FUNDAMENTAL PHYSICS IN ESA'S COSMIC VISION PLAN

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ESA's Cosmic Vision document sets out the most important and exciting scientific questions that European scientists want to see addressed by space missions in the time-frame 2015-2025. Cosmic Vision also marks a breakthrough for fundamental physics: for the first time, a major space agency has given full emphasis in its forward planning to missions dedicated to exploring and advancing the limits of our understanding of deep physical issues, including gravitation, unified theories, and quantum theory. In my talk I will present the conclusions of the Cosmic Vision document and discuss how it may be implemented. If we are to see experiments in space by 2015, exploring quantum measurement theory or looking for violations of deeply held beliefs about space and time, then the community needs to get ready quickly to make proposals next year.

1. Cosmic Vision: the key questions

The European Space Agency (ESA) has recently completed its forward planning exercise for missions in the period 2015–2025. This plan, the successor to its Horizons 2000+, is called Cosmic Vision.[1] For the first time, ESA envisions a systematic program of missions to perform high-precision experiments in Fundamental Physics. For this reason, a new constitutency of physicists — accustomed to working in university or accelerator labs — needs to be aware of the new possibilities that can be open to them.

Cosmic Vision is structured around four key questions that cross the usual internal ESA discipline boundaries (astronomy, solar system science, and fundamental physics). These questions seem to be the drivers for most of the research that the European space research community wants to perform a decade from now. They are:

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1. What are the conditions for planet formation and the emergence of life?
2. How does the solar system work?
3. What are the fundamental physical laws of the universe?
4. How did the universe originate and what is it made of?

In this article I will concentrate on how ESA might help to answer Question 3, on the funamental laws of physics. Of course, there are important implications for fundamental physics from missions designed to answer Question 4. Cosmology, the study of inflation and the current acceleration of the universe: these may well be answered only by fundamental theory. These issues will be addressed in the paper by Professor Barcons. Here I will focus on the possibilities for missions that directly perform fundamental physics experiments.

Cosmic Vision is the result of a long consulation exercise. In 2004 ESA issued a call for scientists to submit theme proposals: short documents pointing at the principal questions that seem interesting and answerable by missions ten to twenty years from now. The community is well aware of ESA's current suite of missions and projects, and in particular what questions they are likely to answer. The question that ESA posed was: given the current program, what should happen afterwards?

The community responded with over 150 theme proposals. There was a remarkably even division among the three traditional ESA research areas. In particular, there were as many proposals in fundamental physics as in astronomy or solar system science. The proposals were distilled by discussions within the science advisory committees of ESA, in particular in the Space Science Advisory Committee (SSAC) and its working groups in the three areas. The resulting synthesis was presented to the community at a town meeting in Paris, 15-16 September 2004. The feedback obtained there was incorporated into the plan, which was written early in 2005 and presented to the Science Programme Committee (SPC: ESA's principal science committee, which must authorise Cosmic Vision) in May 2005. With the approval of SPC, the plan was published in October 2005.

2. Key Question 3: What are the Fundamental Physical Laws of the Universe?

Cosmic Vision divides this key question into three sub-themes:

- Topic 3.1: Explore the limits of contemporary physics: where do we

look for evidence of unified theories?
- Topic 3.2: The gravitational wave universe: a LISA follow-on in the 1 Hz waveband.
- Topic 3.3: Matter under extreme conditions: investigating the Extreme Universe, the corners where really exotic conditions allow us to probe the deepest laws of gravity and nuclear/particle physics.

These are amplified in the following sections.

2.1. *Topic 3.1: Exploring the limits of contemporary physics*

Theorists are convinced that our understanding of physics today is incomplete and even inconsistent. General relativity is a classical theory, the rest of basic physics is described in a quantum way. Quantum measurement theory, governed by the experimentally robust "Copenhagen Interpretation", does not extend in any obvious way to questions regarding the Big Bang or quantum black holes. The highly successful Standard Model of the strong and weak interactions is known to be incomplete. Unifying gravity with the other interactions presents a further challenge. Most of the work on unified theories and quantum gravity is driven by aesthetic principles and demands of mathematical consistency: there is a paucity of experimental data.

There are many scenarios in which data that could help resolve these issues is obtainable in low-energy experiments, by performing "standard" experiments with extremely high precision, looking for deviations from the standard expectations. Such experiments can usefully be done in space: the stable gravity-free environment allows long-duration high-precision experiments. Here are some potential experimental techiques and technologies that could be transported into space:

- Cryogenic accelerometers based on superconduction test masses and readouts (SQUIDS), pioneered by NASA's current GP-B mission, described elsewhere in this volume.
- Cold-atom sources for a variety of experiments.
- Bose-Einstein condensates, built from the cold atoms.
- Atom trap, atomic lasers.
- Ultra-stable optical lasers, microwave sources, Raman lasers.

Some of these techniques have already attracted Nobel Prizes in Physics, including this year (2005. They are ready to be transferred into space, where applications of equal interest are waiting.

Given the large number of possible experimental techniques, and the small size of each likely experiment, Cosmic Vision suggests that an appropriate tool is a **Fundamental Physics Explorer Programme**. This would be a series of small satellite missions in Earth orbit, all using the same basic platform. several instances of this platform could be manufactured on an assembly line, realising considerable cost savings. It may, with careful design, be possible to launch 3 such satellites in succession within an envelope of cost that would normally characterise a medium-cost ESA mission.

What would such a platform provide? Here are some preliminary ideas:

- A 3-axis stabilised spacecraft with drag-free control.
- Low-vibration environment without moving parts (e.g. body-mounted solar array instead of deployable units).
- Sun-synchronous, low-altitude (500–700 km) circular orbit.
- Limited total mass to allow for an optimised launch vehicle.
- Mission lifetime typically 1 year.

It will be important to refine these ideas in the very near future. I will come back to that at the end of this paper.

Here are some of the exciting and challenging themes proposed by ESA's community, which could be supported by a plaform like this, and which could therefore become experiments in the Fundamental Physics Explorer series:

- High-precision test of the equivalence principle (either using the design already developed for the proposed STEP satellite,[2] or employing a newer cold-atom approach). Unified theories all predict that the equivalence principle will be violated at some level, although predicting the size of the violation is harder. Finding it would be a breakthrough of enormous importance.
- Test the inverse square law of gravity at small distances (also looking for evidence of a fifth force). "Braneworld" scenarios suggest possible string-theory effects at macroscopic distances.[3] A deviation of this size would again be a result of enormous importance.
- Test the inverse square law at scales of 10^4 km, a few times larger than the Earth. This could be performed by putting a sensitive gravity gradiometer in elliptical orbit around the Earth.
- Put very precise atomic clocks into orbit. This is already a field in

which there have been important space missions and experiments, but one that can probe the limits of conventional physics. Time, after all, is the basic metrology standard today; even the standard metre is mow defined in terms of the second and an agreed, fixed value of the speed of light.

- Seek time-dependence of the fundamental constants. This would, if found, undermine the most fundamental tenets of physics, including the famous CPT theorem.
- Test the isotropy of space. Like the time-dependence of constants, this would require major changes in the basis of physical theory.
- Perform demanding tests of quantum measurement theory, including decoherence and entanglement. Earth experiments on entanglement[4] have lately shown how closely the Nature conforms to the expectations of the Copenhagen interpretation of quantum measurement theory, especially that the wave function "collapses" at the moment of measurement. How this passes over to the classical behaviour of macroscopic systems (decoherence) is poorly understood. But the distinction between "observer" and "observed", between quantum and classical, is hard to support in unified theories, which hope to describe the quantum evolution of the universe as a whole, and to resolve the dark energy question.

Any of these experiments could change physics forever.

In addition to these scientific payoffs, the emerging technology of cold atoms could eventually lead to technology spinoffs. In particular, the use of atomic interferometry to do jobs that light interferometry does today offers big increases in precision, due to the much shorter wavelength of matter waves. Future space missions in astronomy and Earth observation may use ultra-high-precision gyroscopes, pointing systems, ranging systems, and station keeping, all based on the kind of cold atom technology that has been developed for fundamental physics experiments. The paper by Prof. Schleich in this volume gives a much more detailed description of the possibilities for cold-atom experimental physics in space.

2.2. *Topic 3.2: The Gravitational Wave Universe*

The joint ESA-NASA mission LISA is planned for launch in 2013, and will open the low-frequency gravitational wave window, observing between 10^{-4} and 10^{-2} Hz.[5] Already, ground-based observatories like LIGO, VIRGO, GEO, and TAMA[6] are operating in the high-frequency band, above a few

Hz, with best sensitivities around 100 Hz. The fact that ground-based detectors cannot observe at lower frequencies motivated the need for LISA. But going into space has given LISA another advantage: its sensitivity is very high because it can operate with very much longer arms than are possible on the ground. While ground-based detectors will struggle to extract weak signals from instrumental noise, LISA will be confusion-limited, fighting over much of its band more against a background of gravitational waves from distant sources than against instrumental noise.

Between the LISA and LIGO bands is an intermediate frequency band not so far covered by any planned detector, from about 0.1 Hz to a few Hz. This is a particularly interesting wave band because source confusion is probably not a serious problem, and it is therefore a clean window through which to look for gravitational radiation from the Big Bang.[7] At LISA frequencies and below, it is likely that astrophysical sources of gravitational waves produce random backgrounds that greatly exceed anything anticipated from the Big Bang. At ground-based frequencies the strength of the radiation expected from the Big Bang is very weak, making it hard to detect. The 1 Hz waveband seems to be the ideal place to look right back to the earliest moments of the history of the universe.

Standard inflation theories make predictions of the level of stochastic radiation that one might expect, simply from the parametric amplification of quantum fluctuations at the time inflation begins. This level is rather low, and would require a big program of technology development to make it accessible to a successor to LISA. But non-standard variations on the conditions that led to inflation can produce much more radiation, enough to be detectable even by LISA itself.[8] It should also be noted that gravitational waves in the LISA waveband had, when blue-shifted back to earlier times, a wavelength comparable with the horizon size when the universe was going through the electroweak phase transition. There is thus some possibility of radiation from the dynamics of this phase transition itself. This could be a spectral feature for LISA and it might even extend into the 1 Hz band.

Although the astrophysical sources in this band are expected to be sparse, they are nevertheless interesting. They are typically transient, since anything able to radiate gravitational waves strongly with intrinsic timescales of 1 s will quickly evolve through the loss of energy to gravitational waves. Most sources are expected to be binaries of neutron stars and stellar-mass black holes, in various combinations, passing through this band on their way to coalescence at frequencies around 1 kHz. Other systems could be mergers of intermediate-mass black holes, which are expected to have been formed in abundance in the first generation of stars, and which coalesce at around $10(M/1000M_\odot)^{-1}$ Hz. A reasonable goal for a LISA follow-on might to be to detect and study every such system in the universe that passes through the 1 Hz waveband during the mission. By detecting these signals and following them for several months, such a mission will be able to measure their distances to accuracies of a few percent, and thereby pinpoint the onset of star formation as the universe evolved. In addition it would determine the populations of such binaries, measure the mass distributions of their components, and test models of the evolution of the first generation of stars. Given the strong indications that star formation and heavy element production began remarkably early, such a mission might be the only tool we have to study individual stellar systems at such early times.

Cosmic Vision identifies a Gravitational Wave Explorer mission as the appropriate mission to follow LISA, near the end of the planning timeframe (2025). LISA itself is hoped to observe from 2015 for ten years, so the new mission could provide continuity when LISA turns off. The Gravitational Wave Explorer would have a design similar to that of LISA, but with shorter arms (appropriate for its higher frequency band) and next-generation technology: bigger mirrors, stronger lasers, improved drag-free control. Development of this technology should start soon. Mirrors and lasers can progress right away. Next-generation drag-free control will benefit from the lessons learned in LISA Pathfinder and LISA itself.

As with LISA, a partnership with other agencies would also be desirable. NASA is exploring an even bigger jump in technology to what is called the "Big Bang Observer", with enough sensitivity to see a cosmological background at the level suggested by standard models of inflation. Such a system would require two or more LISA-like configurations. The challenges are significant, but there are cost savings in building identical spacecraft all at once, and perhaps also in distributing launch costs among two or more cooperating agencies.

2.3. *Topic 3.3: Matter in Extreme Conditions*

We learn the most about physics by examining places where matter is subjected to extreme and unusual conditions. Near black holes, matter at high temperature, high density, and with strong magnetic fields somehow generates the quasar phenomenon. Do quasar jets come from a combination of "normal" effects, essentially magnetohydrodynamics in some form, or does it involve the direct extraction of rotational energy from the central black hole? What, indeed, does the central black hole look like in such extreme systems: is it really a Kerr hole, is it rapidly rotating?

Similarly, neutron stars are objects whose detailed physics still defies a convincing description in the nearly 40 years since the discovery of pulsars. Their combination of degenerate matter, superfluidity, superconductivity, strong magnetic fields, exotic nuclear physics, and rapid rotation place them among the most fascinating physical objects in the universe. Understanding their interior physics would provide deep insight into nuclear physics and the high-density details of the Standard Model, and could in principle reveal new physics outside the Standard Model.

These systems can be investigated through the X-rays and gamma rays that they emit. Cosmic Vision identifies two useful tools: a large-area X-ray telescope mission, known in Europe as XEUS and in the USA as Con-X, would have sufficient sensitivity to do detailed spectroscopy and time-series analysis on the emission. It could identify normal mode frequencies of neutron stars (a key to their interior structure), measure the mass and spin of central black holes, test the metric outside a black hole against the Kerr model by measuring a number of expected orbit-related frequencies in the emission, and unravel the mystery of quasar jet production by enabling detailed disc and jet models to be fit to the high-quality data. A later mission that did spectroscopy at even higher energies, in the gamma-ray band, would complement these studies very nicely by looking at the very central regions of quasars and accreting neutron stars.

Cosmic rays currently present one of the most challenging puzzles to our understanding of matter. The flux of high-energy cosmic rays (above about 10^{20} eV) is much higher than expected: such high energy protons should rapidly lose energy as they travel through, and scatter, the photons of the cosmic microwave background. If the current ground-based Pierre Auger Laboratory observations verify that the flux is anomalously large, then a more sensitive, space-based detector capable of looking at cosmic ray showers over a large portion of the Earth may be required in order to get enough statistics to understand the properties of these particles and their sources, which have not been identified.

3. Next steps

Cosmic Vision is the plan for 2015-2025 created by the SSAC. To implement it, the SPC must allocate resources. If SPC agrees to the plan proposed by

SSAC, then we can expect the following timetable:

- In the Spring of 2006, ESA will issue a call for proposals for the Cosmic Vision time-frame.
- Proposals will be due at the end of 2006.
- A number of proposals will be selected for assessment studies, leading to a further review and to the start of Phase A studies in January 2008 for two or three missions.
- The number of missions approved for construction and launch will depend, of course, on the results of the Phase A studies and on the level of resources available. It is expected that approved mission(s) will be able to launch in the first three years of Cosmic Vision, 2015-2018.
- Further calls will be issued later for the second and third "slices" of Cosmic Vision, 2018-2021 and 2021-2025.

For a substantial part of this ambitous program to become reality, the science budget of ESA must at a minimum hold steady or, hopefully, increase gradually even in the period from 2009 onward, when missions are in preparation. One cannot be completely optimistic here: the purchasing power of ESA's annual science budget has fallen by more than 20% in the last ten years. SSAC hopes that, by presenting the members states with an exciting and rich program of missions, with a strong demand from the European scientific community, it will motivate a reversal of this depressing trend. Whether this is successful will depend not just on the ESA program, but also on whether European space scientists make their ambitions and requirements clear to their own national governments.

But besides these long-range strategic issues, there is an immediate requirement: European scientists must get ready to respond to the call for mission proposals in 2006. In particular, the fundamental physics community, a large part of which has little experience of space missions, must turn their ambitious suggested themes into serious and practical proposals.

To assist this new community, ESA is planning to organise a meeting in early May 2006 on the theme of the Fundamental Physics Explorer series. At this workshop, participants will be able to give ESA staff feedback about what features are desirable in the common platform that will host the experiments in this series. And they will be given suggestions by ESA staff on what is expected from a good proposal. Dates and venue for this meeting will be announced soon. The success of Cosmic Vision depends on excellent proposals from the community!

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