EPS POSITION PAPER

The Need for Space Flight Opportunities in Fundamental Physics

The European Physical Society (EPS) is an independent body funded by contributions from National Physical Societies, other independent bodies and individual members. The EPS has 39 Member Societies with over 100,000 members and can call on expertise in all areas where physics is involved. The declared aim of the EPS is to promote physics and help physicists in Europe.

This Position Paper appears in the World Year of Physics 2005 – an initiative of the EPS endorsed by UNESCO and the United Nations that celebrates the centennial of Albert Einstein's *annus mirabilis*.

1. The Aim of this Position Paper

This Position Paper encourages European physicists to make use of the advantages of performing physics experiments in space, and urges governments to strongly support the efforts in this field by ESA, the European Space Agency, and the national European space agencies, thereby securing Fundamental Physics as part of the European quest for space research for the foreseeable future.

2. Space Experiments Address the Foundations of Physics

Space experiments in relativistic gravitation test Einstein's theory of General Relativity, one of the major ingredients for understanding how the Universe became the way it looks and how it will evolve in the future. Such experiments may even discover new forces and particles beyond those currently known and contribute to the long-sought unification of the laws that govern them.

Einstein's theory of General Relativity is built on several assumptions about Nature. Examples are the absolute equality of inertial and gravitational mass, the universality of the gravity-induced shifts of collocated clocks, and the true constancy in space and time of fundamental dimensionless parameters of physical laws such as the electromagnetic fine-structure constant, its gravitational analogue and particle mass ratios.

Testing these assumptions requires measurements at the highest precision attainable in experimental physics. Such measurements are best carried out in space, where experiments can be performed in the low-gravity and low-noise environment of a drag-free spacecraft, and where one can draw on spans of space, and on changes in gravity potentials and gradients that go far beyond those available on the ground.

A breakdown of General Relativity's predictions or assumptions will signal the existence of previously unknown forces, i.e. of 'new physics' beyond the current Standard Model of the strong, electromagnetic and weak forces, and fundamental particles. The existence of new physics is suggested by the apparently contrived and complex structure of the Standard Model, by evidence for unknown forms of (dark) matter and energy in the Universe, and by the fact that the reconciliation of General Relativity and Quantum Theory within String Theory hints toward a rich spectrum of new phenomenological possibilities in gravity and particle physics.

Moreover, space experiments in laser cooling and atomic physics, in particular cooling atoms with lasers in the absence of gravity, will give us the opportunity to measure fundamental atomic forces and symmetries to a level of accuracy, which is out of reach on the ground. Such experiments may well hold clues to how quantum coherences are affected when going from the microscopic level to the macroscopic one.

3. Advantages and Needs of Carrying out Fundamental Physics Experiments in Space

Many Fundamental Physics experiments can be carried out in space with much higher precision than on the ground, opening up a realm where deviations from General Relativity can be expected. Moreover, some experiments can only be carried out in space.

Experiments in space benefit from a number of factors:

- *Large distances*: a gravitational wave observatory using a laser interferometer with a baseline of several million kilometres is only possible in space, opening up the window of low-frequency gravitational waves.
- *Reduced gravity*: microgravity (10^{-4} g to 10^{-6} g levels) enables many new laser-cooling and condensed-matter physics experiments; but even greater will be the improvement possible by drag-free operation (10^{-10} g or lower) of instruments sensitive to torques or displacement forces.
- *Isolation from seismic and gravitational noise*: drag-free operation can also make space a far quieter 'seismic' environment than any ground-based laboratory, and greatly reduce gravitational noise by reducing the magnitude of nearby mass motions.
- *Varying gravitational potential ϕ*: some physical effects (such as the Einstein redshift) vary with ϕ. Space enables far more exact tests because the change in ϕ can be much greater, and at the same time less beset by noise, than in any ground-based experiments.
- *Varying gravitational acceleration g*: other effects (for example on an Equivalence Principle experiment) vary with the magnitude or direction of g; it too can greatly exceed values accessible in corresponding ground-based tests.
- *Separation of effects*: sometimes, as with the two effects – the geodetic effect and frame-dragging – measured in Gravity Probe B, the choice of a particular orbit makes it possible to separate effects that would be hopelessly entangled in any corresponding ground-based experiments.
- *Remote benchmarks*: retro reflectors on the Moon, radar transponders on Mars, radio experiments on board remote probes (Cassini and Pioneer, for example) vastly improve ranging data used in tests of gravitational theories.
- *Above the Earth's atmosphere*: absence of air allows optical 'seeing' in missions like Gravity Probe B and avoids particle annihilation in antimatter searches.

Some experiments combine several attributes of space and can achieve enormous improvements. Performing an experiment at low temperature may bring additional advantages. For example, even the simplest room-temperature test of the Equivalence Principle in space is hundred times more precise than the best possible experiment on the ground; at cryogenic temperatures the improvement is a factor of 10^5.

4. Availability of Technologies Needed for Fundamental Physics Missions

The technologies used in Fundamental Physics experiments, the requirements on spacecraft, and the high degree of spacecraft/experiment interrelationship are distinctly different from missions in Astronomy and Solar System exploration. As spacecraft carrying Fundamental Physics experiments typically have to be in purely gravitational orbits, they require a drag-free control system for fine orbit and attitude control, comprising an inertial sensor, proof-mass charge control, a µN-propulsion system and drag-free control software.

Key technologies, such as high-precision accelerometers, drag-free control using He-proportional thrusters or small ion thrusters as actuators, ultra-stable lasers in space, He-dewars, high precision displacement sensors, magnetic spectrometers, small lightweight H-maser clocks and atomic clocks using laser-cooled atoms were not available a decade ago, but have now been developed and are either already space-qualified or about to be space-qualified.

The first orbiting Fundamental Physics experiment, NASA's Gravity Probe B, convincingly demonstrates that the required technology is available today. In Europe, the LISA Pathfinder and the CNES/ESA collaborative MICROSCOPE missions and the atomic clock ACES on the International Space Station are under development and will be launched in a few years. Fundamental Physics in space is now in the pioneering phase where the established space science disciplines Astronomy and Solar System exploration were 35 years ago.

The development of these technologies will also bring benefits to other domains. This is true particularly with respect to missions devoted to observing the Earth and for the Global Navigation Satellite Systems, such as the European Galileo project. As the best atomic clocks are currently approaching their ultimate limits in a terrestrial environment, it is likely that, in the future, the international atomic time will be delivered by clocks on board of dedicated satellites.

5. What is 'Fundamental Physics in Space'?

Fundamental Physics in space, as defined by the relevant Commission of the Committee on Space Research (COSPAR), includes research activities in two broadly distinct but also interrelated areas: (1) discovering and exploring fundamental physical laws governing matter, space and time, and (2) establishing organizing principles in physics from which structure and complexity emerge.

The first area includes, but is not limited to, activities in gravitational and particle physics related to the testing of General Relativity and alternative theories, the search for and study of gravitational waves in space, the search for antimatter in space, the investigation of possible violations of the Equivalence Principle, the search for new hypothetical long-range forces, and the unification of the fundamental interactions of Nature.

The second area includes using space to study quantum phenomena and their applications, for example, Bose-Einstein condensation, critical phenomena in superfluids, and applications of laser cooling to develop new kinds of clocks. It promotes, amongst other things, deep investigations of the role of symmetry principles in macroscopic physics, and of the extent to which renormalization group theory identifies universal and non-universal properties of complex systems.,

In recent years, several new scientific fields in space science have emerged and it is not always straightforward where they are best placed in the advisory structure of a space agency. ESA's science programme, for example, is divided into Astronomy, Solar System sciences, and Fundamental Physics. Some of these new fields are of interest to both Astronomy and Fundamental Physics, such as gravitational waves, astroparticles, and cosmology.

Gravitational Waves: This key prediction of Einstein's theory of General Relativity, has not yet been directly detected. Gravitational wave observatory missions will provide accurate insight into the structure and dynamics of space and time, and on the dark side of the Universe. The Fundamental Physics return of studying the gravitational field close to the black-hole horizon, and the demonstration of basic General Relativity principles like the "no-hair" theorem, is a core part of the overall scientific return of a gravitational wave observatory in space for detecting and observing low-frequency gravitational waves. Here, the spacecraft have to be drag-free, a requirement typical for Fundamental Physics missions, and the preparatory Laser Interferometer Space Antenna (LISA) Pathfinder mission, is aimed at demonstrating the ability to achieve Galileo/Einstein free-fall at the levels of accuracy needed. The arguments that led to the decision to place these missions in the realm of Fundamental Physics in ESA's science programme in the mid 90s and later on, are still valid today.

Cosmology: The current model of the Universe is beset with ad-hoc assumptions, such as an inflationary epoch in primordial times, and peculiar settings, such as the fine tuning in the hierarchy problem, that call for a deeper framework. In addition, the very serious vacuum and/or dark energy problems and the related cosmological phase transitions lead beyond General Relativity and standard Quantum Field Theory and urge the need to unify all fundamental forces. Observations of the early Universe are an important tool in constraining physics beyond the standard model and quantum gravity. In the Cosmic Vision framework, two types of observations have been proposed: (1) polarization of the Cosmic Microwave Background anisotropies and (2) direct detection of primordial gravitational waves with second- or third-generation missions. Some of the relevant observations will be made by space missions inspired by the Astronomy community, other observations will be made by space missions inspired by the Fundamental Physics community. Obviously then, the former missions should be under the purview of astronomy, the latter missions under the purview of Fundamental Physics, as is already the practice in ESA.

Astroparticle Physics: This field deals with cosmic rays in the energy range 10^9 eV to 10^{21} eV, antimatter and dark matter in space, as well as with aspects of high-energy particle physics that are closely related with the early Universe. It is worthwhile mentioning here that the field of ultra-high energy cosmic rays will almost certainly have reached the limits possible from ground-based observations by the end of the 2010-decade, which will make it necessary to have space-based cosmic ray observatories. We are still without a theoretical framework within which the dark-matter content of the Universe or the extreme high-energy part of cosmic rays can be understood in a natural manner. Similarly, antimatter strongly relates to the primordial structure of the Universe and exhibits a sensitive dependence on Fundamental Physics laws. Astroparticle physics thus touches the deep roots of our understanding of the matter content of the Universe and will play an important role in the future development of the theory of elementary particles. Space missions clarifying these features are to be considered as missions of Fundamental Physics, as is already largely the practice in ESA.

6. An Illustration: Physics Mission Candidates from ESA's Cosmic Vision Programme

In response to a Call for Themes for *Cosmic Vision 2015-2025*, issued in 2004, the international physics community submitted 41 theme proposals to the European Space Agency (ESA). From these, ESA's Fundamental Physics Advisory Group selected a number of candidate experiments for possible technology development in preparation for future space flight.

Candidate experiments for flight on a Fundamental Physics Explorer, a standardised, three-axis stabilised drag-free spacecraft in a low-Earth orbit, are

- high-precision tests of the Equivalence Principle using macroscopic objects
- exploring the physics of Bose-Einstein condensates
- cold atom Cs clock of unprecedented precision
- searches for deviations from Newtonian gravity at small distances
- investigation of the time dependence in fundamental physical constants
- tests of quantum measurement theory (entanglement and decoherence)
- tests of the Equivalence Principle using beams of cold atoms

Candidate missions requiring specially designed spacecraft in special orbits are

- gravitational-wave cosmic surveyor
- deep-space gravity probe to explore the Pioneer Anomaly
- high-energy cosmic ray observatory
- investigation of the post-Newtonian parameter gamma to the highest precision
- large-scale tests of quantum theory
- tests of possible violations of the isotropy of the speed of light

7. Recognition of the 'Fundamental Physics in Space' Community in Europe

Already today, several hundred European physicists are actively involved in the development, study, or proposal phases of various future space missions and experiments in Fundamental Physics. They are working on the theory, experiment design, software development, and preparation of data analysis. In Europe, the ESA Director of Science has invited the space science community for the first time in 1989 to submit ideas for space missions also in the field of Fundamental Physics. Since then, about a quarter of all proposals have consistently come from the Fundamental Physics community in response to ESA's Calls for Proposals, which are typically issued every few years. This clearly demonstrates the vitality of the Fundamental Physics community.

Given a science budget at ESA that has not increased for a decade, there is concern that there might not be enough funding in Europe to implement new missions in Fundamental Physics and, therefore, no support for technology development in that field. It is clear that, for quite some time, Fundamental Physics cannot enjoy the same funding level as the more established disciplines Astronomy and Solar System exploration. Scientific merit of a proposal or mission will always be the primary criterion in any selection process. However, it is difficult to compare scientific merit in completely different fields. Astronomy and Solar System exploration had about an equal share of ESA's science budget when averaging over many years. It is suggested that a modest fraction of the budget for Cosmic Vision should be envisaged for Fundamental Physics. This would also give added weight to attempts to increase the ESA science budget.

The World Year of Physics 2005, which celebrates the centennial of Albert Einstein's *annus mirabilis*, is an appropriate opportunity for widely drawing attention to the needs of the field of Fundamental Physics in space, which is represented by a vital community. This field has enormous discovery potential and will eventually play a decisive role in the physics of the 21st century.

The EPS Executive Committee

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