Fundamental physics in space

What better way of launching science in the new millennium than embarking on a programme of fundamental physics research in space? *Maurice Jacob* looks at existing plans and new possibilities.

The European Space Agency's LISA (Laser Interferometer Space Antenna) project is the flagship fundamental physics experiment in space. The LISA mission will consist of three spacecraft that will form an equilateral triangle with a distance of 5 million km between any two spacecraft. Gravitational waves passing through the solar system will generate small changes in the distances between each of the spacecraft. The distance changes can be made very accurately using laser interferometry.

Addressing fundamental physics questions in space is far from a new idea. In particular, the fascinating prospects of testing Einstein's theory to an unprecedented accuracy using the quietness of space environment and long observation times have long been considered. However, it was soon realized that flight conditions would have to be controlled to a very high precision.

In Europe, the 1971-1979 Fundamental Physics Panel, chaired by Herman Bondi, fully recognized the great interest of such missions but concluded that they were "projects for the 21st century". We are now at the eve of that century.

European plans

In 1989 the European Space Agency (ESA) announced a call for mission proposals also open to fundamental physics. By 1993, fundamental physics proposals represented close to one-third of all of those received. ESA dealt with them via ad hoc committees, and in

A NASA/JPL conference on Fundamental Physics in Space, held in Washington DC, brought together the chairman and three vice-chairmen of Commission H of the International Committee for Space Research (COSPAR). Left to right: vice-chairman Maurice Jacob (also chairman of ESA's Fundamental Physics Advisory Group and the author of this article), chairman Francis Everitt of Stanford, vice-chairman Guenter Albers of Santa Barbara (also chairman of NASA's Fundamental Physics Discipline Working Group) and vice-chairman Stefano Vitale of Trento.

1994 a major project, Laser Interferometer Space Antenna (LISA), was listed among the key "cornerstone" elements of the Horizons 2000 programme (the ESA equivalent of CERN's LHC programme). Horizons 2000 projects ESA scientific activities up to and beyond the year 2010.

In 1994, ESA created a special Fundamental Physics Advisory Group (FPAG) to complement the established Astronomy Working Group and the Solar System Working Group.

In 1996, COSPAR (the international Committee for Space Research) created a new commission for fundamental physics, Commission H. In 1997 the Alpbach Summer School provided a useful and extensive overview of prospects as seen from Europe. The proceedings (ESA-SP-420) are a reference document for the new community working in that domain. So is the more recent Fundamental Physics Road Map established by NASA.

US fundamental physics in space started with microgravity

The Alpha Magnetic Spectrometer (AMS), the pioneer major particle physics experiment for space, had a shakedown flight aboard the Space Shuttle Discovery in 1998. It is seen here in the Shuttle's payload bay.

research associated with manned space flights and, in particular, the study of helium superfluidity, to be complemented by the study of laser-cooled atoms. This was eventually extended to gravity. The important mission Gravity Probe B, testing the frame-dragging effect around the rotating earth, is soon to fly. This domain of research is monitored by NASA's Fundamental Physics Discipline Working Group.

While fundamental physics at ESA did not initially include micro-gravity, things have developed in that direction with FPAG interest for the ACES mission. With its combination of a laser-cooled caesium clock and an H-maser, this should provide the most precise clock ever (accurate to 10^{-16}). This is now approved for the International Space Station.

Interest developed for Satellite Test of the Equivalence Principle (STEP) to achieve 10^{-18} accuracy (the present ground-based limit is 10^{-12}) with a cryogenic system orbiting the Earth. There was also considerable ESA interest and, if everything goes well, this mission could fly in around 2004 as a NASA-led project with strong ESA participation. In the opposite transatlantic direction, there is now a strong US interest in LISA. An ESA-NASA collaboration on LISA could advance the project by a decade to around 2009.

At present, LISA is the flagship fundamental physics experiment. The LIGO terrestrial search for gravitational waves using laser interferometry aims for phenomenal accuracy and was described by Riccardo DeSalvo in the March issue ("The quest for gravitational waves" p10).

A space experiment is in principle very similar, but could extend over several millions of kilometres and would focus on low frequencies (10^{-2} to 10^{-4} Hz). Ground-based detectors are blind to anything below about 10 Hz because of gravitational noise, and they have to focus on high frequencies (10^2 to 10^4 Hz) looking for signals from supernovae and the demise of compact binary stars.

Gravity waves in space

A spaceborne experiment would be sensitive to permanent emission from compact binaries (of the Hulse-Taylor type). Thousands of these (black hole, neutron star and white dwarf binaries) should be detectable in our galaxy. Other viewable phenomena would include the formation, accretion and merging associated with the very massive black holes (1 to 10 million solar masses) known to exist at the centre of most galaxies.

The typical emission frequency of a black hole is inversely proportional to its mass, and very large ones should be within range of LISA anywhere in the universe. Spaceborne experiments could thus study the strong gravity of very compact objects, while ground-based studies will be looking for effects resulting from the Big Bang, cosmic strings, etc. Both terrestrial and spaceborne studies open a new window to astronomy.

Whether or not gravitational waves are soon detected on Earth, they also have to be sought in space. A LISA mission at the end of the next decade would be particularly timely. Three satellites would provide two independent laser interferometers on a heliocentric orbit trailing the earth at 20° . The LISA Pre-Phase A Report (MPQ 233) is a detailed description of the mission, which has now entered industrial study.

However, such a mission relies on technology that has still to be proven in space (exhibiting, for example, very precise accelerometry, drag-free control and very stable laser interferometry). A small dedicated mission is planned in Europe under the codename ELITE and is entering industrial study. However, the most efficient route is probably via an ESA-NASA collaboration, as will also be the case for LISA. This, like other projects, will also benefit from positioning using an electric propulsion engine, which is soon to be tested by another small ESA mission.

Particle physics and space science

Some particle physicists are following with great interest the development of space projects. This is in particular the case for PLANCK, an ESA Horizons 2000 project, which should improve the COBE results on the cosmic microwave background by two orders of magnitude.

The past two decades have seen increased symbiosis between particle physics, astrophysics and cosmology, and this new field of astroparticle physics is now thriving. Probing the deep structure of matter through very-high-energy laboratory collisions reveals physics such as prevailed in the early universe. Today's laboratory experiments simulate conditions 10^{-10} s after the Big Bang.

With laboratory energies necessarily limited, the universe pro-

vides a fantastic range of extraterrestrial particle accelerators. The cosmic-ray spectrum extends up to 10^{12} GeV, so that a cosmic-ray proton colliding with a stationary nuclear proton gives a collision energy of about 10^6 GeV – about a hundred times that of CERN's LHC collider. However, collecting 100 cosmic-ray events per year at LHC collision energies would require a 10^4 sq. m detector. The LHC will provide 10^8 /s.

High-energy physics techniques have been developed for and applied to astrophysics. Examples include detectors of high-energy gamma rays and high-energy neutrinos. This work demands extensive data collection and data handling, in particular for the study of otherwise invisible astronomical objects via gravitational lensing. Other examples include the study of neutrino oscillations and the search for dark matter.

Spaceborne detectors

The pioneer major spaceborne particle physics detector is Alpha Magnetic Spectrometer (AMS), which was designed to search for antimatter in space but which also gives valuable information on the composition and distribution of cosmic rays (June p6). This information is welcome for the analysis of information on atmospheric neutrinos, where there are strong hints for neutrino oscillations.

AMS will be deployed on the International Space Station but has already had a test flight on the Space Shuttle and is preparing for a second. In the US the detector project involves a special collabor-

ation between NASA's space responsibilities and the Department of Energy, traditional paymasters of US particle physics. It relies on a worldwide collaboration of particle physics research centres with a strong European contribution.

More such experiments could appear soon, but their aims should be very specific because of cost. Examples include searches for new forces and probing gravity at small distances. In particular, a mission like STEP should provide checks on the sensitivity that should be attainable in future studies.

Another interesting direction involves searching for heavy stable remnants of the Big Bang, looking in particular for particle-antiparticle annihilations into gamma rays. Candidates are the lightest supersymmetric particles. However, there is little to say about the energy of the expected gamma ray and its intensity. Physicists should look out for other missions providing a ride.

The trail-blazing experiments cover cosmic rays, such as AMS, and X-ray and gamma-ray detectors, such as the Gamma Ray Large Area Space Telescope (GLAST), and particle physicists will enter space research via cross-fertilization between different fields, as has been the case for AMS and GLAST.

I see the future of high-energy physics in space more in terms of physicists than in terms of physics. Know-how developed in particle physics, and in particular for the LHC, is likely to find good use in space research: new tracking chambers, silicon detectors, radiation-hard electronics, bolometers and new photomultipliers. Also, the LHC experiments are likely to trigger a breakthrough in data collection and data handling – 10^{15} bytes per year, a million times the information stored in the human genome. Ingenious particle physicists, at ease with these new techniques, will be eager to apply them in space research.

In this spirit, the Joint Astrophysics Division of the European Physical Society and the European Astronomical Society is organizing a workshop on Fundamental Physics in Space and Related Topics at CERN next year under the joint sponsorship of ESA and CERN.

More collaboration

Researchers always complain about funding for basic research. In the post-cold-war era, governments seem to be saying: "What you do is interesting, but what is the rush? Couldn't you do it more slowly with smaller annual budgets?"

A minimum momentum has to be maintained, otherwise young people would cease to be attracted. More extensive collaborations would ensure new experiments and missions. This is particularly the case for fundamental physics, where the chance to fly a mission depends much on the cost to each partner.

Recent transatlantic contacts have involved compromise, but a door could be opening for extended Europe-US collaboration. ESA has endorsed the principle of such collaborations for fundamental physics. The dawn of a new millennium is a golden opportunity to embark on a new voyage of scientific discovery.

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