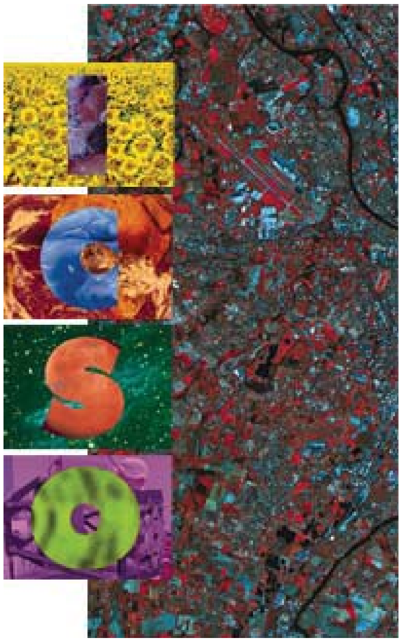
International Conference on Space Optics—ICSO 2000

Toulouse Labège, France

5–7 December 2000

Edited by George Otrio



The LIZA cornerstone an ESA/NASA collaborative mission

Karsten Danzmann

International Conference on Space Optics — ICSO 2000, edited by George Otrio, Proc. of SPIE Vol. 10569
105690Z · © 2000 ESA and CNES · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2307877

The LISA Cornerstone
An ESA/NASA Collaborative Mission

Karsten Danzmann* for the LISA Study Team

**Institut für Atom- und Molekülphysik, Universität Hannover,*
and Max-Planck Institut für Quantenoptik, Außenstelle Hannover,
Callinstr. 38, D-30167 Hannover, Germany

Abstract. *Small prototypes of gravitational wave detectors have been under development for over 30 years. But it is only now that we have the necessary technology available to build large instruments with good sensitivity. After several years of construction, the first ground-based interferometers will go into operation in 2001 and a space-based detector is expected to be launched in 2010. These instruments will complement each other because the gravitational wave spectrum extends over many decades in frequency. Ground-based detectors can only observe the audio-frequency regime above 1 Hz, while sources in the low-frequency regime are only accessible from space because of the unshieldable background of local gravitational noise on the ground.*

I INTRODUCTION

If a body changes its shape, the resulting change in the force field will make its way outward at the speed of light. As early as 1805, Laplace, in his famous *Traité de Mécanique Céleste* stated that, if Gravitation propagates with finite speed, the force in a binary star system should not point along the line connecting the stars, and the angular momentum of the system must slowly decrease with time. In modern language we would say the binary star is losing energy and angular momentum by emitting gravitational waves. In 1993, Hulse and Taylor were awarded the Nobel prize in physics for the indirect proof of the existence of Gravitational Waves using exactly this kind of observation on the binary pulsar PSR 1913+16. A direct detection of gravitational waves has not been achieved up to this day.

Einstein's paper on gravitational waves was published in 1916, but it was not before the late 1950s that it was rigorously proven that gravitational radiation was in fact a physically observable phenomenon, that gravitational waves carry energy and that, as a result, a system that emits gravitational waves should lose energy.

General Relativity replaces the Newtonian picture of Gravitation by a geometric one that is very intuitive if we are willing to accept the fact that space and time do not have an independent existence but rather are in intense interaction with the physical world. Massive bodies produce "indentations" in the fabric of spacetime, and other bodies move in this curved spacetime taking the shortest path, much like a system of billard balls on a springy surface. In fact, the Einstein field equations relate mass (energy) and curvature in just the same way that Hooke's law relates force and spring deformation, or phrased somewhat poignantly: spacetime is an elastic medium.

If a mass distribution moves in an 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 come with the same sign. This is why the lowest order asymmetry producing *electro-magnetic* 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 which are spherically symmetric will not give rise to gravitational radiation. A perfectly symmetric collapse of a supernova will produce no waves, a non-spherical one will emit gravitational radiation. A binary system will always radiate.

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. The main problem is that the relative length change due to the passage of a gravitational wave is exceedingly small. This is not to mean 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 meter here on earth with kilowatts of gravitational radiation intensity. 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.

A Sources for space-based detectors

The two main categories of gravitational waves sources for space-based detectors like LISA are the galactic binaries and the massive black holes (MBHs) expected to exist in the centres of most galaxies.

Because the masses involved in typical binary star systems are small (a few solar masses), the observation of binaries is limited to our Galaxy. Galactic sources that can be detected by LISA include a wide variety of binaries, such as pairs of close white dwarfs, pairs of neutron stars, neutron star and black hole ($5 - -20\,M_\odot$) binaries, pairs of contacting normal stars, normal star and white dwarf (cataclysmic) binaries, and possibly also pairs of black holes. It is likely that there are so many white dwarf binaries in our Galaxy that they cannot be resolved at frequencies below 10^{-3} Hz, leading to a confusion-limited background. Some galactic binaries are so well studied, especially the X-ray binary 4U1820-30, that it is one of the most reliable sources. If LISA would not detect the gravitational waves from known binaries with the intensity and polarisation predicted by General

Relativity, it will shake the very foundations of gravitational physics.

The main objective of the LISA mission, however, is to learn about the formation, growth, space density and surroundings of massive black holes (MBHs). There is now compelling indirect evidence for the existence of MBHs with masses of 10^6 to $10^8\,M_\odot$ in the centres of most galaxies, including our own. The most powerful sources are the mergers of MBHs in distant galaxies, with amplitude signal-to-noise ratios of several thousand for $10^6\,M_\odot$ black holes. Observations of signals from these sources would test General Relativity and particularly black-hole theory to unprecedented accuracy. Not much is currently known about black holes with masses ranging from about $100\,M_\odot$ to $10^6\,M_\odot$. LISA can provide unique new information throughout this mass range.

II THE LISA MISSION

The LISA mission comprises three identical spacecraft located 5×10^6 km apart forming an equilateral triangle. LISA is basically a giant Michelson interferometer placed in space, with a third arm added to give independent information on the two gravitational wave polarizations, and for redundancy. The distance between the spacecraft – the interferometer arm length – determines the frequency range in which LISA can make observations; it was 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 were 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.

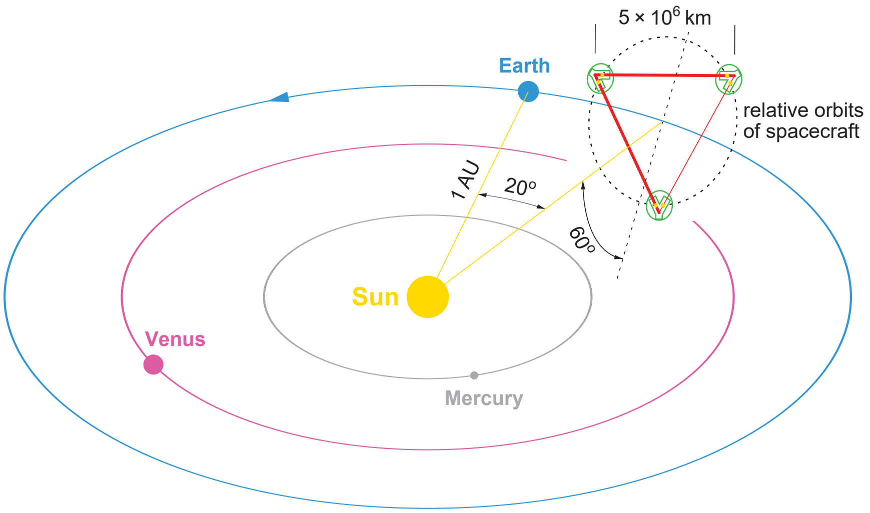


FIGURE 1. LISA configuration: three spacecraft in an equilateral triangle. Drawing not to scale: the LISA triangle is drawn one order of magnitude too large.

While LISA can be described as a big Michelson interferometer, 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 realized with infrared laser light instead of radio waves. The laser light going out from the center spacecraft to the other corners is not directly reflected back because very little light intensity would be left over that way. Instead, in complete analogy with an RF 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 the center spacecraft, the light is superposed with the on-board laser light serving as a local oscillator in a heterodyne detection. This gives information on the length of one arm modulo the laser frequency. The other arm is treated the same way, giving information on the length of the other arm modulo the same laser frequency. The difference between these two signals will thus give the difference between the two arm lengths (i.e. the gravitational wave signal). The sum will give information on laser frequency fluctuations.

Each spacecraft contains two optical assemblies. The two assemblies on one spacecraft are each pointing towards an identical assembly on each of the other two spacecraft to form a Michelson interferometer. 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 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. The 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 $\Delta\ell/\ell = 10^{-23}$ in one year of observation, with a signal-to-noise ratio of 5 .

The spacecraft mainly serve to shield the proof masses from the adverse effects due to the solar radiation pressure, and the spacecraft position does not directly enter into the measurement. It is nevertheless necessary to keep all spacecraft moderately accurately ($10^{-8}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ in the measurement band) centered 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 in three dimensions is used to measure the displacements of the proof masses relative to the spacecraft. These position signals are used in a feedback loop to command micro-Newton ion-emitting proportional thrusters to enable the spacecraft to follow its proof masses precisely. The thrusters are also used to control the attitude of the spacecraft relative to the incoming optical wavefronts, using signals derived from quadrant photodiodes. As the three-spacecraft constellation orbits the Sun in the course of one year, the observed gravitational waves are Doppler-shifted by the orbital motion. For periodic waves with sufficient signal-to-noise ratio, this allows the direction of the source to be determined to arc minute or degree precision, depending on source strength.

Each of the three LISA spacecraft has a launch mass of about 400 kg (plus mar-

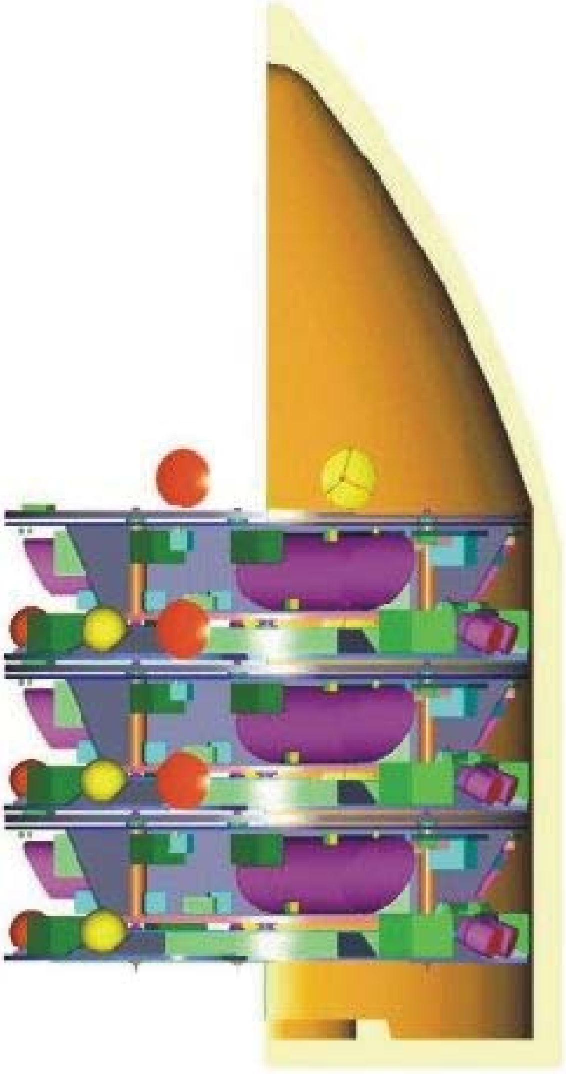


FIGURE 2. 3 LISA composite spacecraft in the Delta II 10ft fairing.

gin) including the payload, ion drive, all propellants and the spacecraft adapter. The 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. Each spacecraft carries a 30 cm steerable antenna used for transmitting the science and engineering data, stored on board for two days, at a rate of 7 kBps in the X-band to the 34-m network of the DSN. Nominal mission lifetime is two years, but consumables are sized for an extended mission of more than 10 years.

LISA is envisaged as a NASA/ESA collaborative project, with NASA providing the launch vehicle, mission and science operations and about 50 % of the payload, ESA providing the three spacecraft including the ion drives, and European institutes, funded nationally, providing the other 50 % of the payload. The collaborative NASA/ESA LISA mission is aimed at a launch in the 2010 time frame. LISA is a Cornerstone mission in ESA's Future Science Program Horizons 2000 and has recently been included in NASA's Roadmap.

R R NCE

1. A.G. Lyne and D.R. Lorimer, Nature **369** (1994) 127.
2. A.V. Tutukov and L.R. Yungelson, MNRAS **260** (1993) 675.
3. C.W. Misner, K.S. Thorne, and J.A. Wheeler, *Gravitation* (Freeman & Co., San Francisco, 1973).
4. P.R. Saulson, *Fundamentals of Interferometric Gravitational Wave Detectors* (World Scientific, Singapore, 1994).
5. B.F. Schutz, *A First Course in General Relativity* (Cambridge University Press, Cambridge, 1985).
6. K.S. Thorne, *Gravitational Radiation, in: S.W. Hawking and W. Israel, eds.,* 300 Years of Gravitation *(Cambridge University Press, Cambridge, 1987) 330–458.*
7. *J. Weber, Phys. Rev.* **117** *(1960) 306.*
8. *M. Bassan, Class. Quant. Grav. Supplement A* **39** *(1994) 11.*
9. *F.A.E. Pirani, Acta Physica Polonica* **15** *(1956) 389.*
10. *M.E. Gertsenshtein and V.I. Pustovoit, JETP* **16** *(1963) 433.*
11. *R. Weiss, Quarterly Progress Report of RLE, MIT* **105** *(1971) 54.*
12. *G.E. Moss, L.R. Miller, and R.L. Forward, Appl. Opt.* **10** *(1971) 2495.*
13. *A. Abramovici et al., Science* **256** *(1992) 325.*
14. *G. Bradaschia et al., Nucl. Instrum. and Methods A* **289** *(1990) 518.*
15. *K. Danzmann et al., GEO 600 – A 300* m *laser-interferometric gravitational wave antenna, Proc.* 1^{st} *Edoardo Amaldi Conference, Frascati, June 1994; and also: J. Hough et al., Proc. MG7, Stanford, July 1994.*
16. *K. Tsubono and* TAMA *collaboration,* TAMA *Project in: K. Tsubono, M.-K. Fujimoto, K. Kuroda, (Eds.),* Gravitational Wave Detection, *Proc.* TAMA *Intern. Workshop, Nov. 1996, p. 183–191, Universal Academy Press (Tokyo, 1997).*
17. *V.M. Kaspi, J.H. Taylor, M.F. Ryba, Astrophys. J.* **428** *(1994) 713.*