2 Astrophysics and General Relativity

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For describing most of astrophysical phenomena, Newtonian gravity is adequate, but for situations involving very strong gravitational fields, or cosmological distances, or the effect of gravity on light, or just extremely precise measurements, relativistic gravity is needed. After more than hundred years, Einsteinian gravity continues to pass all tests thrown at it, and meanwhile reveals new manifestations such as gravitational waves (GW), whose detection has been announced on 11 February 2016 [1]. Indeed, on 14 September 2015 the two LIGO detectors simultaneously observed a transient gravitational wave signal, which has been interpreted as due to the merger of two black holes with masses of about 36 $M_\odot$ and 29 $M_\odot$, respectively. A further event has been detected on 26 December 2015 and announced on 15 June 2016 [2]. Exploring various aspects of general relativity is the area of our research.

[1] B.P. Abbott *et al.*, LIGO and Virgo Collaborations, Phys. Rev. Lett. 116, 061102, 2016.

[2] B.P. Abbott *et al.*, LIGO and Virgo Collaborations, Phys. Rev. Lett. 116, 061102241103, 2016.

2.1 Gravitational Waves

2.1.1 LISA Pathfinder

Ph. Jetzer is member of the LISA Pathfinder (LPF) science working team and of the LISA consortium board. LISA Pathfinder is a European Space Agency (ESA) mission launched on 3 December 2015 from the European Spaceport in Kourou, French Guiana with a Vega rocket. Following six apogee-raising manoeuvres, the spacecraft reached its final science orbit around the first Sun-Earth Lagrange point L1, 1.5 million kilometers from Earth, on 22 January 2016.

The goal of LPF is to place two test masses in a nearly perfect gravitational free-fall, and control and measure their relative motion with unprecedented accuracy, at the level required for a future space-based gravitational wave (GW) observatory, such as LISA. This requirement is achieved through innovative technologies comprising inertial sensors, an optical metrology system, a drag-free control system and a micro-Newton thruster system.

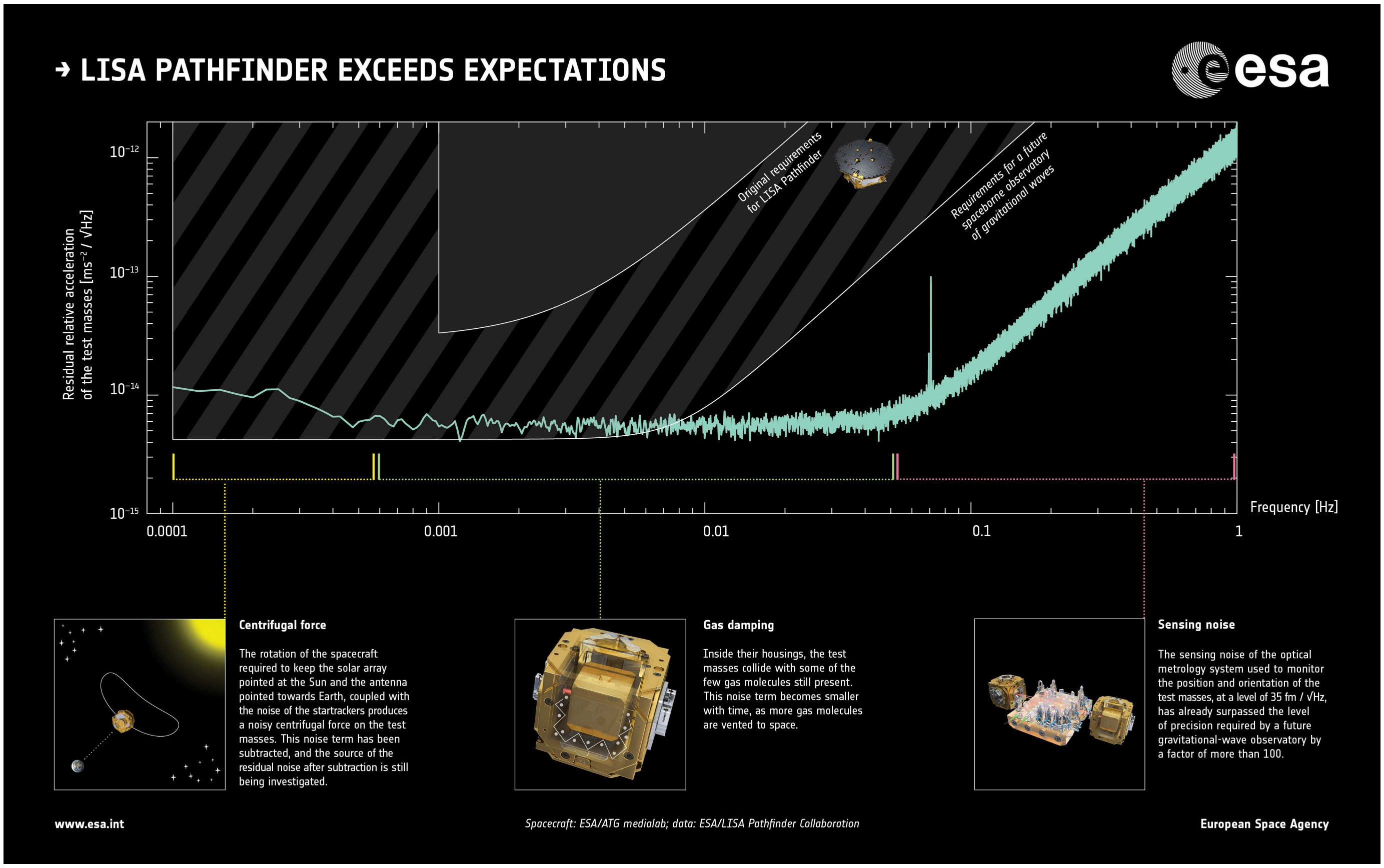
The LISA Technology Package (LTP) is the main payload on board of LPF, which was developed jointly by several European institutes and industries including ones from Switzerland. It contains two identical cubic test masses of 1.9 kg and 46 mm in size made of gold-platinum. Each is suspended in its own vacuum vessel with capacitive sensors to monitor the relative position of the test masses with respect to the satellite, laser interferometry to determine the relative positions and attitudes of the two test masses, and the drag-free control system to adjust the relative alignment of the satellite and test masses through a mixture of micro-Newton (cold gas) thrusters and capacitive actuation. The cubes serve both as mirrors for the laser interferometer and as inertial references for the drag-free control system of the spacecraft, exactly as will be used for LISA.

On 22 February 2016 the two cubes housed in the LTP of LPF were left to move under the effect of gravity alone, and one day later the spacecraft's main operating mode was switched on for the first time. The LPF scientific mission started officially on 1 March. Based on only 55 days of science operations LPF could already demonstrate that the key technologies needed to build a space-based GW observatory are properly working. It turned out that the two test masses are freely falling under the influence of gravity alone, unperturbed by other external forces, to a precision more than five times better than originally required. The two cubes are almost motionless with respect to each other, with a relative residual acceleration lower than 10^{-14} g, with g being Earth's gravitational acceleration. For the remaining forces acting on the test masses, three main sources of noise, depending on the frequency, were identified (see Fig. 2.1).

At the lowest frequencies accessible to the experiment, below 1 mHz (on the left of the figure), one measures a small centrifugal force acting on the cubes, which is caused by a combination of the shape of LPF's orbit and the effect of the noise in the signal of the startrackers used to orient it. The contribution of the centrifugal force to the relative acceleration of the two test masses has been subtracted. Further investigations are under way to better identify the source of the residual noise after subtraction.

At frequencies in the range 1-60 mHz (at the centre of the figure),the control over the test masses is limited by gas molecules bouncing off the cubes: a small number of them remain in the surrounding vacuum. This effect was seen to be reducing as more molecules were vented into space, and it is expected to lower further in time.

At higher frequencies, between 60 mHz and 1 Hz (on the right of the figure),LPF's precision is limited only by the sensing noise of the optical metrology system used to monitor the position and orientation of the test masses. Nicely, the performance of this system has already surpassed the level of precision required by a future gravitational-wave observatory



Centrifugal force

The rotation of the spacecraft required to keep the solar array pointed at the Sun and the antenna pointed towards Earth, coupled with the noise of the startrackers produces a noisy centrifugal force on the test masses. This noise term has been subtracted, and the source of the residual noise after subtraction is still being investigated.

Gas damping

Inside their housings, the test masses collide with some of the few gas molecules still present. This noise term becomes smaller with time, as more gas molecules are vented to space.

Sensing noise

The sensing noise of the optical metrology system used to monitor the position and orientation of the test masses, at a level of 35 fm / √Hz, has already surpassed the level of precision required by a future gravitational-wave observatory by a factor of more than 100.

FIG. 2.1 – ESA/ATG medialab; data: ESA/LISA Pathfinder collaboration

by a factor of more than 100. These findings were announced on 7 June 2016 in a press conference by ESA. In the meantime the LPF performances improved further.

The demonstration of the LPF's key technologies opens the door to the development of LISA, which will be capable of detecting gravitational waves emanating from a wide range of objects in the Universe.

In November 2013 ESA has selected *The Gravitational Universe* as the science theme to be explored by ESA's Large class mission L3. Following the success of LPF, the LISA consortium had to submit to ESA a mission proposal by mid January 2017.

2.1.2 Gravitational waves and LISA

The scope of LISA is to detect and study low-frequency GW from about 0.1 mHz to 1 Hz, and thus to complement ground-based gravitational observatories. LISA opens new possibilities for astrophysical studies by allowing, for instance, to detect supermassive black holes (typically of $10^6 - 10^7\ M_\odot$) merging at cosmological distances. Mergers of a supermassive black hole with another compact object (such as another black hole or a neutron star) produce a very clean GW signal which LISA will be able to measure with high precision. Alternative gravity theories influence the dynamics of such mergers and hence LISA is expected either to directly see the imprints of certain alternative theories or to put severe constraints on them. Another class of objects, which will be observed by LISA, are ultra-compact binaries, in particular of white dwarfs in our Galaxy. They are important sources of gravitational waves in the mHz frequency range. Moreover, it will be possible to detect or put strong constraints on the primordial GW background, which is just, as the cosmic microwave background, a leftover from the Big Bang.

Yannick Bötzel is studying gravitational waves from compact binaries in eccentric inspiralling orbits. In particular he could already provide an elegant analytic solution to the 3PN-accurate Kepler equation, associated with the 3PN-accurate generalized quasi-Keplerian parameterization for compact binaries in eccentric orbits. This is an important step for getting accurate GW templates from compact binaries in inspiralling eccentric orbits.

The detection of gravitational waves and the corresponding determination of polarization modes is a powerful tool to discriminate between general relativity and alternative theories of gravity such as $f(R)$ theories. Besides the usual two transverse-traceless tensor modes present in general relativity, there are indeed up to two additional scalar ones: a massive longitudinal mode and a massless transverse mode (the so-called breathing mode), as well as two vector modes. Lionel Philippoz is addressing the question of whether a given LISA configuration can provide a sufficient sensitivity to those additional polarization modes, and how to extract this information from a signal produced by a stochastic GW background.

Maria Haney joined our group as a post-doc in January 2017. As a member of the LIGO Scientific Collaboration (LSC) since 2014, she is directly involved in the development of tools and pipelines for the analysis of LIGO data.

In March 2017, Philippe Jetzer, Maria Haney and Yannick Bötzel joined the GEO600 collaboration and were subsequently approved for LSC membership, establishing the first LSC group in Switzerland. Our proposed contribution to LSC research includes template waveform development for the gravitational-wave search and parameter estimation efforts, as well as tests of general relativity with gravitational-wave data from binary black hole mergers.

2.1.3 XI International LISA Symposium

The XI International LISA Symposium took place at the University of Zürich (Irchel Campus) from 5 to 9 September 2016 [3]. Given these spectacular developments in the field of GW, it came as no surprise that the interest in the community for the LISA Symposium increased and indeed about 250 participants attended the meeting, which was in all aspects very successful. The format was such as to have only plenary talks, in total some 68 talks. Almost 100 posters were presented. The main topics of the talks covered the first results from LISA Pathfinder, the further development of LISA and an overview of the results obtained so far by the ground based gravitational wave detectors (LIGO and VIRGO) as well as Pulsar Timing Arrays. Several talks covered different aspects of astrophysics and cosmology related to gravitational waves. One talk was devoted on the preliminary results of the satellite Microscope, whose aim is to test the equivalence principle in general relativity. On one afternoon there was a joint eLISA and L3ST (a NASA committee) consortium meeting. There were also programmatic talks given by Prof. A. Gimenez (Science Director of ESA) and by Dr. Paul Hertz (Astrophysics Division director of NASA). It is planned to publish the proceedings soon.

[3] http://www.physik.uzh.ch/events/lisa2016/

2.2 Gravitational Lensing

That gravitational lensing — specifically that light is affected by both space and time parts of the metric, unlike Newtonian bodies, which are affected only by the time part — is too well known to need elaborating here. Nowadays, however, gravitational lensing is valued, more than as a test of general relativity, as a way of detecting matter that would be otherwise invisible.

On the scale of galaxies and clusters of galaxies, gravitational lensing is very important as a probe of dark matter. Extracting the information on mass distributions, however, requires solving a non-trivial inverse problem. R. Küng, P. Denzel and P. Saha, together with external collaborators, have worked on the problem of mapping a mass distribution from lensing observables. One part of this work is the development of an improved method for modelling galaxy lenses and furthermore, a theoretical formulation and computational interface to enable modelling in a citizen-science context. The other aspect is mapping and interpreting dark-matter structure in strong-lensing galaxy-clusters

2.3 Space clocks and relativity

Together with S. Lecomte from CSEM in Neuchâtel, M. Rothacher from ETH Zürich, Q. Wang and P. Rochat from Spectratime in Neuchâtel and some of their collaborators, we conducted a study on behalf of the Swiss Space Office (SSO) for a satellite mission called E-GRIP (Einstein Gravitational Red-shIft Probe) to test general relativity using an on board hydrogen maser. The clock would be sensitive to Earth's gravitational redshift to the level of 2×10^{-6}, as well as to the space-curvature around Earth and the frame-dragging by Earth's spin. In addition, E-GRIP would provide a wealth of science for time and frequency metrology- and geodesy. After delivering a first report in December 2015, we were requested to study the proposal further. The final report (Phase 0 Study Report) was then presented on 20 June 2016 at SSO.

Andreas Schärer worked on how one could measure planetary spin with satellites and to estimate the frame-dragging in spacecraft timing signals. As examples he analysed the Juno mission, a satellite in a highly eccentric orbit around Jupiter, and the Cassini mission around Saturn.

2.4 Scalar-Tensor Theories

Scalar-tensor theories are a promising class of alternative theories of gravitation. They contain, in addition to the metric tensor of GR, a scalar degree of freedom. Upcoming precision experiments might detect violations of general relativity, which could be explained by such theories. Together with Manuel Hohmann from the University of Tartu, Estonia, Andreas Schärer studies multi-scalar-tensor theories. These theories are a further generalization which contain multiple such scalar fields.