4.2.3 LISA Gravitational Wave Observatory

Introduction

The primary objective of the Laser Interferometer Space Antenna (LISA) mission is to detect and observe gravitational waves from massive black holes and galactic binary stars in the frequency range 10^{-4}-10^{-1} Hz. Useful measurements in this frequency range cannot be made on the ground because of the unshieldable background of local gravitational noise.

Sources of gravitational waves

Non-spherically symmetric accelerations of mass cause gravitational waves. The time-dependence of the quadrupole moment is the main term. Thus a binary system will always radiate. While a perfectly symmetrical collapse of a supernova will produce no waves, a non-spherically symmetric one will emit gravitational radiation. The types of gravitational waves are bursts, periodic or quasi-periodic waves, and stochastic backgrounds due to compact binaries, primordial waves and cosmic strings or phase transitions. Bursts due to the coalescence of neutron star binaries can be observed during the final stages (minutes and seconds) of coalescence. Consequently, the frequency is high (1-10^4 Hz) and both the frequency and amplitude increase quickly with time. Such bursts, and those due to supernovae, are most suitable for detection by ground-based interferometers. By contrast, the frequencies of periodic waves from large numbers of galactic binaries and extragalactic massive black hole mergers with frequencies of 10^{-4}-10^{-2} Hz are stable over hundreds of millions of years, and they are observable only from space. Figure 4.2.3.1 shows the expected gravitational wave strain sensitivity for LISA, and the types of sources visible.

Galactic binaries

The sources that can be detected in our galaxy by a space-based interferometer include close white dwarf binaries, neutron star binaries, neutron star black hole (5-20 M_u binaries, contact normal star binaries, cataclysmic binaries (normal star-white dwarf) and also, possibly, black hole binaries.

One type that is guaranteed to be observable is the neutron star binary, for which even intentionally pessimistic abundance estimates give hundreds of sources

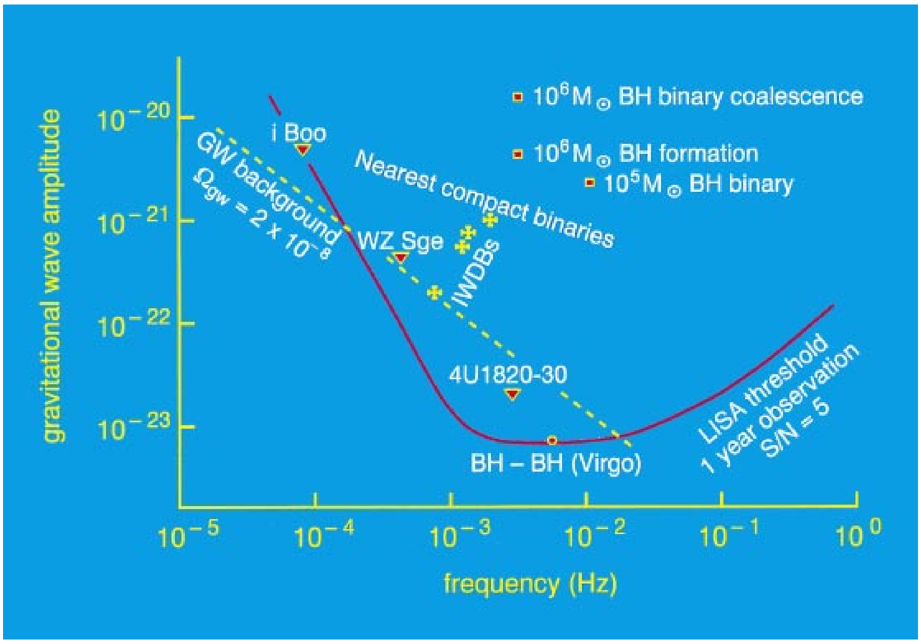


Figure 4.2.3.1 The target sensitivity curve of LISA, and the strengths of expected gravitational wave sources.

For further information on LISA, see http://www.estec.esa.nl/spdwww/future/html

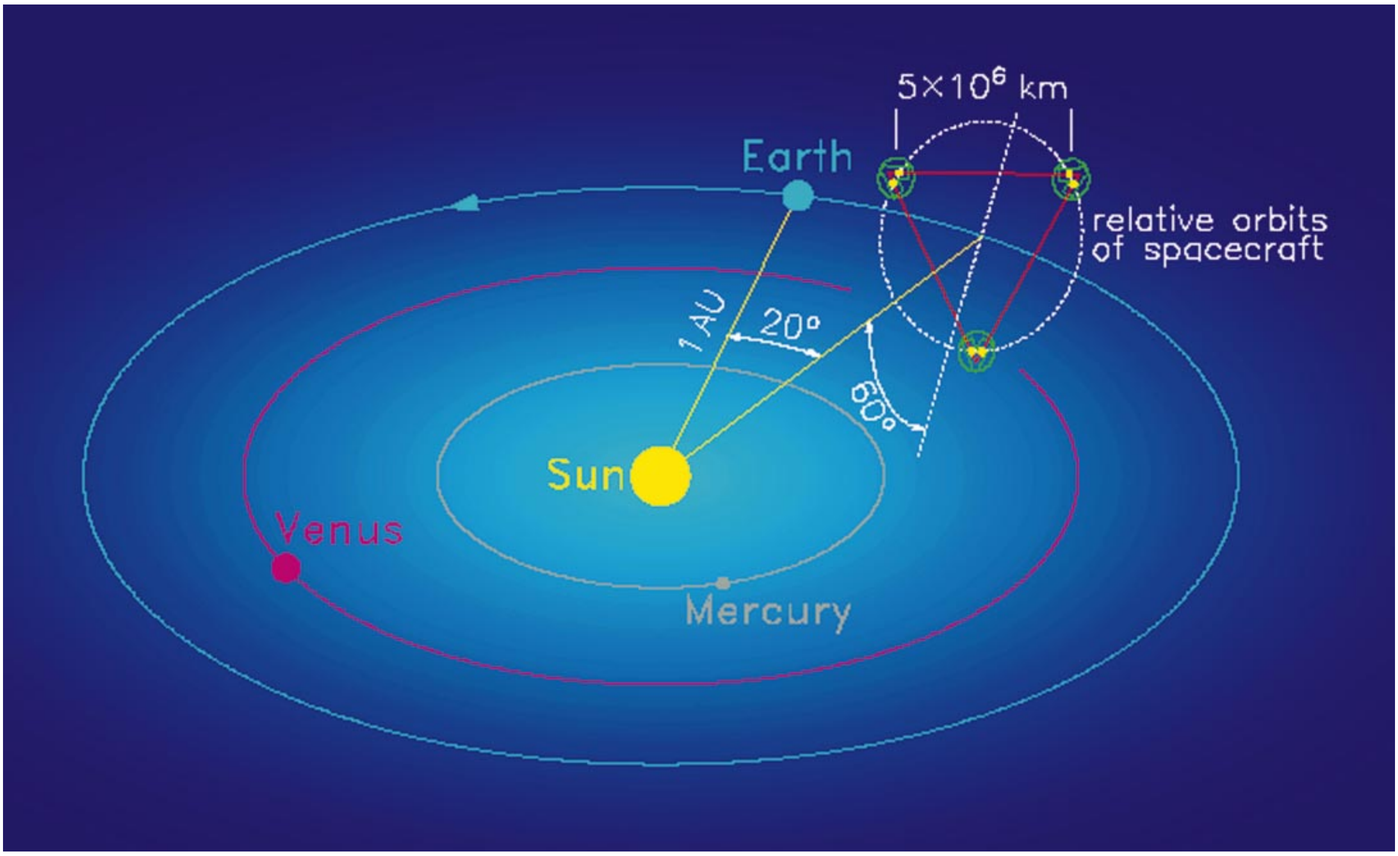


Figure 4.2.3.2 Schematic diagram of LISA configuration (not to scale). Three distant satellites linked by infrared laser beams form a giant 5 million km triangular interferometer which is sensitive to fluctuations in the separation between the satellites caused by gravitational waves. The plane of the triangle is tilted by 60° out of the ecliptic.

throughout the galaxy with frequencies above 10^{-3} Hz that are detectable by a space-based interferometer with high signal-to-noise ratio. The large majority of all observable galactic binaries will be near the galactic centre.

The evolutionary scenario that is expected to lead to neutron star binaries will also form neutron star black hole binaries. In fact, the formation of a black hole has much less probability of disrupting a binary system because less mass is lost. Some estimates predict there should be about 10% as many neutron star black hole binaries as there are neutron star binaries. It is possible that there are also some binaries in the galaxy consisting of two 5-20 M_u black holes, which would be easily detected by a space-based interferometer, but invisible otherwise. A few may also be detectable in the Virgo cluster.

In addition to the above types of binaries, it seems likely that signals from at least a few cataclysmic variables, contact binaries and X-ray binaries will be detected, especially the X-ray binary 4U1820-30, which is so well studied that it is one of the most reliable sources in our catalogue.

It is likely that there are so many white dwarf binaries in our galaxy that they cannot be resolved in either frequency or time at frequencies below about 10^{-3} Hz, leading to a confusion-limited background. This might obscure some low-frequency sources (not neutron stars or black holes) but offers plenty of material for study itself.

Massive black holes

There is now compelling direct evidence for the existence of massive black holes in the nuclei of many galaxies. A generally recognised way of forming massive black hole binaries is the merger of pre-galactic structures or of galaxies that already contain massive black holes. It is now widely accepted that many galaxies show evidence of mergers. There is even evidence of binary black hole systems; an example is 3C66B, which shows a precessing jet. If we assume that 20-50% of galaxies above a certain size contain massive black holes, and that at least moderately-sized massive black holes (10^3-10^7 M_u) were common before the time of most rapid evolution in the precursors of rich clusters, then coalescence rates of several events per year seem possible. A space-based interferometer will detect both the quasi-periodic gravitational wave signals from before binary coalescence and the terminal signals near coalescence, wherever in the Universe the event occurred. Pairs of holes in the mass range of 10^3-10^7 M_u, which could be the most abundant ones, radiate strongly within the observable frequency range.

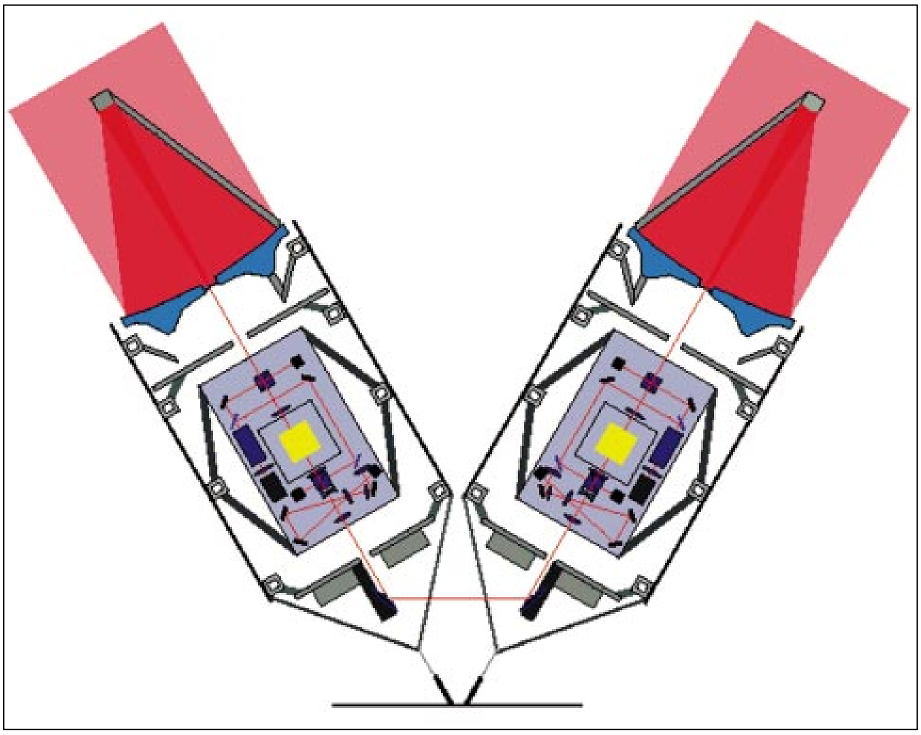
By comparing the detailed wave forms of observed gravitational wave bursts with those predicted for the coalescence of black-hole binaries, one could verify that certain bursts are indeed produced by black-hole coalescences and, as a consequence, verify unequivocally the nature of black holes and General Relativity's predictions of their behaviour in highly dynamical circumstances. The analysis of such events probably constitutes the only way to test Einstein's theory of General Relativity accurately up to the high field regime.

The signal-to-noise ratio is typically several thousand for 10^6 M_u black holes. If detected, waves this strong might not only be useful in testing gravity, as remarked above, but may make an important contribution to fundamental cosmology. By monitoring the amplitude and phase of the merger waves while the detector rotates around the Sun, both the direction and total amplitude of the waves may be determined. Then, if the direction can be used to identify the source of the waves within a known cluster of galaxies, the amplitude will give an independent and highly accurate distance measurement to the source. A cluster redshift measurement would then determine the deceleration parameter q_0. If two or more concordant values of q_0 were obtained, this would verify the correctness of the cluster associations. The resulting accurate value of q_0 would give the mean density of the Universe, and thus measure the total density of dark matter.

The LISA project

Conceptual ideas for space-based interferometers using separate spacecraft were suggested in the US in 1978 and 1981. The concept was further developed in the next decade, leading ultimately to the LISA (Laser Interferometer Space Antenna) proposal to ESA in 1993. A 4-spacecraft LISA mission was studied at assessment level as an M3 mission candidate, but it turned out that the cost for LISA was clearly above the limit for a medium-size project. However, many of the details that are now established regarding the design of the gravitational-wave detector in space were worked out during this assessment phase. For the Horizon 2000+ proposal, two spacecraft were added, essentially for redundancy. However, for the Cornerstone study, the new baseline is expected to be three identical spacecraft, forming a large equilateral triangle in space (Figure 4.2.3.2). The length of each side of the triangle is $5 \cdot 10^6$ km, defining the interferometer arm length. This has been selected for the following reasons. If it were larger, the low-frequency gravitational waves would cancel themselves out, resulting in an undesirable loss of science signal. If it were shorter, the spacecraft control requirements would be correspondingly tightened, and thus more difficult to meet. The Y-shaped spacecraft at each vertex of the triangle serves as a light source and beamsplitter for the interferometry. For reasons of compactness, stability, and reliability, LISA will use solid-state diode-pumped

Figure 4.2.3.3 Detail of the payload on each Y-shaped LISA satellite, consisting of two telescopes and two optical benches each housing a drag-free test mass.



monolithic miniature Nd:YAG ring lasers which generate a continuous 1 W infrared beam with a wavelength of 1.064 μm. Furthermore, with this short wavelength (compared to radio) the light is immune from refraction caused by the charged particles (plasma) that permeate interplanetary space.

From each arm of each spacecraft, a 1 W beam is transmitted to the corresponding remote spacecraft via a 30 cm-aperture f/1 Cassegrain telescope (Figure 4.2.3.3). The same telescopes on each spacecraft are used to focus the very weak return beams from the distant spacecraft. The focused light beams are then directed to sensitive photodetectors, where they are superimposed with a fraction of the original local light. Despite the great distance travelled, the intensity of the received light is high (about 10^8 photons/s), making the signal detection straightforward and many orders of magnitude less demanding than routinely achieved on prototype ground-based interferometers. The interference signals thus obtained from each arm are combined in software by the onboard computers to perform the multiple-arm interferometry required to cancel the phase-noise common to all arms. With the triangular configuration, the three arms give two almost-independent interferometers.

At the heart of each spacecraft are two vacuum enclosures, each containing a polished platinum-gold cube (test mass) that serves as an optical reference ('mirror') for the light beams (Figure 4.2.3.3). When a gravitational wave passes through the system it causes a strain distortion of space which, in turn, causes fluctuations in the separation of the test masses. This leads to fluctuations in the optical path between the masses, causing the phase-shifts that are detected by the interferometry. The distance fluctuations are measured to sub-Å precision which, when combined with the large separation between the spacecraft, allows LISA to detect gravitational-wave strains down to a level of order 10^{-23} in 1 year of observation, with a signal-to-noise ratio of 5. Obviously, great care must be taken to ensure that the optical paths are not disturbed by other means. This is achieved by using ultrastable structures and multilayer thermal insulation on the spacecraft. Furthermore, each test mass is shielded from external disturbances (e.g solar radiation pressure) by the spacecraft in which it is accommodated. 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 FEEP (Field Emission Electric Propulsion) thrusters to enable the spacecraft to follow its test mass precisely and without introducing disturbances in the bandwidth of interest. (For historical reasons, this technique is known as ‘drag-free control’). The same thrusters are used to control the attitude of the spacecraft precisely relative to the incoming optical wavefronts, using signals derived from quadrant photo-diodes.

The LISA spacecraft must be designed to minimise the total mass and required power. Preliminary results yield a mass, per spacecraft, of 260 kg, and an operational power requirement, per spacecraft, of 195 W. Each spacecraft will require a propulsion module for the transfer from Earth orbit to the final position in interplanetary space, whereby each spacecraft will reside in an individual heliocentric orbit of specific inclination and eccentricity in such a way that the three spacecraft move relative to each other on a circular orbit inclined at 60° to the ecliptic. This keeps the distances between them (the interferometer arm lengths of $5 \cdot 10^6$ km) nearly constant, which is desirable from the point of view of the interferometry. To ensure that the gravitational perturbations remain sufficiently small, the constellation is placed at least 20° behind the Earth (on its orbit around the Sun). Nevertheless, there will still be significant Doppler shifts associated with orbit perturbations. These can be compensated for by employing a dual-frequency scheme whereby two closely-spaced optical frequencies are transmitted down the main beams. These undesirable Doppler effects can then be reduced to manageable levels by observing the beat signals from the dual frequencies. However, a related effect can also be harnessed and put to good use. As the constellation orbits the Sun in the course of a year, the observed gravitational waves are Doppler-shifted by the orbital motion. For periodic waves with sufficient signal-to-noise, this allows the direction of the source to be determined. It is expected that the strongest LISA sources (from very distant black holes) should be resolvable to better than an arcminute; and even the weaker sources (galactic binaries) should be positioned to within 1° throughout the entire galaxy. The spacecraft will be equipped with X-band transponders with steerable 30 cm high-gain antennas for communication with Earth.

In summary, LISA is basically a space-based Michelson interferometer, with the advantages of a longer baseline and a quieter environment than on the ground. LISA will benefit substantially from the ongoing development of ground-based interferometers (LIGO, VIRGO, GEO600).

Complementarity of detection on the ground and in space

Electromagnetic waves cover a range of 20 orders of magnitude in frequency, from the ultra-low frequency (ULF) radio waves to high-energy gamma-rays. For almost all of these frequencies (except the visible and radio), it is necessary to place detectors optimised for a particular frequency range (e.g. radio, ultraviolet, infrared, X-ray, gamma-ray) in space to observe galactic and extragalactic objects.

The situation is similar for gravitational waves, which span a range of at least 10 orders of magnitude in frequency. Ground-based detectors will never be sensitive below about 1 Hz because of terrestrial gravity-gradient noise. A space-based detector is free from such noise and can be made very large, thereby opening the range from 10^{-4} Hz to 1 Hz, where both the most certain and the most exciting gravitational-wave sources radiate most of their power.

The importance of low frequencies is a simple consequence of Newton's laws. For systems involving solar-mass objects, lower frequencies imply larger orbital radii, and the range down to 10^{-4} Hz includes the radii of many galactic neutron star binaries, cataclysmic binaries, some known binaries and so on. These are the most certain sources. For highly relativistic systems, where the orbital speeds approach the speed of light, lower frequencies imply larger masses (M about 1/f), and the range down to 10^{-4} Hz reaches masses of 10^7 M_u, typical of the black holes that are thought to exist in the centres of many, if not most, galaxies. Their formation and coalescences could be seen anywhere in the Universe and are among the most exciting of possible sources. Detecting them would test the high field limit of gravitational theory and illuminate galaxy formation and quasar models. Signals from compact objects orbiting supermassive black holes also may well be observable.

For ground-based detectors, on the other hand, the higher frequencies imply that even stellar-mass systems must last for short times, so these detectors will search for sporadic short-lived catastrophic events (supernovae, coalescing neutron-star binaries). Normally, several detectors are required for directional information. If such events are not detected in the expected way, this will upset the astrophysical models assumed for such systems but not necessarily contradict gravitation theory.

By contrast, if a space-based interferometer does not detect the gravitational waves from known binaries with the intensity and polarisation predicted by General Relativity, it will undermine the very foundations of gravitational physics. Furthermore, even some highly relativistic events, like massive black hole coalescences with masses below 10^5 M_u, last roughly a year or longer. This allows a single space-based detector to provide directional information as it orbits the Sun during the observation.

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.

The space-based interferometer proposal has the full support of the ground-based detector community. Just as it is important to make observations at radio, optical, X-ray and all other electromagnetic wavelengths, so too is it important to cover different gravitational-wave frequency ranges. Ground- and space-based observations are therefore complementary in an essential way.