Ten Years of Fundamental Physics in ESA's Space Science Programme

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On 15 June 1989, ESA's Science Directorate issued a Call for Mission Proposals which specifically also asked for proposals in fundamental physics. In response to this Call the scientific community submitted five proposals aimed at detecting gravitational waves, testing the Equivalence Principle, measuring the gravitational constant with high precision, and searching for the elusive Fifth Force and for Dark Matter in the Universe. Today, 10 years later, the new field of fundamental physics in space has matured with one mission (GP-B) about to be launched by NASA, two industrial studies (LISA, STEP) in progress this year in ESA at Phase-A level, and several other experiments either flying or being readied for flight, including experiments on the International Space Station. There is clearly now a community of fundamental physicists in Europe in need of space flight opportunities, just as there are communities of astronomers and Solar System scientists. The only difference is that the technologies enabling meaningful fundamental-physics missions have only became available 30 years later.

Early days

In the beginning, ESA's Space Science Programme (actually ESRO's in those days) consisted only of small magnetospheric satellites. ESRO-II, ESRO-IA, HEOS-1, ESRO-IB, HEOS-2 and ESRO-IV were launched between 1968 and 1972, addressing primarily problems in plasma physics. Throughout the 1970s, Solar System exploration continued to be limited to magnetospheric research, with the launches of GEOS-1 and -2 and ISEE-2. The first astronomy satellites (TD-1, COS-B and IUE) were launched between 1972 and 1978, making observations at UV, X- and γ-ray wavelengths.

There was also interest in fundamental-physics missions in those early days. COPERS (the Commission Préparatoire Européenne de Recherche Spatiale, which existed from December 1960 until March 1964) planned eight ad-hoc groups, representing the main fields in space science at that time, among them a group on Geodesy, Relativity and Gravitation; this group was, however, not realised when ESRO came into existence in 1964. A far-sighted Italian proposal in 1964 suggested that ESLAR (the predecessor of ESRIN) should study drag-free satellites, a key technology required for fundamental-physics missions. This early phase culminated in the Phase-A study of the SOREL (Solar Relativity) mission in 1970-71. The goal of the SOREL mission was to measure:

- the gravitational redshift to 3 parts in 10^6
- the time delay and deflection of laser light passing close to the Sun
- the solar quadrupole moment J_2.

This required a spacecraft that would be drag-free to the level of 10^{-12} m/s^2, and in the one-way laser option a high-precision on-board clock (caesium or hydrogen-maser clock) and in the two-way laser option an on-board laser. None of these technologies existed at that time and would have had to be developed and space-qualified at considerable cost. It was mostly for that reason that the plans for the SOREL mission were not further pursued.

The existence of three distinctly different fields in space science in the 1970s was also reflected in ESA's scientific advisory structure at that time. It consisted of the Launching Programmes Advisory Committee (LPAC, the predecessor of today's SSAC) and the

- Solar System Working Group (SSWG)
- Astrophysics Working Group (AWG)
- Fundamental Physics Panel (FPP).

The FPP had ten members, among them a former Director General of ESRO (H. Bondi) and a later Director General of ESA (R. Lüst). However, the founding fathers of 'Fundamental Physics in Space' soon realised that the technology needed to carry out high-precision experiments in space did not yet exist and the Panel became inactive after 1979. The SSWG and the AWG still exist today.

Composition of ESA's Fundamental Physics Panel (1971-1979)

H. Bondi (Chairman)	R. Lüst
J. Blamont	G. Occhialini
G. Cocconi	I.W. Roxburgh
G. Colombo	E. Schatzman
B. Laurent	D. Sciama

In 1972, the Italian Physical Society organised a summer school in Varenna devoted to Experimental Gravitation. The Proceedings, published in 1974, give an excellent account of the state of the art at that time and include papers not only on the SOREL mission, but also on redshift experiments using high-precision clocks such as Gravity Probe A, the gyroscope experiment (later named Gravity Probe B), the STEP mission, several methods to detect gravitational radiation and the technique of drag-free satellites.

With the launch of Giotto in 1985, ESA's Solar System exploration began to include the exploration of the solid bodies — first comet Halley, and later, with the launch of the Huygens probe in 1997, the Saturnian moon Titan. Missions to the Moon, Mars and Mercury are now under study. Solar physics was added with the launch of Soho in 1995.

Astronomy saw the addition of the new field of astrometry with the launch of Hipparcos in 1989, and ISO, launched in 1993, opened up the possibility of observations in the infrared.

Fundamental physics as a science discipline in its own right was also included in ESA's Long-Term Space Science Programme 'Horizon 2000' (ESA SP-1070) with a chapter on Space Experiments in Relativity and Gravitation by I.W. Roxburgh. The paper does not describe a specific mission in fundamental physics, but lists several possibilities for including fundamental physics experiments on suitable Solar System missions, such as Mercury Orbiter, Solar Probe or a mission to the outer planets. Concerning gravitational waves Roxburgh wrote (in 1984):

'At present we are unable to predict with any confidence the strengths of any such waves passing through the Solar System, but the successful discovery of such waves could be of immense significance for gravitational physics and for astrophysics'.

In 1987, the Austrian Space Agency together with ESA organised a summer school in Alpbach devoted to 'Space Science and Fundamental Physics'. The Proceedings of that summer school (ESA SP-283) include several papers describing future missions in fundamental physics, such as a test of the Equivalence Principle and the detection of gravitational waves with long-baseline interferometers in space.

Restarting fundamental physics in space

With the discontinuation of the FPP in ESA's science advisory structure in 1979, the possibilities of realising a fundamental-physics mission in ESA essentially disappeared and interest within the Agency in fundamental physics almost completely vanished. This changed in the late 1980s with the enunciation of the 'fifth force' hypothesis by E. Fischbach and co-workers, triggering a suite of highly publicised experiments worldwide and calling attention to the fact that gravity, itself the 'oldest' of the known forces, was in some ways also the least understood. A 'fifth force', coexisting with conventional gravity, would lead to a net interaction between macroscopic bodies, which would show small deviations from the behaviour expected from the classical Newtonian inverse-square law of gravity. If such a force were to exist, it would be very small and possibly easier to detect in a gravitationally less disturbed experiment in space.

Fundamental Physics in Space

The field of 'Fundamental Physics in Space' includes those research activities in gravitational and particle physics aimed at finding new, more comprehensive concepts and laws, the testing of existing ones, and the resolution of some very basic inconsistencies. This includes:

- the direct detection and detailed analysis of gravitational waves
- the investigation of possible violations of the Equivalence Principle
- the search for new hypothetical long-range forces
- the testing of General Relativity and its alternative theories
- the unification of the fundamental interactions of nature
- particle physics, in particular the search for antimatter in space
- the development and fundamental application of space-based ultrahigh-precision atomic and other clocks.

The technologies used in fundamental-physics experiments (e.g. high-precision accelerometers), the requirements on spacecraft, and the high degree of spacecraft/experiment interrelationship are distinctly different from missions in Solar System exploration and astronomy. For example, fundamental-physics spacecraft typically have to be in purely gravitational orbits, i.e. they have to be drag-free.

ESA's Call for Mission Proposals for the second medium-size project (M2) within the framework of ESA's Long-Term Space Science Programme 'Horizon 2000' was issued on 15 June 1989. It specifically also asked for proposals in fundamental physics. In response to this Call, five proposals were submitted in the field of fundamental physics (out of a total of 22):

- a mission to detect and observe gravitational waves
- a Satellite Test of the Equivalence Principle (STEP)
- Newton, a man-made 'planetary system' in space to measure the Constant of Gravity G
- GRAVCON, an experiment to measure the Constant of Gravity G
- APPLE, a proposal for the determination of the Fifth Force and the detection of Dark Matter in the Universe.

Of these five proposals, STEP and Newton were given the highest priority by the 'Ad-hoc Working Group on Fundamental Physics'. However, only STEP was selected by the SSAC on 9 February 1990 for study at Assessment Level. Later, in mid-1990, the STEP payload was enlarged by incorporating the scientific objectives of Newton and GRAVCON.

The renewed interest in fundamental physics may have been triggered in ESA by the curiosity about the 'fifth force', but what was not perhaps fully realised at that time was that, unlike in the 1970s, in the early 1990s the technologies for carrying out meaningful fundamental-physics missions had in the meantime become available. Key technologies, such as high-precision accelerometers, drag-free control using He-proportional thrusters or small ion thrusters, ultra-stable lasers in space, He-dewars, high-precision displacement sensors (SQUIDs), magnetic spectrometers, small lightweight H-maser clocks and atomic clocks using laser-cooled caesium atoms had been developed and were either already space-qualified or about to be space-qualified. Already in 1976, NASA sent an H-maser clock to an altitude of 18 000 km on a suborbital rocket flight (Gravity Probe A) to test Einstein's 'clock gravitational frequency shift' formula (the clock on the rocket appears to run faster than the one on the ground). NASA's Gravity Probe B (GP-B), to be launched in October 2000 into a polar orbit at 650 km altitude, will test two predictions of Einstein's theory of General Relativity — geodetic precession and frame-dragging precession — to 1 part in 10^5 and 400, respectively. For GP-B several key technologies had to be developed which are now available for other fundamental-physics missions.

The STEP mission

STEP was proposed to ESA in November 1989 by a team of scientists from Europe and Stanford University. Work at Stanford on the design of the STEP experiment had already begun much earlier, in 1971. The original proposal comprised three accelerometer systems accommodated in a cryogenic dewar to test the Equivalence Principle to a precision of 1 part in 10^{17}, along with a limited geodesy co-experiment and an aeronomy co-experiment. The boil-off helium from the dewar would be used to feed small proportional thrusters to compensate for the drag of the residual atmosphere at orbital (~ 500 km) altitude.

This proposal was studied as an ESA/NASA collaborative project in 1991 at Assessment level and in 1992 at Phase-A level. In the end it was not selected as the M2 project and was subsequently re-proposed in May 1993 as a candidate for the third medium-size project (M3). During the M3 cycle, STEP was studied again at Assessment and Phase-A levels, this time as a European-only project. Again, it was not selected as a flight project because at the time of the selection (April 1996) there were other proposals in the scientific community aimed at achieving STEP's main scientific objective, a test of the Equivalence Principle, at much lower cost and even higher precision. A 20 M€ contribution by ESA to a NASA-led STEP project with a launch in 2004 is now included in ESA's Space Science Programme. ESA's contribution to the project is envisaged to be the Service Module and possibly a few other elements. The Service Module design is presently the subject of a four-month industrial study.

The Equivalence Principle postulates the equivalence between inertial and gravitational mass or, stated differently, that bodies of different mass and/or composition fall with the same acceleration in a gravitational field. This contention cannot be proven, it can only be tested to higher and higher precision. The most precise ground-based tests today have achieved a precision of 1 part in 10^{12}. Experiments on the ground are limited at this level because of unshieldable seismic noise and the weak driving acceleration. In space, this test could be done a factor 10^6 more precisely.

Einstein generalised the Equivalence Principle and made it the foundation of his theory of General Relativity. A violation of the Equivalence Principle at some level would either require a modification of Einstein's theory or constitute the discovery of a new force. There are, in fact, good reasons to believe that General Relativity is not the ultimate theory of gravity. Gravitation, electromagnetism and the weak and strong interactions are the four known fundamental forces of Nature. Einstein's theory of gravity, General Relativity, provides the basis for our description of the Big Bang, the cosmological expansion, gravitational collapse, neutron stars, black holes and gravitational waves. It is a 'classical', non-quantum field theory of curved space-time, constituting an as yet unchallenged description of gravitational interactions at macroscopic scales. The other three interactions are dealt with by a quantum field theory called the 'Standard Model' of particle physics, which accurately describes physics at short distances where quantum effects play a crucial role. But, at present, no realistic theory of quantum gravity exists. This fact is the most fundamental motivation for pursuing our quest into the nature of gravity.

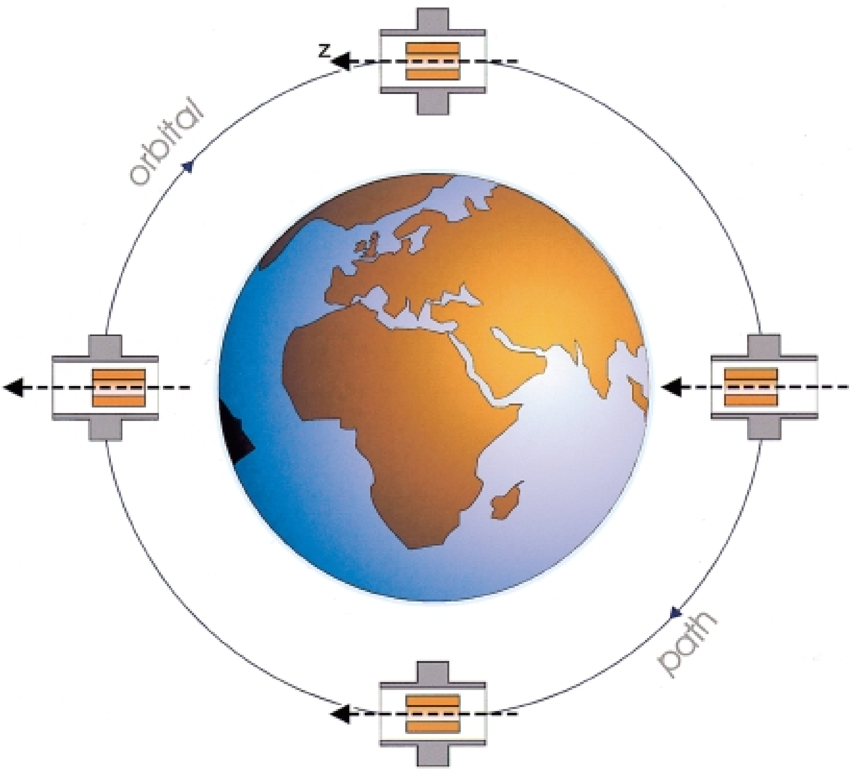


Figure 1. Relative motion of two concentric cylindrical test masses in the case of an Equivalence Principle (EP) violation. The masses are constrained to one-dimensional motion. In this example the inner test mass falls faster towards the Earth. The EP violation signal is periodic at orbital frequency

The Standard Model successfully accounts for all existing non-gravitational particle data. However, just as in the case of General Relativity, it is not a fully satisfactory theory. Its complicated structure lacks an underlying rationale. Even worse, it suffers from unresolved problems concerning the violation of the charge conjugation parity symmetry between matter and antimatter and the various unexplained mass scales. Purported solutions of these shortcomings typically involve new interactions that could manifest themselves as apparent violations of the Equivalence Principle.

The truly outstanding problem remains the construction of a consistent quantum theory of gravity, a necessary ingredient for a complete and unified description of all particle interactions. Super-string theories — in which elementary particles would no longer be point-like — are the only known candidates for such a grand construction. They systematically require the existence of spinless partners of the graviton: dilatons and axion-like particles. The dilaton, in particular, could remain almost massless and induce violations of the Equivalence Principle at a level that — albeit tiny — may well be within STEP's reach.

The simplest way of testing the Equivalence Principle would be to throw two masses (e.g. spheres) of different composition from a high tower and measure any difference in the arrival time on the ground (taking into account the effect of air resistance). Galileo was, for a long time, reputed to have performed such an experiment from the Leaning Tower of Pisa although, as we know today, he never actually did so himself.

The STEP Project is the modern version of this experiment. The test masses are placed inside a satellite in low-Earth orbit, where they 'fall around the Earth' (Fig. 1). In this way, the test masses never strike the ground, and any difference in the rate of fall can build up over a long time period. In Earth orbit the signal is periodic and the experiment can be repeated several thousand times during the mission lifetime. However, even at 500 km altitude, the density of the Earth's atmosphere is sufficient to brake the satellite and to disturb the experiment. The satellite must therefore compensate for the braking by firing a combination of proportional thrusters so that the satellite is 'drag-free' and the test masses inside are free-floating and follow a purely gravitational orbit.

The test masses are in the form of hollow cylinders whose axes are centred on each other to eliminate any disturbances from the Earth's gravity gradient. Any differential motion of these two test masses is sensed by coils coupled to SQUID (Superconducting Quantum Interference Device) magnetometers, forming a super-conducting differential accelerometer. The SQUIDs can detect any differential motion of the two typically 500 g test masses with a sensitivity of 10^{-15} m, the diameter of the nucleus of an atom. To sample a variety of test-mass materials, STEP carries four such differential accelerometers.

The payload chamber is accommodated inside a superfluid helium dewar, which cools the payload to 1.8 K. The cryogenic dewar is mounted below a three-axis-stabilised, drag-free spacecraft (Fig. 2) which uses the helium boil-off from the dewar to feed a number of proportional thrusters to compensate for the residual air drag at orbital altitude. STEP's orbit is circular and at low altitude (~500 km). A Sun-synchronous (i.e. almost polar) orbit was chosen to avoid eclipses, thus providing a highly stable thermal environment throughout the mission lifetime of 6-8 months. During flight, the spacecraft rotates about its long axis at a small multiple of the orbital frequency, in order to spectrally shift the science signal from orbit-fixed systematic error sources.

The LISA mission

The primary objective of the LISA (Laser Interferometer Space Antenna) mission is the detection and observation of gravitational waves from massive black holes and galactic binaries in the frequency range 10^{-4} – 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 ground-based interferometers LIGO, VIRGO, TAMA 300 and GEO 600, with baselines from 0.3 to 4 km and the LISA interferometer in space, with a baseline of 5 million km, 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.

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 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.

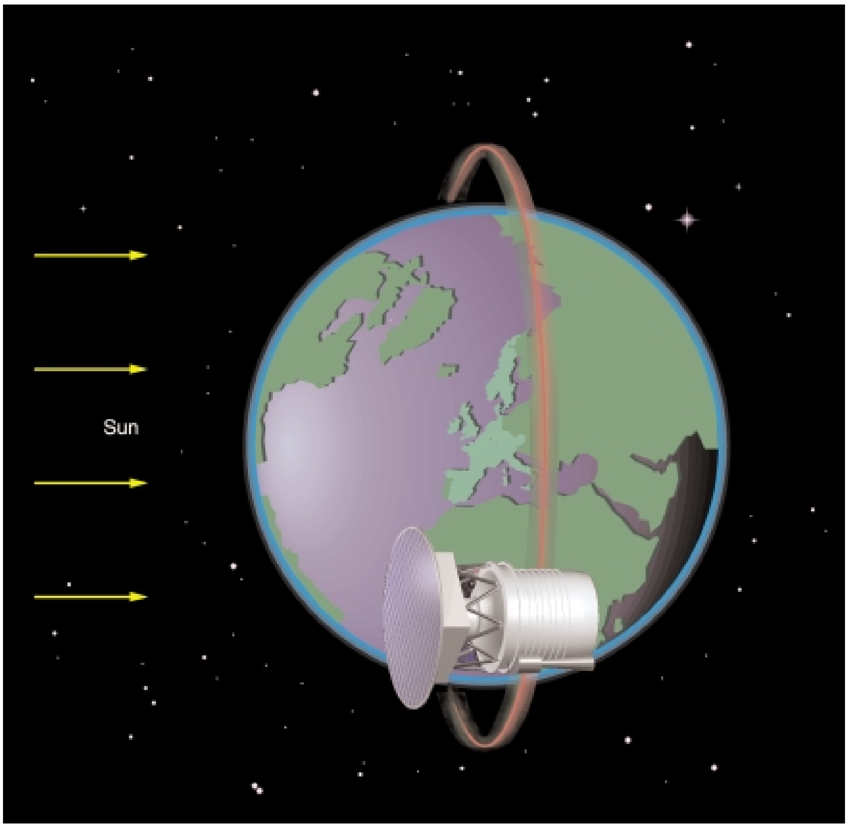


Figure 2. The STEP spacecraft in low-Earth, Sun-synchronous orbit at 500 km altitude

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

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

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

Gravitational waves distort space-time: 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 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 have been and will be made to measure these distance fluctuations) or the distances between shielded proof masses inside widely separated spacecraft, 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 does not 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 metre here on Earth with kilowatts of gravitational radiation intensity. The resulting length changes, though, are very small because space-time is an extremely stiff elastic medium, so that extremely large energies are needed to produce even minute distortions.

It is because of the extremely small distance changes that gravitational waves have not yet been detected. However, with the LISA space interferometer, orbiting the Sun at 1 AU, millions of sources will be detected in one year of observation with a signal-to-noise ratio of 5 or better. The LISA mission comprises three identical spacecraft located $5x10^6$ km apart forming an equilateral triangle (Fig. 3). 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 20º behind the Earth. The plane of the triangle is inclined at 60º 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.

While LISA is basically a giant Michelson interferometer in space, the actual implementation in space is very different from a laser interferometer on the ground and is much more reminiscent of a 'spacecraft tracking' technique, but then 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 that way. Instead, analogous to an RF

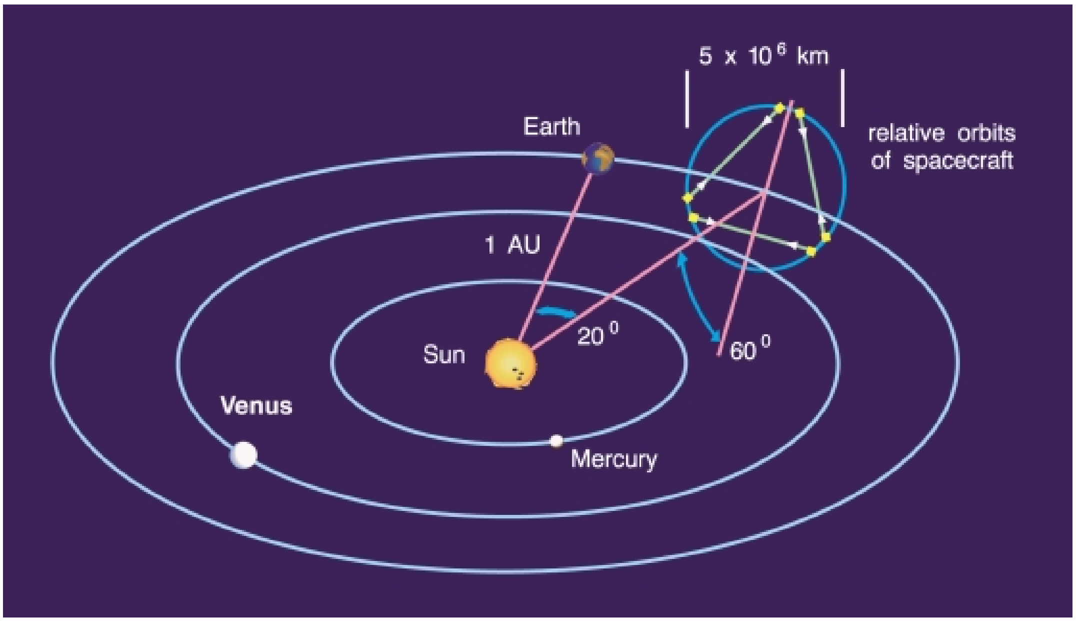


Figure 3. Schematic of the LISA configuration (not to scale). Three distant satellites linked by infrared laser beams form a giant 5 million km triangular interferometer, which is sensitive to fluctuations in the separations between the satellites caused by gravitational waves. The plane of the triangle is tilted by 60º out of the ecliptic

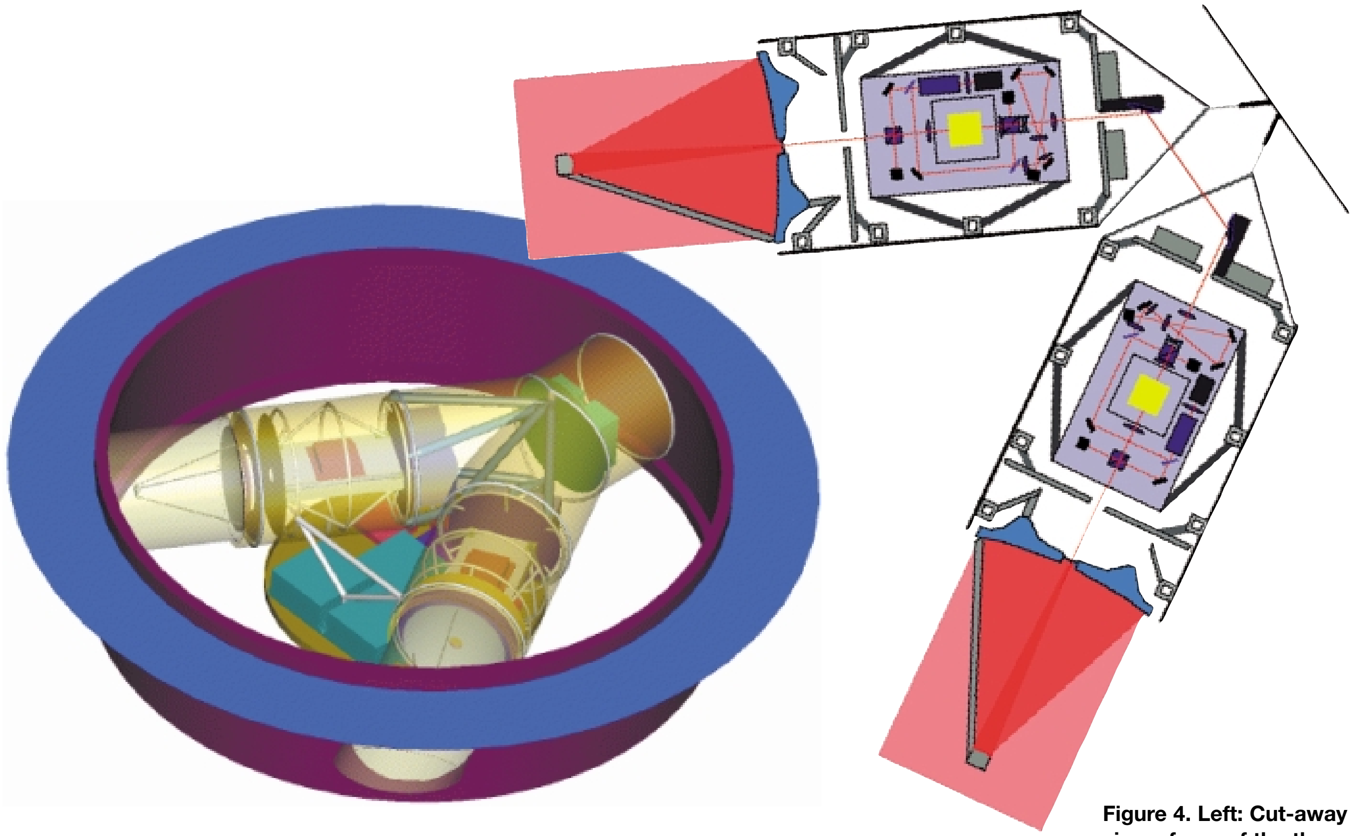


Figure 4. Left: Cut-away view of one of the three identical LISA spacecraft. The main structure is a ring with a diameter of 1.8 m and a height of 0.48 m, made from graphite-epoxy for low thermal expansion. A lid on top of the spacecraft is removed to allow a view of the Y-shaped payload.
Right: Detail of the payload on each Y-shaped LISA spacecraft, consisting of two identical telescopes and two optical benches each housing a drag-free test mass (the yellow cubes in the centres)

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.

Each spacecraft contains two optical assemblies (Fig. 4). The two assemblies on one spacecraft each point towards an identical assembly on each of the other two spacecraft. A 1 W infrared laser beam is transmitted to the corresponding remote spacecraft via a 30-cm aperture f/1 Cassegrain telescope. The same telescope is used to focus the very weak beam (a few pW) coming from the distant spacecraft and to direct the light to a sensitive photodetector, where it is superimposed with a fraction of the original local light. At the heart of each assembly is a vacuum enclosure containing a free-flying polished platinum-gold cube, 4 cm in size, referred to as the 'proof mass', which serves as an optical reference ('mirror') for the light beams. A passing gravitational wave will change the length of the optical path between the proof masses of one arm of the interferometer relative to the other arm. The distance fluctuations are measured to sub-Angstrom 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.

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} m Hz$^{-1/2}$ in the measurement band) centred on their respective proof masses to reduce spurious local noise forces. This is achieved by a 'drag-free' control system, consisting of an accelerometer (or inertial sensor) and a system of ion thrusters. Capacitive sensing is used to monitor the relative motion between each spacecraft and its test masses. These position signals are used in a feedback loop to command micro-Newton ion-emitting proportional thrusters, to enable the spacecraft to follow its test masses precisely and without introducing disturbances in the bandwidth of interest. The same thrusters are used for precision attitude control relative to the incoming optical wave fronts.

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

LISA was proposed to ESA in May 1993 in response to ESA's Call for Mission Proposals for the third Medium-Size Project (M3). The proposal was submitted by a team of American and European scientists who envisaged LISA as an ESA/NASA collaborative project. The mission was conceived as comprising four spacecraft in a heliocentric orbit forming an interferometer with a baseline of $5x10^6$ km.

LISA was selected for study as an ESA-only project, but it became clear quite early in the Assessment Phase that it was not likely to be a successful candidate for M3 because the cost for an ESA-only LISA considerably exceeded the M3 limit of 350 M€. In December 1993, LISA was therefore re-proposed to ESA, this time as a Cornerstone project for 'Horizon 2000 Plus', involving six spacecraft in a heliocentric orbit with a pair of spacecraft at each vertex of an equilateral triangle. Both the Fundamental Physics Topical Team and the Survey Committee realised the enormous discovery potential and timeliness of the LISA Project and recommended it as the Third Cornerstone for 'Horizon 2000 Plus'. However, the Survey Committee also noted that the inclusion of LISA as a Cornerstone *'will require a modest increase in the funding of the ESA Scientific Programme beginning in 2001'*.

Being a Cornerstone in ESA's Space Science Programme implies that, in principle, the mission is approved and that funding for industrial studies and for technology development is provided right away. The launch year, however, is dictated by scientific priorities and the availability of funding. Considering realistic funding scenarios for ESA's Space Science Programme, LISA could probably only be launched after the other two Cornerstones of Horizon 2000 Plus, namely Mercury Orbiter and Interferometry (either GAIA or IRSI), i.e. after 2017. Because of the large inequality between the ESA and NASA science budgets, it must then be expected that even the most optimistic opportunity for ESA to launch the LISA Cornerstone will be pre-empted by an earlier NASA mission. For this and several other reasons, it was decided in January 1997 to put LISA on an equal footing with the other two Cornerstones in Horizon 2000 Plus, with a possible launch as early as 2009. A launch around 2009 would be ideal as it is around that time that the first detection of gravitational waves by the ground-based interferometers in the high-frequency regime can be expected. There still remained, however, the problem of LISA's cost exceeding the Cornerstone limit, with the cost of the six-spacecraft project initially estimated to be about 800 M€.

In 1996 and 1997, the LISA team made several proposals as to how the cost might be drastically reduced without compromising the science, the most important being the reduction in the number of spacecraft from six to three. This was achieved by replacing each pair of spacecraft at the vertices of the triangular configuration by a single spacecraft carrying essentially two identical instruments in a Y-shaped configuration. With these and a few other measures, the total launch mass could be reduced from 6.8 to 1.4 t and the total cost could be reduced accordingly (to $330 M, excluding the payload, according to a recent JPL Team-X cost estimate, a figure not yet confirmed by ESA).

Perhaps most importantly, the LISA Study Team and ESA's Fundamental Physics Advisory Group (FPAG) proposed in February 1997 that the LISA mission be carried out in collaboration with NASA. This makes sense not only from a cost-saving point of view, but also because the LISA team is an international one and the LISA mission-definition work was carried out jointly between Europe and the USA. The FPAG recommended limiting the cost to ESA to 150 M€ in this collaboration, as was done on a smaller scale with a cost cap of 20 M€ for STEP.

Presently, ESA is carrying out a six-month industrial system-level study, with support from the LISA Science Team of about 30 scientists. On the US side, a LISA Mission Definition Team consisting also of about 30 scientists has been formed. Both teams have partial team membership overlap to ensure that both teams work towards defining the same mission. As a first activity, in February 1999 the US team agreed on a Technology Plan with a total budget of $33 M to be implemented by the LISA Pre-Project Office at JPL in the next couple of years.

The need to demonstrate key LISA technologies in space

When LISA was presented together with the other three Cornerstone missions in 'Horizon 2000 Plus' to the scientific communities in the ESA Member States in 1995, prior to the Ministerial Conference in Toulouse, several Delegations expressed concern about the testability of key LISA technologies on the ground, remarking: *'It is very risky to launch a mission costing nearly 800 M€ without having a high degree of confidence that the key technologies will work; however, testing these technologies on the ground under 1 g conditions is not possible'.*

Similar concern was also raised by ESA's Science Programme Committee (SPC) in May 1996: *'The technology required for a successful LISA mission is extremely demanding and, furthermore, some key subsystem elements (e.g. drag-free control,* *zero-g accelerometry) can only be tested in space. The overall technical feasibility of LISA still needs to be demonstrated.'*

In February 1997, during a meeting at JPL, the LISA team came to the conclusion that a technology-demonstration mission is a necessary precursor to the LISA project. By that time it had become clear that the cost for such a mission could be kept relatively low. The LISA team, together with their US colleagues, therefore submitted a detailed proposal to ESA in May 1998 for a technology-demonstration mission (Fig. 5) that would test:

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

In December 1998, an updated proposal was submitted which was broader in scope, also addressing key IRSI and XEUS technology-demonstration needs. This revised proposal suggested a collaboration with NASA on ST-5 (previously called DS-5), with a launch in 2003. For the ST-5 slot of $28 M, there are currently three candidates: solar-sail technology, a cluster of nano-satellites, and a Disturbance Reduction System. The latter would include the testing of key technologies for LISA and would also involve some aspects of space interferometry for imaging interferometry projects. One of these three candidate projects will be selected by NASA in late July 1999, following parallel six-month studies at Phase-A level. ESA was recently invited by NASA to consider a possible collaboration on the Disturbance Reduction System. In the most likely collaborative scenario, ESA would contribute all or part of a small drag-free satellite (with a cost cap of 10 M€) which would carry the relevant technology items from both ESA and NASA, with NASA providing the launch and mission operations.

Ideally, such a technology-demonstration mission should be launched about five years before LISA. A launch much earlier would not allow full utilisation of the latest technologies to be tested, while a launch much later would not allow full advantage to be taken of the knowhow obtained during the technology-demonstrator flight in the design phase of the LISA mission. To preserve the possibility of a aunch of the NASA/ESA collaborative LISA mission in 2009, the technology-demonstration mission should therefore ideally be launched in the 2003-2005 time frame.

On the European side, a technology-demonstration mission addressing the technology for both the LISA and a multi-satellite infrared interferometry mission is foreseen for launch in 2005 as the second in a series of Small Missions for Advanced Research in Technology (SMART-2). ESA would nevertheless be interested in exploring the possibility of carrying out this mission, at least in part, in cooperation with NASA at an earlier time if ESA's technology needs could be realised in a more cost-effective manner.

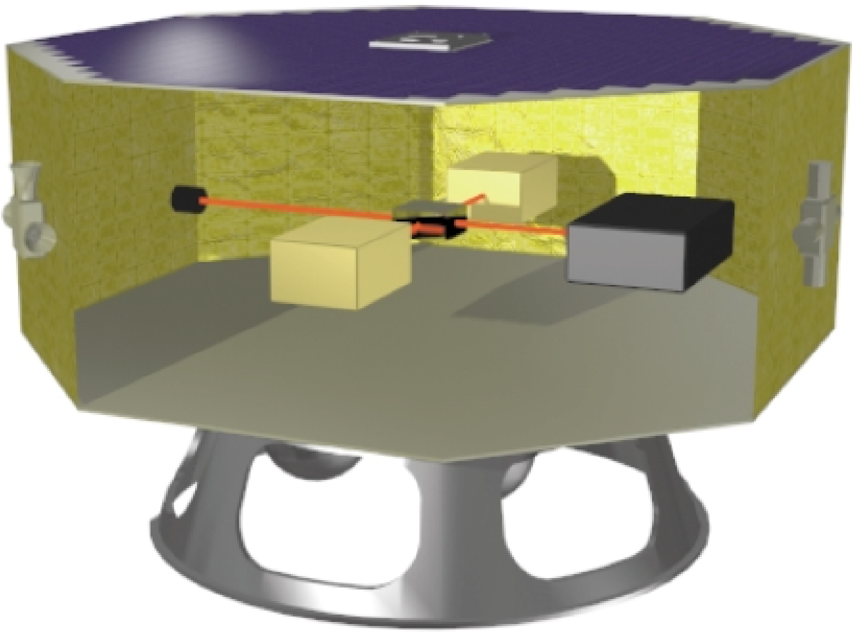


Figure 5. Cut-away view of the proposed LISA technology-demonstration spacecraft, showing two test masses (4 cm Pt-Au cubes, highlighted in yellow) with laser metrology

Next-generation fundamental-physics missions

In response to the Call for Mission Ideas for Horizon 2000 Plus in 1993, ESA received 28 proposals for fundamental-physics missions, which were subsequently evaluated by Topical Team 5 (TT-5). This constitutes the most complete survey of the possibilities of space for fundamental physics so far. Based on their scientific objectives, the proposals were categorised into six groups. One group was aimed at testing General Relativity and its alternative theories of gravity by measuring the so-called 'PPN parameters' (explained below), while another group of proposals searched for new particles in space. One in each group was selected and briefly described below; apart from STEP and LISA, these two proposals consistently received the highest rankings in two evaluations (by the FPAG for M3 and by TT-5 for Horizon 2000 Plus).

Testing theories of gravity (and General Relativity in particular) has received renewed attention especially for the cosmological consequences of possible violations. A large class of alternative scalar-tensor theories contain a cosmological attractor mechanism toward General Relativity. Approximate estimates based upon inflationary cosmologies indicate that in the present epoch General Relativity provides indeed an excellent description of gravitation, accurate to a level of 10^{-7} — 10^{-5}. However, due to the uncertainties of the theoretical estimates, every experiment able to improve the present accuracies is significant. If a discrepancy is confirmed, it would indicate that mass does not curve space as predicted by Einstein's theory. Such a result would be a milestone in our knowledge of the fundamental laws of the Universe. A measurable violation could indicate the type of scalar-tensor theory evolution of the Universe. In the weak-field, small-velocity approximation, theories of gravity are classified using the Parametrised-Post Newtonian formalism (PPN). In the simplest case, this classification is based upon just two parameters, called β and γ. The former measures the amount of nonlinearity in the superposition law for gravity, and the latter the space curvature produced by a unit mass.

The proposed SORT (Solar Orbit Relativity Test) mission is aimed at improving, by four orders of magnitude, the measurement of the PPN parameter γ by measuring the deflection and the time delay of laser light passing close to the Sun. γ is a measure of the strength of the coupling of mass to the curvature of space; in General Relativity γ =1. Present experimental limits on $|\gamma-1|$ are about 10^{-3}. Measurements of γ at the 10^{-7} level have considerable theoretical significance because generic tensor-scalar theories of gravity predict a natural weakening during the cosmological expansion of the observable deviations from General Relativity down to the level of 10^{-7}. SORT proposes to combine a time-delay experiment (via laser signals sent from the Earth and recorded by precise clocks on board two satellites orbiting the Sun) with a light-deflection experiment (interferometric measurement on Earth of the angle between the two light flashes emitted from the same satellites). SORT is the modern version of the SOREL mission studied by ESA in 1970/71. For comparison, SOREL aimed at determining γ to a precision of 5×10^{-4} and β to 5×10^{-3}.

The proposed SSPIN (Satellite Search for Pseudoscalar Interactions) mission is designed to search for a weak spin-dependent force at the level of $g_p \bullet g_s = 6\times10^{-37}$ (where g_p and g_s are spin-coupling constants) at the range of 1 mm, 10 orders of magnitude better than is currently achievable on the ground. This is possible by placing a highly sensitive payload at cryogenic temperature in a drag-free satellite in a geosynchronous orbit. This experiment was previously included in the M2- and M3-STEP payloads and studied for several years. SSPIN would be three orders of magnitude more sensitive than the MSC experiment on M3-STEP, which would put us in the realm of actually detecting the axion, a hypothetical, weakly interacting, massive particle which has been postulated to reconcile the theoretically allowed level of charge conjugation parity (CP) violation in the strong interactions, with the current upper limit to the electric dipole moment of the neutron. It has also been invoked as a possible candidate for the elusive 'Dark Matter' in the Universe.

Both missions rely on drag-free control and high-precision accelerometers. In addition, SSPIN needs cryogenics and SQUID sensing. These techniques will already have been developed for STEP, which is therefore an ideal testbed not only for LISA, but also for fundamental-physics missions in the more distant future. As these missions will probably only fly after 2010, further improvements in technology can be expected which will make them even more exciting for the physics community. As fundamental physics is a very young field, many more competitive ideas for missions can be expected to emerge by the time the next fundamental-physics mission will be selected after STEP and LISA.

Fundamental physics on non-dedicated ESA missions

Existing and future ESA Solar System exploration and astronomy missions also offer attractive possibilities for fundamental physics. Precise, two- or three-way tracking of interplanetary probes, such as the Ulysses and Cassini spacecraft, can set upper limits on low-frequency gravitational waves. These appear as irregularities in the time-of-communication residuals after the orbit of the spacecraft has been fitted. The irregularities have a particular signature. Searches for gravitational waves have produced only upper limits so far, but this is not surprising: their sensitivity is far short of predicted wave amplitudes. This technique is inexpensive and well worth pursuing, but will be limited for the foreseeable future by some combination of measurement noise, the stability of the frequency standards, and the uncorrected parts of the fluctuations in propagation delays due to the interplanetary plasma and the Earth's atmosphere. Consequently, it is unlikely that this method will realise an r.m.s strain sensitivity much better than 10^{-17}, which is six orders of magnitude worse than that of the space-based LISA interferometer.

During conjunctions, the radio signal passing close to the Sun experiences a measurable time delay and frequency shift, which allows one to determine the space curvature parameter γ. The radio-science investigation on Cassini will allow us to test this prediction to a precision of $\sim 10^{-4}$. The best experiment to date was performed by the Viking Mars Lander mission in 1971, which achieved a precision of 2×10^{-3}.

A Mercury Orbiter would allow γ to be measured to a precision of $\sim 2 \times 10^{-5}$ and β to a precision of 7×10^{-4}. On the astronomy side, Hipparcos has already achieved a precision of 10^{-3} for γ and GAIA is expected to achieve a two orders of magnitude improvement over that.

Fundamental-physics experiments on the ISS

Already under development is the AMS (Alpha Magnetic Spectrometer) to be flown on the International Space Station (ISS) in 2004/5. There are also two precursor flights on the Space Shuttle; one has already taken place successfully in 1998, the other will take place in a few years' time. A major objective of the AMS is the search for antimatter in the Universe. According to standard theories, at the very beginning there should be as much matter as antimatter, but the antimatter has not yet been detected. The AMS is a US-led project with most contributions coming from Europe.

Also under development for flight on the ISS is the PHARAO (Project d'Horloge Atomique par Refroidissement d'Atomes en Orbite) clock, which uses laser-cooled caesium atoms to improve the accuracy of the time frequency standard by two orders of magnitude. The French PHARAO atomic clock is complemented on the ISS by a Swiss hydrogen maser clock to provide a longer-term frequency standard; together they form the Atomic Clock Ensemble in Space (ACES). The ultra-high precision of PHARAO will allow 'new records' to be set for two fundamental-physics constants:

– determination of the space-curvature parameter γ to 1 part in 10^5 (two orders of magnitude improvement)
– determination of the gravitational redshift to 3 parts in 10^6 (almost two orders of magnitude improvement over the Gravity Probe A suborbital flight in 1976).

Proposed for flight on the ISS, but not yet accepted, is a test of the Equivalence Principle using protons and antiprotons — the Weak Equivalence Antiproton Experiment (WEAX). In space this test can be done three orders of magnitude more precisely than on the ground.

Fundamental Physics as an emerging space-science discipline

It is now widely understood that the scientific objectives of fundamental-physics missions are distinctly different — *questioning* the laws of Nature — from the scientific objectives of astronomy and Solar System missions — *accepting and applying* the laws of Nature. Also, the technologies used in fundamental-physics missions (the spacecraft typically carry proportional thrusters and high-precision accelerometers to allow drag-free operation), the requirements on spacecraft design (e.g. no moving parts, no deployable solar arrays, extremely high thermal stability) and the high degree of spacecraft/experiment inter-relationship (e.g. the signals from the payload are used to control the spacecraft) are distinctly different from Solar System exploration and astronomy missions.

Fundamental-physics experiments on the ground are limited in achievable precision. Many tests can be carried out in space with much higher precision (e.g. STEP: 10^6 better), whilst some observations can only be made in space (e.g. gravitational waves at low frequencies). It is therefore no surprise that the number of proposals received in response to ESA's Calls for Mission Proposals has been steadily growing: 5 (out of 22) proposals for M2, 16 (out of 48) proposals for M3 and 28 (out of ~100) proposals for Horizon 2000 Plus. Roughly a quarter of all mission proposals have been submitted in the past and are likely to be submitted in the future by the fundamental-physics community.

Fundamental Physics in Space is a rapidly growing new field with enormous discovery potential in physics, and a major technology driver. ESA recognised this in early 1994 by setting up the Topical Team on Fundamental Physics (TT-5) and in December 1994 by setting up the Fundamental Physics Advisory Group (FPAG). NASA followed in 1997 by setting up the Gravitational and Relativistic Physics Panel and the Fundamental Physics Discipline Working Group. In 1996, COSPAR decided to create a new Scientific Commission (SC-H) to cater for the needs of the fundamental-physics community. ESA's Long-Term Space Science Programme was fully described in 1984 in 'Space Science: Horizon 2000' and in 1995 in 'Horizon 2000 Plus'; both publications include chapters on fundamental physics, the latter describing a Cornerstone mission and a number of medium-size and small missions. However, it is also stated in the latter publication that the inclusion of the fundamental-physics discipline will require a modest increase in the funding of ESA's Space Science Programme.

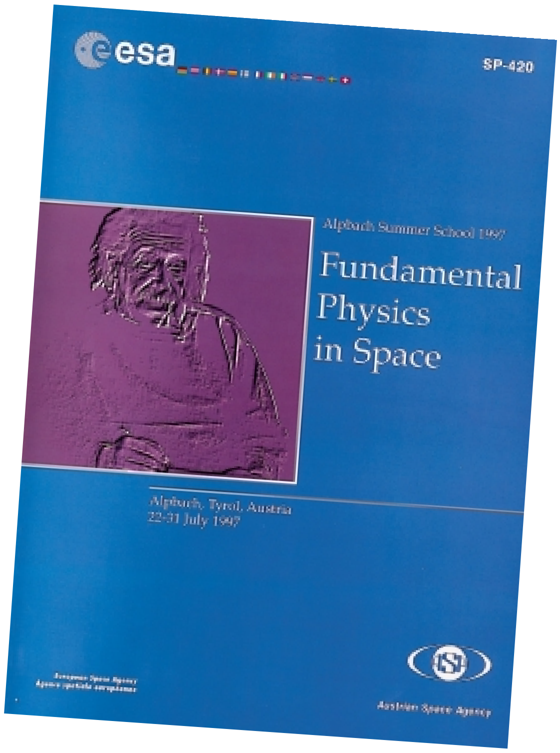
NASA has recently published a 'Roadmap for Fundamental Physics in Space', which represents a long-term framework within which to establish and advocate NASA's future research and technology development programme in fundamental physics. It identifies three sets of focussed scientific investigations (called 'campaigns'), which comprise a scientifically rewarding, technologically challenging, flexible and exciting programme of fundamental-physics research in space. These campaigns are:

- Gravitational and Relativistic Physics
- Laser Cooling and Atomic Physics
- Low-Temperature and Condensed-Matter Physics.

The Roadmap describes a number of missions or experiments in each of these campaigns. The Gravitational and Relativistic Physics Campaign describes six missions, among them the NASA/ESA collaborative STEP and LISA missions.

Fundamental physics as a discipline in its own right is also now recognised by many European space agencies. CNES defined in 1993 a new scientific theme 'Fundamental Physics' and set up a Fundamental Physics Working Group. ASI has recognised the emergence of this new discipline through the appointment of a representative specifically for fundamental physics in its Scientific Council. PPARC has recently set up a science committee and is already demonstrating its interest in fundamental physics by encouraging submissions on gravitational-wave detectors in space. DLR has identified fundamental physics as a scientific discipline with a 'high priority in the future' and has explicitly expressed a wish to participate in LISA and STEP. The Austrian Space Agency (ASA) organised (together with ESA) the 1997 Alpbach Summer School 'Fundamental Physics in Space' (Proceedings available as ESA SP-420).

Following a recommendation by the ESA Space Science Department (SSD) Advisory Committee in 1997 (a group of outside senior scientists who review SSD's activities every two years), a Fundamental Physics Office was set up in SSD in mid-1998, initially with two staff scientists, in addition to the already existing Solar System, Astrophysics and Earth Sciences Divisions.



Conclusion

Considering that the required technologies are now mature, that there is a sizeable community in Europe in need of space flights (a quarter to a third of all proposals come from that community), and that fundamental physics in space is now recognised by many space agencies, it is only a question of time and money until Europe realises its first fundamental-physics mission.