Darwin

The mission

The Infra-Red Space Interferometer 'Darwin' (IRSI/Darwin) is a Cornerstone candidate for ESA's Horizons 2000+ Programme. Darwin has the explicit goal of detecting other Earth-like worlds, analysing their properties, determining the composition of their atmospheres, and ascertaining their ability to sustain life as we know it. It will also provide interferometric imaging of astrophysical objects in the thermal-infrared with unprecedented resolution.

Darwin consists of six 1.5 m telescopes, each of which is a free-flying interferometric unit transmitting its light to a central beam-combining unit. The beam combiners have two optical systems: one for Michelson imaging at very high spatial resolution, and one for 'nulling' interferometry. The latter utilises the wave nature of light to extinguish the light from a star, allowing the detection and analysis of the light from any faint nearby companion. Darwin can therefore detect and analyse the light from Earth-like planets at interstellar distances of up to 25 pc. Analysis of the planets' spectra will demonstrate the presence of any atmosphere and we will be able to determine if the planet possesses an environment benevolent to life, including the detection of a possible biosphere. A separate power and communication satellite flying in close proximity will allow the telescope and beam-combiner units be passively cooled to <40 K to increase sensitivity. The interferometric array can be flown with centimetre precision and the beam combiner contains the necessary delay lines.

Darwin would be launched by an Ariane-5 into an orbit at the second Lagrangian point (L2) of the Earth-Sun system. For thermal reasons, the observing zone is a 40 deg cone around the anti-solar direction. Acquisition and control is achieved with milli- and micro-Newton thrusters. The control system relies on high-precision laser metrology (~ 8 nm rms), and the tracking of fringes in a separate channel at ~ 2 µm. The array baselines are 50 – 250 m for the planet-finding element of the mission, and 0.5 – 1 km for the imaging element. The observing wavelengths are $\sim 4\ \mu m < \lambda \leq 20\ \mu m$.

The study of Earth-like planets

Understanding the principles and processes that generated the Earth, and allowed the evolution of life forms to take place, is clearly something that deserves the utmost attention. It involves not only astronomy and space sciences, but also other disciplines such as geophysics, biophysics and organic chemistry. The successful detection of an Earth-like planet possessing an environment benign to life would also doubtless have implications for philosophical matters and the related humanities.

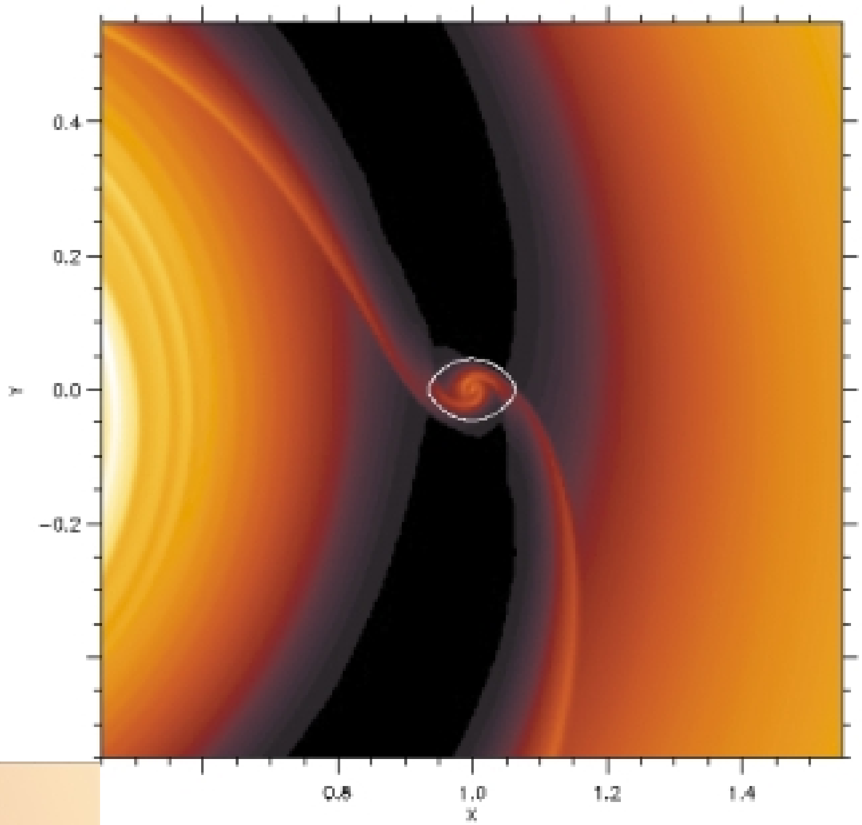
The central questions addressed by the Darwin mission are:

1. How unique is the Earth as a planet?
2. How unique is life in the Universe?

To answer these questions fully, it is necessary to:

- survey a significant sample of nearby stars for Earth-size planets
- directly detect planets within the ‘habitable zone’, i.e. the orbital radii surrounding a star, where water is found in a liquid state, and determine the planets’ orbital characteristics (period, eccentricity, etc.), repeating the observations several times
- observe the spectrum of the planet (Does it have an atmosphere? What is the effective temperature and total flux?) and estimate its diameter
- determine the composition of the atmosphere and search for the presence of H_2O, CO_2 and O_3/O_2 on an Earth-type planet.

Detection of Earth-size bodies circling nearby stars has hitherto been impossible because of the influence of the star itself. The problem is mainly a matter of contrast and dynamic range, but also of weakness of the planetary signal. The star outshines the planet if it is Earth-size or smaller by a factor of more than 10^9 in the visual wavelength regime. Even in the infrared, where the planet’s thermal emission increases and the star’s emission decreases, we still have a contrast of about 10^{6-7}. The thermal IR flux from an Earth-like planet at 10 pc is only 3 or 4 photons m^{-2} s^{-1} in the whole range of spectroscopic interest (4 – 20 µm).



Gap opened by a planet in an accretion disc (scales of the x- and y-axes in AU). The star is at (x,y) = (0,0) and is of 1 solar mass. The accreting planet has 1 Jupiter mass, and the white circle outlines the planets Roche lobe. Observation of the depletion in the disc is a prime target for Darwin (Courtesy of P. Artymowicz)

The ‘nulling interferometry’ technique

Even in the infrared, we can only allow 10^{-5} – 10^{-6} of the stellar light to remain in the input feed to our spectrograph if we want to detect the planetary light and register its spectrum in a reasonable time. Coronographic methods on monolithic telescopes do not suffice to accomplish such an extinguishing of light at the relevant spatial scales. Instead, the technique of ‘nulling interferometry’ is baselined for Darwin. By applying suitable phase shifts between different telescopes in an interferometric array, we can achieve destructive interference on the optical axis of the system (in the combined beam). At the same time, we will have constructive interference a small angle θ away. The output of this system is a set of interference peaks (a ‘map’), with a sharp ‘null’ in the centre of the ‘map’. By placing the central star under this null, and the zone where H_2O will be liquid under the peaks, one can search for planets in the ‘habitable zone’. The actual shape and transmission properties of the pattern around the central ‘null’ depend on the configuration and the distance between the telescopes.

Detecting biospheres through remote sensing

To determine the suitability of an Earth-like planet to host life, we have to make some assumptions about how life changes the appearance of an Earth-like world. We therefore search for a world with an atmosphere that is out of equilibrium. Darwin operates under the assumption that liquid water is a prerequisite for life as we know it. Another necessary atmospheric component is CO_2. The extraordinary amount of molecular oxygen (and thus ozone) in the Earth's atmosphere is created by the various life forms on our planet, and would disappear in the relative short span of 4 million years without it. Therefore, the simultaneous detection of the spectral signatures of the H_2O, O_3 and the CO_2 molecules would imply the presence of a biosphere. Suitable tracers for these substances are located in a wavelength band between 6 µm and about 20 µm.

Imaging at high spatial resolution

Many of the fundamental processes that take place in the Universe can best be studied at infrared wavelengths. The range 4 µm $< \lambda <$ 20 µm is relatively free of obscuration by cold dust, and is instead a very good probe of dust heated above 100 K. Spectroscopy at these wavelengths can be used to characterise the chemical composition of many objects. Darwin will therefore be able to resolve objects down to the milli-arcsecond scale, equivalent to a resolution of 0.3 AU at 140 pc and λ = 10 µm. This is the scale size expected by the depletions believed to exist in planet-forming discs, and caused by condensing planets. A detailed study of the planet-forming process is extremely important and would nicely complement the 'planet finding' part of the mission.

With a sensitivity ~ 1 µJansky at 5 µm, Darwin will address the following issues:

(a) The formation of the galaxies and thus the first stars.

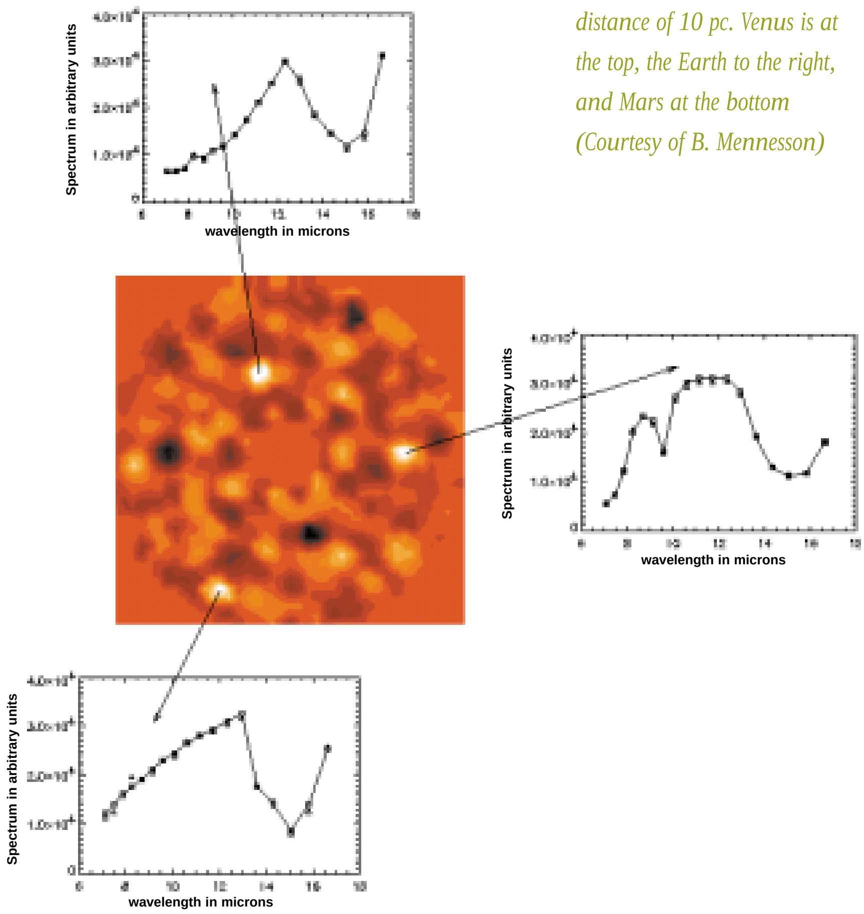
(b) The present formation of stars and planetary systems, with *direct* detection of the formation of planets possible.

(c) Formation and structure of black holes and their role as 'driving engines' of the activity in the centres of galaxies and Active Galactic Nuclei (AGNs).

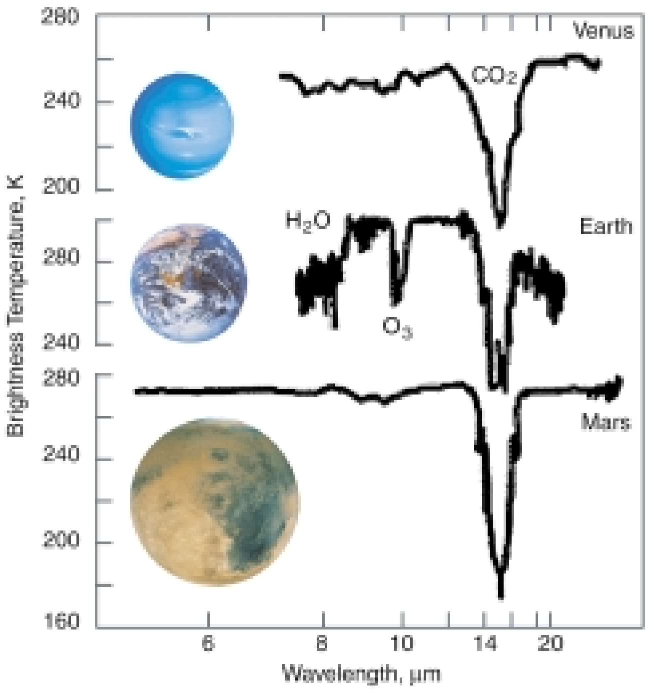
(d) A host of other science touching almost every sub-discipline.

Technology development and precursor missions

An ambitious technology-development plan has been initiated for Darwin, including space qualification and verification activities in the context of ESA's SMART programme. Activities being implemented for the next three years include development and construction of:



A simulated Darwin observation of the inner Solar System as viewed from a distance of 10 pc. Venus is at the top, the Earth to the right, and Mars at the bottom (Courtesy of B. Mennesson)

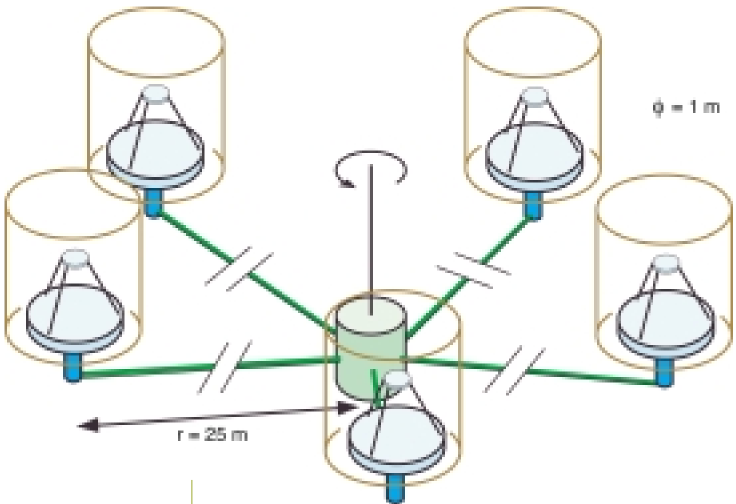


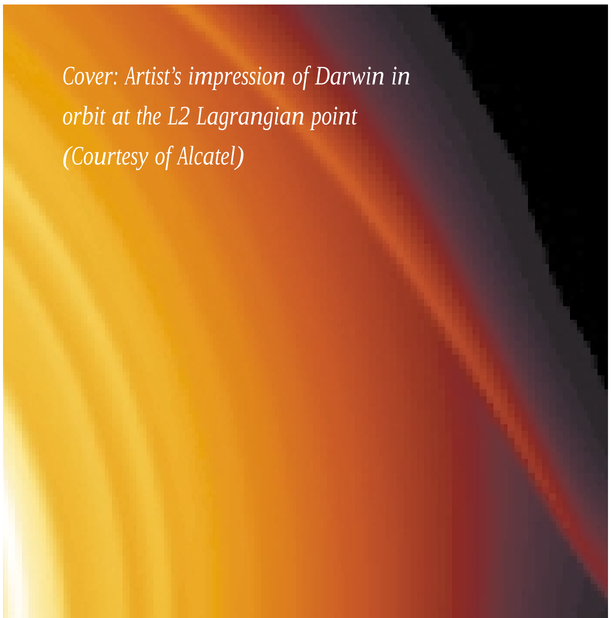
Actual spectra of the terrestrial planets in the Solar System showing the molecular signatures of interest for the Darwin mission

- High-stability optical benches.
- Optics active control.
- Fibre-optic wavefront filtering, single-mode fibres, operating in the 10 µm region of the spectrum, and an investigation into the phasing capabilities of fibres.
- Integrated optics, optical components for nulling and imaging interferometry.
- Achromatic phase shifters for nulling interferometry.
- Detectors and cooling systems.
- Satellite formation flying, including deployment and control and a local GPS system for 1 cm positional accuracy.
- Ultra-high-precision (laser-) metrology.
- Field Emission Electric Emission (FEEP) technology.

One of the key issues is to develop and verify the 'nulling interferometry' technique. A representative breadboard with an associated simulator providing the necessary input signals will be designed and built within the next few years. An associated pre-cursor activity is the observation of dust clouds in the target systems. This can be carried out from the ground, using the breadboard in conjunction with a large enough interferometer. A suitable instrument is the Very Large Telescope Interferometer (VLTI) of the European Southern Observatory (ESO). By using the breadboard together with the VLTI, its qualification would then also provide much-needed 'front-line' scientific data.

The following items are planned to be tested on a precursor mission:
- Deployment, acquisition of observing positions, array configuration and control of a flotilla of spacecraft.
- The metrology components: fringe tracker, laser system and RF GPS system.
- The control system software and hardware.
- Milli- and micro-Newton thrusters.





Cover: Artist's impression of Darwin in orbit at the L2 Lagrangian point (Courtesy of Alcatel) esa

Darwin

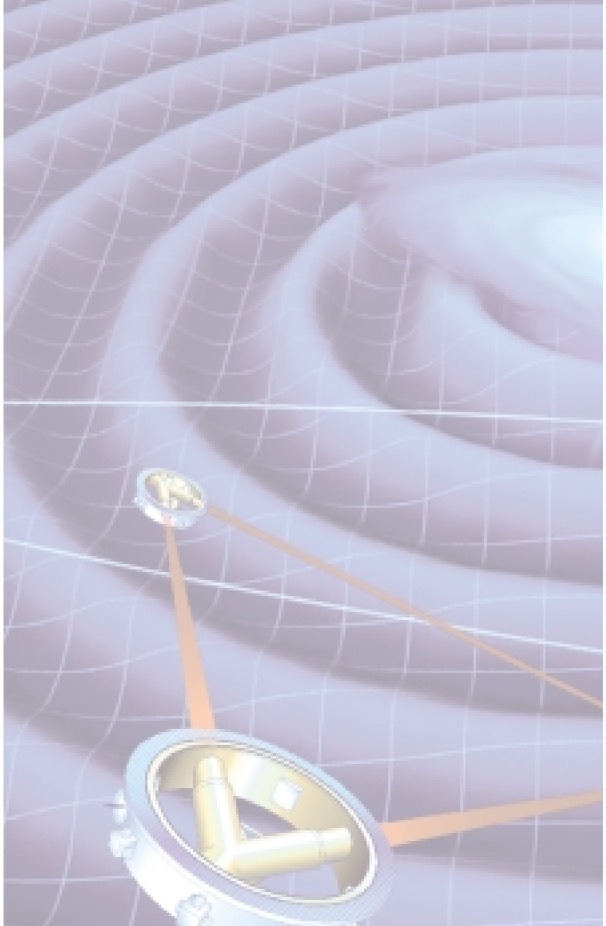
Cornerstone Study Results

Mission Summary

Studying Earth-like planets

Science in perspective

LISA



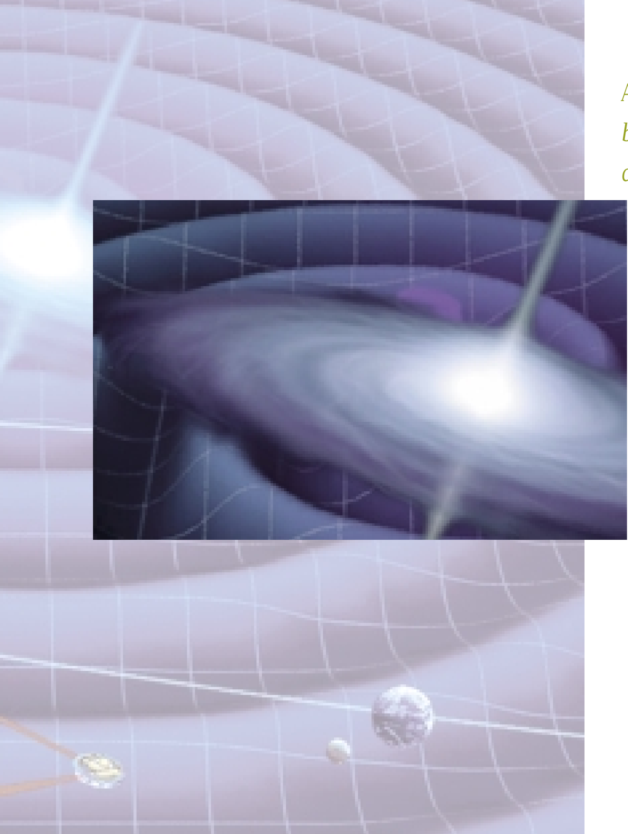
The primary goal of the Laser Interferometer Space Antenna (LISA) mission is to detect and observe gravitational waves from massive black holes and galactic binaries in the frequency range 10^{-4} to 10^{-1} Hz. This low-frequency range is inaccessible to ground-based interferometers because of the unshieldable background of local gravitational noise, and because ground-based interferometers are limited in length to a few kilometres.

The nature of gravitational waves

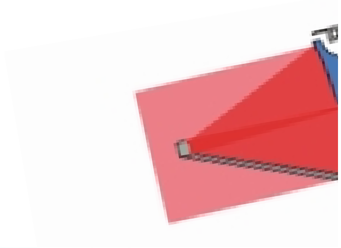
In Newton's theory of gravity, the gravitational interaction between two bodies is instantaneous. According to Special Relativity, however, this should be impossible, because the speed of light represents the limiting speed for all interactions. If a body changes shape, the resulting change in the force field will make its way outward at the speed of light. It is interesting to note that already in 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. Today we would say that this happens because the binary star is losing energy and angular momentum by emitting gravitational waves. It was 188 years later, in 1993, that Hulse and Taylor were awarded the Nobel Prize for Physics for their indirect proof of the existence of gravitational waves using exactly this kind of observation of the binary pulsar PSR 1913+16. A direct detection of gravitational waves has still not been achieved to this day.

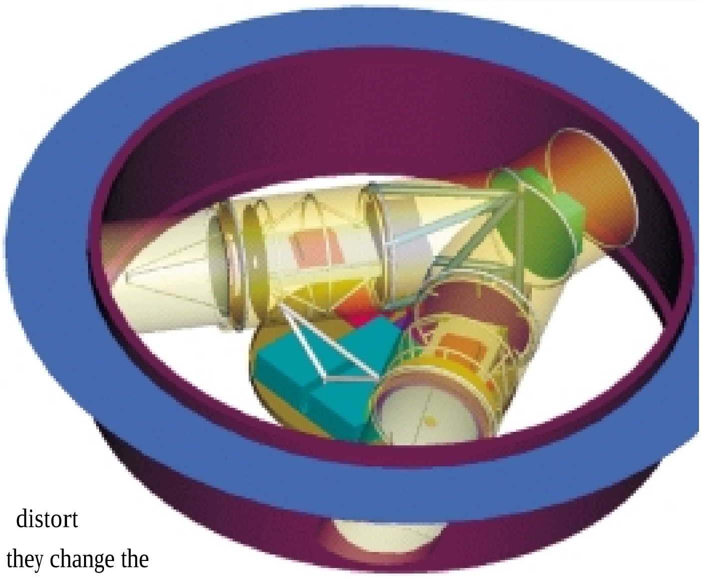
Einstein's paper on gravitational waves was published in 1916, and that was about all that was heard on the subject for over forty years. It was not until the late 1950s that some relativity theorists, H. Bondi in particular, rigorously proved that gravitational radiation was in fact a physically observable 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



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





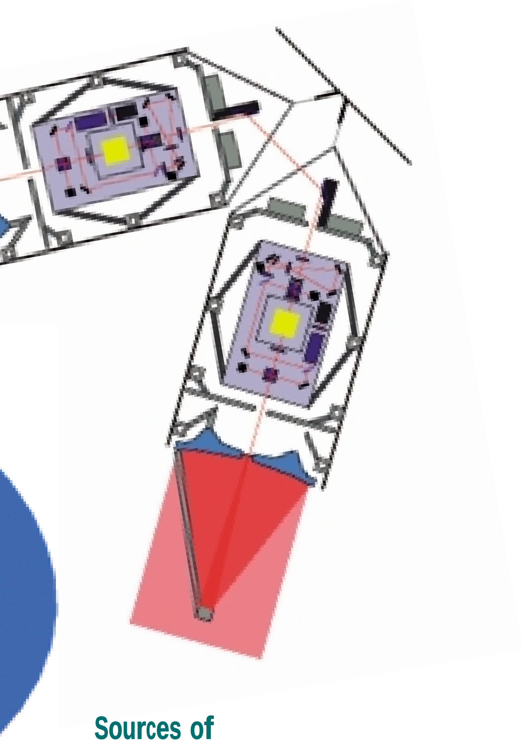
Left: Cut-away view of one of the three identical LISA spacecraft. The main structure is a ring with a diameter of 1.8 m and a height of 0.48 m, made from graphite-epoxy for low thermal expansion.
Right: Detail of the payload on each Y-shaped LISA spacecraft, consisting of two identical telescopes and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

system of billiard balls on a springy surface. In fact, the Einstein field equations relate mass (energy) and curvature in much 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 electrical 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, masses always come 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 symmetrical 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 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. This could be the distance between a spacecraft and the Earth, as in the case of Ulysses or Cassini (attempts have been and will be made to measure these distance fluctuations), or the distances between shielded proof masses inside spacecraft that are 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 are, however, very small because spacetime is an extremely stiff elastic medium, so that it takes extremely large energies to produce even minute distortions.



Sources of gravitational waves

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

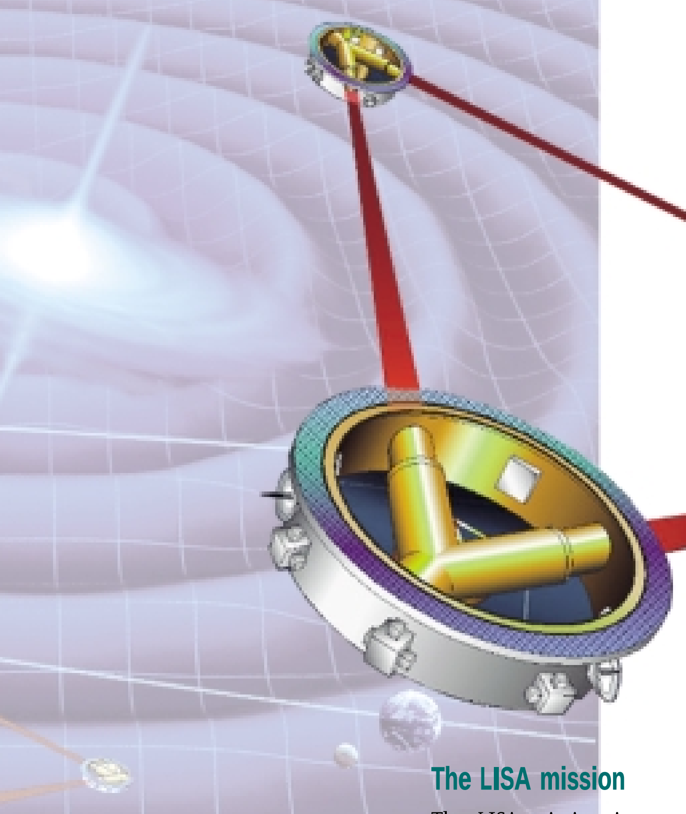
Because the masses involved in typical binary star systems are small (a few solar masses), the observation of binaries is limited to our Galaxy. Galactic sources that can be detected by LISA include a wide variety of binaries, such as pairs of close white dwarfs, pairs of neutron stars, neutron star 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 would 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. 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 thousands 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.

Complementarity with ground-based observations

The ground-based interferometers LIGO, VIRGO, TAMA 300 and GEO 600 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} Hz to 10^{-1} Hz).

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



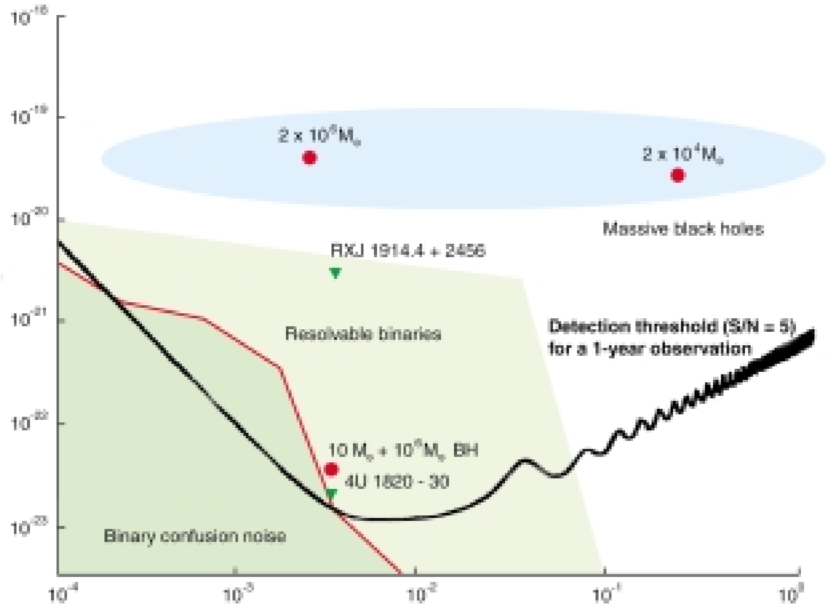
The LISA mission

The LISA mission is comprised of three identical spacecraft located 5 x 10^6 km apart forming an equilateral triangle. LISA is basically a giant Michelson interferometer placed in space, with a third arm added to provide independent information on the two gravitational-wave polarisations and for redundancy. 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 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 deg behind the Earth. The plane of the triangle is inclined by 60 deg 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.

Whilst LISA can be described as a giant Michelson interferometer, its 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 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 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 centre spacecraft, the light is superposed with the on-board laser light serving as a local oscillator in a heterodyne detection. This provides information on the length of one arm modulo the laser frequency. The other arm is treated in 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 provide information on laser frequency fluctuations.

Each spacecraft contains two optical assemblies. The two assemblies on one spacecraft each point 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 (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. 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 $\Delta l/l = 10^{-23}$ 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



LISA's sensitivity to binary star systems in our Galaxy and black holes in distant galaxies. The heavy black curve shows the LISA detection threshold, giving the noise amplitude of 5 σ after 1-year of observation. At frequencies below 3 mHz, binaries in the Galaxy are so numerous that LISA will not resolve them, and they form a noise background; this is also indicated at its expected 5 s level, coloured dark yellow. In lighter yellow is the region where LISA should resolve thousands of binaries that are closer to the Sun than most, or that radiate at higher frequencies. The signals expected from two known binaries are indicated by the green triangles. Many other systems are known to be observable, but are not indicated here. The blue-shaded area is where signals are expected from coalescences of massive black holes in galaxies at redshifts of order z = 1. These signals are complex and may last less than 1 year, so the region is drawn to indicate the expected signal-to-noise ratio above the LISA instrumental noise. Two signals are indicated, for coalescences of binaries consisting of two 10^6 $M_\odot$ and two 10^4 $M_\odot$ black holes. These show how sensitive LISA will be, reaching amplitude signal-to-noise ratios exceeding several thousand. While such events may occur only once per year, signals from small black holes falling into larger ones should be very common. Their strength is indicated by giving one example, where a 10 $M_\odot$ black hole falls into a 10^6 $M_\odot$ black hole at z = 1.

not directly enter into the measurement. It is nevertheless necessary to keep all spacecraft moderately accurately (10^{-8} m / √Hz 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 micro-Newton ion-emitting proportional 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 Field-Emission Electric Propulsion (FEEP) 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 wave fronts 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 arcminute or degree precision, depending on source strength).

Each of the three LISA spacecraft has a launch mass of about 400 kg (plus margin) including the payload, ion drive, all propellants and the spacecraft adapter. The ion drives are used for the transfer from 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 kb/s in X-band to the 34-m network of the DSN. The nominal mission lifetime is two years.

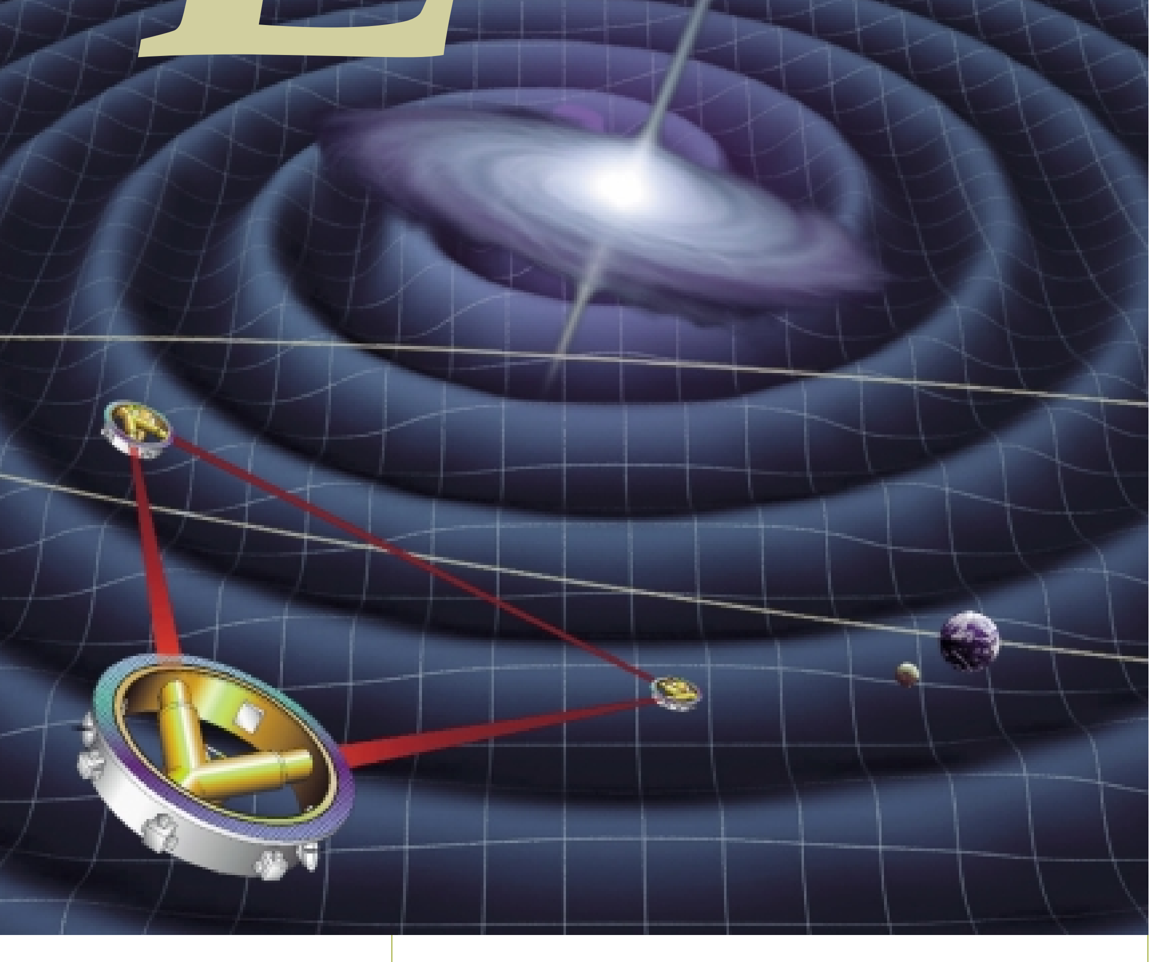
LISA is envisaged as a NASA/ESA collaborative project, with NASA providing the launch vehicle, the X-band telecommunications system on board the spacecraft, the mission and science operations, and about 50% of the payload, ESA providing the three spacecraft including the ion drives, and European institutes, 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.

Based on the LISA pre-Phase-A Report, a technical study had been performed, under the auspices of Dornier Satellitensysteme (DSS). Also involved in this study were Matra Marconi Space (MMS) and Alenia Aerospazio, and various subcontractors. Their Final Technical Report has deepened, verified, corroborated and optimised the earlier findings and has highlighted various options for improvements and alternatives, allowing the LISA Study Team and associated institutions to make informed choices between the alternatives offered.

LISA

Cornerstone Study Results

Mission Summary



Detecting and observing gravitational waves

Science in perspective