LISA – Detecting and Observing Gravitational Waves

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The primary objective of the LISA (Laser Interferometer Space Antenna) mission is the detection and observation of gravitational waves from massive black holes and galactic binaries down to a gravitational wave strain sensitivity of 10^{-23} in the frequency range 10^{-4} – 10^{-1} Hz (Fig. 1). This low-frequency range is inaccessible to ground-based interferometers because of the unshieldable background of local gravitational noise.

In Newton's theory of gravity, the gravitational interaction between two bodies is instantaneous, but according to Einstein's theory of gravity this should be impossible because the speed of light represents the limiting speed for all interactions. If a body changes its shape, the resulting change in the force field will make its way outward at the speed of light. In Einstein's theory of gravity, massive bodies produce 'indentations' in the 'fabric' of spacetime and other bodies move in this curved spacetime taking the shortest path. If a mass distribution moves in a spherically asymmetric way, then the spacetime indentations travel outwards as ripples in spacetime called 'gravitational waves'.

Gravitational waves are fundamentally different from the familiar electromagnetic waves. While electromagnetic waves, created by the acceleration of electric charges, propagate in the framework of space and time, gravitational waves, created by the acceleration of masses, are waves of the spacetime fabric itself. Unlike charge, which exists in two polarities, mass always comes with the same sign. This is why the lowest order asymmetry producing electromagnetic radiation is the dipole moment of the charge distribution, whereas for gravitational waves it is a change in the quadrupole moment of the mass distribution. Hence those gravitational effects that are spherically symmetric will not give rise to gravitational radiation. A perfectly symmetric collapse of a supernova will produce no waves, while a non-spherical one will emit gravitational radiation. A binary system will always radiate.

Gravitational waves are a direct consequence of Einstein's theory of General Relativity (GR). If Einstein's theory is correct, gravitational waves must exist, but up to now they have not been detected. However, there is strong indirect evidence for the existence of gravitational waves: the binary pulsar PSR 1913 +16 loses energy exactly at the rate predicted by GR by emitting gravitational radiation.

Gravitational waves distort spacetime; in other words they change the distances between free macroscopic bodies. A gravitational wave passing through the Solar System creates a time-varying strain in space that periodically changes the distances between all bodies in the Solar System in a direction that is perpendicular to the direction of wave propagation. These could be the distances between spacecraft and the Earth, as in the case of Ulysses or Cassini (attempts were and will be made to measure these distance fluctuations) or the distances between shielded proof masses inside spacecraft that are

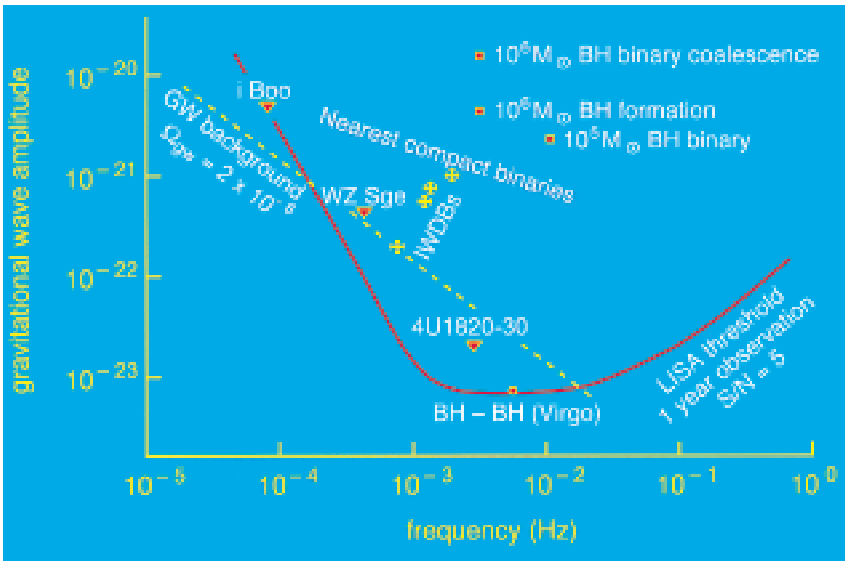

Figure 1. The target sensitivity curve of LISA and the strengths of expected gravitational wave sources

separated by a large distance, as in the case of LISA.

The main problem is that the relative length change due to the passage of a gravitational wave is exceedingly small. For example, the periodic change in distance between two proof masses, separated by a sufficiently large distance, due to a typical white dwarf binary at a distance of 50 pc, is only 10^{-10} m. This is not to say that gravitational waves are weak in the sense that they carry little energy. On the contrary, a supernova in a not too distant galaxy will drench every square metre here on Earth with kilowatts of gravitational radiation. The resulting length changes, though, are very small because spacetime is an extremely stiff elastic medium, so that it takes extremely large energies to produce even minute distortions.

It is because of the extremely small distance changes that gravitational waves have not yet been detected. However, with the LISA space interferometer, orbiting the Sun at 1 AU, millions of sources will be detected in one year of observation with a signal-to-noise ratio of 5 or better.

The LISA mission consists of three identical spacecraft located 5 x 10^6 km apart, forming an equilateral triangle (Fig. 2). The distance between the spacecraft – the interferometer arm length – determines the frequency range in which LISA can make observations; it has been carefully chosen to allow for the observation of most of the interesting sources of gravitational radiation. The centre of the triangular formation is in the ecliptic plane, 1 AU from the Sun and 20° behind the Earth. The plane of the triangle is inclined at 60° with respect to the ecliptic. These particular heliocentric orbits for the three spacecraft have been chosen such that the triangular formation is maintained throughout the year, with the triangle appearing to rotate about the centre of the formation once per year.

While LISA is basically a giant Michelson interferometer in space, the actual implementation in space is very different from a laser interferometer on the ground and is much more reminiscent of the technique called spacecraft tracking, but here realised with infrared laser light instead of radio waves. The laser light going out from the centre spacecraft to the other corners is not directly reflected back because very little light intensity would be left over in that way. Instead, in complete analogy with a radio-frequency transponder scheme, the laser on the distant spacecraft is phase-locked to the incoming light, providing a return beam with full intensity again. After being transponded back from the far spacecraft to

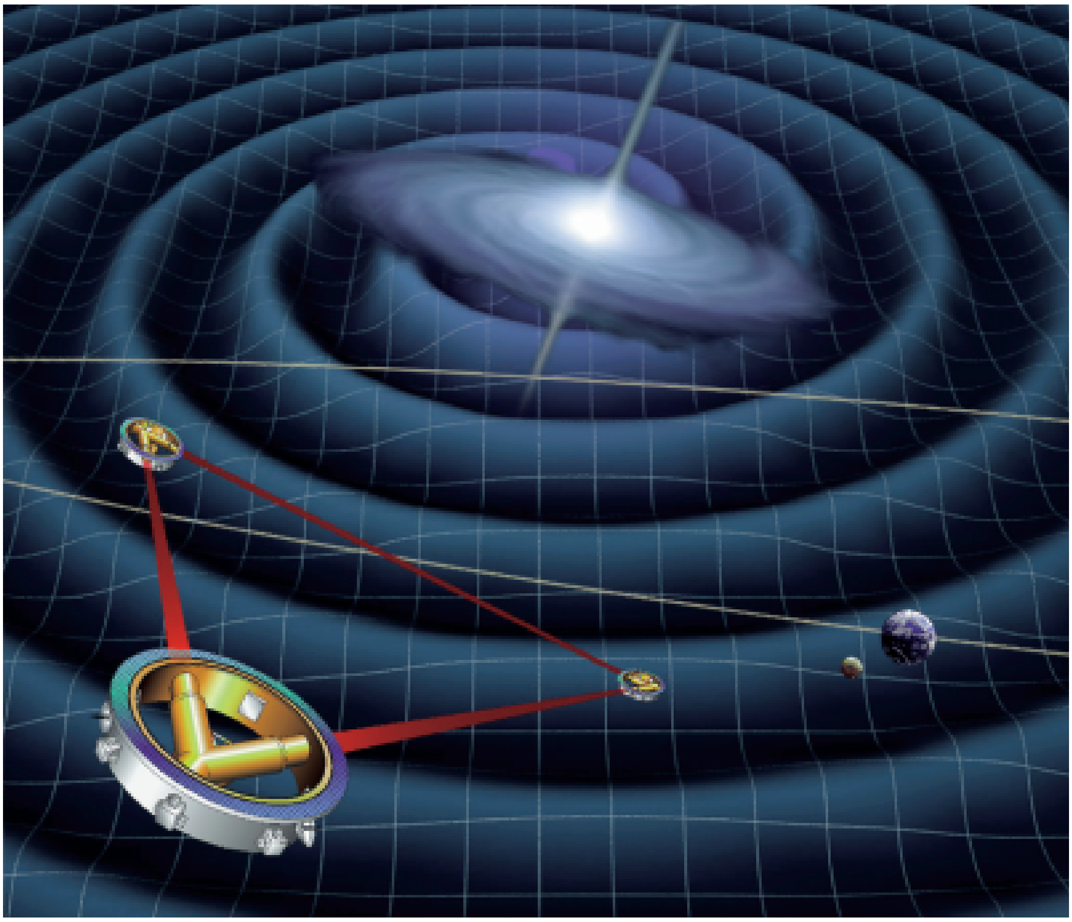

Figure 2. Artist's concept of gravitational waves emitted by a binary system, with the three-spacecraft LISA configuration and the Earth-Moon system

the centre spacecraft, the light is superposed with the on-board laser light serving as a local oscillator in a heterodyne detection.

Each spacecraft contains two optical assemblies (Fig. 3). The two assemblies on one spacecraft each point towards an identical assembly on each of the other two spacecraft. A 1 W infrared laser beam is transmitted to the corresponding remote spacecraft via a 30-cm aperture f/1 Cassegrain telescope. The same telescope is used to focus the very weak beam (a few pW) coming from the distant spacecraft and to direct the light to a sensitive photodetector, where it is superimposed with a fraction of the original local light. At the heart of each assembly is a vacuum enclosure containing a free-flying polished platinum-gold cube, 4 cm in size, referred to as the 'proof mass', which serves as an optical reference ('mirror') for the light beams. A passing gravitational wave will change the length of the optical path between the proof masses of one arm of the interferometer relative to the other arm. These distance fluctuations are measured to sub-Ångstrom precision which, when combined with the large separation between the spacecraft, allows LISA to detect gravitational-wave strains down to a level of order $\Delta l/l = 10^{-23}$ in one year of observation (l is the baseline length of 5×10^{6} km).

The spacecraft mainly serve to shield the proof masses from the adverse effects of the solar radiation pressure, and the spacecraft's position does not directly enter into the measurement. It is nevertheless necessary to keep all spacecraft moderately accurately (10^{-8} m $\mathrm{Hz}^{-1/2}$ in the measurement band) centred on their respective proof masses to reduce spurious local noise forces. This is achieved by a 'drag-free' control system, consisting of an accelerometer (or inertial sensor) and a system of electrical thrusters. Capacitive sensing is used to monitor the relative motion between each spacecraft and its test masses. These position signals are used in a feedback loop to command micro-Newton ion-emitting proportional thrusters to enable the spacecraft to follow its test masses precisely and without introducing disturbances in the bandwidth of interest. The same thrusters are used for precision attitude control relative to the incoming optical wave fronts.

Each of the three LISA spacecraft has a launch mass of about 460 kg (incl. margin). Ion drives are used for the transfer from the Earth orbit to the final position in interplanetary orbit. All three spacecraft can be launched by a single Delta-II 7925H vehicle.

Several large interferometers for the detection of gravitational waves are currently under construction on the ground: two LIGO interferometers in the USA (each 4 km), the French-Italian collaborative VIRGO in Europe (3 km), GEO 600 in Germany (0.6 km), AIGO 500 in Australia (0.5 km) and TAMA 300 in Japan (0.3 km) (interferometer baseline lengths in parentheses). The ground-based interferometers and the LISA interferometer in space complement each other in an essential way. Just as it is important to complement the optical and radio observations from the ground with observations from space at submillimetre, infrared, ultraviolet, X-ray and gamma-ray wavelengths, so too is it important to complement the gravitational-wave observations made by the ground-based interferometers in the high-frequency regime (10 to 10^{3} Hz) with observations in space in the low-frequency regime (10^{-4} to 10^{-1} Hz).

Ground-based interferometers can observe the bursts of gravitational radiation emitted by

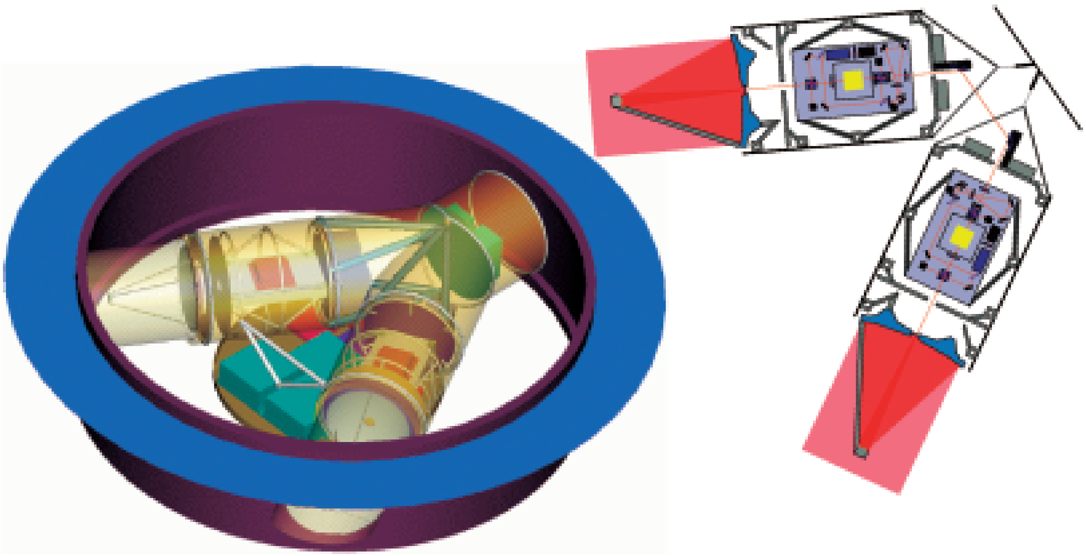

Figure 3.Left: Cut-away view of one of the three identical LISA spacecraft. The main structure is a ring with a diameter of 1.8 m and a height of 0.48 m, made from graphite-epoxy for low thermal expansion. A lid on top of the spacecraft is removed to provide a view of the Y-shaped payload Right: Detail of the payload on each Y-shaped LISA spacecraft, consisting of two identical telescopes and two optical benches each housing a drag-free test mass (the yellow cubes in the centres)

galactic binaries during the final stages (minutes and seconds) of coalescence, when the frequencies are high and both the amplitudes and frequencies increase quickly with time. At low frequencies, which are only observable in space, the orbital radii of the binary systems are larger and the frequencies are stable over millions of years. Coalescences of massive black holes are only observable from space. Both ground- and space-based detectors will also search for a cosmological background of gravitational waves. Since both kinds of detectors have similar energy sensitivities, their different observing frequencies are ideally complementary: observations can provide crucial spectral information.

LISA was proposed to ESA in May 1993 in response to the Agency's Call for Mission Proposals for the third Medium-Size Project (M3). The proposal was submitted by a team of American and European scientists who envisaged LISA as an ESA/NASA collaborative project. The mission was conceived as comprising four spacecraft in a heliocentric orbit forming an interferometer with a baseline of 5 x 10^6 km.

LISA was selected for study as an ESA-only project, but it became clear quite early in the Assessment Phase that it was not likely to be a successful candidate for M3 because the cost for an ESA-only LISA considerably exceeded the M3 limit of 350 MEuro. In December 1993, LISA was therefore re-proposed to ESA, this time as a Cornerstone mission for 'Horizon 2000 Plus', involving six spacecraft in a heliocentric orbit with a pair of spacecraft at each vertex of an equilateral triangle.

Initially, ESA scenarios for the launch of future Cornerstones included an ESA-only LISA launch in 2017 or even later, but then it became clear that by that time the LISA Cornerstone would in all likelihood be pre-empted by an earlier NASA mission. Bearing in mind that it had consistently been the wish of the international LISA Team to see LISA carried out as an ESA/NASA collaborative mission, it was agreed in the summer of 1998 that this would be the new baseline. A launch around 2010 of the ESA/NASA collaborative LISA mission is now widely being considered as extremely desirable. Recently, ESA's Fundamental Physics Advisory Group (FPAG) recommended capping the ESA involvement in this joint endeavour at 150 MEuro. In 1996 and 1997, the LISA team suggested a series of cost-saving measures which should bring the total project cost to about 300 MEuro (excl. the payload), i.e. ESA's contribution of 150 MEuro should allow a 50/50 partnering arrangement. In this arrangement it is assumed that ESA would provide the three spacecraft, while NASA would provide the launch vehicle and the mission operations; the payload would be shared 50/50. The most drastic cost-saving measure was a reduction of the number of spacecraft from six to three; this was achieved by replacing a pair of spacecraft at the vertices of a triangular configuration by a single spacecraft, with essentially two identical instruments on each spacecraft. This and other measures taken together allowed the launch mass to be reduced from 6.8 t to 1.4 t.

An ESA system-level industrial study (June 1999 – February 2000) fully confirmed the feasibility of the three-spacecraft configuration. Nevertheless, LISA is not a candidate for selection as Cornerstone 5 in the September/October 2000 time frame because:

- Unlike BepiColombo and GAIA, the two candidates for CS5, LISA is a collaboration with NASA and a commitment by NASA cannot be expected by September.
- Unlike BepiColombo and GAIA, LISA has no clearly identified technology demonstration mission (BepiColombo has SMART-1 with a launch in 2002, while GAIA does not need a technology demonstration mission).

LISA requires several new technologies, which should be tested in space for extended time periods under zero-gravity conditions. These are:

- the inertial sensor performance to within an order of magnitude of the LISA requirements
- the low-frequency laser interferometry between two proof masses
- drag-free satellite operations with two inertial sensors using field-emission ion thrusters.

Ideally, such a technology demonstration mission should be launched about five years before LISA. A launch much earlier would not allow full utilisation of the latest technologies to be tested, while one much later would not allow full advantage to be taken of the know-how obtained during the technology demonstrator flight in the design phase of the LISA mission. To preserve the possibility of launching the NASA/ESA collaborative LISA mission in 2010, the technology demonstration mission should therefore be flown in 2005.

A LISA technology demonstrator is a strong candidate for ESA's SMART-2 (Small Mission for Advanced Research in Technology) mission foreseen for launch in 2005. The selection process for SMART-2 will take place in October 2000.