Gravitational Wave Detection by Laser Interferometry in Space – LISA

Albrecht Rüdiger,[1]
(1) Max-Planck-Institut für Gravitationsphysik, Albert-Einstein-Institut, Hans-Kopfermann-Str. 1, D – 85748 Garching, Germany

Abstract

The space project LISA shares its goal and principle of operation with the ground-based interferometers currently under construction: the detection and measurement of gravitational waves by laser interferometry. It is only in space that detection of signals below, say, 1 Hz is possible, opening a wide window to a different class of interesting sources of gravitational waves. The project LISA consists of three spacecraft in heliocentric orbits, forming a triangle of 5 million km sides. A technology demonstrator, designed to test vital LISA technologies, is to be launched, aboard a SMART-2 mission, in 2006.

1. Introduction

This second of three talks deals with the space project LISA for the detection and measurement of gravitational waves, for more details see [1, 2, 3, 4].

Ground-based interferometers have gone into their final phase of commissioning, but perhaps even more promising is the space-borne interferometer of the joint ESA-NASA project LISA (Laser Interferometer Space Antenna).

The formation, and the interaction, of massive and supermassive black holes, believed to be at the centers of most galaxies, are perhaps the most violent events in the Universe, and the gravitational waves emitted by them will be our best chance to investigate the physics involved. This type of gravitational waves will come in a frequency region even below 1 mHz, and only space projects will be able to detect them. The events to be detected by the space project LISA may have extremely high signal-to-noise ratios, and failure to find them would shatter the very foundations of our present understanding of the universe. The strongest signals will come from events involving (super-)massive black holes, but also the (quasi-continuous) signals from neutron-star and black-hole binaries are among the events to be detected. The combined observation with electromagnetic and gravitational waves could lead to a deeper understanding of the violent cosmic events in the far reaches of the universe [5].

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2. The space interferometer LISA

Only a space mission allows us to investigate the gravitational wave spectrum at very low frequencies. Once we have left our planet behind and find ourselves in outer space, we have some great benefits for "free": to get rid of terrestrial seismic and gravity gradient noise, to have excellent vacuum along the arms, and in particular to be able to choose the arm length large enough to match the frequency of the astrophysical sources we want to observe.

2.1. The LISA configuration

The European Space Agency (ESA) and NASA have agreed to collaborate on such a space mission called LISA, "Laser Interferometer Space Antenna" [1, 2].

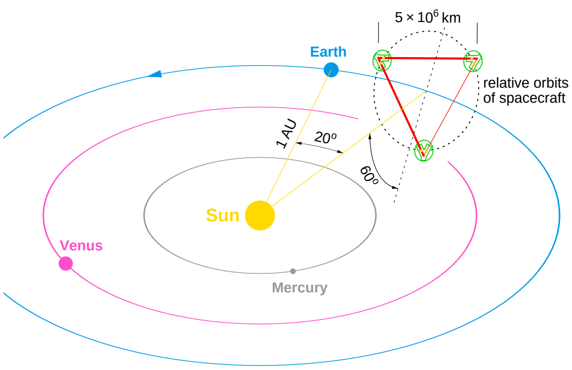

Fig. 1. Orbits of the three spacecraft of LISA, trailing the Earth by 20°. The triangle arms are scaled by factor 10.

Fig. 2. View of LISA spacecraft, housing two optical assemblies. The solar panel at top not shown.

LISA consists of three identical spacecraft, placed at the corners of an equilateral triangle (Figure 1). The sides are to be 5 million km long (5×10^9 m). This triangular constellation is to revolve around the Sun in an Earth-like orbit, about 20° (i.e. roughly 50 million km) behind the Earth. The plane of this equilateral triangle has an inclination of 60° with respect to the ecliptic. The three spacecraft form a total of three, but not independent, Michelson-type interferometers, here of course with 60° between the arms. The spacecraft at each corner will have two optical assemblies that are pointed, subtending an angle of 60°, to the two other spacecraft (indicated in Figure 2, with the Y-shaped thermal shields shown semi-transparent). An optical bench, with the test-mass housing in its center, can be seen in the middle of each of the two arms, and a telescope of 30 cm diameter at the outer ends. Each of the spacecraft has two separate lasers that are frequency-locked so as to represent the "beam-splitter" of a Michelson interferometer.

2.2. *Annual orbit of LISA*

During its yearly motion around the sun, the three spacecraft of LISA will 'roll' on a cone of half-angle 60°. Each individual spacecraft moves on a slightly elliptic orbit around the sun, slightly tilted with respect to the Earth orbit.

This configuration has a number of advantages that make several of the design requirements less stringent. The constant angle to the Sun (angle of incidence 30°) provides a very stable thermal environment for the sensitive parts of the spacecraft. The rather unperturbed orbits of the three spacecraft provide a very stable configuration, very close to an equilateral triangle. The annual rotation of the triangle makes the detector point to different positions in the sky.

2.3. *Drag-free operation*

The distances between the different spacecraft are measured from test masses housed *drag-free* in these three spacecraft. Each LISA spacecraft contains two test masses, one for each link to another LISA spacecraft. The test masses define the reference of the interferometer arm. These test masses are to be freely floating in space. For this purpose these test masses are also used as inertial references for the drag-free control of the spacecraft that constitutes a shield to external forces. The very weak forces required to keep up drag-free operation, less than 100 μN, are to be supplied by field-effect electrical propulsion (FEEP) devices.

2.4. *Noise in LISA*

The LISA sensitivity of Figure 3 consists of three main parts, as indicated by the three differently shaded regions, in which different noise mechanisms take hold.

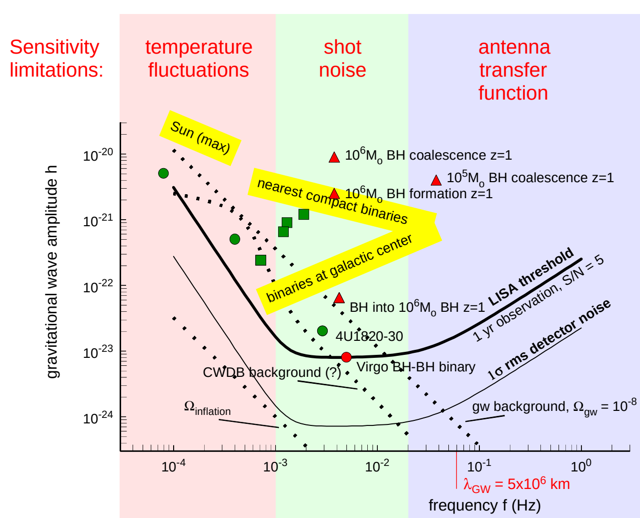

Fig. 3. Sensitivity of LISA: the heavy curve "LISA threshold" represents the signal strength that would provide a signal-to-noise ratio of 5 when averaged over one year.

From 1 W of laser power transmitted, only 10^{-10} W will be received after 5 million km, and due to that low level of light power, shot noise plays a major role in the total noise. It is responsible for the flat middle part of the sensitivity curve. The antenna response rolls off as $1/f\tau$ at frequencies f above the inverse of the round-trip time τ. Thus shot noise leads to the frequency-proportional rise. At frequencies below 1 mHz, the noise is mainly due to accelerations of the test mass, mainly arising from temperature variations.

2.5. Status of LISA

LISA an approved ESA cornerstone mission, has substantiated in a System and Technology Study [2] that improved technology, lightweighting, and collaboration with NASA will lead to a considerable reduction of cost. Launch is foreseen for 2011, with a nominal lifetime of 2 years, but the equipment and thruster supply are chosen to allow even 10 years of operation.

2.6. Technology demonstrator

Some of LISA's essential technologies (gravitational sensor, interferometry, FEEP thrusters) are to be tested in a mission LTP (LISA Technology Package) on board an ESA SMART-2 satellite. The package will contain, on a common optical bench, two gravitational sensors, similar to the ones of LISA. The relative motion between the two freely floating test masses will be monitored with high accuracy by interferometry. The sensitivity in this (scaled-down) experiment will come to within one power of ten to the proposed LISA sensitivity. This package is to be flown at the Lagrange point L1, thus relatively far away from Earth, so as to avoid the many disturbances near the Earth. The launch is definitely set for August 2006.

3. Conclusion

Gravitational wave detection can be regarded as a new window to the universe, and ground-based detectors as well as the space project LISA bear a high potential. When these large interferometers are completed we can reap the fruits of this enormous effort: a sensitivity that will allow us to look far beyond our own galaxy, perhaps to the very limits of the universe.

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