12th International LISA Symposium

Chicago, IL – July, 2018

Meeting Abstracts

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100 – LISA Mission Overview

100.01 – LISA and the Future

In June 2017 ESA has selected the LISA mission for the L3 slot in its futue sceince program. The industrial Phase-A will start this spring. The reboot of the LISA Consortium is under way. 26 years after the first LISA proposal we are getting real!

Author(s): Karsten Danzmann[1]
Institution(s): *1. AEI Hannover*

100.02 – The Physics of Free Falling Observers: LISA Pathfinder Results and Legacy

Since the last LISA Symposium, and before its termination, LISA Pathfinder has accumulated a large wealth of experimental data on various aspects of the physics of geodesic motion of test-masses. Besides showing that LISA can fully meet its requirements, these data have allowed some significant progress in our understanding of the limits of geodesic motion but have also highlighted some areas that require further understanding. The talk will review these findings and shortly discuss their implications for LISA and for other possible missions in the field of experimental gravitation.

Author(s): Stefano Vitale[1]
Institution(s): *1. University of Trento*

100.04 – LISA Mission Status

LISA (Laser Interferometer Space Antenna) has been selected as the third large class (L3) opportunity addressing the previously selected scientific theme "The Gravitational Universe" within the European Space Agency's Cosmic Vision programme. For L3, a launch date of 2034 is targeted with a cost cap for the ESA funded elements of the mission at 1.05 billion Euros. The LISA mission concept underwent detailed early studies (Phase 0) in 2017. Following their successful completion the mission is now proceeding with feasibility assessment in Phase A. The mission studies are led by the European Space Agency (ESA) and executed in collaboration with NASA. ESA member states and NASA are developing contributions to the payload. We present the current overview of the programme, planning, the activities undertaken in Phase A, as well as the collaboration scheme.

Author(s): Martin Gehler[1], Sridhar Manthripragada[2], Paul McNamara[1], James Ira Thorpe[2]
Institution(s): *1. European Space Agency, 2. NASA Goddard Space Flight Center*

100.03 – The LISA Consortium

The Laser Interferometer Space Antenna (LISA) is a gravitational wave
observatory in space, targetting the millihertz frequency band where a
large number of astrophysical and cosmological sources of gravitational
waves is expected. In 2013, the European Space Agency selected the science
theme ``The Gravitational Universe'', which focuses on this rich science.
In 2016, a call was issued by ESA for missions to address this science, and
the LISA Consortium responded to that call with the LISA mission. The
mission is now in the early phases of development and the LISA Consortium
is playing an active role in all aspects of the mission.

This talk will describe the setup of the Consortium, review the current
activities, and give an overview of the Consortium hardware, software and
science deliverables.

Author(s): Martin Hewitson[1]
Institution(s): *1. AEI Hannover*

100.05 – Guenther Hasinger

100.06 – Paul Hertz (NASA)

101 – Space Mission Science and Data Analysis

101.01 – The LISA Science Group

The LISA Science Group (LSG) is the LISA consortium body that will be overseeing the development of scientific data analysis required to deliver the scientific goals of the LISA consortium. The organisation of that scientific activity will be through the definition of work packages that fall into different groups with common themes. The LSG was formed in the past six months and so the purpose of this presentation is to advertise the existence of the LSG to the wider LISA community, summarise the areas of work currently identified and identify the people leading eac one. We will also discuss the manpower likely to be required, and so far committed in the first round of membership applications, to this activity.

Author(s): Jonathan Gair[1]
Institution(s): *1. University of Edinburgh*

101.02 – The LISA Data Processing Group

The Ground Segment (GS) is a core part of the LISA mission with several interdependent key processings: calibrations of the raw (L0 data), reduction of noises with TDI and associated techniques (to produce L1 data) and the generation of the science products (L3 data) with the GW data analysis. The task is particularly challenging both due the large number of GW sources and to the novelty of this mission. The GS is shared between ESA (L0 to L1 - with Consortium support) and LISA Consortium (L1 to L3). The GS deliverables of the Consortium are managed by the LISA Data Processing Group (LDPG), the major part being the Distributed Data Processing Center. The LDPG groups scientists and software/IT engineers in order to design and to prototype the LISA data processing during phase A and to develop and to operate the processing during the next phases. It is organise in 6 teams: System, Operations, Data Computing Center, Simulation Management, Pipeline Management and Science Operation Center support.
In this talk we will describe the LDPG and its activities. We will concentrate on the scientific challenges regarding pipelines for GW science extraction, simulation, computer science, data processing, data management, etc. The various prototyping ongoing activities will be presented, in particular the ones at the core of simulation and LISA Data Challenge.

Author(s): Antoine Petiteau[1]
Institution(s): *1. University Paris-Diderot*

101.03 – Luigi Ferraioli (ETHZ)

101.04 – The New LISA Data Challenges

I present an overview of the activities and plans of the LISA Data Challenges (LDCs) working group. The LDCs are a collaborative effort to tackle open problems in the LISA science analysis, while kickstarting the design and early development of the LISA data system and serving mission formulation studies. The LDC working group curates and prototypes waveform models and data-analysis algorithms; works to establish a common computational infrastructure available to researchers across and beyond the consortium; and invites the astronomy and data-science communities to analyze simulated LISA datasets and to contribute data use cases and astrophysical context. The first datasets, focusing on simple combinations of LISA sources, are now available, accompanied by tutorials and example codes; future issues will add realism and complexity.

Author(s): Michele Vallisneri[1]
Institution(s): *1. Jet Propulsion Laboratory*

101.05 – The Chinese Academy of Sciences Program in Space Gravitational Waves Detection

On behalf of Space Gravitational Wave Detection Working Group in Chinese Academy of Sciences (CAS), ongoing development of gravitational wave detection in space in China has been presented in this talk. The preliminary mission design, primary science drivers, program for technological developments and the road-map will be described.

Author(s): Gang Jin[1]
Institution(s): *1. Institute of Mechanics, Chinese Academy of Sciences*

101.06 – Testing (modified) Gravity in Space: MICROSCOPE's First Results

MICROSCOPE is a CNES/ONERA/ESA mission that aims to test the Weak Equivalence Principle (WEP) in space at the 10^{-15} level, i.e. two orders of magnitude better than the best on-ground tests to date. The WEP is the cornerstone of General Relativity, the postulate that led Einstein to establish his theory: it states that all bodies fall at the same rate, independently of their mass and composition. Alternative theories of gravity, like those developed to overcome such conundrums as dark energy or the unification of gravity with the forces of the standard model of particle physics, generically predict a small violation of the WEP. As a consequence, not only does MICROSCOPE test the very foundation of General Relativity, but it also provides new constraints on theories beyond Einstein's, and is complementary to astrophysical tests allowed by LISA.
Based on technology similar to that of LISA Pathfinder, the MICROSCOPE satellite was launched on April 25, 2016. It has since then provided high-quality data. The first results (using only a small part of the total data) were announced last December.
In this talk, I will first introduce the MICROSCOPE mission, in particular its scientific goals and measurement principles. I will then present the exploitation phase up to now. Finally, I will discuss its first results, with an emphasis on updated constraints on some modified gravity models.

Author(s): Joel Bergé[1]
Institution(s): *1. ONERA / Université Paris Saclay*

101.07 – LISA Science Analysis - aka LISA is not LIGO in Space

The LISA science data will be fundamentally different from anything that has been encountered before in gravitational wave astronomy, containing thousands of overlaping bright signals, including some with very complicated structures. The instrument noise will be non-stationary on time scales that are short relative to the signal durations, and the data will have many gaps and transient distrubances. To properly account for these complications will require a holistic approach to the science analysis that delivers a global solution for all the signals and the non-sationary, non-gaussian noise. I will provide a review of LISA data analysis, covering past sucesses and the current state of the art, including a new approach to noise modeling, and the latest trans-dimensional global analysis algortihm prototype.

Author(s): Neil J Cornish[1]
Institution(s): *1. exTreme Gravity Institute*

101.08 – Achieving the Low End of the LISA Frequency Band

At frequencies below several mHz the LISA sensitivity relies on reference test masses that are in free-fall with an unprecedented small degree of deviation. LPF demonstrated the ability to use an LPF-like geodesic reference system with the precision needed to realize the low-frequency science potential of the LISA at frequencies as low as 20 μHz. LPF hardware heritage and force measurement/subtraction strategies need now to be transferred to the LISA configuration. This talk regards the challenge that we have to face concerning the consolidation of the LPF stray force noise budget understanding and the identification of proper control strategies for example of the gravitational balance, electrostatic surface properties, vacuum levels to ensure to reproduce an environment compatible with sub-femto-g free-fall in LISA.

Author(s): Rita Dolesi[1]
Institution(s): *1. Università di Trento/INFN*

101.09 – Optical Metrology for LISA: Optical Bench Design and Metrology Performance

Detection of passing Gravitational Waves by LISA requires laser metrology with a displacement noise of some 15 pm/sqrt(Hz) over several million km between the spacecraft that make up the LISA constellation. We will present an overview of some of the unique challenges in the LISA optical metrology system and give the status of the development of the Optical Bench Interferometer, which sits at the heart of the LISA instrument. We will present the new baseline design of the Optical Bench developed for the recent ESA Phase 0 study and outline the optical alignment requirements and strategy needed to build it. We will also outline the key performance drivers, and present the current expectations of the achievable metrology performance compared to the requirements of the science cases.

Author(s): Ewan Fitzsimons[1]
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200 – Results from LISA Pathfinder

200.01 – The Lisa Pathfinder Drag-Free Attitude Control System (DFACS)

The Lisa Path Finder (LPF) mission demonstrated some of the most critical technologies needed to measure gravity waves in space by measuring the relative distance between two free-floating test masses. In addition to precise sensing and actuation hardware, LPF demonstrated that the required test mass acceleration noise levels can be achieved by shielding the test masses from external disturbances such as the solar radiation pressure. This was achieved using a drag-free control system that controls the spacecraft position to follow the drag-free test mass. The Drag-Free Attitude Control System (DFACS) controls 15 mostly coupled degrees of freedom in drag-free or electrostatic suspension using the spacecraft thrusters and test mass electrostatic actuation system.
This paper gives an overview of the DFACS control system including sensors and actuators, control principles and control system architecture. An overview of all the control system modes, required to control the spacecraft and test masses from release up to the quiet science levels is also provided. Finally, some in-flight commissioning results of the control system are shown, including comparison to on-ground performance predictions.

Author(s): Jonathan Grzymisch[1]
Institution(s): *1. ESA*

200.02 – Angular and Lateral Jitter Cross Coupling in LISA Pathfinder and LISA

One relevant noise source in LISA, LISA Pathfinder and other precision interferometers is the cross coupling of angular and lateral jitter (for instance of the space craft) into the interferometric phase readout - which should in principle be sensitive only to longitudinal variations. This type of cross-coupling was clearly visible as a "shoulder" in the noise spectral density of LISA Pathfinders acceleration data. We were able to reduce the amount of cross coupling in LISA Pathfinder, by realigning the test masses in flight and we fitted and subtracted the residual noise. For LISA, we plan to suppress this cross coupling by using imaging optics in all test mass and long arm interferometers and proceed with the residual noise like in LISA Pathfinder. Unfortunately, the individual interferometers are dominated by laser frequency noise, such that their signals cannot be used directly for calibration purposes. Therefore, realignment and subtraction like we did in LISA Pathfinder, can be done in LISA only by using the TDI observables. These TDI observables, however, contain a significant number of individual cross coupling noise contributions from all test mass and science interferometers at various different times. Consequently, in-flight alignment for further suppression as well as a final subtraction of the residual cross coupling noise are complex tasks that we are currently investigating.

In this talk I will wrap up the experience on angular and lateral jitter cross coupling gained in LISA Pathfinder and introduce coupling mechanisms and suppression methods currently known to us. Furthermore, I will show how this type of cross coupling will be suppressed in LISA and how the residual coupling will appear in the TDI observables.

Author(s): Gudrun Wanner[1], Ewan Fitzsimons3, Marie-Sophie Hartig[1], Gerhard Heinzel[1], Martin Hewitson[1], Nikolaos Karnesis[2], Sweta Shah[1]
Institution(s): *1. AEI Hannover, 2. APC, 3. ATC*

200.03 – LISA Pathfinder Platform Stability and DFACS Performances

The LISA Pathfinder experiment, and in particular its combination of an optical displacement sensing of sub-picometer precision and a wireless test masses discharge system had led to unprecedented acceleration sensitivity in space, hence being a reference now for Drag-Free missions concerned by very good inertiality of the platform. This presentation is dedicated to expose our researches on the characterization of the LISAPathfinder DFACS performances, in term of the stability achieved by the spacecraft (S/C) locked on the test masses (TMs) that serves as inertial reference frames. A state space model of the in-loop dynamics of the system has first been tested against the observed dynamical behavior, and then been used to assess the "true displacement" (distinct from "sensed displacement") of the S/C, which remains out of the reach of the observations because of closed-loop features that tends to hide sensor noise impact on real displacement. A second necessary step has been to relax the assumption of inertiality of the test masses and assess the stray accelerations on every linear degree of freedom both from previous measurements or experimentally verified models. The stability of the S/C with respect to the test masses, added up to the acceleration noise endured by the masses, provides an estimate of the stability of the platform with respect to its local inertial frame. Such results are ultimately presented for both linear and angular degrees of freedom.

Author(s): Henri INCHAUSPE[2], Eric Plagnol[1]
Institution(s): *1. Laboratoire APC, Université Paris Diderot, 2. University of Florida*

200.04 – Thruster Calibration Measurements for ST7 on LISA Pathfinder

The LISA Pathfinder mission demonstrated the performance of two different types of micronewton thrusters: ESA-supplied cold-gas thrusters and NASA-supplied colloidal thrusters. An important goal of the NASA ST7 mission was to characterize the performance of the colloidal thrusters. Here we report on experiments to calibrate the thrust provided by the colloidal thrusters and measure how that thrust varies with the temperature of the propellant. We describe the experiments and our data analysis method, and summarize our results.

Author(s): Curt Cutler[1], Jacob Slutsky[2], James Ira Thorpe[2]
Institution(s): *1. Jet Propulsion Lab, California Institute of Technology, 2. NASA Goddard Spaceflight Center*

200.05 – Measurements of Test-mass Charging During the LISA Pathfinder Mission

The test masses that serve as free-falling geodesic references for the LISA interferometric measurement are susceptible to electrostatic charging by the high-energy charged particle space environment. In order to minimize electrostatic force noise that could mask gravitational wave signals, the net charge of the test mass must be maintained below a level around 30 million elementary charges. We present measurements made over the course of the 15-months of LISA Pathfinder operations to determine the test mass charging rate, its variation with time and other environmental conditions. We compare our results with predictions from high-energy particle tracking simulations and set out the likely charging rates that will be observed over the course of a 10-year LISA mission.

Author(s): Peter J Wass[1]
Institution(s): *1. University of Florida*

200.06 – LISA Pathfinder Performance Confirmed without Force Compensation: Results in Intermittent Actuation Mode

The quasi-DC force imbalance experienced by the two test masses (TM) on board the LISA Pathfinder (LPF) space mission, dominated by residual spacecraft gravity, is compensated continuously in the standard operation mode, by applying an electrostatic force on one TM to follow the orbit of the other TM. To reduce the noise source deriving from the control, an alternative method has been implemented on LPF: the actuation is limited to short impulses, so that the TM is in free-fall between two successive “kicks”. The intermittent control mode thus provides a measurement of the differential TM acceleration free from the actuator noise and its calibration issues and, in addition, it allows to test a LISA-like actuation configuration. The results show a measurement of the residual acceleration at the subfemto-m/s^2Hz^1/2 level, at frequencies below 1mHz, in agreement with the LPF performance achieved in continuous control mode.

Author(s): Roberta Giusteri[1], Giuliana Russano[1]
Institution(s): *1. University of Trento*

200.07 – Characterization and applications of Particle Detectors Aboard LISA and Future Space Interferometers

Particle detectors aboard interferometers for gravitational wave detection in space
allow for in situ monitoring of the overall energetic particle flux of galactic
and solar origin penetrating the spacecraft and charging the test masses.
Solar energetic particle (SEP) fluxes overcome up to several orders of magnitude the
flux of particles of galactic origin.
No SEP events occurred during LISA Pathfinder. We present here the
optimum characterization of particle detectors to be flown on each S/C of the future
interferometers for gravitational wave detection in space in comparison to
similar instruments placed aboard other missions.
The presented particle detector configuration
will allow for SEP event timing and intensity nowcasting over the three LISA S/C.
Monte Carlo simulations will be used to correlate on-board particle measurements and test-mass charging estimate.
Particle detector observations aboard space interferometers will also provide
precious clues for space weather science and space weather applications
being the first SEP observatories at small heliolongitude intervals.

It is worthwhile to point out that the LISA mission may superpose to the end of the space weather dedicated ESA Lagrange mission in L1/L5 allowing for particle detector measurement normalization and naturally playing the role of a Earth sentinel for intense geomagnetic storms.

Author(s): Catia Grimani3, Simone Benella3, Michele Fabi3, Noemi Finetti[2], Miquel Nofrarias[1], Carlos F. Sopuerta[1], Andrea Cesarini3
Institution(s): *1. Institut de Ciènces de l'Espai , 2. Universita' degli Studi dell'Aquila, 3. University of Urbino "Carlo Bo"*

200.08 – Magnetic Experiments On-board LISA Pathfinder

The differential acceleration measurement between two free-falling test masses on-board LISA Pathfinder is limited in the low frequency regime by force noise applied to the test masses. Several effects can contribute as force noise on the inertial masses and, amongst them, magnetically-induced forces are precisely one of these effects limiting the performance of the instrument in the millihertz band. The origin of this disturbance is the coupling of the residual magnetisation and susceptibility of the test masses with the environmental magnetic field. In order to fully understand this term of the noise model, a set of coils and magnetometers are integrated as a part of the LISA Pathfinder diagnostics subsystem.

In this talk we will explain which are the different magnetic experiments we have carried on board LISA Pathfinder in order to extract the magnetic parameters that characterise LISA Pathfinder's test masses. We will describe how, by analysing the movement of the test masses during magnetic experiments, we can extract not only information about their magnetic properties, but also about the environment that surrounds them. We also provide the magnetic contribution to the LISA Pathfinder noise budget.

Author(s): Juan Pedro López-Zaragoza[1], Miquel Nofrarias[1]
Institution(s): *1. Institut d'Estudis Espacials de Catalunya (IEEC)*

200.09 – In-flight testing of the Injection of the LISA Pathfinder Test Mass into a Geodesic

In the LISA Pathfinder mission some key technologies are tested for the detection of gravitational waves in space. In the scientific payload, the LISA Technology Package (LTP), two test masses are set into nearly perfect geodesic trajectories in order to demonstrate that their relative acceleration noise is smaller than $3*10^{-14}m/s^2/\sqrt{Hz}$. Due to the large mass (2kg) and gaps (few mm) with respect to the hosting housing, each test mass is caged against the high vibration levels characteristic of the spacecraft launch phase by means of the Caging and Vent Mechanism. Once the spacecraft is in its final orbit, the Grabbing Positioning and Release Mechanism has the capability to grab the test mass from any position and attitude in the housing (by means of two opposite cam-shaped grabbing plungers), centre and release it (by means of two opposed release tips) to free fall. The following capture on behalf of the electrostatic actuation and injection in the geodetic trajectory is guaranteed if any linear and rotational velocity component is smaller than 5μm/s and 100μrad/s respectively.
Due to the design of the test mass and the GPRM, in a nominal configuration the release velocity is expected only along the common direction of actuation of the release devices, produced by asymmetries of their adhesion to the test mass and retraction timing. However, the releases performed according to the nominal procedure produced significant deviations from the baseline, characterized by relevant linear and rotational velocities. A test campaign is executed at the end of the extended mission in order to explore different release strategies to reduce the release velocity and improve the repeatability of the results. The upgraded procedure produces an improved behaviour at the release, which is consolidated by a significant statistic of tests. The analysis of the tests shows that in flight the actuation of the GPRM produces a change of geometrical configuration which is compatible with unexpected contacts between grabbing plungers and test mass at the release and with velocity components outside the nominal envelope.

Author(s): Daniele Bortoluzzi[1]
Institution(s): *1. University of Trento*

201 – Astronomy Across the Gravitational Wave Spectrum

201.01 – Laural Nuttall

201.02 – Multi-band Gravitational Wave Astrophysics with PTAs and LISA

Pulsar Timing Arrays (PTAs) are galactic-scale low-frequency (nHz - μHz) gravitational wave (GW) observatories. The primary source of GWs at nHz frequencies is expected to be a stochastic background, formed by a low-redshift ($z < 2$) population of supermassive black hole binaries (SMBHB). This population is predicted to have grown hierarchically from the massive black hole binaries that LISA will detect at mHz GW frequencies. There are many open questions regarding the merger dynamics of SMBHBs, and the relationship between a central black hole and its host galaxy. Within the next decade, PTAs anticipate making a detection of the stochastic background and beginning to study some of these questions. However, there are investigations that will require a combination of PTA and LISA observations to distinguish between various models of hierarchical growth. In this talk, I will discuss the latest PTA constraints on the SMBHB population, and some ways in which PTAs and LISA can jointly study the growth of the massive black hole population.

Author(s): Joseph Simon[1]
Institution(s): *1. Jet Propulsion Laboratory*

201.03 – Constraining the Environments & Progenitors of Black Holes Across the Gravitational Wave Spectrum

The handful of existing LIGO-Virgo detections will soon grow into an extensive catalog of compact binary coalescence events. With more events we can begin the process of mining the statistics and demographics of the population in a bid to understand the respective environments and evolutionary paths of progenitors. At lower frequencies, LISA will be sensitive to many massive black-hole mergers, with a catalog of such events offering insight into black-hole seed formation scenarios and accretion processes. Finally, at nanohertz frequencies, the superposition of gravitational wave signals from many inspiraling supermassive black-hole binaries is helping to constrain black-hole--host-galaxy scaling relationships, and the dynamical environments of host galaxy centers. I will outline a general statistical framework wherein detailed models for gravitational-wave population demographics can be constructed using insight from sophisticated population synthesis simulations. These models can then be deployed in a hierarchical Bayesian analysis to recover joint posterior probability distributions of progenitor properties, evolutionary paths, and dynamical interactions.

Author(s): Stephen Richard Taylor[1]
Institution(s): *1. California Institute of Technology*

201.04 – Dynamics of Massive Black Hole Triplets: Promising Sources for LISA and Pulsar Timing

I will describe a large suite of numerical simulation of massive black hole (MBH) triplets forming by subsequent galaxy mergers. We model the evolution of triple systems including an external galactic potential, dynamical friction, stellar hardening, and post

Newtonian dynamics. Triple interactions are a promising way of merging stalled MBH binaries and guarantees a minimal number of sources for LISA and pulsar timing, should any other dynamical process driving the binaries fail. I will discuss the implications for observations of MBHs with LISA and pulsar timing arrays.

Author(s): Alberto Sesana[1]
Institution(s): *1. University of Birmingham*

201.05 – Intermediate Mass Black Hole Population in Multiband Gravitational Wave Astronomy

In this era of gravitational wave astronomy, one of the most promising astrophysical sources are intermediate-mass black hole (IMBH) binaries. Current ground-based GW detectors like Advanced LIGO and next-generation experiments such as Einstein Telescope can detect IMBH binaries of thousands of solar masses up to cosmological distances. Meanwhile, LISA-like space missions could identify gravitational waves from coalescing IMBH binaries of tens of thousands of solar masses. There is no unambiguous evidence of black holes in the intermediate mass range between stellar and supermassive limits. Therefore, their survey in the gravitational wave spectrum adds valuable information for population synthesis models. With the LISA mission, these IMBH binaries also open a new window of possibility for multi-band gravitational wave astronomy, allowing us to independently test General Relativity and put tighter constraints on the black hole formation channels. This talk provides an overview of the IMBH population that would be constrained by 2030s from ground-based observations and highlights the parameter space that would permit multi-band detections with LISA mission. In doing so, we also demonstrate the limitations of the current gravitational waveform machinery in accessing the astrophysics of IMBHs in multi-band era.

Author(s): Karan Jani[1]
Institution(s): *1. Georgia Institute of Technology*

201.06 – An Unprecedented Opportunity: Black-hole Spectroscopy with LISA Forewarning and LIGO Detuning

Merging black holes observed by ground-based gravitational-wave detectors LIGO and Virgo allow for new tests of Einstein's General Relativity in its strong-field regime. In particular, the detection of multiple ringdown modes will soon enable us to perform black-hole spectroscopy: experimental checks that astrophysical black holes indeed have no hair and are faithfully described by the Kerr metric. The early inspiral of some LIGO's black-hole binaries will be detectable at low frequencies by the upcoming space mission LISA. LISA will predict, with years of forewarning, at what time and at what frequency binaries will be seen merging by LIGO. We will, therefore, find ourselves in the extraordinary position of knowing that a source is about to merge, with the unprecedented opportunity to optimize ground-based operations to increase their scientific payoff. We show how narrowband tunings can be used boost the detectors' sensitivity at frequencies corresponding to the first subdominant ringdown mode, thus vastly improving our prospects to perform black-hole spectroscopy. We define a new consistency parameter between the different modes, called deltaGR, and show that, in this metric, narrowband tunings have the potential to double the effectiveness of black-hole spectroscopy when compared to standard broadband setups.

Author(s): Davide Gerosa[1], Rhondale Tso[1], Yanbei Chen[1]
Institution(s): *1. Caltech*

201.07 – Limits on Gravitational Waves from Individual Supermassive Black Hole Binaries from the NANOGrav 11-year Data Set

Pulsar timing arrays (PTAs) are sensitive to low-frequency gravitational waves (GWs) from supermassive black hole binaries (SMBHBs). We have searched the 11-year data set from the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) for GWs from individual circular SMBHBs. We find no evidence for GWs from individual SMBHBs in the the data, and we present upper limits on the GW strain amplitude for GW frequencies between 1 and 300 nHz. We also show how our sensitivity varies with sky location due to the distribution of pulsars in our array. We use these limits to constrain the luminosity distance to individual sources and to place constraints on the mass-ratios of SMBHBs in local galaxies. We discuss noise modeling and detection techniques that we have developed to distinguish between true GW signals and other spurious signals in the residuals.

Author(s): Sarah Vigeland[1]
Institution(s): *1. University of Wisconsin, Milwaukee*

201.08 – Incoherent Mapping of the Gravitational Wave Background

The Gravitational Wave Background (GWB) is a precious source of information, waiting to be unraveled and explored; to this end, we've constructed a mapper which reconstructs GWB anisotropies on the sky. Our map-making algorithm in sky coordinates uses the incoherent superposition of multiple, generalised detector baselines. The output maps are a maximum likelihood representation of the GWB power on the sky. We've tested the algorithm by reconstructing known input maps with different baseline configurations, and have applied the map-maker to the latest LIGO open data.
In this talk, I will present what type of data we expect to work with, and explain the mapping algorithm. I will motivate the multiple baseline approach, in which lies the strength of our method. Finally, I will present reconstructed maps from simulated data, and results obtained from the LIGO O1 data run.

Author(s): Arianna Renzini[1], Carlo Contaldi[1]
Institution(s): *1. Imperial College*

201.09 – Data Analysis for Massive Black Hole Binaries.

One of the majour sources observed with LISA will be massive black hole binaries. Here we are going to present the new machine learning approach for the parameters estimation and compare the performance with the established approach of the Nested sampling that has shown good performence on the solar mass black hole binaries as the LIGO sources. Moreover we are going to cover the important topic of the influence of the gaps on the performance of the parameter estimation.

Author(s): Natalia Korsakova[2], Michael Williams[2], Hunter Gabbard[2], Nikolaos Karnesis[1], Stas Babak[1], John Veitch[2]
Institution(s): *1. APC, 2. University of Glasgow*

300 – LISA Technology

300.01 – Telescope Design for the LISA Mission

The Laser Interferometer Space Antenna (LISA) Mission Proposal was selected in June 2017 for the L3 opportunity as part of ESA's Cosmic Visions Program. A space-based gravitational wave observatory requires optical telescopes to enable displacement measurements between pairs of drag-free proof masses with a precision of approximately 10 picometers/√Hz over separations of 2.5 million km. We describe the somewhat unusual requirements for these telescopes and a proposed design that would meet these requirements.

Author(s): Jeffrey Livas[2], Shannon Sankar[2], Ewan Fitzsimons3, Isabel Escudero Sanz[1]
Institution(s): *1. European Space Agency, 2. NASA Goddard Space Flight Center, 3. Royal Astronomy Edinburgh*

300.02 – Building LISA Optical benches – Speed and Precision through Automation

The LISA Pathfinder Optical Bench used precision-aligned, hydroxide catalysis bonded optical components for the most critical optical components. The process was extremely successful: the optical path length was stable at the sub pico-metre level and no component alignment changes were detectable over the whole on-orbit lifetime.

We have taken the basic technology used to build the LISA Pathfinder optical benches and added further metrology and component manipulation hardware to enable the automation of what was previously a skilled manual process. We can now reliably bond an optical component to within 4um and 10urad of its target position, well within the LISA alignment requirements. Further the automation allows a single operator to achieve a bond on a timescale of 30 minutes.

We describe the automated bonding system, show the results of test bonds, and show how the system is integrated into the design of a dedicated facility for the construction of the LISA Optical Benches.

Author(s): David Ian Robertson3, Richard Bennet[2], Phil Parr-Burman[1], Ewan Fitzsimons[2], Christian Killow3, Michael Perreur-Lloyd3, Henry Ward3
Institution(s): *1. IGR, University of Glasgow, 2. UK Astronomy Technology Centre, 3. University of Glagow*

300.03 – LISA Telescopes : Scattered Light Issues

The LISA (Laser Interferometer Space Antenna) mission opens a whole new window into the heart of the most energetic processes in the Universe, with fundamental consequences for physics and astronomy. During its five years duration, LISA is expected to detect gravitational waves from the inspired and merger of massive black holes in the centers of galaxies or stellar clusters located at cosmological distances.
LISA is based on laser interferometry technique, and its three satellites form a giant Michelson interferometer. Straylight by the optics, the mechanics, interaction with tubes, is an important source of noise in such antennas and can disturb the measurement of the detector. Indeed, the intensity of straylight is of the same order of magnitude of the beam power coming from the distant satellite and can give a significant phase noise on the LISA sensitivity.
The purpose of our study at APC laboratory is to evaluate the impact of scattered light from the telescope optics of the space project LISA (telescope designed during the ITT ESA and the NASA design) on the detection signal of gravitational waves. It is important to know the intensity of straylight to evaluate the sensitivity of the detector which can be compromised if the signal is muffled by noise from straylight. This study consists in simulating with two different optical design softwares, FRED and Zemax, by using real optical data measured by LMA laboratory, current optical properties specifications (micro-roughness), and by taking into account dust contamination for each phase of the telescope integration. Results from simulations give intensity of straylight when compared to the theoretical intensity threshold. Moreover, the polarization of scattered light has a non-negligible impact on the fraction of straylight that can be recombined with the main beam. This topic is currently under study.

Author(s): Catherine Nguyen[1], Christelle Buy[1]
Institution(s): *1. APC Laboratory*

300.04 – Trajectory Design for the 2034 LISA Mission

The LISA mission has been selected as the L3 cornerstone mission by ESA with a planned launch in 2034. It involves a configuration of three spacecraft in heliocentric orbits. The orbital parameters are chosen such that the relative positions of the three spacecraft span a slowly rotating near-equilateral triangle. The scientific requirements mandate that the corner angles and the rates of change of the arm lengths remain constrained to within defined bounds. This paper summarises the Mission Analysis for the LISA mission following the CDF study conducted at ESA in Spring 2017 and subsequent work in preparation for the Phase A study.

First, the trajectory optimisation and resulting orbit geometry for the operational science orbit is discussed. This includes a preliminary analysis on the impact of insertion inaccuracies and the spacecraft self-gravity on the trajectory. For the transfer to the operational orbit two options have been looked at: Chemical Propulsion, where manoeuvres can be approximated as impulsive velocity changes, and a more fuel efficient Solar Electric Propulsion which requires extended thrust arcs due to the low thrust capability of the propulsion system. The variation of fuel requrements for different launch dates over the year 2034 is discussed for both cases.

Author(s): Waldemar Martens[1], Michael Khan[1]
Institution(s): *1. European Space Agency/ESOC*

300.05 – Analysis of the LISA Telescope Optical Design

Research and development efforts for the LISA long-arm telescopes are ongoing in the US. A robust optical design for these telescopes is the technical foundation upon which all other design attributes are built, including the structural and thermal telescope interfaces. Careful, knowledgeable choices in the optical design stage can have large positive impacts in the successful and timely implementation of the LISA telescopes. We discuss an elegant four-mirror optical design, developed in part by leveraging experiences gained in the full development, fabrication and alignment of a prototype version of a telescope for a gravitational-wave observatory. We also present the results of an analysis campaign into optical sensitivities, alignment tolerances as well as optics fabrication tolerances - all key parameters in the selection of an optical design. Furthermore, we discuss a scattered light trade space which impacts the design of the interface between the optical bench and the telescope, and we quantitatively address the long-held notion of tailoring the design of this interface to greatly reduce or eliminate the existing concerns of extra phase noise from coherent backscattered light. In particular, we show the interface stability required to be robust against backscatter from the telescope optics at expected end-of-mission particulate contamination levels.

Author(s): Shannon Sankar[1], Jeffrey Livas[2]
Institution(s): *1. Goddard Space Flight Center, 2. NASA*

300.06 – A Multi-Axis Heterodyne Interferometry Demonstration for LISA

At NASA GSFC we have developed a LISA interferometry test bed using mostly off the shelf optics and optomechanics. The Multi-Axis Heterodyne Interferometry (MAHI) system uses heterodyne differential wavefront sensing with phasemeter readout to measure length and alignment flucutations of a test mass analog to the precision of a few 10pm/√Hz and few 10nrad/√Hz level or below over most of the LISA band. We will report on the design, construction and operation of the MAHI system, including the calibration of the position and angle sensing using an actuated mirror test mass analog, and the development of a noise model for the major sources of length and angular noise.

Author(s): Paul Fulda4, Ryan Derosa3, Michael Aitken[2], Shannon Sankar3, Jeffrey Livas3, Eugenia DeMarco[1], James Ira Thorpe3
Institution(s): *1. ATA Aerospace, 2. Columbia University, 3. NASA GSFC, 4. University of Florida*

300.07 – Research Progress of the Inertial Sensor for TIANQIN

TianQin is one of the space-borne gravitational wave detection missions proposed by Chinese scientists. The mission requires the non-gravitational disturbances on its test masses to be lower than

$10^{-15} m/s^2/Hz^{1/2}$. A research group from the Center for Gravitational Experiments in Huazhong University of Science and Technology, whose main research interest is the development of precision electrostatic accelerometer, has been engaged to develop the inertial sensor for TIANQIN mission. The key technologies for electrostatic accelerometer were well developed and achieving the requirement of the inertial sensor for gravitational wave detection mission. In this talk, the research progress of the inertial sensor for TIANQIN will be introduce in detail, including the requirement and preliminary design of inertial sensor, capacitive displacement sensing, the primary achievement about the measurement and control for charge and stray potential, the ground-based testing facilities and experiments for the investigation of noise from both surface and bulk effects, the sophisticated suspending scheme for seismic noise rejection during ground testing and so on.

Author(s): Zebing Zhou[1], Yanzheng Bai[1], Li Liu[1], Hang Yin[1], Dingyin Tan[1]
Institution(s): *1. Huazhong University of Science and Technology*

300.08 – Investigating an Optimal Backlink Candidate for LISA

The angular change in LISA needs to be compensated with two moving optical sub-assemblies per S/C. Laser frequency noise limits the readout of the S/C separations but can be suppressed in data post-processing by time-delay interferometry. This requires a precise phase comparison between the two local lasers on each optical bench that is realized by a phase reference distribution system or backlink. Here the differential (non-reciprocal) phase fluctuations are critical because they directly enter the measurement.
Realizing such a backlink connection with a fiber was proven to be working within the requirements by adding post-corrections like balanced detection and attenuation stages. This, however, is not an ideal solution, motivating the search for other, more optimal schemes. In the Three-Backlink Experiment (TBE) three promising candidates are going to be compared in one quasi-monolithic set-up with regards to the non-reciprocity, required to be below 6murad/√Hz. Two optical benches rotate with a sinusoidal motion of a 12h period, simulating a LISA-like test-bed. Chosen to be tested are a fiber connection, a frequency separated fiber-based backlink and a free beam connection. The most significant noise source in a fiber-based backlink is the backscatter due to Rayleigh scattering which may change significantly due to radiation during the mission. A backscatter-experiment has been set up to measure fibers with regard to their scatter behavior before and after being radiated. The working principle of the Free-Beam Backlink solution was successfully demonstrated in a pre-experiment. The optical benches of the TBE are under construction while its laboratory infrastructure is extended. The experimental design including the spurious light estimations, the results from the pre-experiment, the construction progress and the backscatter-experiment are presented.

Author(s): Lea Bischof[1]
Institution(s): *1. Max Planck Institute for Gravitational Physics (Albert Einstein Institute)*

300.09 – A UV LED-based Charge Management System for LISA

The test masses housed in each of the three LISA spacecraft act as references for the local inertial frame. All forces acting on them must be reduced to below the $fN/Hz^{1/2}$ level in the millihertz LISA frequency band. Electric charge build-up on the test masses due to cosmic rays can produce a number of disturbance forces that must be controlled. The LISA charge management system (CMS) maintains the electric potential of the test masses relative to their housings to below the required level. While the LISA observatory is led by the European Space Agency, NASA will provide significant technological and scientific contributions. In 2017, NASA initiated strategic investments in key LISA technologies that could become U.S. flight hardware contributions. The only one of these technologies developed by a U.S. academic institution is a charge management system that seeks to improve upon the technology used by LISA Pathfinder. The CMS developed by the University of Florida uses fiber-coupled UV LEDs to illuminate the test masses or their housings to move electric charge via photemission. These light sources can be operated continuously or in a pulsed mode that takes advantage of existing electric fields within the LISA gravitational reference sensors to promote electron transport in the presence of uncertain test mass and housing surface properties. This talk will describe this vital U.S. contribution to the LISA mission in the context of the envisioned LISA payload architecture and the development and space-qualification activities currently underway.

Author(s): John Conklin[2], Peter J Wass[2], Taiwo Olatunde[2], Stephen Apple[2], Samantha Parry[2], Benjamin Letson[2], Simon Barke[1], Myles Clark[2], Guido Mueller[1]
Institution(s): *1. University of Florida, 2. University of Florida*

301 – Astronomy Across the Gravitational Wave Spectrum Poster Session

301.01 – The Gravitational Signature of Asteroid Populations on LISA Orbits

We have modeled the effect of the asteroid belt on the LISA spacecrafts. To do so, we obtained orbital and other parameters of 700,000 belt asteroids from the Jet Propulsion Laboratory Small-Body Database. Since many of the masses are unknown, we used measured values of albedo, absolute magnitude, and asteroid type to estimate the individual masses via a Monte Carlo method. The asteroids' and LISA spacecrafts' orbits are then simulated, and the force of the asteroids on each spacecraft is calculated. We can then generate several different scenarios by repeating the mass generation. This allows for creating a statistical distribution of the force on the LISA spacecrafts due to the asteroid belt. We expect to obtain a long-term secular influence on the LISA spacecrafts. In addition, we can probe the effects of different initial LISA configurations as well as what influence close-approach asteroids may have on the LISA constellation.

Author(s): David Bronicki[1], Brett Bolen[1], Shane L Larson[2]
Institution(s): *1. Grand Valley State University, 2. Northwester*

301.02 – Gravitational Wave Astrophysics in the Mid-band: Progenitors and Pre-merger Localizations of Advanced LIGO/Virgo Binary-merger Events

We consider the scientific potential of gravitational wave (GW) observations in the ~30 mHz to 3 Hz frequency range with the Mid-band Atomic Gravitational-wave Interferometric Sensor (MAGIS). MAGIS is a probe-class space-mission concept, using an atom-based GW detector, that will provide all-sky strain sensitivities of ~10^-21 sqrt(Hz) and better (1-year) in the frequency mid-band between the LISA/L3 detector and ground-based Advanced LIGO/Virgo interferometers. Primary GW astrophysics mid-band science include observations of the binary black hole (BH) population discovered by Advanced LIGO/Virgo, prior to their merger stage. For such systems, MAGIS will observe the binaries in their inspiral phase, where system parameters such as eccentricities are most easily constrained, and will provide pre-merger, degree-scale localizations that would enable electromagnetic observations of possible precursor emission 1-week to 1-month prior to their mergers as well as prompt post-merger transient emission. Joint GW observations with MAGIS and Advanced LIGO/Virgo covering all stages of binary coalescence will further reduce uncertainties in the GW localizations and distances, and will be powerful paired with galaxy catalogs, to enable unique galaxy counterpart identifications in the case BH-binary mergers are completely absent of detectable electromagnetic precursor or transient signals. These possibilities for MAGIS extend to neutron star (NS) binary systems (BH-NS, NS-NS), and mid-band prospects for such systems will also be considered. Importantly, the full sequence of binary evolution of Advanced LIGO/Virgo merger events through the GW mid-band and post-merger electromagnetic follow-up, will unfold within PhD timescales. The MAGIS team is a collaboration between institutes in the U.S. including Stanford, AOSense, Harvard, NASA/GSFC, NASA/JPL, NIST, NRL, and UC Berkeley, and international partners at Birmingham, Bordeaux, CNRS, Dusseldorf, Ecole Normale Superieure, Florence, Hannover, and Ulm University. Work at the Naval Research Laboratory is supported by the Chief of Naval Research.

Author(s): Chi C. Cheung2, Jason Hogan4, Peter Graham4, Mark A Kasevich4, Roger Romani4, Surjeet Rajendran5, Babak N. Saif[1], **Matthew Kerr[2]**, Michael Lovellette[2], Kent S. Wood3, Peter F. Michelson4
Institution(s): *1. NASA/GSFC, 2. Naval Research Laboratory, 3. Praxis, Inc., 4. Stanford University, 5. UC Berkeley*

302 – Compact Object Binaries Poster Session

302.02 – Population Synthesis on Massive Star Binaries: Astrophysical Implications for Gravitational Wave Sources

There are important but unresolved processes in the standard formation sce- narios of double compact star binaries (DCBs; BH-BH, BH-NS, NS-NS systems), such as the mass transfer and common envelope (CE). We analyze the effects of different assumptions on key physical processes and binary initial conditions on the massive star binary evolution with the binary pop- ulation synthesis (BPS), including a survey of proposed prescriptions for the mass transfer (qcr) and the binding energy parameter (λ) in the CE phase. We find that qcr clearly affects the properties of NS- NS systems while λ has influence on the mass distributions of BH-BH systems. The merger rates of DCBs are increased by the efficient CE ejection. It has been suggested that the difference in the properties of GW150914 and GW151226 may reflect different metallicity. We re- produce their properties with our BPS calculations and find that the property of BH-BH systems at low metallicity is sensitive to λ. The transition in the mode of the evolution toward BH-BH binaries must occur at $Z \sim 0.002 - 0.005$ ($0.13 - 0.25 Z_\odot$) to compare to the observed relative frequency of these two types of events. We predict that the NS-NS merger rate is at least near or even higher than the upper limit of the rate inferred by the indirect method (Kim et al. 2015), otherwise the BH-BH GW systems should be formed through a different evolutionarily pathway than NS-NS systems.

Author(s): Iminhaji Ablimit[1]
Institution(s): *1. Kyoto University*

302.03 – Modelling the Gravitational wave radiation from neutron star white dwarf binaries

In this talk, I will present a model for the gravitational waves (GW) radiated from neutron star-white dwarf binaries. Using the mili-Hz GW observations made by LISA, we may be able to determine the physical parameters of the binaries with very short orbital periods, which have been assumed to be ultracompact X-ray binaries. This model would be useful to understand the population of neutron star-white dwarf binaries, and to search for the black hole-white dwarf binaries.

Author(s): Shenghua YU[1]
Institution(s): *1. National Astronomical Observatories, CAS*

302.04 – Astrophysical Modeling of Gravitational-wave Binary Catalogs

The population of ultra-compact binaries in the Milky Way encodes a fossil record of binary stellar evolution in the galaxy. Taken as a population, the distributions of stellar types, orbital parameters, and masses encodes the signatures of processes that drive the evolution of these systems, including common envelope phases, and epochs of mass transfer.

In the years preceding LISA, Milky Way compact binary population simulations can be used to inform the science capabilities of the mission. Galactic population simulation efforts generally focus on high fidelity models that require extensive computational power to produce a single simulated population for each model. Each simulated population represents an incomplete sample of the functions governing compact binary evolution, thus introducing variance from one simulation to another. We present a rapid Monte Carlo population simulation technique that can simulate thousands of populations on week-long timescales, thus allowing a full exploration of the variance associated with a binary stellar evolution model. We illustrate the application of simulated LISA catalogs to probe various astrophysical processes that drive the population dynamics in the galactic ultra-comnpact binaries.

Author(s): Shane L Larson[1], Katelyn Breivik[1]
Institution(s): *1. Northwestern University*

302.05 – Gravitational Dynamics of Extended Bodies with Arbitrary Mass and Spin Multipoles

Gravitational wave detectors allow to test general relativity and study dynamics and internal structure of compact binaries with a potentially unlimited rigor. Currently, calculation of templates of gravitational waves emitted by the binaries is based on equations of motion of extended bodies in monopole-dipole approximation. Further progress in accurate calculation of the gravitational wave templates strictly depends on our ability to significantly improve theoretical description of dynamics of extended bodies by taking into account the higher-order mass and spin multipoles. This paper employs a scalar-tensor theory of gravity and a formalism of the Cartesian STF tensors to derive translational and rotational equations of motion of N bodies having arbitrary internal structure and infinite set of time-dependent mass and spin multipoles. We assume that spacetime is asymptotically-flat and can be covered by a single global coordinate chart. We also introduce N local coordinate charts attached to each body. The origin of the local coordinates moves along the world line of the center of mass of the corresponding body which is achieved by making an appropriate choice of the post-Newtonian definition of the body's center of mass. Equations of motion of the compact binaries are derived by integrating microscopic equations of motion of matter in the local coordinates and applying matched asymptotic technique to the metric tensor which is a solution of the field equations. We use the strong principle of equivalence to convert the coordinate-dependent form of the equations of motion to their covariant counterpart. This allows us to get a significant generalization of the Mathisson-Papapetrou-Dixon covariant equations of motion with regard to the number of body's multipoles. Equations of motion derived in the present paper can be used for much more accurate prediction of the templates of gravitational waves in compact binary systems immediately before the coalescence when the tidal forces play a dominant role in gravitational dynamics of the bodies leading to significant deviations from the orbital dynamics of pole-dipole massive particles.

Author(s): Sergei Kopeikin[1]
Institution(s): *1. University of Missouri*

302.06 – Characterizing and Detecting Hierarchical Triples in our Galaxy

LISA is expected to resolve tens of thousands of galactic binaries during its nominal 4 year mission lifetime. Given that roughly 15% of low-mass stars live in triples, and that three body interactions can help drive systems toward merger, it is possible that a good fraction of the galactic binaries detected by LISA will be members of a hierarchical triple system. I will discuss the circumstances under which we expect to be able to detect the existence of the hierarchical companion, and how well we can characterize these systems. I will also discuss how the presence of triples will impact the global analysis, and identify the conditions under which the triple may be mis-indentified as a binary system with unusually large mass.

Author(s): Travis Robson3, Neil J Cornish3, Valeriya Korol[2], Nicola Tamanini[1], Silvia Toonen4
Institution(s): *1. AEI Potsdam, 2. Leiden University, 3. Montana State University, 4. University of Amsterdam*

303 – Cosmology & Tests of Gravity Poster Session

303.02 – The Gravitational Compass: new space-based detection methods for circularly polarized gravitational waves

We investigate the sensitivity of space-based gravitational wave observatories based on the platonic solids -- tetrahedron, cube and octohedron -- to a circular polarization of an isotropic stochastic gravitational wave background (ISGWB) as a function of frequency. For such a detector geometry, each vertex is a drag-free satellite and each edge is a laser interferometer arm. Extrapolating the noise model from LISA to these new geometries, we find that these designs can lead to an increase in sensitivity to an ISGWB.

Author(s): Tristan Laine Smith[2], Robert Caldwell[1]
Institution(s): *1. Dartmouth College, 2. Swarthmore College*

303.03 – Probing the existence of ultralight bosons with a single gravitational-wave measurement

We demonstrate that gravitational waves from binary systems can provide smoking gun evidence for ultralight bosons (such as ultralight axions). If ultralight bosons exist, they will form ``clouds'' by extracting rotational energy from astrophysical black holes of size comparable to the boson Compton wavelength through superradiant instabilities. The properties of the cloud are intimately related with those of the black hole, and they are encoded in the gravitational waves emitted by compact objects orbiting the black hole/cloud system. We show that a single measurement of these waves yields at least three independent ways to estimate the mass of the boson from the cloud. Gravitational wave observations by LISA could either confirm the existence of ultralight bosons and measure their mass via ``consistency tests'' similar to the general relativity tests routinely performed with binary pulsars, or rule out the cloud's existence.

Author(s): Otto Akseli Hannuksela[2], Richard Brito[1], Emanuele Berti3, Tjonnie Guang Feng Li[2]
Institution(s): *1. Albert Einstein Institute, 2. The Chinese University of Hong Kong, 3. The University of Mississippi*

303.04 – Constraints on Horndeski Theory Using the Observations of Nordtvedt Effect, Shapiro Time Delay and Binary Pulsars

Alternative theories of gravity not only modify the polarization contents of the gravitational wave, but also affect the motions of the stars and the energy radiated away via the gravitational radiation. These aspects leave imprints in the observational data, which enables the test of General Relativity and its alternatives. In this work, the Nordtvedt effect and the Shapiro time delay are calculated in order to constrain Horndeski theory using the observations of lunar laser ranging experiments and Cassini time-delay data. The effective stress-energy tensor is also obtained using the method of Isaacson. Gravitational wave radiation of a binary system is calculated, and the change of the period of a binary system is deduced for the elliptical orbit. These results can be used to set constraints on Horndeski theory with the observations of binary systems, such as PSR J1738+0333. Constraints have been obtained for some subclasses of Horndeski theory, in particular, those satisfying the gravitational wave speed limits from GW170817 and GRB 170817A.

Author(s): Shaoqi Hou[1], Yungui Gong[1]
Institution(s): *1. Huazhong University of Science and Technology*

304 – Data Analysis Techniques Poster Session

301.10 – The International Pulsar Timing Array Mock Data Challenge

The International Pulsar Timing Array is a galactic-scale gravitational-wave observatory that monitors an array of millisecond pulsars. The timing precision of these pulsars is such (~ 100 ns) that one can measure the correlated changes in pulse TOAs accurately enough to search for the signature of a stochastic gravitational-wave background from super-massive black hole binaries. Since most of the power of the stochastic background is thought to be in frequencies smaller than 1/yr, our signal is expected to grow steadily as we are able to observe at lower frequencies and as we add more pulsars to our array. As our dataset matures we are approaching a regime where new data analysis tools will be extremely useful.

I will summarize the various sources of astrophysical and detector noise that are taken into account in a normal gravitational wave search in pulsar timing data, and show various strategies for their mitigation. Then I will introduce the mock data challenge that the IPTA is organizing. The purpose of this challenge is to foster the development of detection tools for pulsar timing arrays and to cultivate interaction with the international gravitational-wave community.

Author(s): Jeffrey Hazboun[1]
Institution(s): *1. NANOgrav*

304.02 – Bayesian Parameter Estimation with Gaps in LISA: A Data Augmentation Method

One of the highest priorities in the preparation of the LISA mission is the assessment and mitigation of the impact of data gaps on the science performance. It is foreseen that LISA will be affected by interruptions in the phase measurement, from various causes and at various frequencies of occurrence. Some of these interruptions are planned, such as possible laser frequency switches (from days to weeks), high-gain antenna re-pointing (2 weeks) and orbit corrections (months), while other may occur randomly. The model likelihood for correlated stationary time series with missing data is not straightforward to compute, because the approximate diagonalization of the covariance matrix in Fourier space is no longer feasible. We present a Bayesian method that reintroduces the missing data as auxiliary variables in the sampling of the posterior distribution, which dramatically improves its efficiency by recovering the convenient form of the complete data likelihood. In Monte-Carlo algorithms, this simply amounts to adding an extra step in the sampling process. As a case study we apply the method to the estimation of galactic binary parameters with different gap patterns. We show that the parameter precisions are close to the minimal variance bound derived from the Fisher matrix, and we compare these results to the case of complete data.

Author(s): Quentin Baghi[1]
Institution(s): *1. NASA Goddard Space Flight Center*

304.03 – Mitigation of Transients by an In-flight Estimation of the Differential Sensitivity in the MICROSCOPE Space Mission

For the first time, the equivalence principle (EP) has been tested in space thanks to the MICROSCOPE satellite, by measuring the free fall of two test-masses of different compositions in the gravitational field of the Earth. The mission, launched in April 2016, will provide a two-year measurement allowing a test of the EP with a target precision of 10^{-15}. As a sensitive space-based gravitational experiment, the analysis of MICROSCOPE data and the methods developed to achieve it are highly relevant for the future LISA mission. In particular, several transient perturbations are observed in the acceleration data. Similar artifacts have also been measured by LISA Pathfinder, and their impact on the final science performance must be carefully assessed. But these short events can also be used to probe the differential sensitivity of the instrument across the whole spectrum. We present a statistical method to estimate the differential transfer function of the instrument, and show that this estimation can be used to mitigate the glitch signal.

Author(s): Damien Boulanger[2], Quentin Baghi[1], Joel Bergé[2], Pierre Touboul[2], Gilles Métris[1], Manuel Rodrigues[2]
Institution(s): *1. Observatoire de la Côte d'Azur, 2. ONERA*

304.04 – Untrivial Stochastic Backgrounds: A Step towards Their Parameter Estimation

Many cosmological models predict a stochastic isotropic background whose frequency shape is not a power law. In this talk we briefly overview some of the predicted stochastic signals and we explore a method that enables to reconstruct their frequency shapes. The method does not assume any prior on the frequency shape and is thus particularly interesting for the reconstruction of an unexpected stochastic background. It is conceivable to implement this method in the LISA pipeline after improving our understanding of the instrumental noise.

Author(s): Germano Nardini[1]
Institution(s): *1. AEC, Univ. of Bern*

304.05 – The Challenge of Non-gravitational Wave Transients in LISA Data

The extraordinary sensitivity of gravitational wave detectors means they can be disturbed by instrumental and environmental transients and produce non-stationary data. The LISA Pathfinder mission in particular had a significant population of transients of incompletely known origin, which if present in LISA will increase the noise background, diminishing sensitivity to true gravitational waves and even causing possible false alarm detection candidates. This work describes the characteristics of this population of data transients in Pathfinder, will explore their effect on the complicated time delay interferometry output needed for LISA, and characterize the disturbances and possible mitigation strategies using time domain mission simulations.

Author(s): Jacob Slutsky[2], Quentin Baghi[2], Antoine Petiteau[1], Natalia Korsakova[3], Joseph Martino[1]
Institution(s): *1. APC, 2. Goddard Space Flight Center, 3. University of Glasgow*

304.06 – Characterizing LISA Black Hole Mergers

LISA is expected to observe numerous merging binary black hole systems with SNRs that may range from the detection threshold to thousands. Characterizing these signals to understand the properties of the sources and their positions is crucial for many of LISA's science objectives. The analysis requires fast, accurate and fully featured signal models, an efficient treatment for likelihood computations applicable even on long stretches of data, and Bayesian analysis methods suitable for complicated posterior distributions. We report on progress in developing practical techniques for this analysis and remaining challenges. In particular we describe differences between characterizations based only on l=2,m=2 mode wave forms (such as those featured in the current LISA data challenges) and those including higher-order angular modes.

Author(s): John Baker[2], Sylvain Marsat[1]
Institution(s): *1. Albert Einstein Institute, 2. NASA-GSFC*

304.07 – Searching for Compact Binary Mergers in Data from Second-generation Ground-based Interferometers

Advanced ground-based laser interferometers discovered the gravitational-wave signals from the mergers of several compact binaries over the last few years. A fundamental step in such discoveries has been processing the entire strain data produced by the interferometers, blindly searching for unknown signals over a wide parameter space and identifying spots in this parameter space which are likely to correspond to a signal, or at least warrant additional investigations. I will describe the challenges typically encountered in this step of the data analysis, the solutions which have been implemented and used over the last two observing runs, and how such challenges and solutions may or may not apply to a space-based interferometer like LISA.

Author(s): Tito Dal Canton[1]
Institution(s): *1. NASA Goddard / USRA*

304.08 – A Bayesian Approach to Modelling and Estimating LISA Noise

In this presentation, we demonstrate the impact of noise modelling on LISA science. To accurately recover gravitational wave signals and their astrophysical parameters from LISA data, it is paramount to have sophisticated statistical methods that can characterise and remove noise. As LISA will have multiple data streams, with potentially common sources of noise, we require methods from multivariate time series analysis to estimate the spectral density matrix characterising the data streams and their cross-correlations. To achieve this, we model the spectral density matrix of LISA noise using a Bayesian vector autoregression (BVAR) model with an independent Normal-Wishart prior. Gibbs sampling then allows us to decouple a gravitational wave signal from noise and to estimate its key astrophysical parameters. We will describe the methodological framework and present some results from applying the technique to simulated data.

Author(s): Matt Edwards[1], Jonathan Gair[1]
Institution(s): *1. University of Edinburgh*

304.09 – A Fast Fourier-domain Instrument Response for LISA

The space-based detector LISA will detect gravitational-wave signals from a variety of astrophysical sources, from mergers of massive black hole binaries at high redshift to inspirals of stellar-mass systems, complementing the higher-frequency band of ground-based detectors. Previous studies exploring the capabilities of LISA in recovering parameters of astrophysical systems often relied on inspiral-only signals and on the Fisher matrix approximation, due to computational cost limitations. We present a Fourier-domain approach to handle the full time-dependent modulations of the signal induced by the orbital motion of the detector. Using recently developed fast and accurate Fourier-domain waveform models that include the merger and ringdown, we are able to significantly accelerate likelihood computations, opening the way to an extensive coverage of the parameter space using Bayesian analyses.

Author(s): Sylvain Marsat[1], John Baker[2]
Institution(s): *1. Albert Einstein Institute Potsdam, 2. NASA GSFC*

305 – Electromagnetic Counterparts Poster Session

305.01 – Measurement of Magnetic Properties of an actual test mass in LISA/TianQin project by a single-stage torsion pendulum

Achieving the low frequency sensitivity of space-borne gravitational wave observatories requires that the test masses are critically running on the geodesic purity of the trajectories. The test masses in inertial sensors are acted as the interferometer end mirrors and are free-falling with a teeny degree of deviation. Magnetic disturbance can produce noisy torques through the interaction of the test mass with the environmental magnetic field and can be parameterized by the test mass residual dipole moment m and the magnetic susceptibility χ. In our research, a single-stage torsion pendulum, with suspending a solid massive test mass, has been used to measure the magnetic properties of LISA/TianQin-like test masses. The preliminary results exhibit that resolution of remnant moment and of magnetic susceptibility precision is about 1nAm2 and 8×10-7 respectively, which are well below the LISA/TianQin requirements.

Author(s): Hang Yin[1], Yanzheng Bai[1], Li Liu[1], Dingyin Tan[1], Qi Xia[1], Zebing Zhou[1]
Institution(s): *1. Huazhong University of Science and Technology*

305.02 – The Current Progress of Investigating Patch effect using an Electrostatic-controlled Torsion Pendulum

The surface potential variation produces force and force gradient between the proof mass and electrodes and has been identified as a significant error source in terrestrial or space-borne gravitational experiments. To measure the charge distribution and its variation with better precision and higher resolution, we have presented an electrostatic-controlled torsion pendulum with a scanning conducting probe. This scheme combines the scanning capability of the Kelvin probe and the high precision of the torsion pendulum. In order to improve the measuring efficiency, we present a optimized scheme recently. This poster will show the progress of patch effect measurement and design of improvement scheme.

Author(s): Chi Song[1], Yanzheng Bai[1], **Fangchao Yang[1]**, Hang Yin[1], Zebing Zhou[1]
Institution(s): *1. Huazhong University of Science and Technology*

305.03 – The long-term hydrodynamic evolution of Neutron Stars Merger remnants-including GW170817

Based on the special relativistic hydrodynamic equations and updated cooling function, we investigate the long-term evolution of Neutron Stars Merger (NSM) remnants of GW170817, and present the luminosity, flux, mass and radius of remnants, as well as the velocity, temperature and density of shocks. Moreover, three NSM models from one soft equation of state SFHo and two stiff equations of state, DD2 and TM1, are used to compare their influences on the hydrodynamic evolution of remnants. We find the density and temperature of remnants at the maximal luminosity are not sensitive to the power of the original remnant. For the ISM with the solar metallicity and $n_{\rm{H}}=1\, \rm {cm}^{-3}$, the density of the first shock $\sim 10^{-23}$ g cm^{-3} and the temperature $\sim 3\times 10^{5}$ K at the maximal luminosity phase; The temperature of the first shock decreases and there is a thin `dense' shell with density $\sim10^{-21}$ g cm^{-3} after the maximal luminosity. These characteristics may be helpful for future observations of NSM remnants.

Author(s): Menquan Liu[1], Jie Zhang[1]
Institution(s): *1. China West Normal University*

306 – Extreme Mass Ratio Inspirals Poster Session

306.01 – Gravitational Waves of Binary-EMRI and Astrophysical Applications

In this talk, I will present a new multi-band gravitational-wave (GW) source: binary-extreme-mass-ratio-inspiral (b-EMRI), i.e., a compact binary inspirals into a supermassive black hole. The binary itself will emit high frequency GWs which can be detected by aLIGO, and the binary inspiralling to the supermassvie blackhole will form an EMRI and emits low frequency GWs for LISA. I will demonstrate the GWs of b-EMRI, and discuss waveform glitch due to the gravitational recoil. From the glith, I show that LISA can accurately measure the kick velocity of the binary merger, and then measure how many linear momentum carried by GWs.

Author(s): Wen-Biao Han[1]
Institution(s): *1. Shanghai Astronomical Observatory*

306.02 – Listening to the gravitational-wave duet performed by a new type of extreme-mass-ratio inspirals

In this talk I will review our recent work on a new type of gravitational wave source. It consists of a stellar binary black hole falling towards a supermassive black hole. I will show, using both analytical arguments and and numerical simulations, that the infall leads to a capture of the binary by the supermassive black hole. The system evolves subsequently due to gravitational-wave radiation until the merger of the black hole binary. Most importantly, it emits, at the the same time, both milli-Hertz and hundred-Hertz gravitational waves. Such a system is an ideal target for future multi-band gravitational-wave observation using both ground- and space-based interferometers. We also propose a novel method of identifying such a unique event from LISA data stream.

Author(s): Xian Chen[1]
Institution(s): *1. Peking University*

306.03 – A catalog of EMRI flux data (progress report)

Models of the waveforms generated by extreme mass ratio inspirals (or EMRIs) will require self-force calculations that accurately compute the smaller body's trajectory as it orbits in the strong field of a massive Kerr black hole. The simplest approximation to such motion can be computed by using orbit-averaged self forces ("fluxes") to adiabatically evolve the small body through a sequence of geodesic orbits. Such a framework can serve as the foundation to a more complete analysis which includes further self force effects, and likely can be used as an effective "kludge" to stand in for a more accurate solution for the purpose of developing data analysis tools for LISA EMRI observations. Even such adiabatic models require substantial CPU power to produce fluxes which cover enough parameter space at sufficient accuracy to be useful. We are in the process of generating a dense catalog of EMRI flux data that will be publicly released as part of the Black Hole Perturbation Toolkit (http://bhptoolkit.org/) for community EMRI waveform modeling studies. We present here a progress report on the catalog so far.

Author(s): Scott Hughes[1]
Institution(s): *1. Massachusetts Institute of Technology*

306.04 – Second-order self-force calculations

Self-force theory is currently the primary method for modelling extreme mass-ratio inspirals (EMRIs), key sources for the gravitational-wave detector LISA. It is well known that for an accurate EMRI model, second-order self-force effects are critical, but calculations of these effects have been beset of obstacles. In this talk we present the first implemetation of a complete scheme for second-order self-force calculations. As a demonstration, we calculate the gravitational binding energy for quasi-circular orbits about a Schwarzschild black hole.

Author(s): Niels Warburton[1], Adam Pound[2], Barry Wardell[1], Jeremy Miller[2]
Institution(s): *1. University College Dublin, 2. University of Southampton*

306.05 – Prospects for identifying near-extremal black holes with LISA observations of EMRIs

Extreme Mass Ratio Inspirals (EMRIs) are a very exciting potential source of gravitational waves for LISA. Previous work has shown that EMRI observations can provide tight constraints on the spin of the central black hole, assuming that the spin is in the regime thought to be relevant for astrophysical black holes. Recent work has demonstrated that EMRIs in which the primary black hole is near maximally spinning (near-extremal) show qualitatively different features in their waveforms in the last cycles before merger. In this talk, we explore how well LISA might be able to measure the spin for near-extremal systems, if they exist, and hence test for the existence of extremal black holes in the Universe. We also explore the impact that data gaps have on these measurements, and hence assess whether there is a case for having protected periods for EMRIs observed by LISA.

Author(s): Ollie Burke[1], Jonathan Gair[1], Joan Simon[1]
Institution(s): *1. The University of Edinburgh*

306.06 – Gravitational self-force from quasilocal conservation laws

The gravitational waves emitted by binary systems with extreme mass ratios carry unique astrophysical information expected to be probed by the next generation of space-based gravitational wave detectors such as LISA. The detection of these binaries relies crucially on an accurate modeling of the gravitational self-force---that is, the backreaction of the orbiting body's gravitational field upon that of the more massive body---which drives their orbital evolution and gravitational wave emission. We present a novel derivation, based on conservation laws, of their basic equations of motion. In particular, these are formulated with the use of a quasilocal (rather than matter) stress-energy-momentum tensor so as to capture gravitational effects, including the self-force. Our approach offers a fresh geometrical picture from which to understand the self-force fundamentally, and potentially a useful new avenue for computing it practically.

Author(s): Marius Oltean[1], Richard Epp4, Carlos F. Sopuerta[2], Alessandro Spallicci3, Robert Mann4
Institution(s): *1. ICE, CSIC and IEEC, U. Autonoma de Barcelona and LPC2E, CNRS, U. d'Orleans, 2. Institute of Space Sciences (ICE, CSIC) and Institut d'Estudis Espacials de Catalunya (IEEC), 3. LPC2E, Centre National de la Recherche Scientifique (CNRS), Universite d'Orleans, 4. University of Waterloo*

306.07 – A supermassive black hole feeding on a main-sequence star and reverse chirps

Centers of galaxies are a fertile environment for a variety of violent processes, owing to the high density of stars and the presence of a supermassive black hole. Stars may be occasionally deflected onto a deadly trajectory, passing too close to the black hole where they are being tidally disrupted. We explore an alternative stellar-lethal pathway, in which a star approaches the black hole on a slowly shrinking circular orbit, until it overfills its Roche lobe. We show that such a star may than stably transfer its mass to the black hole, evolving through the emission of gravitational waves. The star will survive for 105-10^6 years, producing a millihertz gravitational wave signal, detectable by future detectors such as LISA, if it occurs at the center of a nearby galaxy, up to 10 Mpc. For low-mass stars, the evolution is faster than their Kelvin–Helmholtz cooling rate, driving the star out of the main-sequence. In some cases, the orbit expands, and thus the frequency and amplitude of the signal both decrease with time, resulting in a "reverse-chirp". In this unique class of LISA sources, the microphysical properties of the mass-losing star determine the evolution of the gravitational wave signal it produces.

Author(s): Itai Linial[1], Re'em Sari[1]
Institution(s): *1. Hebrew University*

306.08 – An effective-one-body approach to the orbital evolution of extreme mass ratio inspirals

The effective-one-body (EOB) model continually proves to be a flexible platform for combining information from numerical relativity and post-Newtonian theory into a comparatively simple form. This has allowed it to become one of the most widely used tools in waveform generation for LIGO. In recent years the gravitational self-force formalism, the main method in EMRI modelling, has been shown as a powerful tool in filling in terms in the EOB Hamiltonian unavailable from other methods. In this presentation I will describe progress towards using this self-force information within the EOB framework to allow fast, accurate evolutions of EMRIs. Conceptually this allows a splitting of all self-force information into orbit averaged fluxes representing dissipation, and relatively simple gauge invariant functions which encode conservative effects. Then, using Hamiltonian methods, the standard EOB equations of motion can be written in a simple form which allows fast integration. This offers a promising alternative method to the usual self-force equations of motion used for EMRI evolutions.

Author(s): Chris Kavanagh[1], thibault damour[1]
Institution(s): *1. Institut des Hautes Études Scientifiques*

307 – LISA Pathfinder Poster Session

307.01 – LISA Pathfinder final noise performance down to 20μHz: effect of disturbances on the low-frequency excess noise

In this poster the noise performance of LISA Pathfinder is presented by thoroughly describing the analysis performed in the course of the operations. It will provide a discussion on the analysis performed along a series of several uninterrupted noise-only runs and the corrections applied to raw acceleration noise time-series data.

We present a discussion on the disturbances detected on-board during the operations, followed by a more in-depth analysis on the spurious signals identified in the noise, that we call glitches. The statistical techniques used to evaluate the noise performance of LPF on the corrected noise data are also presented for each analyzed noise run, together with the excess low-frequency noise down to 20μHz that cannot be explained by the modeled noise so far.

Author(s): Eleonora Castelli[1]
Institution(s): *1. University of Trento*

307.02 – Thermo-elastic and thermo-optical induced noise on-board LISA Pathfinder

Thermal gradients on board the LISA Pathfinder mission can induce effects perturbing the main differential acceleration measurement between both free-falling test masses. Apart from thermal forces arising due to gradients around the test mass — radiation pressure, outgassing and radiometer— thermo-optical and thermo-elastic effects can also contribute to the instrument noise. There are two locations where such a distortion can be critical. First, the optical window, i.e. the interface between the optical bench and the test mass. This optical element ---the only not bonded on the Zerodur optical bench--- is clamped in a Titanium ring and therefore is susceptible to mechanical stress or changes in the refractive index due to thermal gradients across the glass. The second location are the struts holding the optical bench inside the thermal shield acting as the main thermal link to the outside (thermally noisier) environment. Temperature changes in these structures can induce net displacements or tilts of the bench with direct impact on the interferometer read-out.

Several dedicated experiments were carried out during LISA Pathfinder operations by applying controlled heat inputs to these locations. In this talk we show the results of the analysis performed for these experiments. We also provide an estimate of the impact of these noise contribution for the LISA.

Author(s): Francisco Rivas[1]
Institution(s): *1. IEEC, ICE-CSIC*

307.04 – The LISA Pathfinder dynamics: calibration experiments and results.

In this talk, I will report about the calibration experiments performed on board the LISA Pathfinder (LPF) satellite during the mission operations, in order to calculate the residual differential acceleration between the two test-masses. The analysis and the results of these experiments will be presented. Finally, the importance of possible calibration experiments to be performed on board the LISA observatory will be briefly discussed.

Author(s): Daniele Vetrugno[1]
Institution(s): *1. University of Trento*

308 – LISA Science Landscape in the 2030s Poster Session

308.01 – Introduction of a Structured Doctoral Programme model for the LISA Doctoral Programme

The IMPRS on Gravitational Wave Astronomy has become major resource for education in the field of gravitational wave physics.We have also set up a new programme called the the geo-Q Research Training Group. It aims to study relativistic geodesy and gravimetry with quantum sensors. The two programme started to provide substantial synergy to members of both programmes by our strong cross disciplinary approach. Our effort to create a joint programme has received excellent feedback from our scientists and various external committee members. Building on this successful establishment of a joint programme, we aim to set up the LISA Doctoral Programme, and to create a next generation of researchers who will carry on building a strong network of third generation gravitational wave detectors and observatories.

Author(s): Fumiko Kawazoe[1]
Institution(s): *1. Uni Hannover/AEI*

308.02 – Finding IMBHs with the Next Generation Very Large Array

Using the Next Generation Very Large Array (ngVLA), we will make a breakthrough inventory of intermediate-mass black holes (IMBHs) in hundreds of globular cluster systems out to a distance of 25 Mpc. IMBHs have masses of about 100 to 100,000 solar masses. Finding them in globular clusters would validate a formation channel for seed black holes in the early universe and inform event predictions for gravitational wave facilities, notably the *Laser Interferometer Space Antenna*. Our IMBH inventory is well suited for ngVLA Early Science starting in 2028.

Author(s): J. Wrobel[3], James Miller-Jones[1], Kristina Nyland[2], Tom Maccarone[4]
Institution(s): *1. Curtin University, 2. NRAO-CV, 3. NRAO-NM, 4. Texas Tech University*

309 – LISA Technology & Mission Design Poster Session

309.01 – High stability single frequency laser technology using in space based gravitional wave detection

A high stability single frequency NPRO (Nonplanar Ring Oscillator) laser and its typical space qualification results are presented. This laser are monolithically integrated including the laser crystal, TEC, PZT, thermister, magnet ,1/2 waveplate,1/4 waveplate and with fiber pumping input and polarization maintaining fiber output . The footprint is about 47(L)*38(W)*20(H)mm which is very small and rugged. Under 1.5W@808nm pumping condition , the fiber output power is about 600mW, the linewidth is less than 300Hz, PER is larger than 20dB. The output frequency can be easily tuned by thermal and PZT with a tuning coefficient of 2.8GHz/°Cand 2.7MHz/V respectively. This laser also passed the very stringent space environment qualifications such as 19.8rms mechanic random vibration test ,450g shock test and 12 thermal cycles between -20°Cand +65°C (slope 5°C/min) which show very little performance degradation. This laser is a very good candidate for using in space based gravitional wave detection.

Author(s): Dijun Chen[1], Guofeng Xin[1], Guangwei Sun[1], Xia Hou[1], Weibiao Chen[1]
Institution(s): *1. Shanghai Institute of Optics and Fine Mechanics,CAS*

309.02 – Program in Laser Interferometer for Space Gravitational Waves Detection

The idea of using space laser interferometer to measure the relative displacement change between two satellites has been considered for space gravitational waves detection in recent years. Some investigations on the key issues of laser interferometer in our working team have been presented in this paper. An on-ground laser interferometer prototype used for the demonstration of satellite-to-satellite ranging has been constructed by us, which is equipped with phasemeter, laser pointing modulation and laser phase-locking control. The experimental results show that path-length measurement sensitivity of the laser interferometer reaches 100 pm/√Hz, and phase measurement precision achieves 2π×10-5 rad/√Hz, and laser pointing modulation precision is better than 80 nrad/√Hz, and laser phase-locking control precision attains 2π×10-4 rad/√Hz within the frequency regime of 1 mHz – 1 Hz. All of these demonstrate that the proposed laser interferometer has very promising feasibility to meet the requirement of the Taiji mission which are put forward by Chinese scientists.

Author(s): Yuqiong Li[1]
Institution(s): *1. Institute of Mechanics, Academy of Chinese Sciences*

309.03 – The discussion of the amplitude fluctuation coupling noise for the phasemeter

Theoretically, the amplitude fluctuation of the incoming signal (due to the fluctuation of the received laser power) do not affect the obtained phase of LISA or Taiji (a LISA-like mission proposed by Chinese Academy of Sciences) phasemeter. However, we find out that the value of the obtained phase always change along with the amplitude fluctuation in the actual test. Noises spectrum are tested in the condition of the zero measurement in which the signal from one channel of a generator are divided into two and then delivered to the two channels of the phasemeter respectively. The ratio and the frequency of this sine fluctuation modulation are set to 0.5%, 0.01 Hz.
In the results of this experiment, some obvious peaks (up to 400 μrad/√Hz) are appeared at 0.01 Hz and its higher harmonics. It means that the amplitude fluctuation can affect the phase noise performance of the phasemeter. Moreover, the peaks also can't be decreased by the method of the common-mode noises rejection. It represents that this peaks might not be caused by the modulation itself but by the difference between the amplitude variations of the two input signals.
In the conference, we will give the preliminary experimental results and the theoretical analysis about the mechanism of the amplitude fluctuation coupling noise in the phase measurement. Moreover, it is also given that whether the noise will influence the phase measurement or not in the LISA or Taiji utilized condition.

Author(s): Heshan Liu[1], Ziren Luo[1], Gang Jin[1]
Institution(s): *1. Institute of Mechanics, Chinese Academy of Sciences*

309.04 – A new algorithm to improve acquisition accuracy for space gravitational waves detection mission

For space gravitational waves detection mission like LISA or Taiji, an important task of the spacecrafts after reaching its orbit is acquisition. In Taiji mission, with the help of acquisition system, pointing error can be reduced from 100μrad to1μrad. On the other hand, the time to accomplish acquisition shouldn't be too long so as not to waste time for scientific measurement. But there isn't a scheme that can fullfill all the requirement. In this paper, a new algorithm based on Brownian motion process is developed, which can improve acquisition accuracy for space gravitational waves detection mission.

Author(s): Ruihong Gao[1], Ziren Luo[1], Heshan Liu[1], Yuqiong Li[1]
Institution(s): *1. Institute of Mechanics, Chinese Academy of Sciences*

309.05 – Prototyping for the Distributed Data Processing Center of LISA

The LISA project preparation requires to study and define a new data analysis framework, capable of dealing with highly heterogeneous CPU needs and of exploiting the emergent information technologies. In this context, the mission'sDistributed Data Processing Center (DDPC) has been initiated. A prototyping of the DDPC already started in order to optimize the detailed desgin during phase A and to response to LISA Consortium needs. The DDPC will have to efficiently manage computing constraints and to offer a common infrastructure where the whole collaboration can contribute to development work. In the continuation of the mission Phase 0 study, new technologies based on virtualization (cloud computing, containers) have already been used to manage specific problems and to deliver encapsulated softwares within their environment to the collaboration. As an example, the LISACode simulator has been containerized and offers now to the collaboration an image including a JupyterHub server allowing to execute the code an plot the resulting data. For the LISA Data Challenge (LDC), we have developed a Web application in order to provide a sharing place for simulation files and to organise the Data Challenge. The full website stack is conterized and uses the continuous integration and continuous deployment platform of the IN2P3 computing center. The Web application is hosted on a virtual machine of the academic cloud. This presentation will show the components and technologies that have been used to provide an on-demand service hosting.

Author(s): Cecile Cavet[1], Antoine Petiteau[1], Maude Le Jeune[1]
Institution(s): *1. APC/CNRS*

309.06 – LISA Payload Opto-mechanical Architectures and Feasibility Verification

In the LISA constellation, orbital dynamics necessitate active compensation of the beam pointing on each spacecraft and drive the payload opto-mechanical architecture. In the extensively studied baseline architecture "Telescope Pointing" (TP), two large assemblies (featuring telescopes, optical benches and inertial sensors) are moved by low-noise/large-stroke linear actuators and are mutually referenced by an optical fiber. The back-up architecture "In-Field Pointing" (IFP) avoids the actuated phase-reference or large moving parts by placing small beam-tilting mechanisms with low angular noise into intermediate pupils of each wide-field-of-view telescopes rigidly connected to one optical bench. A single active inertial sensor also simplifies the drag-free control scheme.

In the current LISA baseline, a link-length of 2.5 million kilometers leads to moderate telescope diameters. A third candidate architecture, which we propose here, becomes attractive in this case and should be considered as back-up as well. In the "Siderostat Pointing" (SP) concept, a common interferometric bench is combined with two narrow-field telescopes. A tilting mirror (siderostat flat) in front of each telescope performs the beam pointing. Offsets between telescope entrance pupil and test mass are minimized by tiny adjustments of the siderostat pivot axis. Conceptual designs show promising features, like a moderate mass budget, high modularity, low complexity as well as an intrinsically elegant redundancy scheme.

A system-testbed at Airbus, co-funded by the German space agency DLR, has been developed as a platform to test key components of all three architectures and to verify feasibility of the two alternatives (IFP, SP). The actual all-Zerodur setup features a pm-precision OH-bonded heterodyne interferometer, a representative 2°-field-of-view 15-cm-aperture telescope and a prototype IFP-mechanism built by TNO. We present new results on driving a walking-piezo actuator with the required noise-level and suitable for applications in all three architectures. First end-to-end measurements for the IFP-architecture will be presented as well.

Author(s): Alexander Sell[1], Christina Brugger[1], Tim Vogel[1], Gert Witvoet[3], Ewan Fitzsimons[2], Noah Saks[1], Klaus Ergenzinger[1], Dennis Weise[1], Ulrich Johann[1]
Institution(s): *1. Airbus Defence and Space GmbH, 2. Royal Observatory Edinburgh, 3. TNO*

309.07 – Residual phase noise characterizations of RF components at low frequency offset

This poster reports residual phase noise characterizations of RF components at low frequency offset (0.1mHz - 10 Hz). The measurement method is explained, then measurement results of the following components are presented: RF mixer Minicircuits ZLW-1H, RF amplifier WanTcom WHM0005R, RF divider Linear Technology LTC6954 and RF divider Microsemi UXN14M9P.

These components shall be used in the developments of ground support equipments (such as low noise frequency generators) suitable for testing the LISA instrument.

Author(s): Pierre Prat[1]
Institution(s): *1. APC / CNRS*

309.08 – Experimental Results of InGaAs Quad Photoreceivers Subjected to Proton Radiation

Laser Interferometer Space Antenna (LISA) requires ultra-low noise Quad Photoreceiver, i.e. a 2 x 2 array of InGaAs p-i-n photodiodes followed by a transimpedance amplifier (TIA) per diode, to measure gravitational waves over 2.5 million kilometer baseline. We have manufactured the quad photoreceivers with three different diameters : 0.5 mm, 1mm, and 2 mm, all followed by a low noise, silicon bipolar operational amplifier. All these devices show a 3dB bandwidth of approximately 20 MHz, which is defined by the transimpedance amplifier circuit. It should be noted that a 2 mm diameter device, having 10 pF capacitance per quadrant, displays approximately 4x more noise density than a 1 mm device, having 2.5 pF capacitance per quadrant.

Based on the radiation environment for LISA mission, we decided to irradiate Quad Photoreceivers at the NASA Space Radiation Laboratory with 30 MeV protons up to a Total Ionizing Dose (TID) of 15 krad, 30 krad, and 50 krad. The highest dose corresponds to a 10+ year-long extended mission for LISA. Three exposures of 15, 30, and 50 krad, each one using 0.5 mm, 1 mm, and 2 mm diameter Quad Photoreceivers, were obtained.

Comparing the test results (3 devices x 3 radiation doses = 9 readings) before and after irradiation, the following observations can be made - (1) The Quad Photodiode's dark current is virtually the same for 15 krad dose. There is a ~7% increase in dark current at 30 krad dose, and ~33% increase in dark current at 50 krad dose. However, the photodiode's dark current was stable in all cases and its shot noise contribution was negligible as compared to other noise sources; (2) The drive current of the Intersil 5135 silicon bipolar Op Amps, shielded by the 1 mm thick Aluminum TO-3 package cap, is unchanged in all conditions; and (3) The output noise density results are essentially unchanged for all devices.

In summary, these tests show the resilience of both the input equivalent noise and transfer function of the Quad Photoreceivers in the presence of proton radiation with a TID up to 50 krad.

Author(s): Abhay Joshi[1], Shubhashish Datta[1]
Institution(s): *1. Discovery Semiconductors, Inc*

309.09 – All-fiber interferometer architecture for inter-spacecraft interferometry

We present a new laser interferometer architecture that can be used to relax the hardware requirements of future space-based displacement interferometers while offering the same displacement sensitivity as the Gravity Recovery and Climate Experiment (GRACE) Follow-On laser ranging interferometer. The all-fiber interferometer architecture, which forgoes the need for a stable glass optical bench, has been developed in response to the various challenges involved in adapting traditional interferometry techniques for space. In particular we aim to address the need to accurately construct and integrate optics on the spacecraft to avoid rotation of the spacecraft from coupling into the displacement measurement. Using multiple inter-spacecraft link measurements and high-speed signal processing, the inter-spacecraft displacement can be synthesized in post-processing. Linear combinations of link measurements can be formed to cancel rotation-to-pathlength coupling and other degrees of freedom that affect the displacement sensitivity. Since the weightings of the linear combinations can be adjusted in post-processing, any errors resulting from the positioning and alignment of the interferometer can be cancelled.

We will present the concept and signal processing required to synthesize the center of mass displacement from multiple inter-spacecraft link measurements. We will also present results of a proof of concept bench-top experiment and discuss the implications of applying the technique in a GRACE-like mission. While it was developed with a next-generation GRACE mission in mind, it is possible that this architecture could also benefit space-based gravitational wave interferometers such as LISA. We look forward to discussions on this topic.

Author(s): Samuel Francis[1], Daniel Anthony Shaddock[2]
Institution(s): *1. Jet Propulsion Laboratory, 2. The Australian National University*

309.10 – Optical fibre injectors for LISA

The optical benches that will make the sensitive displacement measurements for LISA will be supplied with laser light by optical fibres. An optical subassembly will collimate the light from these fibres, with the light going on to encounter beam manipulating optics to form the interferometers.

The custom-developed fibre injectors for LISA Pathfinder directly contributed to the excellent results from that mission, and a development is now underway to design and demonstrate fibre injectors specifically for LISA.

The LISA interferometry design requires fibre injectors that provide highly stable beam pointing, high quality output beam intensity profiles and wavefront smoothness and that can be aligned and bonded to an optical bench to within ~10 microradian absolute accuracy. The devices must also be non-magnetic, robust enough to survive launch, and able to handle 2 W of 1064 nm light for many years.

We report on the latest work to develop fibre injectors suitable for LISA, including results from a dedicated beam pointing stability experiment.

Author(s): Christian Killow[2], Ewan Fitzsimons[1], Michael Perreur-Lloyd[2], Phil Parr-Burman[1], David Robertson[2], Henry Ward[2], Martyn Wells[1]
Institution(s): *1. UK Astronomy Technology Centre, 2. University of Glasgow*

309.12 – Photoelectric quantum yields from gold surfaces for charge control

The reliability of charge control depends on a detailed undestanding of the photoelectric properties of the suarfaces within the gravitational reference sensor. A systematic study has been made of the dependence of quantum yield on surface roughness, angle of incidence and photon energy. The quantum yield has been studied over long periods of time (up to 3 years) and reliable yields have been obtained following surface cleaning and bake-out procedures.

Author(s): Timothy John Sumner[1], Daniel Hollington[1], Peter Wass[1], Fangchao Yang[1]
Institution(s): *1. Imperial College London*

309.13 – Colloid Thruster Life and Performance Modeling for the LISA Disturbance Reduction System

Colloid thrusters successfully operated on the LISA Pathfinder mission for over 3,000 hours, however, additional characterization is necessary to show that such devices can provide the performance and life for the entire LISA mission. A combination of thruster experiments and modeling is being used to assess the long-term performance of these thrusters for up to 60,000 hours. Failure analysis of the individual colloid emitters and their accompanying extractor and accelerator electrodes uses data of both ion and mass flux from multi-hour experiments to inform physics-based models that can then extrapolate to the long-term thruster behavior and performance. Key failure mechanisms such as grid and extractor shorting are determined by tracking the electrospray, internal, and surface fluxes of the propellant throughout the system. Additionally, electron backstreaming modeling is being used to examine tolerable electron fluxes within the system. These performance and life metrics are then be used to assess the implications on the performance of the LISA Disturbance Reduction System. Preliminary results show that relatively minor changes to the thrusters used on LISA Pathfinder provide high confidence in achieving the LISA mission objectives.

Author(s): Richard E. Wirz[1], Anirudh Thuppul[1], Peter Wright[1]
Institution(s): *1. UCLA*

309.14 – Laser frequency stabilization for space missions

Laser frequency stabilization is a key element for LISA, the next generation of gravity field missions based on laser interferometry and tests of special relativity. Here we present our efforts in developing a space-qualified frequency stabilized laser using modulation transfer spectroscopy on an iodine vapor cell as an alternative to an optical cavity. Performance compatible with the LISA requirements together with the results after going through several environmental tests are presented. The development of an optical cavity optimized for the very low frequency (0.2 mHz) Kennedy-Thorndike experiments in space will also be presented. The temperature stability needed is about 500 nK/rtHz at 0.2 mHz, which has been demonstrated by dedicated thermal shields and an active temperature control. Finally, the combination of a spectroscopy unit and an optical resonator in a single frequency stabilization system in order to take advantage of the properties of both systems will be briefly introduced.

Author(s): Josep Sanjuan[1], Thilo Schuldt[1], Martin Gohlke[1], Felipe Guzman[1], Klaus Doeringshoff[2], Markus Oswald3, Klaus Abich[1], Evgeny Kovalchuk[2], Achim Peters[2], Claus Braxmaeier3
Institution(s): *1. German Aerospace Center (DLR), 2. Humboldt-University Berlin, Institute of Physics, 3. University Bremen, Center of Applied Space Technology and Microgravity (ZARM)*

309.15 – Technology development for LISA

After the success of LISA Pathfinder, some of the crucial technologies for LISA still require further development. The European Space Agency conducts a technology programme to support the further development of, among others, aspects of the laser system and the phase measurement system. The poster summarizes the ongoing and planned technology activities, how they fit into the mission development schedule and the their complementarity to activities of international partners and payload providers.

Author(s): Oliver Jennrich[1]
Institution(s): *1. European Space Agency*

309.16 – Performance of an optical three-signal test for the LISA phasemeter

LISA will use high-precision heterodyne laser interferometry for the detection of gravitational waves at frequencies between 0.1 mHz and 1 Hz. A breadboard model for the electronic phase readout system (Phasemeter) of these interferometers was developed in the scope of an ESA technology development by a Danish German consortium and fullfills all performance requirements in electrical two-signal tests. Here we present the advances in the implementation of an optical testbed that enables tests of the whole LISA metrology, including prominently the Phasemeter and the photoreceivers. The experiment is based on an ultra-stable hexagonal optical bench. This allows the generation of three unequal heterodyne beatnotes that have a total phase sum of zero, thus providing the possibility to probe the readout for non-linearites in an optical three-signal test. This is critical for verifying the required readout precision in particular with a large dynamic range that LISA needs to implement time delay interferometry. A summary of the noise hunting conducted so far is given and the resulting performance close to the LISA requirement of 1 pm/sqrt(Hz) in the mHz regime is shown. Highlights include investigations on limitations by polarization effects and photoreceivers.

Author(s): Thomas S. Schwarze[1]
Institution(s): *1. AEI Hannover*

309.17 – Status of the LISA On Table Experiment, an electro-optical simulator of space based gravitational waves detector

LISA On Table (LOT) is an electro-optical simulator developed at APC laboratory, which aim at testing noise reduction techniques – mainly Time Delay Interferometry (TDI)- in a representative acquisition chain for space-based gravitational waves detectors such as LISA. It also allows the testing of prototype instruments such as phasemeters and photodiodes. The experiment consists of an optical interferometer in parallel with an electronic one, in which computer generated - via Direct Digital Synthesizers (DDS) – signals interfere, simulating the interference signals in LISA. We want to address the progress made on the experiment, in particular the first results after the optical interferometer has been put under vacuum. We show that it further reduces instrumental noises, allowing sharper tests of TDI to be conducted. We also present progress on tests of higher generation of TDI, with the development of Doppler effect simulations and evolving delays.

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309.18 – Gaining insight into TDI using LISANode and LISACode

We investigate time delay interferometry (TDI) for varying orbits using both LISANode and LISACode and an analytic model that includes various instrumental noise terms, low pass filtering, ranging uncertainties and the mode coupling induced by the calculation of the power spectral density using standard algorithms. We demonstrate that many effects can be understood analytically by showing the exquisite agreement between theory and simulation. We conclude by proposing that our methodology can be used for optimization of some components of the instrument.

Author(s): Marc Lilley[1]
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309.19 – Far-Field Optical Ground Support Equipment for LISA AIVT

LISA is based on laser interferometry to measure the tiny change in distance between free-falling mirrors, due to a gravitational wave. Space offers a very quiet environment in the measurement frequency range of the instrument and allows longer arm-length, so a better sensitivity.
LISA achieves the requisite approximate $3.10^{-20}/\sqrt{Hz}$ strain sensitivity, resulting in a displacement sensitivity of 11.10^{-12} m/$\sqrt{Hz}$ over a path length of 2.5.109 m. The achievable reductions of disturbances on test masses and displacement sensitivities by the laser ranging system yield a useful measurement bandwidth in the frequency range from 3.10^{-5} Hz to 1 Hz.
France is in charge of the AIVT (Assemblage, Integration, Validation, Tests) of the MOSA (Moving Optical Sub-Assembly), which is an assembly of the Optical Bench, the Telescope and the Gravitational Reference Sensor. To perform this assembly, special check-out equipment will be required, such as the Far-Field Optical Ground Support Equipment which has to simulate the characteristics of the laser beam coming from the far satellite and entering the telescope such as truncated beam shape, leak optical power, and small wavefront perturbation while monitoring also the phase of the beam going out from the telescope.
It will be used to verify the alignment of the transmitted/received pupils, the Point-Ahead Angle Mechanism control, the measurement of the Tilt To Length coupling and the science IFO heterodyne efficiency and performance verification. It has to perform the constraints on the measurements described before: pm/$\sqrt{Hz}$ and nrad/$\sqrt{Hz}$. These requirements will govern the design of the FF-OGSE: its resonance frequencies and thermal stabilities, its dimensions, its optical characteristics, the straylight issues.
We will present the investigations under study in order to define accurately the role and requirements of the FF-OGSE and the detailed tests to be performed with this equipment. We will introduce the possible implementation of test equipment on the optical bench and will give some insights concerning the definition of its characteristics, that will be defined in more details during the phase A.

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309.20 – Design and Testing of a Pulsed Current Driver for UV LED-based Synchronized Charge Control

This presentation will detail the electronics design and preliminary testing for the LISA charge management system (CMS), as well as evaluating new test mass charge control techniques using these electronics. A discharge method using continuous UV emission from Hg lamps was demonstrated on LISA Pathfinder, successfully controlling the charge of the test mass within the Gravitational Reference Sensor (GRS). Hg lamps are projected to be replaced by UV LEDs in LISA. UV LEDs are lighter, more power efficient, and have a higher bandwidth, enabling synchronized charge control. In a synchronized scheme, the UV LEDs are operated in phase with 100 kHz oscillating electric fields within the GRS maximizing the robustness of the discharge operation and adding redundancy options. Electronics to pulse UV LEDs with tens of nanoseconds precision at a 100 kHz repetition rate are being designed at the University of Florida’s Precision Space Systems Laboratory (PSSL). A fast-current source with adjustable duty cycle, amplitude, and phase that can be synchronized to an external reference is being built for in-house lifetime and performance tests of UV LEDs. The electronics are also being built for incorporation within a breadboard system, raising the CMS technology readiness level (TRL) to 4 by the end of 2018. Discussion will include details of the pulsed electronics design, testing results, and the path towards a space-qualified version. The TRL-4 CMS is designed to meet discharging requirements for both DC and synchronized UV LED operation, as well as both fast and continuous charge control techniques. Possible implementations of each of these schemes and their validation using the University of Florida Torsion Pendulum will also be presented.

Author(s): Samantha Parry[1], Paul Serra[1], Taiwo Olatunde[1], Ben Letson[1], Myles Clark[1], Simon Barke[1], Guido Mueller[1], Peter J Wass[1], John Conklin[1]
Institution(s): *1. University of Florida*

309.21 – Stability of Phase Delay of Quadrant Photodetectors for Ultra-Precision Wavefront Measurement

The establishment of intersatellite laser links is a prerequisite for scientific observation of space-based gravitational waves detection. To achieve the sensitivity goal of $1pm/Hz^{1/2}$ for inter-satellite laser interferometry used in TianQin mission, the requirements for beam pointing stability would be about 5×10^{-8}rad for laser beam pointing offset and $1\times10^{-9}rad/Hz^{1/2}$ for laser beam pointing jitter. As the pointing angle of laser beams are measured by using differential wavefront sensing technique with quadrant-photodetectors, the precision measurement of laser beam pointing angle puts forward stringent requirements for the performance of photodetectors. We have studied the frequency response and the phase delay of quadrant photodetectors that could influence the measurement precision of the differential wavefront sensing. In order to meet the requirements of measurement precision, we analyze the transfer function of photodetectors, and obtain that the instability of the reverse voltage applied on the photodiodes should be less than $1\times10^{-4}V/Hz^{1/2}$, and the temperature fluctuation and the temperature difference between circuit channels for each quadrant should be less than $1\times10^{-3}K/Hz^{1/2}$ and 6×10^{-2}K respectively. The updated experimental results will be shown in the conference.

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309.22 – The LISA diagnostics subsystem: impact of the environment in space gravitational wave detectors

The LISA concept relies on the long arm-length differential measurement between free-falling test masses at the end of each interferometer link. The drag-free loop prevents spurious forces to disturb the nominal geodesic motion of these test masses. However, some noise contributions can not be shielded or avoided and, hence need to be monitored on-board. This is the aim of the LISA diagnostics subsystem, i.e. to provide a precise description of the environment on-board the space-craft which helps disentangle different noise sources and building up a noise model of the instrument. In the current baseline it is composed by temperature sensors, magnetometers and a radiation monitor, plus some actuators (as heaters) to induce controlled signals for calibration purposes.

The LISA diagnostic subsystem has a direct heritage from LISA Pathfinder. The data provided by the sensors on-board the satellite ---together with the experiments performed with the diagnostic subsystem--- contain a wealth of information crucial to understand the space environment in the context of a space gravitational wave detector. In this talk we will describe how the LISA Pathfinder data helps understanding the impact of the space environment for gravitational wave missions, the consequences for LISA and the current planning for the development of the diagnostics to be flown on board LISA.

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309.23 – Stability and pertubations of LISA Orbits

In order to detect gravitational waves, the LISA spacecraft are following tests masses that are kept inertial along the line of sight between the satellites. The orbital parameters are also chosen so that the LISA constellation forms a stable equilateral configuration. The requirements primarily come from the accommodation of the Doppler shifts in the available frequency bandwidth of the photoreceivers and the minimization of the flexing angle at each vertex.
With no foreseen orbit control maneuver over more than 10 years (including commissioning, nominal and extended mission phases), the constellation shape and dynamics will be very sensitive to the initial positioning and velocity dispersion, as well as spurious acceleration on the test masses.
In this poster, we propose to review and quantify the orbital effects of some of these perturbations, and, conversely, to assess the possibility of measuring perturbing forces (such as local gravitational imbalance within the satellite) from S/C relative velocities and positions.

Author(s): Hubert Halloin[1]
Institution(s): *1. APC / University Paris Diderot*

309.24 – Stray Light in the LISA Instrument: Characterization Activities

In the LISA mission, the presence of stray light is a concern since a perturbation of the heterodyne phase measurement at the level of several µradian can give rise to significant noise in the LISA gravitational wave measurement. The perturbation scales as the square root of the stray light to nominal beam optical power ratio. Reaching very low deviation of the phase measurement may require a very strong rejection of coherent stray light. Apart from coherent interference in the heterodyne phase measurements, stray light can also shift measurements through an incoherent contribution. Various detectors, such as the CAS (constellation acquisition sensors) could receive light due to backscattering in the telescope optics, or from stars or planets, with a non-negligible power.

A group of French laboratories has started a comprehensive study on the various aspects of stray light, having in mind the MOSA (moving optical sub-assembly) AIVT phase of the mission. We present work undertaken to set-up experiments for characterizing stray light at component and system level.

We present calibrated measurements of coherent back-scatter (BS) from a target with surface roughness, and interpretation of the data by a model description of the BS amplitude. The latter displays
- speckle-type variations when the sample is translated in front of the incident beam
- fast variations when the sample orientation changes with respect the laser beam. These observations are interpreted using an electromagnetic model of the fields scattered by the surface, taking into account the measured surface topography and the design (thicknesses & optical indexes) of the coating constitutive of the mirror.

Particulate contamination of the surfaces will take place during the assembly and launch phases and previous experimental and numerical studies have highlighted the key role of contamination in the scattering budget for high performance optical components. In this context we also present images of a super-polished mirror and the measurements of the coherent BS amplitude from the mirror over time scales long enough that the mirror will get dirty.

Author(s): Michel Lintz[2], Vitalii Khodnevych[2], Sibilla Di Pace[2], Nicoleta Dinu-Jaeger[2], Jean-Yves Vinet[2], Catherine Nary Man[2], Myriam Zerrad[1], Michel Lequime[1], Claude Amra[1]
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309.25 – Performance Testing of 100 UV LED Light Sources for the LISA Charge Management System

The test masses for LISA will need to be kept as free from electrical charge build-up as possible to minimize the effect of electrostatic forces on gravitational wave observations. This means that the test masses will need to be periodically or continuously discharged to neutralize any charge build-up caused by cosmic rays. Discharging of the test masses is done by photoemission under illumination with ultraviolet light with a wavelength around 250 nm. As a future light source for LISA, ultraviolet LEDs (UV LEDs) offer many advantages over the mercury lamps used in LISA Pathfinder. However, since UV LEDs are not a flight-proven technology, they must first go through multiple tests in order to analyze how well they will perform in the expected conditions aboard the spacecraft.
Only two vendors worldwide supply UV LEDs with peak wavelength emission below 260 nm. This presentation will address the current effort to characterize the properties of UV LEDs from both suppliers for use in the Charge Management System (CMS) for LISA. The results from tests on a large sample of ~100 UV LEDs designed to demonstrate performance across the expected operational temperature range for LISA will be presented including: spectra, current-voltage characteristics, UV output in continuous output and in a fast-pulsed mode. A series of stress tests aimed at identifying key factors that will contribute to the degradation of the UV output over the lifetime of the LISA mission will be presented. The plans to conduct lifetime tests on the UV LEDs to analyze the effects of these key factors during an extended time period will also be discussed.

Author(s): Ben Letson[1], Simon Barke[1], Myles Clark[1], Samantha Parry[1], Taiwo Olatunde[1], Guido Mueller[1], Peter J Wass[1], John Conklin[1]
Institution(s): *1. University of Florida*

309.26 – The UF LISA Backlink Simulator

The LISA backlink is used to synthesize the beam splitter of a traditional Michelson interferometer. It is a critical part of the interferometry measurement system and has been identified as a priority target for Phase A studies. The primary method by which the backlink has been implemented in the past is through an optical fiber, which has not yet been shown to meet the reciprocal path length stability requirements without additional hardware beyond previous LISA designs. We have therefore developed the UF Backlink Simulator, a testbed designed to assess the viability of a freespace backlink. This implementation of the backlink uses actuated mirrors in place of an optical fiber, and would serve as an alternative to optical fibers in the event that they are deemed unviable. Furthermore, we are developing a set of mechanical interfaces for off-the-shelf mirror mounts for use with LISA-like ULE glass optical benches, as well as a set of compact actuated mirror mounts which could serve as the mirrors for the LISA backlink. The UF backlink simulator will use them in future testbeds. We present results from an initial proof-of-concept study and describe ongoing enhancements to the testbed which will enable us to demonstrate that the freespace backlink meets the LISA requirements.

Author(s): Andrew Chilton[1], Daniel A Hillsberry[1], Derek Klein[1], John Conklin[1], **Guido Mueller[1]**, Joe Gleason[1]
Institution(s): *1. University of Florida*

309.27 – University of Florida Torsion Pendulum for Testing Key LISA Technology

This presentation will describe the design and performance of a new torsion pendulum facility at the University of Florida. This torsion pendulum facility is testing inertial sensors and associated technology for the upcoming LISA (laser interferometer space antenna) space-based gravitational wave observatory mission. Recently the torsion pendulum facility has been used to test and validate various UV LED based charge control techniques as well as characterize gravitational reference sensor (GRS) acceleration noise.
The torsion pendulum apparatus is comprised of a suspended cross bar assembly that has LISA test mass mockups at each of its ends. Two of the test mass mockups are enclosed by capacitive sensors which provide actuation and position sensing. The entire assembly is housed in a vacuum chamber. The pendulum cross-bar converts rotational motion of the test masses about the suspension fiber axis into translational motion. The 22 cm cross bar arm length along with the extremely small torsional spring constant of the suspension fiber results in a near free fall condition in the translational degree-of-freedom orthogonal to both the member and the suspension fiber. The test masses are electrically isolated from the pendulum assembly and their charge is controlled via photoemission using fiber coupled UV LEDS. Position of the test masses is measured using both capacitive and interferometric readout. The broadband sensitivity of the capacitive readout and laser interferometer readout is 30 nm/$\sqrt{Hz}$ and 0.5 nm/$\sqrt{Hz}$ respectively. The performance of the pendulum measured in equivalent acceleration noise acting on a LISA test mass is approximately 3×10^{-13} ms^{-2}/$\sqrt{Hz}$ at 2 mHz. This presentation will also discuss a number of upgrades to the pendulum facility that will be made in the coming months. One such upgrade will be the integration of a flight-like gravitational reference sensor. This flight-like GRS will allow for noise performance measurements in a more LISA-like configuration and for the testing of novel UV light injectors for test mass charge management.

Author(s): Stephen Apple[1], Andrew Chilton[2], Taiwo Olatunde[1], Daniel A Hillsberry[1], Samantha Parry[1], Peter J Wass[1], Guido Mueller[2], John Conklin[1]
Institution(s): *1. University of Florida, 2. Universtiy of Florida*

309.28 – Ultra-stable Mechanical Interfaces for Optical Bench and Telescope Testing

The size and complexity of components which must exhibit picometer stability have increased significantly from LISA Pathfinder to LISA. This increase is accompanied by an even larger increase in the number and types of pm-stable components for ground testing; the most prominent being the testbeds for the telescope and for the optical bench backlink.

In the past, those structures were built using hydroxide-catalysis bonding of optics on ultra low CTE base plates. These bonds are extremely stable but also irreversible and hence inflexible.

Further more, hydroxide bonding requirements exceptional surface quality which makes this technique very costly.
We started to develop flexible and reversible mounting interfaces which locate off-the-shelf optomechanical components with respect to an ultra low CTE base plate. These mounts have shown urad stability and sub-nm/rtHz stability over two weeks in air in a normal lab environment. In future experiments we aim for pm/rtHz stability inside a thermally stable vacuum chamber. Based on the success of these early tests, we started to design a pm stable test bench for the telescope which is based on these designs. We will present the components, their stability, future planned tests, and a design for the LISA telescope testbed.

Author(s): Simon F Barke[1], Reid Ferguson[1], Todd C Kozlowski[1], Soham Kulkarni[1], Michele Martinazzo[1], Joe Gleason[1], Paul Fulda[1], Guido Mueller[1]
Institution(s): *1. University of Florida*

309.29 – Ultra-stable fiber injectors for rapid development cycles

The development of LISA technology requires state-of-the-art laser interferometry testbeds with picometer pathlength stability, on the one hand, but rapid development cycles with moderate cost factors, on the other. Due to their inherent complexity, quasi-monolithic fiber injectors—so-called fiber injector optical subassemblies (FIOSs)—constitute one of the most challenging components in these respects. Here, we present a new breed of thermally compensated FIOS as a well-balanced compromise of all of the above aspects along with two use cases: 1. Our so-called Hexagon Interferometer is not only capable of probing our prototype LISA phasemeter technology for nonlinearities in the measurement process but also of testing the system's auxiliary functionality, like inter-spacecraft clock tone transfer, PSN ranging, and data communication. 2. Our Three-Backlink Interferometer will be key to investigating and directly comparing several competing realizations of an optical phase reference distribution system (PRDS) between a LISA spacecraft's two optical benches.

Author(s): Daniel Penkert[1], Dennis Schmelzer[1], Michael Tröbs[1], Thomas S. Schwarze[1], Katharina Sophie Isleif[1], Oliver Gerberding[1], Gerhard Heinzel[1]
Institution(s): *1. AEI Hannover*

309.30 – LISA Design Sensitivities

With the recent acceptance of LISA as the ESA L3 mission, and the renewed investment from NASA, it is necessary to revisit and update models for the scientific capabilities of LISA. Because of the large number of parameters involved in describing the astrophysical signal as well as the LISA instrument, it is useful to study performance as a function of multiple parameters and over the full range of relevant values simultaneously. To that end, we examine LISA's scientific capabilities using the L3 mission proposal as a base model to probe the present variation in design sensitivities. We use the phenomenological, precessing, unequal mass and generic spin waveform model, IMRPhenomP, to produce the binary black hole IMR signals expected to be in the milliHertz band. Combining the variations in both source parameters and LISA instrument parameters allows us to model the SNR for any LISA-esque design and source.

Author(s): Andrew Kaiser[1]
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309.31 – LISA Mission Configuration and Self-gravity Variations

LISA's mission is to measure gravitational waves as the strain between pairs of free falling proof masses distant 2.5 million kilometers. Mission design foresees that three identical satellites each containing two proof masses, orbit around the sun on an Earth trailing path in triangular formation allowing three measurement links simultaneously. Variations in the satellite local gravity create TM acceleration and thus an effective strain between the distant proof masses. We discuss the main mechanisms, including fuel depletion and the variation in the "opening angle" between adjacent axes defined by the triangle and the resulting effects on the mission performances.

Author(s): Valerio Ferroni[1]
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309.32 – On-ground Torsion Pendulum Testing with an Exact Copy of the GRS of LISA Pathfinder

In the design of the gravitational reference sensors (GRS) for LISA PF, torsion pendulums have proved to be crucial tools for studying stray forces and for the characterization of the overall gravitational reference sensor performance. An exact copy of the GRS flown in LISA Pathfinder installed in our torsion pendulum facility allows to perform targeted and representative test for supporting both the interpretation of the analogous measurement performed with LISA PF, and the final flight model GRS design/commissioning for LISA. We report here in particular on a measurement campaign dedicated to thermal effects, plus an upcoming series of measurements dedicated to the robustness of the UV test mass discharge system, including the use of LEDs as a UV light source.

Author(s): Antonella Cavalleri[1]
Institution(s): *1. Università di Trento*

310 – Other Poster Session

310.01 – Requirement Analysis and Development Status of the Laser System for TianQin

The TianQin project in China aims for building a space-borne gravitational wave observatory consisting of three spacecrafts in Earth orbit. As one of the most critical parts of this project, the laser system is currently under development. It will be comprised of three major components: a narrow linewidth solid-state laser, a low-noise ytterbium-doped fiber amplifier and a frequency reference unit. Here we will present the analysis of the laser system requirements and its current development status.

Author(s): Guoping Lin[1], Ranran Ji[1], Yaqin Cao[1], Cuifang Hou[1], Feihu Cheng[1], Jian Zhao[1], Ke Deng[1], Jie Zhang[1], Zehuang Lu[1]
Institution(s): *1. Huazhong University of Science and Technology*

310.02 – Radiative Charge Transfer and Association in Ar+H$^+$ and Ar$^+$+H Collisions

A 2013 paper by Barlow et al. [1] revealed the presence of argonium ^{36}ArH$^+$ in the Crab Nebula by detecting the rotational lines J = 1–0 and J = 2–1 at the frequencies 617.53 and 1234.60GHz, respectively. The finding was the first noble gas molecule detected in space. Since then, this astrophysical discovery launched a great amount of investigations dealing with the ionic dimer ArH$^+$ [2-9].

The present work aims at the characterization of two argonium isotopologues, namely, ^{36}ArH$^+$ and ^{38}ArH$^+$, by looking at the radiative processes of charge transfer (1) and association (2):

(1) Ar$^+$(^2P) + H(^2S) → Ar(^1S) + H$^+$ + $h\nu$
(2) Ar($^{1,3}P$) + H$^+$ → ArH$^+$ + $h\nu$.

To accomplish these two tasks, the corresponding potential-energy curves and transition dipole moments are determined in order to construct the ground $X\ ^1\Sigma^+$ and excited $A\ ^1\Sigma^+$, $B\ ^1\Pi$, $C\ ^1\Sigma^+$, and $D\ ^1\Pi$ molecular states and the allowed transition moments that connect the ground and excited singlet states, i.e., A→X, B→X, C→X, and D→X. Once all the required ArH$^+$ curves are well established and their physical features and spectroscopic values are contrasted with previous published data, the cross sections, for the radiative charge transfer in the Ar+H$^+$ collisions and for the formation of the diatomic ions ArH^+ by radiative association, are computed quantum-mechanically at lower and higher energies. Finally, the temperature-dependent rate coefficients are calculated, and the numerical results are discussed and fitted to a selected analytical expression.

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310.03 – The Effect of the Earth Gravity Field Measurement Uncertainty on Gravitational Waves Detection with TianQin

The success of space-borne laser interferometry gravitational wave (GW) detection relies on accurate residual optical path difference measruement. However, the uncertainty of the Earth gravitational field measurement has the potential of introducing noise to space-borne GW missions, through imprecise orbit model, mimicing the GW signal and contaminating the detection. Geocentric GW missions (e.g. TianQin) would suffer from such noise source most strongly, while such effect has not been systematically studied yet. In order to quantitatively investigate this effect, we set up a dynamical model for the TianQin spacecraft to carry out an analytical solution to the orbit. Two representative static Earth gravity field models, EGM2008 and GO_CONS_GCF_2_DIR_R5 (DIR-R5) are adopted, to calculate the corresponding noise budget by Monte Carlo simulation. Both the EGM2008 model and the DIR-R5 model lead to lower noise strength compared with instrumental noise curve of TianQin. With the more updated and accurate DIR-R5 curve buried deeper under the noise, we conclude that with modern Earth gravity field models, the noise contribution from higher order Earth multipole moments will not prevent TianQin from successful gravitational wave detections.

Author(s): Yi-Ming Hu[1]
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310.04 – Multi-dimensional Assembly Method of Ultra-stable Optical Bench Integrated for Spaceborne PDH Laser Frequency Stabilization

A space-compatible assembly method for the integration of an ultra-stable optical system with multi-dimensional precision alignment ability, for the application of spaceborne Pound-Drever-Hall (PDH) laser frequency stabilization in measurements of inter-spacecraft laser interferometry, is presented in this report. For a PDH laser stabilization setup, the Gaussian mode-matching efficiency between incident laser and the ultra-stable Fabry Pérot (FP) cavity will affect the detected PDH signal-to-noise ratio as well as the frequency discrimination sensitivity of the laser control system, and thus greatly influence the final laser frequency stability. Furthermore, an optical assembly method to fabricate an optical system which can maintain a steadily high optical efficiency as well as a mechanical strength to withstand the vibrations and impacts caused during launching, is important for the laser stabilization system to meet the space-qualified requirement. In this work, an in-situ precision adjustment setup, with ability of optical alignment in five dimensions at the same time during the optical integration by applying the hydroxide-catalysis bonding technique, has been developed to assemble the mode-matching optics between laser and the cavity. The method described in this report is also applicable for experiments that need high-precision and multi-dimensional adjustment of components whose exact optical axis is different from its mechanical axis and cannot be correctly measured by the coordinate measuring machine (CMM). Experimental details of this setup and the preliminary results will be presented in the conference.

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310.05 – Fundamentals of the orbit and response for TianQin

TianQin is a space-based laser interferometric gravitational wave detector aimed at detecting gravitational waves at low frequencies (0.1 mHz–1 Hz). It is formed by three identical drag-free spacecrafts in an equilateral triangular constellation orbiting around the Earth. The distance between each pair of spacecrafts is approximately 1.7×10^5 km . The spacecrafts are interconnected by infrared laser beams forming up to three Michelson-type interferometers. The detailed mission design and the study of science objectives for the TianQin project depend crucially on the orbit and the response of the detector. In this paper, we provide the analytic expressions for the coordinates of the orbit for each spacecraft in the heliocentric-ecliptic coordinate system to the leading orders. This enables a sufficiently accurate study of science objectives and data analysis, and serves as a first step to further orbit design and optimization. We calculate the response of a single Michelson detector to plane gravitational waves in arbitrary waveform which is valid in the full range of the sensitive frequencies. It is then used to generate the more realistic sensitivity curve of TianQin. We apply this model on a reference white-dwarf binary as a proof of principle.

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310.06 – In-orbit Testing of High-precision Electrostatic Accelerometer aboard TZ-1 Cargo Spacecraft

High-precision electrostatic accelerometers have been widely used in satellite gravity missions to measure the Earth's gravity field. In our group, space electrostatic accelerometer based on the capacitive sensors and electrostatic control technique has been investigated nearly twenty years for space science research in China such asTISS (test of the Inversed-Square law in Space), TEPO (Test of Equivalence Principle in space with Optical readout), and the satellite gravity measurementmission and so on. In 2017, a flight model of electrostatic accelerometer developed by our group was successfully tested aboard Chinese Tianzhou-1 (TZ-1) cargo spacecraft. This poster will give the in-orbit function and performance verification results of the electrostatic accelerometer.

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Institution(s): *1. Huazhong University of Science and Technology*

310.07 – Progress of Optical Readout interferometer for Gravitational Reference Sensor at Tianqin Research Center

GRS (Gravitational Reference Sensor) plays a key role in gravitational experiments, such as space-based gravitational wave detection and geodesy. The capacitive sensor is typically used in GRS for displacement sensing due to its compactness, and easy-integrating with electrostatic feedback control system. In order to avoid the problem of electrical noise caused by a small gap between electrostatic plates, the optical displacement sensor is an ideal scheme that has been demonstrated successfully by LISA Pathfinder. In this paper, we present updated progress of multiple DOFs optical readout interferometer for gravitational reference sensor at Tianqin Research Center. Based on heterodyne interferometry and DWS (Differential wavefront sensing), we construct a five DOFs optical readout interferometer, and the noise levels of the linear and angular displacement measurements are 10 pm/Hz$^{1/2}$and 3 nrad/Hz$^{1/2}$ at 1 Hz.

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310.08 – LISA Science Overview

The European Space Agency selected the Laser Interferometer Space Antenna, LISA, as its third large-class mission in June 2017. Since this time, ESA and the scientific community have been working on the definition of the mission architecture, as well as the consolidation of the expected science return of LISA.

The concept of the a space-borne gravitational wave observatory has been extensively studied for the past two decades, over which time the science case has progressively become more compelling. Indeed, the science case for LISA has continuously been ranked as outstanding in all major reviews over the years. Now with the success of the LISA Pathfinder technology demonstration mission behind us, LISA is becoming a reality, opening the door to the low frequency gravitational wave science treasure trove which LISA will deliver.

In this poster, I will give an overview of the science case of LISA, followed by a detailed description of each of the areas in which the mission will provide unprecedented science return.

Author(s): Paul McNamara[1]
Institution(s): *1. European Space Agency*

310.09 – Orbit Optimization for Geocentric Space Gravitational-wave Detectors

TianQin is a space-based gravitational-wave detection mission consisting of three geocentric satellites in an equilateral triangle formation. The constellation faces the white-dwarf binary RX J0806.3+1527 and is subject to third-body perturbations. We present optimized TianQin orbits that satisfy 5-year stability requirements on the formation, and point out design features that can help stabilize the long-term orbital evolution.

Author(s): Xuefeng Zhang[1], Bobing Ye[1], Jianwei Mei[1]
Institution(s): *1. Sun Yat-sen University*

310.10 – Seismic Noise Suppression for ground-based Investigation of an Inertial sensor by Suspending the Electrode Cage

Precision electrostatic inertial sensor is one of the most important payloads in satellite gravity missions and space gravitational experiments. This kind of inertial sensor has extremely high resolution, and its testing and investigation on ground is inevitably affected by the seismic noise. To further suppress the seismic noise coupling, an improved pendulum system which an extra torsion pendulum with the electrode cage suspended is presented. Theoretical analysis shows that it can suppressing seismic noise about five orders of magnitude in the low frequency domain. The experimental results have verified this improved method effectively, and the limit of seismic coupling can be successfully lower to about 10^{-11} m/s^2/Hz$^{1/2}$.

Author(s): Dingyin Tan[1], Li Liu[1], Qi Xia[1], Zebing Zhou[1]
Institution(s): *1. Huazhong University of Science and Technology*

310.11 – A Preliminary Drag-free and Attitude Control System Simulation for TianQin Mission

The TianQin mission–a space gravitational wave detection project in China, calls for high requirements on the DFAC (Drag-Free and Attitude Control) design, which includes: nm-level relative motion of the test mass and nano-radian-level attitude stabilization of the spacecraft. On the scientific measurement axis, the drag-free controller will use micro propulsion to compensate the environmental disturbances, and on the other axis the electrostatic suspension control which is also a part of DFAC will be used to stabilize the test mass to its house center. To meet the challenge of controller design, we have built a preliminary end-to-end numerical simulator for TianQin mission. The simulator includes orbit and attitude dynamics of a single spacecraft and relative dynamics of two test masses. The Simulator is built on Simulink platform with the capability of running in real time and in a semi-physical system to integrate inertial sensor circuits hardware in loop in the future. This simulator will be used to investigate a prototype of DFAC of TianQin mission from the instrumental level. Details of this simulator and the preliminary results will be presented in the conference.

Author(s): Hongyin Li[1], Yanzheng Bai[1], Li Liu[1], Chunyu Xiao[1], Zebing Zhou[1]
Institution(s): *1. Huazhong University of Science and Technology*

310.12 – Iodine Frequency Stabilized Laser for Ground Tests of the LISA Payload

We plan to develop a compact and transportable iodine frequency stabilized laser setup, as part of the French activities by a consortium of several partners* for assembly-integration and ground tests of the LISA payload. We take advantage of an existing laser frequency stabilization experiment based on a Telecom laser diode at 1542 nm, frequency tripled and stabilized against a narrow iodine line at 514 nm [1]. The residual frequency noise achieved to date for this experiment is below the LISA mission requirements. We achieve a reproducible frequency stability below $5\times10^{-14}t^{-1/2}$ decreasing to 3.5×10^{-15} level after 200 s of integration time. It corresponds to an amplitude spectral density of the frequency fluctuations < 20 Hz/√Hz.
Furthermore, we demonstrate the ability to transfer the frequency stability achieved around 1.5 µm to the near infrared range, close to 1 µm, in a simple manner, using the usual phase locking loop technique associated to a second harmonic generation process [2].
Thus, we propose to provide a 1064 nm laser source phase-locked to an iodine stabilized Telecom laser operating at 1596 nm. The compact design of the whole setup will make it easily transportable to different sites and could be readily used for ground tests of the LISA payload.

*APC, ARTEMIS, CEA, CNES, CPPM, Insitut FRESNEL, LAM, LMA, LPC, SYRTE

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[1]: Ch. Philippe et al., “Frequency tripled 1.5 µm telecom laser diode stabilized to iodine hyperfine line in the 10^-15 range”, IEEE, **DOI:** 10.1109/EFTF.2016.7477827
[2]: N. Chiodo et al., “Optical phase locking of two infrared continuous wave lasers separated by 100 THz”, Optics Lett. Vol. 39, N° 10, May 15, 2014. https://doi.org/10.1364/OL.39.002936

Author(s): Ouali Acef[1]
Institution(s): *1. CNRS / Observatoire de Paris*

310.13 – Development of Engineering Prototype of Optical Interferometer for GW Mission in SYSU

TianQin Mission is a Chinese mission for gravitational waves detection in space. Based on the preliminary analysis, laser interferometer performance should achieve 1pm/Hz$^{1/2}$. In order to build the high resolution interferometric optics, several key technologies should be developed step by step, such as hydroxide catalysis bonding technique, high precision positioning of optical components, ultra-low noise laser interferometer and high precision optical simulation. As the first step, we finish an engineering prototype of heterodyne laser interferometer with quasi-monolithic mechanical structure, aiming at 10pm/Hz$^{1/2}$-

resulution of displacement measurement in low frequency band. Besides, we integrate a piece of quartz flexure in the optical measurement path, so that the spacecraft's acceleration can be monitored by measuring the relative displacement between the flexure and the ultra-stable optical bench. According to the preliminary experimental results, we have achieved an acceleration measurement noise of 10^{-6} m/s^2/Hz$^{1/2}$@0.1Hz and a displacement measurement noise of 10pm/Hz$^{1/2}$@0.1Hz. The updated experimental results will be reported in the conference.

Author(s): HuiZong Duan[1], Hsien-Chi Yeh[1], Qi Liu[1]
Institution(s): *1. Sun Yat-Sen University*

310.14 – A Flexure-type Accelerometer with Optical Read-out Based on Heterodyne Interferometry

Seismic noise and vibration are common noise sources in precision measurement experiments. The capacitive or resistance sensors are typically used in an accelerometer to measure the relative motion between the proof mass and the reference frame. In this poster, we introduce an accelerometer with a quartz flexure mechanism and an optical readout. Within a small deformation of the quartz flexure, the acceleration is linearly proportional to the relative displacement between the mirror attached on the end of flexure and the frame, and this displacement can be measured by a heterodyne interferometer. According to the preliminary experiment, we obtain a resolution of 10^{-6}m/s^2/Hz$^{1/2}$. The latest experimental results will be reported in the conference.

Author(s): MIN MING[1], HuiZong Duan[2], Hsien-Chi Yeh[2]
Institution(s): *1. Center for Gravitational Experiments, Huazhong University of Science and Technology, 2. School of Physics and Astronomy, Sun Yat-Sen University*

311 – Supermassive Black Holes & Environs Poster Session

311.01 – Dancing to ChaNGa: The Formation of Close Pairs of Supermassive Black Holes in Cosmological Simulations

I present a self-consistent prediction for close Supermassive Black Hole (SMBH) pair formation timescales following galaxy mergers. Using Romulus25, the first large-scale cosmological simulation to accurately track the orbital evolution of SMBHs within their host galaxies down to sub-kpc scales (Tremmel+ 2015, 2017, 2018), we predict that it is relatively rare for galaxy mergers to result in the formation of close SMBH pairs with sub-kpc separation and those that do form are often the result of Gyrs of orbital evolution following the galaxy merger. The likelihood and timescale to form a close SMBH pair depends on the mass and morphology of the merging galaxies. When galaxies are disrupted during a merger, their SMBHs are deposited on long lived, kpc-scale orbits resulting in a population of 'wandering' SMBHs. I discuss the implications of these results for predictions of SMBH merger rates. Finally, I examine the population of "wandering" SMBHs that we predict to exist in massive galaxies, like the Milky Way.

Author(s): Michael Josef Tremmel4, Fabio Governato3, Marta Volonteri[1], Andrew Pontzen[2], Thomas Quinn3
Institution(s): *1. Institut d'Astrophysique de Paris, 2. University College London, 3. University of Washington, 4. Yale University*

311.02 – Probing Massive Black Hole Populations and Their Environments with LISA

With data from the Illustris large-scale cosmological simulation, we provide analysis of LISA detection rates accompanied by characterization of the merging massive black holes and their host galaxies. Massive black holes of total mass ~ 10^6 – 10^9 M☉ are the main focus of this study. Using a custom treatment for the binary massive black hole evolutionary process, we evolve Illustris massive black hole particle mergers from ~kpc scales until coalescence to achieve a merger distribution. With the Illustris output as a statistical basis, we Monte Carlo synthesize many realizations of the merging massive black hole population across space and time. We use those realizations to build mock LISA detection catalogs to understand the impact of LISA mission configurations on our ability to probe massive black hole merger populations and their environments throughout the visible universe.

Author(s): Michael Katz[1], Shane L Larson[1]
Institution(s): *1. Northwestern University*

311.03 – Galaxy Collisions at z=3 and Mergers of Supermassive Black Holes in LISA Band

Supermassive Black Hole (SMBH) binaries are promising sources of gravitational waves (GW) for low frequency GW detectors such as LISA. Highest signal to noise ratio is expected for binaries in 105 - 10^6 M☉ range. SMBHs in this mass range where LISA is the most sensitive lie in bulges of late type galaxies. In this study, we investigate mergers of spiral galaxies initiated at redshift 3 and having various inclinations with respect to initial orbital plane. We follow the evolution of SMBHs from onset of galaxy mergers upto subparsec separations in Keplarian hard binary regimes. We estimate GW driven merger timescales in late phases of binary evolution. Our study suggests that galaxy merger phase is the longest in such type of mergers (~ 2Gyrs). SMBHs in bound phase of evolution take approximately, 40 - 500 Myrs to coalesce, here variations in merger times are caused by binary's eccentricity and central density of merger remnant. We also plot GW strain curves for all our mergers and show that these mergers shall be observable by LISA with high signal to noise ratio.

Author(s): Fazeel Mahmood Khan[1]
Institution(s): *1. institute of space technology, Islamabad*

311.04 – Catalogs of black hole masses

The recent discovery of gravitational waves from merging pairs of massive black holes and even neutron stars has marked the beginning of a new chapter in astronomy. The increasing sensitivity of the next generation of ground-based gravitational wave detectors and of the future space-borne ones will allow for the detection of high redshift merging black hole events, down to the realm of the first-generation black holes which is inaccessible to present and future electromagnetic observations. To better estimate the expected rates of black hole mergers and mass ratios (as in Gergely, L.A., Biermann, P.L., Caramete, L.I., Classical and Quantum Gravity, 2010), existing all-sky catalogues of black hole masses (e.g. BH-Cat: Caramete L.I., Biermann P.L., Astronomy&Astrophysics, 2010) needs to be further developed and refined based on current observations.
In the context of Romanian participation to LISA collaboration, we will present an updated version of the massive and supermassive black hole mass catalog, BH-Cat, together with its mass function and its implication for the LISA space mission. This catalog can be used to predict the mass and space distribution of the first-generation black holes, test the feedback between the black holes and the hosting galaxy evolution activities, study the growth mechanism of the black holes and predict the black holes mass merger ratios.

Author(s): Laurentiu Ioan Caramete[1], Razvan Balasov[1], Peter Biermann[2]
Institution(s): *1. Institute of Space Science, 2. Max-Planck Institute for Radioastronomy*

311.05 – Making Intermediate Mass Black Holes in AGN Disks : Models and Rates

Recent observations of our own Galactic center imply a cusp of $\sim 10^{4}$ stellar mass black holes lying within a parsec of Sgr A*. Dynamical encounters and mergers between stellar mass black holes in galactic nuclei should be expected over cosmic time. Such mergers become much more efficient when a AGN gas disk is present. A mass merger hierarchy of black holes within the disk can lead to the rapid build up of Intermediate mass black holes in AGN disks around the central supermassive black hole. In 2014 we predicted that LIGO would detect a new population of stellar mass black hole mergers from hierarchical merging within AGN disks. Here I will discuss our groups efforts over the past 7 years to model black hole merger dynamics in disks and our predictions for the LIGO and LISA gravitational wave detectors.

Author(s): K.E. Saavik Ford3, Barry McKernan3, Jillian Bellovary[6], N. Leigh[1], B. Hernandez[1], A. Secunda[1], M.M. Mac Low[1], Wladimir Lyra[2], S. Nasim5, G. Fabj4
Institution(s): *1. American Museum of Natural History, 2. California State University Northridge, 3. CUNY Borough of Manh. Comm. Coll., 4. CUNY College of Staten Island, 5. CUNY Hunter College, 6. CUNY Queensborough Comm. College*

311.06 – Spin Evolution of Merging Black Hole Binaries in Illustris

Supermassive black hole (SMBH) binary inspiral time scales are highly uncertian, and their spins are even more poorly constrained. Understanding how spins evolve in black hole (BH) binaries is crucial for determining their gravitational wave (GW) recoil velocities. Spin misalignment, along with unequal mass ratios and spin magnitudes introduce asymmetry in the GW radiation which imparts a recoil velocity to the merged BH. This will in turn affect the SMBH merger rate observable with LISA, and the co-evolution of SMBH with host galaxies. Furthermore, spin precession in misaligned binaries can produce a detectable signature in LISA waveforms. We present a novel study that includes for the first time a model for the spin precession of SMBH binaries, using a live population of accreting super massive black holes (SMBHs) from the state-of-the-art Illustris cosmological hydrodynamics simulation. To model sub-resolution binary evolution, we combine a semi-analytic prescription for gas-driven evolution on large scales with a post-Newtonian approximation scheme for spin precession and GW-driven inspiral on small scales. Our gas-driven model assumes that in gas-rich galaxy mergers, circumbinary accretion disks efficiently align BH spin, and that differential accretion drives greater alignment of the secondary BH's spin in unequal-mass mergers. The BHs are mostly aligned in our fiducial model, but the misalignment fraction -- especially for the primary BH -- is a strong function of the BH accretion rates.
We conclude that incorporating spin precession has little effect on the overall recoil velocity distribution of the merged BHs, though it can shift the high velocity tail slightly towards higher values. We explore how these results could change with a more detailed treatment of BH accretion rates and gas-driven inspiral. We also highlight the types of systems that are least likely to retain their SMBHs, including individual cases in which spin precession changes the recoil velocity by up to 1000 km/s.

Author(s): MOHAMMAD SAYEB[2], Laura Blecha[2], Davide Gerosa[1], Michael Kesden3
Institution(s): *1. Caltech, 2. University of Florida, 3. University of Texas at Dallas*

311.07 – Making Intermediate mass black holes in AGN disks: Simulations

Black hole number density appears to be greatest in galactic nuclei. As a result, AGN disks are one of the most dynamically favorable environments in which to rapidly merge a large population of black holes. I will discuss our groups recent efforts to simulate stellar mass black hole migration and merger in AGN disks, using N-body, Monte Carlo and hydrodynamic simulations. I will discuss the mass build up at migration traps and the evolution from an initial black hole mass and spin distribution with implications for both LIGO and LISA. I will outline our progress so far as well as the problems we face and how we are tackling them.

Author(s): Barry McKernan[2], K.E.Saavik Ford[2], B. Hernandez[1], N. Leigh[1], M.M. Mac Low[1], A. Secunda[1], J. Bellovary[1], S. Nasim[4], G. Fabj3
Institution(s): *1. AMNH, 2. CUNY-BMCC, 3. CUNY-CSI, 4. CUNY-Hunter*

312 – Waveforms & Simulations Poster Session

312.01 – Characterizing the mode content of ringdown waveforms from misaligned black hole coalescences

The ringdown gravitational wave spectrum of supermassive black holes will be in the peak sensitivity of the LISA interferometer. To maximize the measurement and understanding of these signals, accurate ringdown models are required. In this study, we focus on modeling the ringdown gravitational wave emission from Kerr black holes, by perturbing the black hole with small body trajectories calculated with a generalized Ori-Thorne algorithm. By characterizing the ringdown waves as a superposition of Kerr quasi-normal modes, we then determine how the modes' excitations vary as a function of the source parameters such as the larger black hole's spin and the geometry of the small body's inspiral and plunge trajectory. Our results indicate that measuring multiple ringdown modes of black hole coalescence gravitational waves may provide useful information about the source's binary properties, such as the misalignment of the orbit's angular momentum with black hole spin.

Author(s): Halston Lim[1]
Institution(s): *1. MIT*

312.02 – Detecting the Beaming Effect of Gravitational Waves

The ground-based detectors LIGO and Virgo have directly detected gravitational waves (GWs) from merging stellar-mass black holes and inspiraling neutron stars. The standard model that is used in the detection assumes an idealized situation where there is no relative motion between the center-of-mass of the source and the observer. If the source, however, is moving respect to the detector, this could have an impact on the measurement of the GW amplitude. Here we address this "beaming effect" by comparing the light traveling time in an interferometer under the circumstances with and without a relative motion. We find that the motion not only induces a difference in the light traveling time, and hence changing the "apparent" GW amplitude, but also altering the apparent strength of the two GW polarizations. Neglecting this effect in the observation of GWs would lead to a wrong estimation of the distance and orbital inclination of the source, or induce a spurious signal that appears to be incompatible with GR. This beaming effect for GWs differs from the one known for light, revealing a remarkable difference between gravitational and electromagnetic radiation.

Author(s): Alejandro Torres Orjuela3, Xian Chen3, Zhoujian Cao[2], Pau Amaro-Seoane[1]
Institution(s): *1. Autonomous University of Barcelona, 2. Chinese Academy of Sciences, 3. Peking University*

312.03 – Analysis of Effect of Solar Weather on LISA

.A major source of noise for the LISA will be due to solar weather in the form of particles in the solar wind and photon pressure from the solar irradiance. Previous work has only estimated these forces, however, we will use measurements of these quantities taken by the ACE (*Advanced Compton Explorer*) and the VIRGO (*Variability of solar IRradiance and Gravity Oscillations*) spacecraft respectively over an entire solar cycle. We calculate the net force on an individual LISA spacecraft and then examine the resulting Fourier spectrum of these forces to gain a more realistic model of the effect of these noise sources.

Author(s): Brett Bolen[1], Barrett Frank[2], Brandon Piotrzkowski[4], Marco Cavaglià[5], Shane L Larson[3]
Institution(s): *1. Grand Valley State University, 2. Montana State University, 3. Northwestern University, 4. University of Milwaukee, 5. University of Mississippi*

312.04 – Fourier domain gravitational waveforms for precessing eccentric binaries

We build two families of inspiral waveforms for precessing binaries on eccentric orbits in the
Fourier domain. To achieve this, we use a small eccentricity expansion of the waveform amplitudes
in order to separate the periastron precession timescale from the orbital timescale, and use a SUA
transformation to compute the Fourier transform in the presence of spin-induced precession. We
show that the resulting waveforms can yield a median faithfulness above 0.993 when compared to an equivalent time domain waveform with an initial eccentricity of $e_0 \approx 0.3$. We also show
that when spins are large or the accumulated number of cycles is large, using a circular waveform
can potentially lead to significant biases in the recovery of the parameters, even when the system
has fully circularized. This is an effect of the residual eccentricity present when the objects
forming the binary have non-vanishing spin components in the orbital plane.

Author(s): Yannick Boetzel[2], Antoine Klein[1]
Institution(s): *1. CNRS, 2. University of Zurich*

312.05 – LISANode: a prototype performance simulator

As part of the LISA Simulation Group activities we develop a prototype for a high-level instrumental simulator of the mission called LISANode. It answers immediate questions regarding the instrumental performances, gathers requirements for an end-to-end simulator and generates realistic data that are to be used for the LISA Data Challenge. LISANode is a C++ simulator wrapped in a Python interface, based on the notion of simulation graphs broken down into atomic computation nodes. We show that this structure enables high modularity, massive parallelization and great flexibility while abstracting away complex subsystems. We present a first model of the instrument including realistic orbits, split interferometry, clock and timing errors, transient and non-stationary noises have been used to study the performance after Time-Delay Interferometry pre-processing steps.

Author(s): Jean-Baptiste Bayle[2], Marc Lilley[2], Antoine Petiteau[1]
Institution(s): *1. APC, University Paris-Diderot, 2. CNRS/IN2P3*

312.06 – Prompt Electromagnetic Transients from Binary Black Hole Mergers

Massive binary black-hole (BBH) mergers provide a prime source for LISA. These mergers will often take place in plasma-rich environments, leading to the possibility of a concurrent EM signal observable by traditional astronomical facilities. However, many critical questions about the generation of such counterparts remain unanswered. We explore mechanisms that may drive EM counterparts, using ideal magnetohydrodynamical simulations to treat a range of toy-model scenarios involving equal-mass BBHs immersed in an initially homogeneous fluid with uniform, orbitally aligned magnetic fields. We find that the time-development of Poynting luminosity, which may drive jet-like emissions, is remarkably insensitive to aspects of the initial configuration. In particular, over a significant range of initial values, the central magnetic field strength is effectively regulated by the gas flow to yield a Poynting luminosity of $10^{45} – 10^{46} \rho_{-13} M_8^2$ erg s^{-1}. We also calculate the direct plasma synchrotron emissions processed through geodesic ray-tracing. Despite lensing effects and dynamics, we find the observed synchrotron flux varies little leading up to merger.

Author(s): Bernard Kelly[3], John Baker[1], Zachariah Etienne[4], Bruno Giacomazzo[2], Jeremy Schnittman[1]
Institution(s): *1. NASA Goddard Space Flight Center, 2. Universita di Trento, 3. University of Maryland Baltimore County, 4. West Virginia University*

312.07 – Gravitational waves from compact binaries in post-Newtonian accurate hyperbolic orbits

Alhough compact binaries in hyperbolic orbits are expected to be rare gravitational wave (GW) events, recent astrophysical considerations provide strong motivation to explore the possibility of searching for the presence of close binary encounters in the interferometric data streams.
We present *ready-to-use* time-domain GW polarization templates for compact binaries moving in fully 3.5 post-Newtonian (PN) accurate hyperbolic orbits. A crucial input for constructing these waveforms is an *ab-initio* derivation of a 3PN-accurate Keplerian-type parametric solution to describe PN-accurate dynamics of non-spinning compact binaries in unbound orbits.

Author(s): Maria Haney[1]
Institution(s): *1. University of Zurich*

400 – Supermassive Black Holes and Cosmology

400.01 – Cosmology at All Redshifts with LISA

In this talk I will present the current status of cosmological forecasts for LISA. I will show that LISA will constitute a unique cosmological probe able to measure the expansion of the universe from low redshifts (z=0.01) up to very large redshifts (z=10). This is made possible by the use of different gravitational wave sources as standard sirens: stellar origin black hole binaries (low redshift), extreme mass ratio inspirals (intermediate redshift) and massive black hole binaries (high redshift). I will discuss the methodologies used to obtain cosmological constraints with LISA and present the latest cosmological forecasts based on state of the art simulated catalogues of gravitational waves sources.

Author(s): Nicola Tamanini[1], Walter Del Pozzo[7], Alberto Sesana[5], Enrico Barausse[3], Chiara Caprini[2], Stas Babak[2], Jonathan Gair[6], Antoine Petiteau[2], Antoine Klein[3], Emanuele Berti[4]
Institution(s): *1. AEI Potsdam, 2. APC, 3. IAP, 4. Ole Miss, 5. University of Birmingham, 6. University of Edinbrough, 7. University of Pisa*

400.02 – The Electromagnetic Chirp of a Supermassive Black Hole Binary

Supermassive black hole (SMBH) binaries are inevitably produced during
galaxy formation, and the expectation is that these binaries will be
surrounded by plenty of gas. I will discuss the coupled dynamics of a
SMBH binary with a circumbinary gas disk, and the expected characteristics of electromagnetic (EM) emission from such a system.

In particular, I will argue, based on analytic arguments and two-dimensional hydrodynamical simulations, that when a SMBH binary is
merging inside LISA's frequency band, it will remain bright, and that
its emission will be highly time-variable. In particular, relativistic Doppler modulations, lensing effects, and hydrodynamical modulations
of the accretion will inevitably imprint periodic variability in the EM light-curve, tracking the phase of the orbital motion, and serving
as a template for the GW inspiral waveform. Advanced localization of
the source by LISA weeks to months prior to merger will enable a measurement of this EM chirp by wide-field instruments in X-rays and
possibly other wavelengths. A comparison of the phases of the GW and
EM chirp signals will help break degeneracies between system parameters, and probe a fractional difference difference in the propagation speed of photons and gravitons as low as 10^-17.

Author(s): Zoltan Haiman[1]
Institution(s): *1. Columbia University*

400.03 – Evolution of Massive Binary Black holes in Realistic Galaxy Distributions and Their Gravitational Wave Radiation

Mergers of massive binary black holes (BBHs) at galactic nuclei are among the primary sources of gravitational wave radiation (GWR) at relatively low-frequency bands, including the detection range of the Pulsar Timing Array experiments and LISA. One main uncertainty in estimating the strength of the GWR emitted by the massive BBHs comes from their interaction with the stars and gas in their vicinities, which affects when and where GWR becomes dominant in making a BBH lose energy. The evolution timescale of the BBH orbital decay can be significantly different with different galaxy shapes and stellar distributions. By considering realistic galaxy shapes and stellar distributions and including a detailed modeling of the stellar interaction with BBHs, I'll present our recent work on the evolution of massive BBHs in realistic galaxy distributions. We predict the strength of their GWR and compare it with the current limit set by the Pulsar Timing Array experiment. We also give the expected distribution of the surviving BBHs in realistic galaxy distributions.

Author(s): Qingjuan Yu[1]
Institution(s): *1. Kavli Institute for Astronomy and Astrophysics, Peking University*

400.04 – LISA Sources and Detection Rates from Massive Black Holes in the Illustris Simulations

The inspirals of Massive Black Hole (MBH) Binaries are one of the primary targets of the LISA mission. While no examples of progenitors are known, we believe these binaries form following the merger of two galaxies in which the MBH reside. The details of the merger process, however, are highly uncertain as the MBH need to migrate from galaxy-scale separations down five orders of magnitude to reach the Gravitational Wave (GW) regime. Post-merger galaxy environments---through interactions with gas, stars, and dark matter---are believed to mediate the merger of MBH pairs. The Illustris cosmological simulations self-consistently evolve MBH with stars, gas, and dark matter from the beginning of the universe to the present, producing tens of thousands of galaxies and galaxy mergers. We identify each galaxy merger in the simulations and extract both the MBH pair, and the detailed galactic environments which Illustris produces. Using those environments, we calculate the binary merger dynamics in post-processing using comprehensive prescriptions for dynamical friction, stellar scattering, gas drag, and gravitational wave emission. In this talk I will present our results on the expected rates of coalescences of MBH with masses in the LISA sensitive band. I will describe the typical system parameters we expect, and the galaxies that most often host them, which is important for identifying electromagnetic counterparts. Finally, I will connect our predictions for LISA detections with those of Pulsar Timing Arrays which are sensitive to steady orbits of the largest MBH in the universe in the nanohertz regime.

Author(s): Luke Zoltan Kelley[1]
Institution(s): *1. Harvard University*

400.05 – The Effect of AGN Feedback on the Migration Timescale of Supermassive Black Holes Binaries

The gravitational interaction at parsec to sub-parsec scales between a circumbinary gas disc and a super massive black hole binary (SMBHB) is a promising mechanism to drive the migration of SMBHBs toward coalescence. The typical dynamical evolution can be separated in two main regimes: I) Slow migration ($T_{mig} \sim 10^{3-4}\, T_{orb}$), where viscous torques are not efficient enough to redistribute the extracted angular momentum from the binary, leading to the formation of a low density cavity around the binary. II) Fast migration ($T_{mig} \sim 10^{1-2} T_{orb}$), in which the redistribution of angular momentum is efficient and no low density cavity is formed in the circumbinary disc. Using N-Body/SPH simulations we study the effect of AGN feedback in this phase of a SMBHB evolution. We implement an AGN accretion/feedback model in the SPH code Gadget-3 that includes momentum feedback from winds, X-ray heating/radial-momentum and Eddington force. Using this implementation we run a set of simulations of SMBHB+disc in the two main shrinking regimes. From these simulations we conclude that the effect of the AGN mechanical feedback is negligible for SMBHBs in the slowly shrinking regime. However, in the fast shrinking regime the AGN wind excavate a "feedback cavity" leaving the SMBHB almost naked, thus stalling the orbital decay of the binary.

Author(s): Luciano Del Valle[1]
Institution(s): *1. Institute d'Astrophysique de Paris*

400.06 – Model Independent Reconstruction of SGWBs at LISA

In my talk I discuss the possibility of performing a model independent reconstruction of stochastic gravitational wave backgrounds at LISA. The procedure is based on the possibility of breaking the frequency interval accessible at LISA into a series of smaller intervals (bins). In each bin the signal is then reconstructed with a power law determined through the maximum likelihood estimation method. The result obtained at the end of this procedure is a multi power law which approximates the original unknown signal.

Author(s): Mauro Pieroni[1]
Institution(s): *1. UAM/IFT Madrid*

400.07 – Gravitational Waves from a First-order Phase Transition: Spectral Shape and Other Properties

LISA may be able to detect signals from a phase transition at the electroweak scale, a few picoseconds after the Big Bang - the very time the Higgs boson was 'turning on'. By detecting a cosmological gravitational wave background from such a transition we might also be able to find out some details of the phase transition, such as the nucleation rate and temperature. This would provide important information about physics beyond the Standard Model. However, better understanding of the source - as well as the underlying theories of physics beyond the Standard Model - is required before the launch of LISA. I will discuss the results of recent large-scale simulation campaigns, which have allowed us to determine the spectral shape for both thermal and vacuum first-order phase transitions with unprecedented accuracy.

Author(s): David Weir[1], Daniel Cutting[2], Mark Hindmarsh[2], Stephan J. Huber[2], Kari Rummukainen[1]
Institution(s): *1. University of Helsinki, 2. University of Sussex*

400.08 – Gravitational Wave Signal from Phase Transitions due to Turbulence and Magnetic Fields

The first direct detections of gravitational waves from the mergers of binary black holes and binary neutron stars by the LIGO and VIRGO experiments have electrified the physics and astronomy communities. A clear next experimental step is an interferometer in space, which can detect lower frequency signals than a ground-based detector, including supermassive black hole binary coalescences from early galaxy mergers and a known stochastic background from confusion-limited white-dwarf binaries. An even more intriguing signal is the stochastic background from early-universe physics. Gravitational waves provide the only known direct signal of physics when the universe was less than one second old.

In this talk we present a comprehensive study of gravitational waves from first-order cosmological phase transitions, particularly the electroweak phase transition and more speculative transitions at higher energy scales such as a supersymmetric phase transition. The expansion and merging of new-phase bubbles can produce significant gravitational waves, and the resulting long-lasting turbulent plasma motions supply a further dominant source of gravitational waves. Magnetic field generation during turbulence can result in an inverse turbulent cascade, creating a long low-frequency tail of the gravitational wave spectrum along with a relic cosmological magnetic field. Realistic early-universe phase transitions over a wide range of energy scales may therefore be within the reach of space-based detectors. We present numerical simulation of plasma dynamics including magnetic fields using the Pencil Code, a public domain magnetohydrodynamics code able to solve the resulting stochastic gravitational wave spectra. Our particular interest consists in studying the parity and/or chirality symmetry violation during the electroweak phase transition that is potentially related to the matter-antimatter asymmetry and helicity generation in the early universe. Finally, we discuss the range of phase transition energy scales and properties that may be detectable with the envisined space-based interferometer configurations such as LISA.

Author(s): Tina Kahniashvili[1], Axel Brandenburg[2], Arthur Kosowsky4, Sayan Mandal[1], Alberto Roper Pol3
Institution(s): *1. Carnegie Mellon University, 2. NORDITA, 3. University of Colorado at Boulder, 4. University of Pittsburgh*

400.09 – Studying Chaos with LISA

LISA observations will allow tests of Einstein's theory with gravitational waves emitted when a small black hole falls into a supermassive one in an extreme mass-ratio inspiral. One particular probe of extreme gravity that is tailor-made for such inspirals is the search for chaos. Before such a test can be developed, one must first find spacetimes in modified gravity theories that present chaos in EMRI orbits. I will discuss whether chaos is present in the motion of test particles around spinning black holes of parity-violating modified gravity, focusing in particular on dynamical Chern-Simons gravity. Our numerical findings suggest that chaos is actually not present if one were to include all spin corrections to the metric. This, in turn, suggests that the as-of-yet unknown exact solution for spinning black holes in this theory may be integrable, and that there may thus exist a fourth integral of motion associated with this exact solution.

Author(s): Nicolas Yunes[1], Alejandro Cardenas-Avendano[1], Andres Gutierrez[2], Leonardo Augusto Pachon Contreras[2]
Institution(s): *1. Montana State University, 2. Universidad de Antioquia*

400.10 – Fast Self-forced EMRI Evolutions

We present a new, fast method for computing the inspiral trajectory and gravitational waves from extreme mass-ratio inspirals that can incorporate all known (and future) self-force results. Using near-identity (averaging) transformations we formulate equations of motion that do not explicitly depend upon the orbital phases of the inspiral, making them fast to evaluate, and whose solutions track the evolving constants of motion, orbital phases and waveform phase of a full self-force inspiral to O(q), where q is the (small) mass ratio. As a concrete example, we implement these equations for inspirals of non-spinning (Schwarzschild) binaries. Our code computes inspiral trajectories in milliseconds which is a speed up of 2-5 orders of magnitude (depending on the mass-ratio) over previous self-force inspiral models which take minutes to hours to evaluate. The speed of our new approach is comparable with kludge models but has the added benefit of easily incorporating self-force results which will, once known, allow the waveform phase to be tracked to sub-radian accuracy over an inspiral.

Author(s): Maarten Van de Meent[1], Niels Warburton[2]
Institution(s): *1. Max Planck Institute for Gravitational Physics, Potsdam-Golm, 2. University College Dublin*

401 – Electromagnetic Counterparts

401.01 – A Light in the Dark (Ages): Direct Collapse Black Hole Seed Formation Sparked by Radiation from the First Stars in Cosmological Simulations

In the pre-reionization epoch, molecular hydrogen is an efficient coolant, causing gas to fragment and form the first generation of stars, but Lyman-Werner radiation can suppress molecular hydrogen, allowing gas to collapse directly into a massive black hole. The critical flux required for this process is hotly debated, largely due to the uncertainties in the source radiation spectrum, self-shielding, and collisional dissociation rates. Here, we test the power of the direct collapse model in a self-consistent, time-dependant, non-uniform Lyman-Werner radiation field -- the first time such has been done in a cosmological volume. We vary the critical flux needed to spawn seed black holes to study how this impacts the number of seed black holes and the type of galaxies which host them. We focus on black hole formation as a function of environment, halo mass, metallicity, and proximity of the Lyman-Werner source. Massive black hole seeds form more abundantly with lower flux thresholds, but regardless, these seeds typically form in halos that have recently begun star formation. Our results do not confirm the standard picture of direct collapse black hole formation; we discuss the new picture and its implications for LISA.

Author(s): Kelly Holley-Bockelmann4, Glenna Dunn4, Jillian Bellovary[1], Charlotte Christensen[2], Thomas Quinn3
Institution(s): *1. AMNH, 2. Grinnell, 3. University of Washington, 4. Vanderbilt University*

401.02 – Electromagnetic Counterparts to LISA Sources

LISA observations of supermassive black hole (SMBH) mergers will provide unprecedented precision in the measurement of black hole masses, spins, and distances. Because SMBH sources are expected to be seen with very high signal-to-noise (SNR > 10,000 for the strongest sources), they will also provide excellent tests of general relativity and fundamental physics. Yet to fully understand their astrophysical

context, it will be necessary to identify the host galaxies. This can best be done by observing electromagnetic (EM) counterparts with
wide-field telescopes. We discuss here a survey of the current and future EM assets, with a focus on the X-ray telescope on TAP: the Transient Astrophysics Probe, a NASA concept study currently underway. We also show rate estimates and state-of-the-art MHD simulations of SMBH circumbinary accretion disks, giving potential
spectral and timing features of these rare but powerful systems.

Author(s): Jeremy Schnittman[1]
Institution(s): *1. NASA Goddard*

401.03 – Multimessenger Signatures of Massive Black Holes in Dwarf Galaxies

Inspired by the recent discovery of several nearby dwarf galaxies hosting active galactic nuclei, I will present results from a series of cosmological hydrodynamic simulations focusing on dwarf galaxies which host supermassive black holes (SMBHs). Cosmological simulations are a vital tool for predicting SMBH populations and merger events which will eventually be observed by LISA. Dwarf galaxies are the most numerous in the universe, so even though the occupation fraction of SMBHs in dwarfs is less than unity, their contribution to the gravitational wave background could be non-negligible. I find that electromagnetic signatures from SMBH accretion are not common among most SMBH-hosting dwarfs, but the gravitational wave signatures can be substantial. The most common mass ratio for SMBH mergers in low-mass galaxy environments is ~1:20, which is an unexplored region of gravitational waveform parameter space. I will discuss the occupation fraction of SMBHs in low-mass galaxies as well as differences in field and satellite populations, providing clues to search for and characterize these elusive giants lurking in the dwarfs.

Author(s): Jillian Bellovary[1], Michael Tremmel[3], Ferah Munshi[2]
Institution(s): *1. Queensborough Community College, 2. University of Oklahoma, 3. Yale University*

401.04 – Accretion Disks Around Supermassive Binary Black Holes: GRMHD Simulations of Postdecoupling and Merger

A new observational challenge is the coincident detection of gravitational waves (GWs) with electromagnetic (EM) signals from the coalescence of supermassive black hole binaries. Combining GW and EM observations offers a unique probe to understanding black hole cosmological evolution and accretion processes. As a crucial step, we report results from general relativity simulations of circumbinary magnetized disks accreting onto merging black holes, starting from relaxed disk initial data. We evolve the systems after binary-disk decoupling through inspiral and merger and analyze the dependence on the binary mass ratio and intial disk model. We find that incipient jets are launched independently of the mass ratio while the same initial disk accreting on a single non-spinning black hole does not lead to a jet, as expected. For all mass ratios we see a transient behavior in the collimated, magnetized outflows lasting 1–2(M/10^6M_sun) hours after merger: the outflows become increasingly magnetically dominated and accelerated to higher velocities, boosting the Poynting luminosity. We also calculate GW strains and show that EM precursor signals can trigger targeted GW searches in the LISA band with a substantial lead time. Conversely, LISA can also localize a source on the sky weeks before merger, so that wide-field telescopes will have a comfortable lead time to monitor the area.

Author(s): Milton Ruiz[1], Antonios Tsokaros[1], Vasileios Paschalidis[2], Stuart Shapiro[1]
Institution(s): *1. University of Illinois at Urbana-Champaign , 2. Univesity of Arizona*

401.05 – Modeling the Gravitational-wave and Electromagnetic Signatures of Massive Black Holes in Merging Galaxies

Mergers between massive black holes (BHs) are one of the most promising gravitational wave (GW) sources for LISA. These highly energetic GW events could be observed out to very high redshift, in the epoch where massive BH seeds are thought to form. Despite recent progress, however, much is still not known about the BH population even in the local Universe; the rates of BH binary formation, inspiral, and merger are highly uncertain. To address these pressing issues in advance of LISA, we use hydrodynamics simulations on both galactic and cosmological scales to model BH binary inspiral, merger, and GW recoil. In addition to modeling the GW signatures associated with these events, we also characterize the electromagnetic (EM) signatures of the BH binary population. These have proven largely elusive thus far, particularly because accreting BHs are often preferentially obscured during galaxy mergers. We present results from recent work demonstrating that a high fraction of infrared-selected merging galaxies should contain BH pairs resolvable with JWST. Detections of such systems in the coming years will provide important comparisons for models of GW sources in advance of LISA. Finally, we discuss the progress and prospects for identifying candidate recoiling BHs; such objects would provide another EM signature of BH mergers and constrain event rate predictions for LISA.

Author(s): Laura Blecha4, MOHAMMAD SAYEB4, Luke Zoltan Kelley[2], Gregory F. Snyder3, Shobita Satyapal[1], Sara Ellison5
Institution(s): *1. George Mason University, 2. Harvard University, 3. Space Telescope Science Institute, 4. University of Florida, 5. University of Victoria*

401.06 – Comprehensive Multimessenger Astrophysics in the LISA Era

After decades of focused efforts, the observation of an electromagnetic counterpart to the gravitational-wave event GW170817 by a multitude of instruments highlighted the value of multimessenger astrophysics and indicated that short gamma-ray bursts could arise from mergers of pairs of neutron stars, and, more generally, that binary mergers are capable of accelerating particles and producing high-energy emission. Additionally, the recent association of a high-energy neutrino, IceCube-170922A, with a flaring blazar provide much encouragement on the particle messenger front. Continued instrumental breakthroughs in gravitational-wave detectors on Earth and in Space, in electromagnetic and in neutrino observatories shall lead to an information explosion during the coming years and decades. Comprehensive Multisensory Multimodal Integration in Astrophysics shall rapidly expand humanity's cosmic and scientific horizon, and promise a bright future and new opportunities for LISA.

Author(s): Szabolcs Marka[1]
Institution(s): *1. Columbia University*

401.07 – Monsters on the Move: A search for Supermassive Black Holes Undergoing Gravitational Wave Recoil

It has long been assumed that Active Galactic Nuclei reside at the centers of their host galaxies, but is this really true? A galaxy merger is expected to lead to the formation of an SMBH binary, which can shrink through dynamical processes until it eventually coalesces through the emission of gravitational waves. Such events fall outside the frequency range of the LIGO/VIRGO gravitational wave detectors and haven't yet been detected through Pulsar timing arrays. However, numerical relativity simulations show that, depending on the initial spin-orbit configuration of the binary, the merged SMBH receives a gravitational recoil kick that may reach several 1000km/s. The kick causes the merged SMBH to oscillate for up to ~1 Gyr in the gravitational potential well of the galaxy, during which, the recoiling SMBH may be observed as a 'displaced' AGN.

Displacements ~10 – 100pc may be expected even in nearby elliptical galaxies and can be measured as spatial offsets in high resolution optical/infrared images. We present the results of a study of ~100 early type active galaxies, in which isophotal analysis was conducted using Hubble Space Telescope archival and new optical/near-infrared images. We find evidence for significant spatial offsets between the position of the AGN and the photocenter of the galaxy in about 20% of the sample. We discuss our results in the context of the gravitational recoil hypothesis and also consider alternative displacement mechanisms. Determining the statistical likelihood of observing a recoiling SMBH using results from this study will allow us to place an observational constraint on the SMBH binary merger rate which can be compared with theoretical estimates of detection rates for both Pulsar Timing Arrays and LISA. The study will also provide data against which SMBH binary evolution and general relativity (GR) simulations of SMBH binary coalescence can be tested.

Author(s): Yashashree Jadhav[1], Andrew Robinson[1], Davide Lena[2], Bryanne McDonough[1]
Institution(s): *1. Rochester Institute of Technology, 2. SRON, Netherlands Institute for Space Research*

401.08 – Gas Impact on LISA Inspirals

Compact objects inspiraling into supermassive black holes are among the expected sources for LISA. A fraction of these events may occur in the accretion disks of active galactic nuclei, where migration torques exerted by the gas can alter the inspiral and subsequent gravitational wave phase evolution. I will present a study of the gas impact on migrating black holes, focusing on the case of intermediate mass ratio inspirals ($q \sim 10^{-3}$). With high-resolution simulations performed by the moving-mesh code DISCO, I will illustrate how gas torques impact a migrating black hole, and how this effect may be detectable by LISA.

Author(s): Andrea Derdzinski[1], Zoltan Haiman[1]
Institution(s): *1. Columbia University*

401.09 – Associating Host Galaxy Candidates to Extreme Mass-Ratio Inspirals

The inspirals of stellar-mass compact objects into massive black holes in the centers of galaxies are one of the key astrophysical sources for eLISA. These extreme mass-ratio inspirals (EMRIs) have great potential for astrophysics, cosmology, and fundamental physics. Gravitational-wave standard sirens provide an independent measurement of the luminosity distance to a source. With a host-galaxy counterpart, the redshift of the source can be obtained, thus allowing for a direct measurement of the Hubble constant. We investigate the use of the correlation between massive black holes and their host galaxies as astrophysical priors in associating host-galaxy candidates for EMRIs and discuss prospects for ruling out interloping galaxies within the eLISA error boxes of localized EMRIs.

Author(s): A. Miguel Holgado3, Eliu Huerta[1], Alberto Sesana[2], Paul Ricker3
Institution(s): *1. National Center for Supercomputing Applications, 2. University of Birmingham, 3. University of Illinois at Urbana-Champaign*

401.10 – The Known Population of LISA Verificaton Binaries and Their Systematic Search using the Zwicky Transient Facility

Ultra-compact Galactic white dwarf binaries will be the most numerous astrophysical sources detectable by LISA. These binary systems are the result of evolutionary pathways that involve a rich collection of astrophysical phenomena including episodes of common envelope evolution, gravitational wave emission, tidal interaction and mass transfer. Up to now several such sources have been detected in the electromagnetic bands and will be individually detected due to their strong GW signals. These LISA-guaranteed sources are termed `verification binaries' with some being expected to be detected on a timescale of weeks or a few months with LISA. So far, distances have been the most uncertain parameter when predicting the gravitational wave strengths of the bright verification binaries. In this talk I will present new results on the predicted gravitational wave signal and signal-to-noise ratios detectable by LISA for known Galactic binaries using distances from Gaia Data Release 2 (DR2) and the current LISA baseline configuration.
However, the number of known systems is still very limited. The Zwicky Transient Facility (ZTF) is a new ground-based large-area optical survey instrument that saw first light in October 2017 and is now performing science surveys. ZTF has a 47 square degree field of view and acquires an image every 45 seconds with a median limiting magnitude of R=20.3. ZTF will be carrying out variability surveys of the Galactic Plane at both moderate and high cadence. We expect that ZTF will more than double or triple the number of known LISA-detectable sources, as well as identify numerous other ultra-compact binaries that will provide better understanding of the many potential evolutionary pathways for the binaries that LISA will detect. I will describe ZTF and our effort to find LISA verification binaries and discuss preliminary results from some of its observations. These include the detection of a new LISA-detectable 'verification binary'.

Author(s): Thomas Kupfer[4], Tom Prince3, Kevin Burdge3, Valeriya Korol[5], Sweta Shah[1], Gijs Nelemans[6], Tom Marsh7, Gavin Ramsay[2], Paul Groot[6], Danny Steeghs7, Elena Maria Rossi5
Institution(s): *1. Albert Einstein Institute , 2. Armagh Observatory, 3. California Institute of Technology, 4. Kavli Institute for Theoretical Physics/UC Santa Barbara, 5. Leiden Observatory, 6. Radboud University Nijmegen, 7. University of Warwick*

500 – Stellar Compact Binaries

500.01 – Constraining Stellar Binary Black hole formation scenarios with LISA eccentricity measurements

LISA could observe few to few thousands progenitors of black hole binaries (BHBs) similar to those recently detected by Advanced LIGO, opening the door to multi-band gravitational wave astronomy. Gravitational radiation circularizes the orbit during inspiral, but some BHBs retain a measurable eccentricity at the low frequencies where LISA is most sensitive. The eccentricity of a BHB carries precious information about its formation channel: BHBs formed in the field, in globular clusters, in triple systems or in primordial binaries have distinct eccentricity distributions in the LISA band. We generate mock LISA observations, folding in measurement errors, and using Bayesian model selection we study whether LISA measurements can identify the BHB formation channel. We find that a handful of observations would suffice to tell whether BHBs were formed in the gravitational field of a MBH, but several tens of observations are needed to tell apart field formation from globular cluster formation. We also comment on other potential astrophysical implications of multi-band gravitational wave astronomy.

Author(s): Emanuele Berti[2], Atsushi Nishizawa3, Alberto Sesana4, Antoine Klein[1]
Institution(s): *1. Institut d'Astrophysique de Paris, 2. Johns Hopkins University , 3. Nagoya University, 4. University of Birmingham*

500.02 – Probing accreting double white dwarf binaries with LISA and Gaia

Double white dwarf binaries will be the most numerous source for LISA, with millions of systems expected to be radiating gravitational waves with milliHertz frequencies. Included in this population is the subset of accreting double white dwarf binaries which are subject to astrophysical processes, like tidal interactions and mass transfer, that can alter the gravitational wave signal. The combination of electromagnetic observations from Gaia and gravitational wave observations from LISA will allow detailed studies of this population. We present a method which uses multi-messenger observations to infer component masses of the binary as well as the contribution of mass transfer and tides to the total binary orbital frequency evolution for accreting double white dwarf binaries.

Author(s): Katelyn Breivik[2], Kyle Kremer[2], Shane L Larson[2], Michael Bueno[2], Scott Coughlin[1], Vicky Kalogera[2]
Institution(s): *1. CIERA, 2. Northwestern University*

500.03 – Constraining the Milky Way potential with LISA

The upcoming LISA mission is the only experiment that offers the opportunity to study the Milky Way through gravitational wave radiation, exploiting the signal from Galactic double white dwarf (DWD) binaries. In the coming years, a large number of DWDs can be simultaneously detected in both electromagnetic (e.g. with Gaia and LSST) and gravitational wave radiation. This will provide a unique opportunity to perform a multi-messenger tomography of the Galaxy. In my talk, I will show that LISA will detect DWDs far and wide, mapping also the opposite side of the Galaxy and that this will allow: (1) to provide strong and unique constraints on the scale length parameters of the Milky Way stellar components using LISA data alone, and (2) to compute the rotation curve and derive competitive estimates for the disc and the bulge masses using LISA plus optical counterparts.

Author(s): Valeriya Korol[2], Elena Maria Rossi[2], Enrico Barausse[1]
Institution(s): *1. IAP, 2. Leiden Observatory*

500.04 – A Direct Probe of Mass Density Near Inspiraling Binary Black Holes

Now that LIGO has revealed the existence of a large number of binary black holes, identifying their origin is an interesting challenge. They might originate in the galactic field or reside in dense environments such as galactic centers or globular clusters, in which case their center of mass motion as well as their orbital parameters should lead to observalbe changes in the waveforms, which would reflect their gravitational interactions with the surrounding matter. In these cases there could be observable time-dependence in the gravitational wave signal, leading to a net phase change in the gravitational wave signal or even an observable time-dependent Doppler shift. We show that this time-dependence might be observable in future space gravitational wave detectors such as LISA which could provide direct information about the black hole binary environments and otherwise invisible ambient mass.

Author(s): Lisa Randall[1]
Institution(s): *1. Harvard*

500.05 – Ultra-compact Binary Analysis with LISA

The ultra-compact binaries (UCBs) in the galaxy present unique gravitational wave data science challenges. Of order ten thousand sources will be resolvable, with millions of others blending together to form an irreducible foreground of ``confusion noise'' which dominates the LISA band from (roughly) 1 to 4 mHz. Extraction of resolvable signals, and characterization of the confusion noise, has been successfully demonstrated using trans dimensional MCMC-like methods in the Mock LISA Data Challenges in the late 2000s. This talk will describe and demonstrate a modern implementation of a UCB search framework and highlight some representative science output from the analysis using mock data prepared for the LISA Data Challenges.

Author(s): Tyson Littenberg[1]
Institution(s): *1. NASA Marshall Space Flight Center*

500.06 – A million binary black holes in t he Milky Way

LISA is likely to be the only detector for the remnants of the most massive stars in the Milky Way. In this talk, I will present the first combination of a high-resolution cosmological simulation of a Milky Way-like galaxy (Latte simulation from the FIRE collaboration) and a binary population synthesis model. The cosmological simulation provides us with a physically motivated star formation history, chemical evolution and morphology of the Galaxy. This allows us to determine the first realistic map of the binary black holes (and their merger products) in the Milky Way. We find of order of a million binary black holes, mostly located in the galactic halo, at large distance from the galactic disk. I will present the main properties of the binaries and discuss their detectability with electromagnetic signatures and gravitational waves. This presentation will the importance to use improved models for star formation in order to predict compact binary populations.

Author(s): Astrid Lamberts[1], Shea Garrison-Kimmel[1]
Institution(s): *1. Caltech*

500.07 – LISA sources in Milky Way globular clusters

We explore the formation of double-compact-object binaries in Milky Way (MW) globular clusters (GCs) that may be detectable by the Laser Interferometer Space Antenna (LISA). We use a set of 137 fully evolved GC models that, overall, effectively match the properties of the observed GCs in the MW. We estimate that, in total, the MW GCs contain ~21 sources that will be detectable by LISA. These detectable sources contain all combinations of black hole (BH), neutron star, and white dwarf components. We predict ~7 of these sources will be BH-BH binaries. Furthermore, we show that some of these BH-BH binaries can have signal-to-noise ratios large enough to be detectable at the distance of the Andromeda galaxy or even the Virgo cluster.

Author(s): Kyle Kremer[1], Sourav Chatterjee[3], Katelyn Breivik[1], Carl Rodriguez[2], Shane L Larson[1], Frederic Rasio[1]
Institution(s): *1. CIERA-Northwestern University, 2. MIT, 3. Tata Insitute of Fundamental Research*

500.08 – The Merger Rate of Double Degenerate Binaries

Our targeted electromagnetic search for low mass white dwarfs has discovered 82 double-degenerate binaries with orbital periods less than 1 day. Five are LISA verification binaries. The gravitational wave merger timescales range 0.001 - 100 Gyr. We calculate their local space density and estimate the binary merger rate over the entire Milky Way: 3e-3 /yr. Thus observed He+CO white dwarf binaries merge at a rate at least 40 times greater than the formation rate of stable mass-transfer AM CVn binaries. We conclude that most He+CO white dwarf binaries experience unstable mass-transfer and undergo non-explosive mergers.

Author(s): Warren Brown[1], Mukremin Kilic[2]
Institution(s): *1. Smithsonian, 2. University of Oklahoma*

500.09 – A First Realistic Map of Detached White Dwarf Binaries in the Milky Way

LISA will be sensitive to the low-frequency GW emission of several thousand detached white dwarf binaries (DWDs). Predictions of the characteristics of this population will be essential prerequisites for EM searches for LISA verification binaries and estimations of LISA's DWD yield. This population will also contribute significant astrophysical noise to LISA detections, which must be understood and accurately characterized. To enable these population-level analyses, we combine binary population synthesis results with state-of-the-art cosmological simulation results from FIRE to generate the first physically realistic distribution of DWDs in the Milky Way. In this presentation, I will show a preliminary map of DWDs in the Milky Way and present predictions of the GW signatures of systems within 1 kpc of the Sun as observed by LISA. This work will enable a realistic estimate of LISA's ability to detect DWDs and characterize other resolvable GW sources.

Author(s): Sarah Blunt[1], Astrid Lamberts[1]
Institution(s): *1. Caltech*

501 – New Technologies and Future Projects

501.01 – Progress and Plans for a US Laser System for the LISA Mission

NASA Goddard Space Flight Center is developing a master oscillator power amplifier (MOPA) laser transmitter for the ESA-led Laser Interferometer Space Antenna (LISA) mission. Taking advantage of our space laser experience and the emerging telecom laser technology, we are developing a full laser system for the LISA mission. Our research effort has included both master oscillator (MO) and power amplifier (PA) developments, and their environmental testing and reliability for space flight. Our current baseline for the MO is a low-mass, compact micro NPRO (m-NPRO) laser. The amplifier uses a robust mechanical design based on fiber components. We have performed laser system noise tests by amplitude- and frequency-stabilizing the PA output. We will describe our progress and plans to demonstrate a TRL 6 laser system, which is an essential step toward qualifying lasers for space applications, by 2021.

Author(s): Kenji Numata[1], Anthony Yu[1], Hua Jiao[1], Scott Merritt[1], Frankie Micalizzi[1], Molly Fahey[1], Jordan Camp[1], Michael Krainak[1]
Institution(s): *1. NASA Goddard Space Flight Center*

501.02 – Alternative Laser Technologies

Key requirements of the laser for LISA are a high frequency stability, a low relative intensity noise and a continuous optical output power higher than 2 W. The main building blocks of the laser head are the seed laser source, an amplifier, light modulation and power stabilization technologies.
Within the ESA activity “Gravitational Wave Observatory Metrology Laser” we design, build and test a laser head to fulfill these requirements using alternative seed laser technology: an external cavity diode laser (ECDL) with resonant feedback from an additional external cavity as master for further linewidth narrowing. The laser comprises a master oscillator power amplifier (MOPA) concept, where the output of the ECDL with resonant optical feedback is amplified by means of a power amplifier, a semiconductor optical amplifier delivering 300 mW of optical power at the fiber output. The ECDL MOPA is a hybrid micro-integrated device based on a micro-integrated laser platform already flown on several sounding rocket experiments, highly suitable for space missions.
The seed-laser light is amplified by a single-stage fiber amplifier with an amplification factor of about 20 dB. The amplifier utilizes an active Yb-doped fiber that is contra-directionally pumped by three wavelength-stabilized pump diodes to deliver 2.1 W of optical output power. The amplifier is designed to introduce only very low noise, which could mainly arise from amplified spontaneous emission and stimulated Brillouin scattering. The amplifier design is based on design of the fiber amplifier for a high-stability laser for a potential Next Generation Gravity Mission (NGGM) which successfully passed an environmental test campaign.
We will present the design and first results of the laser head breadboard characterization which is currently in the assembly, integration and test phase.

Author(s): Kai Cristian Voss[6], Pelin Cebeci[4], Katrin Dahl[6], Oliver Fitzau[4], Martin Giesberts[4], Christian Greve[1], Martin Krutzik[5], Achim Peters[5], Sana Amairi Pyka[5], Josep Sanjuan[2], Max Schiemangk[3], Thilo Schuldt[2], Andreas Wicht[3]
Institution(s): *1. Airbus Defence and Space GmbH, 2. DLR, 3. Ferdinand-Braun-Institut Leibniz-Institut für Höchstfrequenztechnik, 4. Fraunhofer Institute for Laser Technology, 5. Humboldt-Universität zu Berlin, 6. Spacetech GmbH*

501.03 – The GRACE Follow-on Laser Ranging Interferometer: Creating heritage for LISA

By measuring the distance between two satellites orbiting the earth using microwaves, the Gravity Recovery and Climate Experiment (GRACE) mission successfully monitored the gravity profile of Earth for over a decade. GRACE observed Earth’s environment due to shifting water masses, giving insight into global climate change over long time scales. GRACE has reached the end of its lifetime. Its replacement, GRACE Follow-On will launch in the spring of 2018. The GRACE Follow-On microwave instrument is a build-to-blueprint replacement of GRACE. In addition, a nanometer-precision laser interferometer demonstration instrument has been incorporated to demonstrate a much finer precision measurement.

A partnership between NASA and Germany, the Laser Ranging Interferometer (LRI) on GRACE Follow-On is based on technology originally developed for gravitational wave detection for the Laser Interferometer Space Antenna (LISA). The LRI implements one arm of the three-arm LISA observatory at a distance of hundreds of kilometers. Between the successful LISA Pathfinder/ST-7 mission and the GRACE Follow-on LRI, many of the elements of a picometer-sensitivity space-based gravitational wave detector will be demonstrated in flight.

Author(s): Brent Ware[1], Robert Spero[1], Kirk McKenzie[1], Samuel Francis[1]
Institution(s): *1. California Institute of Technology*

501.04 – Optical Ground Support Equipment: from GRACE Follow-on to LISA

The laser ranging interferometer (LRI) onboard the Gravity Recovery and Climate Experiment (GRACE) follow-on mission, launched in May 2018, is the first inter-spacecraft laser interferometer. The LRI will measure the distance between two spacecraft separated by about 200 km in a low Earth orbit in a similar manner LISA will do in each arm. Relevant parameters such as received power and Doppler shifts are very similar in both missions. For this reason, the LRI on GRACE-FO is an excellent demonstrator of the LISA long baseline interferometry. The local laser interferometry has already been successfully demonstrated in LISA Pathfinder.
A critical aspect for any mission is the relevant testing of units and subsystems at various levels prior to launch. Here we present a variety of instruments developed as optical ground support equipment (OGSE) and designed to verify and ensure the proper behavior of the LRI subsystems prior to launch and throughout the various levels of mission development (unit, subsystem and spacecraft levels). The LRI OGSE has been crucial to characterize the triple mirror assembly (TMA), the interferometer itself, verification of essential functionalities such as differential wavefront sensing and phase-locked loops, the field of view and field of regard, and pointing of the steering mirror, among others. In addition, a link simulator that mimics the inter-spacecraft separation was developed in order to test the LRI link acquisition strategy, which is essential to establish the interferometer link. We will discuss some of the lessons learned through the development of the LRI onboard GRACE-FO and potential overlaps with LISA.

Author(s): Felipe Guzman[1], Josep Sanjuan[1], Claus Braxmaier[1]
Institution(s): *1. DLR - German Aerospace Center*

501.05 – Finding IMBHs with the Next Generation Very Large Array

Using the Next Generation Very Large Array (ngVLA), we will make a breakthrough inventory of intermediate-mass black holes (IMBHs) in hundreds of globular cluster systems out to a distance of 25 Mpc. IMBHs have masses of about 100 to 100,000 solar masses. Finding them in globular clusters would validate a formation channel for seed black holes in the early universe and inform event predictions for gravitational wave facilities, notably the *Laser Interferometer Space Antenna*. Our IMBH inventory is well suited for ngVLA Early Science starting in 2028.

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501.06 – Large GW from Inflation at Interferometer Scales, and Measurement of Non-gaussianity at LISA

In the broad class of models of Natural Inflation, the couplings of the inflaton field can result in
the production of a gravitational wave (GW) signal that is exponentially sensitive to the speed
of the inflaton. The speed of the inflaton increases during inflation, which naturally adds a
blue component to the stochastic GW background produced during inflation, that might reach
observable level at LISA scales. Contrary to the stochastic astrophysical backgrounds, this signal
is chiral and highly non-Gaussian. These distinctive features can be explored through the 2-point
and the 3-point correlators of the LISA signal, as well as from ground-based interferometers.

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501.07 – ROMAN: Reduced-Order Modelling with Artificial Neurons

Order reduction strategies can be used to construct compact representations of waveform models for gravitational-wave sources, which will facilitate the analysis of data from contemporary and next-generation detectors. These waveform representations are obtained through projection onto a reduced basis, but a direct interpolation of the projection coefficients over a high-dimensional parameter space is challenging. A solution is found within the deep-learning paradigm, where artificial neural networks provide a powerful and versatile algorithm for function approximation. We use deep learning to develop a universal interpolation framework for reduced-order waveform models, and propose several associated Bayesian inference techniques for the fast and robust estimation of source parameters.

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501.08 – Transient Astrophysics Probe and X-ray Counterparts of LIGO and LISA Sources

The Transient Astrophysics Probe (TAP) is a wide-field multi-wavelength transient mission proposed for flight starting in the late 2020s. It is currently undergoing a Concept Study funded by NASA to provide input to the 2020 Decadal Survey. TAP's main science goals are time-domain astrophysics and electromagnetic counterparts of gravitational wave (GW) detections. The mission instruments include unique "Lobster-eye" imaging soft X-ray optics that allow a ~1600 deg^2 FoV; a high sensitivity, 1 deg^2 FoV soft X-ray telescope based on single crystal silicon optics; a passively cooled, 1 deg^2 FoV Infrared telescope with bandpass 0.6-3 micron; and a set of ~8 NaI gamma-ray detectors. TAP will observe tens per year of X-ray and IR counterparts of GWs involving stellar mass black holes and neutron stars detected by LIGO/Virgo/KAGRA/LIGO-India, and possibly several per year X-ray counterparts of GWs from supermassive black hole mergers detected by LISA. In this talk we will focus on the TAP instruments that yield the prediction of these counterpart rates.

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501.07 – Testing an optical read-out scheme for future gravitational reference sensors

We report on a test of an optical read-out system to be used in a torsion pendulum currently developed at the Albert Einstein Institute and University of Hannover. The read- out is via modulation/demodulation technique based on four optical levers with quadrant photodiodes. The functionality of the proposed device has been already demonstrated in bench-top measurements and is planned to be tested at the torsion pendulum facility. We present preliminary experimental results for the rotational sensitivity, which is already as good as or better than the conventionally used autocollimators, and in addition provides low-noise readouts for the two pendulum-swing degrees of freedom, which will be used for platform stabilization.

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