic effective” events by interval i.e. once this dose has been achieved, doesn’t matter if additional biogenic impact events occur on the habitat. | J. Salcedo;<br><br>Ciinas Corp, La Calera, COLOMBIA. |
| 11 | Dynamical and Biological Panspermia Constraints Within Multiplanet Exosystems | As discoveries of multiple planets in the habitable zone of their parent star mount, developing analytical techniques to quantify extrasolar intra-system panspermia will become increasingly important. Here, we provide user-friendly prescriptions that describe the asteroid impact characteristics which would be necessary to transport life both inwards and outwards within these systems within a single framework. Our focus is on projectile generation and delivery, and our expressions are algebraic, eliminating the need for the solution of differential equations. We derive a probability distribution function for life-bearing debris to reach a planetary orbit and describe the survival of microorganisms during planetary ejection, their journey through interplanetary space, and atmospheric entry. | D. Veras [1], D. Armstrong [1], J. A. Blake [1], J. Gutierrez-Marcos [1], A. P. Jackson [2], H. Schäefer [1];<br><br>1 University of Warwick, Coventry, UNITED KINGDOM, 2 Arizona State University, Tempe, AZ. |

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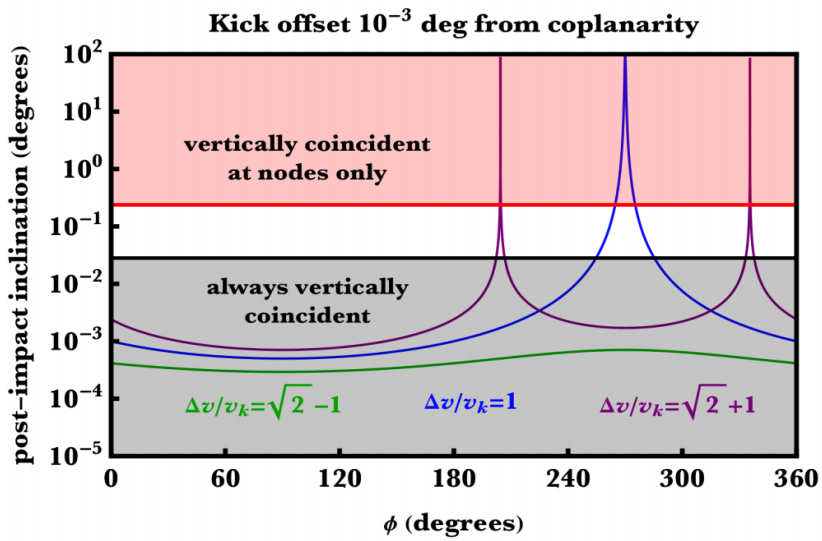
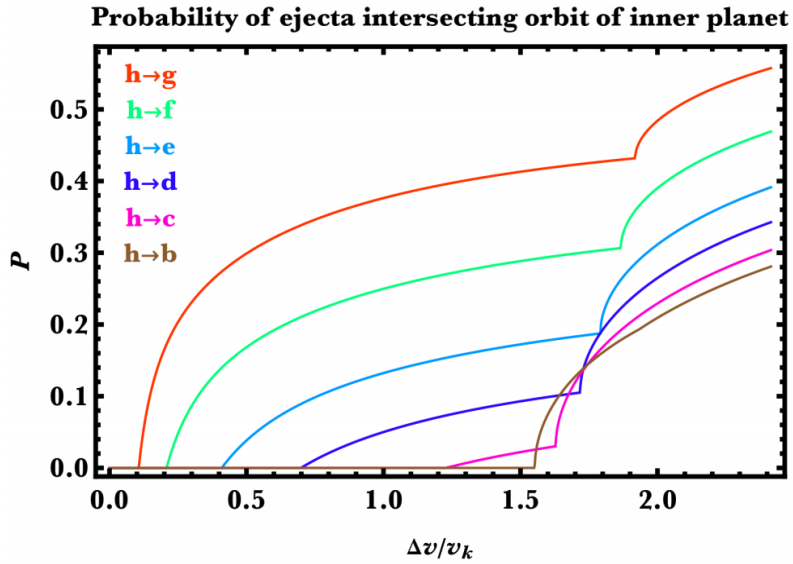
| | | This work is based on the published Astrobiology journal article: Veras et al. (2018, Astrobiology, Volume 18, Issue 9, pp.1106-1122) For example, this figure illustrates how the kick direction from the panspermia-generated collision affects the inclination of the ejecta orbit.<br>  <br><br>This figure illustrates the probability of life-bearing ejecta intersecting the orbits of the planets in the TRAPPIST-1 system<br>  <br> | |
| 13 | Origins of Kepler-1656b's Extreme Eccentricity | Highly eccentric orbits are one of the major surprises of exoplanets relative to the Solar System, and are typically indicative of a rich dynamical history. One system of particular interest is Kepler-1656, which hosts a single known planet on a close-in, highly eccentric (e=0.8) orbit. This orbital configuration places Kepler-1656b on the extreme upper envelope of the e-a diagram and is not a | I. Angelo [1], E. Petigura [1], S. Naoz [1], M. MacDougall [1], A. Stephan [2]; |

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| | | typical outcome of planet formation. Instead, planets formed in a near-circular orbit can be driven to much higher eccentricities via pathways such as planet-planet scattering, perturbation from a stellar flyby, or Kozai evolution induced by an outer stellar or planetary companion in the system. To investigate the possibility of these scenarios, we use Gaia, radial velocities, and ground-based imaging data to place observational constraints on the properties of a potential companion or flyby perturber to Kepler-1656b. We then model the secular evolution of the system in the presence of a third, outer planet using dynamical simulations to assess the likelihood of a high eccentricity excited via the Eccentric Kozai-Lidov effect. | 1 University of California, Los Angeles, Los Angeles, CA,<br>2 The Ohio State University, Columbus, OH. |
| 14 | EUV Spectroscopy with the ESCAPE Mission: Exploring the Stellar Drivers of Exoplanet Habitability | The long-term stability of exoplanetary atmospheres depends critically on the extreme-ultraviolet (EUV) flux from the host star. The EUV flux likely drives the demographics of the short-period planet population as well the ability for rocky planets to maintain habitable environments long enough for the emergence of life. In this talk, I will present the Extreme-ultraviolet Stellar Characterization for Atmospheric Physics and Evolution (ESCAPE) mission, an astrophysics Small Explorer mission currently in Phase A. ESCAPE employs extreme- and far-ultraviolet spectroscopy (70-1600 Angstroms) to characterize the high-energy radiation environment in the habitable zones (HZs) around nearby stars. ESCAPE provides the first comprehensive study of the stellar EUV environments that control atmospheric mass-loss and determine the habitability of rocky exoplanets. ESCAPE will survey over 200 stars, including known planet hosts, to measure EUV irradiance, EUV flare rates, and the characteristics of stellar coronal mass ejections (CMEs). The ESCAPE instrument comprises a grazing incidence telescope feeding four diffraction gratings and photon-counting detector. The science instrument will be assembled and tested in the space hardware facilities at the University of Colorado Boulder (CU) Laboratory for Atmospheric and Space Physics (LASP), and employs the versatile and high-heritage Ball Aerospace BCP-100 spacecraft. Data archives will reside at the Mikulski Archive for Space Telescopes (MAST). | K. France [1], B. Fleming[1], A. Youngblood [1], J. Mason [1], J. Drake[2], ESCAPE Science Team;<br><br>1 LASP / University of Colorado, Boulder, CO,<br>2 Smithsonian Astrophysical Observatory, Cambridge, MA. |
| 18 | Planetary Magnetic Fields, Planetary Interiors, and Habitability | Introduction<br>Even early explanations for Earth's magnetic field linked it to Earth's interior structure. After the discovery of Jupiter's radio emission, it was determined that this radiation is due to Jupiter's magnetic field, which was then tied to the planet's interior structure. Remote sensing and in situ measurements have since shown that the Earth, Mercury, Ganymede, and the giant planets of the Solar System all contain internal dynamos that generate planetary-scale fields; Mars and the Moon show residual magnetism indicative of past dynamos.<br><br>The stellar wind, a super- or transonic magnetized plasma, when incident on a planet's magnetosphere is an energy source to the magnetosphere. The radio emission from an electron cyclotron maser, resulting from this magnetosphere-solar wind interaction, has been detected from the Earth and all of the giant planets in the Solar System.<br><br>Detecting magnetospherically-generated radio emission from extrasolar planets provides a ready means to address a broad range of questions, two of which are i) What characteristics of an | T. Lazio;<br><br>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. |

extrasolar planet might contribute to it being habitable? A planet's magnetic field shields its atmosphere from its host star's stellar wind, which may be a factor in terrestrial planet habitability. (ii) What constraints can be placed on the interior structures and compositions of extrasolar planets? Internal dynamos arise from differential rotation, convection, compositional dynamics, or a combination of these processes. Knowledge of extrasolar planetary magnetic fields has the potential to constrain internal compositions and dynamics, which will be difficult to determine by other means.

A combination of ground- and space-based telescopes will be required, with ground-based telescopes likely focusing on Jovian-mass planets and space-based telescopes likely focusing on ice giants and terrestrial planets. This paper draws heavily on the W. M. Keck Institute for Space Studies report “Planetary Magnetic Fields: Planetary Interiors and Habitability” (Lazio, Shkolnik, & Hallinan 2016), and it incorporates topics discussed at the AAS Topical Conference "Radio Exploration of Planetary Habitability."

Planetary Habitability

Among the factors expected to affect habitability, the Exoplanet Science Strategy identified "[t]he presence and strength of a global scale magnetic field, which depends on interior composition and thermal evolution ...." Further, "... the persistence of a secondary atmosphere over billion-year time scales requires low atmospheric loss rates, which in turn can be aided by the presence of a planetary magnetic field ...."

Spacecraft observations confirm that the solar wind stagnates at the bow of a planet's magnetosphere, with the bulk of the plasma deflected around the magnetospheric cavity (Figure 1). As such, it seems plausible that a global field reduces a planet's atmospheric loss, in particular helping to retain the hydrogen and oxygen ions (i.e., water), and dramatic evidence for atmospheric erosion has been provided by the Mars Atmosphere and Volatile Evolution (MAVEN) mission (Jakosky et al. 2015). Unshielded from the solar wind due to the lack of a global magnetic field, Mars' atmosphere was observed to be eroded during an interaction with a coronal mass ejection (CME). Surprisingly, however, Venus, Earth, and Mars have similar present-day average atmospheric losses, of order 1025 O+ s-1 from their polar regions (Moore & Khazanov 2010). Ideally, a large sample of planets, with a range of atmospheric compositions and magnetic field properties would be available to test the extent to which the presence of a magnetic field protects an atmosphere.

Planetary Interiors

The detection of even a single extrasolar planetary magnetic field could provide essential information on planetary interiors and dynamos. A limiting factor in understanding planetary dynamos is the small sample in the Solar System (Stevenson 2010; Schubert & Soderlund 2011). Just as the discovery of hot Jupiters gave crucial insights to the diversity of planets, the detection of

extrasolar magnetic fields likely will improve our understanding of magnetic dynamos, including in our Solar System.

Inferring planet compositions is an under-constrained inversion problem because planets with disparate compositions can have similar masses and radii. For instance, similar bulk densities could be obtained for a planet with a rock-ice interior and primordial H-He envelope or a water planet or a super-Earth with a H-rich outgassed atmosphere. Magnetic field measurements, providing information about interior structures and compositions, would complement measurements of upper atmosphere compositions obtained by spectroscopy.

The absence of magnetic fields in either ice giants or gas giants would challenge our understanding of their interiors. For ice giants, water is electrically conducting above a few thousand Kelvin, and detections of their magnetic fields would confirm their compositions as being substantially volatile. Similarly, in Jovian planets with massive H-He envelopes, hydrogen is metallic above about 25 GPa, and they are expected to be convective at depth.

The presence of magnetic fields might be most informative for rocky planets, which are not guaranteed to have electrically conducting liquid iron cores. Partial core solidification may limit the range of planet masses that can sustain dynamos, and the extent to which an iron core solidifies is sensitive to the presence of volatiles. Further, the energy budget for convection in Earth's core is marginal. Higher temperature (> 1500 K), stronger tidal heating, higher concentrations of radioactive nuclei, the presence of a thick H-He envelope, or a stagnant lid tectonic regime could turn off convection (and a dynamo) in the core of an otherwise Earth-like planet. It is even possible that different mechanisms operating at different times have been responsible for generating Earth's magnetic field (Ziegler & Stegman 2013). The inference of convection via a magnetic field measurement would constrain the planet's thermal evolution and energy budget and may serve as an indirect indication of plate tectonics.

Observations: Current and Future

An electron cyclotron maser generated by a stellar wind-planetary magnetosphere interaction enables a direct measure of a planet's magnetic field (Figure 2). The emission occurs up to a characteristic frequency determined by the polar cyclotron frequency, which depends upon the planet's magnetic field B, $f_{ECM} = 2.8$ MHz(B/1 Gauss); for Jupiter, $B_J \sim 15$ G and $f_{ECM,J} \sim 30$ MHz. Further, scaling laws exist, based on the Solar System planets (Zarka et al. 1998; Farrell et al. 1999; Christensen 2010). These relations are predictive, with the luminosities of Uranus and Neptune predicted before the Voyager 2 encounters (Desch & Kaiser 1984; Desch 1988; Millon & Goertz 1988). However, only planets with magnetic field strengths comparable to those of Jupiter are detectable from the ground, due to absorption by the Earth's ionosphere; indeed, even the Earth's electron cyclotron maser emission, or the auroral kilometric radiation (AKR), was not discovered until the advent of the Space Age.

Figure 3 presents a graphical summary of most published limits on the radio emission from extrasolar planets. Not shown are a few observations at frequencies above 1000 MHz and a few observations at frequencies around 20 MHz, observations that provide effectively no constraints on planetary radio emission. The lack of effective constraints below about 20 MHz results from the effects of the Earth's ionospheric absorption.

Until recently, most searches for magnetospherically-generated radio emission from extrasolar planets had been at frequencies sufficiently high that they would have been successful only if giant planets could generate magnetic fields an order of magnitude or more stronger than that of Jupiter. Recent observations of HD 80606b with the Low Frequency Array (LOFAR), however, have obtained an order-of-magnitude improvement in sensitivity at frequencies comparable to those at which Jupiter emits (de Gasperin et al. 2020).

Over the next decade, the following are likely: (i) The Juno mission, and potentially subsequent outer planet missions, will improve our knowledge of the magnetic dynamos of the Solar System's giant planets. (ii) Studies of the solar neighborhood will refine the set of extrasolar planets for which magnetic field measurements would be possible and valuable. (iii) Ground-based telescopes, e.g., LOFAR, the Long Wavelength Array at the Owens Valley Radio Observatory (OVRO-LWA), NenuFAR, will improve upon the sensitivity and techniques for detecting extrasolar planetary magnetospheric emissions, with a likely focus on giant planets, and potential surprises from ice giants if their fields are sufficiently strong. (iv) The Sun Radio Interferometer Space Experiment (SunRISE, Kasper et al. 2020), a space-based radio telescope designed to observe solar radio bursts generated by space weather events such as CMEs, such as those that erode Mars' atmosphere, will prove out technologies related to a future mission for studying extrasolar planetary radio emission.

Acknowledgments
It is a pleasure to thank the many colleagues who have aided my understanding of planetary magnetic fields, planetary radio emissions, and the possibilities for (and challenges of) future space missions. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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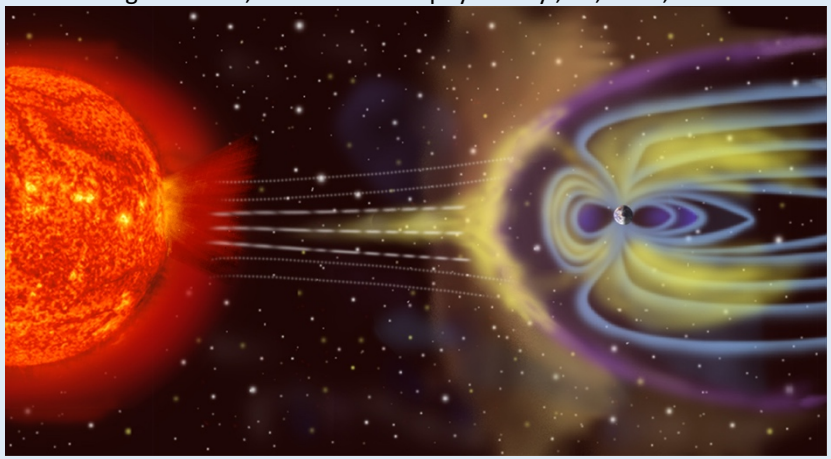

Figure 1. Deflection of a stellar wind around a planet with a planetary-scale magnetic field may prevent or reduce atmospheric erosion over geological time scales. If so, it could be a crucial element of determining whether a planet is or remains habitable. This illustration of the solar wind deflection due to the Earth's magnetic field is based on a variety of spacecraft observations. (Credit: NASA)

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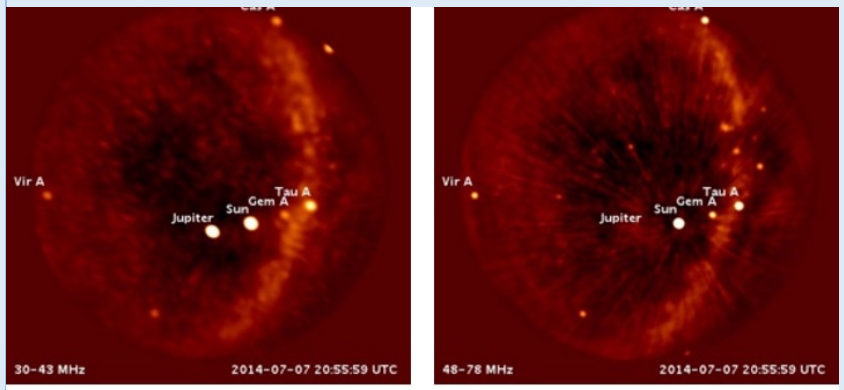
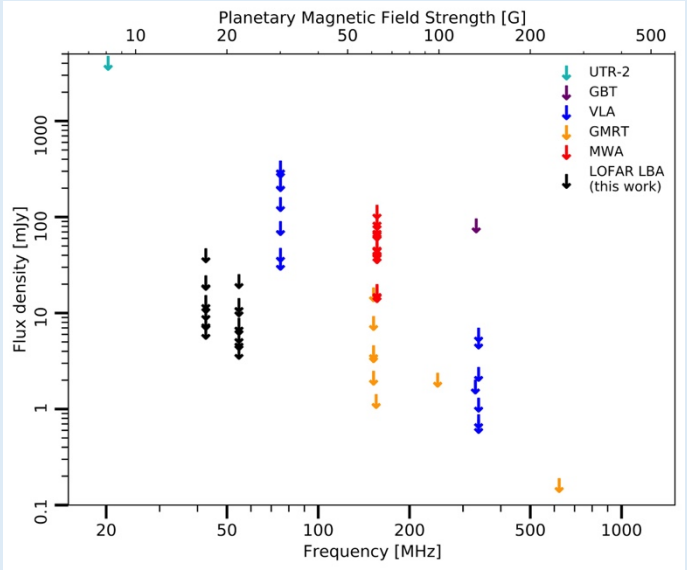
| | | Figure 2. Jupiter as an extrasolar planet, as observed by the Owens Valley Radio Observatory-Long Wavelength Array at 30 MHz--43 MHz (left) and 47 MHz--78 MHz (right). Strong sources are labeled, notably including Jupiter and the Sun. Jupiter's absence in the higher frequency image is consistent with the cutoff frequency of its electron cyclotron maser emission. Ground-based telescopes have been making steady progress toward detecting analogous emissions from nearby giant planets; a space-based telescope would be required to study planets with weaker fields, such as might be expected for ice giants or terrestrial planets. (Credit: M. Anderson)<br>  <br><br>Figure 3. Published upper limits for radio emissions from extrasolar planets (from de Gasperin et al. 2020, and adapted from Lazio, Shkolnik, Hallinan, et al. 2019). Observations have been obtained with Ukrainian T-shaped Radio telescope (UTR-2, cyan), Green Bank Telescope (GBT, brown), the Very Large Array (VLA, blue), Giant Metrewave Radio Telescope (GMRT, orange), the Murchison Wide Field Array (MWA, red), and the Low Frequency Array (LOFAR, black). The LOFAR observations are of the giant planet HD 80606b.<br>  <br> | |
| 19 | Obliquity Variation of Circumbinary Planets | Planet spin-axis variations play an important role in the stability of a planet's climate. For planets around a single star, perturbations from planetary companions could drive spin-orbit resonances and create large variations in the planetary spin-axis orientations. Here, we investigate the spin-axis variations of circumbinary planets -- planets that orbit around stellar binaries. We find that the large | G. Li, R. Chen, M. Tao<br><br>Georgia Institute of Technology, Atlanta, GA. |

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| | | quadrupole potential of the stellar binary could speed up the planetary orbital precession, and detune the system out of spin-orbit resonances. This leads to very small obliquity variations for planets that reside near the same plane as the stellar binaries. Thus, habitable zone planets around the stellar binaries may hold higher potential for stable climate compared to their single star analogues. | |
| 22 | Impact of Photochemistry in Terrestrial P type Circumbinary Exoplanetary Atmospheres | Despite their prevalence, circumbinary planets are often overlooked in the search for life beyond the Earth, primarily due to the unique challenges in supporting life due to the constantly changing insolation in these systems. However, recent studies using 1D and 3D climate models have shown that these time dependent fluctuations are not as detrimental to life as previously thought, and that stable atmospheric conditions can exist for circumbinary planets. However, the role of photochemistry in systems with continually differing radiative intensities and peak types has not been fully explored. Photochemical production of greenhouse gases can significantly alter planetary habitability. Here we present validation of a new one-dimensional time-dependent photochemical climate model of a circumbinary system as well as results showing the impact of atmospheric photochemistry on surface parameters. We find that photochemistry in circumbinary systems can significantly impact surface temperature and enhance atmospheric fluctuations over short timescales. | M. Leung [1], V. Meadows [2]<br><br>1 University of California, Riverside, Riverside, CA,<br>2 University of Washington, Seattle, WA. |
| 23 | Statistical Assessment of Thermochemical Disequilibria in Exoplanets: Implications for Biosignature Detection | Crossing into the next frontier in exoplanet science will require development of quantitative methods that permit reliably characterizing exoplanet atmospheres despite the unavoidable limitations of the low resolution and low s/n data available to current and near-future technology. Exoplanet atmospheres include hundreds of molecules interacting in complex reaction networks, where most of the details of specific molecular species and reaction rates are not known - a problem made more challenging when considering the influence of unknown biology. This combination of observational and model uncertainty creates a unique challenge for exoplanet science, particularly when attempting to infer planetary properties such as degree of disequilibria or the presence of life. Here we demonstrate how the combination of complex systems and atmospheric science can provide a new synthesis for statistically assessing features of exoplanetary atmospheres. We generated ensembles of hot jupiter atmospheres simulated over a wide range of temperatures and metallicities, to produce likelihood distributions of possible atmospheric models centered around a specific observable such as T or metallicity. We then calculated measures of a variety of inferred properties, including abundances of gases, network structure of the atmospheric chemistry and thermodynamic properties and determined which sets of properties most reliably predicted the state of thermochemical disequilibria via machine learning. We discuss implications for the longer-term goal of inferring the presence of life as a driver of atmospheric disequilibrium on terrestrial worlds. | T. Fisher, S. Walker, M. Line, H. Kim;<br><br>Arizona State University, Tempe, AZ. |
| 24 | Testing key concepts of planetary habitability using observations of | The runaway greenhouse transition [1,2], the carbonate-silicate cycle [3,4] and CO_2 surface condensation [4,5] are thought to be three of the most essential geophysical/geochemical processes shaping planetary habitability both inside and outside the solar system [4,6]. However, to date, very little is known about the degree of universality of these processes. | M. Turbet [1], E. Bolmont [1], G. Chaverot [1], D. Ehrenreich [1], J. Leconte [2], C. Lovis [1]; |

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| | nearby rocky exoplanets | At first, I will briefly review recent ideas proposing ways to statistically detect each of these processes at play, using observations of nearby rocky exoplanets [7-12]. These observations are based on the precise measurement of density and/or molecular detections (in particular CO_2) on a large number of rocky exoplanets. I will then focus more specifically on observational tests of the runaway greenhouse [9], which we can actually already attempt in the TRAPPIST-1 multiplanetary system using comparative density measurements among the seven planets [13]. Although we do not detect the runaway greenhouse radius inflation effect predicted in [10], we can use atmospheric model predictions to place strong constraints on the water content of TRAPPIST-1 planets [14].<br><br>While this work has been mostly carried out with the support of 1-D numerical climate models, I will present very recent results obtained with 3D Global Climate Models [15], taking into account the effect of atmospheric dynamics and clouds.<br><br>REFERENCES<br>[1] Kasting (1988), Icarus<br>[2] Goldblatt & Watson (2012), Philosophical Transactions of the Royal Society of London Series A<br>[3] Walker, Hays & Kasting (1981), Journal of Geophysical Research [<br>[4] Kasting, Whitmire & Reynolds (1993), Icarus<br>[5] Turbet et al. (2017), Earth and Planetary Science Letters<br>[6] Kopparapu et al. (2013), The Astrophysical Journal<br>[7] Bean, Abbot & Kempton (2017), The Astrophysical Journal Letters<br>[8] Checlair et al. (2019), Astro2020 white paper<br>[9] Turbet et al. (2019), Astronomy & Astrophysics<br>[10] Turbet (2019), Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics<br>[11] Graham & Pierrehumbert (2020), The Astrophysical Journal<br>[12] Lehmer, Catling & Krissansen-Totton (2020), Nature Communications<br>[13] Turbet et al. (2020), Astronomy & Astrophysics<br>[14] Agol et al. (2020), The Planetary Science Journal<br>[15] Turbet et al., in preparation | 1 Astronomical Observatory of the University of Geneva, Geneva, SWITZERLAND,<br>2 Université de Bordeaux / CNRS, Bordeaux, FRANCE. |
| 25 | New Near-UV $H_2O$ Cross-Sections & Photochemistry of Early Earth-like Atmospheres | We use new laboratory measurements of the absorption properties of water vapor to dramatically revise theoretical predictions of the concentrations of spectrally active trace gases in early-Earth like exoplanet atmospheres, and eliminate a key O_2 false positive scenario. We study the photochemistry of abiotic, habitable planets with anoxic CO_2-N_2 atmospheres. Such worlds are representative of early Earth, Mars and Venus, and analogous exoplanets. H_2O photodissociation controls the atmospheric photochemistry of these worlds through production of reactive OH, which dominates the removal of atmospheric trace gases. The near-UV (NUV; >200 nm) absorption cross-sections of H_2O were previously unmeasured at habitable temperatures (< 373 K). We present the first-ever measurements of NUV H_2O absorption at 292 K, and show it to absorb orders of magnitude more than previously assumed. The enhanced OH production due to these higher cross-sections leads to efficient recombination of CO and O_ [2], suppressing both by orders of magnitude | S. Ranjan [1], E. Schwieterman [2], C. Harman [3], A. Fateev [4], C. Sousa-Silva [5], S. Seager [6], R. Hu [7];<br><br>1 Northwestern University, Evanston, IL,<br>2 UC Riverside, Riverside, CA,<br>3 NASA Ames, Moffett Field, CA, |

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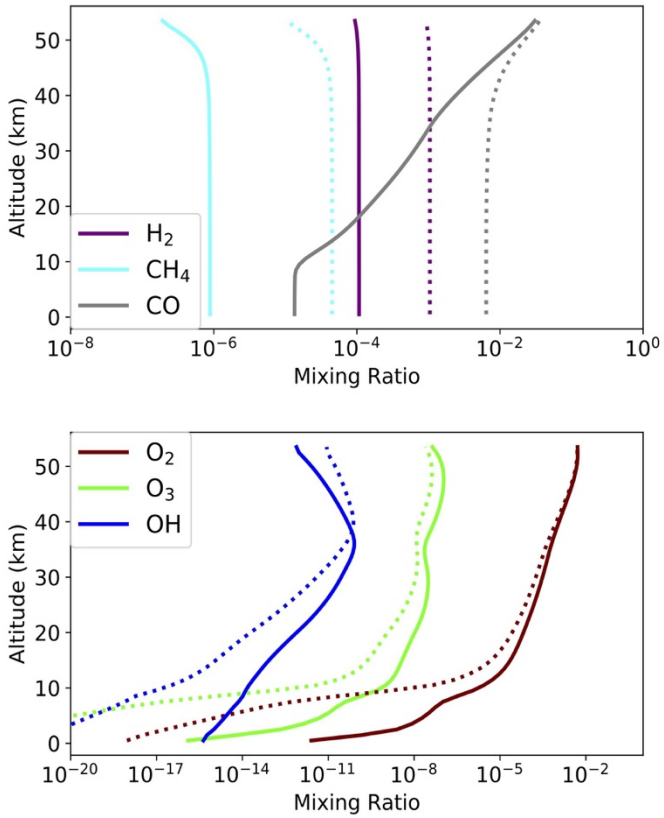
| | | relative to past predictions and eliminating the low-outgassing "false positive" scenario for O_2 as a biosignature. Enhanced [OH] increases rainout of reductants to the surface, relevant to prebiotic chemistry, and may also suppress CH_4 and H_2. Overall, our work advances the state-of-the-art of photochemical models by providing crucial new H_2O cross-sections, and suggests that detection of spectrally active trace gases like CO in rocky exoplanet atmospheres may be more challenging than previously considered. While we focus on CO_2-rich worlds, our results are relevant to anoxic planets in general.<br>  <br><br>FIGURE: Atmospheric concentrations of key reducing and oxidizing trace gases for an early Earth-like exoplanet orbiting a Sun-like star, comparing the atmospheric composition predicted using our new H2O cross-sections (solid lines) compared to the cross-sections recommended by Sander et al (2011). The difference in H2O cross-sections affects atmospheric concentrations of key gases like CO by orders of magnitude. | 4 Technical University of Denmark, Kongens Lyngby, DENMARK,<br>5 Harvard University, Cambridge, MA,<br>6 MIT, Cambridge, MA,<br>7 NASA JPL, Pasadena, CA. |
| 26 | Magnetospheres of Terrestrial Exoplanets and Exomoons - | Characterizing habitable exoplanets and/or their moons is of paramount importance. Here we show the results of our magnetic field topological modeling which demonstrate that terrestrial exoplanet-exomoon coupled magnetospheres work together to protect the early atmospheres of both the exoplanet and the exomoon. When exomoon magnetospheres are within the exoplanet's | J. Green [1], C. Dong [2], S. Boardsen [3]; |

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| | Implications for Habitability and Detection | magnetospheric cavity, the exomoon magnetosphere acts like a protective magnetic bubble providing an additional magnetopause confronting the stellar winds when the moon is on the dayside. In addition, magnetic reconnection develops a critical pathway for the atmosphere exchange between the early exoplanet and exomoon. When the exomoon's magnetosphere is outside of the exoplanet's magnetosphere it then becomes the first line of defense against strong stellar winds, reducing exoplanet's atmospheric loss to space. A brief discussion is given on how this type of exomoon would modify radio emissions from magnetized exoplanets. | 1 Office of the Chief Scientist, NASA Headquarters, Washington, DC,<br>2 Department of Astrophysical Sciences, Princeton Plasma Physics Laboratory, Princeton, NJ,<br>3 Physics, University of Maryland Baltimore County, Baltimore, MD. |
| 27 | Modeling Flood Basalt Volcanic Climate Disruptions: Implications for Terrestrial Planet Habitability | Volcanic flood basalt eruptions in Earth's history have covered thousands of square kilometers with basalt deposits up to kilometers thick [Glaze et al., 2017]. The massive size and extended duration (up to centuries or millennia) result in enormous releases of climactically-relevant gas species such as SO_2 and CO_2 [e.g., Davis et al., 2017]. Historic flood basalt eruptions on Earth such as the Siberian and Deccan Traps are coincident with mass extinction events, although the casual linkages are still being studied [Courtillot et al., 1988; Wignall, 2001; Renne et al., 2015]. Additionally, flood basalt eruptions seem to be a common feature of terrestrial planets in our Solar System [Lancaster et al., 1995; O'Hara, 2000; Head et al., 2011; Jaeger et al., 2010] and are hence plausible on terrestrial exoplanets. Indeed, flood basalt eruptions may have made the ancient martian climate more habitable [e.g., Halevy and Head, 2014].<br><br>However, what is still unknown is precisely how flood basalt eruptions influence planetary climate via their eruption rates and cadence [Davis et al., 2017], height of the volcanic plumes [e.g., Glaze et al., 2017], and relative degassing abundance of climactically-relevant species like SO_2 [Self et al., 2006; Davis et al., 2017]. Once eruptions occur, the complex interplay of photochemistry (e.g., turning SO_2 into H_2SO_4 aerosols), greenhouse gas warming, changes to the atmospheric circulation, and aerosol-cloud interactions can only be properly simulated with a comprehensive global climate model (GCM). Previous work on the terrestrial climate response to large volcanic eruptions has settled on the initiation of "volcanic winter", a cooling response to the reduced surface insolation caused by a widespread blanket of H_2SO_4 aerosols in the upper troposphere and stratosphere [e.g., Robock et al., 2009]. Smaller-scale eruptions produce more varied regional effects, but again, largely with cooler temperature anomalies at the surface [e.g., Oman et al., 2006]. However, these previous works have generally focused on explosive eruptions-single short-duration events that inject material into the stratosphere. This is in contrast to flood basalt eruptions, which have much longer durations and likely injected material both at the surface and at higher altitudes in the troposphere and lower stratosphere.<br><br>Our ongoing work has simulated a short-duration Columbia River Flood Basalt (CRB)-like eruption, a medium-scale flood basalt eruption that occurred ~15-16 Mya in eastern Washington state and Oregon. While the CRB is not believed to have initiated an extinction event, it occurred in the midst | S. Guzewich [1], L. Oman [1], J. Richardson [2], P. Whelley [2], K. Young [1], J. Bleacher [3];<br><br>1 NASA GSFC, Greenbelt, MD,<br>2 University of Maryland, College Park, MD,<br>3 NASA HQ, Washington, DC. |

of the Mid-Miocene climactic optimum [Kasbohm and Schoene, 2018] and there is some evidence of a coincident glaciation [e.g., Armstrong McKay et al., 2014]. The CRB eruption occurred in a variety of phases, the largest termed the Grande Ronde basalt formation. Following Davis et al. [2017], we created an eruption scenario for the Goddard Chemistry Climate Model (GEOSCCM) [Oman et al., 2013] that emits SO_2 in the near-surface atmosphere constantly and periodically (four times per year) an explosive eruption that emits much more SO_2 in the upper troposphere/lower stratosphere. The eruption lasts for 4 years and emits 30 Gt of SO_2 in total. This corresponds to approximately 1/10th of what may have been emitted during the Grande Ronde eruption phase of the CRB [Davis et al., 2017]. Note that we have used a post-industrial atmosphere and ocean with modern continental configuration as our baseline, and simulations with a pre-industrial atmosphere are ongoing. Our simulations do not include SO_2 as a radiatively active species, however H_2SO_4 aerosols are radiatively active. Atmospheric CO_2 is set at 400 ppm. The massive flux of SO_2 into the atmosphere is quickly converted to H_2SO_4 aerosols. Global area-weighted mean visible band sulfate aerosol optical depth reaches 230 near the end of the eruption, comparable to cumulonimbus clouds. This reduces the surface shortwave radiative flux by 85% and top-of-atmosphere outgoing longwave flux by 70%.

Contrary to our expectations, we find that the climate warms during and immediately following the eruption after a very brief initial cooling. Global mean surface temperature peaks 3-4 years after the eruption ends with a +7 K anomaly relative to a baseline simulation without the eruption. Post-eruption regional temperatures, particularly near-equatorial continental areas, see drastic rises of summertime temperatures with monthly mean temperatures equaling or exceeding 40°C, which are uninhabitable temperatures for mammals [Sherwood and Huber, 2010]. These temperature responses are radiative- and circulation-driven. The eruption warms and raises the tropical tropopause, allowing a massive flux of water vapor into the stratosphere. Stratospheric water vapor, usually ~3 parts per million reaches 1-2 parts per thousand. This increase results in increased thermal infrared flux from the stratosphere, which cools that portion of the atmosphere while also warming the surface and troposphere. Such a water flux into the stratosphere may have implications for historic water loss on planets such as Mars and Venus. Despite the massive perturbation to the climate during the four-year eruption, the climate approaches pre-eruption normal after seven years post-eruption. H_2SO_4 aerosols are nearly absent, surface radiative fluxes are near normal, and global temperatures are cooling toward normal levels. However, the stratospheric water vapor is more slowly returning to pre-eruption levels and remains more than one order of magnitude higher than pre-eruption levels after seven years post-eruption.

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| 28 | MHD Effects of the Stellar Wind on Observations of Escaping Exoplanet Atmospheres | Interaction with the stellar wind and accompanying radiation can result in significant atmospheric erosion, potentially affecting a planet's ability to host life. Previous research indicates the atmospheres of close-in, low-mass planets are highly vulnerable to the effects of XUV driven photoevaporation. However, the effects of the stellar wind on low-mass exoplanet atmospheres have only just begun to be addressed. We present 3D magnetohydrodynamical (MHD) simulations of the effect of the stellar wind on the escaping atmosphere of a magnetized planet in the habitable zone of a low-mass M dwarf. We use the TRAPPIST-1 system as the basis of our simulations and model the planet to have an H-rich evaporating outflow, with a pre-defined mass loss rate. Our results show the atmospheric outflow is dragged and accelerated upon interaction with the stellar wind, resulting in a diverse range of planetary magnetospheres which are strongly dependent on the local stellar wind conditions through the orbit and can vary over timescales as short as an hour. We explore the implications of this wind-outflow interaction on potential observations of escaping atmospheres and show that stellar wind interactions provide an explanation for observed variations in transit absorption features. | L. Harbach [1], S. P. Moschou [2], C. Garraffo [3], J. Drake [2], J. Alvarado [4], O. Cohen [5], F. Fraschetti [2,6];<br><br>1 Imperial College London, London, UNITED KINGDOM,<br>2 Center for Astrophysics \| Harvard & Smithsonian, Cambridge, MA,<br>3 Institute for Applied Computational Science, Harvard University, Cambrige, MA, |

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| | | | 4 Leibniz Institute for Astrophysics, Potsdam, GERMANY,<br>5 Lowell Center for Space Science and Technology, Lowell, MA,<br>6 Dept. of Planetary Sciences-Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ. |
| 30 | A Framework for Relative Biosignature Yields from Future Direct Imaging Missions | Future exoplanet direct imaging missions, such as HabEx and LUVOIR, will select target stars to maximize the number of Earth-like exoplanets that can have their atmospheric compositions characterized. Because one of these missions' aims is to detect biosignatures, they should also consider the expected biosignature yield of planets around these stars.<br><br>In this work, we develop a method of computing relative biosignature yields among potential target stars, given a model of habitability and biosignature genesis, and using a star's habitability history. As an illustration and first application of this method, we use MESA stellar models to calculate the time evolution of the habitable zone, and examine three simple models for biosignature genesis to calculate the relative biosignature yield for different stars.<br><br>We find that the relative merits of K stars versus F stars depend sensitively on model choice. In particular, use of the present-day habitable zone as a proxy for biosignature detectability favors young, luminous stars lacking the potential for long-term habitability. Biosignature yields are also sensitive to whether life can arise on Cold Start exoplanets that enter the habitable zone after formation, an open question deserving of more attention.<br><br>Using the case study of biosignature yields calculated for Theta Cygni and 55 Cancri, we find that robust mission design and target selection for HabEx and LUVOIR depends on: choosing a specific model of biosignature appearance with time; The terrestrial planet occurrence rate as a function of orbital separation; Precise knowledge of stellar properties; And accurate stellar evolutionary histories. | N. Tuchow, J. Wright;<br><br>Astronomy and Astrophysics, Pennsylvania State University, University Park, PA. |
| 31 | On the prospect of detecting habitable trojan planets in the Kepler circumbinary planetary systems | We present the results of a study on the prospect of detecting habitable trojan planets in the Kepler Habitable Zone circumbinary planetary systems (Kepler 16, 47, 453, 1647, 1661). We integrated the orbits of 10,000 separate 4-body systems (6-body systems in the case of Kepler 47), each with a one Earth-mass trojan planet in a randomly selected orbit near the Lagrangian points of its host planet. Stable orbits are restricted to a narrow range of semi-major axes in all five systems and limited to small eccentricities in Kepler 16, 47, and 1661. The mean amplitudes of the transit timing variations (TTVs) correlate with the mass of the transiting planet and range from 70 minutes (Kepler 16) to 390 minutes (Kepler 47). These results suggest that the detection of an Earth-mass trojan planet from | J. Sudol [1], N. Haghighipour [2];<br><br>1 Physics and Engineering, West Chester University, West Chester, PA, |

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| | | TTVs is possible in systems like these. The period of oscillation of the TTVs for Kepler-16 is 20 transits (12.5 years), which suggests that the orbital characteristics of such a massive trojan planet could be inferred from a decade of transit data. | 2 Institute for Astronomy, University of Hawai'i-Manoa, Honolulu, HI. |
| 32 | Inter-model Comparisons for Exoplanets | The era of atmospheric characterization of terrestrial exoplanets is just around the corner. Prior modeling of observables is crucial so that one can prepare for challenges in data interpretation.<br><br>Planets are inherently complex objects with multiple interacting systems, including 3-D atmospheric circulation patterns, atmospheric chemistry, and ice formation that affect the climate. As a result, we need a variety of models that use different approaches to simulating these planetary atmospheres. However, many of these models are themselves very complex, and their outputs can vary from one another for a variety of reasons. To address these issues, GCM intercomparisons have been widely used by the Earth science community. For instance, the Coupled Model Intercomparison Project (CMIP) initiated in 1995, currently in its version 6 (Eyring et al., 2016), focuses on the differences in GCM responses to forcings from anthropogenic climate change. CMIP is crucial to assess model performances, to quantify the difference between the model predictions and to understand the model responses. To our knowledge only two inter-model comparisons have been applied to exoplanets, Yang et al., (2016, 2019) and the TRAPPIST-1 Habitable Atmosphere Intercomparison (THAI, Fauchez et al. 2020). In this talk we will discuss the lessons learned from these two projects, the important role that inter-model comparisons can have for exoplanet studies and bridging for future larger projects such as the Climates Using Interactive Suites of Intercomparisons Nested for Exoplanet Studies (CUISINES) NExSS Working Group. | T. Fauchez [1], L. Sohl [2], M. Turbet [3], D. Sergeev [4], E. Wolf [5], K. Tsigaridis [2], M. Way [6], I. Boutle [7], N. Mayne [8], S. Domagal-Goldman [9], R. Kopparapu [9];<br><br>1 NASA GSFC / USRA, Greenbelt, MD,<br>2 NASA GISS / Columbia University, New York, NY,<br>3 Geneva Observatory, Geneva, SWITZERLAND,<br>4 Exeter University, Exeter, UNITED KINGDOM,<br>5 Colorado University, Boulder, CO,<br>6 NASA GISS, New York, NY,<br>7 College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UNITED KINGDOM,<br>8 University of Exeter, Exeter, UNITED KINGDOM,<br>9 NASA GSFC, Greenbelt, MD. |
| 34 | Removing Stellar Activity Signals from Radial Velocity Measurements Using Neural Networks | Future large space missions designed to search for biosignatures in the atmospheres of Earth-like exoplanets will operate more efficiently and have a higher chance of success if stars with possible Earth analogs are known before launch. One way to find these Earth-like candidates is with the radial velocity technique, but this method is currently limited by spurious signals introduced by stellar activity (i.e. faculae, starspots). Here we show that machine learning techniques such as linear regression and neural networks can effectively remove these activity signals from RV observations. Previous efforts have focused on carefully filtering out activity signals in time using Gaussian process regression (e.g. Haywood et al. 2014). Instead, we separate activity signals from true center-of-mass RV shifts using only changes to the average shape of spectral lines, and no information about when the observations were collected. We demonstrate our technique on | Z. de Beurs [1,2], A. Vanderburg [2], C. J. Shallue [3], HARPS-N Collaboration;<br><br>1 Department of Astronomy, University of Texas, Austin, Austin, TX,<br>2 Department of Astronomy, University of Madison-Wisconsin, Madison, WI, |

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| | | simulated data, reducing the RV scatter from 82.0 cm s-1 to 3.1 cm s-1 , and on approximately 700 observations taken nearly daily over three years with the HARPS-N Solar Telescope, reducing the RV scatter from 1.47 m s-1 to 0.78 m s-1 (a 47% or factor of ~ 1.9 improvement). In the future, these or similar techniques could remove activity signals from observations of stars outside our solar system and eventually help detect habitable-zone Earth-mass exoplanets around Sun-like stars. In this way, improvements in RV precision could significantly accelerate the characterization of habitable zone Earth-sized exoplanets. | 3 Center for Astrophysics \| Harvard-Smithsonian, Cambridge, MA. |
| 36 | Investigating the atmospheric evolution of habitable worlds with a coupled climate-interior-redox model | The atmospheric evolution of terrestrial planets is sculped by a range of complex astrophysical, geophysical, and geochemical processes. Interpreting observations of ostensibly habitable exoplanets will require an improved understanding of how these competing influences interact on long timescales. In particular, the interpretation of potential biosignature gases, such as oxygen, is contingent upon understanding the probable redox evolution of lifeless worlds. Here, we develop a generalized model of terrestrial planet atmospheric evolution to anticipate observations of habitable exoplanets. The model, which is shown schematically in Fig. 1, connects early magma ocean evolution to subsequent, temperate geochemical cycling. The thermal evolution of the interior, cycling of C-H-O bearing volatiles, surface climate, crustal production, and atmospheric escape are explicitly coupled throughout this evolution. The redox evolution of the atmosphere is controlled by net planetary oxidation via the escape of H to space, the loss of atmospheric oxygen to the magma ocean, and oxygen consumption via crustal sinks such as outgassing of reduced species, serpentinization reactions, and direct “dry” oxidation of fresh crust.<br><br>The model can successfully reproduce the atmospheric evolution of a lifeless Earth: it consistently predicts an anoxic atmosphere and temperate surface conditions after 4.5 Gyrs of evolution. This result is insensitive to model uncertainties such as the details of atmospheric escape, mantle convection parameterizations, initial radiogenic inventories, the efficiency of crustal oxygen sinks, and unknown carbon cycle and deep-water cycle parameters. This suggests abundant oxygen is a reliable biosignature for literal Earth twins, defined as Earth-sized planets at 1 AU around sunlike stars with 1-10 Earth oceans and less initial carbon dioxide than water.<br><br>However, if initial volatile inventories are permitted to vary outside these “Earth-like” ranges, then dramatically different redox evolution trajectories are permitted. We identify three scenarios whereby Earth-sized planets in the habitable zones of sunlike stars could accumulate oxygen rich atmospheres (0.01 - 1 bar) in the absence of life. Specifically, (i) high initial CO_2:H_2O endowments, (ii), >50 Earth ocean water inventories, or (iii) extremely volatile poor initial inventories, could all result in oxygen-rich atmospheres after 4.5 Gyrs of evolution. These false positives arise despite the assumption that there is always sufficient non-condensible atmospheric gases, N_ [2], to maintain an effective cold trap (Wordsworth & Pierrehumbert 2014). Fortunately, all three of these oxygen false positive scenarios could potentially be identified by thorough characterization of the planetary context. Using time resolved photometry to deduce surface maps | J. Krissansen-Totton [1], J. Fortney [1], F. Nimmo [2], N. Wogan [3];<br><br>1 Department of Astronomy and Astrophysics, University of California, Santa Cruz, Santa Cruz, CA,<br>2 Department of Earth and Planetary Sciences, University of California, Santa Cruz, Santa Cruz, CA,<br>3 University of Washington, Seattle, WA. |

would be especially helpful in ruling out high water inventory, waterworld false positives (Lustig-Yaeger et al. 2018).

The model also sheds light on the atmospheric evolution of Venus and Venus-like exoplanets. We can successfully recover the modern state of Venus' atmosphere, including a dense CO_2-dominated atmosphere with negligible water vapor and molecular oxygen. Moreover, there is a clear dichotomy in the evolutionary scenarios that recover modern Venus conditions, one in which Venus was never habitable and perpetually in runaway greenhouse since formation, and another whereby Venus experienced ~1-2 Gyr of surface habitability with a ~100 m deep ocean (c.f. Way et al. 2016). We explore the likelihood of each scenario and suggest future in situ observations that could help discriminate between these two alternative histories.

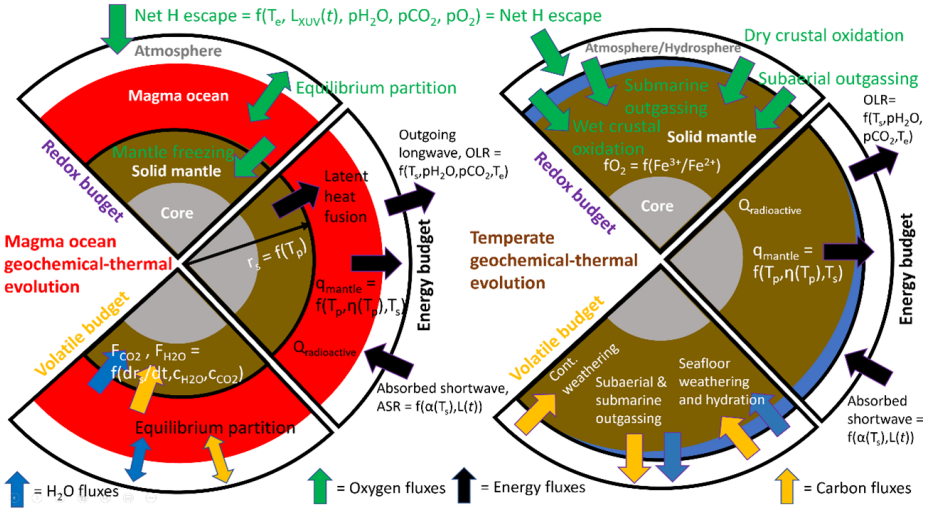


Fig. 1: Schematic of terrestrial planet geochemical evolution model. The planetary redox budget, thermal-climate evolution, and volatile budget are modeled from initial magma ocean (left) through to temperate geochemical cycling (right). Oxygen fluxes are shown by green arrows, energy fluxes by black arrows, carbon fluxes by orange arrows, and water fluxes by blue arrows. Note that the net loss of H to space effectively adds oxygen to the atmosphere. During the magma ocean phase, the radius of solidification, r_s, begins at the core-mantle boundary and moves toward the surface as internal heat is dissipated. The rate at which this occurs is controlled by radiogenic heat production, Q_radioactive, and convective heatflow from the mantle to the surface, q_m. This internal heatflow balances the difference between outgoing longwave radiation, OLR, and incoming shortwave radiation, ASR. The oxygen fugacity of the mantle, fO_2, and the water and carbon content mantle and surface reservoirs are tracked throughout

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| 37 | Imaging Small Planets Around the Very Nearest Stars with METIS on ELT | Space-based transit surveys have revolutionized our understanding of the frequency of small rocky planets at small orbital radii around sunlike stars. The next generation of extremely large telescopes will have the angular resolution and sensitivity to directly image rocky planets around the very nearest stars (Wang et al.). Here we predict yields of the METIS instrument (Brandl et al. 2018), planned for the European Southern Observatory (ESO) Extremely Large Telescope (ELT). Using Kepler occurrence rates, a selection of nearby stars, and simulated contrast curves based on an advanced model of coronagraphic imaging with adaptive optics with METIS on the ELT, we estimate the expected yield from METIS using Monte Carlo simulations. We find the METIS expected yield of planets in the N2 (10.0 - 12.5 µm) band which outperforms the L (3.6 - 4.0 µm) and M (4.8 - 5.0 µm) bands. We also determine the chance of at least one rocky planet detection in the contrast limited regime and at least one Jovian planet in the background limited regime. We find the yield per star and optimal revisit times to increase yield. Finally, we present an optimal observing strategy in order to maximize the possible yield for limited telescope time. | R. Bowens [1], M. Meyer [1], C. Delacroix [2], O. Absil [2], R. van Boekel [3], S. P. Quanz [4], M. Shinde [5];<br><br>1 The University of Michigan, Ann Arbor, MI,<br>2 The University of Liege, Liege, BELGIUM,<br>3 MPIA, Heidelberg, GERMANY,<br>4 ETH Zurich, Zurich, SWITZERLAND,<br>5 IISER Pune, Pune, INDIA. |
| 39 | The Role of Orbital Dynamics In Planetary Habitability | A key component of characterizing multi-planet exosystems is testing the orbital stability based on the observed properties. Orbital dynamics is also a critically important component of testing habitability scenarios for terrestrial planets within the system, and can play a major role in driving the evolution of terrestrial planet climates. In this talk I will describe recent work regarding the effects of orbital dynamics on planetary habitability, including the effect of giant planets on terrestrial planet orbital stability, the maximum number of terrestrial planets dynamically allowed in the Habitable Zone, and global circulation models that demonstrate the climate impacts and water loss rates for eccentric orbits. I will discuss examples of orbital dynaimcal effects on habitability, including the HR 5183, Beta CVn, and Kepler-1649 systems. This work emphasizes the need for refining Keplerian orbits as a crucial input for climate studies and the potential impact of eccentricity on terrestrial planet surface conditions. | S. Kane;<br><br>University of California, Riverside, Riverside, CA. |
| 40 | Dayside land on tidally locked M-Earths | A planet's surface conditions can significantly impact its climate and habitability. In this work, we use a 3D GCM to systematically vary dayside land cover on a tidally locked M-Earth under two extreme and opposite continent configurations, in which either all of the land or all of the ocean is centred at the substellar point. We identify water vapour and sea ice as competing drivers of climate, and we identify land-dependent regimes under which one or the other dominates. We find that land fraction and distribution can cause ample differences in average surface temperature and atmospheric water vapour, with the most discrepant cases occurring at partial dayside land cover with opposite continent configuration. Since M-Earth surfaces will not be directly observable using transit spectroscopy, these differences represent a fundamental uncertainty in an M-Earth's climate, even if the atmospheric composition is well-known. Our results are robust to variations in atmospheric CO_2 concentration, stellar temperature, instellation, and surface albedo. | E. Macdonald [1], A. Paradise [2], K. Menou [2], C. Lee [1];<br><br>1 Physics, University of Toronto, Toronto, ON, CANADA,<br>2 Astronomy and Astrophysics, University of Toronto, Toronto, ON, CANADA. |

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| 41 | On the oligarchic growth in a fully interacting system | In the oligarchic growth model, protoplanets develop in the final stage of planet formation via collisions between planetesimals and planetary embryos. The majority of planetesimals are accreted by the embryos, while the remnant planetesimals acquire dynamically excited orbits. The efficiency of the planet formation can be defined by the mass ratio between formed protoplanets and the initial mass of the embryo-planetesimal belt.In numerical simulations of the oligarchic growth, the gravitational interactions between planetesimals are usually neglected due to computational difficulties. In this way, computations require fewer resources. We investigated the effect of this simplification via modeling the planet formation efficiency in a belt of embryos and self-interacting or non-self-interacting planetesimals.We used our own developed GPU-based direct N-body integrator for the simulations. We compared 2D models using different initial embryo number, initial planetesimal number, and total initial belt mass. For limited cases, we compared 2D to 3D simulations.We found that planet formation efficiency is higher if the planetesimal self-interaction is taken into account in models that contain the commonly used 100 embryos. The observed effect can be explained by the damping of planetesimal eccentricities by their self-gravity. The final numbers of protoplanets are independent of planetesimal self-gravity, while the average mass of the formed protoplanets is larger in the self-interacting models. We also found that above 200 embryos, the non-self-interacting and self-interacting models give qualitatively the same results. Our findings show that the higher is the initial mass of the embryo-planetesimal belt, the higher is the discrepancy between models that use self-interacting or non-self-interacting planetesimals. The study of 3D models showed quantitatively same result as 2D models for low average inclination. We conclude that planetesimal self-interaction must be included either in 2D and 3D models below 200 initial embryo number. | Z. Dencs, Z. Regaly;<br><br>Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Budapest, HUNGARY. |
| 42 | Methane: the Ideal Biosignature for the JWST Era? | The next phase of exoplanet science will focus on characterizing exoplanet atmospheres, including those of low-mass, terrestrial planets. A comprehensive understanding of possible biosignatures that may be detected with the next generation of ground and space telescopes is warranted. While some biosignature gases, such as oxygen and phosphine, have recently been reviewed in depth (Meadows et al. 2018 and Sousa-Silva et al. 2020), these will likely be extremely difficult to detect with JWST. In contrast, while it has not been thoroughly reviewed, methane at Earth-like biogenic fluxes is one of the only biosignatures that may be readily detectable with JWST (Krissansen-Totton et al. 2018a). In fact, an early Earth-like, methane-rich atmosphere would be easier to detect with JWST than modern Earth's oxygen-rich atmosphere (ibid). Here we present our preliminary work on a comprehensive review of methane biosignatures and false positives.<br><br>Biogenic methane production, or methanogenesis, is a simpler metabolism than oxygenic photosynthesis, that is carried out by anaerobic microbes (i.e., those not requiring oxygen for growth). Methanogens use either CO2 and H2 or acetate as substrates (Schwieterman et al. 2018). This process could be widespread due to the likely ubiquity of the CO2+H2 redox couple in terrestrial planet atmospheres, and the antiquity of methanogenesis on Earth (Wolfe and Fournier 2018). We briefly review the current understanding of the origin and evolution of methanogens, the organisms responsible for methanogenesis, and how this process relates to origins-of-life theories. | M. Thompson, J. Krissansen-Totton, J. Fortney;<br><br>University of California, Santa Cruz, Santa Cruz, CA. |

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| | | When CH4 is invoked as a possible biosignature it is often included with a strongly oxidizing companion gas (e.g., CO2 or O2/O3). This is because it is difficult to explain abundant CH4 if a terrestrial planet atmosphere's redox state is more oxidizing so that the thermodynamically stable form of carbon would not be CH4 (Schwieterman et al. 2018). However, even in atmospheres devoid of oxygen, CH4 has a short photochemical lifetime on habitable zone rocky planets, and the large fluxes required to sustain high CH4 abundances are likely much greater than could be supplied by abiotic processes (e.g., magmatic outgassing, serpentinization) (Krissansen-Totton et al. 2018b, Wogan et al. 2020). In addition, many abiotic, geological processes that produce CH4 are expected to also produce abundant CO, which life readily consumes, so the presence of CH4 and CO2 but absence of CO strengthens the case for biogenicity (Krissansen-Totton et al. 2018b). Although CH4+CO2 (minus CO) might coexist in thermodynamic equilibrium on planets without large surface oceans (Woitke et al. 2020), in practice, such atmospheres would be photochemically unstable and, in particular, the CH4 would have a short lifetime (less than ~1 Myrs).<br><br>In addition to briefly discussing methane on Mars and Titan, we review the presence of methane in Jovian and sub-Neptune planet atmospheres. In many giant planets, methane is the most abundant carbon-bearing gas and can be replenished indefinitely because, although methane is photodissociated in the upper atmosphere, hydrogen is never depleted and carbon and hydrogen can recombine deeper in the atmosphere where temperatures and pressures are high enough for methane production to be thermodynamically favorable and kinetically viable (Moses et al. 2013). On the other hand, terrestrial planets with high mean molecular weight atmospheres do not have deep enough atmospheres to replenish methane without an additional source (abiotic or biotic). In terrestrial atmospheres without a replenishment source, methane is photodissociated and hydrogen is lost to space on short timescales (~10s of thousands of years for ~1 bar atmospheres). For planets in the sub-Neptune regime, we seek to determine how much atmosphere is necessary for a planet to sustain methane via thermodynamic recombination against photodissociation. In summary, for terrestrial planets to have methane-rich atmospheres, the methane must be constantly replenished. We explore to what extent abiotic CH4 replenishment is possible based on prior work on abiotic methane sources including water-rock reactions, volcanic outgassing, and impacts (e.g., Etiope & Lollar 2013, Wogan et al. 2020, Kress & McKay 2003). We review methane false positives on terrestrial planets and determine if they are likely to produce methane fluxes as large as those caused by known biogenic sources. Through this comprehensive review, we will develop a framework for identifying methane biosignatures and discuss detectability prospects with JWST. | |
| 43 | Using the Sun-Earth Interaction to Explore Exoplanetary Systems | A crucial component in assessing the potential habitability of an exoplanet is an understanding of its interaction with the host star. As more terrestrial "habitable zone" exoplanets are discovered, the detailed characterization of the space environment of these planets raises new challenges, both from a physical and an observational perspective. The "space weather" environment of the planet is primarily governed by the level of magnetic activity of the star (XUV flux, stellar wind and high energy transients), the orbital distance of the planet, the nature and strength of the exoplanet's | D. Alexander, F. Toffoletto, A. Farrish, A. Sciola;<br><br>Physics and Astronomy, Rice University, Houston, TX. |

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| | | magnetic field and the magnetic and electromagnetic interactions of this coupled system. To address this, we take advantage of the wealth of knowledge gained about the sole existing habitable system of which we are sure, namely, the Sun-Earth system. We approach this by modeling the stellar activity, which governs much of the expected star-planet interaction and so has an important role to play on potential habitability, and the planetary response, which enables us to place constraints on the expected emission signatures of the star-planet interaction.<br><br>On the stellar side, we employ a magnetic flux transport model (SFT), devised from a full 22-yr solar magnetic cycle, to characterize the asterospheric magnetic field in systems with stars of varying levels of activity, up to 10x that of the Sun. This empirical flux transport model incorporates modulations of magnetic flux strength consistent with observed solar activity cycles, as well as surface flux dynamics consistent with observed stellar relationships. We verify the viability of the SFT model for application to stars other than the Sun by reproducing the observed stellar activity-rotation relationship across a wide range of stellar types. We find that the simulations match the activity-rotation relationship in the unsaturated regime of cool stars extremely well and that the observed spread in the observations can be reasonably explained as a result of cycle variability. From our modeling of the asterospheric field at the various levels of activity consider, we are able to detail the star-exoplanet interaction through several quantitative measures such as the ratio of open to total stellar magnetic flux and its variation with stellar latitude, the location and variability of the mean stellar Alfven surface, and the strength of interplanetary magnetic field polarity inversions, all of which have the potential to influence the magnetic environment of the exoplanet.<br><br>On the planetary side, we explore the coupling of the stellar activity to the planetary magnetic environment and determine whether or not such interactions produce potentially observable signatures. In this work, we focus on the expected signatures of auroral radio emission for Earth-like planets orbiting active stars. Magnetized exoplanets are expected to produce radio emission via interaction between the host star's stellar wind and planetary magnetosphere-ionosphere system both of which can be significantly enhanced for very active stars. Auroral radio emission is produced by field-aligned current (FAC) driven electron acceleration and this is calculated using a coupled global magnetohydrodynamic (MHD) and inner magnetosphere model, extending the capabilities of previous work. We find that intense, sporadic FACs, driven by night-side magnetic reconnection and inner magnetosphere plasma flow, contribute significantly to the total radio power produced by wind-ionosphere interaction in terrestrial planets. During periods of strong stellar wind variability, the contribution from these secondary currents can be up to several orders of magnitude greater than the primary current systems which previous models describe. This may be even more pronounced for systems in which the primary current system is strongly limited (e.g. ionospheric saturation). The results suggest that magnetized exoplanets may temporarily produce greater radio power than previously estimated increasing their likelihood of producing a detectable signature. Additionally, due to the strong beaming of the emission, the ideal observing angle is dependent on the intensity of the interaction between the stellar wind and exoplanetary magnetosphere. Such | |

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| | | observations could provide direct information on the strength of the planetary magnetic field and consequently knowledge about planetary dynamos, planetary evolution, atmospheric escape, and the offset of magnetic and rotation axes. | |
| 44 | High pCO_2 reduces sensitivity to CO_2 perturbations on temperate, Earth-like planets throughout most of habitable zone | The nearly logarithmic radiative impact of CO_2 means that planets near the outer edge of the liquid water habitable zone (HZ) require ~106 x more CO_2 to maintain temperatures conducive to standing liquid water on the planetary surface than their counterparts near the inner edge. This logarithmic radiative response also means that atmospheric CO_2 changes of a given mass will have smaller temperature effects on higher pCO_2 planets. Ocean pH is linked to atmospheric pCO_2 through seawater carbonate speciation and calcium carbonate dissolution/precipitation, and the response of pH to changes in pCO_2 also decreases at higher initial pCO_2. Here, we use idealized climate and ocean chemistry models to demonstrate that CO_2 perturbations large enough to cause catastrophic changes to surface temperature and ocean pH on low-pCO_2 planets in the innermost region of the HZ are likely to have much smaller effects on planets with higher pCO_2. Major bouts of extraterrestrial fossil fuel combustion or volcanic CO_2 outgassing on high-pCO_2 planets in the mid-to-outer HZ should have mild or negligible impacts on surface temperature and ocean pH. Owing to low pCO_ 2, Phanerozoic Earth's surface environment may be unusually volatile compared to similar planets receiving lower instellation. | R. Graham;<br><br>University of Oxford, Oxford, UNITED KINGDOM. |
| 45 | Taking the photometric pulse of Venus, our nearest terrestrial planet: Probing atmospheric super-rotation rather than surface features | Terrestrial exoplanets orbiting within or near their host stars' habitable zone are potentially apt for life. It has been proposed that time-series measurements of reflected starlight from such planets will reveal their rotational period, main surface features and some atmospheric information. From imagery obtained with the Akatsuki spacecraft, here we show that Venus' brightness at 283, 365, and 2020 nm is modulated by one or both of two periods of 3.7 and 4.6 days, and typical amplitudes <10% but occasional events of 20-40%. The modulations are unrelated to the solid-body rotation;<br><br>They are caused by planetary-scale waves superimposed on the super-rotating winds. Here we propose that two modulation periods whose ratio of large-to-small values is not an integer number imply the existence of an atmosphere if detected at an exoplanet, but it remains ambiguous whether the atmosphere is optically thin or thick, as for Earth or Venus respectively. Multi-wavelength and long temporal baseline observations may be required to decide between these scenarios. Ultimately, Venus represents a false positive for interpretations of brightness modulations of terrestrial exoplanets in terms of surface features. This study is published recently (https://doi.org/10.1038/s41467-020-19385-6). | Y. Lee [1], A. Garcia Munoz [2], T. Imamura [3], M. Yamada [4], T. Satoh [5], A. Yamazaki [5], S. Watanabe [6];<br><br>1 Technical University of Berlin, Berlin, GERMANY,<br>2 AIM, CEA, CNRS, Gif-sur-Yvette, FRANCE,<br>3 Univ. of Tokyo, Kashiwa, JAPAN,<br>4 PERC, Narashino, JAPAN,<br>5 ISAS/JAXA, Sagamihara, JAPAN,<br>6 Hokkaido Information University, Ebetsu, JAPAN. |
| 48 | Phosphine and the importance of unusual biosignatures | At the edge of our present scientific frontier lies the question: "Can we identify the signs of life on an exoplanet?". Establishing whether a planet is habitable, or inhabited, relies both on the detection of potential biosignature gases and, crucially, the interpretation of their presence. Beyond the most discussed biosignature gas O_ 2, only a handful of gases have been considered in detail. Here we present a broad and thorough investigation on the biosignature potential of phosphine (PH_3), as an example of an unusual, but promising biosignature gas. | C. Sousa-Silva [1], S. Ranjan [2], J. Petkowski [3], Z. Zhan [3], W. Bains [3], S. Seager [3], R. Hu [4]; |

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| | | We first explore phosphine's ecology and biochemistry. On Earth, $PH_3$ is extremely toxic to aerobic life, but is produced in anoxic ecosystems. We then analyze the biosignature potential of $PH_3$, considering not just its spectroscopic potential, but also its photochemistry, thermodynamics, and detectability.<br><br>An ideal biosignature gas a) lacks abiotic false positives, b) has distinguishable spectral features, and c) is sufficiently unreactive to build up to detectable concentrations in exoplanet atmospheres. Phosphine fulfills the first two criteria: on Earth, $PH_3$ is only known to be associated with life and geochemical false positives for $PH_3$ generation on potentially habitable planets are highly unlikely; $PH_3$ possesses three strong features in that are distinguishable from common outgassed species that may be present in terrestrial exoplanet atmospheres, such as $CO_2$, $H_2O$, CO, $CH_4$, $NH_3$, and $H_2S$. Phosphine's weakness as a biosignature gas is its high reactivity, requiring high outgassing rates for detectability. We simulate the atmospheres of habitable terrestrial planets with $CO_2$- and $H_2$-dominated atmospheres and find that $PH_3$ can accumulate to detectable concentrations on planets with surface production fluxes of 1010 to 1014 cm-2 s-1 (corresponding to surface concentrations of 10s of ppb to 100s of ppm), depending on atmospheric composition and UV irradiation. While high, these $PH_3$ surface flux values are comparable to the global terrestrial production rate of methane or $CH_4$ (1011 cm-2 s-1) and below the maximum local terrestrial $PH_3$ production rate (1014 cm-2 s-1). The main conclusion of the presented work is that $PH_3$ is a promising biosignature on oxygen-poor rocky planets, where it has no known abiotic false positives from any source that could generate the high fluxes required for detection.<br><br>Whether alien life will produce familiar gases (e.g., oxygen) or exotic biosignatures (e.g., phosphine), painting a confident picture of a potential biosphere will require a holistic interpretation of an atmosphere and its molecules. In this talk we will describe the ongoing efforts to decipher potential biospheres through the identification of volatile molecules, in particular those that might be produced by non-Earth-like life on exoplanets | 1 Center for Astrophysics \| Harvard-Smithsonian, Cambridge, MA,<br>2 Northwestern University, Chicago, IL,<br>3 MIT, Cambridge, MA,<br>4 JPL, Pasadena, CA. |

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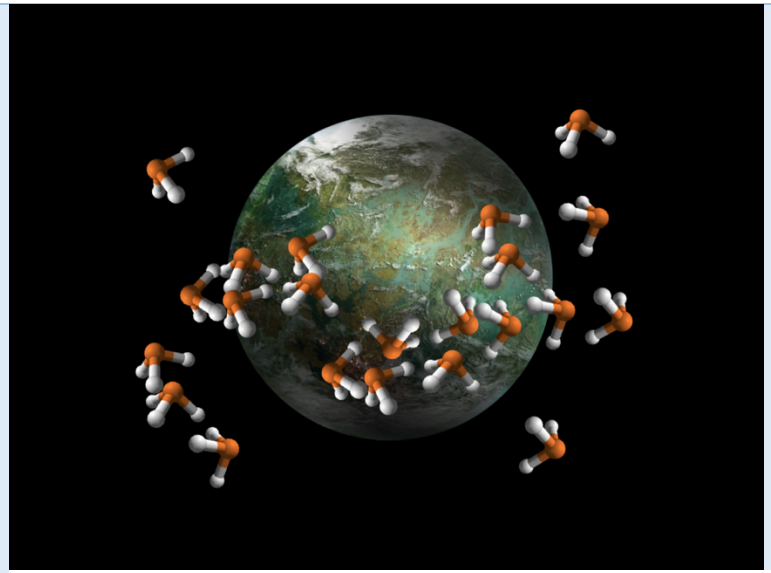
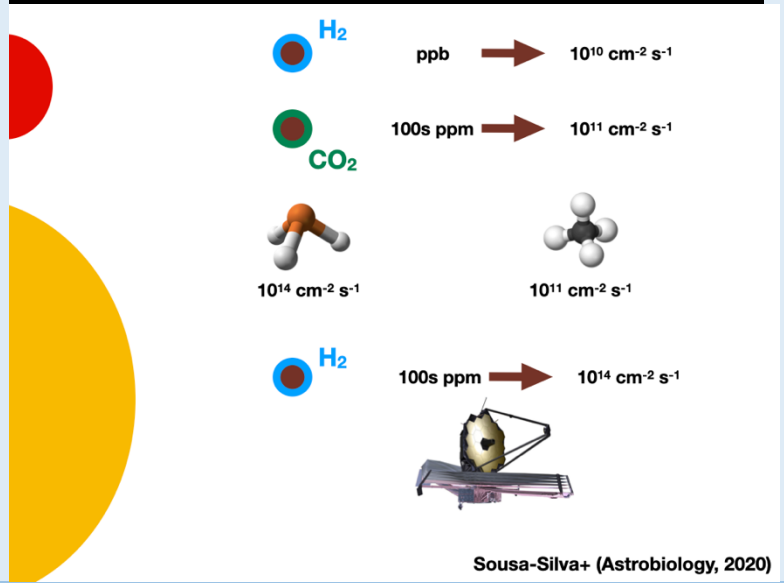
| | |    | |
| 50 | Hiding Planets Near and Far | Recent ground and space-based observations show that stars with multiple planets are common in the galaxy. Most of these observational methods are biased toward detecting large planets near to their host stars. Because of these observational biases, these systems can hide small, close-in planets or far-orbiting (big or small) companions. These planets can still exert dynamical influence on known planets and have such influence exerted upon them in turn. In certain configurations, this influence can destabilize the system; | T. Faridani [1], S. Naoz [1], L. Wei [2];<br><br>1 UCLA, Los Angeles, CA,<br>2 UCSD, San Diego, CA. |

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| | | In others, the star's gravitational influence can shield the system from destabilization. For example, in systems with planets close to the host star, effects arising from general relativity can help to stabilize the configuration. We derive criteria for hidden planets orbiting both beyond and within known planets that quantify how strongly general relativistic effects can stabilize systems that would otherwise be unstable. As a proof-of-concept, we investigate the several systems and show where within them an undetected planet could lie. | |
| 51 | Entering the Habitable Zone: An Earth-like Perspective | Whether a planet has liquid water at its surface depends on at least two energy sources: solar and internal. As a star ages, it brightens and delivers more energy to a planet at a given orbital distance. The planet ages, too. It produces heat within through radiogenic decay. One mode to eliminate internal energy is through mantle convection. By this process, CO2 and water cycle between the planet's surface and interior based on how efficiently the planet eliminates internal energy. The efficiency of mantle convection on Earth remains debated, with multiple hypotheses describing the convective dynamics of Earth having been put forth. Geological proxy data allow us to validate these hypotheses over different parameter space regions with some level of certainty. We consider validated models Earth-like. That these different Earth-like models would lead to different volatile cycling patterns should not surprise us. It does raise the question of how each Earth-like model influences surface temperature histories. We find that the time Earth-like planets enter the habitable zone varies by billions of years. The timing depends on both the amount of solar energy absorbed from the star based on the planet's orbital distance and albedo as well as how efficiently convective processes eliminate internal energy. How both energy sources evoled matters. For the same aged planet, whether it resides in the habitable zone may may depend on its efficiency at eliminating internal heat. We demonstrate this point for an Earth-like at different orbital distances and consider how an episodic convective regime may impact these probabilities. | J. Seales, A. Lenardic;<br><br>Rice University, Houston, TX. |
| 53 | The Effect of Cryoconite on the Deglaciation Thresholds of Snowball Planets | A possible material that may form on the cold surfaces of extrasolar planets is cryoconite - a dark, powdery, windblown dust that accumulates on snow, glaciers, and ice caps. Because of its low albedo, the presence of cryoconite may have altered Earth's energy budget and deglaciation threshold during globally ice-covered, "snowball" episodes. Using a one-dimensional energy balance climate model, we simulated the equilibrium climate response of an airless planet with varying surface percentages of cryoconite to a range of instellations from F-, G-, K-, and M-dwarf stars. Assuming an Earth-like land/ocean distribution, we find that the effect of cryoconite is greatest for planets orbiting stars with more visible and near-UV output. This is because cryoconite has a much lower albedo at these shorter wavelengths, compared with pure water ice and snow. For an F-dwarf planet with the land surface covered with a 75%/25% water ice/cryoconite mixture, full deglaciation occurs with ~33% less instellation than a similar planet with no cryoconite on its surface. For planets orbiting M-dwarf stars, whose spectral output peaks at infrared wavelengths, the albedos of ice and snow at these longer wavelengths are comparable to those of cryoconite, resulting in relatively small differences in the deglaciation thresholds between cryoconite concentrations on these planets. These results have implications for the climate stability of planets with substantial land fractions, for which cryoconite could be a significant contributor to the overall planetary albedo. | N. Duong, A. L. Shields;<br><br>Department of Physics & Astronomy, University of California, Irvine, Irvine, CA. |

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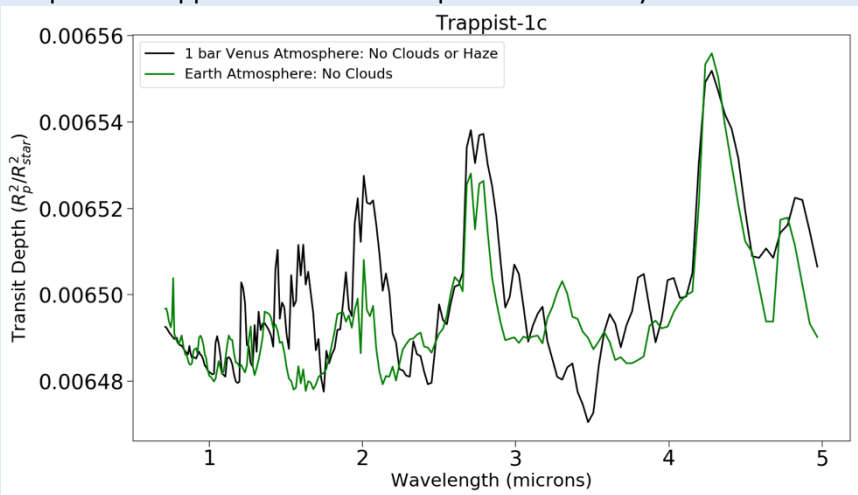
| | | This work is the first to explore the radiative effects on climate and habitability of the formation of cryoconite onto the cold surfaces of exoplanets. | |
| 54 | Transmission Spectroscopy of Exo-Solar Systems in the TESS Era | Venus has long been thought of only as a lifeless, desolate world, that has remained that way since the birth of the solar system. However, recent studies using 3-D climate models have illustrated that Venus could have maintained habitable temperatures up to 1 Gyr ago. This finding further increased the need to understand the processes that are responsible for Earth and Venus being so dramatically different today, despite their similarities in size and mass. One method for identifying the reasons for the difference between Earth and Venus will be studying analogous exo-planetary systems with both a terrestrial planet in the Venus zone (VZ) and in the habitable zone (HZ). This will involve comparing their atmospheres, whose properties will be derived using transmission spectroscopy. This will not be a simple task however, as previous works have shown that retrieval algorithms can have difficulty correctly determining whether a given transit spectrum is derived from a Venus- or Earth-like planet. To avoid the ambiguities associated with retrieval methods, this work will determine whether the relative size of CO2 features in transmission spectra in the near-infrared can be used as a proxy for whether a planet is more Earth-like or Venus-like. Modelled transmission spectra will be created for a potential exo-Earth and exo-Venus, which will include several cloud and haze scenarios for each planet. Comparing the array of spectra from each planet will determine whether the truncation of features caused by clouds and hazes can cause an Earth-like planet to appear as a Venus-like planet with heavy cloud cover.   | C. Ostberg, S. R. Kane, P. Dalba;<br><br>Earth and Planetary Sciences, University of California Riverside, Riverside, CA. |
| 57 | New Estimates of Nitrogen Oxide and Hydrogen Cyanide | Fixed nitrogen species generated by the early Earth's atmosphere are thought to be critical to the emergence of life and the sustenance of early metabolisms. Previously, Wong et al. (2017) estimated nitrogen fixation in the Hadean Earth's N2/CO2-dominated atmosphere, but that study only considered a limited chemical network that produces NOx species (i.e., no HCN formation) via the thermochemical dissociation of N2 and CO2 in lightning flashes, followed by photochemistry. Here, we present an updated model of nitrogen fixation on the Hadean Earth. We use CEA (Chemical Equilibrium with Applications) and a Geant4 simulation to estimate lightning-induced NO | M. Christensen [1], D. Adams [2], M. L. Wong [3], Y. Yung [2];<br><br>1 Bellarmine Preparatory, Tacoma, WA, |

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| | | and HCN formation. We used KINETICS (the 1-D Caltech/JPL photochemical model) to assess the photochemical production of fixed nitrogen species that rain out into the Earth's early ocean and our updated photochemical model contains hydrocarbon and nitrile chemistry. We study the impact of a novel pathway for HCN production via HCN2, inspired by the experimental results of Trainer et al. (2012), which suggest that reactions with CH radicals (from CH4 photolysis) may facilitate the incorporation of N into the molecular structure of aerosols. Results show that this new reaction pathway results in a four-fold increase in the total HCN rainout rate. Finally we calculate the equilibrium concentration of fixed nitrogen species under kinetic steady state in the Hadean ocean, considering loss of NOx to photoreduction and loss of HCN to hydrolysis. Results with an assumed surface methane mixing ratio of 3% atmospheric concentration of methane show that HCN concentrations exceed the ~0.01 M of HCN required for protein synthesis, possibly relevant to the emergence and sustenance of early life (eg., Holm & Neubeck, 2009). | 2 Planetary Science, Caltech, Pasadena, CA,<br>3 Planetary Science, University of Washington, Seattle, WA. |
| 58 | Habitability Models for Exoplanet Sciences | Habitability is positively correlated with the abundance and diversity of life on Earth. This correlation should also be true for other habitable worlds unless they operate under a different biological process than Earth. Future space telescopes, like the JWST, will search for biosignatures from the atmosphere of nearby transiting exoplanets, such as those around the TRAPPIST-1 system. Planets with higher habitability, i.e., with a potential for a larger biosphere, are expected to produce stronger biosignatures. Thus, estimates of habitability would be essential to interpret and complement biosignature detections. Astrobiologists have been proposing different habitability models for some time, with little integration and consistency among them. However, procedures for measuring habitability, known as Habitat Suitability Models (HSMs), are well established in biology since the early 1980s. Ecologists have been using these models for more than four decades to study the habitability of Earth from local to global scales. These models are used to characterize the critical environmental factors that are responsible for the gradual transition from low to high habitability states. The models are extendable to global biospheres and hence suitable for exoplanet studies.<br><br>The main goal of this project is to develop a set of global habitability models for the exoplanet science community. Together with exoplanet climate models, these models could be used to explore the potential habitability states of known exoplanets. Our specific objectives are to (1) create and validate different global habitability models with terrestrial data, (2) determine the minimum set of measurable planetary parameters for global habitability assessments, and (3) apply these models to a few exoplanets of interest, such as the TRAPPIST-1 system. These models would improve the comparison and characterization of potentially habitable worlds, prioritize target selections, and help study correlations between habitability and biosignatures.<br><br>We are adapting and expanding the methods from the HSMs to global biospheres using a fundamental mass-energy habitability model. Our model is validated with terrestrial biomes using ground and satellite data from NASA's Earth Science Data Systems (ESDS). Archived data from different global climate models (e.g., ROCKET-3D) and our runs of 1D and 2D climate models are | A. Mendez;<br><br>PHL @ UPR Arecibo, Arecibo, PR. |

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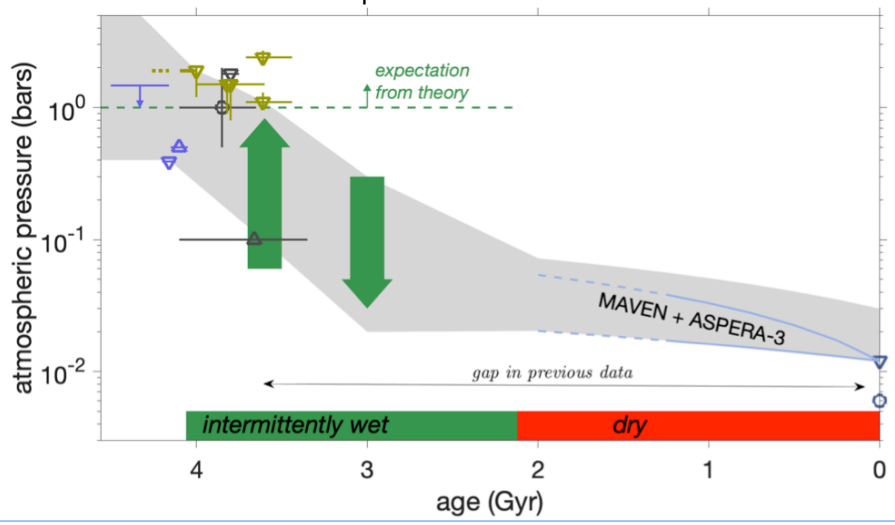
| | | used to explore habitability space as a function of measurable planetary parameters such as radius, mass, and stellar flux. We are using exoplanet data from NASA's Exoplanet Archives and the PHL's Habitable Exoplanets Catalog, for systems such as TRAPPIST-1, to determine the relative habitability potential of each planet. A positive correlation between habitability estimates and future biosignature detections might support any life-detection hypotheses. | |
| 59 | Mars ~3 Ga had river-forming climates at low average pCO2, raising the likelihood of false negatives in the search for habitable exoplanets | Mars is the only currently accessible geologic record that can provide an independent test of Earth-derived models of planetary habitability. Mars is the only planet whose surface is known to have become uninhabitable. We are studying this environmental disaster as a benchmark for rocky exoplanets.<br><br>The most important climate-regulating greenhouse gas on Earth and Mars today is CO2. To constrain past pCO2 on Mars (on Mars, pCO2 ≈ total atmospheric pressure), we used Mars' geologic record of the changing distribution of paleochannels and paleolakes, in combination with Global Climate Models. It is usually assumed that CO2 warming was near-maximum at times in Mars history when rivers flowed. To the contrary, we found evidence that even after average CO2 had dropped, rivers still flowed. Specifically, we found a decline over time in the preferred elevation for rivers, and a shift from early-stage elevation control to late-stage latitude control. These changes are simply explained, based on comparison to Global Climate Models (GCMs), by a reduction in the total strength of the atmospheric greenhouse effect, with a decline in average pCO2 from ≫102 mbar for early river-forming climates, to ≲102 mbar for later river-forming climates. To explain late-stage rivers, strong non-CO2 greenhouse warming must have continued intermittently through ~3 Ga. River-forming climates at low average pCO2 on Mars constrain Mars warming mechanisms and atmospheric evolution, challenge Habitable Zone theory, and raise the likelihood of false negatives in the search for habitable exoplanets.<br>  <br> | E. Kite [1], M. Mischna [2], A. Morgan [3], S. Wilson [4], M. Richardson [5];<br><br>1 University of Chicago, Chicago, IL,<br>2 JPL/Caltech, Pasadena, CA,<br>3 Planetary Science Institute, Tucson, AZ,<br>4 Smithsonian Institution, Washington, DC,<br>5 Aeolis Research, Chandler, AZ. |

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| | | Zooming in to Mars' atmospheric evolution, the figure shows how our result changes our view of the Red Planet's atmospheric decay. Estimates from the shifting spatial distribution of water flow on Mars on average pCO_2 (thick green arrows) are shown in the context of independent estimates on paleo-atmospheric pressure on Mars (symbols) and expectations from CO2 + H2O Habitable Zone theory (green dashed line). Wet-to-dry transition age from Martin et al. 2017 (jarosite). Purple symbols: constraints from analysis of meteorite data (not all consistent with one another). Downward-pointing gold triangles: upper limits from the embedded-crater method. Dark gray symbols: constraints from analysis involving rover data. Sky-blue lines: extrapolation of present-day CO2 escape-to-space rate from MAVEN and ASPERA-3. Modern-era value (blue triangle) includes both the present-day atmosphere (blue circle) and also CO2 known to be currently stored in polar ice deposits, which would be released at high obliquity. The gray band is drawn to guide the eye (omitting possible ancient periods of atmospheric collapse), taking account of the possibility of additional present-day polar CO2 ice reserves. | |
| 60 | Water on hot rocky exoplanets and the sub-Neptune-to-super-Earth transition | Data suggest that most super-Earths formed as gas-rich sub-Neptunes, but whether super-Earths still have atmospheres is unknown. We identify a pathway by which sub-Neptunes can develop long-lived 2-200 bar H2O-dominated atmospheres during their conversion to Super-Earths, and show that this is a common outcome for efficient interaction between a nebula-derived atmosphere and oxidized magma, followed by atmospheric loss. H2O that is made by reduction of iron oxides in the magma is highly soluble in the magma, forming a dissolved reservoir that is protected from loss so long as the H2-dominated atmosphere persists, and whose large size buffers the H2O atmosphere against loss after the H2 has dispersed. This idea is imminently testable with JWST and has numerous implications for the interpretation of mass-radius data for transiting super-Earths.<br><br>In addition to this new result, we will also summarize results from our recently published study of the transition over time from sub-Neptune atmospheres to super-Earth atmospheres (Kite & Barnett PNAS 2020). We describe the (narrow) range of conditions under which super-Earths will have secondary atmospheres Gyr after primary-atmosphere loss. The figure (from Kite & Barnett PNAS 2020) shows selected processes (italics) and reservoirs (upright font) in the model. Atmosphere-interior exchange is central to the transition from primary to secondary atmospheres. Timescales are approximate. | E. Kite [1], L. Schaefer [2], M. Barnett [1];<br><br>1 University of Chicago, Chicago, IL,<br>2 Stanford University, Stanford, CA. |

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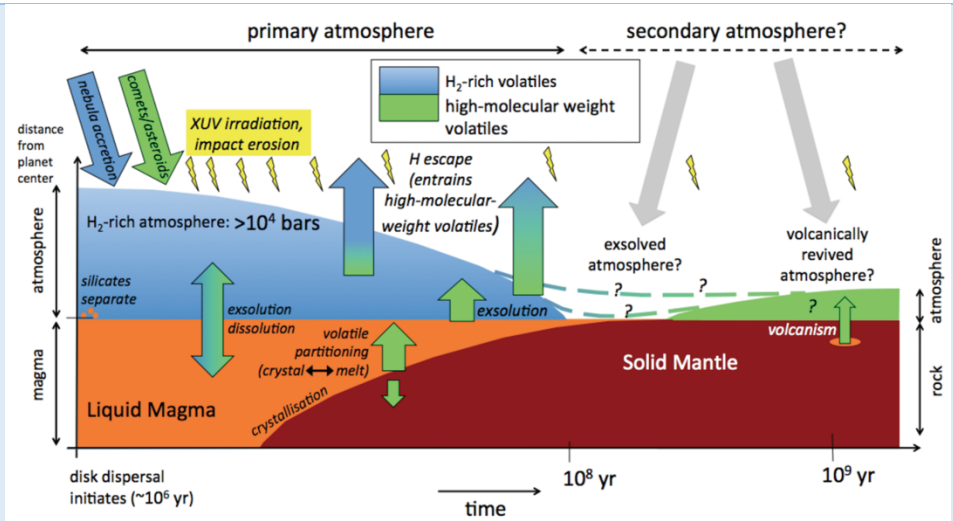
| | |  | | |
| 61 | The Large Interferometer for Exoplanets (LIFE) mission: characterizing habitable planets in the mid-infrared | One of the long-term objectives of extrasolar planet research is the investigation of the atmospheric properties for a large number (~ 100) of terrestrial exoplanets. This is partially driven by the idea to search for and identify potential biosignatures, but such a dataset is - in a more general sense - invaluable for understanding the diversity of planetary bodies. First steps in this direction will be taken in the coming 10-15 years with funded or selected ground and space-based projects and missions. However, none of them will be able to deliver such a comprehensive dataset. An alternative to the currently discussed large space based coronographic missions or the starshade concept in the optical and near-infrared, is to separate the photons of the planet from those of its host star by means of an interferometer at mid-infrared (MIR) wavelengths. LIFE is a project initiated in Europe with the goal to consolidate various efforts and define a roadmap that eventually leads to the launch of a large, space based MIR nulling interferometer to investigate the atmospheric properties of a large sample of (primarily) terrestrial exoplanets [1,2,3]. | D. Angerhausen [1], S. Quanz [1], M. Meyer [2], the LIFE initiative;<br><br>1 ETH Zürich, Zürich, SWITZERLAND,<br>2 University of Michigan, Ann Arbor, MI. |

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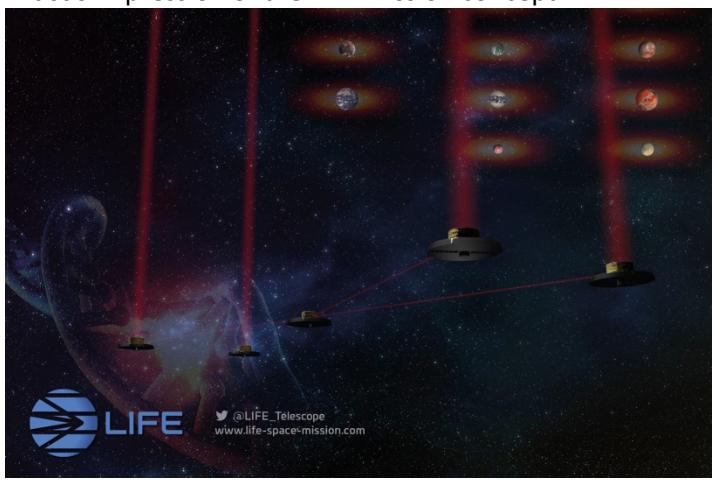
| | | Artist's impression of the LIFE mission concept.<br>  <br><br>Centered around clear and ambitious scientific objectives the project will define the relevant science and technical requirements. The status of key technologies will be re-assessed and further technology development will be coordinated. LIFE is based on the heritage of ESA/Darwin and NASA/TPFI, but significant advances in our understanding of exoplanets and newly available technologies will be taken into account in the LIFE mission concept.<br><br>We will give the Habitable Worlds community an understanding of the potential of LIFE by presenting a series of recent and upcoming studies from the LIFE initiative covering topics from the expected yield of dozens of potentially habitable planets to the anticipated precision when characterizing the atmospheric properties of these targets.<br><br>References: [1] Quanz, S. P., Kammerer, J., Defrère, D., et al. 2018, Optical and Infrared Interferometry and Imaging VI, 10701,107011I.<br>[2] Defrère, D., Léger, A., Absil, O., et al. 2018, Experimental Astronomy, 46, 543.<br>[3] Quanz, S.P., et al., arXiv:1908.01316, White Paper submitted to ESA | |
| 62 | Hubble WFC3 Transmission Spectroscopy of the Habitable Zone Super-Earth LHS 1140 b | Atmospheric characterisation of temperate, rocky planets is the holy grail of exoplanet studies. These worlds are at the limits of our capabilities with current instrumentation in transmission spectroscopy and challenge our state-of-the-art statistical techniques.<br>I will present the transmission spectrum of the temperate Super-Earth LHS 1140 b, obtained using the Hubble Space Telescope (HST). The Wide Field Camera 3 (WFC3) G141 grism data of this habitable zone (T = 235 K) Super-Earth (R = 1.7 R_E) shows tentative evidence of water. However, the signal-to-noise ratio, and thus the significance of the detection, is low and stellar contamination models can cause modulation over the spectral band probed. We attempted to correct for contamination using these models and found that, while many still lead to evidence for water, some could provide reasonable fits to the data without the need for molecular absorption although most of these cause also features in the visible ground-based data which are nonphysical. Future | B. Edwards;<br><br>University College London, London, UNITED KINGDOM. |

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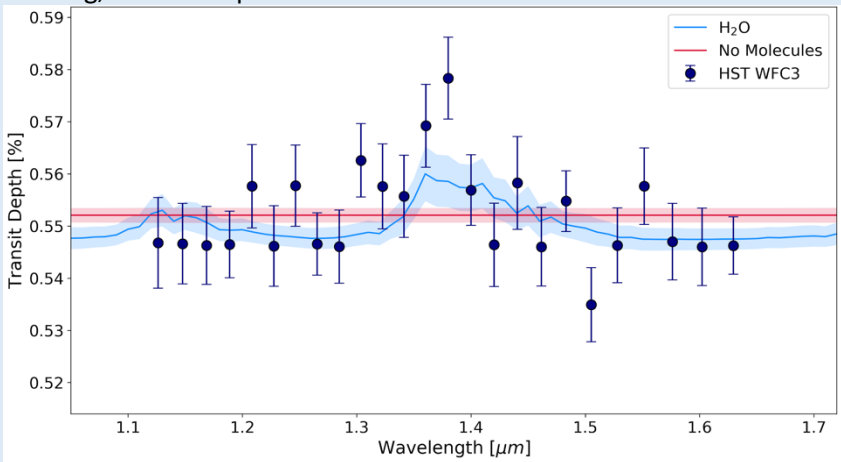
| | | observations with the James Webb Space Telescope (JWST) should be capable of confirming, or refuting, this atmospheric detection.<br>  <br> | |
| 63 | Interiors of water-rich planets: what do we know about them? | Although water is necessary for life as we know it, a large fraction of water in planetary interiors may lead to unique conditions, under which the interior structure differs from the simple layered structure of a water ocean on top of a rocky surface, that supports life. We combined thermal evolution model with experimental data of ice-rock interaction at high pressure, and find that ice and rock are miscible in each other in planetary interiors. We show that water-rich planets are expected to have an interior structure of a mixed ice and rock ball, surrounded by a water / steam layer of less than 1% of the planet's mass. In this case, the mass of the water layer is determined by the ice-rock interaction properties. We conclude that when water-ice is abundant in planetary interiors the ice and rock tend to stay mixed for billions of years, and the interior structure differs from the simple layered structure that is usually assumed. | A. Vazan;<br><br>Open University of Israel, Ra'anana, ISRAEL. |
| 64 | Habitability at the End of the Universe | Earth will face its ultimate habitability crisis when the Sun leaves the Main Sequence and enters its subgiant stage in about 5 billion years. Long before that -- in a billion years or less -- barring technological intervention, habitability will end when the Sun brightens enough for the Earth to succumb to a runaway greenhouse. For a 1.2 Solar mass F star, the Red Giant crisis puts a conclusive end to habitability after only 5 billion years on the Main Sequence, and planets initially in the nominal habitable zone will succumb to a runaway greenhouse considerably before that. It took nearly 4 billion years (and 2 billion years after the initial rise of O_2) for complex multicellular life to arise on Earth, so if the bottlenecks faced on Earth typically take much longer to overcome, the prospects for complex life on G star planets are dim. Even if the transition to multicellularity can take place more rapidly, planets orbiting F stars do not look like likely candidates for hosting such life.<br><br>However, a red dwarf star such as our nearest neighbour, Proxima Centauri, will still be shining more or less unchanged a trillion years from now. Does this mean that, over the far future course of our Universe, habitable zone planets about such stars -- assuming they can retain or regenerate a | R. Pierrehumbert;<br><br>Physics, University of Oxfoerd, Oxford, UNITED KINGDOM. |

sufficient volatile inventory at the start of the main sequence -- have essentially unlimited time available for complex life to emerge? In this talk, I will examine the ultimate limits on the lifespan of habitability.

The definition of the outer edge of the conventional liquid water habitable zone is defined by radiative and thermodynamic properties of CO_ 2, without reference to the geodynamic and geochemical processes that determine the amount of CO_2 in a planet's atmosphere [1] . In reality, atmospheric CO_2 is determined by a balance between the source due to volcanic outgassing from the planetary interior and the sink due to silicate weathering. This was proposed in [2] as a potential constraint on habitability, but the subject has only recently attracted considerable interest. Studies with specified outgassing rates have shown that weathering processes can severely constrict the habitable zone (e.g [3]), and can lead to such interesting phenomena as climate limit cycles [4,5]. In reality, outgassing itself is a dynamic process, subject to constraints due to mantle chemistry and dynamics [6] and recycling of crustal carbonates, by plate tectonics or stagnant-lid processes. The collective behavior of volatile cycling, engaging both planetary interior processes, crustal processes, and atmospheric processes, ultimately determines the lifetime of habitability for a planet with given orbit, subject to the evolving instellation appropriate to the planet's host star.

In this talk, we present results from a simple model coupling planetary interior evolution to an energy-balance atmosphere and a model of the silicate weathering sink. CO_2 outgassing is represented as a function of interior temperature and heat flux out of the interior. The modeling work is very much in the spirit of models discussed in Refs. [7,8], but with a number of significant variants. Most importantly, we use the MAC weathering formulation [3], which allows for both the kinetic-limited and equilibrium-limited weathering regimes. Additionally, since we are focused on limits on habitability time, the results discussed in this talk will be given in the limit of efficient crustal recycling, as opposed to [8], which used a crustal model corresponding to a stagnant-lid regime. There are also differences in the representation of outgassing and seafloor weathering, and the effects of these will be discussed. A key planetary habitability parameter is the mass fraction of long-lived radionuclides in the planet's silicate mantle.

Some typical results are shown in the accompanying Figure. The climate model allows for ice-albedo feedback, which can allow for multiple states, bifurcations and climate oscillations. However, in order to reveal the key features in their simplest form, ice-albedo feedback is suppressed in this calculation, though when global mean temperature approaches the freezing point of sea water, falling into a Snowball state would become likely in the presence of ice-albedo feedback. The mass fraction of 235U and 232Th is assumed the same as Earth's. Instellation L is given relative to Earth's present instellation L_e. r is the planetary radius, in units of Earth's radius. The Figure gives the evolution of surface temperature as a function of time since Zero Age Main Sequence for a low-mass K or M star that does not increase its luminosity significantly over the time period shown.

Except in the case of a large Super Earth with Earthlike instellation, the freeze-out time is 12 billion years or less, with more severe limitations for planets farther out in the nominal habitable zone. Even in the Super-Earth case the planet freezes over in under 30 billion years (not shown). It is clear that habitability is lost owing to a tectonic freeze-out crisis long before stellar evolution terminates habitability. In these calculations, seafloor weathering is represented by a small residual weathering that persists even after surface conditions become cold. This is an important effect, because in its absence weathering smoothly approaches zero as freezing conditions are approached, and the planet hovers indefinitely in near-freezing conditions. With ice-albedo feedback, such states typically enter climate oscillations, but the seafloor weathering can on its own cause a transition to globally sub-freezing conditions. These results highlight the extreme importance of seafloor weathering to habitability.

For planets in the habitable zone of low-mass stars, tidal heating can be a significant source of interior heating that can maintain tectonic recycling of carbonates into atmospheric CO_2. However, tidal dissipation for an isolated planet will quickly circularize the orbit and spin the planet down into a tide-locked state, whereafter tidal heating ceases. Gravitational interaction with a relatively nearby gas giant planet can maintain eccentricity, however, and allow sustained tidal heating. The energy available from such processes will be discussed, in comparison to the energy available from radiogenic heating.

It is interesting to note that while technological innovations a technological civilization could employ to stave off a runaway greenhouse catastrophe are very challenging (and probably completely unavailable, save for migration, for the Red Giant catastrophe), even our own civilization has the capability of preventing the tectonic freeze-out catastrophe. It takes very little energy to reverse the silicate weathering sink. Geodynamic processes accomplish this very inefficiently, but if carried out on the surface by technological processes require only a tiny fraction of the starlight reaching the planet's surface to be harnessed. As an example, the CO_2 released by worldwide cement production -- counting just the chemical process of liberating CO_2 from carbonates and not the fossil fuels burned for energy -- is already enough to essentially offset estimated global silicate weathering. Cement production primarily produces a complex mix of CaO with other minerals, rather than stable silicates, and if left on its own would eventually re-absorb most of the CO_2 emitted, but the process captures most of the energy requirements needed in the process of creating more weathering-resistant silicates.

Our Universe is too young for planets near the inner edge of the nominal habitable zone of M or K stars to have faced a tectonic freeze-out crisis, but even under the optimistic assumptions employed here planets further out in the nominal habitable zone are already at risk. This risk is compounded for planets with inefficient crustal recycling [8], or for planets with a lower mass mixing ratio of long-lived radionuclides than Earth. Given that uranium and thorium are currently thought to be produced primarily in rare and exotic events (merging neutron stars and collapsars)

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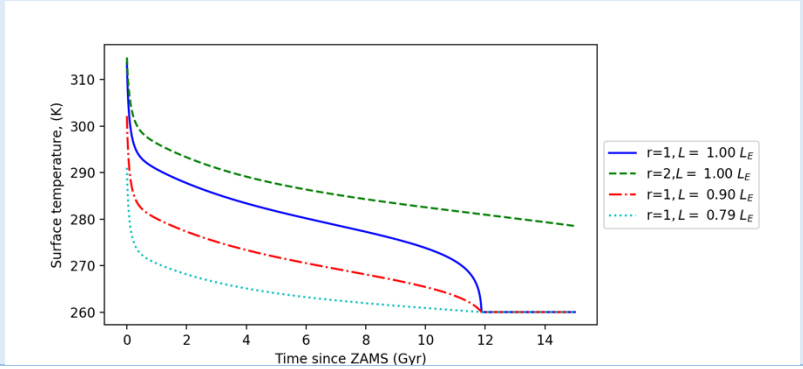
| | | the galactic distribution of these key elements may be quite inhomogeneous despite their long lifetimes. This raises the question of whether sufficient supply of long-lived radionuclides can be a limiting factor in habitability. But even assuming a sufficient supply of such elements, the physics and geochemistry determining outgassing and weathering is rich and complex, and all existing models (including those presented here) are highly over-simplified, and just barely scratch the surface of the habitability question. This is a very fertile field for future research crossing the disciplinary boundaries of astrophysics and atmospheric physics with research capabilities most often housed in the Earth Science disciplines. As capabilities for characterizing the CO_2 content of rocky planet atmospheres develop [9], prospects for testing models of volatile cycling against astronomical data will become a key area in the study of habitability.<br><br>REFERENCES: [1] Kopparapu R. K. et al., 2013, ApJ, 765,131<br>[2] Pierrehumbert R. T., 2011, ApJLett, 726, L8<br>[3] Graham R.J. & Pierrehumbert R. T., 2020, ApJ, 896, 115<br>[4] Haqq-Misra J et al., 2016, ApJ, 827, 120<br>[5] Paradis A. & Menou K., 2017, ApJ, 848, 33<br>[6] Dorn D. et al., 2018, A&A, 614, A18<br>[7] Rushby A. et al. , 2018, Astrobio., 5, 469<br>[8] Foley B. et al., 2018, Astrobio., 7, 873<br>[9] Snellen I et al, 2015, A&A, 576, A59<br>  | |
| 65 | Transport of surface oxidants into internal ocean by brine migration through ice shells | We propose a physical mechanism for the transport of oxidants formed at the surface of icy moons or exoplanets by irradiation of ice into their internal oceans. This oxidant flux is important for the redox state of the internal ocean and hence its habitability. Our work is motivated by Jupiter's moon Europa but may have applications to other icy moons and exoplanets. On Europa we propose that the drainage of near-surface brines formed during the formation of chaotic terrains can transport oxidant through the ice shell and deliver oxidants to the internal ocean. We estimate that Europa's regolith contains approximately 1016 mols of O_2 formed by irradiation. If these oxidants are mixed into the brines that are generated during the formation of chaotic terrains, then brine migration can deliver 85% of the surface oxidants to the ocean on time scales of 104 years, see Figure. In this process, the rate of oxidant delivery is therefore limited by the formation of chaotic terrains rather | M. Hesse [1], S. Vance [2], J. Jordan [3], A. Oza [4];<br><br>1 Geological Sciences, University of Texas at Austin, Austin, TX,<br>2 Jet Propulsion Laboratory, California Institute of Technology, Pasadena,, CA, |

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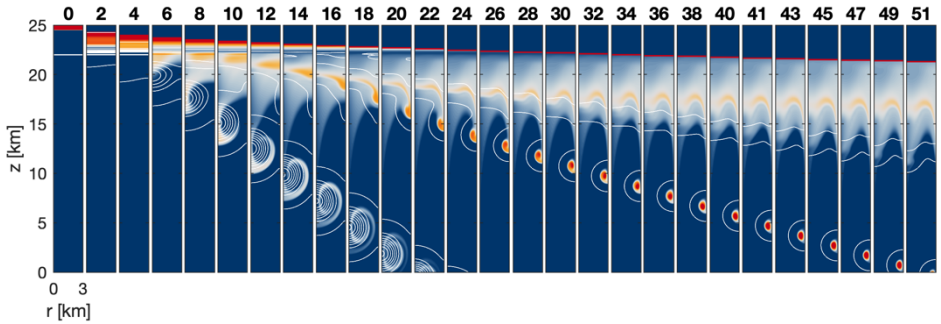
| | | than the brine migration. Given that one quarter of Europa's surface is classified as chaos and Europa's mean surface age of 40-90 million years, we estimate that the rate of O_2 delivery to the ocean is approximately 108 mol/yr. This is lower than previous estimates, which assume that the entire inventory of surface oxidants is delivered to the ocean due to complete overturn of the ice shell. The process we envision does not require overturn of the ice shell but requires the formation of near surface brines facilitated by the presence of impurities. If these conditions are met on other icy moons or exoplanets brine drainage may also provide an oxidant flux into internal oceans.   | 3 Earth, Environmental & Planetary Sciences, Rice University, Houston, TX, 4 Physikalisches Institut, University of Bern, Bern, SWITZERLAND. |
| 67 | Climate on High Obliquity Planet | Planets with high obliquity may widely exist in the universe in absence of a large moon. This type of planets have extremely strong seasonal variation, and receive more radiation in the polar regions than in low latitudes, and therefore, are expected to have drastically different climates from the Earth-like low obliquity planets.Using a model hierarchy, from a 1D Eady-like model to a 3D dry dynamic model and then to a full GCM, we aim to approach the questions:<br>1) whether high obliquity planets are generally warmer or colder than low obliquity equivalents,<br>2) how the habitable zone changes with obliquity,<br>3) whether obliquity affects likelihood of water molecules that are evaporated from the surface ocean being detected through spectroscopy,<br>4) how atmosphere circulates on high obliquity planets, and 5) whether the atmospheric circulation has some potentially observable aspects that can be used to infer the planet's climate using future observations. The significance of understanding the climate under different configurations is not merely a curiosity about exoplanets;<br><br>In fact, these seemingly exotic exoplanet regimes provide an opportunity to test our theories. From this work, we realized that atmospheric motions, even in the tropics, do not necessarily rise (or sink) in warm (or cold) regions/latitude bands. There are deeper reasons besides the vertical density profile leading to the top-amplified structure of mid-latitude eddies on Earth. Also, changes in general circulation can dramatically affect the troposphere-stratosphere tracer exchange. | W. Kang;<br><br>EAPS, MIT, Cambridge, MA. |
| 68 | The Sun's Magnetic Activity is Normal for its Age | It has been recently claimed that the Sun's activity is abnormally low relative to analogous stars observed by NASA's Kepler space telescope (Reinhold et al. 2020). Stars were identified that have temperatures, luminosities, and rotation periods that are similar to the modern Sun. Using the range of photometric variability as a proxy for magnetic activity (R_var), the activity levels of stars in | J. Curtis;<br><br>Columbia University, New York, NY. |

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| | | this sample reach values much higher than that of the contemporary Sun. The implication is that the Sun's magnetic dynamo (and associated phenomena like variations in total solar irradiance, high-energy emission, and flaring events) could also exhibit much higher excursions in the future or the recent past.<br><br>However, the primary conclusion of the Reinhold et al. study is due to a biased sample of solar twins stemming from an erroneous temperature scale, rather than an abnormally inactive Sun. The temperatures used to assemble the solar analog sample are biased toward warmer values by ~200 K, resulting in the sample actually being composed of early-K and late-G dwarfs instead of true solar analogs. Since magnetic activity tightly correlates with Rossby number, it makes sense that such stars are naturally more active while spinning at the solar rate due to their larger convective zones, longer convective turnover times, and therefore smaller Rossby numbers. Compiling a list of true solar analogs observed by Kepler is challenging due to the fact that their rotation periods are difficult to measure in broadband optical light. However, the few stars that can be curated have activity levels on par with the Sun's present day range. This is consistent with other results from stellar astrophysics;<br><br>For example, the chromospheric activity survey of solar twin stars in the 4-Gyr-old M67 cluster found activity levels consistent with the Sun's contemporary range. | |
| 69 | On the Lithology and Mineralogy of Polluted White Dwarf Materials | To better understand rocky exoplanet compositions we compare materials being accreted by “polluted” White Dwarfs (WDs; n = 22) to meteorites, terrestrial planets, and Sun-like stars from the Hypatia Catalog (FGKM class; n = 4,350). We use Mg, Si, Ca, and Fe as these elements comprise >95% of terrestrial planetary cations (Ni and Al comprising most of the remainder) and are sufficient to broadly identify planetary rock types; they are also simultaneously available for nearly two dozen WDs. In the event, we find some overlap between Hypatia and WD compositions, however 32% (7) of WDs range to Ca contents above levels observed for Hypatia stars, while another 18% (4) have both uniquely high Fe and low Mg. White Dwarfs also range beyond composition estimates for bulk terrestrial planets, but they do not exceed the compositional ranges for meteorites, indicating that most WDs could represent a—perhaps random—sampling of differentiated planetary material. For example, mesosiderites (mixtures of pyroxene and metallic Fe) appear to be good analogs for three WDs: HE0106-3253, PG1015+161, and WD1145+017, while one WD (PG0843+517) is strikingly like an iron meteorite (although a different report of PG0843 by Gänsicke et al. [2012] indicates an admixture of silicate material). However, most meteorite classes are imprecise analogs: (a) four WDs overlap nicely with urelites (primitive, C-rich achondrites) for Mg, Fe and Si, but only two (GD61 and WDJ1242+5226) have sufficiently low Ca; (b) another four have Mg and Si that matches chondritic meteorites, but again, only two (WD2207+121 and WD1551+175) are not overly enriched in Ca; (c) the four most Ca-enriched WDs have Ca contents similar to Howardites (achondrites, thought to derive from Vesta) but dissimilar with respect to other cations. There are several possibilities for such mismatches, among which are accretionary dynamics, and observational bias; | K. Putirka [1], S. Xu [2];<br><br>1 Earth and Environmental Sciences, Fresno State, Fresno, CA,<br>2 Gemini Obsesrvatory/NSF's NOIR Lab, Hilo, HI. |

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| | | the most intriguing possibility, though, is that WD materials represent fractionation paths not accessible to (or yet discovered in) our solar system. | |
| 70 | Photochemistry of planetary atmospheres with 3D Global Climate Model | The next generation of space and ground-based telescopes (JWST, ARIEL, ELTs) should give us improved transmission/emission spectra for a large diversity of exoplanets, allowing to probe their atmospheric composition. For a better understanding of this data, atmospheric models taking into account photochemistry are required. Several 1D atmospheric models have been developed and can be applied to a diversity of exoplanets. However, taking into account 3D geometry for the analysis can become necessary due to the interplay between atmospheric circulation, chemical kinetics and the potentially very steep temperature gradient between the day and night sides. In particular the terminator is the location of the most important gradient and is the region probed by transmission spectroscopy. This effect becomes very significant on tidally-locked planets like hot Jupiters/Neptunes as well as temperate planets around red dwarfs as the TRAPPIST-1 planets.<br><br>In this context we developed a generic (photo)chemical module including photochemistry online for the LMDZ generic 3D Global Climate Model (GCM). Using this new development I will present you our work on atmospheric characterization of exoplanets and early Earth. Thanks to this model we have the possibility to study a wide range of (exo)planets atmospheres. In particular we performed simulation of Trappist-1e atmosphere to observe M-dwarf stellar spectra consequences on Earth like atmosphere. Considering the different stellar UV activity of M-dwarf, photochemistry could be highly impacted. We found that Trappist-1e gather favorable conditions to sustain an ozone layer one order of magnitude more abundant than Earth. Ozone is an important molecule providing a UV shield to protect the surface and potential biological activities. This ozone shield play also a key role in atmospheric dynamic as it is observed on early Earth by triggering the Great Oxidation Event (GOE). Keeping using the GCM we performed simulation to study the GOE on Earth considering potential 3D effect of ozone and on Trappist-1e considering UV activity impact. | Y. Jaziri [1], B. Charnay [2], F. Selsis [1], J. Leconte [1], F. Lefèvre [3];<br><br>1 Laboratoire d'astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, 33615, Pessac, FRANCE,<br>2 LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 5 place Jules Janssen, 92195, Meudon, FRANCE,<br>3 LATMOS/IPSL, Sorbonne Université, UVSQ, CNRS, Paris, FRANCE. |
| 71 | A Snowball in Hell: The Potential Steam Atmosphere of TOI-1266c | Many outstanding questions remain concerning the ultimate fate of terrestrial planets that pass through a runaway greenhouse phase, such as Venus is thought to have in its past. Developing a better understanding of this process is critical, given the concerns about the long pre-main sequence super-luminous phases of smaller host stars (Luger & Barnes, 2015; Ramirez & Kaltenegger, 2014) which may desiccate many of the exoplanets found within the conventional habitable zone. One way to begin exploring this transition is to identify low-density targets orbiting small stars; one such planet is TOI-1266c, a super-Venus orbiting an early M dwarf that resides in the 'radius valley' (Fulton et al., 2017). Its moderate instellation (~2.4 times what the Earth receives), combined with its low apparent density (ranging from 2.2-9.2 g/cm2), suggests that the planet may have retained a substantial volatile reservoir over the course of its lifetime. The pre-main sequence super-luminous phase of TOI-1266 is roughly 400 Myr, which in combination with the enhanced extreme ultraviolet and X-ray fluxes would drive substantial atmospheric loss. This could remove up to a few percent of the planet's mass in hydrogen within ~4 Gyr (see Luger et al., 2015). In the context of the uncertainties in the planet's density, this scale of atmospheric loss largely precludes a H_2-dominated atmosphere at present. If TOI-1266c is then a failed ice giant | S. Harman [1], R. K. Kopparapu [2], G. Stefansson [3], A. S. Lin [4], S. Mahadevan [4], N. Batalha [1], C. Hedges [1], J. Kasting [4];<br><br>1 NASA Ames Research Center, Mountain View, CA,<br>2 NASA Goddard Space Flight Center, Greenbelt, MD,<br>3 Princeton University, Princeton, NJ, |

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| | | without a substantial primordial atmosphere, its ice-rich core would continually supply volatiles to the “atmosphere”, leaving the planet in an effectively perpetual runaway greenhouse state<br><br>Here, we outline the potential atmospheric states of TOI-1266c using combined radiative-convective and photochemical modeling to explore what a potential steam atmosphere might look like. Additionally, we have worked to incorporate the uncertainties in the planet’s mass and the host’s age and activity through a comprehensive suite of atmospheric escape simulations. Together, several interesting outcomes emerge (predominantly driven by the size of the assumed volatile envelope) that either would suggest the planet is a super-Venus or super-Mercury, or an unexpected window into the evolution of steam atmospheres. As such, TOI-1266c represents a unique proving ground for theories related to the evolution of sub-Neptunes and Venus-like worlds, which in turn would ground future observations of exoplanets that may have undergone similar processes, as well as Earth-like planets that may be in the process of becoming uninhabitable.<br><br>References:<br>Fulton, B.J., Petigura, E.A., Howard, A.W., Isaacson, H., Marcy, G.W., Cargile, P.A., Hebb, L., Weiss, L.M., Johnson, J.A., Morton, T.D. & Sinukoff, E., 2017. The California-Kepler survey. III. A gap in the radius distribution of small planets. ApJ, 154(3), p.109.<br>Luger, R. and Barnes, R., 2015. Extreme water loss and abiotic O2 buildup on planets throughout the habitable zones of M dwarfs. Astrobio., 15(2), pp.119-143.<br>Luger, R., Barnes, R., Lopez, E., Fortney, J., Jackson, B. & Meadows, V., 2015. Habitable evaporated cores: transforming mini-Neptunes into super-Earths in the habitable zones of M dwarfs. Astrobio., 15(1), pp.57-88.<br>Ramirez, R.M. & Kaltenegger, L., 2014. The habitable zones of pre-main-sequence stars. ApJL, 797(2), p.L25. | 4 Pennsylvania State University, University Park, PA. |
| 74 | Planetary Archaeology: Exploring Planets Transiting Red Giant Stars | Despite the discovery of thousands of transiting planets orbiting main sequence stars, the population of planets around red giant stars remains poorly understood. Recent studies have shown that comparisons between this planet population and analogous main sequence systems can reveal effects of stellar evolution and orbital dynamics on the inflation of planetary atmospheres, as well as planet orbital evolution and eventual engulfment. The current NASA TESS mission is rapidly expanding our ability to detect planets transiting evolved stars and better understand this uniquely valuable planet population. I will present the most recent planet discoveries around evolved stars from TESS, and place these systems in the context of the larger planet population to highlight the new constraints these systems provide on our understanding of planetary orbital evolution. Specifically, I will focus on the planets found with the shortest orbital periods, and how their TESS light curves provide new constraints on models of star and planet tidal evolution and interaction. Finally, I will discuss the future followup of other planetary candidates around evolved stars from TESS, and describe the potential of future missions such as JWST to characterize the atmospheres and compositions of these dying planets. | S. Grunblatt;<br><br>Astrophysics, American Museum of Natural History, New York, NY. |
| 76 | Potential storage of molecular hydrogen in CaTiO_3 | Finding habitable exoplanets has recently drawn interest from not only astrobiologists and astrophysicists but also earth scientists. Studies have shown that evaluating habitability of a planet requires a fully understanding of deep volatile storage and its contributions to surface evolution. | S. Fu [1], K. Leinenweber [2], S. Shim [1]; |

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| | perovskite in the deep interiors of rocky planets | Hydrogen storage in the candidate minerals of deep interior can also greatly affect their properties, such as melting behavior and viscosity, and thus the dynamic evolution of planets. Considering elemental abundances, MgSiO_3 bridgmanite is believed to be an abundant mineral in the interiors of Earth-like planets (similar in sizes and masses). We have studied hydrogen storage in CaTiO_3 perovskite, an important structural analog of MgSiO_3 bridgmanite and chemical component in CaSiO_3 perovskite (third most abundant phase in the Earth's lower mantle. We saturated CaTiO_3 with water at 500 °C and 10 GPa and maintained it for 8 hours in multi-anvil apparatus. Synthesized products were characterized by synchrotron X-ray diffraction, confirming a perovskite structure. Raman spectroscopy shows the sample has vibrational modes at ~3964 and ~4014 cm-1, indicating storage of hydrogen in a form of molecular H_2 instead of hydroxyl (OH) in the structure of CaTiO_3 pervoskite. This is an unusual form of storage given the fact that so far water storage in the deep mantle minerals is known to take a form of hydroxyl. If further investigation supports this initial finding, such a speciation requires breakdown of water and therefore potential release of oxygen from the rocky interior. The results may have important implications for understanding the role of deep volatile cycle for the atmosphere of rock planets. | 1 School of Earth and Space Exploration, Arizonat State University, Tempe, AZ,<br>2 Eyring Materials Center, Arizonat State University, Tempe, AZ. |
| 81 | A Bolt from the Blue - Lightning on Terrestrial Exoplanets | The Global Electric Current (GEC) is dependent on both the atmosphere (ionosphere) and the surface of the planet as its boundaries. The GEC discharges itself in two major ways - with fair weather currents occurring in cloudless conditions and lightning occurring in thunderstorms. Whether a planetary electric current (PEC) exists on terrestrial planets is an important question; The establishment of a PEC would help to discern whether a planet is a true Earth analog.<br><br>In this investigation, the bulk composition of a sample of terrestrial planets and their atmospheres are investigated and the possibilities of planetary electric fields analyzed. Direct detection of molecules created by lightning channels is established as well as the atmospheric composition and the cloud forming processes.<br>(Masters student research) | L. Lewis;<br><br>Open University, London, UNITED KINGDOM. |
| 82 | Stellar flares and planetary habitability: atmospheric escape, chemistry and radiation dose enhancement | Stellar flares can have a significant influence on planetary atmospheres and their radiation environment by enhancing atmospheric escape, altering their chemistry and radiation dose enhancement on their surface. Data from missions such as Kepler, Gaia and TESS have provided us with the flare frequency distribution (FFD) of flares around a variety of stars. We model the impact of enhanced XUV radiation and Stellar Proton Events on potentially habitable planets. We use the energy-limited equation to model how XUV radiation from flares can enhance atmospheric escape in planets in habitable zones around a variety of stars. We make estimates of ozone depletion for planets with Earth-like atmospheres. We also model the impact of Stellar Proton events on terrestrial planets and calculate radiation dose enhancement on their surfaces. We explore the role of planetary magnetic field strength and atmospheric column depth in regulating the radiation dose on the surface. We discuss the implications of our results on the habitability of terrestrial planets in habitable zones around a variety of stars. | D. Atri;<br><br>New York University Abu Dhabi, Abu Dhabi, UNITED ARAB EMIRATES. |

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| 85 | Early (In)Habitability Among Exoplanets: A 1D Parameterized Approach Linking the Mantle-Tectonics-Atmospherics System | With the plethora of terrestrial-like exoplanets recently discovered from the Kepler mission [1], ranging from ~ 0.5 to ~ 2 Earth radius (E_R), it is natural to consider how many of these bodies may have had an atmosphere that allowed for stable liquid water at the surface. Although many discovered terrestrial exoplanets fall within or on the edges of the classically defined habitable zone [2], many do not. Further, the distance and flux from the host star alone may not be a sufficient metric to assess habitability. The habitability of a planetary body is significantly influenced by linked atmospheric and interior processes, such as mantle convection, tectonic mode, geochemical evolution, melting and outgassing, as well as atmospheric development, physics, and chemistry [3-6].<br><br>With the early atmospheric development of a planet inherently linked to its interior evolution, the thermal and chemical interior evolution of a rocky planetary body is integral to elucidating its surface and atmospheric evolution. Here we apply parameterized models of thermal-chemical mantle convection with atmospheric moist static energy balance and single column models, to understand the linked behavior and evolution of a planet, its interior, atmosphere, and surface temperatures. From Earth-like mobile lids to Mars-like stagnant lids and heat-pipe planets, we investigate the role of differing tectonic states in creating a habitable surface environment. We consider planetary radii ranging from that of Mercury to super-Earths (~0.4 - 2.5 E_R). Internal structures, mineralogies, radiogenic abundances, and volatile inventories are constrained from coupled hydrostatic equilibrium models and estimates of Earth's starting compositions from chondritic material [7,8]. Additionally, we examine the influence that initial atmospheric composition and stellar properties have on habitability.<br><br>Our preliminary results indicate that melt production, and therefore atmospheric generation, is enhanced in the first billion years of planetary evolution for mobile lids before tapering off to lower levels. Stagnant lids by contrast show enhanced melt production and atmospheric generation rates at > 1 Gyr and until cessation of convection. Enhanced melt production rates are achieved for stagnant lids < 1 E_R and for mobile lids ≥ 1 E_R as compared to their respective_ tectonic counterparts. For mobile lids > ~1.5 E_R, melt production largely ceases by 2-3 Gyr due to efficient heat loss.<br><br>These results suggest that mobile lids generate atmospheres early in punctuated melting events (within the first few 100 million years, but less than 1 billion years), whereas stagnant lids generate atmospheres across longer timescales through stable melting over billions of years. For small Earth-like terrestrial planets (< 1 E_R) stagnant lids produce denser atmospheres than their mobile lid counterparts. Larger Earth-like mobile lid terrestrial planets (> 1 E_R) produce thicker melt generated atmospheres than stagnant lid counterparts. In aggregate these results suggest that mobile lids are more efficient at generating secondary atmospheres through outgassing for planets ≥ ~1 E_R, and stagnant lids are more efficient for planets < 1 E_R, suggesting there exists an optimal planetary size / tectonic state phase space for both atmosphere generation and timing. | M. Weller [1], D. Ibarra [1], A. Evans [1], A. Johnson [2], T. Kukla [3];<br><br>1 Brown University, Providence, RI,<br>2 Purdue, West Lafayette, IN,<br>3 Stanford University, Stanford, CA. |

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| | | Our preliminary results provide insight into a more comprehensive understanding of processes that are likely to foster the presence of stable liquid water at the surface of a planet. We will discuss properties of the atmospheres produced from outgassing and the constraints for the timing of potential habitability for each tectonic state, planetary size, and insolation rate.<br><br>References: [1] Rogers (2015) Astrophys. J., 801, 1;<br>[2] Choudhuri, (2012). Astrophysics for Physicists, Cambridge University Press;<br>[3] Foley, B. J. (2015), Astrophys. J., 812;<br>[4] Tosi et al. (2016), Geophys. Res. Abstr., 18;<br>[5] Lenardic et al. (2016b), J. Geophys. Res. Planets, 121;<br>[6] Weller and Kiefer (2019) J. Geophys. Res. Planets.<br>[7] McDonough and Sun, (1995), Geology, 120;<br>[8] Driscoll and Olson (2011), Icarus, 213 | |
| 86 | Magnetic Fields, Atmospheres, and the Connection to Habitability (MACH) | Is a global magnetic field required for a planet to retain an atmosphere or be habitable at its surface? This question is relevant for the history of climate evolution in our own solar system, and for evaluation of exoplanet habitability. Answering the question requires expertise from a diverse set of communities, some of which have diverged from each other over the past several decades. For example, modelers and observers of the terrestrial magnetosphere have limited overlap and interaction with modelers and observers of unmagnetized planets or the giant planets in our solar system. There is relatively limited interaction between any of the above communities and those who study exoplanets, though efforts have recently been increasing, as demonstrated by this meeting, to bridge the solar system and exoplanet communities. This presentation will describe recent progress toward determining whether planetary magnetic fields are critical component of their habitability, with emphasis on the activities of a newly-formed NASA Heliophysics DRIVE Science Center. This Center, named MACH (Magnetic Fields, Atmospheres, and the Connection to Habitability) includes representatives from multiple sub-disciplines in Heliophysics, Planetary Science, and Astrophysics (including exoplanets). Over the next several years the Center will support activities related to analysis of spacecraft observations of planetary plasma interactions, modeling of the interaction of planetary atmospheres and magnetic fields with their space environment, and the construction of a theoretical framework for atmospheric escape and habitability that includes both magnetized and unmagnetized planets. The MACH team has already made progress in comparing the atmospheric loss rates from Venus, Earth, and Mars in a consistent manner, and in extending models for atmospheric ion loss from Mars and Venus to Earth-strength fields. An overarching goal for the Center is to provide a web tool for the entire community that provides atmospheric loss rates as a function of planetary properties, stellar properties, and planetary magnetic field strength. The MACH Center will host a community-wide workshop in 2021 centered around this topic, and is seeking to grow their interactions with interested scientists from relevant disciplines. | D. Brain [1], W. Peterson [2], O. Cohen [3], T. Cravens [4], K. France [2], Y. Futaana [5], A. Glocer [6], M. Holmstrom [5], L. Kistler [7], Y. Ma [8], T. Moore [6], L. Peticolas [9], R. Ramstad [1], K. Seki [10], R. Strangeway [11], A. Vidotto [12], A. Yau [13];<br><br>1 LASP, University of Colorado - Boulder, Boulder, CO,<br>2 LASP, University of Colorado, Boulder, CO,<br>3 University of Massachusetts, Lowell, Lowell, MA,<br>4 University of Kansas, Lawrence, KS,<br>5 IRF, Swedish Institute of Space Physics, Kiruna, SWEDEN,<br>6 NASA/GSFC, Greenbelt, MD, |

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| | | | 7 University of New Hampshire, Durham, NH,<br>8 University of California, Los Angeles, Los Angeles, CA,<br>9 Sonoma State University, Rohnert Park, CA,<br>10 University of Tokyo, Tokyo, JAPAN,<br>11 Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Los Angeles, CA,<br>12 Trinity College, Dublin, Dublin, IRELAND,<br>13 Physics and Astronomy, University of Calgary, Calgary, Alberta, AB, CANADA. |
| 87 | Effect of mantle oxidation state on the magma ocean atmospheric evolution | The magma ocean period was a critical phase determining how Earth's atmosphere developed into habitability. However, there are major uncertainties in the role of key processes such as outgassing from the planetary interior and escape of species to space that play a major role in determining the atmosphere of early Earth. We investigate the effect of outgassing of various species and escape of H_2 for different mantle redox states upon the composition and evolution of the atmosphere for the magma ocean period.<br><br>We included an important new atmosphere-interior coupling mechanism: the redox evolution of the mantle, which strongly affects the outgassing of species. We simulated the volatile outgassing and chemical speciation at the surface for various redox states of the mantle by employing a C-H-O based chemical speciation model combined with an interior outgassing model. We then applied a line-by-line radiative transfer model to study the remote appearance of the planet in terms of the infrared emission and transmission. Finally, we used a parameterized diffusion-limited and XUV energy-driven atmospheric escape model to calculate the loss of H_2 to space. We have simulated the thermal emission and transmission spectra for reduced and oxidized atmospheres present during the magma ocean period of Earth. Reduced/thin atmospheres consisting of H_2 in abundance emit more radiation to space and have a larger<br><br>effective height than oxidized/thick atmospheres, which are abundant in H_2O and CO_2. We obtain that the outgassing rates of H_2 from the mantle into the atmosphere are a factor of ten times higher than the rates of diffusion-limited escape to space. Our work presents useful insight | N. Katyal [1], G. Ortenzi [2], J. L. Grenfell [2], L. Noack [3], F. Sohl [2], M. Godolt [1], A. G. Muñoz [1], F. Schreier [4], F. Wunderlich [1], H. Rauer [2];<br><br>1 Technical University, Berlin, GERMANY,<br>2 DLR, Berlin, GERMANY,<br>3 Free University, Berlin, GERMANY,<br>4 DLR, Oberpfaffenhofen, GERMANY. |

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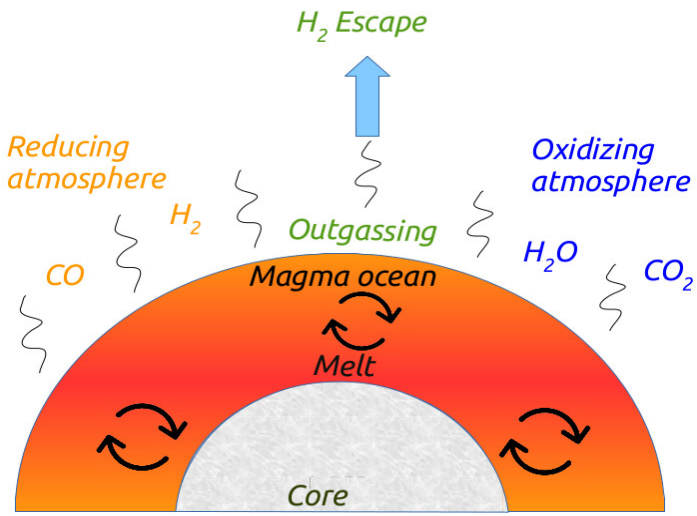
| | |  into the development of the terrestrial atmosphere during the magma ocean period and provides input to guide future studies that discuss exoplanetary interior compositions and their possible links with atmospheric compositions. | |
| 89 | Stellar Variability & Precision Radial Velocimetry: Lessons for atmospheric characterization | Ultra-stabilized echelle spectrographs (e.g., ESPRESSO, HPF, EXPRES, NEID) are enabling a new generation of precision radial velocity planet surveys. Thanks to improved instrumentation, the dominant source of "noise" is typically intrinsic stellar variability, rather than measurement uncertainties. This has motivated a variety of approaches to mitigate the effect of stellar variability on Doppler planet surveys. I propose to provide a survey of recent progress in developing, verifying and validating advanced statistical and machine learning methods for enabling Doppler planet surveys to pierce the veil of stellar variability. I would discuss the implications for planning futureextremely precise radial velocity surveys and the potential implications for planning future observations to characterize the atmospheres and/or surfaces of potentially habitable exoplanets. | E. Ford [1,2], C. Gilbertson [1], Z. Guo [3], J. K. Luhn [1], M. Palumbo [1];<br><br>1 Astronomy & Astrophysics, Pennsylvania State University, University Park, PA,<br>2 Natural Sciences, Institute for Advanced Study, Princeton, NJ,<br>3 Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, UNITED KINGDOM. |
| 91 | Is there any other habitable planets in universe except Earth? | Astrophysicists have already discovered about 4292 confirmed exoplanets via ground-based methods, especially via the radial velocity (RV) method.Most of these planets are much bigger than Earth, and only a few of them are rocky planets that could conceivably harbor life. Scientists are enthusiastic enough to find habitable planets to look for trace of other lives there.Optimum position is calculated at 1.08 astronomical units for an Earth-like planet at which the biosphere would realize the maximum life span.We already found earth sized planets within the habitable zones around the host star using radial velocity and transit method.Methodology to find those planets and analyzed data regarding planets' detection method have been presented.List of potential habitable | M. Ahmed;<br><br>Indian Institute Of Science Education And Research Kolkata, West Bengal, INDIA. |

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| | | exoplanets are ranked and displayed according to distance from earth (light years).To characterize these planets, we are likely to need new space-based telescope equipped with ultra-modern technology as space missions employ the HZ to select promising targets for follow-up habitability assessment. Some conceptions regarding these telescopes and recent findings regarding potential habitable planets are discussed. | |
| 93 | Stellar Energetic Particle-driven Production of Biologically Relevant Molecules in Atmospheres of Young Earth-like Exoplanets Around Active G-K Stars | The chemistry of N_2, CO_2, CH4-rich atmospheres of terrestrial-type exoplanets around active G-K stars is a complex problem: the star's ionizing radiation in the form of X-ray and Extreme UV radiation and the precipitating energetic particles accelerated in coronal mass ejection driven shocks can drive complex chemistry in the exoplanetary atmosphere, and ignite the production of complex molecules (Airapetian et al., 2016). We developed a set of atmospheric models to simulate the formation of organic molecules that can be considered as atmospheric pre-biosignatures from exoplanets around active stars. The model has recently been extended to account for the production of ions, their role in the enhanced chemistry in the lower atmosphere, as well as the interaction of these ions with the aerosols. We applied the photochemical-collisional model to simulate the chemistry of a young terrestrial-type exoplanets resembling the Hadean Earth to highlight the creation of atmospheric pre-biosignatures, relevant greenhouse gases, and the presence of aerosols driven by stellar activity sources. We also discuss the impact of that modified atmospheric chemistry on the exoplanetary climate. | G. Gronoff [1], V. Airapetian [2], B. Hayworth [3], B. M. Hegyi [1], J. Kasting [3];<br><br>1 SSAI /NASA LaRC, Hampton, VA,<br>2 NASA GSFC/SEEC, Greenbelt, MD,<br>3 Pennsylvania State University, University Park, PA. |
| 97 | Stable, Closely-Spaced Three-Planet Systems | We explore the orbital dynamics of systems consisting of three planets, each as massive as the Earth, on coplanar, initially circular, orbits about a one solar mass star. The initial semi-major axes of the planets are equally-spaced in terms of their mutual Hill radius, which is equivalent to a geometric progression of orbital sizes for small, equal-mass, planets. Our simulations explore a wide range of spacings of the planets and were integrated for virtual times of up to 10 billion years or until the orbits of any pair of planets crossed. Our results for three-planet systems are qualitatively similar to those found for analogous five-planet systems for which system lifetimes depend primarily on orbital separation. Three-planet systems are generally longer-lived, but we find narrow regions of long-lived systems for surprisingly closely-spaced three-planet systems, away from the separation beyond which systems are expected to be long-lived due to three-body resonances, that we do not find in five-planet systems. These regions are located far from strong mean motion resonances. We present an analysis of these regions and find that differences in initial longitudes can have larger effects on lifetimes than differences in initial orbital separations. We compare the early evolution of short-lived with long-lived systems using similar orbital separations. We find that early conjunctions play a major role in the angular momentum deficit evolution, which greatly affects the system lifetime. | S. Gavino [1], J. Lissauer [2];<br><br>1 Laboratoire d'Astrophysique de Bordeaux, Pessac, FRANCE,<br>2 NASA Ames Research Center, Moffett Field, CA. |
| 98 | Ground-Based Exoplanet Direct Imaging in the Next Decade: The Path to Imaging Another Earth | In this talk, we describe technical progress with and forecast the science capabilities of the next generation of extreme AO systems on large ground-based telescopes. Systems like SCExAO and complementary ones like MagAO-X serve as incubators for critical direct imaging technologies on the ground and in space. Key wavefont control advances - some of which may be relevant for NASA flagship missions-- include predictive control, linear dark field control, and additional novel methods that address non-common path aberrations. Completely rethought direct imaging survey | T. Currie [1,2], O. Guyon [1];<br><br>1 NAOJ/Subaru, Hilo, HI,<br>2 NASA-Ames, Moffett Field, CA. |

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| | | approaches are in their infancy but already showing promise for far higher direct imaging discovery yields. I describe the utility of these instruments in mitigating risk and enabling breakthrough science for Roman-CGI and how they serve as prototypes for dedicated extreme AO systems with ELTs that may image habitable zone Earths around the nearest stars, some of which could be followed up spectroscopically with NASA missions to identify biomarkers. | |
| 101 | Magma ocean differentiation regime in the earliest formed rocky bodies -Internal or External? | The fate of major volatiles during the evolution of protoplanetary bodies and its subsequent effect on the volatile accretion history of rocky planets is poorly understood. Evidence for the widespread differentiation of the earliest formed planetesimals and planetary embryos makes the volatile inventories of these bodies susceptible to fractionation between core, magma ocean (MO), and atmosphere (and subsequent loss to space). This is especially important for carbon (C) and nitrogen (N), which are prone to fractionation into all three reservoirs, albeit in different proportions depending upon the chemistry of the MOs. Recent findings have shown that even the parent bodies of primitive chondrites did not escape differentiation such that their interiors, overlain by unmelted chondritic crusts, also underwent large-scale melting. Therefore, to track the evolution of C and N from primitive dust to present-day planets, it is important to constrain their fate during end-member protoplanetary differentiation regimes, i.e., internal, closed system MOs (MO-core fractionation) and external, open system MOs (atmosphere-MO-core fractionation).<br><br>Here we present a thermodynamic modelling framework to track C and N fractionation between atmosphere, MO and core reservoirs as a function of the composition of their accreting materials and sizes of the parent bodies. For external MOs, C and N in the MOs were calculated based on their vapor pressure-induced solubility in the silicate melts while the exchange between MOs and core forming alloy melts for external as well as internal MOs were calculated using alloy-silicate melt partition coefficients. For bodies with external MOs, 89-99% of the accreted C and N inventories reside in the atmosphere resulting from MO degassing, 1-11% in their cores, and less than 1% C-N in their silicate reservoirs. Whereas for bodies with internal MOs, the cores are the major C and N bearing reservoir (90-99%). The relative prevalence of external versus internal magma ocean regimes can be used to explain the C-N inventories of different groups of iron meteorites. Consequently, C-N inventories of larger planets were likely affected by the relative prevalence of feedstock rocky bodies in the Solar System that underwent end-member protoplanetary differentiation regimes. | D. Grewal, R. Dasgupta;<br><br>Rice University, Houston, TX. |
| 102 | A very early origin of isotopically distinct nitrogen in the inner Solar System protoplanets | Understanding the origin of nitrogen (N) and other life-essential volatiles like carbon and water in the Solar System and beyond is critical to evaluate the potential habitability of rocky planets. Whether the inner Solar System planets accreted these volatiles from their inception or had an exogenous delivery via volatile-rich, carbonaceous material from the outer Solar System is, however, not well understood. Using previously published data of nucleosynthetic anomalies of Ni, Mo, W and Ru in iron meteorites in conjunction with their 15N/14N ratios, we show that the earliest accreting protoplanets in the inner and outer protoplanetary disk accreted isotopically distinct N. While the Sun and Jupiter captured N from nebular gas, concomitantly growing protoplanets in the inner and outer disk possibly sourced their N from organics and/or dust - with | D. Grewal [1], R. Dasgupta [1], B. Marty [2];<br><br>1 Rice University, Houston, TX,<br>2 Université de Lorraine, Nancy, FRANCE. |

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| | | each reservoir having a different N isotopic composition. Hence the processes that led to the enrichment of 15N in the organics and/or dust relative to the nebular gas either predated or were synchronous with the formation of protoplanets. A distinct N isotopic signature of the inner Solar System protoplanets coupled with their rapid accretion suggests that non-nebular, isotopically processed N was ubiquitous in the growth zone of the inner Solar System rocky bodies within ~0-0.3 Myr of the formation of CAIs. Because the N isotopic ratios of the bulk silicate Earth falls between those of inner and outer Solar System reservoirs, we infer that N in the present-day rocky planets represents a mixture of both inner and outer Solar System reservoirs. | |
| 103 | XUV-Driven Atmospheric Mass Loss of M Dwarf Planets due to Flaring | The habitability of planets orbiting M dwarfs may be compromised by the host star's XUV flux that results from flares, which can increase the quiescent XUV flux by up to 2 orders of magnitude. This wavelength range warms and ionizes Earth-like planets' upper atmospheres, expanding this layer and driving atmospheric loss. The main goal of the present work is to quantify the contribution of the XUV flux due flares in the atmospheric escape of Earth-like planets in the habitable zones of M dwarfs. We therefore developed a new module for VPLanet called FLARE that simulates stellar flares for stellar masses between 0.2 and 0.6 solar masses. We simulate planets with masses between 0.5 and 5 masses of Earth, and with a initial surface water abundances between 1 and 10 times modern Earth's ocean abundance. We find that flaring can remove up to 4 additional Earth oceans, significantly reducing these planets likelihood to support habitable conditions. We also find that flares increases oxygen accumulation in the atmospheres by up to 800 bars. For those planets that also retain surface water, this excess oxygen could also create a protective ozone layer against the biological damage caused by the enhanced XUV radiation from flares. | L. Amaral [1], R. Barnes [2,3], A. Segura [1,3];<br><br>1 Departamento de Física de Plasmas y de Interacción de Radiación con la Materia, Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, MEXICO,<br>2 Astronomy Department, University of Washington, Seattle, WA,<br>3 NASA Virtual Planetary Laboratory Lead Team, Seattle, WA. |
| 104 | Impact of Tides on the Potential for Exoplanets to Host Exomoons | Exomoons may play an important role in determining the habitability of worlds outside of our solar system. They can stabilize conditions, alter the climate by breaking tidal locking with the parent star, drive tidal heating, and perhaps even host life themselves. However, the ability of an exoplanet to sustain an exomoon depends on complex tidal interactions. Motivated by this, we make use of simplified tidal lag models to follow the evolution of the separations and orbital and rotational periods in planet, star, and moon systems. We apply these models to known exoplanet systems to assess the potential for these exoplanets to host exomoons. We find that there are at least 36 systems in which an exoplanet in the habitable zone may host an exomoon for longer than one gigayear. This includes Kepler-1625b, an exoplanet with an exomoon candidate, which we determine would be able to retain a Neptune-sized moon for longer than a Hubble time. These results may help provide potential targets for future observation. In many cases, there remains considerable uncertainty in the composition of specific exoplanets. We show the detection (or not) of an exomoon would provide an important constraint on the planet structure due to differences in their tidal response. | A. Tokadjian;<br><br>USC/Carnegie Observatories, Los Angeles, CA. |

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| 105 | Drifting into habitability | Following on from the work of Vinson and Hansen, we investigate simple models of thermal balance on terrestrial planets in the habitable zone of low mass main sequence stars. For planets in or near mean motion pairs, the mutual planetary perturbations can maintain asynchronous spins, even in the regime where tidal forces are strong.<br><br>The resulting planetary spins are still almost synchronous, but not quite, and the so the pattern of stellar illumination drifts slowly over the planetary surface. We examine the implications of this kind of irradiation pattern for the thermal balance of simple planetary atmosphere models and how this might influence the concept of habitability. We include in this a discussion of how climate is affected when the orbital dynamics of the multiplanet system is chaotic in nature. | B. Hansen;<br><br>University of California, Los Angeles, Los Angeles, CA. |
| 106 | Planetary Systems Biochemistry | Currently, there are no standardized assessment criteria or uncertainty estimations by which astrobiologists can evaluate biosignatures. This stands in contrast to other recent major discoveries in science that required similar international coordination to what the actually discovery of alien life will surely require. Without consensus assessments for life detection, it will be impossible for our community to agree on the validity of biosignature interpretation even if a signal is detected. Before we can confidently claim detection, we must be able to anticipate the signatures of life in low resolution datasets. Determining the multivariate patterns living systems produce will enable our community to move, for the first time, towards consensus assessments. Emerging approaches are now pointing to comprehensive statistical frameworks that do not consider just one line of evidence, but will be enable integration of multiple lines of evidence to increase confidence in a discovery. This talk is more aspirational than review of the current state of science, and presents ideas on how statistical approaches to quantify life in its planetary context - developing predictive quantitative frameworks that capture the multivariate coupling between planets and life - will be a key component of the critically needed theoretical infrastructure necessary for astrobiologists to make consensus assessments in the face of limited and noisy data. | S. Walker;<br><br>School of Earth and Space Exploration, Arizona State University, Tempe, AZ. |
| 107 | Computational study on the importance of UV light in the production of molecules of prebiotic importance in an astrobiological context | Many studies on prebiotic chemistry indicate that UV radiation could have played a very important role in the evolution of prebiotic chemistry (e.g Ferris, 1983; Barks, 2010). The surface of the Earth during the Archean period (approximately 3.8 Ga) was exposed to high doses of UVC radiation (200-280 nm) and UVB (280- 315 nm) in comparison with the radiation that arrives today (e.g Sagan, 1973; Cockell, 1998) due to lack of layer of ozone, its atmospheric composition, and higher activity of the sun in this wavelength range. In an astrobiological context, it is known that stars have constant UV emissions, particularly dwarf M-type stars. Depending on the atmospheric composition of a potentially habitable hypothetical planet and the spectral type of the star that hosts it, the planet could receive part of the UV radiation emitted by the star. This radiation might change the potential chemical reactivity and synthesis of some organic compounds on the planetThe atmosphere of the Earth 3.8 Ga ago possibly composed of carbon dioxide ($CO_2$). There are no enough experimental works regarding the $CO_2$-rich atmosphere as to establish the role of the UV radiation in the formation/destruction of prebiotic organic molecules. In this work, we use the ATMOS photochemical model to calculate the amount of UV light that would reach the surface of a potentially habitable planet with an atmosphere composed of $CO_2$, $N_2$ and $H_2O$ around a | M. Armas Vazquez, A. Segura, A. Heredia;<br><br>Physics of plasmas and the interaction of radiation with matter, ICN UNAM, Mexico City, MEXICO. |

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| | | young Sun-like star and dwarf-like stars M with different levels of chromospheric activity. For other hand, we analyzed a known route of adenine synthesis from formamide through computational methods, to know how UV radiation affects these molecules of prebiotic importance and if it could have been important for trigger reactions for the production of molecules of prebiotic importance. | |
| 108 | IN-SITU EXPLORATION OF THE EXOPLANET NEXT DOOR: REVEALING THE CHEMISTRY, HABITABILITY AND EVIDENCE OF BIOLOGICAL PROCESSES IN THE CLOUDS OF VENUS | With its thick CO_2 atmosphere, moonless skies, and proximity to the Sun, Venus is considered to be a close analog to common, presumably lifeless, rocky exoplanets. However, the recent suggestion of PH_3 in the clouds of Venus (Greaves et al., 2020) has sparked renewed interest in the prospects for living organisms residing in the skies of Earth's nearest planetary neighbor. As a disequilibrium species, PH_3 is readily photolyzed and chemically reacts with H, OH and H_2O. In addition, PH_3 interacting with the ubiquitous H_2SO_4 cloud particles readily converts into phosphorous and phosphoric acids (H_3PO_3 and H_3PO_ 4, respectively). Together, these limit the mean lifetime of PH_3 molecules in the Venusian clouds to < 10 hours. The possible discovery of ~1-20 ppb PH_3 then means that this amount needs to be regenerated approximately every half Earth day. With no known natural photo- or thermo-chemical means to sufficiently generate PH_3 from other phosphorus compounds, a working hypothesis is that PH_3 is generated by microbial organisms, as occurs on Earth.<br><br>Irrespective of whether PH_3 is eventually confirmed by future observations, in-depth investigation of the present atmosphere of Venus is fundamentally important for understanding mysterious climate history of the planet, as well as the workings of exo-Venuses that are likely going to be the most observable type of exoplanets in the foreseeable future. As proposed by recent mission studies - both a large Flagship class mission (Gilmore et al., 2020) and a more narrowly focused New Frontiers class mission (Baines et al., 2020) - a balloon-based mission to the clouds of Venus would use in-situ measurements to directly investigate the chemistry, dynamics, and potentially biological processes within the cloud environment of our "exoplanet next door". Utilizing the large (~80 m s-1) zonal winds that predominate at < 60o latitude, the aerobot mission concept would circle the planet more than a dozen times over a notional 100-Earth-day science phase as it likely wanders poleward from its deployment near 10o latitude, with an excellent chance of visiting high latitudes >50$^{o}$. Onboard instrumentation would sample the environment over all times of day including the composition of the air and aerosols, including (1) phosphorous compounds potentially linked to life processes, (2) UV-absorbing materials which possibly are also linked to astrobiology, (3) the reactive sulfur-cycle gases that create the dominant H_2SO_4 aerosols, and (4) the noble gases, their isotopes and the isotopes of light gases - key to understanding the formation and evolution of the planet and its atmosphere. A digital holographic microscope would image particles in three dimensions at 0.7 micron-scale spatial resolution, searching for cellular morphologies. The balloon mission also directly and continuously measures the pressure/temperature structure, and, supported by balloon-tracking orbiter, winds in all three dimensions. The aerobot, capable of multiple 10-km-altitude traverses centered near 55-km (~0.5 bar, 25C), would enable 3-dimensional maps of these environmental characteristics as well as the dynamically/chemically influenced size distribution of aerosol particles via a nephelometer/particle-counter (Renard et al., | K. Baines [1], J. Cutts [2], S. Atreya [3], S. Seager [4], C. Wilson [5], D. Nikolic [2], C. Lindensmith [2], G. Serabyn [6], S. Madzunkov [2], J. Renard [7], O. Mousis [8], M. Delitsky [9], S. Limaye [10];<br><br>1 Planetary and Exoplanetary Atmospheres, Jet Propulsion Laboratory, Pasadena, CA,<br>2 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA,<br>3 University of Michigan, Ann Arbor, MI,<br>4 Massachusetts Institute of Technology, Cambridge, MA,<br>5 University of Oxford, Oxford, UNITED KINGDOM,<br>6 California Institute of Technology, Pasadena, CA,<br>7 Centre National= de la Recherche Scientifique, Orleans, FRANCE,<br>8 Aix Marseille Universite, CNRS, CNES, LAM, Marseille, FRANCE,<br>9 California Specialty Engineering, Pasadena, CA,<br>10 Space Science and Engineering Center, University of Wisconsin - Madison, Madison, WI. |

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| | | 2020) testing, for example, the life cycle hypothesis of Seager et al (2020). These traverses also reveal the vertically-varying characteristics of atmospheric stability, gravity and planetary waves and Hadley cells, important for understanding the mechanisms that power and sustain the planet's strong super-rotation. Such altitude excursions also enable measurements of radiative balance and solar energy deposition via a Net Flux Radiometer (Aslam et al.,<br>2015), another key to understanding super-rotation.<br><br>References Aslam, S., et al. (2015) EPSC Abstracts, Vol 10. EPSC2015-388.<br>Baines, K. H. et al. (2020). New-Frontiers Class In-Situ Exploration of Venus: The Venus Climate and Geophysics Mission Concept. White paper submitted to Planetary Science Decadal Survey 2023-2032.<br>Gilmore, M.S., Beauchamp. P. M., Lynch, R., Amato, M. J., et al. (2020). Venus Flagship Mission Decadal Study Final Report. https://www.lpi.usra.edu/vexag/reports/Venus-Flagship-Mission_FINAL.pdf<br>Greaves JS., Richards MS., Bains W. et al. (2020) Phosphine in the cloud decks of Venus. Nature Astronomy doi.org/10.1038/s41550-020-1174-4.<br>Renard, J.-B., Mousis, O., Rannou, P., Levasseur-Regourd, A. C., Berthet, G., Geffrin, J.-M., Hadamcik, E., Verdier, N., Millet, A.-L., and Daugeron, D. (2020) Counting and phase function measurements with the LONSCAPE instrument to determine physical properties of aerosols in ice giant planet atmospheres, Space Science Reviews, 206, 28.<br>Seager S, Petkowski JJ, Gao P, et al. (2020) A proposed life cycle for persistence of the Venusian aerial biosphere. Astrobiology 2021, 21:2. DOI: 10.1089/ast.2020.2244 | |
| 109 | The variation of T_eq for the exoplanets detectable by Roman in direct imaging: a catalogue of targets | The Nancy Grace Roman Space Telescope (previously named WFIRST) will be the first mission to analyse exoplanets by directly imaging them in reflected starlight. This technique will allow us to characterize a population of long-period planets which cannot be studied by current facilities, increasing our knowledge on the diversity of (exo)planetary atmospheres.<br><br>In this work, we studied the exoplanet detection yield of the Roman Space Telescope's coronagraph instrument (CGI). For that, we explored the NASA Exoplanet Archive and computed, for all confirmed exoplanets, 10000 possible orbital realizations based on their Keplerian parameters and corresponding uncertainties. For each realization, we checked if the planet orbits at any point within the Inner and the Outer Working Angles of the coronagraph and is also brighter than the minimum contrast of the instrument. From this statistical exercise, we obtained the probability of detecting each planet (P_detect) and found that up to 76 planets have non-zero P_detect and are therefore potentially Roman-accessible. For each of them, we computed the range of observable phase angles and equilibrium temperatures. We find that the orbits of these Roman-accessible planets have larger eccentricities than the orbits of those characterized so far in transit. This results in large variations of the equilibrium temperature along the orbit, which may affect the atmospheric structure. | Ó. Carrión-González [1], A. García Muñoz [1], N. C. Santos [2,3], J. Cabrera [4], S. Csizmadia [4], H. Rauer [4,5];<br><br>1 Technische Universität Berlin, Berlin, GERMANY,<br>2 Universidade do Porto, Porto, PORTUGAL,<br>3 Instituto de Astrofísica e Ciências do Espaço, Porto, PORTUGAL,<br>4 Deutsches Zentrum für Luft-und Raumfahrt, Berlin, GERMANY,<br>5 Freie Universität Berlin, Berlin, GERMANY. |

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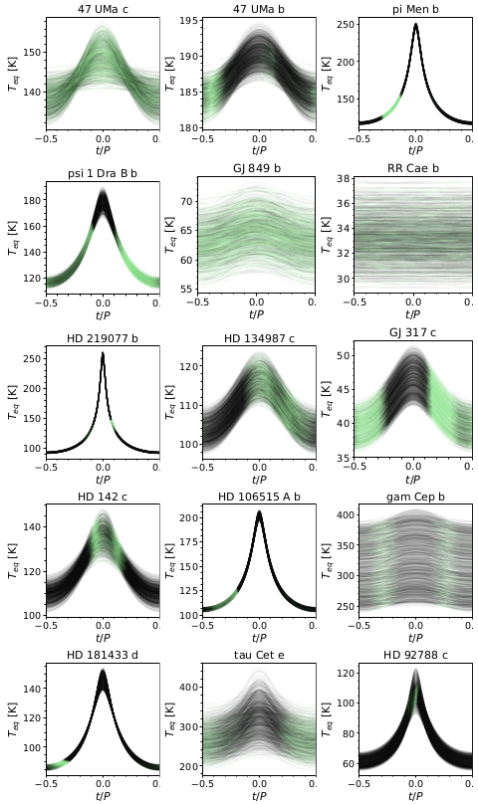
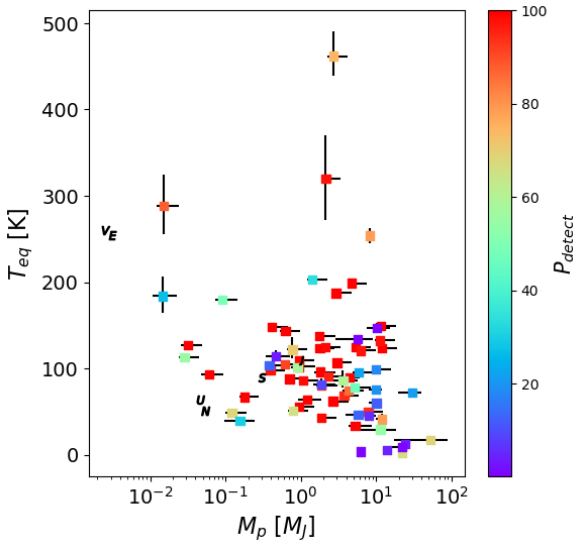
| | | Here we present a catalogue of Roman-accessible planets, including several targets with equilibrium temperatures of about 300 K. We discuss the possible atmospheric changes that exoplanets in eccentric orbits may undergo and the most favourable planets to show atmospheric variability during the time that they remain observable by Roman. The remaining years until the launch of this mission should allow to improve the orbital characterization of these planets, which will be key to refine our results.<br>  <br><br>  <br> | |
| 110 | INFERRING TIME EVOLUTION OF VOLCANISM IN EXTRASOLAR PLANETS AND ITS IMPLICATIONS ON HABITABILITY | Geophysical conditions are now understood to play a key role on the habitability of extrasolar planets. Studies on the geological time evolution of magnetic fields, crustal chemistry and the atmosphere of rocky extrasolar planets are relevant in this context. These phenomena are influenced by the evolution of internal heat and volcanism of these planets. In this paper we will be presenting our investigations on the geological time evolution of volcanism in 53 potentially habitable extrasolar planets in our galaxy based up our model extrapolating our geophysical knowledge of rocky planets in the inner solar system. We will also explain how the results of this study will influence the habitability of these extrasolar planets. Volcanism is known to be an important dissipation mechanism of internal heat in rocky planetary objects like Earth.<br><br>Different aspects of volcanism in the inner solar system are studied extensively. There are models which address the time evolution of volcanism in rocky extrasolar planets. The phenomenon of cessation of volcanism in planetary objects is not understood in detail so far. In our model we | V. Kumar [1,2], Girish T E [2], Sathyan N S [1], Longhinos B 2and Binoy.J [1];<br><br>1 Physics, Government College for Women, Thiruvananthapuram, Thiruvananthapuram, Kerala, INDIA,<br>2 Physics and Geology, University College, Thiruvananthapuram, INDIA. |

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| | | suggested that the major volcanism in the Earth will cease in the near geological future based on the critical internal value needed to sustain volcanic /tectonic activity in rocky solar system planetary objects.The time evolution of volcanism in Earth and Mars has probably influenced the origin of life and biological evolution in these planets. Planetary mass possibly decides its thermal and volcanic history over geological time scales .The current internal heat parameters inferred for inner solar system planetary objects is found to be proportional to the basic geophysical properties of these planetary objects such as mass. In this context we also could find a planetary mass-volcanic cessation age relation from our model. This relation is supported by the inferences of cessation ages of inner solar system planetary objects.<br><br>For the case of Earth, we have also found a linear regression relation between surface heat flux and maximum intensity of volcanism using relevant observations during the past 200 Myrs. The results of our geophysical studies of inner solar system and its comparison with the known features of biological evolution in Earth are extrapolated to 53 PHESP to find its internal heat and volcanism at specific geological ages. The tidal heat contributions to the internal heat of extrasolar planets due to the influence of host star is also inferred in this context. From the host star ages, around 10 extrasolar planets (majority are Kepler candidates) out of 53 is found to be at present in the declining phase of volcanism which is suggested to be the best period for origin of lifeforms in these extrasolar planets. The time evolution of volcanism and its possible role in the habitability of selected extrasolar planets like will be also discussed in detail in this context. In addition to this we also study the dynamical interactions of extrasolar planets with its host star to know about the stellar activity variations of the host star of extrasolar planets which will affect the habitability conditions of the extrasolar planets. | |
| 111 | Idealised convection in pure steam atmospheres | Atmospheres with a significant mass fraction of condensable gases may not be uncommon among terrestrial or sub-Neptune exoplanets. A wide variety of important planetary climate problems involve understanding of dynamical properties of condensible-rich atmospheres. Recent theoretical advances have shown that non-dilute dynamics, either in large or local scales, differs in fundamental ways from that in the dilute conditions. We further examine the properties of small-scale moist convection in non-dilute atmospheres using numerical simulations. Here we start with an extreme case of pure steam atmospheres using an idealized, fully compressible, non-hydrostatic model, with parameterized instantaneous condensation, rainout, and evaporation. Our preliminary results show that, in agreement with previous theory, pure steam atmospheres cease convective buoyancy due to the stringent relation between temperature and pressure. There seems to be a lack of hurricanes in such worlds even when rotation is included. We will discuss further situations wherein very simple clouds are included or a high supersaturation ratio is allowed. Implications for convective parameterization in global models will be also discussed. | X. Tan, R. Pierrehumbert, M. Lefevre;<br><br>University of Oxford, Oxford, UNITED KINGDOM. |
| 112 | Retrieving Earth's phase curve | The EPOXI extended mission phase for the Deep Impact spacecraft observed the Earth in 2008 and 2009 as an analog for a habitable terrestrial exoplanet. The EPOXI data ranges over visible and near-infrared wavelengths and consists of five observations. They are at five different phase angles and three are equatorial observations and two polar (one North and one South) over a 24 hour period. | R. De Cock [1], S. Dineshkumar [2], T. Hewagama [3], C. Lisse [4], T. Livengood [5]; |

This data is used to create the phase curve and it is compared to a Lambertian scattering disk as can be seen in Figure 1.

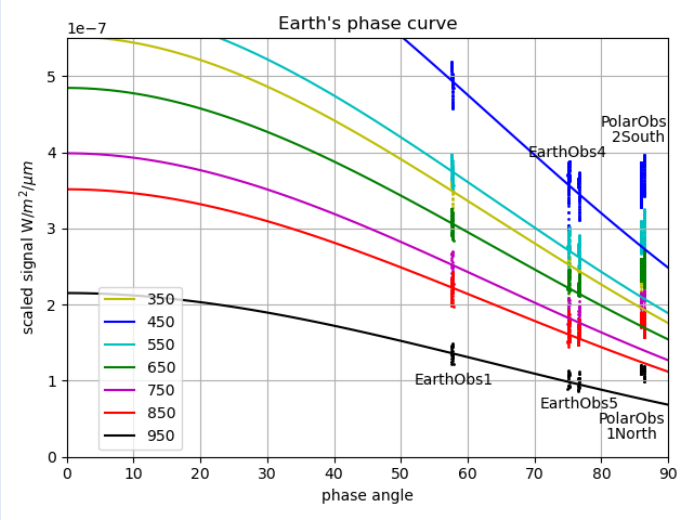
Table 1: Scaled values of geometric albedo and standard deviation for every wavelength and observation.

| Observations | Wavelengths [$\mu m$] 350 | 450 | 550 | 650 | 750 | 850 | 950 | Phase angle [deg] |
|---|---|---|---|---|---|---|---|---|
| EarthObs1 | $0.294 \pm 0.010$ | $0.229 \pm 0.009$ | $0.176 \pm 0.007$ | $0.167 \pm 0.007$ | $0.172 \pm 0.009$ | $0.188 \pm 0.011$ | $0.143 \pm 0.009$ | 57.7 |
| EarthObs4 | $0.289 \pm 0.017$ | $0.231 \pm 0.015$ | $0.181 \pm 0.010$ | $0.173 \pm 0.009$ | $0.180 \pm 0.011$ | $0.199 \pm 0.014$ | $0.149 \pm 0.011$ | 75.1 |
| EarthObs5 | $0.291 \pm 0.013$ | $0.234 \pm 0.012$ | $0.183 \pm 0.008$ | $0.174 \pm 0.006$ | $0.182 \pm 0.009$ | $0.201 \pm 0.013$ | $0.148 \pm 0.011$ | 76.6 |
| PolarObs1North | $0.343 \pm 0.016$ | $0.296 \pm 0.015$ | $0.240 \pm 0.010$ | $0.236 \pm 0.008$ | $0.248 \pm 0.007$ | $0.271 \pm 0.009$ | $0.213 \pm 0.007$ | 85.9 |
| PolarObs2South | $0.353 \pm 0.015$ | $0.312 \pm 0.015$ | $0.255 \pm 0.016$ | $0.246 \pm 0.015$ | $0.251 \pm 0.015$ | $0.270 \pm 0.016$ | $0.207 \pm 0.012$ | 86.4 |

The model lines are made using Equation 1 where A_g is the geometric albedo, pi F is the incoming flux and the final term is the Lambert phase function [Madhusudhan and Burrows, 2012].

$$j(\alpha) = A_g \cdot \pi F \cdot \left[ \frac{\sin(\alpha) + (\pi - \alpha) \cdot \cos(\alpha)}{\pi} \right]$$

The geometric albedo to create the lines is 0.2 [Mallama, 2009]. This value is greatly smaller than the classic value for geometric albedo of 0.4341, showing that there is research to be done. Besides this, it can be seen that the difference between model and empirical data is dependent on wavelength. Furthermore, the polar observations have clearly a higher signal than the model for all wavelengths. Since the geometric albedo is the only variable, one can solve for the required geometric albedo to match the model with the data. These values can be seen in Table 1.




From these values, it can be seen that the shorter wavelengths require higher values than longer wavelengths. Furthermore, it shows that the polar observations are distinct from the equatorial ones and it shows that results can be misleading if only equatorial observations would be used. Additionally, it can be seen that despite the different phase angle, the equatorial observations have a similar geometric albedo for each wavelength. The same can be said for the polar observations, even though they are opposite poles. In general, all these numbers are much lower than the geometric albedo of 0.434. Now the values for geometric albedo from EarthObs1 are used to plot

1 TU Delft, Delft, NETHERLANDS,
2 University of Maryland, College Park, MD,
3 NASA GSFC/Astrobiology Institute, Greenbelt, MD,
4 Johns Hopkins University, Baltimore, MD,
5 NASA/GSFC, Greenbelt, MD.

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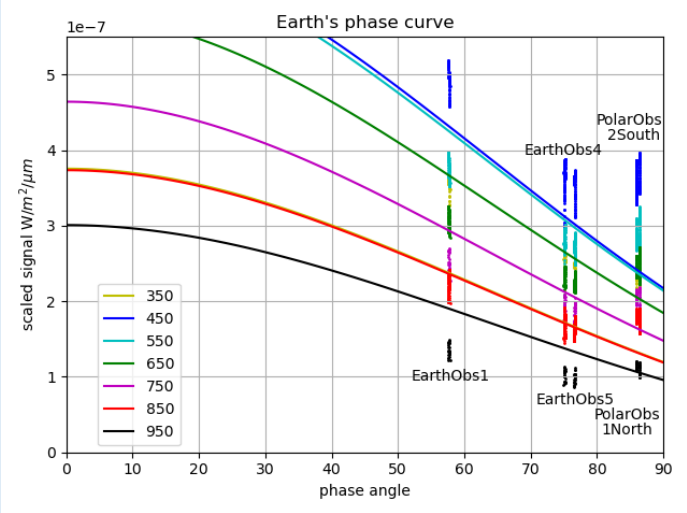
| | | the model lines, the result can be seen in Figure 2. This figure visualises what is said before, that the equatorial observations are similar but the polar observations are clearly different.<br>  <br><br>The analysis still needs to be extended to the infrared region but the visible already shows potential for research. The same potential is expected from the infrared, due to the high signal-to-noise ratio compared to what would be available for a real exoplanet observation. The next step of the research will also involve adapting and improving an exoplanet model made by Dr. D. M. Stam (TU Delft) as the goal is to be able to predict the signal for a certain phase angle.<br><br>Footnote: Taken from https://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html, acquired on 01/12/2020.<br>References:<br>Nikku Madhusudhan and Adam Burrows. ANALYTIC MODELS FOR ALBEDOS, PHASECURVES, AND POLARIZATION OF REFLECTED LIGHT FROM EXOPLANETS. The As-trophysical Journal, 747(1):25, feb 2012. doi: 10.1088/0004-637x/747/1/25. URL https://doi.org/10.1088%2F0004-637x%2F747%2F1%2F25.<br>Anthony Mallama. Characterization of terrestrial exoplanets based on the phase curves and albedos of mercury, venus and mars. Icarus, 204(1):11 - 14, 2009. ISSN 0019-1035.doi: https://doi.org/10.1016/j.icarus.2009.07.010. URL http://www.sciencedirect.com/science/article/pii/S0019103509003017. | |
| 113 | Survival of Primordial Planetary Atmospheres: Mass Loss from Hot and Temperate Low-Mass Planets | The most widely-studied mechanism of mass loss from extrasolar planets is photoevaporation via XUV ionization, primarily in the context of highly irradiated planets. However, the EUV dissociation of hydrogen molecules can also theoretically drive atmospheric evaporation on low-mass planets. For temperate planets such as the early Earth, impact erosion is expected to dominate in the traditional planetesimal accretion model, but it would be greatly reduced in pebble accretion scenarios, allowing other mass loss processes to be major contributors. We apply the same prescription for photoionization to this photodissociation mechanism and compare it to other possible sources of mass loss for temperate “early Earth”-type planets and highly irradiated “mini- | A. Howe [1], M. Meyer [2], F. Adams [3];<br><br>1 NASA Goddard Space Flight Center, Greenbelt, MD,<br>2 Astronomy, University of Michigan, Ann Arbor, MI, |

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| | | Neptune”-type planets to retrieve the observed “evaporation valley.” We find that photodissociation is likely a subdominant, but significant component of mass loss for many of these planets. This mechanism could also preferentially remove hydrogen from a planet's primordial atmosphere, thereby leaving a larger abundance of primordial water. We discuss the implications of these results for models of the formation and evolution of rocky planets. | 3 Physics, Astronomy, University of Michgian, Ann Arbor, MI. |
| 116 | Modelling atmospheric biosignature and climate responses for Earth-like planets orbiting M-dwarf stars | We investigate the atmospheric responses in climate and photochemistry in order to assess habitability and potential biosignatures for Earth-like planets orbiting M-dwarf stars. We apply the coupled climate-chemistry column model 1D-TERRA which features a flexible climate model applicable over a wide range of atmospheric conditions ranging from Mars-like to Venus and which includes a comprehensive chemical network containing several thousand gas-phase reactions. Our numerical scheme is part of a model suite which includes a parameterization of air shower events including the influence of both ion and gas phase chemistry coupled with climate effects. Results present the influence upon commonly assessed chemical species such as oxygen, ozone, methane and nitrous oxide and we investigate their role to act as potential biosignatures over a range of external conditions including spectral type and activity. | J. Grenfell [1], F. Wunderlich [1], M. Scheucher [1], M. Sinnhuber [2], K. Herbst [3], H. Rauer [4];<br><br>1 Extrasolar Planets and Atmospheres, DLR, Berlin, GERMANY,<br>2 KIT, Karlsruhe, GERMANY,<br>3 CAU, Kiel, GERMANY,<br>4 DLR, Berlin, GERMANY. |
| 117 | The Space Environment of the Habitable Zone Exoplanet TOI 700d | We investigate the space environment conditions near the Earth-size planet TOI 700 d using a set of numerical models for the stellar corona and1 wind, the planetary magnetosphere, and1 the planetary ionosphere. We drive our simulations using a scaled-down stellar input and1 a scaled-up solar input in order to obtain two independent solutions. We find that for the particular parameters used in our study, the stellar wind conditions near the planet are not very extreme—slightly stronger than that near the Earth in terms of the stellar wind ram pressure and1 the intensity of the interplanetary magnetic field. Thus, the space environment near TOI 700 d may not be extremely harmful to the planetary atmosphere, assuming the planet resembles the Earth. Nevertheless, we stress that the stellar input parameters and1 the actual planetary parameters are unconstrained, and1 different parameters may result in a much greater effect on the atmosphere of TOI 700 d. Finally, we compare our results to solar wind measurements in the solar system and1 stress that modest stellar wind conditions may not guarantee atmospheric retention of exoplanets. | O. Cohen [1], C. Garraffo [2], S. Moschou [3], J. Drake [3], J. Alvarado-Gómez [4], A. Glocer [5], F. Fraschetti [6];<br><br>1 Lowell Center for Space Science and Technology, University of Massachusetts, Lowell, MA,<br>2 Institute for Applied Computational Science, Harvard University, Cambridge, MA,<br>3 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA,<br>4 Leibniz Institute for Astrophysics Potsdam, Potsdam, GERMANY,<br>5 NASA Goddard Space Flight Center, Greenbelt, MD,<br>6 University of Arizona, Tucson, AZ. |

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| 120 | Photoevaporation of Water Dominated Exoplanet Atmospheres | The atmospheres of close-in, low-mass exoplanets are extremely vulnerable to the effects of stellar UV to X-ray radiation. Photoevaporation can significantly ablate planetary atmospheres or even strip them entirely, potentially rendering a planet uninhabitable. Existing hydrodynamical studies of this important atmospheric mass loss mechanism have mainly considered hydrogen/helium dominated atmospheres. Currently, the effect of more complex chemistry on photoevaporative mass loss has only been the subject of a limited number of studies. In the era of more advanced exoplanet atmospheric observations, it is more important than ever to determine what, if any atmosphere, these planets may have been able to retain. Here, I present preliminary results of hydrodynamic simulations, showing how the atmosphere of a low-mass planet undergoing photoevaporation is affected by the inclusion of water. | L. Harbach, S. Mohanty, J. Owen;<br><br>Imperial College London, London, UNITED KINGDOM. |
| 121 | H2O-Rock Reactions at the Deep Interiors of Water-Rich Planets | Water-rich planets can be found in our solar system (Uranus and Neptune) and extrasolar systems (some of the sub-Neptunes). While they have a critical ingredient for habitability, $H_2O$, it is uncertain how such a dramatically different setting (very large amount of $H_2O$) would impact the habitability. The models for water-rich planets so far have assumed little chemical interaction between $H_2O$ and minerals at high pressure, mainly due to the paucity of data on mineral-water reactions at high pressures and high temperatures. We have conducted a series of experiments on possible chemical reactions between key mineral phases of the rocky mantle and $H_2O$ at high pressures and high temperatures expected for the water-rock interfaces of 1-6 Earth-mass water-rich planets. We found that $H_2O$ solubility in silica ($SiO_2$) increases dramatically with pressure, reaching 2:1 ratio between $SiO_2$ and $H_2O$ in a single solid phase at pressures over 40 GPa. In contrast, a large amount of MgO can dissolve in dense liquid $H_2O$ at high pressure. In our experiments on $(Mg,Fe)_2SiO_4$ olivine in a $H_2O$ medium, MgO component disappears from X-ray diffraction patterns while silica rich minerals appeared at 20-50 GPa at high temperatures. The recovered samples show morphology consistent with dissolution of MgO in dense liquid $H_2O$ at the pressure range, explaining the X-ray observation. The solubility of MgO in dense liquid $H_2O$ appears to be similar to that of NaCl in $H_2O$ at room conditions. Our data indicate that the solubility of MgO decreases at pressures above 50 GPa. These experimental results suggest that the $H_2O$ layer of the Earth-sized water-rich planets (for example, TRAPPIST-1c and 1f if they are water rich) would contain a large amount of MgO. The $H_2O$ layer of larger water-rich planets (for example, GJ1214b) would have much lower concentration of MgO. The compositional gradient by MgO in $H_2O$ layer can impact thermal evolution of the water-rich planets. The rock-$H_2O$ interface in these planets would have silica rich composition because of chemical leaching of MgO by $H_2O$. The low-density hydrous silica at the interface would form a thin layer which may control the geochemical interaction between the rocky layer and the $H_2O$ envelope of the water-rich planets. | S. Shim [1], C. Nisr [1], T. Kim [2], Y. Lee [2], K. Leinenweber [1], A. Chizmeshya [1], S. Speziale [3], V. Prakapenka [4], C. Prescher [4], S. Chariton [4], T. Sergey [4], Y. Meng [5], Z. Liu [6];<br><br>1 Arizona State University, Tempe, AZ,<br>2 Yonsei University, Seoul, KOREA, REPUBLIC OF,<br>3 German Research Center for Geosciences, Potsdam, GERMANY,<br>4 University of Chicago, Chicago, IL,<br>5 Argonne National Laboratory, Argonne, IL,<br>6 University of Illinois at Chicago, Chicago, IL. |
| 122 | Discovering Earth Analog Candidates in the Near-UV | Habitable planets may be found on Sun-like stars. In such systems, an Earth analog can be sought that shares Earth's albedo spectrum. We propose using an anomalous characteristic of the albedo of Earth to identify Earth 2.0 candidates. We present a specialized telescope adept at making the requisite observation. In the portion of solar spectrum where black body radiation has its peak intensity in green then decreasing into the shorter wavelength region toward the UV, the correlated | T. Ditto [1,2];<br><br>1 Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, NY, |

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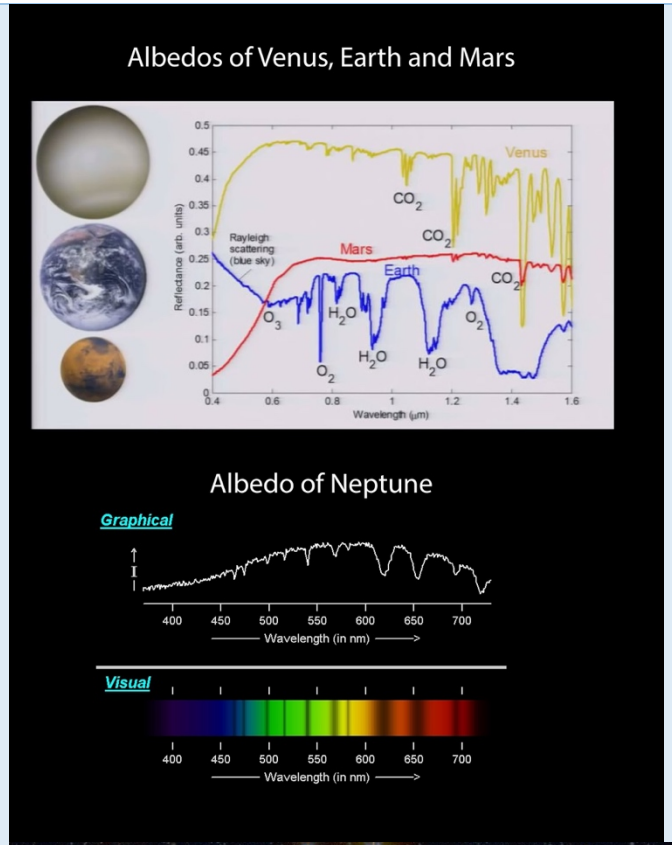
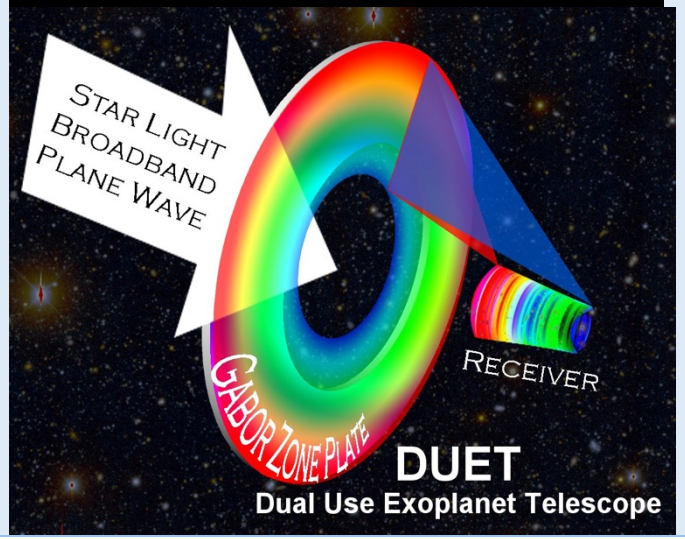
| | | spectral emission of Earth's albedo shows a unique gain in emitted energy above 400 nm when compared to all other planets in our Solar System.<br><br>Earth is luminescent in the near-UV band. The earth may be "a pale blue dot," but surprisingly it is bright in the near-UV. By way of contrast, Neptune, a blue planet, loses flux in the near-UV in proportion to the Sun's spectrum. The gain in reflected energy by Earth in the region of interest is attributable to Raleigh scattering in the atmosphere and a lowering of absorption in oceans. In the former, we see a more productive albedo scattering from Earth's atmospheric gas abundances such as nitrogen. In the latter, the absorption curve from the Sun spectrum in water dies out into the blue. We used Earth observing satellite data to document the Earth albedo spectrum. Although photons are scarce when observing exoplanets with G-Class parent stars in the region of interest from 350-550 nm, there are more photons than in longer wavelengths. Gathering photons within perhaps four binned bands of 50 nm width we could test for a differential gain relative to a parent star in the near-UV. If a directly observed exoplanet shows a differential gain relative to its G-Class parent star in the near-UV, the differential between parent star and child planet is a signal indicating an Earth analog candidate.<br><br>The novel telescope proposed to make this observation uses a Gabor Zone Plate (GZP) as its primary objective. We show how this instrument enjoys a feature that isolates a star and its exoplanetary system from all proximate stars by use of its secondary spectrometer. The optical physics are a direct descendant from Newton's dual prism experiment. The slit between the primary and secondary along with a secondary dispersive optic such as a grating excludes all sources outside confined angles encompassing the target system alone. Within the target, direct spectrographic observation of individual albedos is feasible. We choose the near-UV not simply for its utility in running the proposed differential flux test for an Earth analog. We show that coronagraphy in this band is facilitated by higher contrast absorption lines compared to longer wavelengths. The troughs of the star absorption lines give access to peaks of albedo lines, dropping the contrast ratio by two to nearly three orders of magnitude across selected Fraunhofer lines. Further coronagraphy is facilitated by a unique circular line of foci coming from the GZP primary. We show how this permits Angular Differential Imaging without physically rotating the telescope. A third coronagraph called BLOC (Bifurcated Light Optical Coronagraph) is being investigated. This last design uses the nulling interferometric method with the improvement that the null occurs only over an inner diameter extinguishing the host star but does not touch the region where exoplanets can be observed. The proposed telescope called DUET (Dual Use Exoplanet Telescope) is intrinsically spectrographic and has the alternative use of taking indirect radial velocity measurements by Doppler shift. It has been tested on an optical bench. We present our laboratory results. | 2 3DeWitt LLC, Ancramdale, NY. |


Albedos of Venus, Earth and Mars
Venus
Mars
Earth
Rayleigh scattering (blue sky)
$CO_2$
$O_3$
$H_2O$
$O_2$
Reflectance (arb. units)
Wavelength (μm)
Albedo of Neptune
Graphical
Visual
400
450
500
550
600
650
700
Wavelength (in nm)


Star Light
Broadband
Plane Wave
Gabor Zone Plate
Receiver
DUET
Dual Use Exoplanet Telescope

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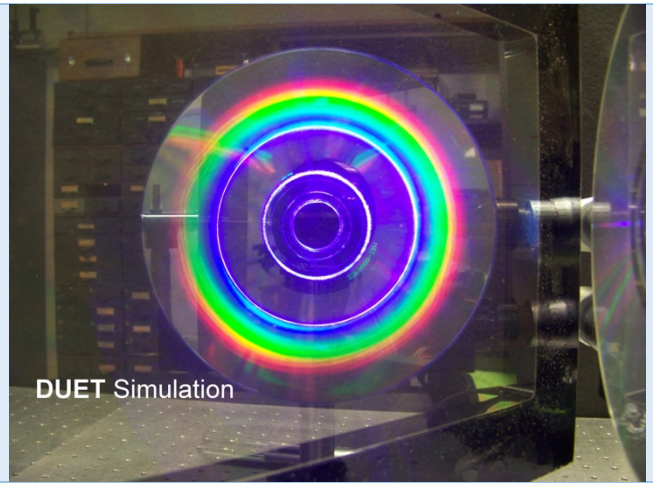
| | |  | |
| 123 | Delivery of water and volatiles to planets in the habitable zone in the Proxima Centauri system | The model and initial data used for calculations<br>Schwarz et al. (2018) studied migration of exocomets in the Proxima Centauri system. Besides the exoplanet with a semi-major axis a_b=0.0485 AU located in a habitable zone, they also considered the exoplanet “c” with a semi-major axis a_c from 0.06 to up to 0.3 AU (for test calculations up to 0.7 AU). Kervella et al. (2020) and Benedict and McArthur (2020) considered that the semi-major axis a_c of the exoplanet “c” equals 1.489±0.049 AU.<br><br>In the first series of calculations, according to Kervella et al. (2020), I considered a star with a mass equal to 0.122 of the solar mass, and two exoplanets with the following semi-major axes and masses: a_b=0.0485 AU, a_c=1.489 AU, m_b=1.27m_E and m_c=12m_E, where m_E is the mass of the Earth. For the exoplanet “b”, the initial eccentricity e_b and initial inclination i_b were considered to be equal to 0, and the initial eccentricity e_c of the exoplanet “c” are equal to 0 or 0.1. Initial inclination of the exoplanet “c” was considered to be i_c=e_c/2=0.05 rad or i_c=e_c=0. For interest, I also considered i_c=152°; such calculations characterize the case when orbits of planetesimals were inclined to the orbit of the exoplanet.<br><br>In the second series of calculations, as in Benedict and McArthur (2020), I considered a_b=0.04857 AU, e_b=0.11, m_b=1.17m_E, a_c=1.489 AU, e_c=0.04, m_c=7m_E. I supposed i_b=i_c=0. m_c is different in the two series. In both series of calculations, the densities of the exoplanets “b” and “c” were considered to be equal to densities of the Earth and Uranus, respectively.<br><br>In different calculation variants, initial semi-major axes of planetesimals were in the range from a_min to a_max=a_min+0.1 AU, with a_min from 1.2 to 1.7 AU with a step of 0.1 AU. Initial eccentricities e_o of planetesimals equal to 0 or 0.15 for the first series of calculations, and e_o=0.02 or e_o=0.15 for the second series. Greater initial eccentricities could be a result of the mutual gravitational influence of planetesimals. Initial inclinations of the planetesimals equal to | S. Ipatov;<br><br>V.I. Vernadsky Institute of Geochemistry and Analytical Chemistry of RAS, Moscow, RUSSIAN FEDERATION. |

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| | | e_o/2 rad. 250 planetesimals were considered in each calculation variant. The motion of planetesimals and exoplanets was calculated with the use of the symplectic code from Levison and Duncan (1994).<br><br>Considered time interval exceeded 20 Myr<br>Based on the obtained arrays of orbital elements of migrated planetesimals and exoplanets stored with a step of 100 yr, I calculated the probabilities of collisions of planetesimals with the exoplanets. The calculations were made similar to those in (Ipatov and Mather, 2003, 2004a-b; Ipatov, 2019a-b; Marov and Ipatov, 2018), which had been made for the planets of the Solar System, but for different masses and radii of a star and exoplanets. If the probability of a collision with an exoplanet for some planetesimal reached 1 with time (it was obtained for a few planetesimals), then for a later time this planetesimal did not considered for calculation of the mean probability for the calculation variant.<br><br>Probabilities of collisions of planetesimals with the exoplanet “b” and “d”<br>For the second series of calculations, the probability p_b of a collision of one planetesimal, initially located near the orbit of the exoplanet “c”, with the exoplanet “b” was non-zero in 5 among 18 variants at e_o=0.02 and in 3 among 6 variants at e_o=0.15. At e_o=0.02 for the five variants, p_b equaled to 0.004, 0.004, 1.28×10-5, 0.00032 и 9.88×10-5. The mean value of p_b for one of 4500 planetesimals equaled to 4.7×10-4, but among them there were two planetesimals with p_b=1. At e_o=0.15 for three variants, p_b equaled to 0.008, 0.004 and 3.6×10-6. The mean value of p_b for one of 1500 planetesimals equaled to 2.0×10-3, but among them there were three planetesimals with p_b=1. For both e_o=0.02 and e_o=0.15 in one of 24 variants p_b=0.008, in three variants p_b=0.004, and in other 4 variants p_b was between to 4×10-6 and 3×10-4. For all three considered variants of the first series at e_c=0.1 and e_o=0.15, the values of p_b were in the range 0.008-0.019. For other calculations of the first series, p_b=0. For the second series of calculations, the probability p_d of a collision of a planetesimal from the zone of the orbit of the exoplanet “c” with the exoplanet “d” (a_d=0.02895 AU, m_d=0.29m_E, e_d=i_d=0) was nonzero only for seven variants (among 24). At e_o=0.02 for four variants, p_d equaled to 0.004, 0.00068, 0.000143 and 3.0×10-5. The mean value of p_d over 4500 planetesimals equaled to 2.7×10-4, but for one planetesimal p_d=1. At e_o=0.15 for three variants, p_d equaled to 0.008, 0.004 and 2.58×10-5. The mean value of p_d over 1500 planetesimals equaled to 2.0×10-3, but for three planetesimals p_d=1. For the second series, the mean values of p_b and p_d averaged over 6000 planetesimals equaled to 8.5×10-4 and 7.0×10-4.<br><br>Only one of several hundreds of planetesimals reached the orbits of the exoplanet “b” and “d”, but the probabilities p_b and p_d of a collision of one exoplanetesimal with these exoplanets (averaged over thousands planetesimals) are greater than the probability of a collision with the Earth of a planetesimal from the zone of the giant planets in the Solar System. The latter probability for most calculations with 250 planetesimals was less than 10-5 per one planetesimal (Ipatov, 2019b). | |

Therefore, a lot of icy material could be delivered to the exoplanets “b” and “d”. Probabilities of collisions of planetesimals with the exoplanet “c”. For the first series of calculations at i_c=e_c=0 and e_o=0.15, the values of the probability p_c of a collision of one planetesimal, initially located near the exoplanet “c”, with this exoplanet were about 0.06-0.1. For i_c=e_c/2=0.05 and e_o=0.15, p_c was about 0.02-0.04. For the second series of calculations, p_c was about 0.1-0.3, exclusive for a_min=1.4 AU and e_o=0.02 when p_c was about 0.7-0.8 (and the main growth was before T=1 Myr).

Usually there was a small growth of p_c after 20 Myr. For both series of calculations, most of planetesimals were usually ejected into hyperbolic orbits in 10 Myr. The ratio of the number of planetesimals ejected into hyperbolic orbits to the number of planetesimals collided with the exoplanets usually exceeded 1 if the number of planetesimals decreased by a factor of several. For variants of the second series, this ratio was less than 1 only at a_min=1.4 AU and e_o=0.02. In some calculations a few planetesimals could still move in elliptical orbits after 100 Myr.

Conclusions

For the Proxima Centauri planetary system, most of planetesimals from the vicinity of the exoplanet “c” with a semi-major axis a_c of about 1.5 AU were ejected into hyperbolic orbits in 10 Myr. Some planetesimals could collide with this exoplanet after 20 Myr. Only one of several hundreds of planetesimals from the vicinity of this exoplanet reached the orbit of the exoplanet “b” with a semi-major axis a_b=0.0485 AU or the orbit of the exoplanet “d” with a semi-major axis a_d=0.029 AU, but the probability of a collision of such planetesimal (that reached the orbits) with the exoplanets b and d can reach 1, and the collision probability averaged over all planetesimals from the vicinity of the exoplanet “c” was ~10-3. If averaged over all considered planetesimals from the vicinity of exoplanet “c”, the probability of a collision of a planetesimal with the exoplanet “b” or “d” is greater than the probability of a collision with the Earth of a planetesimal from the zone of the giant planets in the Solar System (which is less than 10-5 per one planetesimal). A lot of icy material could be delivered to the exoplanets “b” and “d”.

Acknowledgments: The work was carried out as a part of the state assignments of the Vernadsky Institute of RAS № 0137-2020-0004 and the author acknowledges the support of Ministry of Science and Higher Education of the Russian Federation under the grant 075-15-2020-780 (N13.1902.21.0039) “Theoretical and experimental studies of the formation and evolution of extrasolar planetary systems and characteristics of exoplanets”.

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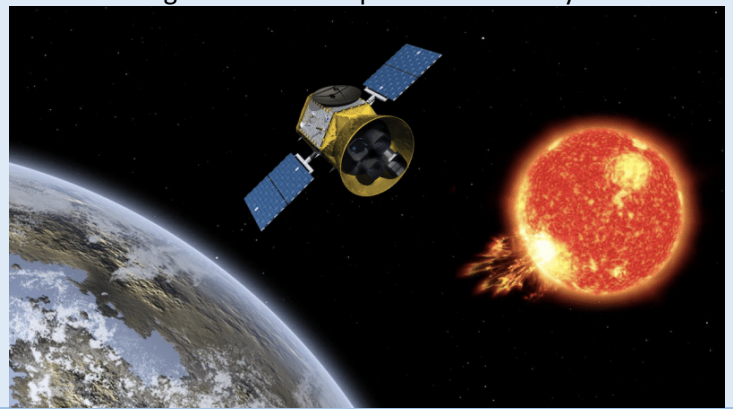
| 125 | Stellar Flares and Habitable(?) Worlds from the TESS Primary Mission | In our search for habitable worlds, we have to account for explosive stellar flaring and coronal mass ejections (CMEs) impacting exoplanets' surface or cloud habitability. These stellar outbursts are a double-edged sword. On the one hand, flares and CMEs are capable of stripping off atmospheres and extinguishing existing biology. On the other hand, flares might be the (only) means to deliver the trigger energy for prebiotic chemistry and initiate life. In this talk, I will highlight our TESS study of all stellar flares from Years 1 & 2 of the mission, driven by the "stella" convolutional neural network. This state-of-the-art machine learning approaches allow us a fast, efficient, and probabilistic characterization of flares. I will discuss our new insights on flaring as a function of stellar type, age, rotation, spot coverage, and other factors. Most importantly, I will link our findings to prebiotic chemistry and ozone sterilization, identifying which worlds might lie just in the right regime between too much and too little flaring. With the TESS extended mission and increased cadences (20s, 2min and 10min), stellar flare studies and new exoplanet discoveries will ultimately aid in defining criteria for exoplanet habitability.  | M. Günther;<br><br>Massachusetts Institute of Technology (MIT), Cambridge, MA. |
| 127 | Investigation of Raman and other spectroscopic signatures with | The exploration of organic biosignatures on extraterrestrial bodies is an ambitious endeavor, with future missions employing spectroscopic techniques to search for signs of microbial life. It is both timely and critical to develop an understanding of Raman spectral biosignatures representative of | C. Foreman [1], M. W. Messmer [1], M. Dieser [1], H. J. Smith [2], A. E. Parker [3]; |

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| | advanced statistics: an approach for cataloguing Polar microbes | microbial life in order to accurately interpret spectral data from extraterrestrial bodies. We propose an advancement in single cell microbial Raman analysis using multivariate statistical approaches.<br><br>This study analyzed microbes from Antarctica and Greenland, cataloguing their spectral profiles using UV/Vis, Fourier-Transform Infrared Spectroscopy (FTIR), and Raman spectroscopy. Principal component analysis (PCA) of the Raman signatures of cellular components was used to construct a targeted spectra integration (TSI) biplot to visually discern how different microbial spectra vary with respect to cellular features (e.g. lipids, proteins, carbohydrates and pigments). Supervised and unsupervised statistical analyses were used to support the TSI biplot analysis. This approach allowed for a unique, multi-technique analysis of spectral information from Polar microbial isolates that identified trends based on biosignatures. | 1 Chemical and Biological Engineering and Center for Biofilm Engineering, Montana State University, Bozeman, MT,<br>2 Center for Biofilm Engineering and Dept of Microbiology and Immunology, Montana State University, Bozeman, MT,<br>3 Mathematical Sciences and Center for Biofilm Engineering, Montana State University, Bozeman, MT. |
| 129 | SETI prioritization and follow-up of potentially habitable TESS planet candidates | In its extended mission, The Transiting Exoplanet Survey Satellite (TESS) continues to search for cool planet candidates on wide orbits. Some of these planet candidates are expected to be small, terrestrial, and in the habitable zone, motivating the Search for Extraterrestrial Intelligence (SETI) on these targets. Some TESS Objects of Interests (TOIs) are also opportune multiplanetary systems, enabling planet candidates to be confirmed relatively more easily. In the Solar System, most radio communication between the Earth and spacecraft is emitted along the ecliptic. Transiting planets, with their ecliptic directed in our line of sight, provide an opportunity to probe such communication in exoplanetary systems. Furthermore, stars with multiple transiting planets allow enhanced SETI opportunities by eavesdropping on interplanetary communications of a potential advanced civilization. We present a SETI prioritization scheme to rank TOIs in terms of their habitability potential. Based on this target selection, we also provide a status update on the SETI follow-up of opportune TOIs as part of the SETIwTESS working group. | T. Daylan [1], H. Isaacson [2], V. Gajjar [2], A. Shporer [3], S. Croft [2], R. Traas [4], G. Ricker [1];<br><br>1 MIT, Cambridge, MA,<br>2 UC Berkeley, Berkeley, CA,<br>3 MIT, Cambridge, CA,<br>4 University of Wisconsin-La Crosse, La Crosse, WI. |
| 130 | About the diversity of M-star astrospheres and the role of cosmic rays within | With upcoming missions like the James Webb Space Telescope, we soon will be on the verge of detecting and characterizing Earth-like exoplanetary atmospheres around cool stars. However, recent observations showed that their radiation environment might be much harsher than that of the Sun. Thus, exoplanets in potentially habitable zones are most likely exposed to an enhanced stellar radiation environment, which could affect their habitability, for example, in the form of a hazardous flux of energetic particles. Knowing the stellar radiation field and modeling radiation exposure on a planet's surface is crucial to assess its habitability. In this study, we present 3D magnetohydrodynamic-based model efforts investigating the astrospheres of three diverse M-star astrospheres and provide numerical estimates of the modulation of galactic cosmic rays (GCRs) within. We show that the impact of GCRs on the Earth-like exoplanets cannot always be neglected in the context of exoplanetary habitability. | K. Herbst [1], K. Scherer [2], S. Ferreira [3], L. Baalmann [2];<br><br>1 University of Kiel, Kiel, GERMANY,<br>2 University of Bochum, Bochum, GERMANY,<br>3 North-West University, Potchefstroom, SOUTH AFRICA. |

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| 131 | Keck/MOSFIRE Spectro-photometric variability of a Young Planetary-Mass Brown Dwarf | High precision time-resolved spectro-photometry provides us with information about the cloud structure at different pressure levels of the atmospheres of brown dwarfs, and directly imaged exoplanet analogs. The monitoring of the easier observable exoplanet analogs, provide an idea on how exoplanet analog atmosphere structures look like. We show the results of spectrophotometric monitoring in the J-band of the Beta-Pic b exoplanet analog, 2MASS J2208136+2921213, during ~2.5 h using the MOSFIRE at the Keck 1 telescope. We find a maximum variability amplitude of 3% in the J-band, that decreases with wavelength, and slightly enhanced variability in the Na I alkali line. The Na I alkali line traces deeper layers of the atmosphere of 2MASS J2208136+2921213, allowing us to provide an estimation of where the different cloud layers are settled in the atmosphere of the object using radiate transfer models. | E. Manjavacas [1], T. Karalidi [2], J. Vos [3], B. Biller [4], B. Lew [5];<br><br>1 Space Telescope Science Institute, Baltimore, MD,<br>2University of Central Florida, Orlando, FL,<br>3 AMNH, New York, NY,<br>4 University of Edinburgh, Edinburgh, UNITED KINGDOM,<br>5 University of Arizona, Tucson, AZ. |
| 132 | Flare Rates, Rotation Periods, and Spectroscopic Activity Indicators of a Volume-Complete Sample of Mid-to-Late M dwarfs within 15 Parsecs | M dwarfs with masses below 0.3 the solar value provide the only opportunity for atmospheric studies of terrestrial exoplanets in the next decade. Stellar flares can remove or alter these planetary atmospheres. Hence, it is essential that we determine both the present flare rate of the host star, and construct the past history of flares throughout its lifetime. We studied the flare rates, rotation periods, and spectroscopic activity indicators of a volume-complete sample of 125 single stars within 15 parsecs and with masses between 0.1-0.3 solar masses, which were observed during the first year of the TESS Mission. We gathered multi-epoch high-resolution spectra and determined the equivalent widths of several chromospheric activity indicators. Thirty-five of our stars had a previously published rotation period;<br><br>We present 18 new rotation periods from MEarth photometry (spanning 65 - 180 days) and 20 new rotation periods from TESS photometry (spanning 0.17 - 5 days). From the TESS time series, we find that stars in this sample share a flare frequency distribution with a communal slope of alpha = 1.98 +/- 0.02, but with rates that can differ up to 6 orders of magnitude. Our sample divides into two groups: 26% have H-alpha in emission, a saturated flare rate, and are rapidly rotating. The remaining 74% show little to no H-alpha in emission, exhibit few flares (such that the majority do not show a single flare during the TESS observations), and, when measured, long rotation periods. For 53 of the 89 stars in the second group, the photometric rotation period has not been determined, but we expect all of these stars to have rotation periods in excess of 100 days. Our study provides a means to estimate the flare rate based on either the H-alpha equivalent width or the rotation period, and constrains the radiation environment of the most spectroscopically accessible terrestrial exoplanets. This constraint may be important for understanding future near-term detailed atmospheric studies of terrestrial exoplanets with the next generation of ground-based extremely large telescopes and the James Webb Space Telescope. | A. Medina [1], J. Winters [2], J. Irwin [2], D. Charbonneau [3];<br><br>1 Astronomy, Center for Astrophysics \| Harvard & Smithsonian, Cambridge, MA,<br>2 Center for Astrophysics \| Harvard and Smithsonian, Cambridge, MA,<br>3 Center for Asrophysics \| Harvard and Smithsonian, Cambridge, MA. |

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| | | This work was supported by the NSF through a Graduate Research Fellowship, NASA through the XRP and TESS GI programs, and through a grant from the John Templeton Foundation. | |
| 134 | Simulating Roman Astrometry of Terra Hunting Stars | Discovering Solar-system analogs may be an essential step in finding habitable planets. However, Earth-mass planets on year-long orbits and gas giants on decade-long orbits lie at the edge of current detection limits. The Nancy Grace Roman Space Telescope, scheduled to launch in late 2025, will be capable of precision astrometry using its wide field imager. For bright stars, Roman may be able to achieve astrometric accuracy of 1-10 µas. The Terra Hunting Experiment (THE), starting in 2022, will take nightly radial velocity observations of at least 40 bright G and K dwarfs for 10 years, in search of planets that are Earth-like in mass and temperature. We have simulated an observing program that combines Roman astrometry observations with THE radial velocity measurements. These astrometric measurements can break the mass-inclination degeneracy in radial velocity observations. Additionally, astrometry and radial velocity measurements are complementary: the radial velocity method is most sensitive to planets close to their host star, while the astrometric signal is largest for more distant planets. Definitive astrometric measurements require that we trace stellar motion over a significant fraction of the orbital period of the planet. By combining measurements from a Roman astrometry observing program with Gaia data, we can increase the baseline of astrometric observations in order to discover gas giants on Jupiter-like orbits. As Jupiter has played a critical role in the habitability of Earth, discovering Jupiter-analogues around THE stars could help in determining the habitability of Earth-analogues that may be discovered. | D. Yahalomi [1], D. N. Spergel [2], R. Angus [3];<br><br>1 Department of Astronomy, Columbia University, New York, NY,<br>2 Center for Computational Astrophysics, Flatiron Institute, New York, NY,<br>3 Department of Astrophysics, American Museum of Natural History, New York, NY. |
| 135 | From clouds to crust - Cloud diversity and surface conditions in atmospheres of rocky exoplanets | One of the fundamental questions for planetary science is how surfaces of other planets similar to the rocky bodies in our solar system look like. What is the rock structure like? Will there be water? Are there any active atmospheric cycles? How can we detect these different conditions? The current space missions and ground based instruments allow the detection of specific gas species and some cloud compositions in atmospheres of giant exoplanets. With instruments installed in the near future and space crafts currently being build or planned, these kind of observations will be available for planets with smaller sizes and an overall rocky composition. We aim to further understand the connection of the conditions of the upper atmosphere with the conditions on the crust of the planet (temperature, pressure, composition). Our equilibrium chemistry models allow us to investigate the expected crust and near-crust-atmosphere composition. With this, we investigate the conditions under which liquid water is actually stable at the surface of a planet and not incorporated in hydrated rocks. Based on this crust - near-crust-atmosphere interaction we build an atmospheric model, which allows us to investigate what kind of clouds are stable and could be present in atmospheres of rocky exoplanets. This allows us to link the high altitude gas phase and cloud compositions to the surface conditions. | O. Herbort [1], P. Woitke [1], C. Helling [1,2], A. Zerkle [1];<br><br>1 St Andrews Centre for Exoplanet Science, University of St Andrews, St Andrews, UNITED KINGDOM,<br>2 SRON Netherlands Institute for Space Research, Utrecht, NETHERLANDS. |
| 136 | Measurements of the Ultraviolet Spectral Characteristics of Low-mass | M dwarf stars have emerged as ideal targets for exoplanet observations. Their small radii aids planetary discovery, their close-in habitable zones allow short observing campaigns, and their red spectra provide opportunities for transit spectroscopy with JWST. The potential of M dwarfs has been underlined by the discovery of remarkable systems such as the seven Earth-sized planets orbiting TRAPPIST-1 and the habitable-zone planet around the closest star to the Sun. | D. Wilson;<br><br>McDonald Observatory, University of Texas at Austin, Austin, TX. |

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| | Exoplanetary Systems (Mega-MUSCLES) | Accurately assessing the surface conditions of planets around M dwarfs requires a firm understanding of how M dwarfs differ from the Sun, beyond just their smaller size and mass. Of particular importance are the time-variable, high-energy ultraviolet and x-ray regions of the M dwarf spectral energy distribution (SED), which can influence the chemistry and lifetime of exoplanet atmospheres, as well as their surface radiation environments. Ideally, ultraviolet and x-ray observations should be obtained for any star with exoplanets of interest. Unfortunately, those wavebands are extremely faint for most M dwarfs, requiring too large an investment of telescope time to obtain data at most stars.<br><br>The Measurements of the Ultraviolet Spectral Characteristics of Low-mass Exoplanetary Systems (Mega-MUSCLES) Treasury project, together with the precursor MUSCLES project, will produce full SEDs of a representative sample of M dwarfs, covering a wide range of stellar mass, age, and planetary system architecture. We have obtained x-ray and ultraviolet data for 12 stars using the Hubble, Chandra and XMM space telescopes, along with ground-based data in the optical and state-of-the-art DEM modelling to fill in the unobservable extreme ultraviolet regions. Our completed SEDs will be available as a community resource, with the aim that a close MUSCLES analogue should exist for most M dwarfs of interest.<br><br>In this presentation I will overview the Mega-MUSCLES project, describing our choice of targets, observation strategy and SED production methodology. I will also discuss notable targets such as the TRAPPIST-1 host star, comparing our observations with previous data and model predictions. Finally, I will discuss the applications of the Mega-MUSCLES data for future observations with JWST. | |
| 138 | Finding Missing Earths: An Integrated Analysis of Multi-planet Systems and Assessing Likelihood of Potentially Habitable Worlds | Our current picture of exoplanetary systems is unfinished, and the search for and characterization of habitable planets in these partially explored systems is still ongoing. To address this, we combined the specific yet incomplete information about any given multi-planet system with population-level statistical knowledge and developed DYNAMITE (DYNAmical Multi-planet Injection TEster) to predict the presence, locations, and sizes of previously unknown planets in these systems. Determining the physical parameters and orbital dynamics of potentially habitable exoplanets will provide a wealth of information that can be used for targeted follow-up observations to assess the likelihood of habitability. Our analysis examines multi-planet systems individually and in ensembles, looking for additional planets and categorizing their potential for habitability. Tests performed on known systems show successful predictions of the approximate period and sizes of these planets, which are sensitive out to rocky planets in the habitable zones of G stars and smaller. We will share the latest DYNAMITE results for currently hidden worlds in the habitable zone around nearby stars and their observational signatures. In the future, we expect to be able to predict which new exoplanet systems are most likely to contain an Earth-like planet as these systems are discovered. | J. Dietrich [1], D. Apai [2];<br><br>1 Astronomy, University of Arizona, Tucson, AZ,<br>2 Astronomy and Planetary Sciences, University of Arizona, Tucson, AZ. |
| 139 | Probing solid compositions in | The bulk elemental ratios of planetary cores and atmospheres are a critical factor in determining a planet's habitability. Upcoming missions like JWST and Ariel will enable spectroscopic surveys of molecules and atoms in exoplanet atmospheres, allowing us to determine bulk atomic ratios in the | M. McClure [1], C. Dominik [2], M. Kama [3]; |

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| | planetary core formation zones | outermost atmospheric layers. Radius and mass measurements from TESS and ground-based RV follow-up can determine the bulk density of exoplanets, allowing us to infer their core compositions, with significant degeneracies. In principle, the observed bulk elemental abundances of a given exoplanet should be traced back to its radial birth location in a protoplanetary disk, indirectly probing the process of planet formation. However, planets may form their cores first and then migrate, accreting their envelopes at different locations and times relative to their cores. Furthermore, with current observational methods, we can only measure the radial gas phase composition of disks (e.g. with ALMA);<br><br>We are blind to the finer details of the solid composition, e.g. iron, refractory carbon, or ice content at the disk midplane. To connect observed exoplanet compositions with the planet formation processes, we need techniques to probe the solid composition at locations where planets might form in disks.<br><br>We present a new technique to assess the composition of solids retained in protoplanetary disks during their lifetimes. Using near-infrared spectroscopy of the famous TW Hya disk, we take a snapshot of the gas phase abundances of several key elements (e.g. C, O, Si, Fe) inside the dust sublimation radius of this disk. These elements are all depleted from the gas phase, suggesting that they are trapped in solid dust grains at the inner edges of TW Hya's known millimeter rings. We identify one refractory-rich dust trap in the terrestrial planet forming region and one trap in the outer rings that is enhanced in nitrogen relative to Solar System bodies. These results highlight how bodies forming in this disk could have compositions both similar to, and different than, our own solar system. Applying this technique to more disks with a broad range of ages will give us insight into the composition of planetary cores formed at different disk radii and times. | 1 Leiden Observatory, Leiden University, Leiden, NETHERLANDS,<br>2 Anton Pannekoek Institute, University of Amsterdam, Amsterdam, NETHERLANDS,<br>3 University College London, London, UNITED KINGDOM. |
| 140 | How does the background atmosphere affect the onset of the runaway greenhouse? Insights from 1D radiative-convective modeling. | There is a strong interest to study the runaway greenhouse effect [1-4] to better determine the runaway greenhouse insolation threshold and therefore the inner edge of the habitable zone (HZ). Some studies [5-7] have shown that the onset of the runaway greenhouse may be delayed due to an increase of the Outgoing Longwave Radiation (OLR) by adding radiatively inactive gas (e.g. N_2 or O_2, as in the Earth's atmosphere). For such an atmosphere the OLR may “overshoot” the Simpson-Nakajima limit [4], i.e. the moist greenhouse limit of a pure vapor atmosphere. This has direct consequences on the position of the inner edge of the HZ [8-11] and thus on how close the Earth is from a catastrophic runaway greenhouse feedback. The OLR overshoot has previously been interpreted as a modification of the atmospheric profile due to the background gas [7,12]. However there is still no consensus so far in the literature on whether an OLR overshoot is really expected or not (see Figure 1).<br><br>The first aim of our work is to determine, through sensitivity tests, the main important physical processes and parametrizations involved in the OLR computation with a suite of 1D radiative-convective models. By doing multiple sensitivity experiments we are able to explain the origin of the differences in the results of the literature for a H_2O+N_2 atmosphere. We showed that physical | G. Chaverot [1], E. Bolmont [1], M. Turbet [1], J. Leconte [2];<br><br>1 Observatory of Geneva, University of Geneva, Geneva, SWITZERLAND,<br>2 Bordeaux Astrophysics Laboratory, Bordeaux, FRANCE. |

processes usually assumed as second order effects are actually key to explain the shape of the OLR (e.g., line shape parameters). This work can also be useful to guide future 3D GCM simulations. We propose also preliminary results from the LMD-Generic model to study how these effects may be understand in a 3D simulation. Secondly we propose a reference OLR curve, done with a 1D model built according to the sensitivity tests, for a H_2O+N_2 atmosphere, to solve the question of the potential overshoot.

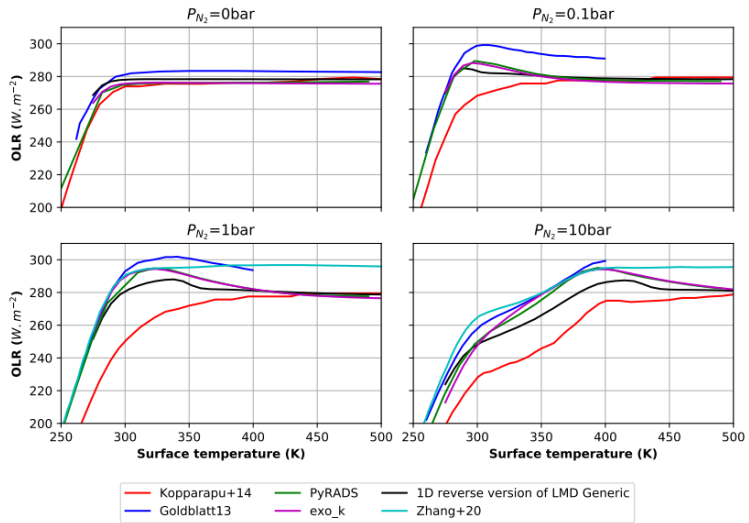


Figure 1: Literature overview of the Outgoing Longwave Radiation (OLR) for different N_2 pressures, computed with 1D radiative-convective models. There is no OLR overshoot on the red and the cyan curves [9,11] but the blue, green, magenta and black curves [6,7,13,14] show an overshoot of the OLR value.

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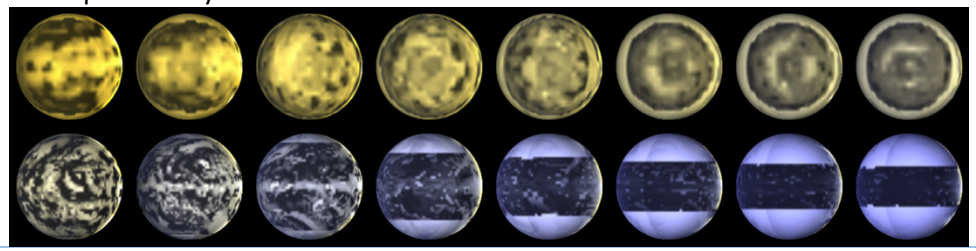
| 141 | On the origin and persistence of the tiger stripe fissures and eruptions on Enceladus | Active eruptions from the south polar region of Saturn's small (~500 km diameter) moon Enceladus are concentrated along a series of lineaments known as the 'tiger stripes', thought to be partially open fissures that connect to the liquid water ocean beneath the ice shell. We propose a model for the formation of the tiger stripes that explains why the tiger stripes are located only at the south pole, why there are multiple, parallel, regularly-spaced fissures, why the fissures are spaced ~35 km apart, and how the eruptions can persist over time. Secular cooling and the resulting ice shell thickening generate global tensile stresses that cause the first fracture to form at one of the poles, where the ice shell is thinnest due to tidal heating. We present new models for the evolution of stresses in a cooling ice shell and for the formation of the first cracks. After the first crack forms, the tensile stresses are partially relieved, preventing a similar failure at the opposite pole. We propose that subsequent activity then concentrates in the vicinity of the first fracture as the erupted water ice loads the flanks of the open fissure, causing bending in the surrounding elastic plate and further tensile failure in bands parallel to the first fracture, leading to a cascading sequence of parallel fissures until the conditions no longer permit through-going fractures. Open conduits can be maintained over long timescales by turbulent dissipation within the fissures. | M. Rudolph [1], M. Manga [2], D. Hemingway [3,4];<br><br>1 Earth and Planetary Sciences, University of California, Davis, Davis, CA,<br>2 Earth and Planetary Science, University of California, Berkeley, Berkeley, CA,<br>3 Planetary Science Institute, Tucson, AZ,<br>4 Maxar Technologies, Palo Alto, CA. |
| 143 | Enabling new science with the ExoPlaSim 3D climate model | The Kepler mission delivered thousands of exoplanets. TESS has already provided over 2,000 candidates, and nearly 100 new confirmed planets, and will deliver many more. At the same time, radial velocity surveys have provided us with many planets of their own, and masses for many transiting planets. With this incredible growth in the population of known exoplanets has come the realization that exoplanets are very diverse, terrestrial planets in particular--creating an urgent need for exoplanet climate modellers to simulate a wide range of planetary climates. However, most 3D climate models are computationally expensive, and take time to learn. While lower-dimensional models are faster, they lack the physical complexity of 3D models. We present ExoPlaSim, a fast and flexible intermediate-complexity 3D model with a convenient Python API, suitable both for HPC clusters and your laptop. This model, based on the PlaSim model for Earth, bridges a gap in the modelling hierarchy, enabling modellers to quickly produce thousands of 3D models across the habitable parameter space, adding complexity to 1D and 2D experiments, and guiding higher-complexity 3D models. I will discuss our efforts to validate the model against higher-complexity 3D models of Earth-like and tidally-locked planets, its overall performance, and showcase the science made possible by ExoPlaSim.<br>  | A. Paradise [1], E. Macdonald [2], K. Menou [1], C. Lee [2], B. Fan [1];<br><br>1 David A. Dunlap Department of Astronomy & Astrophysics, University of Toronto, Toronto, ON, CANADA,<br>2 Department of Physics, University of Toronto, Toronto, ON, CANADA. |

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| 144 | Ground Based IR Spectroscopy: Henrietta and MIRMOS | We are developing ground-based, near-infrared, low-resolution spectrographs that can be used for studying exoplanetary atmospheres. Our current plan is to produce a prototype spectrograph for the Las Campanas Observatory 40-inch Swope telescope, and then a facility spectrograph for the 6.5-meter Magellan telescopes. This pair of projects will study the systematic limitations to achieving high-precision spectrophotometry from the ground including: scintillation noise, instrument scattered light, and variations in subpixel sensitivities. These systematic limitations can be mitigated by a variety of techniques, but perhaps the most promising is the diffuser technology that has already been so powerful for ground-based photometry. In this poster we present the error budgets and instrument design of these instruments, as well as their predicted performance. Our predictions indicate that these spectrographs should achieve less than 100 ppm noise and have just 50% excess noise over the Poisson limit. | N. Konidaris [1], J. E. Williams [1,2];<br><br>1 The Observatories, The Carnegie Institution for Science, Pasadena, CA,<br>2 The University of Southern California, Los Angeles, CA. |
| 145 | Atmospheric and Spectral Simulations of TOI-700 d, a Habitable Zone Earth-Sized Planet Synchronously Rotating Around an M Dwarf | The recently discovered TOI-700 d is a nearby Earth-sized planet synchronously rotating around an M star in the conservative habitable zone. In order to evaluate the planet's potential for habitability, we use a three-dimensional climate model to simulate possible habitable states. Our suite of simulations involves both ocean-covered and desiccated planets, with a variety of atmospheric compositions, pressures, and rotation states. We also synthesize transmission spectra, combined-light spectra, and integrated broadband phase curves for our modeled cases. We find that TOI-700 d can potentially maintain temperate surface conditions and liquid water under a wide range of climates, making it a strong candidate for a habitable world. However, the resulting transmission spectra and synthesized phase curves reveal spectral feature depths and peak fluxes that do not exceed 10 ppm, which will prohibit the James Webb Space Telescope from characterizing its atmosphere. This highlights the great challenges the community faces for characterizing potentially habitable worlds that are similar to TOI-700 d. We also discuss future plans to include photochemistry in our climate modeling which can strongly impact both habitability and observed spectral features. Our further understanding of TOI-700 d will make it a valuable point of comparison against other potentially habitable planets around later M dwarfs, such as TRAPPIST-1. | G. Engelmann-Suissa [1], E. Wolf [2], R. Kopparapu [3], G. Villanueva [3], T. Fauchez [3], A. Mandell [3], G. Arney [3], E. Gilbert [4], J. Schlieder [3], T. Barclay [3], E. Quintana [3], E. Lopez [3], J. Rodriguez [5], A. Vanderburg [6];<br><br>1 University of Washington, Seattle, WA,<br>2 University of Colorado Boulder, Boulder, CO,<br>3 NASA Goddard Space Flight Center, Greenbelt, MD,<br>4 University of Chicago, Chicago, IL,<br>5 Center for Astrophysics, Cambridge, MA,<br>6 University of Wisconsin Madison, Madison, WI. |
| 146 | Quantifying the impact of stellar UVscaling relations on modelling planetary atmospheres | As JWST and other next-generation observatories begin to operate, follow-up observations of planets discovered by missions like Kepler and TESS will enable exceptional characterization of exoplanetary atmospheres. Understanding the stellar environments these planets reside in is critical to these efforts, with the UV regime of the host star's spectrum driving important non-equilibrium chemistry — particularly photochemistry. Before JWST begins observing, we must understand how to best leverage active UV-capable observatories such as HST to constrain these host star spectra. Using the MUSCLES Treasury Survey, we quantify how using reconstructed proxy UV spectra based on Ca II H & K optical lines (mimicking situations in which a planet's host star has not been observed | D. Teal [1], E. Kempton [2];<br><br>1 Astronomy, University of Maryland, College Park, College Park, MD,<br>2 University of Maryland, College Park, College Park, MD. |

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| | | in the UV) impacts photochemical modeling of exoplanetary atmospheres. We use the Atmos 1-D coupled photochemical and climate model to simulate habitable zone planets in orbit around each of the stars in the MUSCLES catalog to determine the planets' atmospheric thermal profiles and chemical compositions using both observed (actual) and reconstructed (proxy) versions of the host star spectrum. We furthermore generate the resulting transmission spectrum in each case, to quantify the impact of the stellar UV reconstruction on the observable properties of the atmosphere. | |
| 148 | The Language of Stars | NASA Frontier Development Lab (FDL) is a research accelerator that brings together data scientists and space scientists to solve some of the most difficult space and planetary problems using AI. This project is a spin-off of one of the main challenges, that identified star spots in Kepler data. But in this spin-off project we are looking at applications of specific AI techniques (natural language processing - NLP) to time series (light curves) in order to identify both unique features and patterns in time series in general, and in light curves in particular. We both construct and derive informational building blocks that are characteristic to the light curves of the stars in a subset of Kepler data and we compare these methods to more traditional machine learning applications (clustering). We show how this new methodology, rooted in NLP, can be a good alternative for the analysis of light curves and potentially for identifying exoplanetary transit as unique "linguistic" features.<br><br>The idea for this project came from asking the following questions, one pertaining to advancing a potentially new methodology in machine learning, and another one pertaining to astrophysics:<br>1. Can we use NLP to discover features in time series?<br>if yes, how good is it comparatively to other methods, such as clustering?<br>2. Can we create a "dictionary" of star features that we can use as a genetic code to catalogue and identify any star, and that we can also use to simulate stars that we have not yet observed?<br><br>Starting with these questions, we embarked on an exploratory research, to understand whether a duo of a combination of ML methods and an application to star light curves can help us discover features and patterns within time series, in general, and within light curves, in particular. The rationale or the big WHY of such methodological & science specific exploration stems from a few facts that we tried to connect coherently: NLP is good at discovering patterns in messy/noisy, unstructured data (such as languages); NLP is great for creating vocabularies, dictionaries, taxonomies; NLP is also good at creating new and large texts (data) from small lists of dictionaries and vocabularies. Based on these assumptions, our first methodological challenge came from trying to understand the best method or algorithm to create textual data (for our NLP goals) from numeric data (from our given time series). In other words, the first step was to create the "words", "letters" or the "n-grams" from light curves data. For this proof of concept, we used 632 original Kepler light curves, with the idea to scale it up to analyze and parse more than 110K light curves, data available during the FDL program (summer 2020); if this proves successful, we aim to afterwards add TESS light curve data as well. | A. Berea [1], A. Munoz-Jaramillo [2];<br><br>1 George Mason University, Fairfax, VA,<br>2 Southwest Research Institute, Boulder, CO. |

The light curve data we used therefore consists of 632 time series, collected over a period of about 4 years on a cadence of every 20 minutes.We used 6 different methodologies to create 6 different corpora from the entire dataset - each corpus is a collection of 632 individual "books", where each book/light curve is a sequence of n-grams that we created based on these methods:
1.1. Bin-based (large) - we binned the data in bins of 10 (1 order of magnitude), and for each bin we assigned a "binXX" n-gram;
1.2. Bin-based (small) - we binned the data in bins of 100 (2 orders of magnitude), and for each bin we assigned a "binXXX" n-gram;
1.3. Peaks and troughs - for each sequence of consecutive peaks and trough in the time series, we assigned "posXX" or "negXX" n-gram, where "pos" stands for the peak in the time series, "neg" stands for the trough in the time series, and XX is the number of consecutive peaks or troughs observed in the data;
1.4. PD clustering-based - this method is based on measurements of entropy and complexity in the time series;
1.5. Zipf distribution-based - in this method, we fitted a Zipf distribution to each star light curve and created the n-grams based on the rank of the frequency of the data given by the distribution. The Zipf Law is one of the most important laws observed in human languages, but also in physical phenomena such as earthquakes, and is scale invariant, a very important property for pattern detection in a wide range of scales;
1.6. 3-movement-based - in this method, we partitioned the data into 6 types of movements of any 3 consecutive data points in the light curves.

Entropy measurements
A first observation from our analyses has been that methods 1.1 and 1.2. show the Shannon entropy of the n-grams is the closest to the Shannon entropy of the light curves, and can be interpreted as the method that closest preserves the information from the light curve through the text transformation. Shannon entropy is one of the most important measures of information in natural language processing. PRELIMINARY RESULTS. Clustering. We tried many clustering methods on the actual data, in order to extract features that we would a posteriori use for n-gram creation (i.e., unsupervised k-means clustering, knn, hierarchical, etc.). Out of all the tried clustering methods, the one that is also based on entropy and which we used in our n-gram method 1.4, PD clustering, shows the most promising results in isolating specific features within the light curves. We also clustered based on the difference time series, and the difference isolates even better specific features in the light curves.Topic Modeling. After creating the n-grams, we performed topic modeling (TM), an NLP specific method, that is grouping the n-grams within a corpus based on their probability of occurrence within a star. The TM method showed us which star features are most likely to occur next to each other across all 632 light curves.

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| 149 | K2-18b: first water vapour detection in a habitable-zone planet | Today, more than 4000 exoplanets have been detected, with super-Earths being the most common in our galaxy. We still know very little about these planets, with their basic parameters such as radius and mass - when available - suggesting a great variety among them. However, the density alone does not reveal the chemical composition and climate of these planets, nor casts light into their formation history. To answer those questions, we need to observe their atmospheres. Currently, the WFC3 camera on-board the Hubble Space Telescope is the most powerful instrument to perform infrared transit spectroscopy of exoplanets. Atmospheric characterisation of super-Earths is within reach of the WFC3 but such observations have been very limited so far, with no confirmed detection of molecules.<br><br>In this talk, I will present the first detection of a molecular signature from the atmosphere of a super-Earth. HST transit observations of K2-18b, a planet of eight Earth masses orbiting an M2.5 red dwarf, have revealed a strong signature of water vapour. In addition, K2-18 b is orbiting within the habitable zone of its star, providing the first opportunity to study the nature of a temperate planetary body beyond the mass-radius relationship.<br><br>More specifically, we analysed here eight transits of K2-18 b obtained with the WFC3 camera onboard the Hubble Space Telescope, using our specialised, publicly available, tools - Iraclis and TauRex - to perform the end-to-end analysis from the raw HST data to the atmospheric parameters. Our analysis resulted in the detection of an atmosphere around K2-18 b with an ADI (a positively defined logarithmic Bayes Factor) of 5.0, or approximately 3.6 sigma confidence, making K2-18 b the first habitable-zone planet in the mass regime 1-10 M⊕ with an observed atmosphere around it. We modelled the atmosphere following three approaches: a cloud-free atmosphere containing only H2 O and H2 /He, a cloud-free atmosphere containing H2O, H2/He and N2 (N2 acted as proxy for “invisible” molecules not detectable in the WFC3 bandpass but contributing to the mean molecular weight), and a cloudy (flat-line model) atmosphere containing only H2 O and H2 /He.<br><br>However, the current data are still very limited, proving only the existence of the atmosphere and the presence of water vapour. These results make K2-18b one of the prime targets for future characterisation studies with the next generation of space telescopes such as the JWST and Ariel. Such observations will help us reveal the presence of additional molecules, such as methane, understand the thermal structure of the atmosphere, and, ultimately, assess the potential habitability of this planet. | A. Tsiaras;<br><br>Physics and Astronomy, UCL, London, UNITED KINGDOM. |

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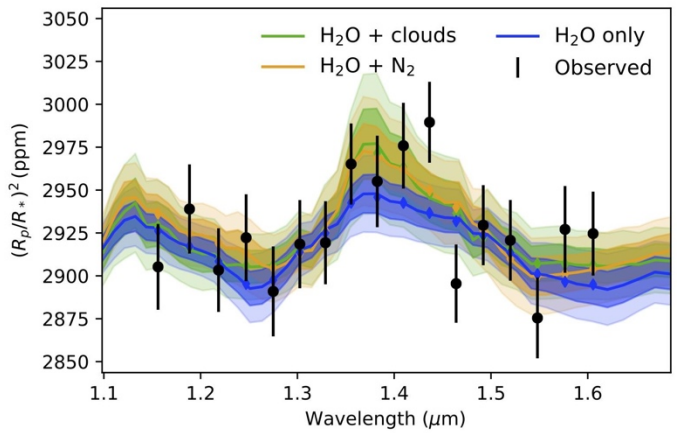
| | |  | |
| 150 | On the Potential of Silicon as a Building Block for Life | Despite more than one hundred years of work on organosilicon chemistry, the basis for the plausibility of silicon-based life has never been systematically addressed nor objectively reviewed. We present a comprehensive assessment of the possibility of silicon-based biochemistry. We assess whether or not silicon chemistry meets the requirements for chemical diversity and reactivity as compared to carbon. To expand the possibility of plausible silicon biochemistry, we explore silicon's chemical complexity in diverse solvents found in planetary environments, including water, cryosolvents, and sulfuric acid. In no environment is a life based primarily around silicon chemistry a plausible option. We find that in a water-rich environment silicon's chemical capacity is highly limited due to ubiquitous silica formation. Any sort of biochemistry is implausible in cryogenic solvents, because of solubility limits. Sulfuric acid, surprisingly, appears to be able to support a much larger diversity of organosilicon chemistry than water. We should therefore think about silicon as a contributor to biochemistry (as a common heteroatom in hypothetical sulfuric acid biochemistry and a rare specialized heteroatom in water solvent) rather than a main building block of life. | J. Petkowski [1], W. Bains [1], S. Seager [2];<br><br>1 EAPS, MIT, Cambridge, MA, 2 MIT, Cambridge, MA. |
| 151 | Observational constraints for pebble-driven planet formation | Planet formation via the accretion of mm to cm size particles, often called pebbles, has been recently invoked to explain the diversity of planetary types and systems, as well as our own Solar System. However, this formation mechanism heavily relies on the availability of pebbles in the outer disk (beyond tens of au) and the pebble inward flux. I will discuss recent ALMA observations constraining the amount of pebbles available in disks and their outermost location as a function of time. By combining infrared spectroscopy and the ALMA results, I will present tantalizing evidence for the inward drift of pebbles. Finally, I will speculate on how to constrain observationally the pebble inward flux and discuss cross-disciplinary collaborations that are necessary to make progress in this field. | I. Pascucci;<br><br>LPL/University of Arizona, Tucson, AZ. |
| 152 | Prospects for interdisciplinary efforts in the study | Space radiation is one of the main factors affecting habitability. Galactic Cosmic Rays (GCRs) impacting a planetary/small body surface, directly and/or generating considerable particle showers in an eventual atmosphere, can break molecular bonds of molecules at the surface or in the | F. Da Pieve [1], B. Gu [2], N. E. Koval [3], G. Gronoff [4], D. Munoz-Santiburcio [3], J. |

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| | of survival of biomolecules under space radiation in planetary/small-bodies science | subsurface. Solar Energetic Particles (SEPs), linked to transient events on stars, and the solar wind can have both a destructive effect on biomolecules or trigger their formation [1,2,3].<br><br>The study of the impact of high and moderate energy radiation such as GCRs and SEPs on planetary/small bodies is generally done via Monte Carlo particle transport methods, which allow a "condensed history approach" of the very particle track, considering water as proxies for biological matter [4,5]. This is almost justified as water represents the main constituent of life as we know it, and at the high energy of the directly impacting particles the details of any eventual biomolecule immersed in the water sample would not be determinant.<br><br>However, the effectiveness of such radiation in inducing biological damage is linked, to a remarkable extent, to the details of the energy deposition stage by the impact particle (and lower energies secondaries generated in water hydrolysis) into the target, and to the relationship between initial energy deposition and chemical evolution of the defects, and their eventual biological consequences/effects. At present, the effectiveness of such radiation in inducing biological damage in a realistic target composed by water+biomolecule is still subject to considerable uncertainties [6], a topic of relevance also for particle therapy and space medicine. The critical issue of understanding the details of such energy deposition is obviously also of importance for radiation that naturally impact biological molecules in an energy range that is, from the very start, lower than GCRs, such as the solar wind and SEPs.<br><br>In all these cases, for detailed investigations of the survival of fundamental chemical bonds for life, a condensed history approach of Monte Carlo particle transport tools is not sufficient anymore. A detailed tracking of the structure of the particles paths is needed and the entity of the molecule can play a role as the chemical elements/type of bonds/ and dimensions of the molecule can influence its resistance to radiation. Still, Monte Carlo track structure codes essentially work only with the physics given by impact cross sections on the sole water, there is no real consideration of the electronic/chemical characteristics of the hosted biomolecule [6]. Limitations given by such an approach have been highlighted, but on the positive side a massive effort is being done to follow the different steps of radiation effects until the more macroscopic biological damage.<br><br>The study of the processing of planetary/small bodies by radiation in the context of the study of possible destruction mechanisms/rise of biomolecules must rely on approaches that are able to consider several types of targets and processes occurring in the intermediate/low energy region. Radiation physics is obviously fundamental for the formation of secondary molecules that can be generated at any astronomical environment. Thus, similarly to the case of recently developed photochemical databases of different organic molecules detected in different astronomical environment [7], efforts to obtain calculated quantities to build up future databases of radiation impact cross sections will be needed. | Teunissen [1], J. GuO [5], E. Artacho [3,6], F. Cleri [7], A. C. Vandaele [1], J. Kohanoff [2];<br><br>1 Royal Belgian Institute for Space Aeronomy, Brussels, BELGIUM,<br>2 Queen's University of Belfast, Belfast, UNITED KINGDOM,<br>3 CIC nanoGUNE BRTA, Donostia - San Sebastián, SPAIN,<br>4 NASA Langley Research Centre, and Science Systems and Application Inc., Hampton, VA,<br>5 School of Earth and Space Sciences, University of Science and Technology of China, and CAS Center for Excellence in Comparative Planetology, USTC, Hefei, CHINA,<br>6 University of Cambridge, Cambridge, UNITED KINGDOM,<br>7 IEMN, UMR 8520, University of Lille, Lille, FRANCE. |

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| | | In this contribution we would like to highlight how a chain of models from different communities could be of help to define the stability under radiation of certain of biomolecules, in different scenarios. In particular, calculations of radiation impact cross sections on water and small biological units, nowadays possibly calculated via first principles approaches [8], can be given as input to Monte Carlo track structure codes, extending the capabilities of the latter to more realistic targets. The role of quantum chemistry/electronic structure is nowadays well established in the study of planetary atmospheres, interstellar medium, planetary interiors, photochemical escape and prebiotic chemistry [9]. Given the physical limitations and high costs of irradiation experiments, quantum chemical calculations offer an efficient approach that can boost the understanding of radiation physics and also consolidate already existing MC track structure codes. Such calculations can support basic science and could, one day, help in making use of Monte Carlo track structure codes not only for space medicine/particle therapy but also for assessing the survival of organics/biomolecules on planetary/small bodies. We suggest that such calculations can fill critical knowledge gaps in the concept of habitability, by determining the survival of critical bonds for the biological units and their eventual polymerization to more interesting targets. We suggest that a robust interaction between the planetary/small bodies community and physical chemists/chemical physicists would be beneficial in the future to understand the limit of life around different type of stars.<br><br>References: [1] V.S. Airapetian, A. Glocer, G. Gronoff, E. Hebrard, W. Danchi, Nature Geoscience 9 (6), 452-455 (2015)<br>[2] V.S. Airapetian , Nature Astronomy 2, 448-449(2018)<br>[3] Y.A. Yamashiki, H. Maehara, V. Airapetian et al., The Astrophysical Journal 881 114 (2019)<br>[4] J. Guo, C. Zeitlin, R.F. Wimmer-Schweingruber, et al., The Astrophysical Journal 810 (1), 24 (2015)<br>[5] F. Da Pieve, G. Gronoff, J. Guo et al., J. Geophys. Res: Planets (2020) doi: 10.1029/2020JE006488<br>[6] H. Palmans, H Rabus, A L Belchior et al., Br. J. Radiol. 88(1045):20140392 (2015)<br>[7] M. J. F. Rosenberg, O. Berne, C. Boersma, et al., Astronomy and Astrophysics 532, A128 (2011)<br>[8] B. Gu, B. Cunningham D. Muñoz-Santiburcio, et al., J. Chem. Phys. 153, 034113 (2020)<br>[9] D. Kao, M. Gacesa, R.M. Wentzcovitch et al., Astro2020 Science White Paper arXiv:1904.07161 | |
| 153 | Estimates of Photochemical Oxygen Loss Rates from Mars-like Exoplanets | The evolution of the atmosphere of Mars and the loss of volatiles over the lifetime of the solar system has been a key motivation for the Mars Atmosphere and Volatile Evolution (MAVEN) mission. Studies based on MAVEN data have demonstrated that the major atmospheric oxygen loss process is photochemical - that is, the escape of fast O atoms produced by dissociative of the major ionospheric ion species, O_2+. A hot oxygen corona is also produced by this process and some O loss is due to ion loss associated with the solar wind interaction with the planet. Note that at Venus and Earth, all the hot O atoms produced by the dissociative recombination reaction have speeds less than the escape speed and cannot directly escape, although ion loss is possible. Using our Mars-based knowledge, this talk will consider how we can extend our understanding of this key atmospheric loss process to different size Mars-like exoplanets and to different levels of stellar ionizing radiation. The effects of different upper atmosphere compositions will also be discussed. | T. Cravens [1], A. Renzaglia [1], A. Rahmati [2], O. Hamil [1], J. Fox [3];<br><br>1 University of Kansas, Lawrence, KS,<br>2 University of California, Berkeley, CA,<br>3 Wright State University, Dayton, OH. |

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| | | Oxygen loss has direct relevance to the retention of volatiles (whether carbon dioxide or water) by planets, and thus to issue of habitability. | |
| 154 | Refining extreme precision radial velocity measurements by understanding stellar activity's effect on asymmetric line shifts. | Recent advances in extreme-precision radial-velocity measurements on the order of 30 cm/s have made it easier to detect Earth-sized planets with longer periods around Solar-like stars by analyzing the reflex motion of their host stars with high-resolution spectroscopy. True Earth analogs, with radial-velocity semi-amplitudes of ~10 cm/s, still remain just out of reach. The precision of radial-velocity measurements is currently constrained by stellar activity, contamination in telluric modeling, and instrumental drift. By analyzing spectra taken from potential host stars over time, we can see changes in line symmetry that could lead to spurious RV shifts. However, it is not clear how much stellar activity can induce a long-term and asymmetric modification to spectral line shapes, compromising the radial-velocity extraction process. We use high signal-to-noise time-series spectra from the EXPRES spectrograph to empirically compare line shape changes of known activity sensitive lines to more static lines. We then quantify the effects that these lines can have on radial velocity precision. The implications for understanding stellar activity sensitivity for specific lines include being able to reduce the radial velocity scatter enough to eventually fill in a new parameter space of Earth-analog exoplanet radial-velocity detection. | D. Nguyen;<br><br>Department of Physics and Astronomy, San Francisco State University, San Francisco, CA. |
| 155 | Assessment of Ammonia as a Biosignature Gas in Exoplanet Atmospheres | Ammonia (NH_3) is a poor biosignature gas because of its extreme solubility in water. We simulate exoplanet atmosphere transmission spectra, with varying NH_3 biological surface fluxes, considering both photochemistry and solubility (i.e., including surface deposition). We find that NH_3 is detectable with JWST only for a very favorable case of an H_2-dominated rocky planet orbiting an M dwarf star, and only if NH_3 exists above about 5 ppm column-averaged mixing ratio. The most favorable scenario for the detection of ammonia has an unrealistic NH_3 biological surface flux, at levels on the order of 1015 molecules cm-2 s-1 (~ 4.5×106 Tg year-1). This value is roughly 20,000 times greater than the biological production of NH_3 on Earth, and about [10,000 times greater than Earth's CH_4 biological production. Nonetheless, NH_3 could accumulate on planets with limited surface water. In summary, while one might envision NH_3 accumulating in a planet atmosphere with intensive bioactivity, the planet surface would have to be covered with life that produces NH_3 with far higher fluxes than life found in even the most highly NH_3 producing niche environments on Earth. | J. Huang [1], S. Seager [1], J. J. Petkowski [1], S. Ranjan [2], Z. Zhan [1];<br><br>1 Massachusetts Institute of Technology, Cambridge, MA, 2 Northwestern University, Evanston, IL. |
| 158 | Venus D and H Loss: An Overview of Measurements and Outstanding Questions | The highly elevated D/H ratio of Venus relative to the Earth indicates that the planet has lost most of its initial water to space, likely as an indirect result of runaway greenhouse warming. However, the large mass of the planet combined with its relatively cool thermosphere means that thermal loss is extremely inefficient at removing large quantities of H or D, and that escape must proceed by nonthermal mechanisms, including photochemical and ion loss. Significant outstanding questions remain about the absolute magnitude of D and H loss at present, the relative importance of ion and neutral loss for these species, and the drivers that control variations in loss both today and throughout time. We will present a review of Mariner, Pioneer Venus Orbiter, and Venus Express spacecraft observations of D and H loss as neutrals and ions, as well as prior data-driven modeling estimates of overall D and H escape, which have uncertainties of a factor of several in absolute escape rates, ion vs. neutral loss ratios, and fractionation factor. Each of these has a potentially | M. Chaffin [1], C. Fowler [2], R. Elliott [1], G. Collinson [3], J. Chaufray [4], H. Groller [5], R. Ramstad [1], S. Xu [6], S. Curry [6], R. Lillis [7];<br><br>1 University of Colorado, Boulder, CO,<br>2 Space Sciences Laboratory, University of California, Berkeley, Boulder, CO, |

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| | | significant impact on the total inventory and timing of water loss by Venus, as well as implications for the loss of water from Venus-like planets throughout the universe. New modeling and potentially new measurements are required to understand these processes more fully: as one example we will present new neutral modeling results relevant to the photochemical escape of Venus H. We emphasize that because thermal H and D loss is inefficient at Venus, a detailed understanding of the active loss processes of H and D from the atmosphere to space is required to understand Venus as an integrated evolving system. | 3 NASA Goddard, Greenbelt, MD,<br>4 LATMOS, Guyancourt, FRANCE,<br>5 University of Arizona, Tucson, AZ,<br>6 University of California, Berkeley, Berkeley, CA,<br>7 University of California, Berkeley, CA. |
| 159 | A Public Data Challenge for Exoplanet Science with the Roman Space Telescope Coronagraph Instrument | With the recent application of coronagraph instruments to the field of exoplanet science, the range of detectable exoplanets has expanded drastically. However, the analysis techniques needed to take full advantage of this new technology have not yet been perfected. We have recently concluded a public data challenge that served to advance the state of these analysis techniques, as well as to familiarize the community with the capabilities of the Roman Space Telescope's Coronagraph Instrument. In this challenge, participants were asked to identify and describe directly imaged exoplanets in simulated data. Each team submitted astrometry and photometry measurements for each planet in the fictional planetary system, as well as estimates of the planets' orbital parameters (semi-major axis, period, etc.), mass, radius, and albedo. In this talk, we share the design of the data challenge, evaluate the performance of each participating team based on root-mean-square error metrics, and compare the teams' results to our in-house analysis. This data challenge provided an opportunity to train and educate several early career scientists on how to interact with space coronagraph data, and the results show that three of the seven teams demonstrated excellent recovery of key astrophysical observables of exoplanets. | E. Bogat [1,2], N. Zimmerman [1], J. Girard [3], J. Gonzalez-Quiles [4], M. Turnbull [5], T. Meshkat [6], A. Mandell [1], Z. Li [7], S. Hildebrandt [8,9];<br><br>1 NASA GSFC, Greenbelt, MD,<br>2 SURA, Washington, DC,<br>3 STScI, Baltimore, MD,<br>4 Johns Hopkins University, Baltimore, MD,<br>5 SETI, Mountain View, CA,<br>6 IPAC, Pasadena, CA,<br>7 UC Riverside, Riverside, CA,<br>8 Caltech, Pasadena, CA,<br>9 NASA JPL, Pasadena, CA. |
| 161 | On Retrieving the Composition of Terrestrial Exoplanet Atmospheres | Bayesian methods have become a standard tool in the retrieval of exoplanetary atmospheric spectra. An ''ignorance prior'' is normally used for the chemistry of the atmosphere to preclude any constraint before observation. We assert that the common paradigm of parameterizing the chemistry as a spectrally active trace species and an inactive filler gas (such as H_2/He or N_2), successfully applied to atmospheres of hot Jupiters, should no longer be relied upon for atmospheres with high mean molecular weight, as it places a biased prior on the abundance of the background gas. As a solution, Benneke & Seager (2012) suggested using symmetric, simplicial priors, such that no gas is assumed to be background and all included species are treated equally. We test the validity of the common paradigm by comparing full retrievals with the trace & background parameterization and with symmetric priors. We find that using the former approach can result in unjustified or even spurious constraint on the retrieved abundances of the background gas in certain situations. We also find that the Rayleighan slope of the spectrum in the optical and UV range plays an important role in constraining the abundances of spectrally inactive gas. We explore degeneracies with other effects, including aerosols and disequilibrium chemistry. | J. Ih, E. Kempton;<br><br>University of Maryland, College Park, MD. |

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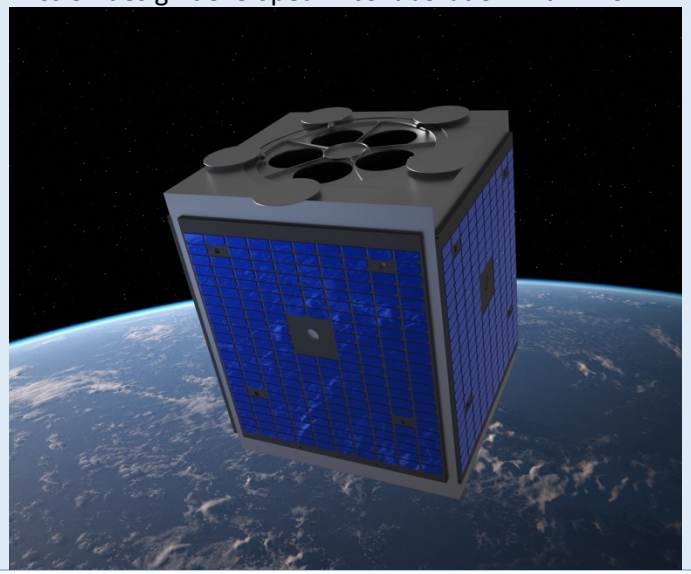
| 163 | Abiotic Oxygen on the Atmospheres of Venus-Like Exoplanets | Photolysis of $CO_2$ in $CO_2$-dominated atmospheres could potentially generate large amounts of abiotic $O_2$ in exoplanetary contexts (e.g., Gao et al., 2015). Interestingly, ground-state $O_2$ has never been observed on Venus, despite high $CO_2$ photolysis rates in the upper atmosphere (Trauger & Lunine, 1983; Krasnopolsky, 2006). This lack of $O_2$ has been attributed to catalytic cycles involving $HO_x$, $ClO_x$, $SO_x$, and $NO_x$ molecules that can efficiently recombine photochemically generated CO and O into $CO_2$ (DeMore & Yung, 1982; Mills et al., 2007; Yung & DeMore, 1999). Hitherto, it is unknown how these photochemical networks would be impacted by different stellar spectra. In this study, we model the photochemistry of Venus-like exoplanets around various stellar types. We use the Caltech/JPL 1-D photochemical model KINETICS, based upon the work of Zhang et al. (2012) and Bierson & Zhang (2020), to simulate 464 chemical reactions between 68 chemical species composed of H, C, O, N, S, and Cl. We consider an atmosphere primarily composed of $CO_2$ (~90 bars) and $N_2$ (~3 bars) with trace amounts of $H_2O$, $SO_2$, OCS, HCl, and the photochemical products thereof. These trace species contribute the $HO_x$, $ClO_x$, $SO_x$, and $NO_x$ catalysts that control the steady-state abundance profiles of abiotic $O_2$ in the atmosphere. Our model also simulates the condensation and evaporation of $H_2O$ and $H_2SO_4$ in the atmosphere's cloud region. We assume that the surface mixing ratios of trace atmospheric species are controlled by surface mineralogical buffers relevant to Venus (Zolotov, 2018). We compare the effect of G- and M-dwarf spectral energy distributions on Venus-like worlds, placing the planets at orbital distances with the same total incident flux as Venus. Our preliminary results show that different spectral energy distributions result in different $O_2$ buildup. In particular, the high FUV/NUV ratio of TRAPPIST-1 can cause a Venus-like planet to contain several percent $O_2$ in the upper atmosphere. However, around a Sun-like star, where the NUV flux outweighs the FUV flux by orders of magnitude, the column mixing ratio of $O_2$ is limited to $\ll 1$ ppm. | M. Wong [1], V. S. Meadows [1], P. Gao [2], C. Bierson [3], X. Zhang [2];<br><br>1 Department of Astronomy & Astrobiology Program, University of Washington, Seattle, WA,<br>2 University of California, Santa Cruz, Santa Cruz, CA,<br>3 Arizona State University, Tempe, AZ. |
| 164 | Habitable Zones in Binary Star Systems with a Circumbinary Giant Planet | To date more than three dozen binary star systems are known to host circumbinary planets. In this contribution we investigate if and where such systems can host additional potentially habitable worlds. So-called dynamically informed habitable zones are valuable concepts in this respect as they allow us to consider the orbital evolution of the system as well as the actual insolation received by additional Earth-like planets that orbit the binary star. Here, we present an analytic method for calculating dynamically informed habitable zones in circumbinary systems known to host giant planets. By determining the extent of dynamically informed habitable zones in Kepler-16, Kepler-34, Kepler-35 and Kepler-413 systems we show that the presence of a giant planet strongly affects the chances of additional terrestrial planets to be habitable even when they are on dynamically stable orbits. | N. Georgakarakos [1], S. Eggl [2], I. Dobbs-Dixon [1];<br><br>1 New York University Abu Dhabi, Abu Dhabi, UNITED ARAB EMIRATES,<br>2 University of Washington, Seattle, WA. |
| 167 | The Normal-incidence Extreme Ultraviolet Photometer (NExtUP) | The evolution and loss of exoplanetary atmospheres depend critically on the host stars' extreme ultraviolet (EUV) spectra and fluxes. EUV radiation is absorbed at high altitude, in the exosphere and upper thermosphere, where the gas can be readily heated to high temperatures conducive to escape. EUV heating is thought to be a dominant atmospheric loss mechanism during most of a planet's life. | J. Drake [1], C. Garraffo [1,2], A. Youngblood [3], V. Kashyap [1], B. Wargelin [1], B. Fleming [3], K. France [3], P. Cheimets [1], D. Caldwell [1], O. Siegmund [4], J. |

There are only a handful of accurately measured EUV stellar fluxes, all dating from Extreme Ultraviolet Explorer (EUVE) observations in the '90s. These observations were mostly single snapshots of what are highly variable and often flaring sources. Consequently, current models of stellar EUV emission are uncertain by more than an order of magnitude and are the largest uncertainty in planetary atmospheric loss models.

The Normal-incidence Extreme Ultraviolet Photometer (NExtUP) is a smallsat design that will use innovative, efficient normal-incidence multilayer technology, both periodic and aperiodic, to form sharp images of stars in 5 EUV bandpasses between 150 and 900 Å, down to flux limits two orders of magnitude lower than EUVE. A prime focus microchannel plate detector will measure the EUV fluxes formed at different temperatures in stellar outer atmospheres during quiescent and flaring states. NExtUP may also accomplish a compelling array of secondary science goals, including using line-of-sight absorption measurements to understand the structure of the local interstellar medium, and imaging EUV emission from energetic processes on solar system objects at unprecedented spatial resolution.

Proposed for the recent NASA Pioneers opportunity, NExtUP is low-cost and efficient, requiring no mechanisms or special orbital conditions during operation. It draws on decades of mission heritage expertise at SAO and LASP, including similar instruments successfully launched and operated to observe the Sun. NExtUP would be flown on a spacecraft supplied by MOOG Industries, with a mission design developed in collaboration with NASA AMES.



Mason [3], J. Bookbinder [5], J. D. Alvarado-Gómez [6], M. Barstow [7], G. Gronoff [8], R. Gladstone [9], T. Koskinen [10], M. Lopez-Morales [1], S. Moschou [1], S. Wolk [1];

1 Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA,
2 Institute for Applied Computational Science, Harvard University, Cambridge, MA,
3 Laboratory for Atmospheric and Space Physics, Colorado University, Boulder, CO,
4 Space Sciences Laboratory, University of California Berkeley, Berkeley, CA,
5 NASA AMES, Moffett Field, CA,
6 Leibniz Institute for Astrophysics Potsdam, Potsdam, GERMANY,
7 Institute of Space & Earth Observation, University of Leicester, Leicester, UNITED KINGDOM,
8 NASA Langley Research Center, Hampton, VA,
9 Southwest Research Institute, San Antonio, TX,
10 Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ.

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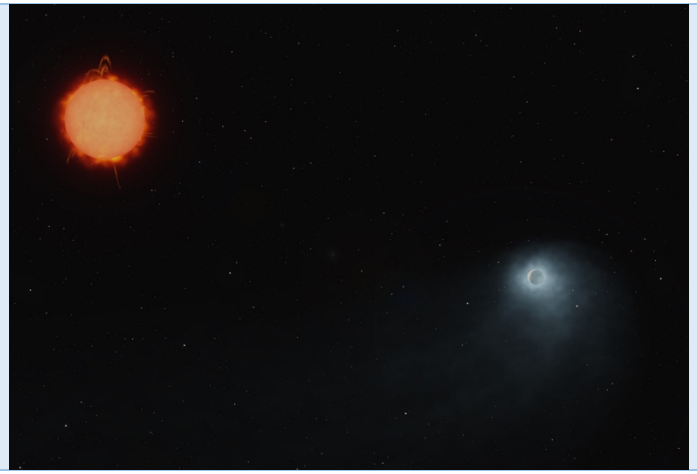
| | |  | |
| 168 | ELT Imaging of Protoplanetary Disks and, Eventually, Protoplanets | Imaging young or still-forming planets with masses and orbital characteristics like the giant planets in our solar system requires extremely large telescopes (ELTs). The Large Binocular Telescope Interferometer (LBTI) provides the resolution of a 23-m telescope, and can be used now to provide ELT-scale observations of bright protoplanetary disks. We employ the technique of non-redundant masking interferometry, along with the adaptive optics and co-phasing systems, to achieve diffraction-limited imaging with this large telescope. Co-phased LBTI operation is currently only possible for bright targets, and we have therefore observed bright protoplanetary disks to date. After presenting the images we have obtained and discussing the scientific implications of these data, I will describe our current work to enhance the LBTI sensitivity, and future plans to extend these ELT imaging observations to planets that are still forming in young protoplanetary disk systems. Such observations can image protoplanets orbiting within 5 AU of young stars, probing parameter space where we see giant planets in our solar system and expect giant planet formation in typical young systems. | J. Eisner;<br><br>Astronomy, University of Arizona, Tucson, AZ. |
| 169 | Interdisciplinary Modeling of Planetary Habitability | Planetary habitability arises from a planet's properties and its system's architecture, i.e. a high-dimensional parameter space with complex feedbacks. Compounding the complexity is the nature of modern science: the knowledge and expertise required to self-consistently model the relevant processes span multiple scientific disciplines. To overcome these obstacles, we have constructed a theoretical model of planetary system evolution that connects relatively simple models of phenomena such as mantle-core dynamics, volatile cycling, atmospheric escape, climate, orbital dynamics, stellar activity, galactic perturbations, etc., to simulate potentially habitable planets for billions of years. Additionally, we have compiled this model into a modular, open source software package called VPLanet that enables these disparate processes to be simulated with a single executable and facilitate interdisciplinary research. In this presentation, we briefly review the functionality of the VPLanet model and then present recent results. First, we show that the tidally heated magma oceans of the potentially habitable planets of TRAPPIST-1 may experience a wide range of geochemical scenarios that may result in desiccation and/or atmospheric oxygen accumulation. Next, we show how planets orbiting short-period binary stars can experience a | R. Barnes [1], P. Barth [2], C. Wilhelm [1], D. E. Graham [3], R. Garcia [4], L. Amaral [5], R. Luger [6], R. Deitrick [7], P. Driscoll [8], D. Fleming [4], H. Smotherman [4], T. R. Quinn [4], L. Carone [3], A. Segura [5], P. Gupta [4], V. S. Meadows [4], P. Molliére [3], L. Noack [9], J. Livesey [4], I. Guez [4], T. Henning [3];<br><br>1 Astronomy, University of Washington, Seattle, WA, |

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| | | complicated orbital and instellation evolution due to the tidal damping of the host stars' orbit. Then we consider the range of climates of Earth-like planets in multiplanet systems orbiting FGK stars with an energy balance model to predict that most planets are free of surface ice, but those with ice are more likely to support ice belts than ice caps. Finally, we discuss how to contribute to the development of the VPLanet model. | 2 St. Andrews University, St. Andrews, UNITED KINGDOM,<br>3 University of Heidelberg, Heidelberg, GERMANY,<br>4 University of Washington, Seattle, WA,<br>5 Universidad Nacional Autónoma de México, Mexico City, MEXICO,<br>6 Flatiron Institute, New York, NY,<br>7 University of Bern, Bern, SWITZERLAND,<br>8 Carnegie Institute for Science, Washington, DC,<br>9 Freie Universitat Berlin, Berlin, GERMANY. |
| 170 | Tracking Bioenergetic Shifts in Terrestrial Serpentinites | Serpentinization is a long duration, expansive geologic process that is feasible wherever aqueous solutions interact with ultramafic-mafic protolith. In sheltered subsurface environments where groundwaters of variable chemistry or oceans beneath icy crusts interact with mantle-type rocks, this exothermic, energy yielding transformation of planetary materials has the potential to create habitable niches. Olivine and pyroxene minerals in parent rocks alter to serpentine-dominated assemblages, while ferrous iron is oxidized and hydrogen in molecular water is reduced to diatomic hydrogen, generating daughter materials generally more hydrated, oxidized, and diverse when compared to parent materials. Planetary history and sequential periods of distinctive weathering control the geochemical system, and, by extension, its bioenergetic habitability. Implications for elemental cycling, gas release, and support of a putative extraterrestrial chemosynthetic biosphere are considered. | D. CARDACE;<br><br>University of Rhode Island, Department of Geosciences, Kingston, RI. |
| 171 | A Search for Life in a Thousand Earths: The Nautilus Space Observatory | An outstanding, multidisciplinary goal of modern science is the study of the diversity of potentially Earth-like planets and the search for life in them. This goal requires a bold new generation of space telescopes, but even the most ambitious designs yet can only hope to characterize several dozen potentially habitable planets. Such a sample may be too small to truly understand the complexity of exo-earths, which will likely need to be studied and interpreted as a network of coupled complex systems. We describe here a notional concept for a novel space observatory designed to characterize 1,000 transiting exo-earth candidates. The Nautilus Space Observatory concept is based on an array of identical spacecraft carrying very large diameter (8.5 m), very low weight, multi-order diffractive optical elements (MODE lenses) as light-collecting elements. The mirrors typical to current space telescopes are replaced by these MODE lenses, that have a 10 times lighter areal density and that are 100 times less sensitive to misalignments, enabling lightweight structures. MODE lenses can be cost-effectively replicated through molding. The Nautilus Space Observatory | D. Apai [1], T. D. Milster [2], D. Kim [1], A. Bixel [3], G. Schneider [4], B. Rackham [5], J. Arenberg [6];<br><br>1 Astronomy / Planetary Science, University of Arizona, Tucson, AZ,<br>2 J. C. Wyant College of Optical Sciences, University of Arizona, Tucson, AZ, |

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| | | concept has a potential to greatly reduce fabrication and launch costs and mission risks compared to the current space telescope paradigm through replicated components and identical, lightweight unit telescopes. The Nautilus Space Observatory is designed to survey transiting exo-earths for biosignatures up to a distance of 300 pc, enabling a rigorous statistical exploration of the frequency and properties of life-bearing planets and the diversity of exo-earths. As the key step toward the full Nautilus Space Observatory, we also proposed the single-unit Nautilus Probe, a NASA Probe-class mission for exoplanet exploration, faint objects, and time-domina astrophysics.We present here an update on the Nautilus Space Observatory and Nautilus Probe concepts, as well as an update on the ongoing technology development work that advances the technology readiness level and the diameter of the ultralight MODE lenses, the key technology that underpins these revolutionary space observatories. | 3 Astronomy, University of Arizona, Tucson, AZ,<br>4 Astonomy, University of Arizona, Tucson, AZ,<br>5 Earth and Planetary Science, Massachusetts Institute of Technology, Boston, MA,<br>6 Northrop Grumman Aerospace Systems, Redondo Beach, CA. |
| 173 | Phosphine In The Atmosphere Of Venus? | There is controversial evidence about the possible discovery of phosphine in the upper atmosphere of Venus, based on data obtained by various ground- and space-based observations. These data and their analyses are sufficiently complex and subtle as to leave the detection in doubt. To try to place a stringent upper bound of well under one part in ten to the ninth, or to obtain a definitive detection and map its value across the Venusian disk, we intend to investigate the feasibility of a relatively low-cost mission to Venus based on adapting a CubeSat for this purpose. We will determine whether such a satellite can be converted to take high resolution infrared/microwave spectral images of Venus in a flyby mission that would encompass low to high latitudes on Venus, or, preferably, via braking to enter orbit around Venus. We will carry out the needed studies, which involve, for example, propulsion, trajectory, navigation, communication, and data acquisition and transmission. | I. Shapiro, Kelly Chance, Peter Cheimets, Clara Sousa-Silva;<br><br>Center for Astrophysics \| Harvard & Smithsonian, Cambridge, MA. |
| 174 | A High Quality Atmospheric Target in a Sparse Region of Mass-Radius Space around HD 63935 | We present the discovery of the sub-Neptune-size planet orbiting HD 63935, a bright (V=8.6), sun-like (Teff=5560K) star. The planet, HD 63935 b (TOI509.01), was identified in TESS Sector 7 (at twice the correct orbital period). Our analysis of the photometric and radial velocity data yields a robust detection of the planet with a period of 9.0600+0.00064/-0.00070 days, radius of 3.058±0.065 Earth radii, and mass of 10.7±1.6 Earth masses. We identify two additional highly significant candidate signals at 21 and 115 days in the radial velocity data. We suggest these signals are most likely to be planetary in nature, although we examine other potential explanations. The candidate at 21 days has a crossing time consistent with the gap in the TESS sector 7 light curve. If it is transiting, we anticipate two transits in the upcoming TESS Sector 34. For the confirmed planet, we calculate a density of 2.1±0.3 g/cm3, consistent with interiors ranging from rocky to ice-dominated, with a hydrogen envelope making up a few percent of the planet mass. The planet resides on the sub-Neptune "occurrence cliff", a drop in short-period planet occurrence around 3 Earth radii, separating the sub-Neptune population from the giant planets. In addition to our characterization, we also describe our survey's efforts to choose the highest-quality atmospheric targets for followup with JWST. This planet is the best known atmospheric target on the "occurrence cliff", making it an intriguing prospect for additional followup observations. It also resides in a so-far unexplored region of parameter space comprising small (2.6R_earth < R_p < 4R_earth), moderately high irradiation (100 F_earth < F_p < 1000 F_earth) planets around G-stars. | N. Scarsdale, J. Murphy, N. Batalha, The TESS-Keck Survey Team;<br><br>Astronomy & Astrophysics, University of California, Santa Cruz, Santa Cruz, CA. |

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| | | No such planets with known masses have JWST SNR proxy values as high as HD 63935 b (~118) or published transmission spectra, emphasizing the new regions of parameter space being made accessible to exploration by the TESS mission in general and this system in particular. | |
| 176 | On the detectability of rocky exoplanet surfaces | For the interpretation of upcoming observations of terrestrial -- potentially habitable -- planets, it is not only crucial to understand how atmospheric species imprint their spectral signatures onto planetary emission spectra, but also whether spectral features of rocks and minerals of various types may be detectable.<br><br>We are presenting first results from our new radiative transfer framework, which takes the radiative properties of both the atmosphere and the surface into account. Taking the hot rocky super-Earth LHS 3844b as benchmark -- motivated by the recent findings of Kreidberg et al. (2019) -- we explore the detectability of various plausible rocky surfaces with JWST. Since the measured Spitzer phase curve of this planet indicates that this planet does not possess a thick atmosphere, the surface should in principle be detectable. Hence, this planet is a first benchmark target for future characterization efforts of exoplanetary geology. However, even atmospheres that are optically thin may provide sufficient extinction within molecular absorption bands to mask the surface.<br><br>In order to predict realistic planetary spectra stemming from both atmospheres and surfaces, we a have constructed a large grid of plausible atmosphere/surface models. We have considered O_2- and N_2-dominated atmospheres with various trace species, such as CO_2, SO_2, CO and H_2O, all potential additives from volcanism, and surfaces of basaltic, granitoid and feldspathic crust, as are commonly found in the solar system bodies. Using the JWST noise simulator Pandexo to simulate LHS 3844b secondary eclipse observations we have found the following observables:<br><br>(i) The surface albedo in the near-infrared plays a crucial role for the planetary spectrum in that wavelength range. We find that the differences both in the reflected as well as the emitted part of the spectrum are large enough to be detectable with the NIRSpec/G395M instrument. In addition, the surface has a significant effect on the atmospheric temperature profiles and surface temperatures. For instance, due to its high reflectivity, the feldspathic surface leads to surface temperatures up to 60 K cooler compared to the other cases.<br><br>(ii) In the mid-infrared, the surface will be detectable with MIRI/LRS. Since both O_2 and N_2 are weak absorbers, there a number of spectral windows in which the planetary emission follows the surface features. For instance, two sweet spots are located at 5 - 7 micron and 9.5 - 12 micron. This coincides well with the Si-O bands located at ~ 8 - 12 microns, resulting in prominent rocky features.<br><br>Although focusing on a very hot case study, we believe that our results help gain a broader understanding of the emission spectra of terrestrial planets, as the explored atmospheric | M. Malik, E. Whittaker, E. Kempton;<br><br>Astronomy, University of Maryland, College Park, MD. |

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| | | compositions and surfaces are typical for a broad range of rocky planets. From the current surface geology we can start learning about the internal structure and past evolution of these planets. | |
| 177 | Planetary atmospheric response to the stellar energetic particles in the habitable zones of TRAPPIST-1-like systems | Habitable zone planets orbiting active stars are expected to be subject to particularly high doses of particle radiation that could affect the evolution of life. We describe test-particle simulations of ∼GeV protons to investigate the propagation of energetic particles accelerated by flares or traveling shock waves within the turbulent and magnetised stellar wind of a TRAPPIST-1-like system. We find that only a few percent of particles injected within half a stellar radius from the stellar surface can escape, and that the escaping fraction increases strongly with increasing injection radius. Escaping particles are strongly focused onto two caps within the fast wind regions and centered on the equatorial planetary orbital plane. Based on a scaling relation between far-UV emission and energetic protons for solar flares applied to M dwarfs, the innermost putative habitable planet, TRAPPIST-1e, is bombarded by a proton flux up to 6 orders of magnitude larger than experienced by the present-day Earth. We present preliminary results of the chemical response of the upper planetary atmosphere to the particle flux at various phases of its orbit around the star. | F. Fraschetti [1,2], J. Drake [1], G. Gronoff [3], J. Alvarado [4], S. Moschou [1], C. Garraffo [1], O. Cohen [5], L. Harbach [1];<br><br>1 Center for Astrophysics\|Harvard & Smithsonian, Cambridge, MA,<br>2 Planetary Sciences, University of Arizona, Tucson, AZ,<br>3 NASA, Hampton, VA,<br>4 Leibniz Institute for Astrophysics, Potsdam, GERMANY,<br>5 University of Massachusetts Lowell, Lowell, MA. |
| 178 | Carbon Dioxide Outgassing Constrains the Habitability of Rocky Planets after their Host M Dwarf's Pre-Main Sequence Phase | M dwarf habitable zones move inward with time over the star's extended pre-main sequence phase such that rocky planets that are currently orbiting in an M dwarf's habitable zone may have once orbited interior to it. Before the habitable zone contracts to envelop the planet, the planet will likely be in a runaway greenhouse phase, losing water from its atmosphere while outgassing carbon dioxide to its atmosphere. Once the habitable zone contracts to the planet's orbit, any water outgassed from the interior may condense to form liquid oceans, if the surface temperature and pressure allow liquid water to be stable. However, if the planet has outgassed enough carbon dioxide during its runaway greenhouse phase, surface temperatures will be too high for outgassed water to condense and the planet will not be habitable. To calculate the rate of carbon dioxide outgassing before the habitable zone reaches the planet, we add a geochemical model to the VPLanet software package that self-consistently tracks water and carbon dioxide flows across a planet's mantle, crust, and atmosphere for a stagnant lid tectonic mode. Our model simulates the interior thermal evolution of the planet (including the core) to calculate outgassing rates from magma production rates over time. We also simulate the evolution of the host star to calculate the rate of atmospheric escape of water during its runaway greenhouse phase. We validate our model by reproducing the 92 bars of carbon dioxide and 30 ppm of water vapor observed in Venus' atmosphere today, as well as its lack of a magnetic field. We then apply this validated model to calculate the coupled atmosphere-interior evolution of the potentially habitable TRAPPIST-1 planets, assuming they possess stagnant lids and Earth-like compositions. We identify the | R. Garcia [1], R. Barnes [1], P. Driscoll [2], V. Meadows [1];<br><br>1 University of Washington, Seattle, WA,<br>2 Carnegie Institution for Science, Washington D.C., DC. |

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| | | parameter space in which our simulated planets become habitable after their host star's pre-main sequence phase. We show that the habitability of a planet currently orbiting in the habitable zone around an M dwarf depends strongly on the initial carbon dioxide budget and the fraction of magma that erupts to the surface (extrusive volcanism) on that planet. While planets in the habitable zone with low initial carbon dioxide budgets or low fractions of extrusive volcanism can support liquid water, planets that have outgassed too much carbon dioxide during their runaway greenhouse phase will, despite being in the habitable zone, become Venus-like worlds with thick carbon dioxide atmospheres and no liquid water. We investigate TRAPPIST-1e's potential habitability and demonstrate that, assuming an Earth-like composition, it requires a carbon dioxide budget on the order of bars or an extrusive volcanism fraction of 0.001 to become habitable after the pre-main sequence phase. Our model shows that TRAPPIST-1e's potential for habitability is severely limited unless it is either volatile poor or erupts very little magma to its surface. | |
| 179 | Sulfur oxide profiles on Venus: Interactions among atmospheric chemistry, dynamics, and microphysics | Venus can be considered our nearest exoplanet. Several of its distinctive features are due to the sulfur chemistry occurring in its atmosphere. The vertical profile of the primary sulfur species, SO_2, reflects the combined effects of gas-phase chemistry, aerosol and cloud microphysics, and dynamics. The primary reservoir for SO_2 lies in the troposphere. Through the cloud layers, but particularly within the upper cloud, SO_2 oxidizes and reacts with water to form sulfuric acid, one of the main constituents of the cloud particles. Another, so far unidentified species is present within the upper cloud that accounts for half of the solar energy absorbed within Venus' atmosphere. Polysulfur, S_x, is one of the leading candidates for this unidentified species. If this identification is correct, then its production is linked to the loss of SO_2 as air parcels are convected and mixed upward through the cloud layers. At higher altitudes, in the upper mesosphere, an inversion layer has been observed where SO_2 abundances again increase with increasing altitude. This inversion layer may arise from upward transport of sulfuric acid, polysulfur, and/or chlorine-sulfur compounds. It may also, at least partially, arise from transport and quenching. The current state of research on these phenomena will be reviewed and potential implications for extrasolar planet simulations and observations discussed. | F. Mills [1,2], C. D. Parkinson [1], J. Li [3], J. P. Pinto [4], Y. L. Yung [3,5], K. Willacy [5];<br><br>1 Space Science Institute, Boulder, CO,<br>2 Fenner School of Environment & Society, Australian National University, Canberra, AUSTRALIA,<br>3 California Institute of Technology, Pasadena, CA,<br>4 University of North Carolina at Chapel Hill, Chapel Hill, NC,<br>5 Jet Propulsion Laboratory, Pasadena, CA. |
| 180 | Tools to Find Living Worlds: The HabEx and LUVOIR Mission Concepts | A threshold was crossed in the late 20th century with the discovery of planets around other stars (e.g., Mayor & Queloz 1995). At this key point in history, humanity knows that exoplanets are both abundant and diverse — and the possible discovery of life-bearing worlds is within our grasp. This monumental objective demands powerful and flexible new tools, as well as application of multi-disciplinary scientific skills.<br><br>The next frontier is to extend our characterization capabilities to rocky exoplanets, including finding the "pale blue dots" in the solar neighborhood. With the right tools, we can determine whether those worlds have Earth-like surface conditions and probe them for signs of life. Focusing on the planetary systems most like the solar system, those with Earth-size exoplanets orbiting in the habitable zones of Sun-like stars, increases the chances of finding and recognizing biosignatures. | B. Gaudi [1], A. Roberge [2], The HabEx and LUVOIR Study Teams;<br><br>1 The Ohio State University, Columbus, OH,<br>2 NASA/GSFC, Greenbelt, MD. |

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| | | Concurrently, we will nurture a new discipline — comparative exoplanetology — by studying a huge range of exoplanets and comparing them with the vastly better studied Solar System planets.<br><br>As preparation for the 2020 Astrophysics Decadal Survey (Astro2020), in 2016, NASA initiated studies of four large space telescope concepts. Two of these concepts — HabEx and LUVOIR — have the driving goal of finding and studying potentially habitable exoplanets around Sun-like stars, as well as enabling a wide range of revolutionary astrophysics and Solar System studies. Here we will outline the observational requirements for achieving these goals, describe the technical solutions proposed by the two concepts, and compare their capabilities and challenges. The results of these detailed mission concept studies, which spanned nearly four years, were presented to Astro2020 last year and are currently being considered for prioritization as NASA's next Great Observatory. | |
| 182 | Modeling Atmospheric Escape from Magnetized Rocky Exoplanets With (Exo) Planetary Ionosphere-Thermosphere Tool for Research (ExoPLANET-ITTR) | Recent Kepler and TESS observations discovered many rocky exoplanets in habitable zones around active main-sequence stars. The upper atmospheres of exoplanets are subject to two important energy sources derived from their host stars. First, the stellar photon flux in the X-ray and XUV bands ionizes and heats the upper atmosphere, driving atmospheric heating, affecting the conductance, and enhancing atmospheric escape. Second, the stellar wind's interaction with the exoplanet's intrinsic magnetic field transfers energy to the atmosphere through field aligned currents and Poynting flux.That energy is dissipated in the high latitude cusp and auroral regions through Joule heating which can inflate the atmosphere and also enhance the atmospheric escape rate. This presentation will discuss recent advances in modeling these energy inputs and their consequences for exoplanetary habitability. In particular, we present the development of a new model, the (exo) PLANETary Ionosphere-Thermosphere Tool for Research (PLANET-ITTR). The model and its validation are presented as well as application of the model for two physical scenarios. First, we examine the determination of ionospheric conductance for planetary systems and present verification of the conductance calculation with widely used empirical models for modern Earth. We will also model the case of elevated stellar XUV input appropriate for close-in exoplanets as well as the early Venus and Mars and discuss the consequences for the stellar wind magnetosphere coupling. Second, we study the onset of hydrodynamic escape under conditions of enhanced stellar XUV flux. We will derive the loss time of hydrogen dominated primary atmospheres of terrestrial (exo)planets and sensitivity of the atmospheric loss time scale to various stellar inputs. | S. Kang, A. Glocer, V. Airapetian, W. Danchi;<br><br>NASA/GSFC, Greenbelt, MD, |
| 183 | A SmallSat to Study the Structure and Evolution of ExoJupiter Atmospheres (SEEJ) | The most important effects on an exoplanet atmosphere are driven by high-energy photons and particles from the host star, which heat and ionize the planetary atmosphere, potentially leading to its loss. The rarest, largest flares are disproportionately important. SEEJ will study the Structure and Evolution of ExoJupiter atmospheres with long observations, with cumulative exposures well beyond those conducted by any other mission. SEEJ will measure how often high energy flares of a given size occur, and establish, for the first time the statistics of these crucial events on exoplanet hosts. Observing transits SEEJ will measure the thermospheric scale height, and so the inflation or damage to the exoJupiter atmosphere. SEEJ will provide the data for theory to tie the rare flares and their effects together via improved models of exoplanet thermospheres.The X-rays emitted by an exoplanet host star is critical to the atmosphere of the planet. Specifically, X-rays can induce | S. Wolk [1], C. Moore [2], J. Hong [3], S. Romaine [2], A. Moorhead [4], L. Kaltenegger [5], B. Wargelin [2], V. Kashyap [2];<br><br>1 High Energy, SAO, Cambridge, MA,<br>2 SAO, Cambridge, MA, |

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| | | both life-enabling and life-threatening photochemistry in planetary atmospheres. Similarly, observed X-ray flares may be harbingers of coronal mass ejections which can aid the development of life by removing primary, hydrogen-dominated atmospheres or threaten its existence by depleting secondary atmospheres and specific critical species such as ozone. An understanding of the behavior of stellar coronae at all phases of stellar/planetary evolution is fundamental to our ability to gauge the cumulative impact of stellar X-rays on planetary atmospheres.<br><br>■ The First Objective of SEEJ is to characterize the X-ray emission for a diversity of planet hosting stars through long term monitoring, and use this as input to exo-planet atmospheric models to determine effect on planetary atmospheres, and possible feedback between the planet and star.<br><br>■ The Second Objective of SEEJ is to detect and measure planetary exospheric structure through the shape and extent of the upper atmosphere for a variety of exoplanets.<br><br>SEEJ will provide detailed X-ray transit light curve profiles of suitable targets accumulating them by observing multiple exoplanet transits. SEEJ will monitor roughly 40 transits of as many as 7 X-ray bright exoplanet hosts in a single year. | 3 Harvard University, Cambridge, MA,<br>4 MSFC, Huntsville, AL,<br>5 Cornell University, Ithaca, NY. |
| 185 | Our Inhabited Heliosphere: The Implications of Stellar Motion through Galactic Interstellar Clouds On Planetary Atmospheres | The Sun is currently moving through a rich and complex suite of partially ionized, warm, interstellar clouds. An interface, dictated by pressure balance, magnetic fields, and charge exchange, signifies the interaction between a outward moving stellar wind and the inward force of the surrounding local interstellar medium (LISM). As stars and the ISM each comprise roughly half of the luminous matter in galaxies, these interactions are ubiquitous. The interaction is also dynamic. While stellar wind strengths change slowly, at least during the main sequence, the density of interstellar clouds ranges by more than six orders of magnitude. The implication is that the solar heliosphere and stellar astrospheres are permanent features of planetary systems and are constantly changing. The stellar magnetic field and particle interactions can lead to a filtering of low and high-energy (i.e., cosmic rays) particles. The particles that make it through the filter can be deposited in the atmospheres and on the surfaces of planets in the system. Therefore, the galactic interstellar environment, and the resulting interface with the star, can potentially have an influence on the habitability of a planet. This is a refined and planetary system specific version of the galactic habitable zone paradigm. I will discuss work to measure and model the morphology and physical properties of the LISM. These clouds reside in our immediate cosmic neighborhood, within 20 pc. This same volume contains several detected astrospheres and the nearest and most favorable exoplanetary systems with planets in habitable zone orbits. I will also discuss the the influence the LISM has on observations to characterize the atmospheres of exoplanets. Finally, I will present results of a project to observe the interstellar environment that the Sun traversed in its most recent past (e.g., within the last 5 Myr) and evaluate the corresponding impact on our historical heliosphere. While perhaps not a primary driver of habitability in general, it is worth exploring the | S. Redfield;<br><br>Wesleyan University, Middletown, CT. |

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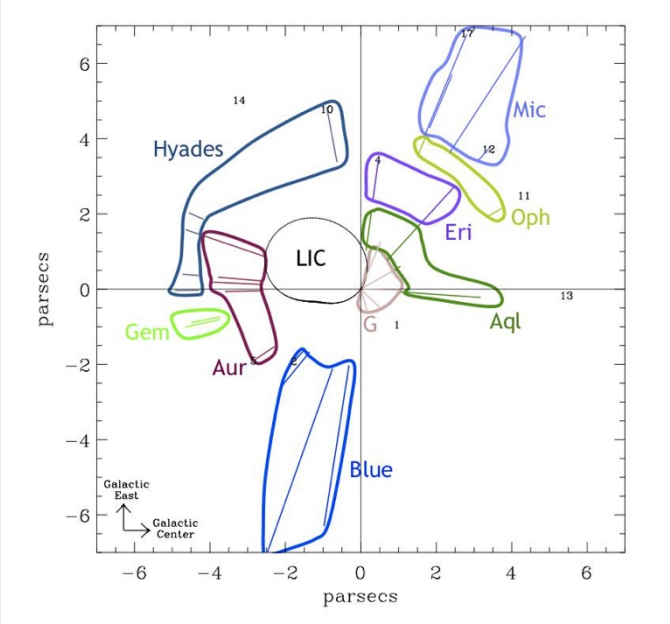
| | | impact of these planetary system-ISM interactions, and identifying extreme systems where it may have a significant influence on habitability.<br>  <br> | |
| 186 | Land planets in a ROCKE-3D GCM perturbed parameter ensemble: fractional habitability | Land is required not only to provide life a stable surface but also to support a stable carbonate-silicate cycle. Modeling studies have surmised that land planets may support a wider and longer continuous habitable zone than aqua planets, both at the moist greenhouse limit and at the outer edge. The habitability of a planet is not well characterized by its mean state but by its diversity of climate regimes that distribute heat and water, if present, over its surface heterogeneously, producing environmental niches that will differ in suitability for life. A planet's climate is subject to the interaction of many planetary features that affect its circulation patterns including: parent star, orbital dynamics, atmospheric composition, surface composition. Given such a diverse parameter space, if a habitable planet harbors water, how might it distribute over the planet and where will the liquid water be for life?<br><br>Because most exoplanet climate modeling studies thus far have biased the literature sampling of the parameter space to aqua planets, Earth continents, the Sun, M stars, and extremes of atmospheric CO_2 content, in this study we filled the gaps through a perturbed parameter ensemble (PPE) in the NASA Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics general circulation model (ROCKE-3D GCM). We simulated the climates of idealized planets that are all land with flat topography. We conducted a Latin hypercube sampling from the following ten variables in 110 experiments: stellar temperature and spectra from observed G, K, and M stars; irradiance spanning from that of TRAPPIST1-e to early Venus; rotation period including tidally locked, 3:2 spin-orbit, and 1-128 Earth days; obliquity from 0 to 90°; surface | N. Y. Kiang [1], C. Colose [2], R. Ruedy [2], R. Barnes [3], G. S. Elsaesser [4], S. Harman [5], S. R. Kane [6], G. L. Russell [1], M. Van Lier-Walqui [4], E. T. Wolf [7], I. Aleinov [4], A. Del Genio [8], S. D. Guzewich [9], K. Tsigaridis [4], M. J. Way [1], N. Kiang [10];<br><br>1 NASA-GISS, New York, NY,<br>2 SciSpace, New York, NY,<br>3 University of Washington, Seattle, WA,<br>4 Columbia University, New York, NY,<br>5 NASA Ames Research Center, Moffett Field, CA, |

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| | | pressure from 0.5-10 bar; CO_2 content (in N_2/CO_2 atmospheres) from 0 to 10 bar; surface albedo 0.11-0.3; surface roughness from the GCM minimum of 0.005 to 0.7, the average of bare soils on Earth; two soil textures having water holding capacity at the minimum, sand, and optimum for life, silt loam; and initial soil water content spanning the field capacities of the two soil textures, which give 0.008-0.026% of the Earth's ocean. Thus, these were fairly dry planets, but with water free to circulate and accumulate in different climate zones and in the atmosphere.<br><br>We evaluated the planets' "climatological period" to quantify mean climate states and, through multivariate statistical analysis, identify continuous, non-linear relations between the parameters and several metrics of habitability, including surface water cover, aridity, soil relative extractable water, and the planetary water phase budget. From these we derived classifications of rocky land planet climatologies, such as eyeball, billiard ball, and Fabergé egg planets. We identified parameter thresholds for transitions to slushball, clement, and steam planet states. 80% of the variance in surface temperature may be explained by stellar type, irradiance, and greenhouse gas content, with the solar day length, surface pressure, and obliquity only weakly significant. Available liquid water for life by mass and areal extent are then correlated with temperature, with obliquity up to about 60° weakly promoting surface wetness. We look for surface water metric relationships to those parameters and climate features that might be observed by exoplanet missions, including stellar type, irradiance, planetary albedo, cloud cover, and upper atmosphere water vapor. This framework offers a modeled context to quantify the uncertainty in habitability given many parameters that cannot be observed. This ensemble of idealized land planets lays foundations for further filling the parameter space with more diverse specifications of the planet size, and compositions of the surface and atmosphere for understanding the climatologies of land planets in particular. | 6 University of California, Riverside, CA,<br>7 University of Colorado, Boulder, CO,<br>8 NASA GISS (Retired), New York, NY,<br>9 NASA-GSFC, Greenbelt, MD. |
| 188 | The PEACH Model: Physiology, Exoclimatology, and Astroecology for Characterizing Habitability | A primary objective of the field of astrobiology is to identify worlds outside of our own that are capable of supporting life. Here, we apply an integrative approach between astrophysics, climate modeling, and ecophysiology to explore the relationship between alien environments and terrestrial life. I will discuss the development of a novel system that can be used as a tool to assess the habitable regions on exoplanet surfaces. In this model, simulated exoplanet environments are convolved with a real biological layer. Exoplanet environments are simulated using the climate model, Resolving Orbital and Climate Keys of Earth and Exoplanet Environments (ROCKE-3D, Way et. al. 2018). ROCKE-3D is a fully-coupled 3- dimensional oceanic-atmospheric general circulation model (GCM) featuring interactive atmospheric chemistry, aerosols, the carbon cycle, vegetation, and other tracers, as well as the standard ocean, sea ice, and land surface components. The GCM output is coupled in the astroecology model with empirically-derived thermal performance curves of 1,627 cell strains representing extremophiles from all six Kingdoms, termed the biokinetic spectrum for temperature (BKST, Corkrey et al. 2016). The BKST arises from a meta-analysis of cellular growth rate as a function of temperature. In this agent-based model, created with the software NetLogo, the survivability of a biological organism is determined by its thermal response to simulated local and global exoplanet temperature dynamics. This model can be applied to produce a list of exoplanets with the highest probability of having temperate surface conditions compatible | A. Ceja [1], S. Kane [1], M. Way [2];<br><br>1 Earth and Planetary Sciences, University of California, Riverside, Riverside, CA,<br>2 NASA Goddard Institute for Space Studies, New York, NY. |

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| | | with terrestrial-based thermophysiology, as well as surface maps highlighting potentially thermally habitable regions. Life, however, is dependent upon multiple variables including the presence of liquid water, nutrient content, and an energy source. Caveats of the methodology and application of our results are discussed with implications for extraterrestrial evolution and observable biosignatures. | |
| 189 | Towards New Frameworks for Identifying Statistical Laws in Elemental Use Across Ecosystems on Earth as Driven by Planetary Context | As the number of detected exoplanets grows exponentially, actively looking for signatures of life becomes increasingly possible. However, as the field advances, and we begin to get data about these planets' atmospheres, new approaches to understanding exoplanets and their observable properties are necessary to realize this goal due to the inherent limitations of noise and uncertainty in our data. Part of the challenge is that we do not understand the universal rules underlying how biospheres interact with geospheres across diverse planetary contexts. To develop such understanding will require new quantitative tools allowing us to study how the presence of a biosphere leads to detectable signals. Here we develop a new approach, leveraging big data available cataloging metagenomic diversity across Earth to uncover statistical patterns within biochemistry at the ecosystem scale. In some cases we have both metagenomes and detailed environmental data that provides context for understanding how biochemistry across varying ecosystems is shaped by planetary environments. In particular, we are interested in identifying multivariate, statistical regularities that might allow inferring properties of metabolisms on planetary surfaces, which are accessible to remote detection. For this, we investigate ecological elemental composition ratios (C, N, P) across biochemical networks constructed from the metagenomic data, including studying scaling laws associated with elemental use in biochemistry. We present results indicating molecular C:N:P ratios have a tight fixed ratio around 23C:3N:1P across ecosystem scale biochemical space, suggesting a universal property of elemental use in the molecules composing life. The goal is to build a quantitative framework for predicting ecosystem-level biochemistry within a given planetary context. | P. Vergeli [1], B. Karas [1], H. Hartnett [2], H. Kim [3], S. Walker [4];<br><br>1 School of Earth and Space Exploration, Arizona State University, Tempe, AZ,<br>2 School of Earth and Space Exploration, School of Molecular Sciences, Arizona State University, Tempe, AZ,<br>3 Beyond Center, Arizona State University, Tempe, AZ,<br>4 School of Earth and Space Exploration, Beyond Center, Arizona State University, Tempe, AZ. |
| 190 | The impact of stellar flares and superflares on life: first experiments to reveal the UV surface habitability of exoplanets | The increasing discovery of exoplanets in the last decades has boosted the search for life in the universe, and particularly the studies for the characterization of planetary habitability. Stellar radiation is one of the fundamental factors to be studied in this context, as it can have an influence on the planetary environment and can be a constraint for life through direct or indirect effects. Depending on the atmospheric composition and pressure, UV radiation wavelengths (200-400 nm) can reach the surface of the planets and could be harmful to life. Moreover, it is unknown if UV fluxes from very energetic events as flares and superflares could limit the surface habitability of a planet. Previous studies have analyzed the UV surface environments on exoplanets to study the impact of UV radiation on life, however, this has only been approached partially from a theoretical point of view (i.e. modeling of the biological impact of UV). In a recent interdisciplinary study, we experimentally determined through laboratory experiments and for the first time, the impact that flares and superflares could have on microorganisms. We found out that previous studies underestimated the chances of “life as we know it” to thrive under these conditions. In this talk, I will describe the drawbacks of methodologies used in previous studies, and I will present our latest results about the impact of flares and superflares on potential microbial life in exoplanets aimed to | X. Abrevaya [1,2], O.J. Oppezzo, P. Odert, M. Leitzinger, M. Patel, G.J.M. Luna, A.F. Forte Giacobone, A. Hanslmeier;<br><br>1 Instituto de Astronomía y Fisica del Espacio (IAFE), UBA - CONICET, Ciudad Autónoma de Buenos Aires, ARGENTINA,<br>2 Institutsbereich für Geophysik, Astrophysik und Meteorologie, Universität Graz, Graz, AUSTRIA. |

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| | | study UV surface habitability. These efforts are part of the EXO-UV program, an international interdisciplinary collaboration that seeks to expand the characterization of UV radiation environments through experimental approaches. | |
| 191 | Assessment of Isoprene as a Possible Biosignature Gas in Exoplanets with Anoxic Atmospheres | Research for possible biosignature gases on habitable exoplanet atmospheres is accelerating, with observations possible with next-generation telescopes. We explore isoprene, C_5H_ 8, as a biosignature gas, motivated by isoprene's substantial production rate on Earth (rivaling that of methane at ~ 500 Tg yr-1). Furthermore, because isoprene's geochemical formation is highly thermodynamically disfavored at temperate terrestrial planet conditions, isoprene has no known abiotic false positives. We model the photochemistry and spectroscopic detectability of isoprene in habitable temperature, rocky exoplanet anoxic atmospheres with a variety of atmosphere compositions under different host star UV fluxes. We focus on anoxic atmospheres because in Earth's oxygen-rich environment isoprene is rapidly destroyed by oxygen-containing radicals. We find that isoprene can only accumulate to detectable levels if it enters a "runaway" phase whereby the production rate surpasses the destruction rate, controlled by the flux of UV-destructive photons. In such a situation, isoprene would be detectable with 20 JWST transits for the most favorable exoplanet scenario, a super-Earth sized exoplanet transiting an M dwarf star with a H_2-dominated atmosphere. In this situation the simulated isoprene column-averaged mixing ratio is on order of 100 ppm, ~ 100 times Earth's average production rate (which does occur in niche environments on Earth). One caveat is that isoprene's 3 - 4 micron spectral feature is hard to distinguish from that of methane's. Despite the challenges, isoprene is worth adding to the menu of potential biosignature gases: isoprene production is ubiquitous to a diverse array of evolutionary distant organisms, from bacteria to plants and animals—few, if any volatile secondary metabolites have a larger evolutionary reach. | Z. Zhan [1], S. Seager [1,2], J. Petkowski [1], C. Sousa-Silva [1], S. Ranjan [1], J. Huang [3], W. Bains [1, 4];<br><br>1 Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA,<br>2 Department of Physics, Massachusetts Institute of Technology, Cambridge, MA,<br>3 Department of Chemistry, Massachusetts Institute of Technology, Cambridge, MA,<br>4 Rufus Scientific, Melbourn, UNITED KINGDOM. |
| 192 | Evaluating Methane as a Biosignature on Habitable Anoxic Planets Orbiting FGKM Stars | On terrestrial planets, the abundances of key trace gases such as methane CH_4 are controlled by photochemistry and source fluxes such as the rate of volcanic outgassing, water-rock reactions, or biological production. The interpretation of CH_4 as a biosignature is thus ultimately dependent on the production flux inferred from its abundance and the likelihood that this flux could be produced by geological sources alone. Prior work has shown that the buildup of CH_4 in the atmosphere at a given flux is highly favored for planets with oxygen-rich atmospheres orbiting K and M dwarfs, relative to Sun-like stars. However, relatively limited attention has been given to anoxic, Archean-like atmospheres and their flux-abundance relationships. We use a photochemical model to predict the atmospheric CH_4 mixing ratio as a function of its production rate for anoxic planets in the habitable zones of FGKM stars. We then compare the fluxes to those produced by primitive bacterial biospheres and geologic processes to evaluate what levels of CH_4 would suggest biological activity. We find that the flux-abundance relationships, photochemical destruction pathways, and ultimate detectability of CH_4 in anoxic exoplanets are highly dependent on the host star spectrum (FIGURE 1). For example, at low abundances CH_4 destruction by the OH radical dominates for anoxic planets orbiting all stellar types but is much less efficient for anoxic planets orbiting M dwarfs, which may challenge biosignature interpretations based on CO_2-CH_4 disequilibrium. In contrast, at high methane fluxes/abundances, direct photolysis of CH_4 is the | E. Schwieterman [1], C. Reinhard [2];<br><br>1 Earth and Planetary Sciences, University of California, Riverside, Riverside, CA,<br>2 Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA. |

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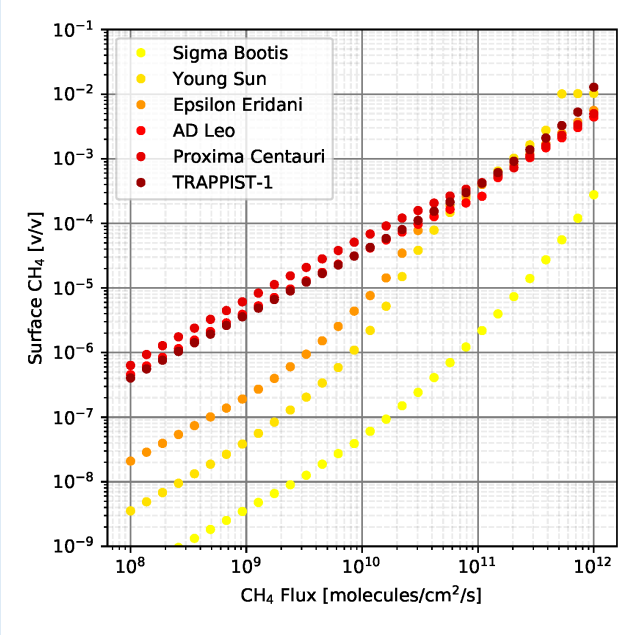
| | | dominant loss channel for MGK stars and at sufficiently high fluxes their flux-abundance relationship converges. The surface flux at which this convergence occurs is dependent on the distribution of NUV and FUV photons. We find that a biosphere similarly productive to that of Archean-Earth would likely produce similar methane mixing ratios on habitable anoxic planets with MGK stellar hosts (in contrast to oxygen-rich cases where the mixing ratios can be enhanced by a factor of ~1,000 when comparing an M dwarf host to a G dwarf host). For F dwarf stars, the dominant loss channel for methane is always OH, which would limit methane accumulation but also strongly reduces the potential for biosignature false positives. This research was supported by Exobiology grant 18-EXO18-0005.<br>  <br><br>Figure 1 - Surface CH_4 mixing ratios as a function of surface CH_4 fluxes (in molecules/cm2/s) for anoxic, Archean Earth-like planets placed in the habitable zones of FGKM stars. | |
| 194 | Spin-Orbit Variations, Greenhouse Gases, and Superhabitable Conditions on Terrestrial Worlds in Multi-Planet Systems | Heller and Armstrong (Astrobiology, 2014) describe a number of ways in which an Earth-like world ("Earth twins" with a tidal heat flux F_t less than 0.04 W/m2, and within their star's habitable zone) might be "superhabitable," with surface environments that are more amenable to life than the common benchmark of modern Earth. Over Earth history, several time periods are known from the geologic record that could meet these criteria, providing multiple opportunities to explore known superhabitable and inhabited planetary conditions from an astrophysical perspective.<br><br>Earth during the Mid-Cretaceous Period circa 100 million years ago satisfies several Heller and Armstrong (Astrobiology, 2014) superhabitability criteria, as applicable to Earth twins: 1) elevated CO_2 levels (Foster et al., Nature Commun. 2017; Huber et al., Global Planet. Change 2018; Lenton et al., Earth-Sci. Rev. 2018) providing enhanced climate warming that more than offset a slightly | L. Sohl [1,2], M. A. Chandler [1,2], M. Way [2];<br><br>1 Center for Climate Systems Research, Columbia University, New York, NY,<br>2 NASA Goddard Institute for Space Studies, New York, NY. |

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| | | reduced solar insolation (Gough, Solar Phys. 1981); 2) extensive coastal regions and interior seaways covered by shallow marine waters (Frisch et al., 2011); 3) reduced equator-to-pole temperature gradients (Upchurch et al., Phil. Trans. Royal. Soc. Lond. B 1998; Hunter et al., Palaeogeogr. Palaeoclim. Palaeoecol. 2013); and 4) atmospheric O_2 levels slightly greater than modern Earth (Lenton et al., Earth-Sci. Rev. 2018).<br><br>The Mid-Cretaceous is the archetypal stable planetary greenhouse environment, and was among the warmest, most extensively inhabited times on Earth since continents became emergent. Geologic evidence suggests that the warm temperatures were mainly a product of higher greenhouse gas levels compared to modern, with atmospheric CO2 estimates ranging from 750 to 3000 ppmv. Carbon dioxide was elevated in part due to increased volcanic activity and higher spreading rates at the Earth's mid-ocean ridge plate boundaries. The Cretaceous climate was one in which high latitudes were free of major ice sheets, and probably had a cryosphere that was seasonally limited, with some faunal evidence suggesting high latitude temperatures that were above freezing year-round.<br><br>A common problem with simulating superhabitable greenhouse states is that, although elevated CO_2 increases the global mean surface temperature, coupled GCMs do not generate meridional temperature gradients that are as shallow as geologic evidence suggests. There is irrefutable evidence that polar regions were extremely warm in the Cretaceous, while some paleoclimate proxies suggest that the tropics remained relatively cool. However, dynamic coupled models do not move sufficient heat poleward to both warm high latitudes and limit tropical temperatures to levels that don't exceed the tolerances of known complex life forms. If our GCM simulations are underestimating heat redistribution, then we are probably underestimating the amount of available habitat space on warmer worlds.<br><br>One climate forcing not yet explored in detail with GCMs for greenhouse worlds is high-frequency, low-amplitude spin-orbit variability ("Milankovitch cyclicity"). We know from Earth history that these relatively subtle variations, the product of Earth's orbital interactions with other planets of the Solar System, have proven sufficient to contribute to modulation of relatively warmer and colder climates during the most recent ice age (2.5 million years ago to present). We also know from the deep-time geologic record that this variability has left detectable signals in sedimentary and stable isotopic successions, implying a spin-orbit climatic influence beyond simply pushing the planet in and out of glacial states (Meyers and Malinverno, PNAS 2018; Olsen et al., PNAS 2019). Teasing out the contributions of spin-orbit variability to greenhouse climates may help round out our understanding of exogenous climate forcings, and close the gap between modeled and reconstructed climates. We may also be in a better position to ask similar questions about spin-orbit interactions and climate variability in other multi-planet systems. | |

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| | | ■ We have used ROCKE-3D to explore the Cretaceous superhabitable climate states by varying levels of atmospheric CO_2 from modern pre-industrial Earth levels (285 ppm = 1X) to 16X CO_2 and have successfully produced a range of warm climates that match aspects of the Cretaceous geologic record. With these simulations all exhibiting some climate features that are not supported by the geologic record (either cold poles or overheating tropics) the addition of reasonable spin-orbit states may resolve some mismatches, and will help us produce the most accurate simulations possible. Using Laskar et al. (A&A 2004, 2010) as a guide, we have reviewed the range of possible spin-orbit configurations for the interval between 105-95 million years ago, and used the estimated minimum and maximum values for obliquity (22.04 to 24.13 degrees) and eccentricity (0.00035 to 0.06453) to drive an additional series of simulations that combine both elevated CO_2 and spin-orbit variability. The results of these simulations will be presented at this meeting. | |
| 195 | A 1.5 Radiative-Convective Terrestrial Climate Model With Realistic Clouds | Microphysical and dynamic processes occurring within clouds significantly influence numerous large-scale dynamic, energetic, and chemical processes occurring within the atmospheres of nearly all Solar System planets. It is expected that these same atmospheric processes heavily influence the radiative energy balance of exoplanets. The most observationally relevant manifestation of this phenomenon is that clouds can inhibit the ability of remote sensing techniques to probe an underlying surface and/or the deep atmosphere. In past observations of the sub-Neptune GJ 1214 b, a high-level optically opaque cloud layer is painted as a hinderance in the characterization of its atmosphere (Helling 2020), whereas the presence of clouds in this atmosphere allude to fundamental atmospheric processes occurring at the macro- and micro-physical scales. Ultimately, as observational facilities and exoplanet data become more detailed, the sophistication of our understanding of fundamental exoplanetary atmospheric processes must also evolve. However, complex atmospheric modeling becomes expensive with increasing sophistication, suggesting it is pertinent to develop atmospheric models that are accurate but not too computationally expensive to utilize.<br><br>One-dimensional planetary atmosphere models offer a powerful and computationally efficient approach to exploring a broad range of planetary and atmospheric conditions. This characteristic of one-dimensional atmospheric models is used extensively in exploring the habitability of exoplanets in the form of the inner and outer edges of habitable zones (Kasting et al. 1993;<br><br>Kopparapu et al. 2013). Unfortunately, many such one-dimensional models lack a physical treatment of clouds. According to Shields et al. (2013), the influence of cloud condensates can strongly influence the habitability of terrestrial planets around red dwarf stars, and Kopparapu et al. (2013) suggest that exploring their effect on computed habitable zones around main sequence stars is critical in understanding the full extent of the habitable zone.<br><br>For example, instead of terrestrial planets succumbing to a runaway greenhouse on the inner edge of the habitable zone, clouds could scatter enough incoming radiation back into space to balance | J. Windsor, T. Robinson;<br><br>Department of Astronomy and Planetary Science, Northern Arizona University, Flagstaff, AZ. |

the energy in the atmosphere in a more temperate manner which could increase the likelihood of habitability (Shields et al. 2013). For planets at the outer edge of the habitable zone, fractional or total cloud coverage on their disk, in some cases, could have profound impacts on surface temperature and, thus, their potential habitability (Pierrehumbert et al. 2016).

Here, we improve and generalize a widely-used, one-dimensional planetary climate model to include a microphysical treatment of clouds and condensation properties. The CLIMA model (Kasting 1988;

Kopparapu et al. 2013) - which is one of the most commonly applied one-dimensional terrestrial atmospheric radiative-convective equilibrium models - lacks a realistic treatment of water vapor and carbon dioxide condensate clouds. To improve this model, and to broaden its range of applicability, we have incorporated a well-known one-dimensional cloud model (Ackerman and Marley 2001) via a two-column (clear versus clouded) treatment of the atmosphere (Marley et al. 2010).

The most well-known terrestrial planet whose climate heavily depends on the influence of clouds is Earth. Thus, we present a validation of our new climate tool against Earth. In past applications of the Kasting et al. (1993) and Kopparapu et al. (2013) climate model to Earth, the influence of clouds is hidden by tuning the albedo of the surface to a rather unphysical value (roughly 0.3). In order for our partially-cloudy climate model to reproduce an Earthlike temperature-pressure profile, the planetary surface albedo is adopted to a more realistic 10%, roughly corresponding to a realistic average surface albedo for Earth.

In light of the large diversity of known exoplanets, there is need to explore a wide range of planetary and atmospheric conditions. Using our newly-developed cloudy-clear climate model, we will investigate a range of insolations, surface gravities, atmospheric compositions, and cloud properties for rocky worlds. Each simulation can be executed in a matter of minutes, allowing the exploration of a wide range of atmospheric compositions that correspond to the myriad exoplanet examples in our universe.

In summary, clouds substantially impact the climate and atmospheric structure of worlds throughout our Solar System, from giant planets like Jupiter to smaller bodies such as Earth, Venus, Mars, and Titan. Furthermore, a critical feature of habitable planets, like our Earth, is that a substantial fraction of their visible disk is obscured by clouds. Thus, not only do aerosols play a key role in the radiative balance of nearly all Solar System planets, but clouds are also expected to significantly sculpt the spectral appearance of many (if not all) Earth-like exoplanets. Our novel one-dimensional terrestrial planetary atmospheric structure model, with its new treatment of clouds, is well-suited to broad explorations of exoplanetary climates.

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| 196 | Analyzing the metallicities of Hot Jupiters in orbit around low-metallicity Population I stars and potential theories regarding their origin and propagation | Hot Jupiters are large exoplanets similar to the size of Jupiter with relatively short periods of orbit around their star. Though it has been recognized as a common phenomenon that Hot Jupiters are found around high-metallicity stars, it has been proposed that this is simply due to the greater ease of discovering exoplanets orbiting those stars due to their stronger spectral lines, or due to the greater chance of core accretion of gas giants near more metallic stars. In those scenarios, it would be quite possible that a greater number of undiscovered Hot Jupiters exist orbiting around stars with lower metallicity. However, since there have not been any Hot Jupiters discovered around a Population II star to date, it is necessary to define some boundaries in regards to this exploration. Here we (1) determine the abundances of Hot Jupiters in orbit around low-metallicity Population I stars, and (2) analyze the relationship between metallicity of a host star and the mass of orbiting Hot Jupiters. For the purpose of this paper, we chose to specifically examine low-metallicity Population I stars (defined in our study as having stellar metallicities less than or equal to 0 dex compared to the Sun). We set the upper limit to 0 as it gives us an objective way to define low-metallicity Population I stars. To compile the data used for this analysis, we used the NASA Exoplanet Archive and placed filters on certain parameters to limit the scope specifically to exoplanets with periods between 1.3 and 111 days, inclusive and masses of 0.36 to 11.8 Jupiter masses, inclusive (essentially eliminating planets that did not fit the Hot Jupiter parameter), as well as the metallicity parameter, <= 0 for the Stellar metallicity. We find that prior results are supported in that the abundance of Hot Jupiters increases rapidly with increasing metallicity. However, a key finding of our study was that the mass of Hot Jupiters around a home star has a weak association or even a slightly negative correlation with increasing metallicity. This means that lower-metallicity stars may actually be able to sustain high-mass gas giants despite their lower ability to provide a more metallic planetary core for core accretion. The presence of Hot Jupiters around low-metallicity stars is a significant point of inquiry as the conventional perspective has been that high-metallicity stars help facilitate creation of metal-rich planetary cores, which aid in core accretion in gas giants. If these processes are still possible to a certain efficiency in satellites of low-metallicity stars, there may be potential alternate explanations for exoplanetary formation. Moreover, it is important to note that optimization of exoplanetary detection methods to prevent some of the discrepancies faced in regards to demographics of the home star of a Hot Jupiter. Future analyses with a greater sample set of exoplanets, once they are discovered, would likely bring fruitful results in pursuit of these objectives. | A. Kalra, R. Sriram, S. Sandadi;<br><br>Carmel High School, Carmel, IN. |

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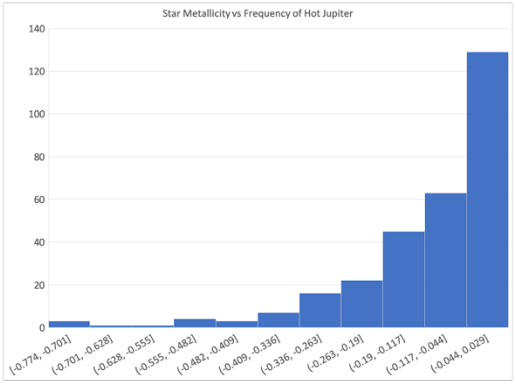
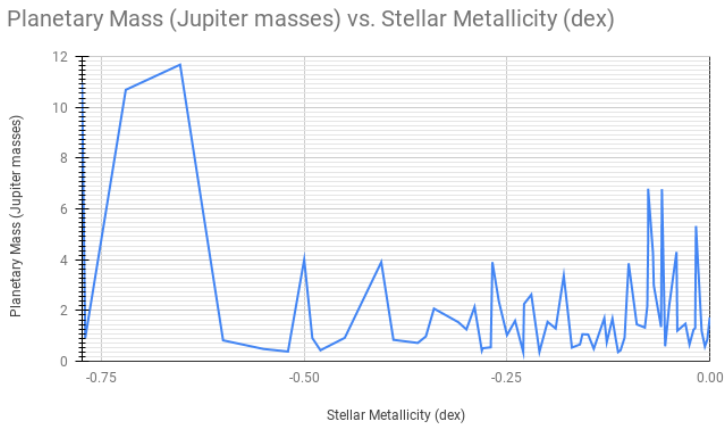
| | |  <br>  | |
| 198 | MAGRATHEA: Terrestrial Planet Interior Solver and the Degeneracy of Interiors | MAGRATHEA is a newly developed planet structure code for differentiated terrestrial planets. Our open source code supports spherically symmetric layers of iron, rock, ice/water, and ideal gas (with more options planned in future versions). MAGRATHEA integrates the hydrostatic equation to find the planet radius and pressure, density, temperature, and phase as a function of radius for a planet with the designated mass in each differentiated layer. Our code features a transparent structure for equations of state in each layer allowing for collaboration with high pressure physicists. The first version has over 30 experimentally and theoretically determined equations of state that the user may compare and choose between. The inferred densities of observed exoplanets allow for diverse compositions. Differentiated planets of three or more layers do not have a unique interior composition from observed mass and radius. With MAGRATHEA, we explore the likely interior structure of planets in planetary systems across a large parameter space. | D. Rice [1], C. Huang [2], J. Steffen [1];<br><br>1 University of Nevada, Las Vegas, Las Vegas, NV,<br>2 Lunar and Planetary Laboratory, The University of Arizona, Tucson, AZ. |
| 199 | The Coupled Role of Stellar Abundances, Exoplanet Radiogenic Heat Budgets and | A planet's heat budget is a combination of the retained heat of formation, the energy released due to the gravitational segregation of a Fe core and decay of the long-lived radionuclides U, Th and 40K. While secular cooling and the energy of core segregation are dependent on the formation history and magma ocean evolution, the amount of radiogenic heat a planet contains is solely a | C. Unterborn [1], B. Foley [2], S. Desch [1], P. Young [1]; |

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| | the Lifetime of Temperate Climates on Rocky Exoplanets | function of a planet's total amount of these elements. As refractory elements, U and Th are likely to exist in the same proportions relative to rock building elements in the planet as in the host-star. 40K is moderately volatile, and a planet's abundance is dependent on the degree of processing during planet formation. Recent observations of Solar twins show a range of stellar Th abundances between 60 and 250% of the Sun's (Unterborn et al., 2015), with similar ranges expected for U and bulk K. If this range of radionuclide compositions is indicative of the range of exoplanet radiogenic heat budgets, the thermal and chemical evolution of these planets may be quite different from the Earth.Here I present the results of recent coupled climate and convection models for 1-6 Earth mass stagnant lid planet with probabilistically determined radiogenic heat budgets constrained by observationally-determined abundances of U, Th and K. These models allow us to estimate the rates of surface volcanism, CO_2 degassing from the interior and surface weathering processes. These models allow us to more realistically examine the short-, medium- and long-term climatic effects of varying radionuclide abundance given the different half-lives of the individual elements. An important output of our models is the lifetime of degassing across our parameter space. Using these degassing lifetimes, I will show that the habitable zone planets TRAPPIST-1 e, f and g are likely too old to be actively degassing today without additional tidal heating as an additional source of heat or the planets undergoing plate tectonics. Additionally, I will present a sample of observed rocky exoplanets both young and massive enough to be likely degassing today, making them prime targets in our search for planets with temperate climates. These results show the importance of estimating the age of a planetary system when assessing its likelihood to harbor Earth-like and habitable exoplanets. | 1 Arizona State University, Tempe, AZ,<br>2 Penn State University, State College, PA. |
| 201 | High Orbital Obliquity Promotes Planetary Oxygenation | Next-generation telescopes such as the LUVOIR or HabEx concepts will soon be able to characterize distant exoplanets better than ever before. However, while these telescopes will primarily be limited to observations of exoplanet atmospheres, a planet's habitability potential relies on additional surface environment conditions as well. As potential habitats for life, the characteristics of a planet's ocean are particularly impactful on planetary habitability. Indeed, life on Earth spent the majority of its evolutionary history in the ocean. The majority of previous exo-ocean research has focused on ocean circulation and associated heat transport and oceans effect on habitability via climate. However, the effect of planetary properties on marine biogeochemical cycles and biological activity have not yet been fully explored. As a first step, we explore these relationships for differing orbital obliquities. We begin by using the ROCKE-3D general circulation model (GCM) to simulate atmosphere and ocean dynamics for varying orbital obliquity. We then use wind fields from those simulations as input data for the biogeochemical cycling software cGENIE in order to characterize the spatiotemporal patterns of nutrients and photosynthetic activity for each obliquity scenario. We additionally consider the effects of differing oceanic phosphate inventories and remineralization length scales for settling organic particulates.We find that export of particulate organic carbon (POC) and sea-to-air fluxes of oxygen (fO_2) increase with increasing obliquity in all model scenarios, given sufficient nutrient availability. We also find, similar to on Earth, that biological activity increases with increasing phosphate levels and increases with decreasing remineralization depth. We find that while nutrient inventory (in this case phosphate) has a first order control on | M. Barnett [1], S. Olson [2];<br><br>1 Department of Geophysical Sciences, University of Chicago, Chicago, IL,<br>2 Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, Lafayette, IN. |

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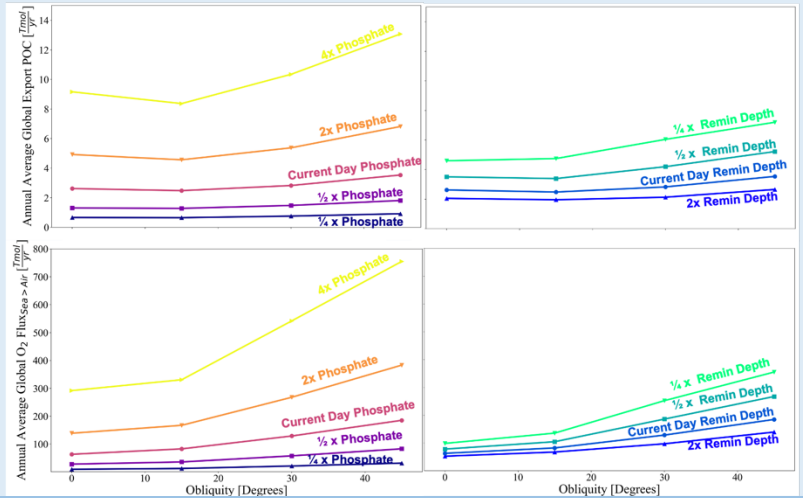
| | | biological activity and oxygen production, remineralization depth and obliquity also exhibit significant effects on both biological activity and oxygenation potential. These results suggest that life on planets with higher obliquity may be easier to detect without needing a larger biosphere. Additionally, our results imply that present-day Earth may not be the optimal environment for the evolution of complex life as it is sometimes considered.<br><br>Figure 1: Annual averages for global export particulate organic carbon (POC, panels a and b) and global oxygen sea-to-air flux (fO_2, panels c and d) for planet models with various obliquities (0, 15, 30, or 45 degrees), various phosphate inventories (1/4, ½, 1, 2, and 4x current Earth levels ), and various remineralization depths (1/4, ½, 1, and 2x current Earth levels). An increase in both export POC and fO_2 can be seen in both models with various phosphate inventories (panels a and c) and various remineralization depths (panels b and d) as obliquity increases.<br>  <br> | |
| 202 | Modeling X-ray and EUV driven Hydrodynamics Escape from Earth-like (magnetized and unmagnetized) Exoplanets with Exo-GITM. | The search for habitable exoplanets received new momentum with recent discoveries of tens of exoplanets in habitable zones around cool stars. Many of host stars are represented by active M dwarfs and young G and K dwarfs generating intense X-ray and Extreme UV (XUV) radiation fluxes from their quiescent coronae and intense and frequent flares. This suggests that many of rocky exoplanets are exposed to large fluxes (100-300) of stellar XUV radiation that are by a factor of 30-300 greater than that received by our planet today. The stellar XUV fluxes ionize and heat the upper atmospheres of exoplanets, driving significant atmospheric escape via hydrodynamic escape of both ions and neutrals. Here, we present the results of application of the One-Dimensional (1-D) Global Ionosphere Thermosphere Model (GITM) to an Earth-like planet exposed to 1,<br>10 and 60 times XUV fluxes of the current Earth. The results suggest the upper atmospheric mass loss is dominated by oxygen and nitrogen ion escape between XUV fluxes of 1-10 XUV_Earth, while the planetary atmosphere transitions to a hydrodynamic escape state at the XUV flux of ~60 XUV_Earth. We present the thermodynamic atmospheric parameters and total atmospheric escape rates for unmagnetized and magnetized Earth-like planets for parameter regimes relevant to the | J. Bell [1], S. Kang [2], W. Danchi [2], V. Airapetian [2,3], A. Glocer [4];<br><br>1 Ionosphere-Thermosphere Mesosphere Lab, Code 67 [5], NASA Goddard Spaceflight Center, Greenbelt, MD,<br>2 NASA Goddard Space Flight Center, Greenbelt, MD,<br>3 American University, Washington, DC,<br>4 NASA Goddard Spaceflight Center, Greenbelt, MD. |

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| | | ongoing search for spectral signatures of escape processes that could impact the atmospheric evolution of rocky planets and their potential habitability. | |
| 203 | Searching for biomarkers in the potentially habitable atmospheric zones of Y dwarfs | We report on an ongoing search for biomarkers in the potentially habitable atmospheres of a sample of a dozen Y dwarfs with Teff estimated at around or below 400 K. This work is being carried out using public data from large area optical surveys such as DES and PANStarrs. We focus on a search for g-band emission as an analogue to terrestrial bioluminiscence. The amount of bioluminiscent molecules in the photospheres of Y dwarfs is constrained by the optical to mid infrared colors. Future plans to extend this search using current telescopic facilities and upcoming surveys such as Euclid and Vera Rubin LSST are discussed. | E. Martin [1,2], J. Villafañe [3];<br><br>1 Instituto de Astrofísica de Canarias, San Cristóbal de La Laguna, SPAIN,<br>2 CSIC, Madrid, SPAIN,<br>3 Universidad de La Laguna, San Cristóbal de La Laguna, SPAIN. |
| 204 | Detection of Transiting Exoplanet Candidates at Austin College's Adams Observatory: Ground-Based Support for NASA's TESS Mission | NASA's Transiting Exoplanet Survey Satellite (TESS) monitors more than 200,000 stars in the search for transiting exoplanets. One of the primary goals of the TESS mission is to identify 50 planets smaller than four Earth radii with measured masses [1]. Because of the wide field of view and corresponding large pixel size of the TESS telescope, high precision ground-based observations are needed to confirm planetary transits and eliminate false positives [2]. The TESS Follow-up Observing Program Sub Group 1 (TFOP SG1) was developed to coordinate ground-based photometric follow-up observations [3].<br><br>The Adams Observatory at Austin College provides ground-based photometric support for the TESS project through TFOP SG1. Located on the roof of the IDEA Center science building, this facility houses the largest research telescope in north Texas and offers outstanding opportunities for research, education, and public outreach. In addition to TFOP, the Adams Observatory contributed to exoplanet transit observations as a member of the KELT Follow-Up Network [2]. The main telescope at the Adams Observatory is a 0.61-m f/8 DFM telescope of Ritchey-Chrétien design. When coupled with a Finger Lakes Instruments (FLI) Proline 16803 imager, this system produces a 26' x 26' field of view and a 0.38" pixel scale. Under optimal conditions, we can detect a minimum transit depth of ~3.0 ppt, which for an M-dwarf star would correspond to an exoplanet with radius ~3 Earth radii.<br><br>In summer 2020, we observed 11 stars identified by the TESS Science Team as potentially having exoplanets. Our high-precision follow-up observations offer three possible scenarios for these TESS targets: 1) a light curve from the target star indicating a possible transiting exoplanet,<br>2) a light curve from a nearby star indicating a nearby eclipsing binary (NEB) star system, and 3) flat light curves for both the target star and nearby stars. Of the 11 stars, four stars exhibit Case 1 behavior and have been verified as planetary candidates. An NEB has been detected near one target star (Case 2), and the star has been "retired" from TESS exoplanet studies. Six observations exhibit flat light curves (Case 3), which could indicate that either the planet is too small (and the corresponding dip in light too shallow) for detection at the Adams Observatory, or that the TESS | D. Baker, T. O'Dwyer, C. Schnaible, B. Skinner;<br><br>Physics Department, Austin College, Sherman, TX. |

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| | | observation is a false positive. These results may be useful for eliminating other possible causes of light curve variations in the search for small Earth-sized exoplanets.<br>References:<br>[1] Ricker G. R. et al. (2015), JATIS 1(1), 014003.<br>[2] Collins K. A. et al. (2018), AJ 156:234.<br>[3] Collins K. (2019), AAS Meeting, 2019AAS...23314005C. | |
| 205 | A Flare-Type IV Burst Event from Proxima Centauri and Implications for Space Weather | Studies of solar radio bursts play an important role in understanding the dynamics and acceleration processes behind solar space weather events, and the influence of solar magnetic activity on solar system planets. Similar low-frequency bursts detected from active M-dwarfs are expected to probe their space weather environments and therefore the habitability of their planetary companions. Active M-dwarfs produce frequent, powerful flares which, along with radio emission, reveal conditions within their atmospheres. However, to date, only one candidate solar-like coherent radio burst has been identified from these stars, preventing robust observational constraints on their space weather environment. During simultaneous optical and radio monitoring of the nearby dM5.5e star Proxima Centauri, we detected a bright, long-duration optical flare, accompanied by a series of intense, coherent radio bursts. These detections include the first example of an interferometrically detected coherent stellar radio burst temporally coincident with a flare, strongly indicating a causal relationship between these transient events. The polarization and temporal structure of the trailing long-duration burst enable us to identify it as a solar-like type IV burst. This represents the most compelling detection of a solar-like radio burst from another star to date. Solar type IV bursts are strongly associated with space weather events such as coronal mass ejections and solar energetic particle events, suggesting that stellar type IV bursts may be used as a tracer of stellar coronal mass ejections. In this talk, we discuss this event and its implications for the occurrence of coronal mass ejections from Proxima Cen and other active M-dwarfs. | A. Zic [1,2];<br><br>1 Department of Physics and Astronomy, Macquarie University, Sydney, AUSTRALIA,<br>2 CSIRO Astronomy and Space Science, Epping, AUSTRALIA. |
| 206 | Are Giant Planets Necessary for Habitability? | Because the Earthly life is the only type of life known to the mankind, it is logical to expect life-harboring planets to show similar characteristics as those of Earth. For instance, a habitable planet is expected to be rocky, and similar to Earth, to have formed through the collision of (rocky) protoplanetary bodies. As in our solar system, water is expected to have been delivered to the accretion zone of such an object by hydrated planetesimals and planetary embryos from regions beyond its orbit. Because in our solar system, Jupiter and Saturn formed much earlier than Earth, the above scenario has raised the question of whether giant planets are necessary for the delivery of water. By extension, some researcher have argued that the detection of a habitable extrasolar planet would be an indication of the existence of farther planetary bodies in their systems. To address this question, we have carried out a large number of simulations of terrestrial planet formation where we have studied the influence of the existence and absence of giant planets on the water content of the final bodies. Results demonstrate that while giant planets may affect the inventory of water-carrying objects, they play no role in the mechanics of the transfer and transport of water to rocky planets. Our simulations confirm that water delivery is in fact due to the mutual interactions of planetary embryos, a process that occurs even when no giant planet exists. We will present the results of our study and discuss their applications to extrasolar habitable planets. | N. Haghighipour, M. Andrews;<br><br>Univ. of Hawaii, Honolulu, HI. |

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| 207 | Deep Imaging of Nearby Habitable Zones with VISIR-NEAR and an Upgraded LBT | Direct imaging of exoplanets in the thermal infrared would add quantitative details on their temperatures, luminosities, albedos, and level of internal/additional heating, all of which factor into their potential habitability. The ESO/Breakthrough-sponsored New Earths in the Alpha Centauri Region (NEAR) program recently completed the first ultra-deep imaging campaign in the thermal infrared with the upgraded VISIR-NEAR instrument. In this talk, I will describe the NEAR campaign and the unprecedented sensitivity that it demonstrated for imaging rocky habitable-zone exoplanets. I will also discuss on-going efforts to upgrade the mid-infrared capabilities of the LBT based on the lessons from NEAR, which would enable coordinated deep explorations for low-mass habitable-zone planets in both the Northern and Southern skies. Finally, I will discuss expectations for a NEAR-like instrument on an ELT, which could potentially enable imaging Earth-like planets in the habitable zones of nearby stars. | K. Wagner;<br><br>University of Arizona, Tucson, AZ. |
| 208 | The Phosphorus-Potassium Abundance Telescope | Phosphorus and potassium are essential elements for understanding planetary habitability. Phosphorus is a key element in biological molecules involved in metabolism and RNA and DNA, but its low abundance in Earth's crust makes it a limiting nutrient in terrestrial ecosystems. The radioactive isotope 40K is the dominant heat source in planetary interiors for the first 1-2 gigayears and important thereafter. Interior heating is necessary for degassing, building an atmosphere, and maintaining a stable climate. Despite their importance, there are very few stars with measured abundances of K and P due to difficulties in observing them from the ground. We propose a CubeSat with a moderately high resolution (R=25,000) near-infrared (0.9-1.6 micron) spectrograph that will obtain precision abundances for P, K, and ancillary elements for 1000 bright, sun-like FGK main sequence stars. This represents an order of magnitude increase in the number of stars with P measurements and enables a robust statistical understanding of the habitability of the solar neighborhood from the perspective of these elements. | P. Young [1], H. E. Hartnett [1], N. R. Hinkel [2], P. Scowen [1];<br><br>1 School of Earth and Space Exploration, Arizona State University, Tempe, AZ,<br>2 Southwest Research Institute, San Antonio, TX. |
| 209 | External Photoevaporation of Protoplanetary Disks in Strong and Intermediate UV Environments | Does external radiation environment of stellar nurseries affect protoplanetary disk properties and evolution? Protoplanetary disks are sites of planet formation, and the properties of disks and their dispersal could be strongly influenced by external UV radiation. Recent studies suggest that external photoevaporation dominates disk dispersal process over encounters in young clusters, e,g., in Orion nebula cluster. In a strong UV environment, such as in the Trapezium in Orion, the protoplanetary disks in an immediate vicinity of a massive O6V star are found strongly affected photoevaporating away from the ionizing source. Protoplanetary disks near the O6 star show lower mass and smaller disk sizes compared to the disks in weaker UV environments. We present our discoveries of photoevaporating protoplanetary disks (proplyds) in a 1-2 Myr old NGC 1977 in an intermediate UV environment around B1V star, and more new discoveries of proplyds in younger NGC 2024 near a B0.5V and around O8V+B1 stars. The proplyds found in NGC 2024 are younger than those in NGC 1977 (ages 0.2-0.5 Myr), which imply that even at such young age, planet formation may have already been affected by external photoevaporation. These proplyds were discovered from archival data of the Hubble Space Telescope and Spitzer, and we also use ground-based data including published ALMA results for our analysis. We compare properties of these proplyds and disks in these regions to those in strong and weak radiation environments. This study is part of our NExSS program, Earth in Solar System (EOS, PI Apai). | J. Kim;<br><br>Astronomy, Arizona, University of, Tucson, AZ. |

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| 210 | Chemical Fingerprints of Formation in Rocky Super-Earths' Data | The composition of rocky exoplanets in the context of stars' composition provides important constraints to formation theories. In this study, we select a sample of exoplanets with mass and radius measurements with an uncertainty <25% and obtain their interior structure. We calculate compositional markers, ratios of iron to magnesium and silicon, as well as core-mass fractions (cmf) that fit the planetary parameters, and compare them to the stars'. We find four key results that successful planet formation theories need to predict: (1) In a population sense, the composition of rocky planets spans a wider range than stars. The stars' Fe/Si distribution is close to a Gaussian distribution 1.63 ±0.9, while the planets' distribution peaks at lower values and has a longer tail, 1.15 (+1.4/-0.8). It is easier to see the discrepancy in cmf space, where primordial stellar composition is 0.32 ±0.13, while rocky planets' follow a broader distribution 0.24 (+0.33/-0.18). (2) We introduce uncompressed density ($\rho_0$) at reference pressure/temperature) as a metric to compare compositions. With this, we find what seems to be the maximum iron enrichment that rocky planets attain during formation ($\rho_0$ ~6 and cmf ~0.8. (3) Highly irradiated planets exhibit a large range of compositions. If these planets are the result of atmospheric evaporation, iron enrichment and perhaps depletion must happen before gas dispersal. And (4), we identify a group of highly-irradiated planets that, if rocky, would be 2-fold depleted in Fe/Si with respect to the stars. Without a reliable theory for forming iron-depleted planets, these are interesting targets for follow up. | M. Plotnykov [1], D. Valencia [2]<br><br>1 Physics, University of Toronto, Toronto, ON, CANADA,<br>2 Astronomy and Astrophysics, University of Toronto, Toronto, ON, CANADA. |
| 211 | There's more to life than $O_2$: Simulating the detectability of a range of molecules for ground-based high-resolution spectroscopy of transiting terrestrial exoplanets | In the near future, we will be able to search for life on transiting terrestrial exoplanets using extremely large ground-based telescopes (ELTs). Their ability to access the visible and near infrared wavelengths, where the $O_2$ bands are prominent, will complement the James Webb Space Telescope's strength in longer wavelength molecule detection. Ground-based telescopes capable of high-resolution spectroscopy are crucial for detecting $O_2$, but using them to detect other environmental molecules or alternative biosignatures has not been fully explored. Although $O_2$ is the most readily detectable biosignature on an Earth-like world for high-resolution observations, it must always be interpreted in the context of its planetary environment due to the possibility of abiotic generation. This context may include the presence of other molecules that can point to a habitable environment, or that can strengthen its interpretation as being more likely to be produced by life. To better understand the accessibility of environmental context using ground-based telescopes, we simulated high-resolution observations of Archean and pre-industrial Earth atmospheres transiting a range of M-dwarf hosts, ensuring photochemical consistency with each host star's spectral type. These simulations included explicit treatment of telescope, instrument, detector, and telluric effects to model realistic signal-to-noise values in high-resolution spectra. Using the cross-correlation technique, we then determined the detectability of $O_2$, $O_3$, $CH_4$, $CO_2$, CO, and $H_2O$ in these atmospheres. We match the near-infrared $O_2$ detectability calculations of previous studies, and show that $CH_4$ and $CO_2$ are potentially accessible for very nearby systems. However, for an Earth-like atmosphere in the TRAPPIST-1 system, we were unable to detect $CH_4$ and $CO_2$ above a three-sigma level within a reasonable number of transits. Molecule detectability is broadly dependent on spectral type, but could also be strongly influenced by other host star properties such as luminosity and size. Our study demonstrates that the | M. Currie, V. Meadows ;<br><br>Astronomy and Astrobiology, University of Washington, Seattle, WA. |

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| | | upcoming ELTs may play a major role in terrestrial exoplanet characterization beyond O_2 detection, and our results can inform molecule and target prioritization for observers in the near future. | |
| 212 | Flaring effects form a M dwarf in a prebiotic Earth-like planet | In this work we modified a photochemical model (ATMOS) to study both the effects of a flare and a succession of flares emitted by a M-dwarf on the atmosphere of a prebiotic Earth-like planet. We sought to determine if interaction between star and planetary atmosphere could arouse a false positive while using O2 and O3 as biosignatures in search of life outside the Solar System. For this reason, we have created a control layer on top to handle model's input (atmosphere, stellar flux, time) during the flare event. Allowing us to see the consequences of increased stellar flux on an Earth-like planet at an equivalent au form it's host star (AD Leonis). | A. Miranda [1], A. Segura [1], E. W. Schwieterman [2];<br><br>1 ICN, UNAM, CDMX, MEXICO,<br>2 Department of Earth and Planetary Sciences, University of California, Riverside, CA. |
| 213 | Missing evidence for giant impacts during terrestrial planet formation | According to the standard theory of terrestrial planet formation, the giant impact era extends over tens of millions of years and encompasses dozens of impacts between planetary embryos ranging in size from Earth's Moon to potentially two half-Earth bodies. These collisions are expected to occur at or exceeding escape velocity and create enormous quantities of ejected planetary debris. Due to the strong scattering present in the planet-forming terrestrial disk, this debris is scattered onto stable orbits in what is now the main asteroid belt.<br><br>Using a large suite of terrestrial planet formation N-body simulations modified so that modeled giant impacts generate ejecta according to scaling laws developed from impact simulations (Leinhardt & Stewart,<br>2011), we estimate the efficiency of this giant-impact-ejecta-to-asteroid-belt process. We find that on average about a percent of all planetary ejecta ends up in the asteroid belt. In a typical "Grand Tack" terrestrial planet formation simulation this translates to nearly an entire modern asteroid belt's mass of material. This is entirely inconsisent with the understanding that most of the modern asteroid belt is related to primitive chondritic like material with only a small fraction <5% (excluding Vesta) related to possibly differentiated inner solar system material.<br><br>In order to be consistent with the record of debris in the asteroid belt, planet formation must have either been significantly less violent--consistent with a pebble accretion model for planet formation--or debris much more friable or even non-existent, if it were mostly vapor, for instance. The pebble accretion model for planet formation is the pre-dominant mechanism for the formation of the giant planets and consistent with the formation of super-Earth planets as well. It seems that it could also be the primary growth mechanism for even small worlds. Regardless, we have shown the main asteroid belt is a Lagerstätten of the solar system containing leftover planetary debris from the era of planet formation. | S. Jacobson [1], C. Sandine [2];<br><br>1 Earth and Environmental Sciences, Michigan State University, East Lansing, MI,<br>2 Geophysical Sciences, University of Chicago, Chicago, IL. |
| 214 | To Cool is to Keep: Residual H/He Atmospheres of | Current theory predicts that observed rocky super-Earths accreted large nebular hydrogen/helium envelopes before disk dispersal. These atmospheres have since been mostly lost through hydrodynamic outflows. Such super-Earth atmospheres may soon be observable, but their mass, | W. Misener, H. Schlichting;<br><br>UCLA, Los Angeles, CA. |

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| | Super-Earths and sub-Neptunes | composition, and redox state resulting from their evolution are largely unexplored, despite these processes' potential impact on habitability. I will present the observable outcomes of the evolution of super-Earths from their initial states since disk dispersal. Using theoretical models, I will demonstrate that loss of the primordial atmosphere can be incomplete, leading to a thin residual H/He envelope. The masses of these remnant atmospheres vary by orders of magnitude depending on the planet's mass and the flux it receives from its host star. Super-Earths finish mass loss with atmospheric masses ranging from 10^-9 to 10^-2 planet masses for typical parameters. I will discuss the implications of this residual hydrogen for subsequent secondary atmospheres, including their masses, composition, and observational signatures. | |
| 215 | To Cool is to Keep: Residual H/He Atmospheres of Super-Earths and sub-Neptunes | Current theory predicts that observed rocky super-Earths accreted large nebular hydrogen/helium envelopes before disk dispersal. These atmospheres have since been mostly lost through hydrodynamic outflows. Such super-Earth atmospheres may soon be observable, but their mass, composition, and redox state resulting from their evolution are largely unexplored, despite these processes' potential impact on habitability. I will present the observable outcomes of the evolution of super-Earths from their initial states since disk dispersal. Using theoretical models, I will demonstrate that loss of the primordial atmosphere can be incomplete, leading to a thin residual H/He envelope. The masses of these remnant atmospheres vary by orders of magnitude depending on the planet's mass and the flux it receives from its host star. Super-Earths finish mass loss with atmospheric masses ranging from 10^-9 to 10^-2 planet masses for typical parameters. I will discuss the implications of this residual hydrogen for subsequent secondary atmospheres, including their masses, composition, and observational signatures. | W. Misener, H. Schlichting;<br><br>UCLA, Los Angeles, CA. |
| 216 | Multi-broadband Transit Photometry at Wyoming Infrared Observatory | Optical transmission spectra of transiting exoplanets are excellent probes of detecting scattering in atmospheres of giant planets. Different sources of scattering, such as Rayleigh scattering, can imprint distinctive features in the spectra and provide constraints on the presence of clouds or hazes. Throughout summer 2020 we observed planetary transits using the 2.3m Wyoming Infrared Observatory. With an ensemble of 4 Sloan ugri filters across multiple transit events, we have created ultra-low resolution transmission spectra. We present preliminary, high cadence, multi-broadband transit photometry of HAT-P-7b, HAT-P-14b, HAT-P-41b, HD 189733b, KELT-9b, KELT-23Ab, KOI-13b and WASP-48b. Various analysis were performed with Markov-Chain Monte Carlo (MCMC) and Gaussian processes to infer the planets radius and characterize the atmosphere. Our analysis can also be used to improve periods and mid-transit times and to search for transit timing variations that may indicate the presence of other planets. | C. Gardner [1], H. Kobulnicky [1], H. Jang-Condell [1], D. Kasper [2], D. Galloway [1], B. Parker [1], E. Cook [1], A. Piccone [1], M. Lyon [1], M. Lindman [1];<br><br>1 Physics and Astronomy, University of Wyoming, Laramie, WY,<br>2 University of Chicago, Chicago, IL. |
| 217 | Modeling Ionizing Radiation Outputs from Planet Hosts: Coronal X-ray/EUV and Wind Mass Fluxes of k1 Ceti | Recent observational studies of rocky exoplanets with Kepler and TESS missions suggest that many rocky exoplanets are detected in the habitable zone around magnetically active solar-like stars. These stars are efficient generators of ionizing radiation in the form of X-ray and Extreme UV (EUV) flux (collectively known as XUV), wind mass loss and eruptive events. While these outputs are the critical factors affecting the planetary atmospheres via initiation of atmospheric erosion and their impact on atmospheric chemistry, they are poorly known. Here, we present the results of data driven three-dimensional magnetohydrodynamic modeling of the global corona of a young (650 | V. Airapetian [1], M. Jin [2], T. Lueftinger [3], S. Boro Saikia [4], O. Kochukhov [5], B. van der Holst [6];<br><br>1 Code 67 [1], American University and |

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| | | Myr) solar-like star, k1 Ceti, using observational data inputs at two epochs separated by 11 months. Over the course of 11 months, the global corona had undergone drastic transition from a simple dipole to a tilted multipole global magnetic field, which provides favorable conditions for formation of Co-rotating Interaction Regions (CIRs) and associated strong shocks, the source of energetic protons and the impact of their dynamic pressure on exoplanetary magnetospheres. The modeled XUV and wind fluxes provide the framework for evaluating their impact on atmospheric loss from the early terrestrial exoplanets that will be tested in the upcoming multi-observatory multi-epoch observations of evolving young solar-like stars. | NASA/GSFC/SEEC, Greenbelt, MD,<br>2 Code 67 [1], SETI, Mountain View, CA,<br>3 University of Vienna, Vienna, AUSTRIA,<br>4 Astronomy, University of Vienna, Vienna, AUSTRIA,<br>5 Astronomy, Upsalla University, Upsalla, SWEDEN,<br>6 Climate and Space Sciences and Engineering, University of Michigan, Ann Harbor, MI. |
| 218 | An Initial Exploration of the 3-D Structure of Terrestrial-like Exoplanetary Atmospheres Orbiting Around Different Parent Star Types | In recent years, many different types of exoplanets have been discovered and understanding the conditions and chemical cycles present on these diverse worlds will be enable by the spectroscopic characterization their atmosphere. Terrestrial-like exoplanets can contain many chemical species, yet only a few have the distinct spectral features and atmospheric abundance to be detectable, viz., CO_2, CO, CH_4, H_2O, O_2, and O_3. O_2 and O_3 can be produced abiotically by photolysis of CO_2 and biotically in the presence of life. Around Sun-like stars, CO_2 photolysis by FUV radiation is balanced by recombination reactions dependent on water abundance. Planets orbiting stars with more FUV radiation could be depleted in water due to prolonged high FUV exposure. For these exoplanets, a catalytic cycle relying on H_2O_2 photolysis can maintain a CO_2 atmosphere. This cycle breaks down for low atmospheric hydrogen mixing ratios, causing a significant fraction of the atmospheric CO_2 being converted to CO and O_2 on timescale of about1 Myr (Gao et al., 2015), especially on planets in the habitable zones of K- and M- type stars. The abundances of other species are determined by planetary atmospheric conditions during formation and subsequent evolution. This evolution is largely dependent upon the FUV-NUV radiation ratio from the parent star, the balance of CO_2 photolysis with recombination water abundance dependent reactions, and various catalytic chemical cycles characterized via atmospheric composition, dynamics, energetics, and chemical behavior. The 1-D photochemical models previously used to understand these processes are inconsistent, producing conflicting results under similar circumstances arising from their limited capabilities. We estimate conditions for the state and evolution of terrestrial-type exoplanets orbiting around GJ-436 with varying star/planet distances to determine abundances for key observable species by considering the effects of 3-dimensional GCM heating/cooling, dynamics, and HO_x and ClO_x photochemistry and catalytic cycles. Specifically, we: 1. Characterize terrestrial-like exoplanet dayside heating budgets of EUV heating/CO_2 15-µm cooling in a 3-D GCM model allowing a self-consistent quantification of the associated photochemistry and climatological upper atmospheric circulation using existing validated published models for planets with terrestrial-type atmospheres GJ-436. 2. Assess the influence of HO_x and ClO_x, photochemistry and catalytic | C. Parkinson [1], S. W. Bougher [2] F. P. Mills [1], Y. L. Yung [3], A. S. Brecht [4];<br><br>1 Space Science Institute, Boulder, CO,<br>2 CLaSP, University of Michigan, Ann Arbor, MI,<br>3 GPS, California Institute of Technology, Pasadena, CA,<br>4 NASA AMES Research Center, Moffet Field, Mountainview, CA. |

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| | | cycles, heating/cooling in 3-D GCM modeling to the determine distribution of key species abundances for terrestrial-type planetary atmospheres. | |
| 220 | Earth-like: How Orbital Parameters Drive Detectable Atmospheric Chemistry and Aerosol Changes | With the growing list of confirmed extrasolar planets, discovering and ultimately characterizing an Earth-twin seems to be just around the corner. But observational and theoretical work studying these planets also tell us that a rocky planet with Earth's mass and radius may have a fundamentally different rotation rate, eccentricity, and/or obliquity (e.g., Barnes, 2017; Dietrick et al., 2018; He et al., 2020). Even Earth's own history includes smaller-scale variations in day length (e.g., Williams, 2000) and climatically-significant changes in obliquity and eccentricity that form the Milankovitch cycles (e.g., Imbrie et al., 1992). For departures from generally Earth-like parameters, a number of studies have demonstrated the complex (and often substantial) role that orbital parameters play in driving atmospheric dynamics and climatology (e.g., Dressing et al., 2010; Haqq-Misra et al., 2018; Colose et al., 2019).<br><br>Because of the radiative properties of key atmospheric constituents, it is critical that explorations of the chemistry and climate of Earth-like planet atmospheres be addressed simultaneously. Here, we highlight some of the ways that photochemical and aerosol processes respond to not only the direct effects of non-terrestrial orbital forcings, but also to the associated climatological conditions that result from those same forcings. To do so, we employ ROCKE-3D (Way et al., 2017), a 3-D general circulation model that has developed from (and now in parallel with) ModelE2 (a modern Earth GCM; Kelley et al., 2020). This allows us to leverage an extensive history of Earth science validations in building an Earth-like (if not necessarily precisely like Earth) ensemble.<br><br>Preliminary tests show that there are potentially detectable differences between scenarios with and without chemical, aerosol, and climate interactions, and that interactively simulating the chemistry exaggerates seasonal signals in the integrated planetary spectrum. Particularly in the context of Earth's biologically-mediated seasonal composition changes (e.g., Olson et al., 2018), these photochemically-driven seasonality signals make a better understanding of the connections between orbital parameters and atmospheric state an essential step towards reliably interpreting observations of terrestrial exoplanets. They also form a bridge connecting ground truth and the nearer-term goals of characterizing rocky planets around smaller stars, which has been the focus of recent work (e.g., Chen et al., 2020).<br><br>References: Chen, H., Wolf, E.T., Zhan, Z. and Horton, D.E., 2019. Habitability and Spectroscopic Observability of Warm M-dwarf Exoplanets Evaluated with a 3D Chemistry-Climate Model. The Astrophysical Journal, 886(1), p.16.<br>Colose, C.M., Del Genio, A.D. and Way, M.J., 2019. Enhanced habitability on high obliquity bodies near the outer edge of the habitable zone of Sun-like stars. The Astrophysical Journal, 884(2), p.138.<br>Dressing, C.D., Spiegel, D.S., Scharf, C.A., Menou, K. and Raymond, S.N., 2010. Habitable climates: the influence of eccentricity. The Astrophysical Journal, 721(2), p.1295. | S. Harman [1], K. Tsigaridis [2,3], E. Schwieterman [4], R. K. Kopparapu [5], S. Guzewich [5];<br><br>1 NASA Ames Research Center, Mountain View, CA,<br>2 NASA Goddard Institute for Space Studies, New York, NY,<br>3 Columbia University, New York, NY,<br>4 University of California - Riverside, Riverside, CA,<br>5 NASA Goddard Space Flight Center, Greenbelt, MD. |

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| | | Haqq-Misra, J., Wolf, E.T., Joshi, M., Zhang, X. and Kopparapu, R.K., 2018. Demarcating circulation regimes of synchronously rotating terrestrial planets within the habitable zone. The Astrophysical Journal, 852(2), p.67.<br>He, M.Y., Ford, E.B., Ragozzine, D. and Carrera, D., 2020. Architectures of Exoplanetary Systems. III. Eccentricity and Mutual Inclination Distributions of AMD-stable Planetary Systems. The Astronomical Journal, 160(6), p.276.<br>Imbrie, J., Boyle, E.A., Clemens, S.C., Duffy, A., Howard, W.R., Kukla, G., Kutzbach, J., Martinson, D.G., McIntyre, A., Mix, A.C. and Molfino, B., 1992. On the structure and origin of major glaciation cycles 1. Linear responses to Milankovitch forcing. Paleoceanography, 7(6), pp.701-738.<br>Kelley, M., Schmidt, G.A., Nazarenko, L.S., Bauer, S.E., Ruedy, R., Russell, G.L., Ackerman, A.S., Aleinov, I., Bauer, M., Bleck, R. and Canuto, V., 2020. GISS-E2. 1: Configurations and climatology. Journal of Advances in Modeling Earth Systems, 12(8), p.e2019MS002025.<br>Olson, S.L., Schwieterman, E.W., Reinhard, C.T., Ridgwell, A., Kane, S.R., Meadows, V.S. and Lyons, T.W., 2018. Atmospheric seasonality as an exoplanet biosignature. The Astrophysical Journal Letters, 858(2), p.L14.<br>Way, M.J., Aleinov, I., Amundsen, D.S., Chandler, M.A., Clune, T.L., Del Genio, A.D., Fujii, Y., Kelley, M., Kiang, N.Y., Sohl, L. and Tsigaridis, K., 2017. Resolving orbital and climate keys of earth and extraterrestrial environments with dynamics (ROCKE-3D) 1.0: a general circulation model for simulating the climates of rocky planets. The Astrophysical Journal Supplement Series, 231(1), p.12.<br>Williams, G.E., 2000. Geological constraints on the Precambrian history of Earth's rotation and the Moon's orbit. Reviews of Geophysics, 38(1), pp.37-59. | |
| 221 | The thermal field of “Los Azufres” as analog for the search of life on other planets | Geothermal fields harbor environments with conditions resembling primitive Earth and have been proposed as sites where the first life forms might have emerged. Mexico contains many thermal areas as it is crossed from west to east by the Trans-Mexican Volcanic Belt. In particular, the geothermal field of Los Azufres is located in Western Mexico and contains several hot springs, fumaroles, acid lakes, and solfatara fields with unique microbial ecosystems. We propose that the geothermal field of Los Azufres as a good analog for the development of methodologies for the search of past or present life in other places from the solar system and beyond. Our microbiomic studies of thermal sites within Los Azufres have allowed the finding of microorganisms belonging to all domains of life as well as viruses. By sequencing and analyzing metagenomes we were able to recover metagenome assembled genomes for Sulfolobales, Thermoplasmatales, and Micrarchaeota populations, including ‘Candidatus Aramenus sulfurataquae’, ‘Candidatus Cuniculiplasma sp. AZ01’, and ‘Candidatus Micrarchaeum sp. AZ1’. Also, genome sequences were obtained for archaeal viruses that allowed the definition of their core genes. In addition, we were able to detect Proteobacteria, Actinobacteria, Firmicutes, and Nitrospirae as dominant bacterial phyla in several hot springs. In particular, the genome of Acidocella sp. MX-AZ02 was obtained from and acid lake with high levels of heavy metals, and the genomes of Acidibrevibacterium and Aciditerrimonas populations were recovered from fumaroles. Finally microalgal populations related to green and red algae have been detected by metagenomic sequencing Genomic analyses allowed the study of the genetic potential of these microorganisms and we propose that they play a relevant role in biochemical cycles at Los Azufres. Functional studies revealed adaptations for stress response, such as: heat shock, oxidative stress, osmotic shock, and heavy metal resistance. In consequence, we consider that the microbial and viral communities found at Los Azufres may help us better | H. Bolivar-Torres, R. Marín-Paredes, L. E. Servín-Garcidueñas;<br><br>Universidad Nacional Autonoma de Mexico, Morelia, MEXICO. |

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| | | understand the origin of life on Earth, provide clues about the interactions between organisms, and describe the radiation of different ways to obtain energy and resources for life. Besides, data related with our research could provide the first steps toward developing biosignatures and building models for exploring similar environments in other worlds, e.g the ancient fumaroles recently found on Mars, and similar environments in Jovian satellites or exoplanets. | |
| 222 | Nitrogen Fixation at Early Mars | The Mars Science Laboratory (MSL) recently discovered nitrates near Gale Crater (eg., Stern et al., 2015; Sutter et al., 2017). One possible mechanism for ancient nitrate deposition at Mars is through HNOx formation and rain-out in the atmosphere, for which lightning-induced NO is likely the fundamental source. This study investigates nitrogen fixation in early Mars' atmosphere, with implications for early Mars' habitability. We consider a 1 bar atmosphere of background composition CO_2 with abundances of N_2, H_2, and CH_4 varied from 1-10% to explore a swath of potential early Mars climates. We derive lightning-induced thermochemical equilibrium fluxes of NO and HCN by coupling the lightning-rate parametrization of Romps et al. (2014) with Chemical Equilibrium with Applications, and we use a Geant4 simulation platform to estimate the effect of solar energetic particle (SEP) events. These fluxes are used as input into KINETICS, the Caltech/JPL coupled photochemistry and transport code, which models the chemistry of 50 species linked by 495 reactions to derive rain-out fluxes of HNOx and HCN. We compute equilibrium concentrations of cyanide and nitrate in a putative northern ocean at early Mars, assuming hydrothermal vent circulation and photoreduction act as the dominant loss mechanisms. We find oceanic concentrations of ~0.1-3 nM nitrate and ~0.1-10 𝝁;M cyanide. HCN is critical for protein synthesis at concentrations > 0.01 M (eg., Holm and Neubeck, 2009), and our result is astrobiologically relevant if secondary local concentration mechanisms occurred. Nitrates may act as high potential electron acceptors for early metabolisms, though the minimum concentration required is unknown. Our work derives concentrations that will be useful for future laboratory studies to investigate the habitability atearly Mars. Importantly, the aqueous nitrate concentrations correspond to surface nitrate precipitates of ~1-8 x 10-4 weight percent that may have formed after the evaporation of surface waters, and these values roughly agree with the lower boundary of recent MSL measurements. | D. Adams [1], Y. Luo [2], M. Wong [3], P. Dunn [4], C. Dong [5], R. Hu [6], Y. Yung [2];<br><br>1 California Institute of Technology, Pasaadena, CA,<br>2 California Institute of Technology, Pasadena, CA,<br>3 University of Washington, Seattle, CA,<br>4 UC Berkeley, Space Sciences Laboratory, Berkeley, CA,<br>5 Princeton University, Princeton, NJ,<br>6 JPL, Pasadena, CA. |
| 223 | Antipodal Anticorrelations: Consequences of Tectonic Activity on Topography and Implications for Surface Mapping | Earth's surface topography counts very few points on land antipodal to other points on land. Moreover, this "antipodal anticorrelation" has been a feature of the globe at least since the break-up of Pangaea. We quantify this by calculating topographical power spectra, and present evidence that anticorrelation is preferred and maintained by the motions of plate tectonics. That is, mantle convection, as supported through our parallel analysis of plate velocities, appears to inhibit erasure of anticorrelation on the time scales of supercontinent break-up and re-formation. This hypothesis gains support from published work that links the plate structure and size distribution to the dynamics of mantle convection and its influence on the lithosphere, and shows preferences for a specific parity in surface harmonic structure. We corroborate this with our own fully-3D models of mantle convection. | A. Adams [1], G. Laughlin [2];<br><br>1 Astronomy, University of Michigan, Ann Arbor, MI,<br>2 Astronomy, Yale University, New Haven, CT. |

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| | | Combining these spectral analyses with a simple model of erosion and volcanism, we are also able to estimate -- if Venus also had active plate tectonics at some point in its history -- how long it has been in its current stagnant lid state. Our analysis estimates this transition occurred roughly 600 million years ago. In the context of future exoplanetary characterization, if active plate tectonics are a potential requirement of planetary habitability, antipodal anticorrelation may constitute an important observable clue. | |
| 229 | Discovery of an Extremely Short Duration 'Building Block' Flare from Proxima Centauri | At a distance of only 1.3 pc, Proxima Cen is the closest exoplanetary system orbiting an M-type flare star, making it a benchmark case to explore the properties and potential effects of stellar activity on exoplanet atmospheres. Here, we present the discovery of an extreme flaring event from Proxima Cen by the the Australian Square Kilometre Array Pathfinder (ASKAP), the Atacama Large Millimeter/submillimeter Array (ALMA), the Transiting Exoplanet Survey Satellite (TESS), the du Pont telescope at Las Campanas, and the Hubble Space Telescope (HST). In the millimeter and FUV, this flare is the brightest ever detected, brightening by a factor of >1000 and >14000 as seen by ALMA and HST, respectively. The millimeter and FUV continuum emission trace each other closely during the flare, suggesting that millimeter emission could serve as a proxy for FUV emission from stellar flares and become a powerful new tool to constrain the high-energy radiation environment of exoplanets. Optical emission is decoupled, peaking at a much lower level with a time delay. The extremely short duration of this event indicates that it could originate from a single flare loop or `building block.' These are the first results from a larger campaign executed in April-July 2019 consisting of roughly 40 hours of simultaneous observations of Proxima Cen spanning radio to X-ray wavelengths. | M. MacGregor [1], A. Weinberger [2], P. Loyd [3], E. Shkolnik [3], T. Barclay [4], W. Howard [5], A. Zic [6], R. Osten [7], S. Cranmer [1], A. Kowalski [1], E. Lenc [6], A. Youngblood [1], A. Estes [1], D. Wilner [8], J. Forbrich [9], A. Hughes [10], N. Law [5], T. Murphy [11], A. Boley [10], J. Matthews [10];<br><br>1 Dept. of Astrophysical and Planetary Sciences, University of Colorado Boulder, Boulder, CO,<br>2 Earth & Planets Laboratory, Carnegie Institution for Science, Washington, DC,<br>3 School of Earth and Space Exploration, Arizona State University, Tempe, AZ,<br>4 NASA Goddard Space Flight Center, Greenbelt, MD,<br>5 Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, NC,<br>6 CSIRO Astronomy and Space Science, Epping, AUSTRALIA,<br>7 Space Telescope Science Institute, Baltimore, MD, |

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| | | | 8 Center for Astrophysics \| Harvard & Smithsonian, Cambridge, MA,<br>9 Centre for Astrophysics Research, University of Hertfordshire, Hatfield, UNITED KINGDOM,<br>10 Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, CANADA,<br>11 Sydney Institute for Astronomy, University of Sydney, Sydney, AUSTRALIA. |
| 230 | It's Getting Hot in Here: The Effect of Giant Planet Core Formation on Surrounding Protoplanetary Disk Solids | High resolution telescopes such as ALMA and the VLT have allowed a direct look at the formation process of giant planets, yielding observations of circumplanetary disk and young giant planet candidates. While observations of forming giant planets provide insight into giant planet origins, the composition of the environment around forming giant planets is also important. Due to their rapid accretion of materials, forming giant planets release a large amount of energy into their environments in the form of heat. While the chemical effect of this local heating by young Jupiter-sized giant planets on the surrounding gas has been studied by Cleeves et al. (2015), the chemical effects of localized heating from forming giant planets on solid materials in the surrounding area have not yet been investigated.<br><br>In our work, we explore the temperature effect of forming giant planets on the surrounding protoplanetary disk environment and the resulting chemical effect on surrounding solid material. We do this by first mapping the dynamic evolution of particles of various sizes using equations of motion including drag force from the surrounding gas on the particles. The resulting dynamic track is then used to calculate the temperature environments the particle experiences as it moves through the disk factoring in contributions from the central star and the planetary core. Finally, the effect of the temperature environments on thermal dissociation of the particle ice mantle is calculated at each time step.<br><br>We find that heating from the forming giant planet can cause various degrees of ice mantle loss depending on initial starting position of the particle and orbital separation of the giant planet core from the central star. In this talk, we will summarize the dependence of particle volatile depletion on particle radius, giant planet core orbital separation, protoplanetary disk material opacity, and giant planet core mass accretion rate. We also quantify the particle flux percentage chemically affected by the thermal effects from the giant planet core as well as determine what percentage of affected particles are accreted by the giant planet core. | M. Barnett, F. Ciesla;<br><br>Department of Geophysical Sciences, University of Chicago, Chicago, IL. |

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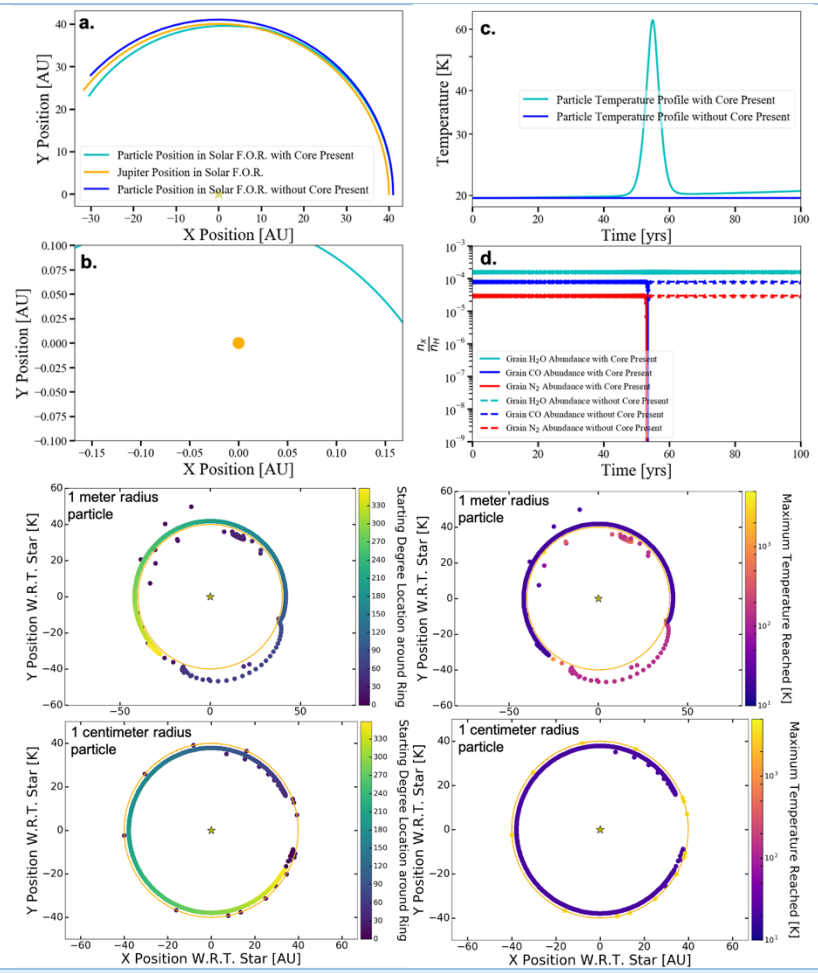
| | |  | |
| 231 | The physics of falling raindrops: a robust starting point for understanding exo-water cycles | The evolution of a single raindrop falling below a cloud is governed by fluid dynamics and thermodynamics fundamentally transferable to planetary atmospheres beyond modern Earth's. Here, we show how three properties that characterize falling raindrops—raindrop shape, terminal velocity, and evaporation rate—can be calculated as a function of raindrop size in any planetary atmosphere. We demonstrate that these simple, interrelated characteristics tightly bound the possible size range of raindrops in a given atmosphere, independently of poorly understood growth mechanisms. By returning to the physics equations governing raindrop falling and evaporation, we demonstrate that raindrop ability to vertically transport latent heat and condensable mass can be well captured by a new non-dimensional number. Our results have implications for precipitation efficiency, convective storm dynamics, and rainfall rates, which are properties of interest for understanding planetary radiative balance and (in the case of terrestrial planets) rainfall-driven surface erosion. | K. Loftus, R. Wordsworth;<br><br>Harvard University, Cambridge, MA. |

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| 232 | Developing simulated environments for studying habitability; Mistakes made and lessons learned | Habitability is the capacity of an environment to host the complex chemistry and energetics that life needs. At planetary scale, interactions between solid, liquid and gaseous components at the surface, together with incoming and outbound radiation generate diverse environmental niches that can encourage the emergence and evolution of life forms. Discerning such interactions is the goal of observational astronomy and exploration missions. Earth-based laboratory experimentation also offers a flexible capability to validate information from such missions, and to better understand how our own planet has transitioned from an abiotic world to one in which an evolving biosphere has changed the coupling of matter and energy at its surface.<br><br>Replicating complex planetary environments in simple bench-scale experiments requires interdisciplinary and stepwise approaches with many challenges and pitfalls. I will present my experience in designing mesocosm-scale environmental systems for multi-annual experimentation with various terrestrial, aquatic, atmospheric and biological scenarios. I will then discuss steps taken to further develop such systems for terrestrial exoplanet research. Such experimental approaches are critical stepping stones for better constraining exoplanetary processes, and can aid in developing and refining methods for geochemical biosignatures detection using remote observation and planetary exploration. | D. Zaharescu;<br><br>Freelance, Atlanta, GA. |
| 235 | Probing the capability of future direct imaging missions to spectrally constrain the frequency of Earth-like planets | A critical question in the search for extraterrestrial life is whether exoEarth candidates (EECs) are Earth-like, in that they host life that progressively oxygenates their atmospheres. We propose answering this question statistically by searching for O_2 and O_3 on EECs detected by future direct imaging missions such as HabEx or LUVOIR. In this paper we explore the ability of these missions to constrain the fraction, fE, of EECs that are Earth-like for different estimates of the occurrence rate of EECs (η_earth). A positive detection of O_2 and O_3 on at least 1 EEC would allow us to significantly constrain f_E. However, an important consideration is whether these missions could still allow us to constrain f_E in the event of a null detection, where we do not detect O_2 or O_3 on any observed EEC. To determine this, our approach is to use the Planetary Spectrum Generator to simulate observations of EECs with O_2 and O_3 levels based on Earth's history. We consider four instrument designs: LUVOIR-A (15 m), LUVOIR-B (8 m), HabEx with a starshade (4 m, "HabEx/SS"), HabEx without a starshade (4 m, "HabEx/no-SS"). We also consider three estimates of η_earth: 24%, 5%, and 0.5%. In the case of a null-detection where we do not detect O_2 and O3 on any EECs we find that for η_earth = 24%, LUVOIR-A, LUVOIR-B, and HabEx/SS would constrain the fraction, f_E , of EECs that are Earth-like, to ≤ 0.094, ≤ 0.18, and ≤ 0.56, respectively, for the most likely range of estimates of Proterozoic O_2. This also indicates that for f_E greater than these upper limits, we are likely to detect O_3 on at least 1 EEC. In contrast, we find that HabEx/no-SS cannot constrain f_E, due in large part to the lack of an ultraviolet channel on the coronagraph. For η_earth = 5%, only LUVOIR-A and LUVOIR-B would be able to constrain fE in the case of a null detection, to ≤ 0.45 and ≤ 0.85, respectively. Finally, for η_earth = 0.5%, none of the missions would allow us to constrain fE in the case of a null detection, as it will likely be difficult to detect EECs in that scenario. We conclude that the value of η_earth has a strong effect on our ability to constrain f_E in the event of a null detection, and although missions with larger aperture mirrors are more robust to | J. Checlair [1], G. Villanueva [2], B. Hayworth [3], S. Olson [4], T. Komacek [1], T. Robinson [5], P. Popovic [6], H. Yang [1], D. Abbot [1];<br><br>1 University of Chicago, Chicago, IL,<br>2 NASA Goddard Space Flight Center, Greenbelt, MD,<br>3 The Pennsylvania State University, State College, PA,<br>4 Purdue University, West Lafayette, IN,<br>5 Northern Arizona University, Flagstaff, AZ,<br>6 Institut du Globe de Paris, Paris, FRANCE. |

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| | | uncertainties in η_earth, all are susceptible to an inconclusive null detection if η_earth is sufficiently low. | |
| 236 | Waterworlds May Have Better Climate Buffering Capacities than Their Continental Counterparts | The long-term habitability of a planet is often assumed to be controlled by its ability to cycle carbon between the solid planetary interior and atmosphere. This process allows the planet to respond to external forcings (i.e., changes in insolation, changes in volcanic outgassing rates, etc.) and regulate its surface temperature through negative feedbacks on atmospheric CO2 involved in silicate weathering. Continental weathering and seafloor weathering rates have different, non-linear dependencies on pCO2 and will respond differently to changes in external forcings. Because waterworlds (planets with only seafloor weathering) have a weaker pCO2 dependence than continental worlds (such as modern Earth), we find that waterworlds are better at resisting changes in surface temperature resulting from perturbations in insolation than their continental counterparts, and may be more habitable in this respect. | B. Hayworth, B. Foley;<br><br>Pennsylvania State University, State College, PA. |
| 238 | Efficiency of the oxygenic photosynthesis on Earth analogs | We study the efficiency of the oxygenic photosynthesis (OP) on Earth-like planets in the habitable zone of their host stars.<br><br>We focus on rocky planets within the habitable zone. We use recent habitable zone models to characterize the planet, and estimate the photon flux and the exergy flux on their surface as a function of the host star effective temperature. We find that G and F-stars provide the best environment for OP: in the OP wavelength range, both photon flux and the exergy flux increase as a function of the star temperature. Finally we also introduce for notion of exergetic efficiency to evaluate the OP effectiveness. | C. Giovanni, R. M. Ienco;<br><br>Physics Department, University of Naples, Naples, ITALY. |
| L1 | The Effect of Radiative Time Step on the Climate of a Habitable Planet | Research on terrestrial exoplanet atmospheres has been at the forefront of discussion pertaining to the possibility of habitable worlds outside of our solar system. In particular,<br>3D general circulation models (GCMs) are crucial to evaluate potential climate states and their associated temporal and spatial dependent observable signals. Though much insight has been gained about these atmospheres, there has yet to be any consideration as to how the climate could be affected by radiative transfer timesteps in 3D climate models. We address the gap in this research by testing the sensitivity of exoplanet atmospheres to various radiative transfer timesteps and investigate any causality between the two. Using the Exoplanet Community Atmosphere Model, we can analyze the effect different radiative timesteps have on the global mean surface temperature, specific humidity, TOA albedo, cloud water, and cloud fraction by building multiple cases modeling terrestrial exoplanet systems. | Washington, R., Fauchez, T., Koppararu, R., Wolf, E.<br><br>NASA Goddard Space Flight Center |
| L2 | Detecting Biosignatures of Nearby Rocky Exoplanets: Simulations of High | The imminent arrival of the Extremely Large Telescopes (ELTs) will finally deliver the observational power capable of assessing the habitability of nearby rocky exoplanets. These mostly non-transiting worlds can be characterized with the High Resolution Spectroscopy (HRS, R>20,000) technique; | Sophia Vaughan, Jayne Birkby, Ray Pierrehumbert;<br><br>University of Oxford |

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| | Spectral Resolution Observations with the ELTs | A powerful method for revealing exoplanet atmospheres that uses the Doppler shift to disentangle the planet from the spectrum of its host star. Oxygen, a key biosignature, is accessible with HRS at 760nm where the planet spectrum contains essentially only reflected light, which brings both new challenges and advantages for HRS. Here, we present our new simulator that explores these in the context of the nearest rocky exoplanet, Proxima b. We simulated one night of high resolution (R=100,000) optical reflected light spectroscopy of the Proxima Centauri system based on an ELT-sized telescope, and noise properties of the ELT. We used model planet spectra from the Carl Sagan Institute designed specifically for Proxima b, which include the reflected stellar lines of the M5.5V host star for active and inactive states. We find that with HRS alone, the 10-7 optical contrast of Proxima b is too low to allow a significant detection in this scenario and, if the contrast were higher, the Doppler shift of the planet is likely too slow to extract a signal. This indicates that High Contrast Imaging (HCI) in combination with optical high resolution integral field spectrographs, or a careful multi-epoch HRS approach, is needed to detect the O2 A-band for our nearest rocky exoplanet. The simulator is highly versatile and we are now extending it to other systems and atmospheres, alongside adding HCI to simulate the early IFS instruments expected for the ELTs, including HARMONI, METIS, and GMagAO-X+IFS. | |