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LISA PATHFINDER
FIRST STEP TOWARD A GRAVITATIONAL WAVE SPACE OBSERVATORY

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On behalf of the LISA Pathfinder collaboration (*)

Abstract

We briefly review the concept of a space-based gravitational wave interferometer, and the science it can explore in the milliHertz frequency region. Then we discuss the LISA Pathfinder technology demostrator mission that is currently flying and will soon deliver the first results.

1 Gravitational astronomy from space

Gravitational waves have finally been detected [1], one century after being predicted by A. Einstein [2]. The very first signal has already shown the amazing power of gravitational astronomy, offering detailed information about the merging of two black holes of unexpected mass. In the years to come, Earth-based Advanced Interferometers will provide a great wealth of information about compact objects like neutron stars and black holes in their final stages of life

before merging.
What is the role then of a space observatory like LISA, expected to operate no sooner than fifteen years from now ?
Theoretical predictions suggest that a wide variety of astrophysical sources emit gravitational waves (g.w.) in that part of the frequency spectrum, from 0.1 mHz to about 100 mHz, that is only accessible by a space interferometer. Signals gathered in this band can provide crucial insights about binary stars formation, Extreme Mass Ratio Inspirals, SuperMassive Black Holes and galaxy mergers. An observatory in that frequency range has moreover guaranteed signals for calibration, the so called Verification Binaries, of which all parameters are know by e.m. observations and whose g.w. flux is precisely predicted.

2 The LISA mission concept

The frequency range below 1 Hz, where all these sources are to be observed, is only accessible by a space-borne detector, that is immune from Earth-generated, low frequency disturbances, like seismic and Newtonian noise. LISA is a space mission concept, developed over two decades through several different configurations, that addresses this request. LISA's basic scientific and technological fundamentals are well established since many years [3]. Its actual design has undergone several revisions, but has reached a stable configuration since 1998 [4]; it relies on a few pillars:

- *The orbital configuration:* a redundant set of three interferometers with arm length of 1-5 Gm (milion kilometers), hosted by a constellation of three satellites arranged at the vertices of a gigantic triangle. Each spacecraft (S/C) passively move on a different "smart" heliocentric orbit [5]: while keeping the relative distance roughly constant, the triangular pattern rotates around its center, that moves on the ecliptic, trailing the Earth by some 20^0. This motion modulates the g.w. signals, giving them a unique signature.
- *The optical transponders:* the divergence of a laser beam is such that, even using a large telescope, only a few parts in 10^9 of the incoming beam can be received at the far end of such a long interferometric arm, thus making it unfeasible to reflect the light back with a mirror. A transponder [6] is a

phase-preserving amplifier that will regenerate the beam to its full power (1-5 W) and send it back to the other S/C for phase comparison.

- *Time delay interferometry:* The distances between S/C's vary in time, due to Keplerian dynamics, of 1-2 %, i.e. up to 10^5 km: the unequal arm length gives rise to frequency noise in the interferometer. This noise can be depressed, by several order of magnitude, by recording the phase signal of each arm and then, off-line, synthesizing linear combinations of the signals emitted at different times [7], before comparing them, thus canceling most of the the frequency noise. So, the usual optical path difference with equal arms $X(t) = y_1(t) - y_2(t)$ is substituted by:

$$X(t) = y_1(t) - y_2(t) - y_1(t - 2L_2/c) + y_2(t - 2L_1/c) \tag{1}$$

  More complex relations (second order TDIs) would apply if one also wants to cancel the Doppler effect of different S/C velocities .

- *Test masses in free fall:* aboard each S/C, two test masses (TMs), one for each interferometer arm ending at that node, are in geodesic motion, shielded by the spacecraft from any external disturbance, and responding only to space-time perturbation. A feedback loop, acting on the S/C microthrusters, recenters the S/C on the TM along the sensitive axis. All other Degrees of Freedom (DoFs) are stabilized by electrostatic forces. Each interferometric arm acts then as a huge differential accelerometer.

In 2011, financial constraints forced NASA to withdraw its support for the LISA mission. European scientists undertook an intense effort to "rescope" the mission so that it could fit in the "ESA only" budget: the ambitious goal was to achieve the same physics with half the budget. This study produced a new configuration, called "eLISA": still with three spacecrafts, but with only one interferometer (two arms, therefore giving up redundancy and polarization detection capabilities), a reduced (1 or 2 Gm) arm length (thus making do with less laser power and without a pointing mechanism for the telescopes) and a shorter mission duration. This project, presented to ESA in 2013 [8], gained for the theme *The Gravitational Universe* the selection to third large ESA mission of the Cosmic Vision Plan (L3), for launch in 2034. Nevertheless, recent re-analyses of the science, technology and finances for the mission make us hopeful that the full, three arm configuration can be regained before the detailed mission formulation.

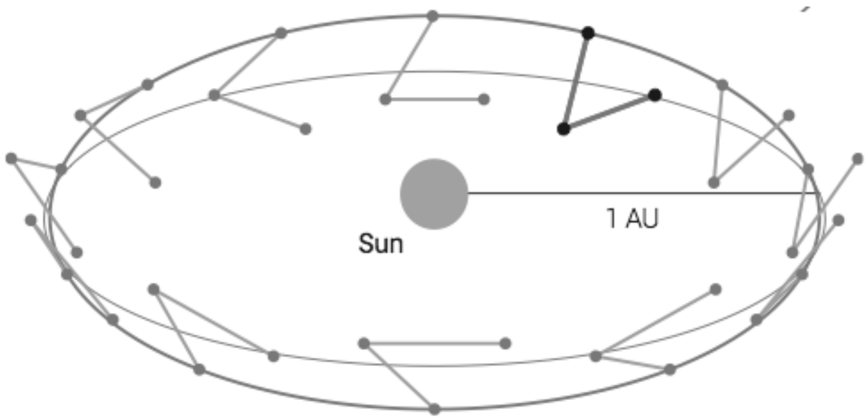

Figure 1: The *smart orbits* of the space g.w. observatory: each spacecraft moves on an independent, passive, Keplerian orbit, and the constellation mantains a triangular formation, while rotating around its center. Picture from ref. [8]

3 LISA Pathfinder, the technology demonstrator

The technical difficulty of the LISA project made it sensible to test as much as possible of the enabling technology in a dedicated mission. Particularly challenging is the assessment of the quality of free fall that can be achieved in space, despite extensive laboratory investigations, carried out with torsion pendulums [9], of the residual forces that can locally disturb the inertial motion of the TM. Other items that need to be space-tested are the interferometric read-out of the TM positions, the Gravitational Reference Sensor (GRS) that senses motion in the other degrees of freedom and applies electrostatic feedback, its front-end electronics (FEE) the microthrusters, TM decaging and release (with minimum velocity) and more.

Therefore ESA has approved and realized a dedicated space mission to verify all the flight hardware that can be tested in a single-spacecraft mission, and to evaluate the level of geodesic motion that current technology can achieve

and measure. Such mission, called LISA Pathfinder [10], is active and operational now.
In LISA Pathfinder, a single spacecraft holds two independent TMs: once spaceborne, each TM is released within its GRS and their relative distance is measured by a differential interferometer: in many respects, this is a LISA arm shrunk from few Gm down to 38 cm. Feedback loops act on the spacecraft and on the second TM to make sure that they both follow the first TM in its free fall. Most of the hardware (with few exceptions like the telescope, the pointing mechanism and the TDI) are therefore tested in an enviroment that is representative of the final LISA mission. Moreover, a large number of noise sources, i.e. all *local* sources, like thermal, magnetic, laser shot and radiation pressure, long term changes in local gravity etc. can be accurately assessed and measured, so that a reliable noise budget can be formulated for the LISA mission.

LPF was launched with the sixth VEGA launcher on Dec 3rd 2015, one

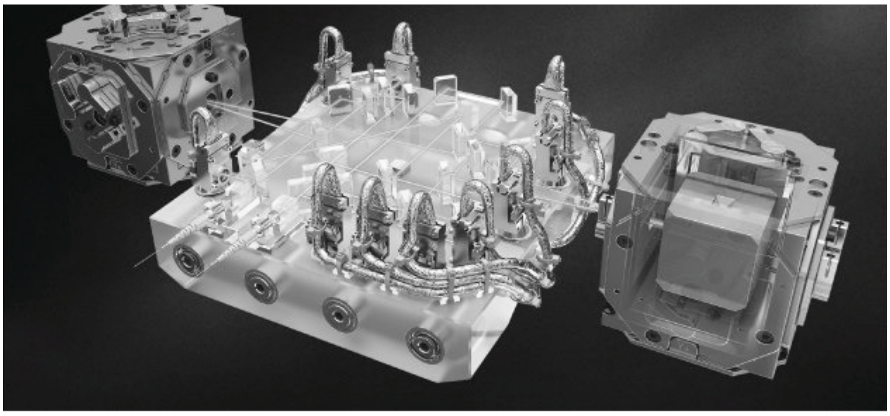

Figure 2: Schematics of the LISA Pathfinder payload: two Test Masses, each surrounded by its GRS (electrostatic sensors and actuators) and, in between them, the monolithic Optical Bench, with all the optics needed to operate 4 different interferometers

century after publication of Einstein's first paper on the *General Theory of Relativity* and few weeks after the detection of the first g.w. signal by LIGO, thus marking an unforgettable year for Gravitational research. After a few orbits around the Earth, raising each time its apogee, it has started its journey toward the first Lagrangian point (L1) of the Sun-Earth system, where the gravitational gradient is a minimum, about 1.5 Gm from the Earth. It has now reached its target orbit, a large, slow orbit around L1 where it has undergone testing and commissioning. At the time of this talk, operations are under way and the first results are extremely promising. However, no data has yet been published, and expectations are high for the first release due in June.

4 Post-conference update: first results from LISA Pathfinder

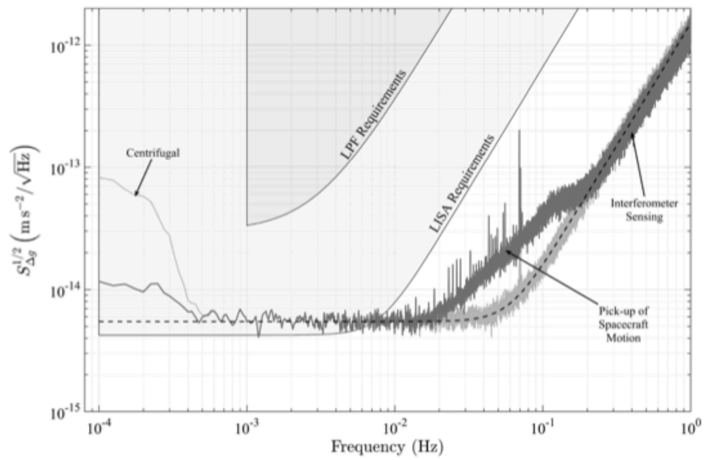

Figure 3: Spectrum of the differential acceleration noise of the two Test Masses of LISA Pathfinder. We also show the requirements, well exceeded the present mission and closely approached for the future LISA observatory. Some known sources of noise, measured and subtracted, are also indicated. The rise on the right is readout noise (white in displacement), that grows as ω^2 when converted to acceleration. Figure from ref. [11].

On June 7th 2016, about two weeks after the workshop, the first LPF data were released [11]. The results are excellent, beyond the most optimistic expectations: the interferometer readout noise is $35 fm/\sqrt{Hz}$, that is 100 times better than the requirements and than noise measured on ground, where mirrors could be carefully hand-aligned. The purity of free-fall is gauged by the differ-

ential acceleration of the two test masses, and is measured to be $5.2 \cdot 10^{-15} ms^{-2}$ i.e. below the femto-g range. This is also lower, by a factor 5, than the mission requirements and closely approaches the tougher spec required for LISA. Even more striking, the specs are exceeded not only on the required frequency region, i.e. down to 1 mHz, but on a band extending almost down to 0.1 mHz, i.e. on the full LISA sensitivity band. Figure 3 shows the residual acceleration noise, together with the LISA Pathfinder requirements and the LISA requirements, that are approached to within a factor 1.5. Moreover, the noise in the "flat" region 2-8 mHz, that is mainly of Brownian origin, appears to be decreasing with time: a probable reason for this is the continuing decrease in pressure due to venting to open space.
The tests and investigations on LISA Pathfinder will continue for the next several months, with the aim of characterizing all components of the residual noise, but we can already confidently state that LISA Pathfinder is doing its job and the road to LISA looks brighter than ever.

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