Gravitational Waves and Massive Black Holes?

– The LISA and LISA Pathfinder Missions

Ground-based telescope view (left) of the collision between the galaxies NGC4038 and NGC4039, which reveals long arcing insect-like 'antennae' of luminous matter flung from the scene of the accident. Investigations using the Hubble Space Telescope have revealed over a thousand bright young clusters of stars – the result of a burst of star formation triggerd by the collision. The green outline shows the area covered by the higher resolution Hubble image (right). Dust clouds around the two galactic nuclei give them a dimmed and reddened appearance, while the massive, hot young stars of the new formed clusters are blue
(Image courtesy of B. whitmore (STSci), F. Schweizer (DTM), NASA)

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Though they have not been directly detected so far, gravitational waves are a necessary consequence of Einstein's theory of General Relativity. They distort space and time, changing the perceived 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 that 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 separated by a large distance, as in the case of LISA.

The collaborative NASA/ESA Laser Interferometer Space Antenna (LISA) mission, planned for launch in 2012, will be the first space mission to search for these elusive gravitational waves. As the technology needed for the project is highly demanding, a precursor technology-demonstration mission is considered to be a necessary pre-requisite. Called LISA Pathfinder (formerly SMART-2) and planned for launch in 2008, it was given the go-ahead on 7 June by ESA's Science Programme Committee (SPC).

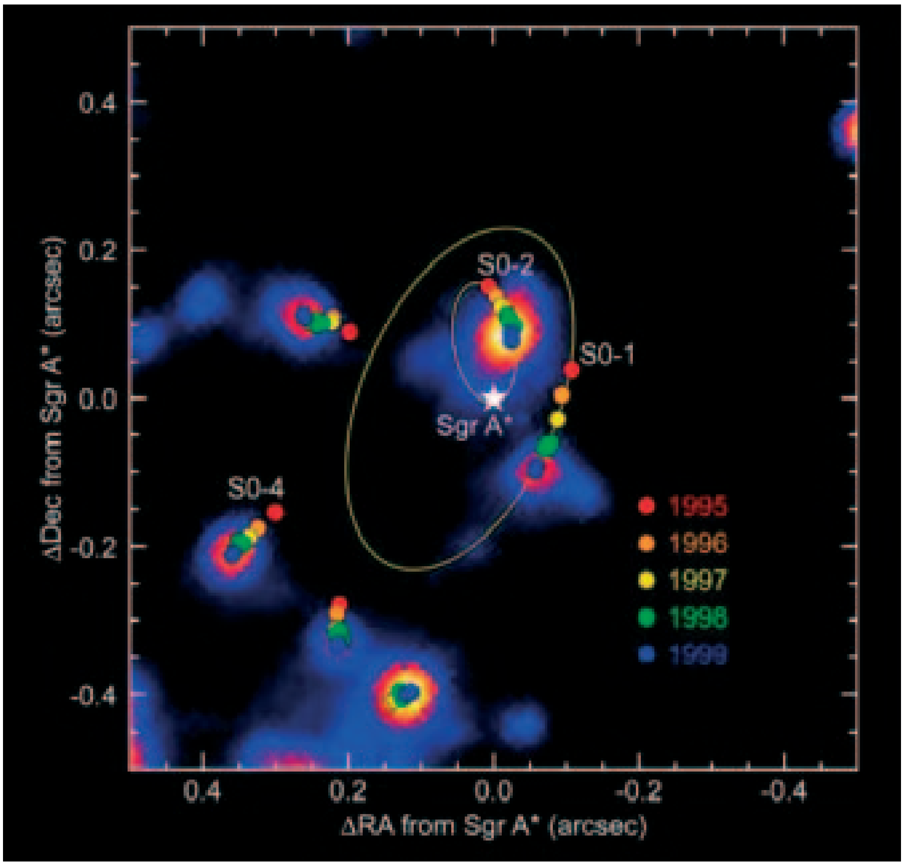
What Are Gravitational Waves ?

In Newton's gravitational theory, the gravitational interaction between two bodies is instantaneous, but according to Special Relativity this should be impossible because the speed of light represents the limiting speed for all interactions. So, if a body changes its shape the resulting change in the force field should make its way outwards no faster than the speed of light.

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, and in particular Herman Bondi (before he became the first Director General of ESRO, ESA's forerunner), proved rigorously 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.

Einstein's Theory of 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 then produce 'indentations' in the fabric of 'spacetime', and other bodies move in this curved spacetime taking the shortest path, much like a system of billiard balls crossing a spongy surface. In fact, Einstein's equations formally relate mass (energy) and spacetime curvature in just the same way that Hooke's law relates force and spring deformation. Put more poignantly, spacetime is an elastic medium and 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: the latter are created by the acceleration of electric charges and propagate in the framework of space and time, whereas gravitational waves are created by the acceleration of masses and are waves of the spacetime fabric itself. As early as 1805, Laplace, in his famous Traité de Mécanique Céleste stated that, if gravitation propagates with a 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. 188 years later, in 1993, Hulse and Taylor were awarded the Nobel Prize for Physics for their indirect proof of the existence of gravitational waves using exactly the kind of observation that Laplace had suggested, on the binary pulsar PSR 1913+16. However, the direct detection of gravitational waves has still not been achieved.



Stellar motions in the vicinity of Sgr A. The orbital accelerations of stars close to the Galactic Centre have been studied with near-infrared high-resolution observations. The resulting data allow constraints to be placed on the position and mass of the central supermassive black hole*

Gravitational waves are only very weakly coupled to matter and, therefore, suffer negligible scattering or absorption. This makes them an ideal cosmological and astrophysical 'information carrier', because all of the gravitational waves that have ever been emitted in the Universe are still traveling untouched through space. The main problem is that the 'straining' of spacetime, i.e. the fractional change in the distance between masses, due to the passage of a gravitational wave, is exceedingly small.

For example, the periodic change in distance between two proof masses, separated by millions of kilometres, due to a typical white dwarf binary at a distance of 50 parsec* is only 10^{-10} m. This is not to say that gravitational waves are weak in the sense that they carry little energy.

** A parsec is a measurement unit for astronomical distances, equivalent to 3.084 x 10^{13} km. There are 3.26 light years in 1 parsec. The nearest star is approximately 1.3 parsec from Earth, the Sun's distance from the centre of our galaxy is about 8500 parsec, and the farthest known galaxy is several billion parsecs away.*

Complementarity with Ground-based Observations

Astronomical observations of electromagnetic waves cover a range of 20 orders of magnitude in frequency, from ULF radio waves to high-energy gamma-rays. Almost all of these frequencies (except for visible and radio) cannot be detected from the ground, and therefore it is necessary to place detectors optimised for a particular frequency range (e.g. radio, infrared, ultraviolet, X-ray, gamma-ray) in space.

The situation is similar for gravitational waves. 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 also be made very large, thereby opening the range below 1 Hz, where both the most certain and the most exciting gravitational-wave sources radiate most of their power.

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 Massive Black Holes (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: observations can provide crucial spectral information.

The experimental search for gravitational waves was started by Joseph Weber in the early 1960s, at a time when very little was known about their possible sources. He developed the first resonant-mass detector, made of a massive aluminium bar 1.53 m long and 0.66 m in diameter. Weber's bar was at room temperature, had a mass of 1400 kg and a resonant frequency of 1661 Hz. A passing gravitational wave would cause the bar to oscillate at that frequency; a system of piezoelectric transducers would then convert the oscillations into an electrical signal. In order to exclude stochastic noise sources, Weber employed two identical experimental setups, one at the University of Maryland, the other at the Argonne National Laboratory near Chicago, 1000 km away. He recorded several coincident signals and claimed evidence for observation of gravitational waves. These and subsequent observations by Weber were greeted with great excitement in the early 1970s; however, there was also growing scepticism as the observations implied that the strength of the gravitational waves was very much in excess of what was expected for supernovae explosions in our Galaxy.

The sensitivity of the bar detectors can be improved by increasing their mass and by lowering their temperature. Today, three decades after Weber's pioneering experiments, there are five operational bar detectors in different parts of the World all working at cryogenic temperatures and having a higher mass than Weber's bars: EXPLORER at CERN (CH), ALLEGRO in Louisiana (USA), NIOBE in Perth (Aus), NAUTILUS in Rome (I), and AURIGA in Padua (I). They all are about 3 m-long aluminium bars with a mass of 2300 kg and a resonant frequency of about 900 Hz (NIOBE is made of niobium, has a mass of 1500 kg and a resonant frequency of 700 Hz). So far, gravitational waves have not been detected.

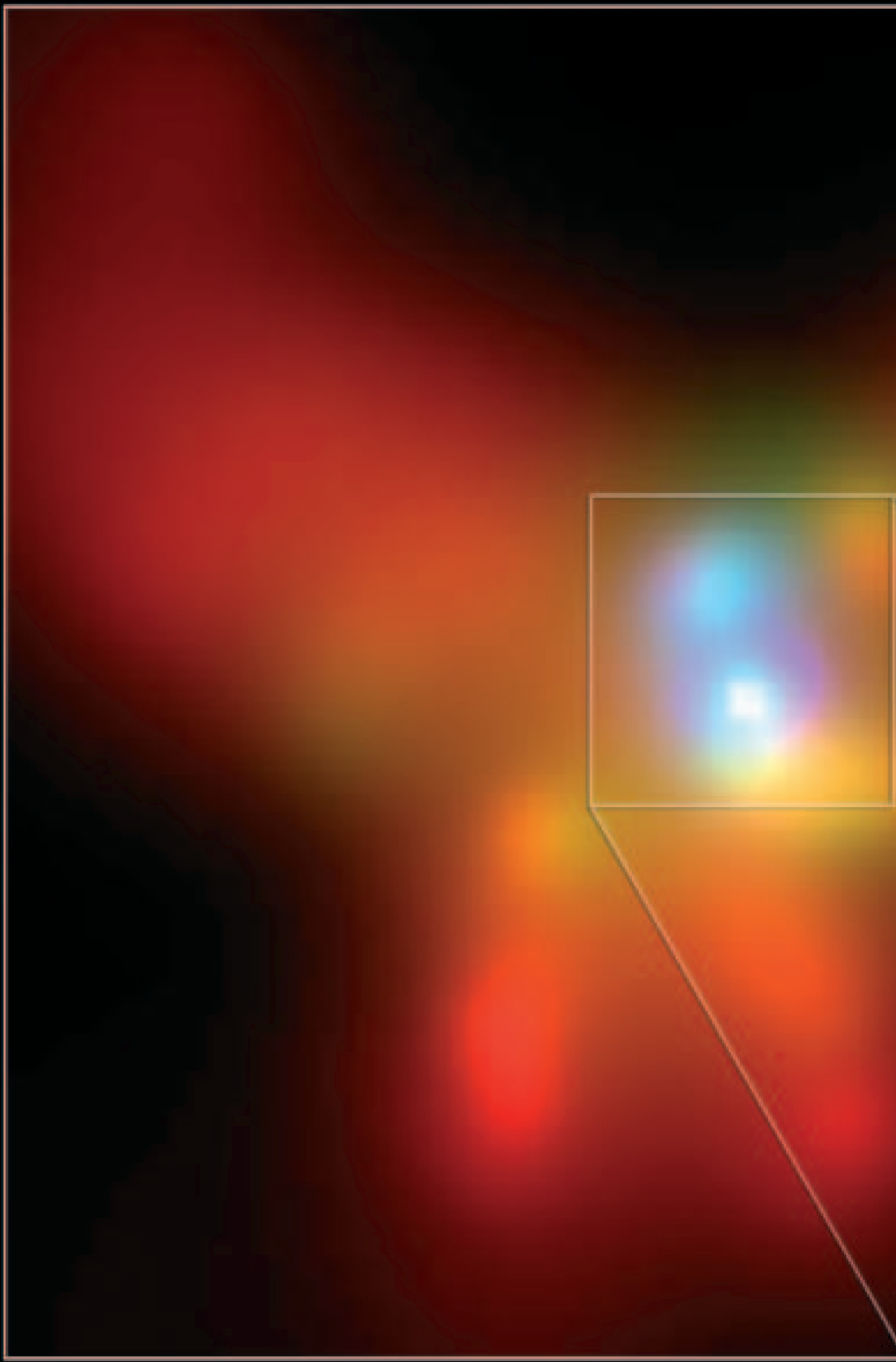
Spherical detectors have several advantages over cylindrical bar detectors. At present small (65 cm diameter) cryogenic spherical detectors (resonant frequency 3250 Hz) are becoming operational at Leiden University in The Netherlands and at the University of São Paulo in Brazil as precursors for later large spherical detectors up to 3 m in diameter.

In the early 1970s the idea emerged that Michelson interferometers using laser light might have a better chance than bars of detecting gravitational waves. The technology and techniques for such laser interferometers have now been under development for nearly 30 years. Today, six interferometers are either under construction or already operational:

in the USA		*In Europe*	
Hanford (Washington):	4 km arm length (LIGO)	near Pisa, Italy:	3 km arm length (VIRGO)
	2 km arm length (LIGO)	Hannover, Germany:	600 m arm length (GEO600)
Livingston (Louisiana):	4 km arm length (LIGO)		
in Japan			
Tokyo, Japan:	300 m arm length (TAMA300)		

LIGO, GEO600 and TAMA300 have already begun data runs. However, the sensitivity of the first-stage detectors may be only marginally sufficient to detect gravitational waves. Therefore, step-by-step improvements will be made until the network finally reaches the advanced detector sensitivity goal sometime between 2005 and 2010.

On the contrary, a supernova in a not too distant galaxy will drench every square metre 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 and so it takes extremely large energies to produce even minute distortions.



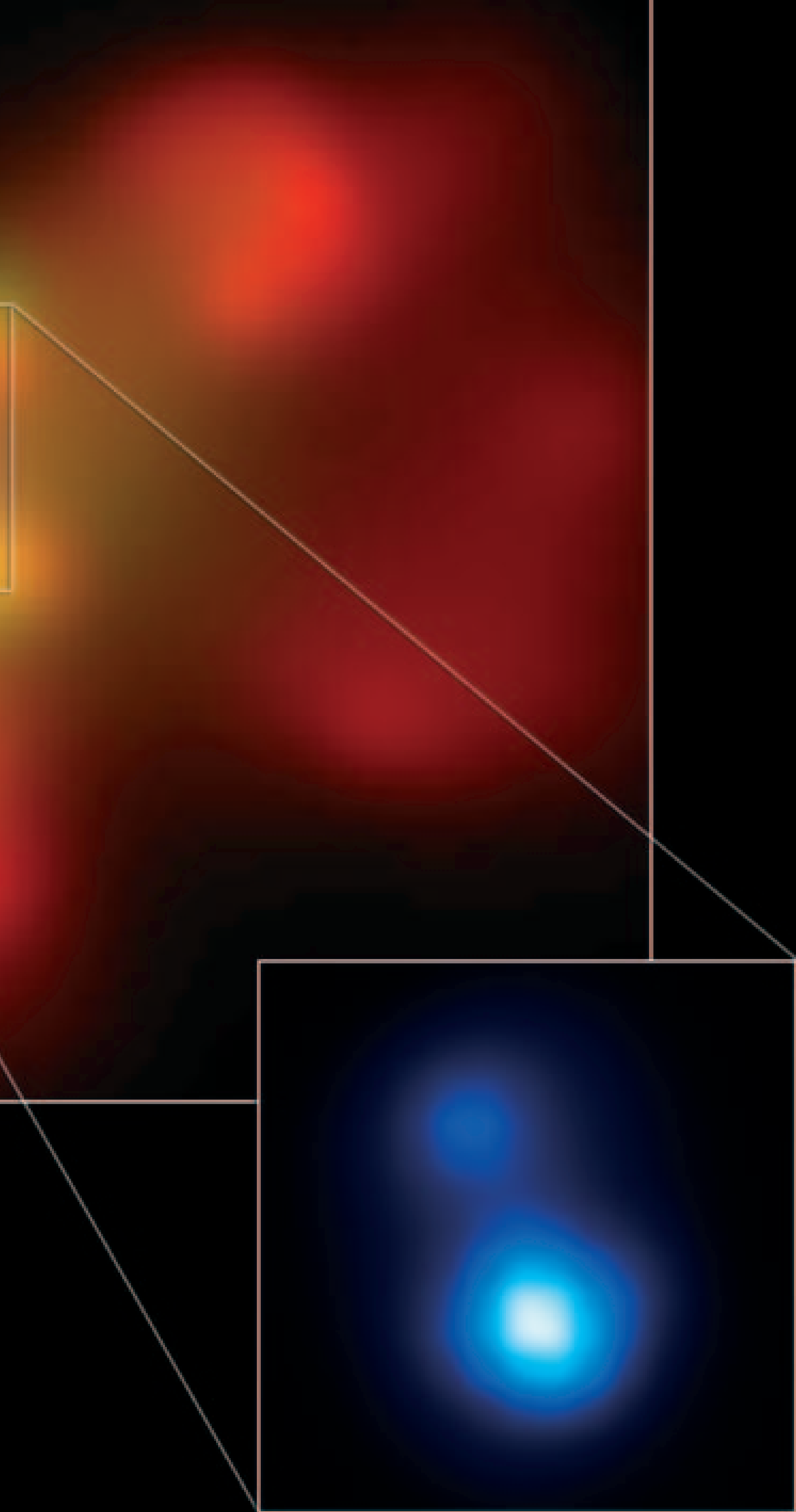
Where Do Gravitational Waves Come From ?

The two main categories of sources for the gravitational waves for which LISA will be searching are galactic binary star systems and massive black holes expected to exist in the centres of most galaxies. Because the masses involved in typical binary star systems are small (a few times the mass of the Sun), the observation of binaries is limited to our own 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 to 20 solar masses) binaries, pairs of contacting normal stars, normal-star and white-dwarf (cataclysmic) binaries, and possibly also pairs of black holes. Some galactic binaries are already so well studied that they are considered to be 'calibration sources'. One such example is the X-ray binary 4U1820-30, located in the globular cluster NGC 6624. If LISA would not detect the gravitational waves from such known binaries with the intensity and polarisation predicted by the Theory of 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 massive black holes with masses 10^6 to 10^8 times that of the Sun in the centres of most galaxies, including our own. The most powerful sources are the mergers of massive black holes in distant galaxies. Observations of signals from these sources would test General Relativity and particularly black-hole theory to unprecedented accuracy. Little is currently known about black holes with masses ranging from about 100 to 10^6 times that of the Sun and LISA can provide unique new information throughout this mass range.

During the gravitational capture of a star by a black hole, gravitational waves will be continuously emitted, allowing an accurate map to be made of the spacetime surrounding the black hole. It will therefore finally be possible to verify whether the 'black holes have no hair' theorem* is true.

** The 'black holes have no hair' theorem was introduced by John Wheeler in the early 1970s as a principle predicting the simplicity of the stationary black-hole family. The theorem shows that mass, charge, and angular momentum are the only properties that a black hole can possess.*



This image, taken by the Chandra spacecraft, shows the butterfly-shaped galaxy NGC 6240, which is the product of the collision of two smaller galaxies. The central region of the galaxy has two active giant black holes (inset) (Courtesy of NASA/CXC/MPE/S. Komossa et al.)

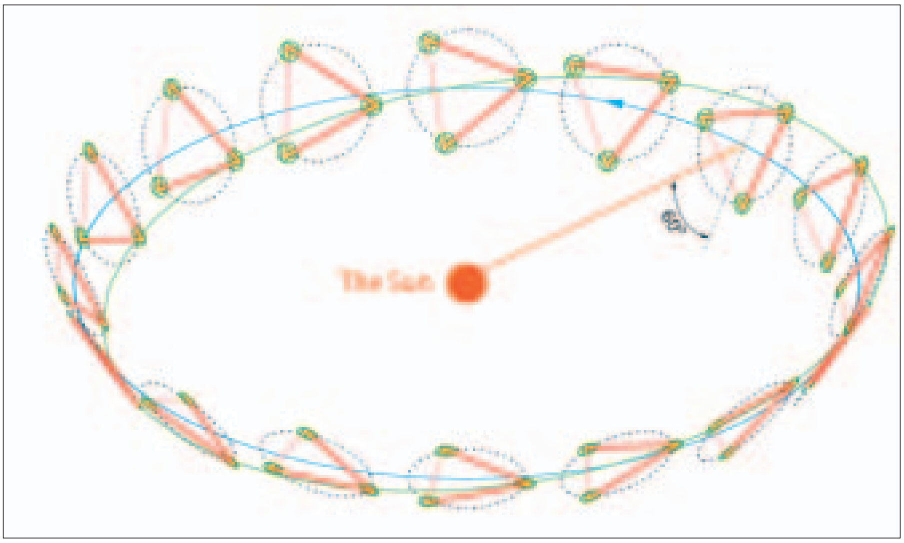
The LISA Mission

The key scientific goals for the LISA mission are to:

- determine the role of massive black holes in galaxy evolution by observing gravitational waves emanating from their coalescence
- make precise tests of Einstein's Theory of General Relativity by observing gravitational waves from the capture of dense compact objects by massive black holes
- determine the population of compact binaries in our Galaxy by observing the gravitational wave signals that they emit
- probe the physics of the early Universe by observing cosmological backgrounds and bursts.

Achieving these scientific goals requires three identical spacecraft positioned 5 million kilometres apart at the corners of an equilateral triangle. The distance between the spacecraft (the arm length of what is effectively a Michelson interferometer) determines the frequency range in which observations can be made. The centre of the triangular formation is in the ecliptic plane, at the same distance from the Sun as the Earth, and trailing the Earth by approximately 20 degrees. This position behind the Earth is a result of a trade-off between minimising the gravitational disturbances from the Earth-Moon system and the communications needs. Going farther away would further reduce the disturbances, but the greater distance would require larger antennas or higher transmitter powers. The plane of the spacecraft triangle is inclined by 60 degrees with respect to the ecliptic, which means that the formation is maintained throughout the year, with the triangle appearing to counter-rotate about the centre of the formation once per year.

While LISA can be described as a Michelson interferometer in space, the actual implementation is somewhat different from that of a ground-based interferometer. The laser light going out from the prime spacecraft to the other corners is not directly reflected back because very little light would be received that way. Instead, the laser on the receiving spacecraft is phase-locked to the incoming light, generating a



LISA consists of a constellation of three spacecraft flying in formation at the corners of an equilateral triangle, inclined at 60 degrees with respect to the ecliptic plane, in a heliocentric orbit. The equilateral triangle performs a complete rotation around its centre during one year, while rotating around the Sun. This concept permits detection of the direction of the gravitational wave sources

return beam of full intensity. The transponded light from the spacecraft is received by the other one on the same arm and superposed with the onboard laser light that serves as the local oscillator in a so-called 'heterodyne detection'. As this entwines laser frequency noise with a potential gravitational wave signal, the signal from the other arm is used to take out the laser frequency noise and obtain the pure gravitational wave signal.

The nature of the elliptical orbits flown by the three spacecraft, and to a lesser extent the gravitational perturbations caused by the Earth, the Moon and the large planets, are sufficient to perturb the triangular formation and cause relative velocities between the spacecraft of up to 20 m/s. In the course of a year, therefore, the distances between the spacecraft can change by many thousands of kilometres. The relative velocity causes the transponded light to be Doppler-shifted by up to 20 MHz. The resulting signal is well outside the LISA detection band and can be removed by onboard data processing.

As each spacecraft has a launch mass of approximately 460 kg (including the payload, propulsion module, propellants and launch adapter), all three can be launched by a single Delta-IV. After launch, the trio separate and use their own propulsion modules to reach their operational orbits 13 months later. Once there, they will jettison their propulsion modules and their attitude and drag-free control will be left to the micro-Newton thrusters on each spacecraft.

Each spacecraft carries two 30 cm-diameter, steerable high-gain antennas for communication with the Earth. Using the 34 m antennas of the Deep-Space Network and 5 W transmitter power, data can be transmitted (in X-band) at a rate of 7 kbit/s for 8 hours every two days, and stored onboard in 1 Gbyte of solid-state memory at other times. The nominal mission lifetime is 5 years once the spacecraft have reached their operational orbits.

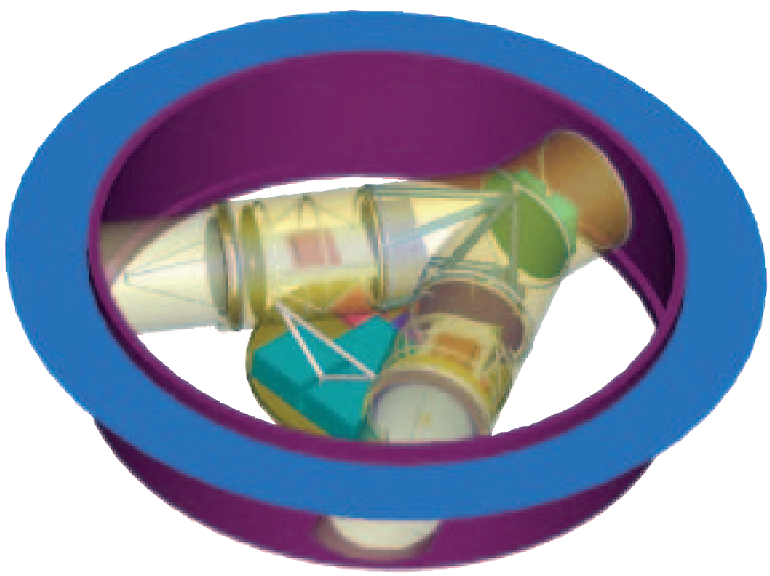
How Will the Gravitational Waves Be Detected ?

The principle of a gravitational wave detector in space is relatively simple: the distances between two or more test masses free to follow geodesics (i.e. in free fall) are changed by the passing of a gravitational wave. The detection of the gravitational wave and the measurement of its strength are directly derived by the interferometric measurement of the distance between the test masses.

Each spacecraft carries two optical assemblies, which point towards an identical assembly on the other two spacecraft. In this way, the three spacecraft form two independent Michelson interferometers, thereby providing redundancy. An infrared laser beam (1 W and 1064 nm wavelength) 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 (a quadrant photodiode), 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

Each of the three LISA spacecraft will carry two telescopes arranged in a Y-shaped tube, with associated lasers and optical systems, pointing in directions separated by 60 degrees. The telescopes will communicate with the spacecraft at the other two corners of the equilateral triangle. Central to each optical system will be the 'proof mass', a 4.6 cm-sided cube made from a gold-platinum alloy. This proof mass acts as a reflector for the laser beams

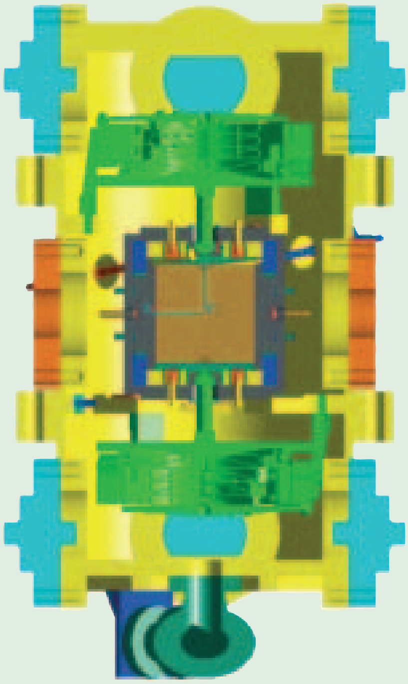


The LISA Technology Package

The LTP represents one arm of the LISA interferometer, in which the distance between the two proof masses is reduced from 5 million km to about 30 cm. As for the LISA mission itself, the proof masses play a double role, serving as optical references (mirrors) for the interferometer and as inertial sensors for the Drag-Free Attitude Control System (DFACS).

The two identical proof masses (4.6 cm cubes) are housed in individual vacuum cans. Capacitive sensing in three dimensions measures their displacement with respect to their housings. These position signals are used in a feedback loop to command micro-Newton thrusters to enable the spacecraft to remain centred on the proof mass. Field Emission Electric Propulsion (FEEP) thrusters and cold-gas proportional thrusters will be used as actuators. Although the proof masses are shielded from non-gravitational forces by the spacecraft, cosmic rays and solar-flare particles can significantly charge them, leading to electrostatic forces. A system of fibre-coupled UV lamps will discharge the proof masses at regular intervals. As surface effects can also cause electrostatic forces, the proof masses have to be coated very carefully to avoid contamination.

As each proof mass is designed to 'float' in space, surrounded by gaps of several millimetres, a caging mechanism is needed to maintain them in a safe position during launch. The mechanism must apply the necessary loads without damaging the coating of the proof masses and the surrounding electrodes. It must also be capable of repositioning the masses correctly afterwards, in order to allow the weak capacitive actuators to re-take control.



The LTP inertial sensor. The proof mass is surrounded by the electrode housing and is located in a vacuum enclosure. Optical windows allow the laser beam to be reflected by the face of the cube. UV optical fibres within the enclosure illuminate the cubes in order to discharge any charging produced by cosmic rays. The proof mass is kept in a safe position during launch by a 'caging' mechanism.

The positions of the proof masses with respect to the spacecraft or each other are measured by an interferometric system that is capable of picometre precision in the frequency range 10^{-3} Hz – 10^{-1} Hz. The residual temperature fluctuations aboard the spacecraft require the use of materials with very small coefficients of thermal expansion.

The Disturbance Reduction System (DRS) is a NASA-supplied system with the same mission goals as LTP, but using slightly different technology. Its baseline design foresees two inertial sensors and an interferometric readout similar to that planned for LTP. However, the thrusters for the drag-free control system use ionised droplets of a colloid accelerated in an electric field to provide propulsion. In this way LISA Pathfinder will effectively test two drag-free attitude control systems and three different micro-propulsion thruster technologies.

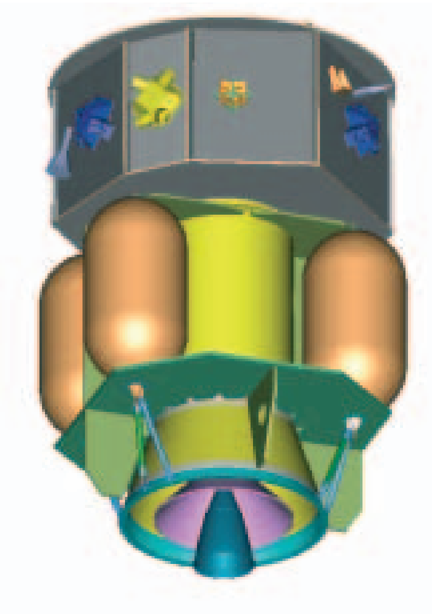
platinum-gold 46 mm cube - the so-called 'proof mass' - that serves as the optical reference (mirror) for the light beams. A passing gravitational wave will change the length of the optical path between the proof masses of one arm of the interferometer relative to the other arm. The distance fluctuations are measured to a precision of 40 pm (averaged over one second) which, when combined with the large separation between the spacecraft, allows LISA to detect gravitational wave strains with great accuracy (down to a level of order $\Delta L/L = 10^{-23}$ in 1 year of observation with a signal-to-noise ratio of 5).

The spacecraft serves mainly to shield the proof masses from the adverse effects of solar radiation pressure, so that they follow a purely gravitational orbit. Although the position of the spacecraft does not enter directly into the measurement, it is nevertheless necessary to keep all spacecraft moderately accurately centred on their respective proof masses to reduce spurious local noise forces. This is achieved by means of a 'drag-free' control system (explained below) consisting of test-mass position sensors and a system of micro-Newton thrusters.

Capacitive sensing in three dimensions measures 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 follow the proof masses precisely. As a reference point for the drag-free system, one of the masses (or any point between) can be chosen. The FEEP thrusters are also used to control the attitude of the spacecraft relative to the incoming optical wavefronts.

The LISA Pathfinder Mission

Despite the simplicity of the LISA mission concept, the technological challenges faced to achieve it are enormous. The main difficulty is to make the test masses follow



CAD drawing of the LISA Pathfinder spacecraft, with the science package containing the LTP and the DRS sitting atop the propulsion module, which will carry it out to the L1 halo orbit

a geodesic, near-perfect free-fall trajectory by employing a so-called 'drag-free' system. This implies keeping each proof mass within an enclosure that suppresses the disturbances from the external forces (e.g. aerodynamic, radiation pressure and other disturbances of the surrounding space environment) and the internal forces (e.g. self-gravity, electro-magnetic forces and other forces coming from the spacecraft itself).

This protection is achieved by a combination of extremely accurate construction of the entire spacecraft and the use of a sophisticated Drag-Free Attitude Control System (DFACS). The DFACS is based on measurements of the displacement of the test masses inside their enclosures using capacitive sensors and a laser metrology system and it controls the motion of the spacecraft surrounding the proof masses by means of ultra-precise micro-propulsion thrusters.

On Earth, one can never reproduce the free-fall conditions required to quantitatively prove the correct working in space of the DFACS. It was to demonstrate this and the other key technologies needed for the LISA mission that ESA decided to undertake the LISA Pathfinder precursor project (formerly the SMART-2 mission). The Pathfinder will accommodate a LISA Technology Package (LTP) provided by European institutes and industry, and a Disturbance Reduction System (DRS) that is very similar to the LTP and has the same goals, but is provided by NASA.

The LTP (see previous page) will:

- demonstrate DFACS in a spacecraft with two proof masses with a performance of the order of 10^{-14} $ms^{-2}/\sqrt{Hz}$ in the bandwidth 10^{-3} – 10^{-1} Hz (the LISA requirement is an order of magnitude higher at 10^{-15} $ms^{2}/\sqrt{Hz}$)
- demonstrate the feasibility of performing laser interferometry in the required low-frequency regime with a performance as close as possible to that required for the LISA mission ($10^{-11}m/\sqrt{Hz}$ in the frequency band 10^{-3} Hz –10^{-1} Hz)
- assess the longevity and reliability of the LISA sensors, thrusters, lasers and optics in the real space environment.

As the environment on the LISA Pathfinder spacecraft will be comparatively 'noisy' in terms of temperature fluctuations and residual forces, the Pathfinder technology demonstrator is deliberately aimed at meeting specifications that are about a factor of 10 more relaxed than those for LISA itself.

The LISA Pathfinder spacecraft is a simple-looking octagonal box, about 1 m high and 2.1 m in diameter, with a small fixed solar array mounted on the top). The LTP is mounted above the DRS, inside the central core of the spacecraft, the two experimental packages being separated by a horizontal floor.

LISA Pathfinder will be launched in early 2008 by a small European vehicle into a low Earth orbit. Like LISA, it will use its own propulsion module to reach its operational 'halo orbit' around the Sun-Earth Lagrangian point (L1) about 1.5 million km from Earth. This orbit has been selected because it provides a quiet

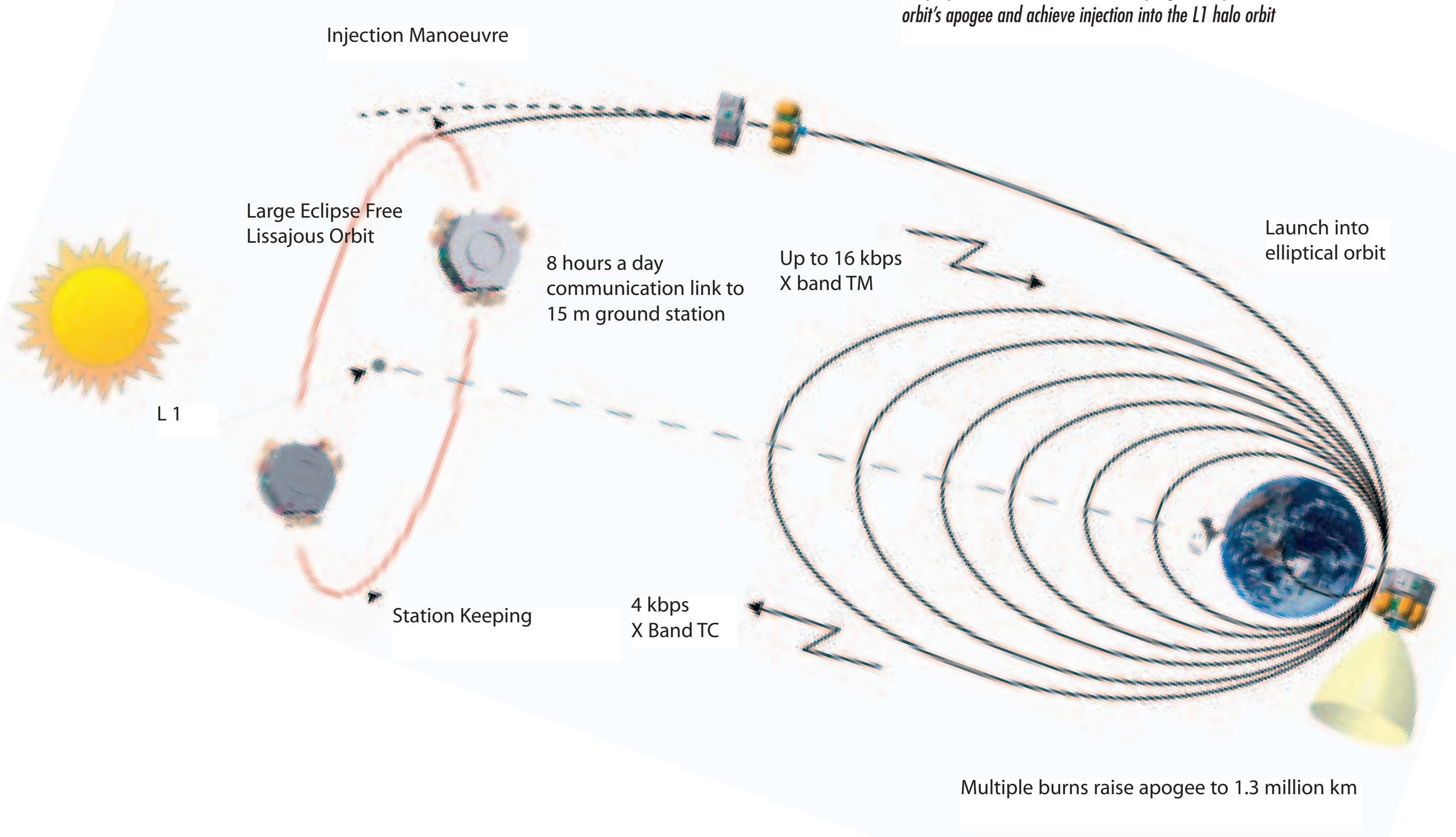
Current Project Status

LISA is a NASA/ESA collaborative project that is currently under development. The sharing of management responsibilities and provision of mission elements between the two agencies is presently being negotiated on the basis of ESA taking responsibility for overall payload integration and testing and NASA for the provision of the three spacecraft, the launch vehicle, and the ground segment (Deep Space Network), including the mission operations. The science operations will also be shared.

The payload will be shared 50/50, with the European elements funded by national space agencies in the ESA Member States. The scientific data will be analysed by two independent data-analysis teams, one in Europe and one in the USA.

In November 2003, ESA's Science Programme Committee (SPC) decided to include ESA's share of the LISA mission in the Agency's long-term plan for space science. Preparations for a two-year system level industrial study, starting in October this year, are in progress. The SPC also decided to include the LISA Pathfinder precursor project, subject to affordable Cost at Completion and formally secured LTP payload funding. In June 2004, the SPC approved the financial envelope for the project and recommended to Council to approve the draft LTP Multilateral Agreement between ESA and those Member-State funding agencies providing elements of the LTP.

Since March 2004, LISA Pathfinder has been in the Implementation Phase, with Astrium (UK) as the Prime Contractor. The industrial contract was officially signed at a ceremony on 23 June. The System Requirements Review, the first milestone during the Implementation Phase, was completed with the Board meeting on 25 June.



The transfer trajectory sequence, for which 11 separate burns of the propulsion module are needed to progressively raise the orbit's apogee and achieve injection into the L1 halo orbit

environment in terms of 'tidal forces' (produced in the vicinity of massive bodies, from which L1 is sufficiently far away), thermal stability, magnetic field, and radiation, is reachable year-round, and also allows daily visibility from a single ground station. The 'halo' in fact is a three-dimensional orbit with a shape similar to the contour of a potato chip.

Following the orbital transfer, initial set-up and calibration phases, the in-flight demonstration of the LISA technology, consisting of 90 days of LTP, 70 days of DRS, and 20 days of joint operations, will take place in the second half of 2008, thereby providing timely feedback for the development of the LISA mission itself.

What the Future Holds

As the first space-based gravitational wave detector, LISA is an extremely ambitious programme that has the potential to open a radical new window on astronomy. We will be able to look at the Universe in a completely new way and we are expecting great discoveries, possibly even a quantum leap in our present understanding of the most powerful cosmic events. The technological challenge, however, is enormous. Extremely delicate measurements will have to be performed by highly sophisticated spacecraft, capable of harnessing all of nature's forces and yet still able to listen for the 'whisper' of gravitational waves.

LISA Pathfinder, though not able itself to detect gravitational waves due to its single spacecraft configuration, will thoroughly test the gravitational wave detection technologies and pave the way for the unique LISA gravitational wave observatory, which will be the largest ever manmade 'construction' in space.

On 2 April 2004, ESA's Directorate of Scientific Programmes issued a Call for Themes for the Agency's Cosmic Vision 2015-2025 Programme. Among the 150 proposals submitted by the scientific community were several for research themes to follow up the LISA mission. They range from studies of gravitational-wave cosmology, to the search for dark matter and missing baryonic matter, to the search for super-massive black holes in the Universe. These proposals illustrate just how much interest the LISA mission is generating in the astronomy and astrophysics communities with its inherent promise of providing a completely new view of the Universe, perhaps heralding a revolution similar to those brought by the births of radio and X-ray astronomy.