



Cosmic Vision

Space Science for Europe 2015-2025



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for Europe 2015-2025*

Cover

*A fresco painted 1509-1511 by Raphael (1483-1520) in the Vatican (Stanza della Segnatura, Palazzi Pontifici) perhaps depicts the embodiment of Astronomy.
(Copyright Photo SCALA, Florence)*

Replacing the original astronomical globe is Mars viewed by the High Resolution Stereo Camera (ESA/DLR/FU Berlin, G. Neukum) carried by the ESA Mars Express spacecraft, merging into an image (G. Hasinger, Astrophysikalisches Institute, Potsdam) of X-ray sources in the Lockman Hole made using the Newton X-ray Observatory spacecraft.

Chapter divider

*Artist's impression of a quasar located in a primieval galaxy a few hundred million years after the Big Bang.
(ESA/W. Freudling, ST-ECF/ESO)*

BR-247 'Cosmic Vision'

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Published by: ESA Publications Division, ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands

Editor/Design: Andrew Wilson
Layout: Jules Perel

Copyright: © 2005 European Space Agency
ISSN: 0250-1589
ISBN: 92-9092-489-6
Price: EUR 10
Printed in The Netherlands

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Foreword

'Science is shaped by ignorance' says David Gross, 2004 Nobel Prize in Physics. Space science is no exception: by going after our knowledge gaps (or ignorance chasms) in the Universe around us, we focus on questions that then both direct and motivate us. Identifying these questions has been the starting point of the current soul-searching exercise, which occupied a full year in the life of Europe's space scientists. Watching them go into action and feeling their response has been both an intense experience and a unique privilege.

Today's science rests on the contribution of every citizen. In our case, this means asking each European to invest about €1 per year in two equally noble purposes: to be a little less ignorant about our Universe and to give a much-needed boost to Europe's space industry. (Of this yearly Euro, our European taxpayers should know that 80 cents will go to industry, in the form of technology-intensive contracts).

Throughout our Cosmic Vision 2015-2025 exercise, it was apparent that scientists were conscious of the responsibilities they carry towards Europe's taxpayers as much as towards their own future community. They were, and are, also conscious of the burden they carry: the opinions of a community that has more than doubled in the last two decades deserves the respect of Europe's decision-makers. We know they have to deal with the numerous factors that have intolerably squeezed our meagre yearly €1 for space science.

With Cosmic Vision 2015-2025, we show that we do not complain – we get organised.

After the questions, came not the answers, of course. Rather, as you will see, priority-based science strategies were identified, as well as roadmaps for the development of the technological tools necessary for such strategies.

Just as cognac, schnapps or grappa distil the spirit out of a variety of fruits, from grapes to plums (and the occasional potato...), the pages that follow capture the spirit of Europe's space scientists. Our distillation process adhered to a time-honoured tradition that has been followed by ESA over the 30 years since its creation. It has been the responsibility of ESA's Directorate of Science advisory structure, i.e. the Astronomy Working Group, the Fundamental Physics Advisory Group and the Solar System Working Group, to evaluate and discuss the '*dictionnaire des idées reçues*' from the community. Ultimately, it was the Space Science Advisory Committee (SSAC) that took responsibility for the conception and writing of Cosmic Vision 2015-2025, with the fundamental support of the Science Directorate Executive.

The SSAC, the Working Groups and indeed the whole community are keenly aware of the foreseeable costs of space missions as well as of ESA's Directorate of Science current (and foreseeable) budget. We know that not all of the ideas given here will be realised. We are not having intoxicated

dreams: with maturity, we are putting forward a realistic set of scientific strategies out of which the implementation of missions must logically follow.

A feeling of '*schicksalsgemeinschaft*', that special sharing of a common destiny, permeated the SSAC and rendered our working together both effective and pleasant, albeit at times strenuous. To ESA, to Europe's decision-makers and, above all, to the next generation of space scientists, we present our work. Our confidence in doing so stems from the vast intellectual contribution received as an input: we are profoundly grateful for it.



A handwritten signature in black ink that reads "G. Bignami".

Giovanni F. Bignami
Chairman, SSAC



Executive Summary

Ten to twenty years from now, a succession of clever new spacecraft will need to be ready to fly in ESA's continuing Science Programme, now called Cosmic Vision. They will tackle some of the big scientific questions that are posed in this document. Such long-term planning has already proved its worth in the Horizon 2000 (1984) and Horizon 2000 Plus (1994-1995) plans. They enabled Europe's scientific, technological and industrial teams to commit themselves with confidence to the many years of hard work that it takes to conceive and execute space projects of world-beating quality.

In that highly successful tradition, Cosmic Vision 2015-2025 aims at furthering Europe's achievements in space science for the benefit of all mankind. The plan is based on a massive response by the scientific community to ESA's call for themes, issued in April 2004. A total of 151 novel ideas (listed in Annex 2) were submitted, more than twice as many as for the equivalent exercise in 1984.

ESA's scientific advisory committees and working groups then made a preliminary selection of themes, which were discussed in a workshop in Paris in September 2004, attended by nearly 400 members of the scientific community. After an iteration with the Science Programme Committee (SPC) and its national delegations, ESA's Space Science Advisory Committee (SSAC) prepared the present plan with the keen assistance of ESA's Directorate of Science. The SSAC is made up of scientists chosen for their scientific standing and who are

expected to represent the views of the European science community as a whole rather than any particular national interest. A further encounter with the wider space science community occurred at a symposium in Noordwijk in April 2005. On 5 May 2005, in Helsinki, the SPC saw a draft of the report and endorsed the approach.

Science in the 21st Century is seeking answers to profound questions about our existence, and our survival in a tumultuous cosmos. What is even more important is the rate of increase of our knowledge. We can now pose questions that seemed beyond our reach less than a generation ago. Many of the answers can be sought and found only with space projects of ever-increasing ingenuity. ESA is not alone in recognising the scientific challenges, and it embraces collaboration with other agencies whenever that is opportune. However, Europe has made its most distinctive contributions to space science by giving its own scientists every opportunity to prioritise their goals.

Cosmic Vision 2015-2025 addresses four main questions that are high on the agenda of research across Europe (and, indeed, worldwide) concerning the Universe and our place in it:

- what are the conditions for planet formation and the emergence of life?
- how does the Solar System work?
- what are the fundamental physical laws of the Universe?
- how did the Universe originate and what is it made of?

Chapters 1 to 4 spell out the opportunities under these headings, and identify specific aspects of each general theme that are judged to be especially ripe for investigation by new space tools in the period 2015-2025. Chapter 5 reviews the technology that will have to be developed. Finally, this planning on behalf of the scientific community and aerospace industry takes into account the Science Directorate's preliminary reckoning of the practical constraints of technology. In *Proposed Strategies and Their Implementation* (Chapter 6), the outcome of these deliberations is summarised in four tables that correspond to our four key questions. A compacted version of those tables is shown overpage.

The team preparing Cosmic Vision 2015-2025 has subdivided the four main questions by selecting areas where major progress can be expected in the next two decades. Under each of the resulting sub-headings, one, two or three appropriate space techniques (or tools) are nominated. It is here that technical progress in the next 10 years is required, and the targets finally chosen and the progress made will determine what we can confidently do scientifically maybe 20 years from now. In some cases, the same technique or tool appears in more than one context, thanks to its cross-disciplinary character.

The breadth of the investigations represented in the table is enormous. They range from the poles of the Sun to the birth of the Universe, from gigantic cosmic structures to sub-atomic particles. Also

remarkable is the way that very different techniques converge on the same question, whether it is the origin of life or the fundamental physics of the cosmos that make our existence possible.

The space tools in the table should be seen as candidate concepts for missions, rather than as cut-and-dried requests for individual funding. Still less are they firm promises to the scientific community. Too many projects have been proposed for them all to be affordable in the 2015-2025 timeframe. Exactly how much can be accomplished will depend on the Level of Resources of the Science programme, but also, in part, on what international collaborations can be arranged. Competition between the candidate concepts will be unavoidable.

In any case, some flexibility must remain in the space science programme, to allow for unforeseen opportunities or difficulties, whether in the science or in the technology. The readiness of the technology – often highly innovative – will be a factor in the selection and sequencing of the eventual missions.

It is foreseen that ESA's Directorate of Science will issue a succession of Calls for Mission Proposals to implement the plan. Following a successful tradition, international collaboration with non-European space agencies, including NASA, will be a key ingredient in the implementation of this programme. Within Europe, interactions with national space programmes, and also with the European

Southern Observatory (ESO) and the European Organisation for Nuclear Research (CERN), will be explored in full. Within ESA itself, strong coordination with the Earth Observation Programme, the Aurora Exploration Programme and other programmes will give an overall boost to the scientific and technological activities proposed here.

Thanks to the blend of ambition and realism in our plan, Europe's aerospace industry has not only expressed a strong interest in the ideas, but also pledged its support for the future of science in space. With every new space technique or tool envisaged here, Europe's technological competence will grow.

Above all, Cosmic Vision 2015-2025 should appeal to the new European Space Council, because it fosters the European Union's visible presence in space activities from which many strategic, industrial, cultural and educational benefits will flow. The plan is an expression of trust in Europe's political will, from the large and multi-faceted space science community in universities and institutes throughout the continent. The scientists who gladly contributed their best ideas and expertise to our study now confidently expect support for the timely implementation of this exciting programme.

Scientific Questions

subdivided into topics where important progress can be expected in the Cosmic Vision 2015-2025 timeframe

1. What are the conditions for planet formation and the emergence of life?

1.1 From gas and dust to stars and planets

Map the birth of stars and planets by peering into the highly obscured cocoons where they form

1.2 From exo-planets to biomarkers

Search for planets around stars other than the Sun, looking for biomarkers in their atmospheres, and image them

1.3 Life and habitability in the Solar System

Explore *in situ* the surface and subsurface of the solid bodies in the Solar System most likely to host – or have hosted – life

Explore the environmental conditions that makes life possible

2. How does the Solar System work?

2.1 From the Sun to the edge of the Solar System

Study the plasma and magnetic field environment around the Earth and around Jupiter, over the Sun's poles, and out to the heliopause where the solar wind meets the interstellar medium

2.2 The giant planets and their environments

In situ studies of Jupiter, its atmosphere, internal structure and satellites

2.3 Asteroids and other small bodies

Obtain direct laboratory information by analysing samples from a Near-Earth Object

3. What are the fundamental physical laws of the Universe?

3.1 Explore the limits of contemporary physics

Use stable and weightless environment of space to search for tiny deviations from the standard model of fundamental interactions

3.2 The gravitational wave Universe

Make a key step toward detecting the gravitational radiation background generated at the Big Bang

3.3 Matter under extreme conditions

Probe gravity theory in the very strong field environment of black holes and other compact objects, and the state of matter at supra-nuclear energies in neutron stars

4. How did the Universe originate and what is it made of?

4.1 The early Universe

Define the physical processes that led to the inflationary phase in the early Universe, during which a drastic expansion supposedly took place. Investigate the nature and origin of the Dark Energy that is accelerating the expansion of the Universe

4.2 The Universe taking shape

Find the very first gravitationally-bound structures that were assembled in the Universe – precursors to today's galaxies, groups and clusters of galaxies – and trace their evolution to the current epoch

4.3 The evolving violent Universe

Trace the formation and evolution of the supermassive black holes at galaxy centres – in relation to galaxy and star formation – and trace the life cycles of matter in the Universe along its history

Candidate Projects

in strategic sequences (question by question)

Near-Infrared Nulling Interferometer

Mars Landers
+ Mars Sample Return
(with Aurora Programme)

Far-Infrared Observatory

Solar Polar Orbiter
Terrestrial Planet
Astrometric Surveyor
Europa Landers

Earth Magnetospheric Swarm

Solar Polar Orbiter

Jupiter Exploration
Programme *including* Europa
Orbiter and Jupiter probes

Near-Earth Object
Sample Return

Interstellar Heliopause Probe

Fundamental Physics Explorer Programme

Large-Aperture
X-ray Observatory

Deep Space Gravity Probe

Gravitational Wave
Cosmic Surveyor

Space Detector for Ultra-High-Energy Cosmic Rays

Large-Aperture
X-ray Observatory

Wide-Field Optical-Infrared Imager

All-sky Cosmic Microwave
Background Polarisation
Mapper

Far-Infrared Observatory

Gravitational Wave
Cosmic Surveyor

Gamma-Ray Imager



Introduction

One memorable morning, early in 2005, a discovery machine built in Europe made the most distant landing ever attempted on another world. The European Space Agency's probe Huygens, crammed with scientific instruments, descended to the surface of Titan, a mysterious moon of Saturn. It revealed icy landscapes with river basins carved by liquid hydrocarbons, in a kind of world previously unknown to science. Huygens made headline news worldwide, but not without an element of surprise that Europe should have pulled off such an impressive feat.

The very name of the mission, Cassini-Huygens, celebrated the European astronomers who explored Saturn and its rings and moons in the 17th Century. The basic technologies – propulsion by rockets, descent by parachute and communication by radio – were all pioneered in Europe. Yet modern Europe is suspected, rightly or wrongly, of being politically lukewarm towards space science, because it spends much less on it than does NASA.

To conceive and execute the Huygens mission took more than 20 years. Two space scientists in France and Germany formally proposed an ESA probe to Titan in 1982. Six years later, the joint NASA/ESA/ASI Cassini-Huygens mission was approved. After intensive work by Europe's space scientists and engineers, the completed Huygens probe was attached to Cassini in good time for the launch in 1997. Continuing transatlantic collaboration throughout the long flight to Saturn ensured the probe's perfect delivery to Titan. Cassini's big radio

Why Space Science Needs Long-Term Planning

dish, contributed by the Italian space agency, ASI, received the signals from Huygens and relayed them to the Earth. The success of this mission is, first and above all, due to the interest and perseverance of the proposing scientists, and to the highly creative and ingenious solutions worked out by industry to build an engine that has pushed the human frontiers on space exploration. None of this – a development time of 17 years, preceded by a long preparatory effort – would have been possible if ESA had not had a **long-range space science plan**.

Scientists, technologists, national funding agencies, space industry and international partners, all relied very heavily on the existence of ESA's long-term plan to build confidence in the success of a project that took two decades to develop. Huygens is by no means an exception in the length of development of a space science mission, which typically takes decades to return its final science. The Horizon 2000 plan, which planned the Cassini-Huygens mission, was prepared in 1984; Horizon 2000 Plus in 1994-1995. The present Cosmic Vision 2015-2025 document is the logical continuation into the next decade of the ESA science planning cycles.

The year of 2005 is especially apt for taking stock of the new science performed from space on the continent of Ptolemy, Tycho, Kepler, Galileo, Newton and Einstein. A century after the '*annus mirabilis*' of the theory of relativity, photoelectric effect and Brownian motion, we celebrate 30 years of activity of the European Space Agency, itself

born on a previous decade of work by the European Space Research Organisation (ESRO). We, the European space scientists, are proud to have again given a new contribution to mankind in its quest for understanding the Universe. After about 4000 years of naked-eye astronomy, Galileo initiated 400 years of astronomy with ever-more powerful telescopes, followed by 40 years of space astronomy. In each of these historical periods, astronomers have gathered more information about the Universe than in the previous one, in a spectacular example of the acceleration of science.

Why do astronomy? Astronomy, the understanding of our Universe and mankind's place in the Universe, is the mother of all science. Lack of interest in basic science, in addition to the devastating economic effects it has – no basic science means no applications – is always the symptom of profound diseases of any society.

Why look at the heavens from space? Most of our information on celestial objects comes through the electromagnetic radiation that planets, stars and galaxies emit throughout the spectrum. They obviously do not care that on our planet only a small (frequency) window, the one to which our eyes became adapted, penetrates the atmosphere. Placing telescopes in orbit has provided astronomers with an immense leap in their powers of observation. The recent Nobel Prize to Riccardo Giacconi for the development of X-ray astronomy is but one example of the recognition of such a widening of horizons.



Huygens revealed a world previously unknown to science: first colour view of Titan's surface. (ESA/NASA/JPL/Univ. Arizona)

There is another dimension of research in space that is more akin to traditional exploration: exploration *in situ*. Europe is currently present on many planets in the Solar System, including the Moon, Mars, the Saturn/Titan system, Venus and, tomorrow, Mercury. Europe is thus acquiring data on all the major solid-body atmospheres in the Solar System: Venus, Mars and Titan. The potential benefits for understanding the evolution and fate of the fourth solid-body atmosphere in the Solar System, that of our Earth, are apparent. Planetology helps us to put in context the particular planet on which we happen to live. On the other hand, participating in missions closing in on the Sun has given us a new view of our own star, which ultimately controls our lives.

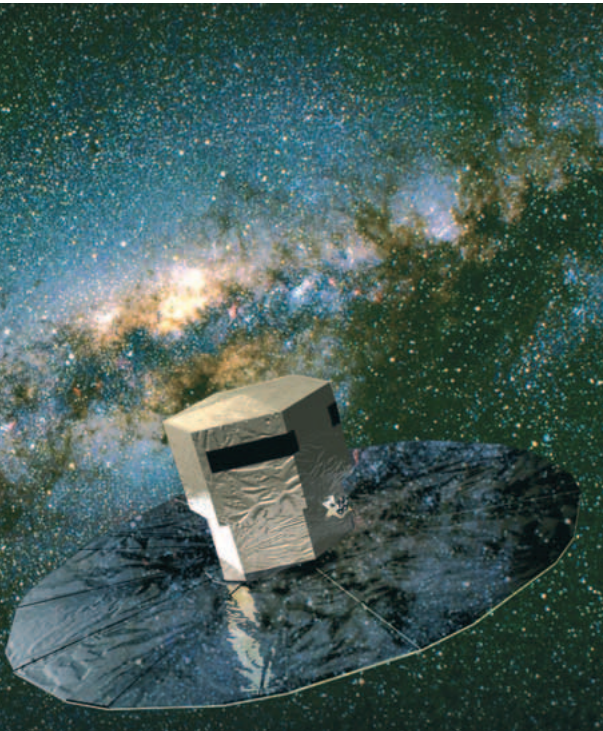
There is more to space astronomy besides the electromagnetic spectrum and *in situ* exploration. We also receive information from the Universe through essentially untapped channels, such as gravitational waves – another of Einstein's predictions – that have so far only been indirectly observed. Through them, we expect to improve our understanding of a variety of phenomena, such as merging neutron stars, forming gigantic black holes in the centres of Galaxies, and the very first instants of the explosion that gave birth to the Universe.

Finally, the 'corpuscular' channel has been exploited from the very first cosmic-ray experiments aboard satellites for sampling the origin and composition of nuclei synthesised in stars, as well as for understanding their importance in the energy balance of our Galaxy, and their



significance for interplanetary space and indeed our Earth. To these now-traditional particle astronomy studies, new physics dimensions could be added that address exotic species or energy levels so far unexplored.

In this global panorama of science advances, rendered possible by access to space, Europe has contributed, through ESA, complemented by additional national efforts, in a major way. Through creativity, organisation and determination, Europe has achieved leadership in a number of research areas since ESA's foundation. However, ESA and its Member States have achieved successes in space science that are disproportionate to their relatively small budgets. They come from pursuing difficult and highly original projects in an unwavering fashion over many years. Like Aesop's tortoise competing with the hare, Europe gets there in the end – whether to the sludgy surface of Titan or into orbit with the world's most sensitive X-ray and gamma-ray telescopes, XMM-Newton and Integral.



Gaia will decipher the history of the entire Galaxy.

After proving its competence in space astronomy with COS-B for gamma-rays (1975) and Exosat for X-rays (1983), the scientific mission through which ESA 'came of age' was probably Giotto (1985-1986). Witness the breathtaking movie of Giotto's approach to within less than 600 km of comet Halley, much closer than any other space agency dared to go. The Rosetta mission, launched in 2004, will land on a comet in 2014, reinforcing the leading position achieved by Giotto.

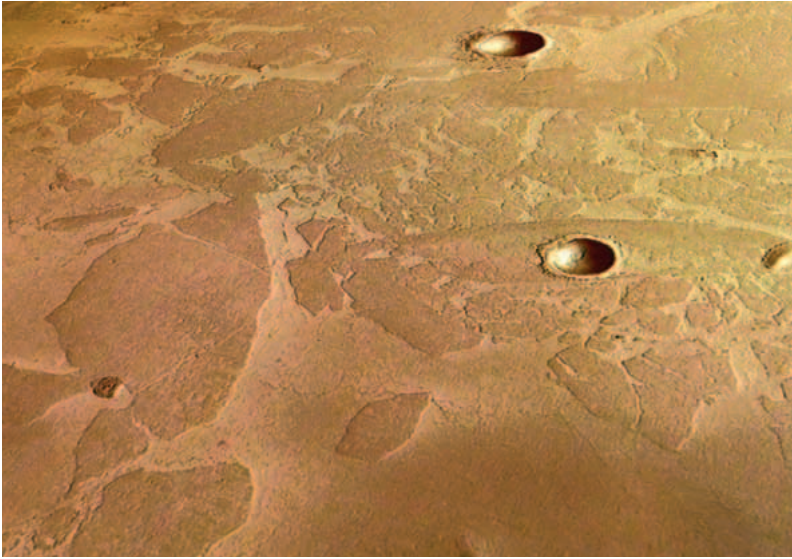
In 1989, Hipparcos was launched, a unique satellite that gave unprecedented and, as yet, unmatched accuracy in measuring the positions and motions of stars within a range of hundreds of light-years in our Galaxy and, for the first time, solved the discrepancy between the age of the oldest stars in the Milky Way and the expansion age of the Universe. This mission will be followed in 2012 by Gaia, a much more powerful satellite, able to map one billion stars in six dimensions and decipher the history of the entire Galaxy. Space

astrometry, by now an established European specialty, has given us direct access to the distance ladder, whose steps measure our Universe.

Both Giotto and Hipparcos were projects that NASA in principle might have done but did not. The scientific and political will came from Europe. Yet willpower on behalf of individual science projects was not enough. By the early 1980s, Europe's scientific institutes, aerospace companies and governments all realised that to create and preserve talented teams, as well as to be reliable partners in international collaborations, ESA needed long-term commitments in planning and funding.

Horizon 2000 and Horizon 2000 Plus

After continent-wide brainstorming in 1983-1984, Horizon 2000 replaced the previous *à la carte* style of mission selection by an appetising *table d'hôte*. There was judicious provision for updating the programme with missions still to be chosen. Despite some delays and descoping owing to budgetary constraints, the promises of Horizon 2000 will be broadly fulfilled when the astronomical missions Herschel and Planck set off into space in 2007. The second step in this decadal series is Horizon 2000 Plus, including highly promising missions such as Gaia, BepiColombo, JWST, LISA and Solar Orbiter. A brief résumé of the most striking results obtained or still expected from these two long-term designs is given below.



Mars Express has found what appears to be a dust-covered frozen sea near the Martian equator. (ESA/DLR/FU Berlin; G. Neukum)

In November 1995, the Infrared Space Observatory gave us views of the 'cold' Universe and its chemical history that had never previously been seen, discovering, most importantly, 'water, water everywhere'. Herschel will follow up this success by going to longer wavelengths and exploring colder regions, where more complex molecules are formed. Meanwhile, its launch companion, Planck, will explore our Universe and its origin at even longer wavelengths. In a sense, Planck will obtain high-resolution images of the Universe in infancy, and from there precise measurements of its basic constituents.

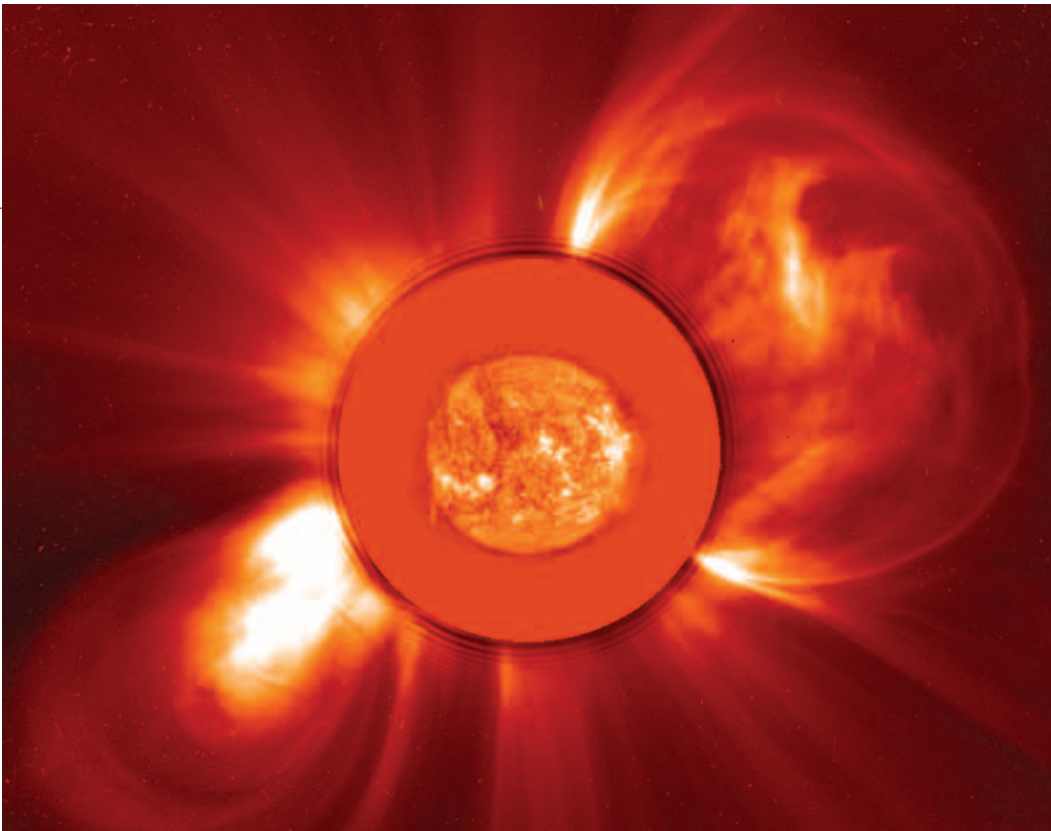
The study of our magnetosphere, the magnetic bubble that travels with our Earth and protects it from the outbursts of our star and from the steady flux of cosmic rays, is another area where ESA is making the most important contribution, following up a series of earlier small missions. The key idea was that of flying four identical spacecraft in formation, allowing for the first time synchronous study in three-dimensions of particles and fields in our magnetosphere. Here, ESA had to fight bad luck, because the first Cluster mission was lost in the failure of the debut Ariane-5 launch in 1996. However, the decision was quickly taken

and acted upon to fly a replica of the mission. This took place in 2000, and Cluster has continued to fly with success. In 2003-2004, through an ESA-Chinese collaboration, the mission was enriched by two Chinese satellites ('Double Star') carrying many European instruments.

X-ray astronomy attracted the earliest observations in space science, and is a field where Europe in general and ESA in particular have been active since the beginning. After the positive outcome of the Exosat mission in the early 1980s, which flew a first generation of X-ray optics, the XMM-Newton observatory was launched in 1999. Still fully operational, it features novel X-ray optics of unprecedented throughput and is opening up high-sensitivity X-ray spectroscopy for many classes of celestial objects, including black holes and neutron stars, as well as large reservoirs of ionised matter trapped by the gravity of celestial objects. ESA's tradition in gamma-ray astronomy, dating back 30 years, is being extended with the Integral observatory (2002). This unique mission combines high-resolution imaging and spectroscopy in the crucial, yet poorly explored, wavelength region where most nuclear radiation is emitted by the most energetic objects in the local Universe.

In planetary research, competition with NASA has mostly given way to cooperation, such as through the imaginative Cassini-Huygens mission. However, Mars Express, a European mission, and certainly the cheapest mission ever sent to Mars, has been producing first-class scientific data, despite

Thanks to SOHO, solar mysteries are being solved. (ESA/NASA – SOHO/LASCO)



the loss of Beagle-2, with breathtaking three-dimensional high-resolution images, and the discovery of water and methane, the chemical prerequisite/markers of possible biotic activity. The launch of the sister mission Venus Express in 2005 promises comparably high achievements at the cloud-masked planet, which still presents many puzzles despite 40 years of investigation by American and Soviet spacecraft. Closer to the Sun and even more baffling is the planet Mercury, the target for one of the main projects of Horizon 2000 Plus: BepiColombo. Named for the Italian scientist who improved NASA's reconnaissance of Mercury in 1974-1975 with the gravity-assist method, this mission is now a joint European-Japanese project.

In other fields, ESA shares its science leadership with NASA, through partnership and cooperation. The first major joint success was the longest lived (so far) cooperative mission, the International

Ultraviolet Explorer (IUE, 1978), an astronomy mission with NASA and the United Kingdom. The Hubble Space Telescope, still operating, has opened a new observational era for astronomy, and similar astronomical and cosmological breakthroughs are expected from its successor, the James Webb Space Telescope, also a joint ESA/NASA/CSA venture. Ulysses (1990), still operating, has been exploring the heliosphere, the bubble of particle, gas, radiation and magnetic field travelling with our Sun through interstellar space. But perhaps the best example ever of a successful cooperative mission is given by SOHO, still operational after a decade in orbit. Thanks to SOHO, a number of mysteries and questions about the inner and outer structures of our Sun have been answered. Another challenge is LISA (Laser Interferometer Space Antenna), a joint ESA-NASA project which, by searching for gravitational waves, will open a new window on the Universe. On LISA Pathfinder

(2009), ESA will test European and American contributions to the amazing technology required for this project.

At the time of writing, ESA is flying a total of 17 scientific and other satellites. Thanks to the two long-term programmes for science, Horizon 2000 and Horizon 2000 Plus, there are now in orbit 15 ESA scientific spacecraft, of which nine are directly operated by ESA. They have earned high respect from scientists all around the world, who like to be involved in the missions. Most of the media coverage of ESA's activities concerns these scientific spacecraft, which is not surprising because they far outnumber the satellites in orbit for other ESA programmes. The quality of engineering achievable with a long-term plan is part of the explanation for this remarkable number of missions in progress. Europe's scientific, technological and industrial teams were able to commit themselves with confidence to the many years of hard work that it takes to conceive and execute world-beating space projects to high technical standards. As a result, several missions are still harvesting scientific knowledge long after they were expected to finish.

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Such is the story so far. The individual successes of this long-term planning of ESA's space science programme nevertheless conceal the general problem that even a tortoise needs nourishment. Many of the fantastic missions described above were decided before the Level of Resources of the Science Programme began

to decrease. Despite tireless trimming of mission costs – by technical finesse, by new management practices and by recruiting international partners to share the expense – some consequences of the erosion of ESA's space science budget during the past 10 years are now plain to see.

One was the first-ever cancellation of an approved ESA science mission. Eddington was meant to follow up SOHO's success in studying the Sun's interior by its rhythmic variations in brightness, and apply the same seismic method to the stars. And had it not been cancelled, Eddington would have checked out half a million stars for the possible presence of Earth-sized planets passing in front of their parent stars. Painful surgery also eliminated Europe's Mercury Lander intended to fly on BepiColombo. Some other missions have been deferred to an extent that endangers their expected performances, strains the loyalty of the scientific and industrial teams, puts the personal careers of young researchers at risk, and is actually wasteful of money.

At the time of writing, celebrations are under way for the 30th anniversary of ESA. ESA is a different organisation from what it was 30 years ago and it reflects a different environment. The evolution of our space science community deserves special attention. It is the one on which ESA's Science Programme 'insists' and which is served by the programme. It represents the future for Europe, not only in terms of new ideas and work but also for the Programme governance it constantly expresses through ESA's advisory bodies.

In time-honoured fashion, the community was called upon to express its new ideas in April 2004, and did so with unprecedented enthusiasm. The community was patently conscious of the responsibility it had to take to build its own future through responding to the need for space science in a new Europe. A total of 151 novel ideas (listed in Annex 2) were submitted, more than twice as many as for the equivalent exercise in 1984-1985. The number of participants per proposal has also significantly increased, together covering the whole space science community of Europe. In some countries, such as Spain, the increase has been dramatic. Decision- and policy-makers are today confronted with an obvious engagement of an important sector of our society.

Cosmic Vision 2015-2025 tries to give justice to all such aspirations. It aims boldly at furthering Europe's achievements in space science, for the benefit of all mankind. As with its predecessors, the plan has been created 'by the scientists, for science and industry'. ESA's scientific advisory committees and working groups (Annex 1) made a preliminary selection of themes, which were discussed in an open workshop in Paris in September 2004, attended by almost 400 members of the scientific and industrial communities. After an iteration with the Science Programme Committee (SPC) and its national delegations, and a second open Symposium in April 2005, ESA's multinational Space Science Advisory Committee (SSAC) prepared the present plan, with the keen assistance of ESA's Directorate of Science, and presented it to the SPC in May 2005.

Cosmic Vision 2015-2025 addresses four main questions that are high on the agenda of research across Europe (and, indeed, worldwide) concerning the Universe and our place in it:

- what are the conditions for planet formation and the emergence of life?
- how does the Solar System work?
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- how did the Universe originate and what is it made of?

Chapters 1 to 4 spell out the opportunities under these headings, and identify specific aspects of each general theme that are judged to be especially ripe for investigation by space projects in the period 2015-2025. **Chapter 5** reviews the technologies that will have to be developed. In **Chapter 6**, *Proposed Strategies and Their Implementation*, the planning by the scientists, for scientists and industry is matched to the Science Directorate's reckoning of the constraints of technology and cost. Potential space tools to address each of our four key questions are summarised in four tables. A possible scheme for their orderly implementation during the next 20 years is described. This envisages that the Science Programme Executive may wish to make a Call for Mission Proposals early in 2006 for the first post-2015 projects. Finally, **Chapter 7**, *Conclusions*, reflects on the interface between scientific discovery and political willpower, as Europe faces the opportunities and challenges of space exploration in the 21st Century.



Chapter 1

A question that fascinates mankind is what was the succession of events after the Big Bang and the formation of stars and galaxies, and under which conditions, that led to the origin of life on Earth? Equally captivating is the question of whether life exists elsewhere in the Universe and, if so, in what forms, on which kind of planets and linked to which type of stars. As we are working on theories to explain the physical processes by which life might appear and evolve on a planet, we are in the somewhat peculiar situation in which only one planet hosting life is presently known. No other sign of life has ever been detected either on the other planets or satellites in the Solar System or elsewhere in the Universe. For the time being, life on Earth provides a solitary example to guide our physical, chemical and biological investigations.

A decade ago, when the Solar System was the only planetary system known, theories were developed to account for the formation and evolution of such a system. Since then, the discovery of more than 160 planets orbiting stars beyond the Sun has taught us the limit of such an approach. The formation of many of these systems, with giant planets ('hot Jupiters') orbiting closely to the stars, seemed impossible within the framework of the theories accepted as little as 10 years ago. Based on this salutary example, we can only wonder what scientific and philosophical revolution the discovery of life on another planet will provoke.

We are now at a unique moment in human history. For the first time since the dawn of philosophical and scientific thought, it is

What are the Conditions for Planet Formation and the Emergence of Life?

within our grasp to answer, rigorously and quantitatively, two fundamental questions:

- are there other forms of life in the Solar System and did they have an independent origin from those that developed on Earth?
- are there other planets orbiting other stars similar to our own Earth, and could they harbour life?

Spelling out these themes in more specific scientific terms leads to the following questions:

- what are the conditions for stars to form and where do they form?
- how do they evolve as a function of their interstellar environment?
- do stars hosting planets have special characteristics?
- what are the conditions for planets to form around stars?
- what are the different kinds of planets orbiting stars? What is their mass range? Are there planets similar to those of the Solar System?
- which planets are surrounded by atmospheres? What are the characteristics of these atmospheres?
- what are the conditions for life (of any form) to appear on these planets?
- for life to survive and evolve, what are the environmental conditions – geological, hydrological, atmospheric and climatic, and the stellar magnetic and radiation environment?

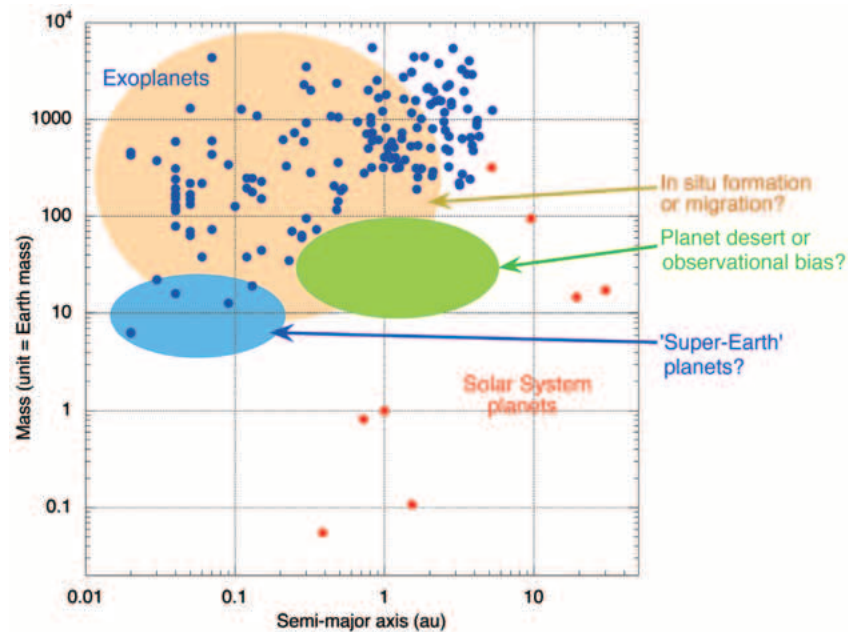
For the first time, we are able to build instruments that allow us to investigate

directly how unique the Earth is and whether or not we are alone in the Universe. Discovering Earth's sisters and possibly life is the first step in the fundamental quest of understanding what succession of events led to the emergence and survival of life on Earth. For this, we need to know how, where and when stars form from gas and dust and how, where and when planets emerge from this process. This is certainly one of the most important scientific goals that ESA and Europe could set themselves.

1.1 From gas and dust to stars and planets

The atoms from which the present generations of stars and planets were formed went through a succession of violent processes from the very early times, when the Universe began and the first generation of stars formed. Most objects we see today are made from the ashes of stars that no longer exist. Indeed, this also applies to mankind, as we are literally stardust. The stars that produced the carbon we have in our bodies, and the oxygen we breathe, were formed, evolved and died long ago. Much information comes both from ground-based and space observatories on the way that stars evolve throughout their lives. Data on how stars die are being and will be obtained by X-ray and gamma-ray space observatories. Conversely, the way that stars and planetary systems form remains much less well known.

Many sorts of observations at many different wavelengths are required in order



Comparative characteristics of exoplanets and Solar System planets. The exoplanets discovered so far are very different from Solar System planets. Masses and semi-major axis are plotted (blue dots) for 160 exoplanets (*The Extrasolar Planets Encyclopaedia*, J. Schneider) and eight Solar System planets (red dots); Pluto lies beyond the frame of the figure). (W. Benz, Univ. Bern, Switzerland)

to characterise the large variety of stars found in a galaxy and all their possible evolutionary states. ESA continues to play a leading role in the understanding of many aspects of the life and death of stars. Its pioneering astrometric satellite, Hipparcos, provided unprecedented information on the luminosities, motions and ages of stars in the solar neighbourhood. Gaia, now in preparation, will build on this expertise and extend the measurements to the whole Milky Way Galaxy, bringing within its astrometric reach even the faintest and/or the most rapidly evolving stars. In addition to luminosities, motions and ages of stars all over the Galaxy, the spectrophotometric instrument aboard Gaia will provide detailed chemical information on the atmospheres of the brightest stars among the one billion objects it will observe.

While our understanding of stellar evolution is making giant leaps forward, we still lack a comprehensive theory explaining why and how stars form from interstellar matter and, apparently quite often, planetary systems with them. The formation of planets has to be considered in the wider context of star formation and circumstellar disc evolution.

Magnetic fields and turbulence are often invoked as playing a key role in the birth process. The large diversity of orbital characteristics among the exo-planets points to the importance of planet-disc and planet-planet interactions. These can lead to surprising consequences, such as large-scale inward migration of giant planets and/or pumping of the orbital eccentricity, which then raises questions about the long-term stability of these systems. The problem is therefore essentially to establish which basic characteristics of the star-formation process determine the bulk properties of the planetary system that eventually emerges, several tens of millions of years later.

The star- and planet-formation processes require a multi-wavelength approach, mostly from near-infrared to millimetre wavelengths. A large part of this wavelength range is absorbed by Earth's atmosphere, and observable only from space. With ESA's Infrared Space Observatory (ISO) mission completed, the Herschel far-infrared observatory in preparation, and ESA's planned participation in NASA's James Webb Space Telescope (JWST), and with ESO's ground-based facilities including the joint Europe-US Atacama Large Millimeter Array (ALMA) project, the European star formation community is in a very strong position.

However, a key window in the electromagnetic spectrum has yet to be fully opened to make further definitive progress in this field: the far-infrared. These wavelengths are best suited to observe and



study the dusty regions where stars and planets are forming, for three main reasons: the peak of the spectral energy distribution emitted by these regions is located at these wavelengths, key water lines are found in this spectral range, and the dust extinction is minimal. Since Earth's atmosphere is opaque at these wavelengths, this spectral window can be opened only from space. Even with a 3.5 m telescope, Herschel is not sensitive enough to resolve proto-stars. Hence a new-generation **far-infrared observatory** space mission is required. A spatial resolution of the order of 0.01 arcsec will be needed to resolve the proto-stars and their associated discs in the nearest star-forming regions, together with high- and low-resolution spectroscopy capabilities in order to characterise line emission and dust mineralogy.

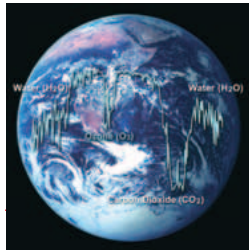
1.2 From exo-planets to biomarkers

The first detection of a planet orbiting a solar-type star, achieved by a European team, occurred only 10 years ago. Many of the 160-odd planets found as of today have unexpected orbital characteristics. These

discoveries have sparked a large number of observational efforts, all over the world, to find more of these objects, as well as theoretical studies aimed at explaining their characteristics. The European astronomy community has played a particularly important role in this endeavour, building on the synergy between ground-based and space projects. A joint ESA-ESO working group is now dedicated to this cooperation.

To understand the origin of the Solar System in general and of the Earth in particular, it is essential to place our planetary system into the overall context of planetary system formation. To guide the theory, a complete census of all the planets from the largest to the smallest out to distances as large as possible is required. This can be achieved by making use of a variety of detection techniques, ranging from the high-precision measurement of radial velocities, high-accuracy astrometry to detect the tiny reflex motion of the star in the plane of the sky, and photometry to measure the changes of brightness during a transit or during a gravitational lensing event.

Hubble Space Telescope's panoramic view of a star-forming region in the Large Magellanic Cloud (LMC), a neighbouring galaxy only 160 000 light-years from Earth. With its high resolution, the Hubble is able to view details of star formation, showing glowing gas, dark dust clouds and young, hot stars. However, far-IR wavelengths would open a key window to observe and study the dusty regions where stars and planets are forming. (NASA/ESA; Hubble Heritage Team (AURA/STScI)/HEIC)

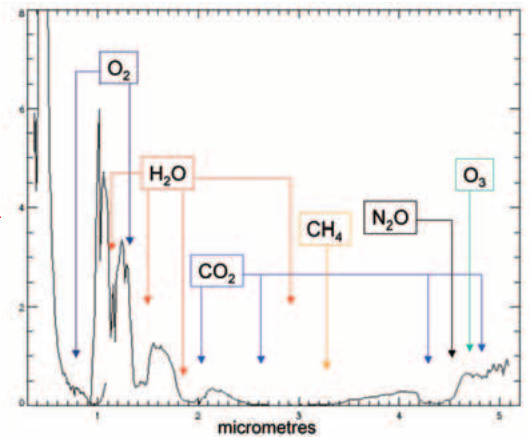


Detecting the biomarkers in the spectrum of an Earth-like planet is a difficult problem.

A large and complete sample will tell us which stars are most likely to host which kinds of planets. It will, for example, allow quantification of the influence of the chemical characteristics of host stars (is metallicity a key factor for planetary formation?), and of their position and motion with respect to the galactic plane and the global rotation of the Galaxy. The statistical analysis of the planets' orbital parameters and mass will unravel correlations which might point towards the key physical mechanisms involved in the formation and evolution of these systems. Most likely, we will also discover planets with masses and temperatures compatible with the formation of an atmosphere and the presence of liquid water, i.e. planets in the 'habitable zone'.

All the discoveries of planets have so far come from ground-based telescopes, although space-based instrumentation has already provided some extraordinary insights, such as Hubble Space Telescope observations of a photometric transit of one exo-planet in front of its mother star, and the evaporation of the atmosphere of another exo-planet. The situation is about to change with the prospective detection of planets of nearly the same size as the Earth by the French-ESA Corot mission and later by NASA's Kepler.

Only the extremely stable environment of space observatories will bring the possibility of high-precision photometry and astrometry. A major census of the giant planets by ESA's Gaia astrometric mission will deliver systematic insights into the



Spectrum of the Earth, taken by the OMEGA visible and infrared mineralogical mapping spectrometer of Mars Express on 3 July 2003. Since the Earth filled about one OMEGA pixel from the 8 million km distance, the spectrum corresponds to the entire illuminated crescent, dominated by the Pacific Ocean. It covers the 0.35-5.15 μm visible and near-IR domain, with spectral sampling varying from 4 nm to 20 nm. Several molecules were easily identified in this region. (ESA/IAS Orsay)

frequency of giant planets in the Galaxy. It will thereby set important constraints concerning the properties of the host stars, and their locations in the Galaxy, that favour the formation of planets. In addition, since the presence and location of one or several giant planets may severely affect the formation of smaller planets in a system, Gaia will provide important information on the likelihood of finding Earth-like planets orbiting their stars in the habitable zone.

The coming decade will be devoted to the statistical exploration of planetary populations and to the understanding of the best conditions for planetary system formation. Thereafter, within the 2015-2025 timeframe, new observational techniques will allow us to separate the photons coming from the planets from those stemming from the host star, and will open an entirely new era of direct detection of exoplanets and planetary imaging and spectroscopy. This will represent a major step forward in our ability to study exo-planets, during which the temperature,



Earth observed by Voyager-1 on 14 February 1990 from 42.6 AU, showing a crescent of only 0.12 pixel. (NASA)

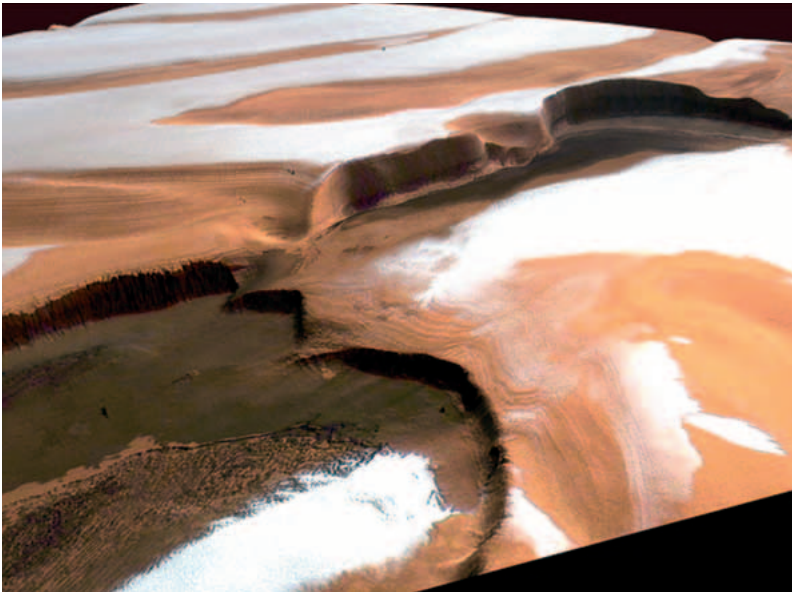
chemical composition and other characteristics of the atmospheres of these bodies can be measured. With these capabilities, we will also have the means to search in the spectrum for possible markers of biological activities.

Only a space observatory will have the ability to distinguish the light from Earth-like planets and to perform the low-resolution spectroscopy of their atmospheres needed to characterise their physical and chemical properties. The target sample would include about 200 stars in the solar neighbourhood. Follow-up spectroscopy covering the molecular bands of CO₂, H₂O, O₃ and CH₄, typical tracers of the Earth spectrum, will deepen our understanding of Earth-like planets in general, and may lead to the identification of unique biomarkers. The search for life on other planets will enable us to place life as it exists today on Earth in the context of planetary and biological evolution and survival.

To make it possible, a major technical hurdle has to be overcome: the high

brightness ratio between the star and the planet. Pioneering work by ESA and European laboratories is leading to the development of advanced technology based on optical interferometry to achieve destructive interferences reducing, or nulling, the star's light but leaving the planet's unmodified. A **near-infrared nulling interferometer** operating in the wavelength range 6-20 μm would provide the tool necessary to achieve these objectives. Based on the technology and expertise already being developed, and implemented around 2015, it would make Europe a pioneer in this field and guarantee its continuing leadership in exo-planet research.

On a longer timescale, a complete census of all Earth-sized planets within 100 pc of the Sun would be highly desirable. Building on Gaia's expected contribution on larger planets, this could be achieved with a high-precision **terrestrial planet astrometric surveyor**. Eventually, the direct detection of such planets followed by high-resolution spectroscopy with a large telescope at infrared, visible and



Layers of water ice and dust in Mars' north polar cap, observed by Mars Express. The cliffs are almost 2 km high, and the dark material could be volcanic ash. (ESA/DLR/FU Berlin; G. Neukum)

ultraviolet wavelengths, and ultimately by spatially-resolved imaging, will mark the coming-of-age of yet another entirely new field of astronomy: comparative exo-planetology.

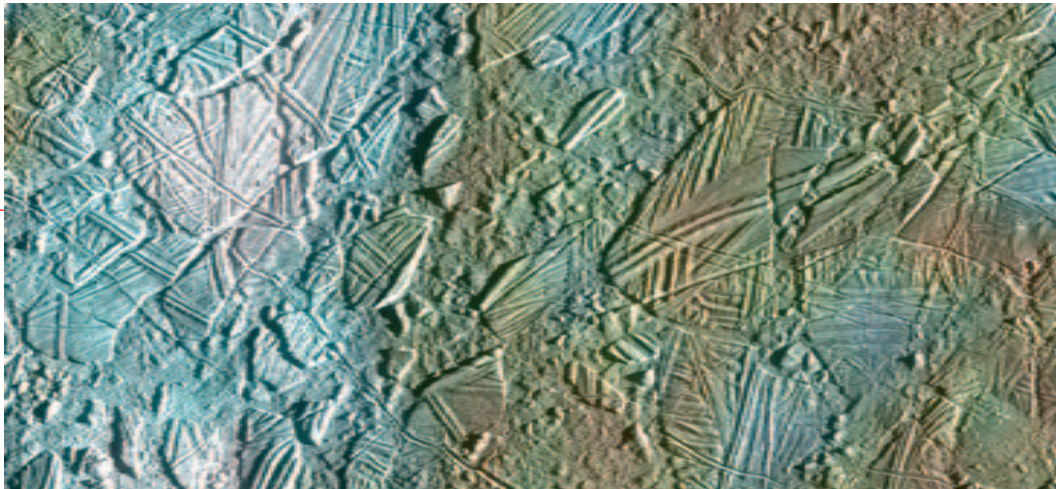
1.3 Life and habitability in the Solar System

The quest for evidence of a second, independent genesis of life in the Solar System must begin with an understanding of what makes a planet habitable and how the habitable conditions change, either improving or degrading with time. For instance, the environmental conditions on the Earth today are not the same as when life first arose on this planet. The early Earth, with its oxygen-free atmosphere, high ultraviolet radiation, high temperatures and slightly acidic waters, could not support the highly evolved life forms so familiar to us. However, life could not have arisen on a planet with the environmental conditions that exist on Earth today.

We can define the basic habitable conditions for life, as we know it. For life to appear, a planet needs liquid water, a

source of carbon, a source of energy and a source of nutrients including nitrogen (N), phosphorus (P), sulphur (S), magnesium (Mg), potassium (K), calcium (Ca), sodium (Na) and iron (Fe). For life to survive, the nutrients need to be renewed and this can only be done by active geological processes, such as recycling of the crust by some form of tectonic activity. For life to evolve, however, the environmental conditions on a planet need to evolve as well. On Earth, the phenomenon of habitat evolution is related to the parallel processes of geological evolution and the interaction of life processes with the planet, leading most conspicuously to the appearance of free oxygen and a protective ozone layer in the atmosphere.

A major problem on Earth is that plate tectonics have eliminated all of the first 500 million years of rock history and severely altered the next 500 million years, so that the crucial first billion years when life arose and took a foothold is barely recorded. This gap in our knowledge can be filled by studying other planets that did not develop plate tectonics and still have a record of the early environmental conditions. Mars is an ideal goal. Although the present conditions at the surface of the planet are not conducive to the long-term sustenance of life, Mars had an early history that was similar to that of the early Earth and conditions that were suitable for the appearance of life. A major question is: how did continued evolution of the planet affect the habitable environment and what happened to the planet to make its surface uninhabitable today?



Europa is a high-priority target in the search for habitability in the Solar System. (NASA/Galileo)

Spacecraft going to Mars can therefore address basic questions regarding the habitability of the Solar System, such as:

- what were the conditions during the earliest period in the history of the terrestrial planets when the planets became habitable and when life appeared, at least on Earth?
- did geological evolution on Mars affect the habitable environment, and what happened to the planet to make its surface apparently uninhabitable today?
- was there ever, or is there still, life on Mars?

The spacecraft will need to investigate the structure, geochemistry and mineralogy of rocks in various geological locations on Mars in order to identify their origin and geological history. More generally, they need to gather information about the mechanisms that controlled the evolution of the Martian environment and the history of water on Mars. It is essential to place any *in situ* measurements in context; for example, did the rocks form in a liquid water environment? Such investigations should also include science packages to search for evidence of extinct or extant life.

Additional geophysical investigations of the deep and crustal structure of the planet are

needed to understand its present state and activity. Measurements of climatic conditions are also required, to trace their evolution and the conditions of habitats back in time. Access to specific, selected locations on Mars, including rough and high terrain, and to the subsurface, will be essential for investigating many different geological and environmental settings and thus maximising the chances of detecting traces of life, if any.

These goals may require the development of new technologies for **Mars landers**, such as capable rovers, precision landing and deep drilling. Orbiting spacecraft could be used to carry out remote sensing of the planet, its atmosphere and climate, and its plasma-magnetic environment, while acting as a relay satellite. Monitoring of the present environment is also needed to understand the present condition of the habitat and also in preparation of future manned missions.

Ultimately a high-priority goal, which should be achievable in the 2015-2025 timeframe, is a **Mars sample return** project, bringing back samples from selected sites already studied by landers. While *in situ* measurements at multiple locations will provide invaluable information, there are some investigations that require terrestrial

laboratory analyses, including isotopic measurements, microfossil identification and age dating.

Jupiter's moon Europa, which possesses an interior ocean, also has a high priority in the search for habitability in the Solar System. It is important to determine Europa's internal structure and especially its internal heat sources. Analysis of the composition of the ocean and icy crust is of paramount importance for determining the availability of nutrients. The plasma and radiation environment around Jupiter and its interaction with Europa would also provide important information regarding the survivability of any life throughout the moon's history. These science goals could be achieved by a dedicated **Europa orbiter and/or lander**. While highly desirable, a Europa lander may not be technologically feasible within 2015-2025.

Ferocious particle radiation at Europa, which visiting spacecraft will have to endure, would

make life quite impossible on its surface. This illustrates another important aspect of habitability, namely the magnetic coupling between the central star and its planetary system. The Earth's habitability, in particular, is maintained by a slowly evolving Sun that gives almost constant illumination while screening us from energetic particles coming from supernovae in the Galaxy. The solar wind, expanding from the hot solar corona throughout the heliosphere, carries turbulent magnetic fields out to the edge of the Solar System, which drastically reduce the flux of cosmic rays. To characterise completely the conditions needed to sustain life, especially in an evolved form, we must therefore understand the solar magnetic system, its variability, its outbursts in large solar eruptions and the interactions between the heliosphere and the planets' magnetospheres and atmospheres. A **Solar Polar Orbiter** would provide much-needed insight into the structure of the Sun's magnetic field, especially by observing it from above the poles (Section 2.1).

Toolkit for Theme 1

Tools

1. What are the conditions for planet formation and the emergence of life?

Place the Solar System into the overall context of planetary formation, aiming at comparative planetology.

1.1 From gas and dust to stars and planets

Map the birth of stars and planets by peering into the highly obscured cocoons where they form

Investigate star-formation areas, proto-stars and proto-planetary discs and find out what kinds of host stars, in which locations in the Galaxy, are the most favourable to the formation of planets

Investigate the conditions for star formation and evolution

Far-infrared observatory with high spatial and low to high spectral resolution

1.2 From exo-planets to biomarkers

Search for planets around stars other than the Sun, looking for biomarkers in their atmospheres, and image them

Direct detection of Earth-like planets, with physical and chemical characterisation of their atmospheres for the identification of unique biomarkers

Systematic census of terrestrial planets

Ultimate goal: image terrestrial planets with a large optical interferometer

Near-infrared nulling interferometer with high spatial resolution and low-resolution spectroscopy

Terrestrial planet astrometric surveyor

1.3 Life and habitability in the Solar System

Explore in situ the surface and subsurface of solid bodies in the Solar System most likely to host – or have hosted – life

Mars is ideally suited to address key scientific questions of habitability. Europa is the other priority for studying internal structure, composition of ocean and icy crust and radiation environment around Jupiter

Environmental conditions for the appearance and evolution of life include not only geological processes, the presence of water and favourable climatic and atmospheric conditions, but also the magnetic and radiation environment commanded by the Sun's magnetic field

Mars exploration with landers and sample return

Europa orbiter and/or lander in Jupiter Exploration Programme (JEP)

Solar polar orbiter to chart the Sun's magnetic field in 3-D



Chapter 2

The search for the origins of life discussed in Chapter 1 must begin in our own Solar System. Understanding how the Sun behaves over a range of timescales, how the planets can be shielded from its radiative and plasma output, why the nine Solar System planets are so different from one another, and what the small bodies such as comets and asteroids can tell us about our origins – these are only a few aspects of the question. The generic circumstances under which planets are habitable are unknown, but must depend on the radiative output and magnetic activity of the neighbouring star, on the behaviour of the space environment surrounding the planets, on the material from which the planets originally accreted, and so on.

The exploration of the Solar System also encompasses many other scientific questions of fundamental importance, beyond the origins of life. Why do the Sun and other stars generate magnetic fields? Why do these fields result in a high-temperature corona and a solar (or stellar) wind? How do planetary atmospheres and magnetospheres respond to the interaction with the solar wind? Why do planets and moons have such a variety of atmospheres and surfaces? What determines the presence of water on planets, now or in the past? What are comets and asteroids made from and what does this tell us about the origin of the Solar System?

European scientists and ESA have taken on a leading role in the exploration of our Solar System over the past 40 years, addressing these questions. The achievements are

How Does the Solar System Work?

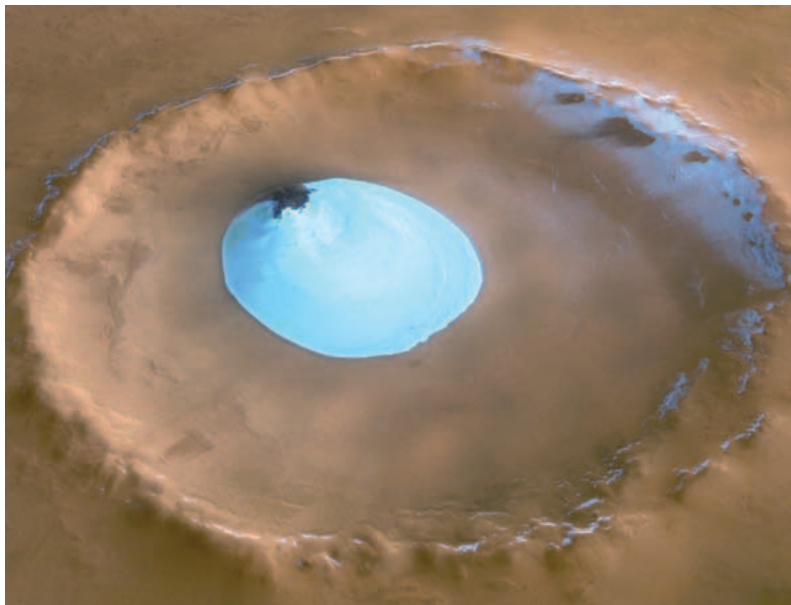
multiple and impressive, and will remain so for the next decade.

The Sun and the heliosphere have been explored by the Ulysses and Solar and Heliospheric Observatory (SOHO) missions. Ulysses has produced the first characterisation of the 'three-dimensional Sun' through its pioneering flight over the solar poles, demonstrating the very significant differences between the minimum and maximum of the activity cycle, as well as revealing very large gaps in our understanding of how magnetic fields and particles fill the heliosphere. SOHO has pioneered techniques for looking below the solar surface, by helioseismology, revealing a complex range of mass motions that transport energy and magnetic field through the solar convection zone. The coronal imaging instruments aboard SOHO have revealed a new, dynamic, multi-thermal solar corona that has forced scientists to rethink their ideas of how the corona is heated. Finally, SOHO has convincingly demonstrated the generic causal link between massive solar eruptions and disturbances in the Earth's space environment, dominated by coronal mass ejections. In the future, ESA's Solar Orbiter mission will examine the Sun from vantage points unique in two respects: from close in, at about one-fifth of the distance from the Sun to the Earth, and from up to about 30° out of the ecliptic plane.

The Earth's space environment was explored by HEOS-1 and -2 back in the days of the European Space Research Organisation that preceded ESA, and more

recently by the pioneering and innovative four-spacecraft Cluster mission. Cluster is a unique enterprise. For the first time in the magnetosphere of the Earth, it has been possible to obtain accurate measurements of the motion of the plasmas found there, as well as of the shape of the boundaries that lie between the terrestrial and solar magnetic fields. It is now clear that the Sun and solar wind exercise a very strong degree of control over the magnetosphere. Cluster, along with the Double Star mission, carried out in collaboration with the Chinese Space Agency, has also revealed for the first time the complex hierarchy of spatial and temporal scales that govern this interaction. European expertise in this field also extends to studies of the magnetosphere of Saturn, through extensive participation in the NASA-ESA-ASI Cassini-Huygens mission, with an abundance of data already from the Cassini orbiter. The space plasma community is looking forward with great excitement to exploring the enigmatic magnetosphere of the planet Mercury as part of the ESA-JAXA BepiColombo mission. Among its unique features, compared with other magnetic planets, Mercury's magnetosphere has no ionosphere.

Europe took the lead in the exploration of comets with the remarkable encounter in 1986 of the Giotto spacecraft with comet Halley. This bold mission showed for the first time the actual shape of the cometary nucleus, the complex processes by which material sublimates from the nucleus to form in particular the tail, and the extensive interaction of cometary material with the



Mars Express in 2005 revealed water ice in a 35 km-diameter crater on the Vastitas Borealis plain, which covers much of Mars' far northern latitudes. (ESA/DLR/FU Berlin; G. Neukum)

solar wind that extends millions of km from the comet. The European cometary community is looking forward to the arrival of the Rosetta spacecraft and lander at comet Churyumov-Gerasimenko in 2014.

Mars Express is currently mapping the Martian surface and monitoring its climate system with new instruments that have already provided major discoveries. The unprecedented colour, stereo and spectral images, as well as the multi-wavelength spectral observations, are revealing new aspects of Martian geology and climatology, including recent volcanism, glaciers, water ice reservoir, and allowing the identification of evaporitic minerals that formed in the presence of liquid water. Furthermore, traces of methane in the atmosphere have been detected. The European planetary science community awaits the first ESA mission to Venus, Venus Express, to be launched later in 2005. This cross-disciplinary mission will undoubtedly make important breakthroughs concerning the surface and atmosphere of Venus, as well as its interaction with the solar wind.

The spectacular results from Huygens have revealed Saturn's moon Titan to be a

fascinating place. Many features can be said to resemble those found on Earth, such as drainage channels and oceans, but other features are strikingly different: the dominance of hydrocarbons in the atmosphere and on the surface, rocks made of dirty ice, and methane rain! Even at this early stage in the analysis of the data, it is clear that these results will have an enormous influence on planetary science.

The future of Solar System science in Europe is bright for the next decade. We will explore the innermost planets (Mercury, Venus and Mars) in extraordinary detail with the BepiColombo, Venus Express and Mars Express missions. We will continue to look at the Sun with the ESA-NASA SOHO and the JAXA-ESA Solar-B spacecraft, and eventually with Solar Orbiter, as well as making contributions to the international STEREO mission. The very pleasant windfall of an extended Cluster mission will enable Europe to continue to set the international standard in multi-point measurements of the magnetosphere, complemented by investigations of magnetospheres at Mercury and Saturn. But what comes after that? This is the question we now address.

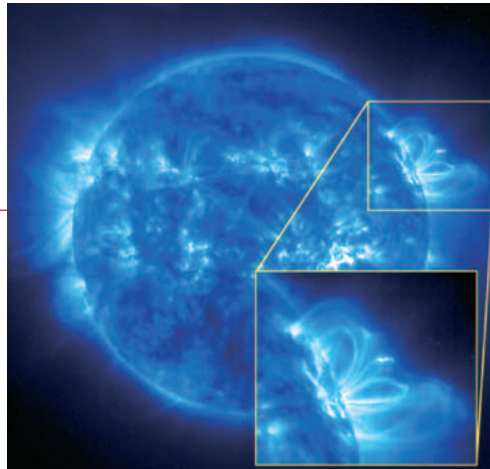
2.1 From the Sun to the edge of the Solar System

The Sun dominates the Solar System. Its radiation provides the means to sustain life, but its continuous and occasionally violent activity provides the means to destroy it. Both are critically important areas to be studied. Only in the Solar System can we establish the 'zero-order truths' concerning

the Sun, its all-important magnetic field and the interaction of the solar wind with the planetary environments, which can then be extended to planetary systems elsewhere in the Universe.

The varying magnetic field of the Sun is directly responsible for changes in the solar ultraviolet and X-ray emission, and is also closely related to the physics of long-term solar cycles and their possible forcing role in climatic variations. It is responsible for the solar activity that leads to the solar wind plasma interacting with the planetary environments. The solar magnetic field is continuously generated and destroyed on timescales ranging from fractions of a second to decades, and it fills the heliosphere, a volume of space that extends to at least 10 billion km from the Sun. These topics will remain major scientific challenges in the Cosmic Vision 2015-2025 timeframe.

The structure of the global magnetic field at the Sun's visible surface is not known and its determination will require observations from above the poles. To understand the field's origin, through the dynamo process believed to operate at the base of the convection region, calls for the mapping of the global 3-D subsurface flows, especially at the poles, and imaging of the subsurface structure through local and global helioseismology. In this way, one can obtain a picture of how the field is transported immediately below the surface, and how that relates to what emerges through the surface. The primary requirement is for a **solar polar orbiter**.



The structure of the Sun's global magnetic field at the visible surface remains unknown.

The magnetic field in the Sun's corona drives solar activity on timescales of hours to weeks to years to centuries, through the level of ultraviolet and X-ray emissions from the corona. However, the critically important techniques to measure that field are only now being developed. These include the study of important emission lines in the infrared and by spectropolarimetry at shorter wavelengths using the Hanle effect, whereby scattering of emission-line radiation in the presence of a magnetic field leads to polarised light. At present, some of these techniques are being pioneered using ground-based instrumentation, but making such observations from space is likely to prove highly desirable owing to the broader possible wavelength coverage, especially in the ultraviolet domain.

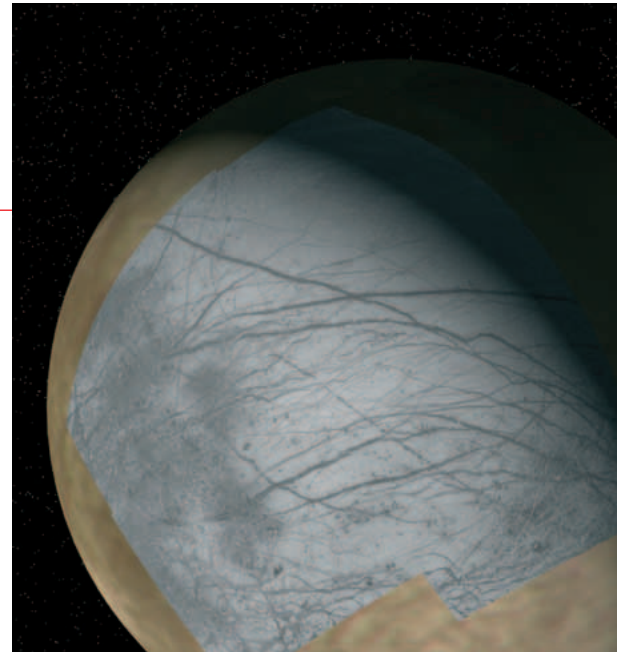
The expansion of the Sun's atmosphere fills the heliosphere with the plasma and magnetic field that are collectively known as the solar wind. In this medium, processes that are generic to all of astrophysics (heating, the acceleration of particles and turbulence) can be studied with comparative ease. These processes also dictate how the Sun's magnetic field interacts with planetary environments. Some planets (Mercury, Earth and the gas giants) have magnetic fields that provide partial shielding. Mars has a thin

*Models of Europa's structure. Far right: ice cliffs on Europa.
(NASA/JPL)*

atmosphere and a weak remnant magnetic field, while Venus has a dense atmosphere and no magnetic field. With so many different planets, the Solar System provides a vast range of laboratories for studying the possible interactions of exo-planets with the winds from their host stars.

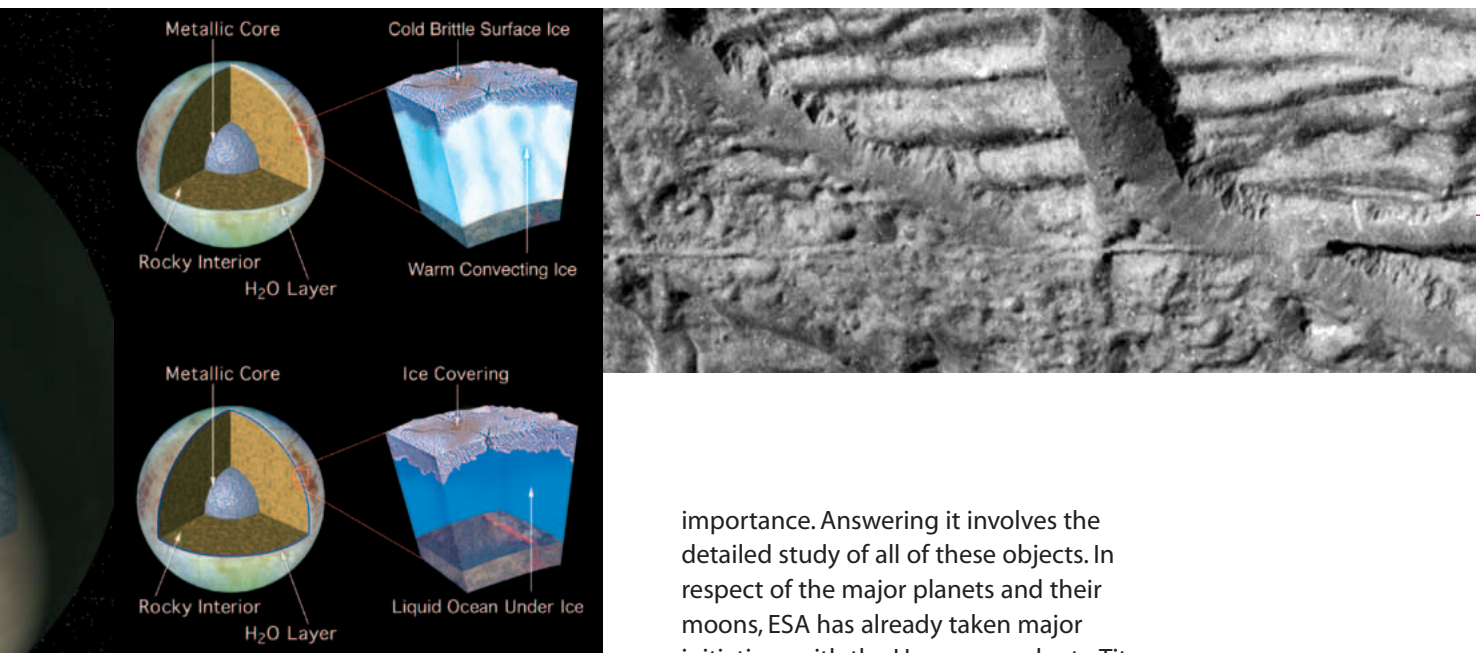
While the scales of planetary magnetospheres are vast (up to 10 million km at Jupiter), the inescapable fact is that the interaction between the magnetic fields of the planet and the Sun occurs over a range of scales between a few km and a few planetary radii! Similar hierarchies of scales are likely to arise in other fundamental processes such as turbulence, magnetic field annihilation and particle acceleration, leading to the astonishing diversity of structures and dynamical behaviours that characterise most astrophysical media.

Measurements have never been made on the smallest scales required, even in the Earth's magnetosphere, and as a result the fundamental aspect of the electrodynamics of the plasma Universe – the cross-scale coupling – has remained inaccessible. To understand the generic processes in plasma physics, it is now vital to move on from Cluster, which has four satellites operating in company at relatively large distances, to simultaneous observations at a much larger number of points. This will lead to the resolution of both the hierarchy of scales involved in cross-scale coupling as well as the smallest and fastest plasma processes. The possibility of using a fleet of satellites in an



Earth magnetospheric swarm provides an exciting prospect in the timescale of Cosmic Vision 2015-2025.

The magnetosphere of Jupiter is another wonderful laboratory for studying how plasmas behave in space. With its rapid rotation, strong magnetic field and internal sources of plasma, it has been compared to binary stellar systems and even pulsars. It is the most accessible environment for studying some further fundamental processes such as the plasma's interactions with neutral gas and with the planet's moons, magnetodisc stability, the relaxation of rotational energy and associated energetic processes, and the loss of angular momentum by magneto-plasma interactions. The last two processes are important in understanding accretion mechanisms that lead to the formation of planetary systems. A group of at least three spacecraft operating together with an optimised plasma payload, as part of a **Jupiter exploration programme**, will permit the first fundamental advances in understanding the structure and dynamics of this fascinating plasma environment.



The boundary with interstellar space – the heliopause – is the final frontier of the Sun's empire. Were a spacecraft to travel the 10 billion km or more needed to reach it, and then pass through it, our instruments would enter the interstellar medium, a completely distinct environment from the Solar System that has never been sampled *in situ*. An **interstellar heliopause mission** would provide the first 'ground truth' measurements of what the interstellar medium really feels like, and directly observe the interplay between the various components of the interstellar medium – plasma, dust, magnetic fields and neutral atoms – with the Solar System's outermost defences.

2.2 The giant planets and their environments

In addition to the Sun and the interplanetary medium, the Solar System comprises the planets, their satellites, small bodies such as comets and asteroids, and dust. How this possibly unique environment arose and how it has evolved are scientific questions of the highest

importance. Answering it involves the detailed study of all of these objects. In respect of the major planets and their moons, ESA has already taken major initiatives with the Huygens probe to Titan, the SMART-1 mission to the Moon, Mars Express, Venus Express and the BepiColombo mission being prepared for Mercury. To continue its prominent role, ESA needs to choose carefully further aspects of planetary science to pursue in the Cosmic Vision 2015-2025 timeframe. The main goal should now be an in-depth exploration of one of the giant planets in the outer Solar System, of which Jupiter is the most accessible.

When considered together with its rings, its diverse moons, and its complex environments of dust, gas and plasma, a giant planet can be seen as a miniature analogue of the Solar System. Studying it can help to build a firmer understanding of the formation of full-scale planetary systems. At present, *in situ* exploration in the Solar System is the only way we can examine giant planets in detail and provide strong constraints on scenarios for their formation. In the period 2015-2025, such investigations will benefit from complementary studies of exo-planetary systems. Giant planets play a key role in the evolution of planetary systems in general, and the accessible local examples are somehow related, if only in size, to the 'hot Jupiter' type of giant exo-planets.

The study of the giant planet systems addresses many important scientific questions:

- how were the planets and their moons formed from the solar nebula? Different formation scenarios, such as disc instability versus core accretion, need to be tested.
- what is the internal structure of the giant planets themselves, and, in particular, do they have a solid core, and of what size? These questions can be answered by carrying out deep atmospheric soundings, through remote sensing and *in situ* investigations, coupled with accurate measurements of the planetary gravitational and magnetic fields.
- what are the processes involved in the formation and evolution of the atmospheres of these planets and their moons? As illustrated dramatically by the exploration of the dense atmosphere of Saturn's moon, Titan, in the Cassini-Huygens mission, a combination of remote-sensing and atmospheric probes is needed.
- what is the internal and subsurface structure of their satellites, especially the icy ones; what is the geological history, and how does this reflect their formation? Here, the gravitational and magnetic fields, as well as the surface morphology, topology, mineralogy and composition, need to be studied.
- how are their complex plasma, gas and dust environments coupled to the central giant planet, to its satellites and rings, and to the interplanetary

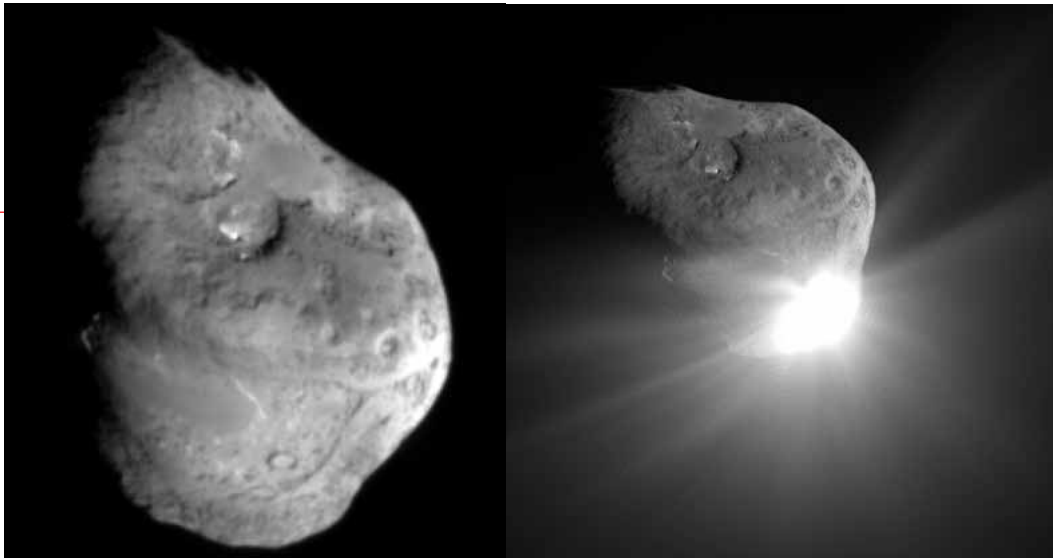
medium? The *in situ* measurements need to be related to plasma injections from the solar wind, from moons such as Io, and from the planet itself; also to the role of planetary rotation, and the consequences of any magnetospheric activity such as aurorae.

The vast range of topics requiring study calls for a staggered approach with a series of missions to a planet such as Jupiter. Measurements will be needed of many different physical quantities: atmospheric composition and dynamics, gravitational and magnetic fields, plasmas and planetary and lunar surfaces. Possible scenarios for a **Jupiter exploration programme** are outlined in Chapter 5. The spin-off from such investigations into understanding the structure of giant exo-planets cannot be over-stated.

2.3 Asteroids and other small bodies

As the primitive, leftover building blocks of planet formation, small bodies of the Solar System offer clues to the chemical mixture from which the planets formed. They hold unique information on the initial conditions and early history of the solar nebula, and their study is essential to understanding the processes by which interstellar material becomes new planetary systems with the possibility of bearing life.

ESA has already taken major initiatives in this field, with the pioneering encounters of the Giotto spacecraft with comets Halley and Grigg-Skjellerup, and by the dispatch



Comet Tempel 1 5 min before and 67 sec after Deep Impact's strike on 4 July 2005. The nucleus is about 5 km across. (NASA/JPL-Caltech/UMD)

of the Rosetta mission to comet Churyumov-Gerasimenko for a much more thorough investigation of the primordial material, with an orbiter and a lander. The natural next step in ESA's exploration of small Solar System bodies would be a sample return mission of material from one of the near-Earth asteroids.

These objects are dynamically connected to the family of Main Belt asteroids – they can be considered essentially to be extensions of it. By choosing an object belonging to one of the most primitive classes of this family, and by analysing samples taken in various well-determined geological contexts, many long-standing questions can be answered:

- what were the composition and the physical properties of the building blocks of the terrestrial planets?
- what were the processes occurring in the solar nebula accompanying planetary formation?
- what is the nature and origin of the organic materials in primitive asteroids?
- are there lessons for our understanding of the origin of life in the Solar System?
- do asteroids of primitive classes contain pre-solar material not yet known in meteoritic samples?

- do they contain chondrules, the main component of the carbonaceous chondrite class of meteorites, for which the formation process is warmly debated?
- how do the elemental, mineralogical and isotopic properties of the asteroid samples vary with geological context on the surface?
- how do space weathering and impacts affect the surface composition of an asteroid?
- what was the timeline and duration of major events, such as agglomeration, heating and degassing, and aqueous alteration?
- how did the various classes of asteroids and meteorites form and acquire their present properties, and how are the asteroidal and meteoritic classes related?

By far the most efficient way to address these questions is by a **near-Earth object sample return**, making possible extensive and unique diagnostics achievable only by ground-based laboratory analyses of these samples. Combined with detailed imaging and spectroscopic investigations of the parent body, laboratory analysis of asteroid samples will improve the interpretation of all meteoritic data and provide a new

understanding of all astronomical spectra of asteroids acquired so far.

Clearly, a full understanding of the populations, histories and relationships of asteroids and meteorites will eventually require sample return missions to asteroids belonging to each of the spectral classes. In the first asteroid sample return mission, the Japanese Hayabusa spacecraft will arrive in 2005 at the near-Earth asteroid 25143 Itokawa. Successful return of samples in this case will unravel the nature of

differentiated S-type asteroid material. But only a sample return mission to one of the most primitive, carbon-rich C-type objects, as proposed here, will address the main questions on the origin of the Solar System.

Ultimately, exploration of the icy Kuiper belt objects, the likely building blocks of the cores of the giant planets, will be desirable, but as they lie at the distance of Neptune and beyond, any thorough investigation is unlikely to be feasible in the Cosmic Vision 2015-2025 timeframe.

Toolkit for Theme 2*Tools***2. How does the Solar System work?****2.1 From the Sun to the edge of the Solar System**

Study the plasma and magnetic field environment of the Sun, the Earth, the Jovian system (as a Solar System in miniature), and out to the heliopause where the solar wind meets the interstellar medium

Earth magnetospheric swarm

The Solar System, pervaded by the solar plasma and magnetic field, provides a range of laboratories to study the interactions of planets with the solar wind

Jupiter exploration programme

Understanding the origin of the Sun's magnetic field requires observations of the field at the visible surface around the poles

Solar polar orbiter

In situ observation of the heliopause would provide 'ground truth' measurements of the interstellar medium

Interstellar heliopause probe

2.2 Gaseous giants and their moons

Study Jupiter *in situ*, its atmosphere and internal structure

Jupiter exploration programme

Study European surface *in situ*

Jupiter probes

Giant planets with their rings, diverse satellites and complex environments constitute systems that play a key role in the evolution of planetary systems

Europa lander

2.3 Asteroids and other small bodies

Obtain direct laboratory information by analysing samples from a near-Earth asteroid

As building blocks in the Solar System, the most primitive small bodies give clues to the chemical mixture and initial conditions from which the planets formed in the early solar nebula

Near-Earth object sample return



Chapter 3

The most important challenge facing fundamental physics today is to understand the foundations of nature more deeply. Physicists know that the laws of physics as formulated at present do not apply at extremely high temperatures and energies, so that events in the first fraction of a second after the Big Bang are not at all understood. Matter as we know it today did not then exist; protons and electrons formed later. Yet whatever happened during this first instant created the conditions that led to everything we see today: atoms, stars, galaxies and people. Many physicists believe that in these extreme conditions physics was governed by the 'ultimate theory', a single theory that explains and unifies all the separate laws and forces as they appear today.

Physicists need experimental data to guide them to this theory, to turn mathematical speculation into solid understanding. Experiments in giant accelerators, such as the Large Hadron Collider (LHC) under construction at CERN, offer one approach. Their energies are many orders of magnitude below the energies in the Big Bang, but physicists have reasons for expecting some clues to the ultimate laws to turn up in accelerator experiments. Increasingly, however, physicists are also turning to two other ways of finding clues to the way physics unifies at high energies: high-precision tests of 'known' laws of physics; and quantitative studies of cosmology, of the structure and evolution of the Universe as a whole.

Cosmologists have already made three surprising discoveries that challenge current

What Are the Fundamental Physical Laws of the Universe?

physics and point toward unified theories. The first is the realisation that most of the matter in the Universe is in an unknown form, not made of the atoms and molecules of which we are made. This is called *dark matter*. The second is *inflation*: during that mysterious split second after the Big Bang, the Universe seems to have expanded with a huge acceleration, ending in a smoothly spread-out state with just enough irregularity to have led to the formation of galaxies, stars and planets. No known force can produce this rapid expansion, but unified theories seem to provide a mechanism. Even more challenging is the third and most recent discovery: the Universe has more recently begun to accelerate again, albeit at a much slower rate. The energy field producing this acceleration is called *dark energy*. Its existence is thought to be a strong clue to the nature of the unified theory, but the interpretation of this clue is still unclear.

A form of dark energy was, in fact, predicted by Einstein. He called it a *cosmological constant*, and showed that it could create a repulsive effect in the Universe, opposing the normally attractive action of gravity. He did not want to make the Universe expand rapidly, but rather to explain how it could remain static despite the inward pull of normal gravity. When, a few years later, the expansion of the Universe was discovered by Hubble, Einstein rejected his cosmological constant.

Physicists have revived his mathematical device recently to explain inflation and the current acceleration, but with an important

difference: the repulsion is not constant in time. Inflation, however strong it was for a time, ended a tiny fraction of a second after the birth of the Universe. But physicists are not satisfied with simply inserting a mathematical term into Einstein's equations, without a theory underlying it. They want to explain *how*, at least twice since the Big Bang, some unknown dark energy has made gravity push the Universe apart rather than try to pull it back on itself. It would be hard to overstate the challenges that the dark energy and dark matter present to theoretical physics, and therefore also the opportunity for new theories, for a new understanding of fundamental physics.

Unified theories of physics do not only predict large-scale cosmological effects, and they do not 'kick in' only at the very highest energies. They must leave traces even in ordinary physics, if we can make sufficiently sensitive measurements to see them. Many theories predict how large these traces should be. Physicists in the laboratory have created ingenious experiments to probe the fundamental laws and look for these violations, but the Earth is not the best place to do this. Aside from the noisy environment, Earth-bound laboratories cannot eliminate the effects of gravity except by allowing apparatus to go into free-fall for very short times. The size and duration of many experiments is therefore severely limited.

Space-based astronomy has already played a major role in identifying the major cosmological problems facing physics, and

space missions will play an even more important role over the coming decades in gathering the information that physicists require to solve them. There are two reasons for this:

There are places and times elsewhere in the Universe where matter has been forced into much more extreme conditions than we can ever hope to create on the Earth. By probing the very early Universe or observing hot and dense matter very near to black holes, astronomers can explore the laws of physics in conditions that cannot be accessed in any other way. Space-based X-ray observatories can see hot gas on the very edge of a black hole. Observations of the cosmic microwave radiation give us a direct picture of the fireball that was the Universe 380 000 years after the Big Bang. Gravitational-wave observatories in space will study black holes in ultra-fine detail, and also have the ability to see right through the cosmic fireball to the first split second after the Big Bang.

Space provides the quiet environment necessary for extremely delicate experiments aimed at detecting tiny deviations from the laws of physics as we currently understand them. To find the tiny violations expected in our present physical laws, physicists need to probe stringently the laws of Einstein's general relativity; they must challenge fundamental quantum theory – the framework that describes everyday matter so well – with more formidable experimental tests than have been

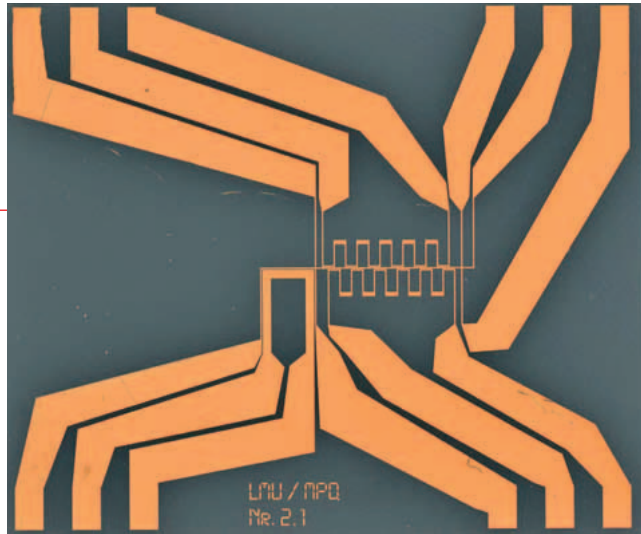
possible in ground-based laboratories; and they should even probe whether space itself has a structure on very small distances, as is expected on some scale in almost all unified theories.

In all these areas, space science has the potential to reveal more big surprises about the natural world, more unexpected discoveries that will challenge our current understanding of the laws of physics and guide us toward the deepest laws of the Universe.

ESA missions such as the Hubble Space Telescope (ESA jointly with NASA) and the XMM-Newton X-ray observatory have already provided key insights. The LISA gravitational wave observatory, another joint project with NASA, will be launched just before the period 2015-2025, and will provide unprecedented observations of black holes and very possibly of completely unexpected phenomena invisible to conventional telescopes. Current NASA missions like Gravity Probe-B (GP-B) and the Wilkinson Microwave Anisotropy Probe (WMAP) are making fundamental studies of gravity and the early Universe, but they are unlikely to have the sensitivity to probe deeply enough to reveal big surprises. ESA's upcoming Planck mission may well see, in its observations of the cosmic microwave background, the first evidence of the gravitational waves created in the Big Bang, which would be a major step towards the information needed for better fundamental physics.

Although these missions are already breaking new ground, a more systematic

A Bose-Einstein condensate can be created on a microchip.



programme of missions is needed. European scientists have a wealth of ideas for breakthrough experiments and ultra-sensitive observatories in space. If these ideas can be harnessed, ESA can take world leadership in exploring fundamental physics in space during the period 2015-2025. And doing this will enable European industry to master unique new technologies that should have much wider applications in the future.

Four areas of space science offer outstanding opportunities for unexpected discoveries in fundamental physics: tests of physical laws as they are understood today, observations of gravitational waves, studies of hot X-ray-emitting matter, and investigations of the accelerating Universe. The first three are discussed in detail here and the accelerating Universe is taken up in Chapter 4.

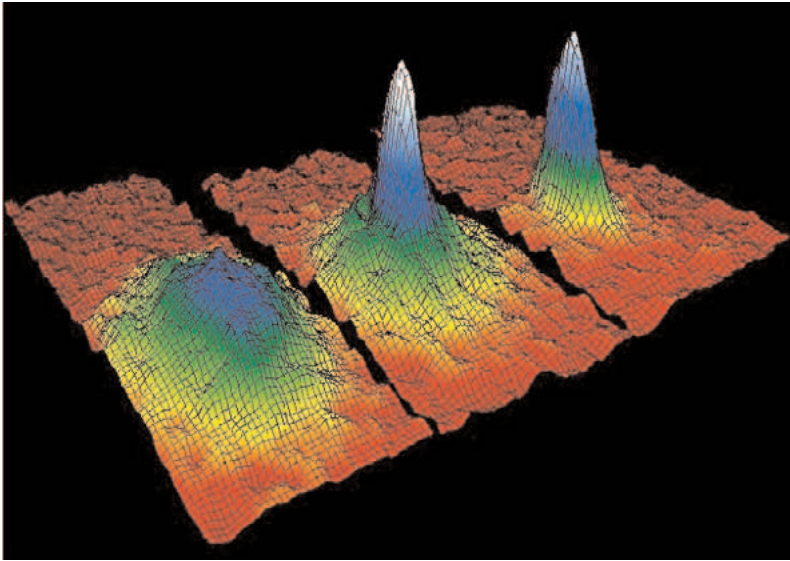
3.1 Exploring the Limits of Contemporary Physics

During the period 2015-2025 it will be possible to use several maturing technologies to conduct experiments in space to look for the slight deviations in our standard physical laws that might contain crucial clues to the deeper unified theory of physics that physicists seek. The European fundamental physics community responded to the Cosmic Vision initiative with an outpouring of suggestions for high-precision experiments in space aimed at the areas felt most likely to uncover new physics.

Many of these experiments share key characteristics. Most require an Earth-

orbiting platform that is extremely quiet, with levels of vibration much lower than are available on the International Space Station. Such extreme isolation requires *drag-free technology*, such as has been demonstrated by GP-B and as will be achieved by ESA's LISA Pathfinder mission and later by LISA itself. Many of the experiments require, in addition, *cryogenic environments* – temperatures within a few degrees of absolute zero. This has already been achieved in GP-B and a number of astronomy missions. Finally, a large number of the experiment ideas submitted by the community are based on the new *cold-atom technology*, in which individual atoms or groups of atoms are manipulated at ultra-low temperatures, where quantum mechanics dominate their behaviour. Under such conditions, atoms exhibit a wave-like character, they lose their individual identities, and they become raw material for potentially the most accurate measuring tools ever available. Cold-atom technology is well-developed in ground-based experiments, as was recognised by the award of the 2001 Nobel Prize in Physics for Bose-Einstein condensates. Physicists are now ready to adapt this technology to space experimentation.

Here are some questions that the European fundamental physics community would like



A Bose-Einstein condensate in the laboratory.

to answer, which together represent a broad attack on the frontiers of known physics:

Do all things fall at the same rate?

Galileo showed that all things fall at the same rate in a gravitational field, and this 'equivalence principle' underpins Einstein's theory of general relativity. However, unified theories of physics all seem to introduce tiny extra forces that allow objects made of one kind of material to fall slightly more rapidly than objects of another. There are even predictions of the size of these violations. The CNES Microscope mission will look for these violations with a sensitivity never achieved in ground-based experiments, and ESA and NASA have both studied proposals for an even more sensitive mission called STEP. A drag-free experiment in Earth orbit, using cryogenic cooling and ultra-sensitive measurement devices to monitor the free-fall behaviour of different materials, could measure effects at the predicted level and finally reveal the existence of extra gravity-like forces. A cold-atom mission containing an atomic interferometer could test the equivalence principle using single atoms at a similar level of accuracy.

Do all clocks tick at the same rate?

Einstein broadened the equivalence

principle to include clocks: all measures of time must behave in the same way in gravitational fields. All clocks must therefore experience the same gravitational redshift, running slower when they are near to gravitating bodies than when they are far away. The redshift effect is well-established near the Earth, and is in fact built in to the operation of satellite navigation systems (Galileo and GPS), which depend on accurate atomic clocks for precise positioning. But does it work the same way, to high accuracy, for other clocks, based on other physical principles? Do photon clocks (based on photons running back and forth in a cavity) or molecular clocks (based on the vibrational frequencies of molecules) or indeed human ageing (astronauts in orbit) all go faster in orbit to the same extent? In unified theories of physics, one would expect small deviations among them. An Earth-orbiting mission carrying several different types of ultra-precise clocks could detect a violation of the universality of the redshift even if it was four orders of magnitude smaller than our current best limits.

Does Newton's law of gravity hold at very small distances?

On the Earth and in the Solar System, Newton's law of gravity works very well. Small corrections due to Einstein's general relativity are well understood. But in some unified theories, the way that gravity depends on the distance between objects should change when the separations are smaller than a particular amount, either because of new short-range forces or because gravity itself changes. Because of

The CNES-ESA Microscope mission to test the equivalence principle, to be launched in 2009. New technology will enable even more sensitive space-based tests during the Cosmic Vision timeframe. (CNES)



the weakness of the gravitational force, we currently have no information from laboratory experiments about how it behaves across distances smaller than a few tenths of a millimetre. Ultra-precise tests of Newton's gravity using a drag-free satellite in Earth orbit could improve on similar experiments on Earth, because of the quiet environment and the length of time for which an experiment can be run. Space experiments could measure gravity down to micron distances, an improvement by a factor of 1000 on what is known today.

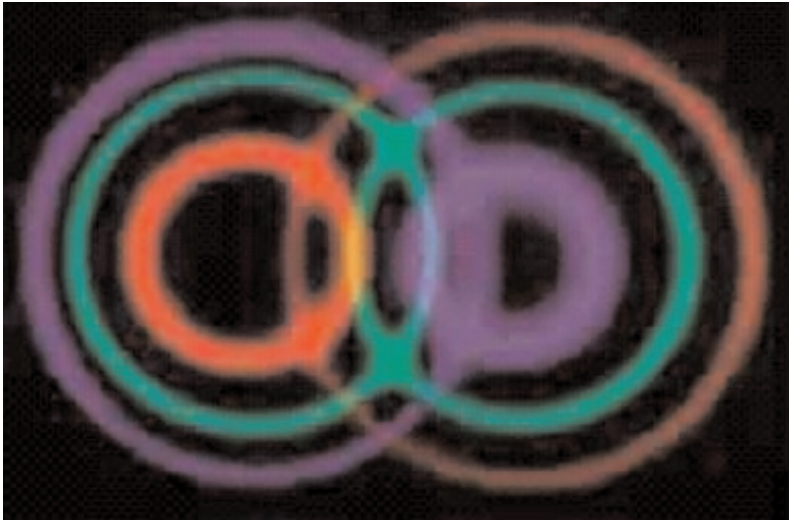
Does Einstein's theory of gravity hold at very large distances?

Unified theories usually predict small changes in gravity in the Solar System beyond those that can be ascribed to general relativity. Although general relativity is very well tested today, there is still plenty of room for surprises caused by extra fields or extra dimensions in unified theories. Intriguingly, NASA cannot explain anomalies in the tracking of its Pioneer-10 spacecraft, which has journeyed further from the Sun than any other. A mission using lasers on drag-free satellites (as developed for LISA) orbiting the Sun could test general relativity by measuring the bending of light passing the Sun. The Pioneer anomaly could be tested with a special package that might be part of a European exploratory mission to the outer planets, or with even better sensitivity by a dedicated **deep space gravity probe**.

A drag-free satellite in Earth orbit could test the inverse-square-law over intermediate distances.

Do space and time have structure?

In the 19th Century, scientists regarded space as a smooth, flat arena in which natural forces acted on matter. Einstein modified this picture by describing gravity as the curvature of space-time, although he still believed that the old view of space was valid in small regions. But 20th Century physics showed a more complicated picture. For one thing, Nature is not symmetric under reflection in a mirror: an approaching neutrino will always be spinning clockwise about its direction of motion, never anti-clockwise, no matter where it was produced. As another example, it appears that some part of fundamental physics must favour particles over antiparticles, in order to explain the absence of antimatter in the observed Universe. Other losses of symmetry are also possible. Many physicists, including the famous British physicist Paul Dirac, have suggested that there might be slow changes with time in the values of fundamental constants, such as the masses of elementary particles. Alternatively, the electric force exerted by a tiny charge, like an electron, might not be the same in all directions. All of these effects are possible within unified theories, and observations of more of them would give strong clues to decide which theory may be right. Experiments to test for time-dependence of constants or direction-dependence of the



Interference fringes in an entanglement experiment.

electric force could be performed on a drag-free spacecraft with cold-atom technology and/or ultra-stable clocks.

Does God play dice?

In the first half of the 20th century, physicists evolved quantum theory to describe atoms and elementary particles. They found that the theory did not predict exactly the outcome of experiments, but only gave probabilities for various outcomes. They concluded that exact predictions were impossible, even in principle. Einstein famously rejected this standard interpretation of quantum theory, using the phrase, '*God does not play dice*'. Recent ground-based experiments have made Einstein's point of view look increasingly untenable. They investigate a phenomenon called *entanglement*, where two photons are created in such a way that the polarisation of one depends on that of the other, but neither polarisation is individually predictable. Entangled photons seem to behave exactly as standard quantum theory expects – with polarisations that are random until they are measured – and not at all as if they had an unknown but deterministic polarisation state that was set when they were created. And even in standard quantum mechanics, there is still an incomplete understanding of

how the probabilistic picture gives way to the deterministic mechanics of Newton when we deal with large collections of atoms, such as footballs, weather systems and planets. This transition is sometimes referred to as *decoherence*, contrasting with the coherent behaviour that is seen, for example, in entangled systems.

Now, quantum theory is the foundation of our understanding of atoms and molecules, and it is extraordinarily successful in describing the materials of our natural environment. One of the goals of unified theories of physics is to extend quantum theory to gravity, to create a theory of quantum gravity. It is of crucial importance for the development of unified theories, therefore, that quantum theory be tested and understood as deeply as possible. Many exciting and deep experiments on quantum theory are possible in space, again using cold-atom techniques, ultra-stable clocks and drag-free spacecraft. Entanglement and coherence/decoherence could be tested over very large and ultra-small distance scales. A space mission could create an ensemble of millions of atoms in a single coherent ultra-cold quantum state (a Bose-Einstein condensate), and then use this as a source for an atom laser and an atom interferometer.

Can we find new fundamental particles from space?

All unified theories predict many more particles than physicists have seen so far. Most would have very high masses, beyond the energies accessible at facilities like CERN. Dark matter may well consist of one or more

species of massive elementary particles. What is more, there is currently a troubling puzzle in observations of cosmic rays, which are high-energy particles from space. It appears that there are more ultra-high-energy particles than one would expect, because standard cosmic rays of this energy would be slowed rapidly by scattering of the photons of the cosmic microwave background radiation. This anomaly may point to new kinds of cosmic-ray particles or to new sources of conventional cosmic rays in the dark matter of the Universe. Space experiments can complement the experiments on the ground that are currently looking for dark matter (so far unsuccessfully) and anomalous cosmic rays. With long observation times and the ability to look down on large parts of the Earth's atmosphere, an orbiting cosmic-ray experiment could accumulate data much more rapidly than ground-based experiments. In an ultra-quiet, cryogenic, drag-free environment in space, searches can be made for special kinds of possible dark matter particles that would be difficult to detect on the ground.

Some of these questions could be addressed using technology available today, while others (particularly involving cold atoms) require a careful programme of technology development to move the experimental techniques out of the laboratory and into space. If initiated now, a **fundamental physics explorer programme** could lead to a series of breakthrough missions in the early part of the Cosmic Vision 2015-2025 timeframe.

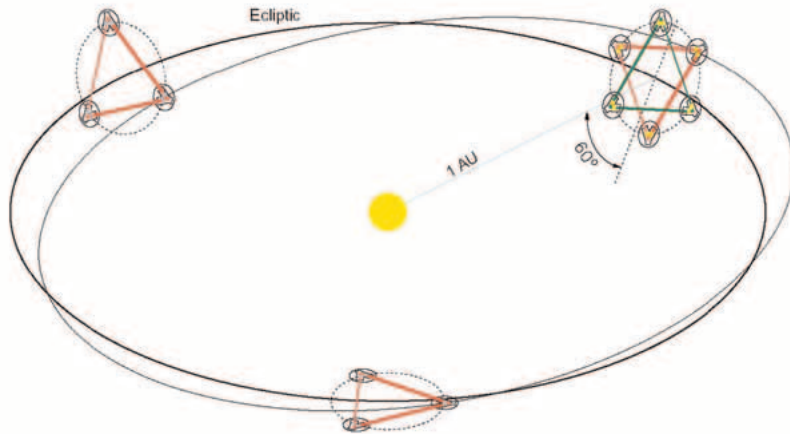
In the longer term, these pioneering high-precision space experiments will lead to new technologies with much wider applicability in space: better gyroscopes, better time standards, better platforms and techniques for observing the Earth, and better ways of tracking and coordinating spacecraft. In many cases, these improvements will not be incremental, but will instead be dramatic advances in performance by several orders of magnitude.

3.2 The gravitational wave universe

Gravitational waves were predicted by Einstein almost immediately after he formulated his theory of general relativity 90 years ago. They have the potential to bring us completely new information about the Universe and its most extreme objects. Observable gravitational waves should be produced by massive objects (especially black holes) colliding or moving in tight orbits around one another, by the Big Bang, and possibly by unknown components of the dark matter of the Universe.

Visible light, radio waves, X-rays and gamma rays – collectively called electromagnetic radiation – have until now been the principal source of information for astronomers about the Universe. But astronomers have found that only 4% of the mass in the Universe is even capable of producing electromagnetic radiation. The rest, if it generates any signal at all, can produce only gravitational radiation. Some of the most important places in the Universe where we must look for clues to

A full-scale system to detect the Big Bang in gravitational waves. Individual configurations could be used to search for the earliest stars and black holes.



fundamental physics, such as the Big Bang and black holes, will be directly visible only through the gravitational waves they emit.

But gravitational waves are very weak, and they have not yet been directly observed. The technical challenges of detecting by laser beams the tiny motions that they cause have been conquered only recently, and a number of large-scale gravitational wave observatories are now under construction on the ground. The ESA-NASA LISA mission will launch in 2014 and will be the first space mission to look at the Universe through this new window. LISA will observe at mHz frequencies (much lower than those of the ground-based detectors), where the sources are so plentiful that the LISA team can be confident of seeing the first of them within days of turning the instrument on. LISA will survey the Universe for colliding massive black holes, and stringently test general relativity. It may even measure the dark energy at early times.

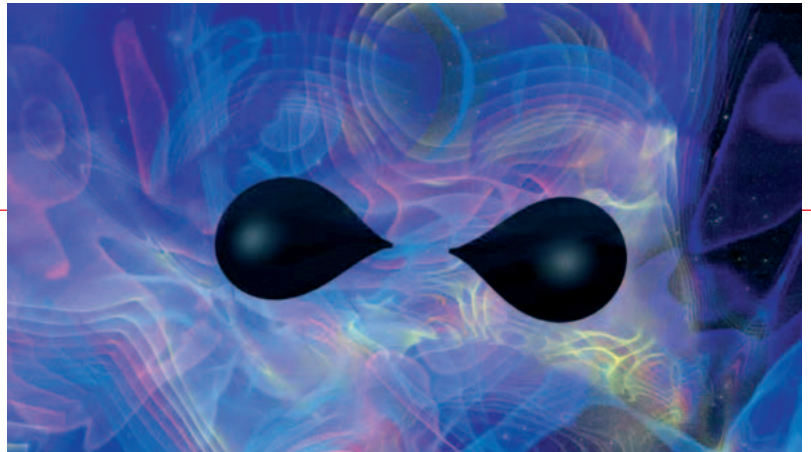
On the other hand, LISA is unlikely to see the cosmic gravitational radiation background created immediately after the Big Bang, unless the intensity of the waves is much higher than current theoretical predictions indicate. In LISA's frequency range, even a more sensitive mission would not see that cosmic radiation

because it would be buried beneath gravitational waves from astrophysical systems, such as ordinary binary systems throughout the Universe. The key to observing this radiation is to look for it at frequencies of 0.1-1.0 Hz, between the LISA band and the frequencies observable from the ground. This is a cleaner band, with fewer stellar sources to mask the Big Bang radiation.

A new gravitational wave mission in the period 2015-2025 could open this frequency band. It should be technologically more advanced than LISA, using higher-power lasers, larger mirrors and better drag-free sensing and control. A LISA-like detector involving a single array of three spacecraft could by itself detect and measure the distance to every binary source of gravitational waves in this frequency band in the Universe. Most will be pairs of neutron stars or black holes on their way to merging. Coordinated observations with space-based X-ray and infrared telescopes could use the excellent positional accuracy of the gravitational wave identifications to locate the systems in clusters or even in individual galaxies, and to study the subsequent merger events. Such a mission could address several questions in fundamental physics and astrophysics:

- it could measure the *acceleration or deceleration of the expansion of the Universe* out to high redshifts, essentially to the beginning of star formation. This would in turn answer the question of whether the dark

A numerical simulation of two black holes about to merge, and their emitted gravitational waves.
(W. Benger/ZIB and the Albert Einstein Institute)



- energy is time-dependent or behaves like Einstein's cosmological constant.
- it could determine the time in the history of the Universe at which *star formation* began.
 - it could sample the population of *intermediate-mass black holes* by detecting all the binary systems made up of these objects in the observational frequency band, anywhere in the Universe. These black holes are thought to be the highly abundant end-products of the evolution of the first generation of stars. They could have played a key role in the formation of the giant black holes in the centres of galaxies, and in the entire evolution of galaxies. Their binaries would be tracers of their population, distribution and history.
 - it could search for and detect for the first time (or set stringent upper limits on the abundance of) many plausible but hard-to-detect objects. These include *cosmic strings* (not to be confused with the strings of string theory), which are very long one-dimensional mass concentrations that arise naturally in many unified field theories. Binaries of *MACHOs* (Massive Compact Halo Objects), the unseen objects near our Galaxy detected in certain gravitational lensing events, should also reveal themselves, provided these mysterious objects are compact and relativistic.
 - its superior sensitivity would allow it to search for other possible *compact and massive components of dark matter*. Our ignorance of the dark side of the

Universe leaves open many possibilities for minor or major constituents of dark matter.

Beyond these possibilities for a single-array three-spacecraft mission, a more ambitious system involving more spacecraft and pushing the new technology to its limits might be capable of detecting the cosmic gravitational wave background from the Big Bang, at the levels predicted by inflation theory. These waves should have been emitted during the first tiny fraction of a second after the initiation of the Big Bang and should have travelled to us essentially unaffected by all the matter they pass through along the way. This makes them ideal probes of the laws of physics at the highest energies. The frequency of the radiation today is related to the temperature of the Universe when the waves were emitted. Waves in the 1 Hz frequency band come from a time when the Universe was far hotter than temperatures at which physics is understood today.

The frequency band around 1 Hz is thought by astronomers to be an ideal 'window' into this background radiation. At lower frequencies where LISA will operate, the stellar systems in the Universe produce more gravitational waves than we expect from the Big Bang, masking the cosmic

background. At higher frequencies, where the ground-based detectors operate, the amplitude of the background radiation is likely to be much weaker.

Even at 1 Hz the cosmic background waves will be weak, and to find them would require two detector arrays operating very near each other. They would search for the background by cross-correlation – by looking for a common component of gravitational-wave ‘noise’ in the independent detectors. Further spacecraft may be needed to discriminate between foreground binary sources and the background radiation, much as the satellites observing the cosmic microwave background rely on ground-based radio observations to identify and subtract foreground sources. The cross-correlation technique is already being used by ground-based detectors to search for the cosmic background of gravitational waves at their higher frequencies, but they do not have the sensitivity to reach the predictions of inflation theory. The advanced space-based detector system described here would be about a million times more sensitive to the energy of the background radiation than the upgraded Advanced LIGO detectors that are expected to begin operating near the time of the LISA launch.

Detecting the radiation coming directly from the Big Bang by this **gravitational wave cosmic surveyor** is the most important goal that ESA’s fundamental physics programme could aim for. Implementation of such an ambitious dual array would no doubt require partnerships

with other agencies. NASA is currently developing its own plans for such a mission, called the Big Bang Observer. With planning, the task could be done in stages, once the first array had proved the technology and accomplished the important single-array science observations at 1 Hz. By developing the appropriate technologies and launching a pioneer mission in this waveband towards the end of the 2015–2025 period, ESA could take a decisive step towards this goal.

3.3 Matter under extreme conditions

Black holes are the most exotic prediction of general relativity. They have the strongest possible gravitational fields, and yet in general relativity they are among the simplest objects to describe. The entire gravitational field of a black hole is determined by just three parameters: its total mass, its total spin angular momentum, and its total electric charge. It is as if extreme gravity crushes the individuality out of these objects, so that they are all essentially identical, regardless of how they were formed. Gravitational wave detectors, especially LISA, will register gravitational waves from disturbed black holes and from objects orbiting black holes, and they will be able to test whether real black holes are as simple as relativity predicts.

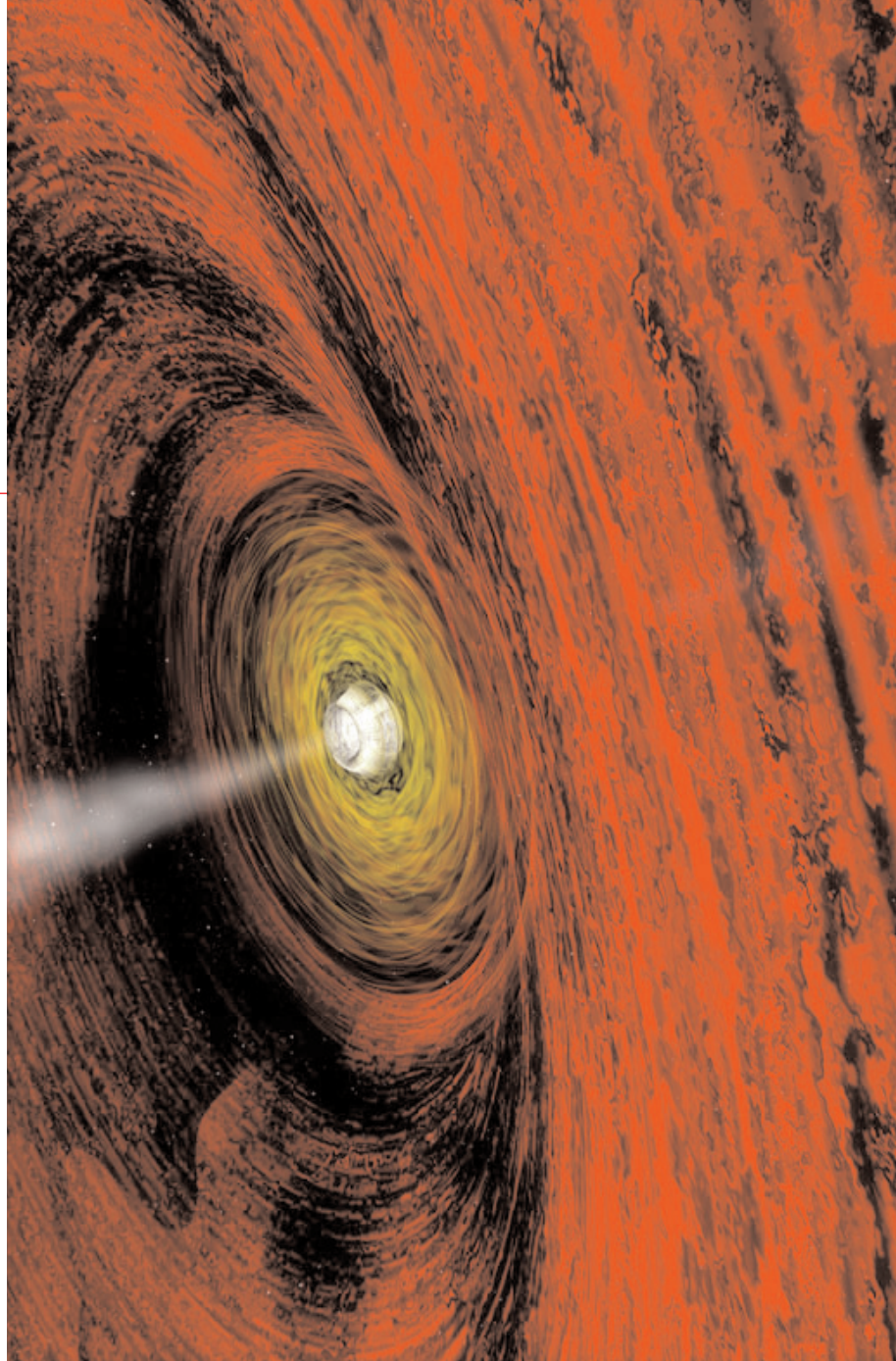
However, black holes also create some of the most extreme conditions for matter in the Universe. Matter falling into black holes is heated to very high temperatures, making it visible to X-ray telescopes and gamma-ray

A jet from an accreting black hole (illustration by A. Hobart).

detectors. The giant black holes that formed very early in the centres of galaxies seem to have powered the quasars and to have played a key role in the evolution of the galaxies themselves.

There is even a possibility that the energy that powers quasars comes from the rotational energy of spinning black holes, and that large-scale magnetic fields funnel that energy in the form of jets of energetic particles. Although black holes are a one-way street for matter, so that anything that falls into them never re-emerges, they can exchange energy and angular momentum with their surroundings to some degree. Whilst this is understood theoretically, it has never been observed in detail.

Recent X-ray and gamma-ray results from ESA's XMM-Newton, NASA's Chandra and ESA's Integral missions have shed light on the accretion and ejection mechanisms taking place around black holes and neutron stars, and the crucial interplay between black holes and galaxy evolution. Effects predicted by Einstein's general theory of relativity, such as a strong gravitational redshift or the effects of rapid rotation, have just begun to be detected in very bright sources. In the future, the aim will be to probe deep inside the gravitational well of black holes and neutron stars, to provide for the first time a thorough test of general relativity in the strong field limit, to investigate the physics of strong interactions in ultradense environments, to observe the huge amounts of gas involved in binary black hole mergers, and to understand the violent



processes at work in hypernova explosions which form gamma-ray bursts and lead to the enrichment of matter in heavy elements.

X-ray emission is typically produced where material falls in a strong gravitational field. Black holes have the strongest gravity, so the X-ray emission produced just outside the event horizon carries the imprint of the most extreme observable space-time curvature. Detailed studies of the X-ray spectra and time variability give tests of strong-field gravity such as the existence of a last stable orbit, the closest possible location of matter around the black hole.

The mass and the angular momentum of the black hole can be measured by time-resolved X-ray spectroscopy, using the accreting material as a ‘test particle’ for the space-time structure very close to the black holes. Other effects predicted by Einstein’s theory of gravity, like strong bending of the light, epicyclic motions and precession around the spin of the black hole, can be tested directly. The ‘cosmic censorship’ conjecture, according to which the spin of black holes is limited by their mass, can also be tested by studying a sufficiently large number of them.

Neutron stars are only slightly less extreme than black holes in terms of gravity, but with the crucial difference that they have a surface rather than an event horizon, so their internal structure has observable consequences. This is important, as the structure of matter is not well understood at the super-nuclear densities expected in the core of a neutron star. X-ray observations give diagnostics of the strength of gravity close to, or even on the surface of, the neutron star, and hence give an observational constraint on the central density, constraining models of the strong

interaction between nuclear particles. Orbital motions of the accreting material around neutron stars and effects of strong gravity on the matter being episodically ejected from the surface can be used to constrain directly the physical state of the ultra-dense material inside the neutron star, possibly creating exceptional states of matter, such as massive particles, super-fluid baryons or quark-gluon plasma. Similarly, X-ray spectroscopy with XMM-Newton has yielded the first measurement of the surface magnetic fields in an isolated neutron star, opening new ways to probe its extraordinary nuclear physics.

A **large-aperture X-ray observatory**, which could probe gas very close to black holes and examine neutron stars in great detail, is considered in its broader astrophysical context in the next chapter (Sections 4.2 and 4.3). The obvious synergy between the gravitational wave and X-ray views of black holes excitingly suggests that an observational understanding of strong gravity is within reach during the Cosmic Vision timeframe. A **gamma-ray imaging observatory** is also mooted there.

Toolkit for Theme 3*Tools***3. What are the fundamental physical laws of the Universe?****3.1 Explore the limits of contemporary physics**

Probe the limits of general relativity, symmetry violations, fundamental constants, short-range forces, quantum physics of Bose-Einstein condensates, and ultra-high-energy cosmic rays, to look for clues to unified theories

Use the stable and gravity-free environment of space to implement high-precision experiments to search for tiny deviations from the standard model of fundamental interactions

Fundamental physics explorer programme

Test the validity of Newtonian gravity using a trans-Saturn drag-free mission

Deep space gravity probe

Observe from orbit the patterns of light emitted from the Earth's atmosphere by the showers of particles produced by the impacts of sub-atomic particles of ultra-high-energy

Space detector for ultra-high-energy cosmic rays

3.2 The gravitational wave Universe

Make a key step towards detecting and studying the gravitational radiation background generated at the Big Bang. Probe the Universe at high redshift and explore the dark Universe

Primordial gravitational waves, unaffected by ionised matter, are ideal probes of the laws of physics at the fantastic energies and temperatures of the Big Bang. They open an ideal window to probe the very early Universe and dark energy at very early times

Gravitational wave cosmic surveyor

3.3 Matter under extreme conditions

Probe general relativity in the environment of black holes and other compact objects, and investigate the state of matter inside neutron stars

The study of the spectrum and time variability of radiation from matter near black holes shows the imprint of the curvature of space-time as predicted by general relativity. This has strong implications for astrophysics and cosmology in general

Large-aperture X-ray observatory



Chapter 4

Since antiquity, the Earth's inhabitants have observed the sky with curiosity and perspicacity, taking advantage of technological progress to help understand what the Universe is made of. Our present knowledge is the result of centuries of continuous cross-fertilisation between astronomical observations and theoretical constructions. Successive steps have taken mankind closer and closer to comprehending the complexity, origin and evolution of the Universe: by recognising that we live in a planetary system and that the Earth is orbiting the Sun; by establishing that the Sun is embedded in a spiral galaxy, far from its centre; by demonstrating that the Universe is expanding and later discovering that this expansion is accelerating; and realising from dynamic evidence that most of the matter in the Universe is in an unknown form, called dark matter.

Previous chapters have anticipated several aspects of the continuing quest. The mystery of how star and planetary systems form, the detection and characterisation of exo-planets and their atmospheres, and the conditions for the emergence of life are themes in Chapter 1. The origin of the Solar System features in Chapter 2, together with the need to understand the Sun's behaviour. Chapter 3 shows how much physicists now rely on the observation of astronomical objects and events to understand the fundamental physical laws of nature.

Beyond these fascinating subjects, recent discoveries have transformed our wider

How Did the Universe Originate and What is it Made of?

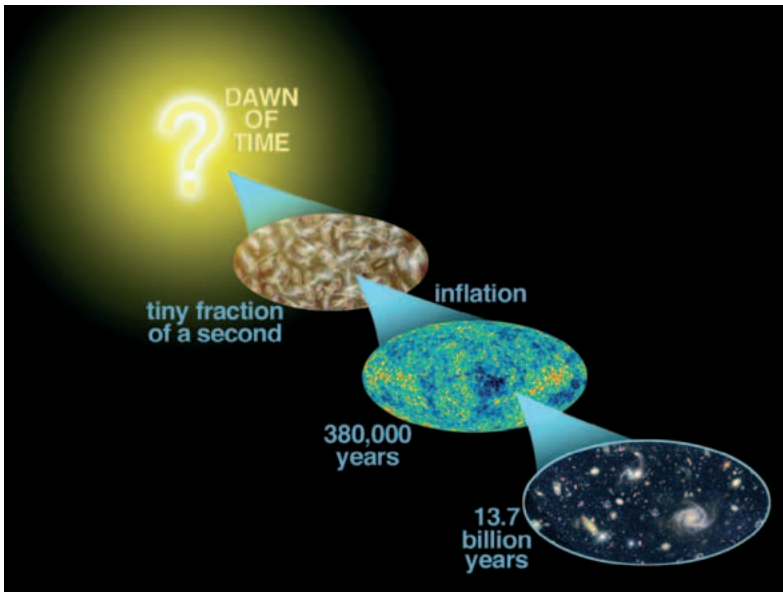
view of the Universe. Here is a small selection of them:

- the observational confirmation of an early phase of accelerated expansion, called inflation, which took place during the first fractions of a second of the life of the Universe, and which was theoretically predicted in the 1980s.
- the recent, totally unexpected discovery of a later and continuing phase of accelerated expansion of the Universe, which leaves us looking for the driving force behind it. Termed dark energy, this component of the Universe currently has no clear explanation in terms of a comprehensive physical model, and remains a big challenge for fundamental physics (see also Chapter 3).
- the observation of galaxies at ever-increasing distances, notably with the Hubble Space Telescope and XMM-Newton in space and large telescopes from the ground, such as the Very Large Telescope (VLT) at the ESO or the Keck telescopes in Hawaii.
- a much more precise estimation of the age of the oldest stars in the Galaxy, and therefore of a minimum age of the Universe, using data from ESA's Hipparcos mission – results now confirmed independently by NASA's Wilkinson Microwave Anisotropy Probe (WMAP) observations of the cosmic microwave background.
- the discovery of the origin of the extremely violent explosions known as gamma-ray bursts, thanks initially to the Italian-Dutch satellite BeppoSAX.
- the discovery of strong gravity effects around black holes, including those from rapid rotation, observed in X-rays, as well as many new physical characteristics of neutron stars, including magnetic field measurements with XMM-Newton and Chandra.

These discoveries are the results of both ground-based and spaceborne observations. The contribution from space has been, and will continue to be, essential for two major reasons. Being free of the absorption caused by the Earth's atmosphere, they open up the whole range of electromagnetic radiation emitted in the Universe. Secondly, space provides an extremely stable environment for the operation of instruments, so facilitating uniquely sensitive and accurate measurements.

As a consequence of a fantastic increase in our knowledge of the Universe in the past two decades, fundamental questions can now at least be better identified and formulated. Here are some examples directly related to this chapter, mainly dealing with the origin and evolution of the Universe and the formation and evolution of the structures that we see now:

- how did the Universe originate and what happened in the very early phases of its existence? What can be observed now, to learn about the extreme physical conditions at that early epoch?
- less than 5% of the mass of the Universe has been identified as ordinary matter. What is the nature of



Two of the most important scientific goals that ESA could set, on behalf of Europe, are detecting the imprints of the very early stages of the evolution of the Universe in radiation observable today, and understanding how the Universe, as we observe it today, took shape.
(NASA/WMAP Science Team)

through the violent mechanisms taking place in interaction with black holes and neutron stars. These scientific issues will remain at the centre of cosmological and astrophysical interest for at least the next two decades.

4.1 The early Universe

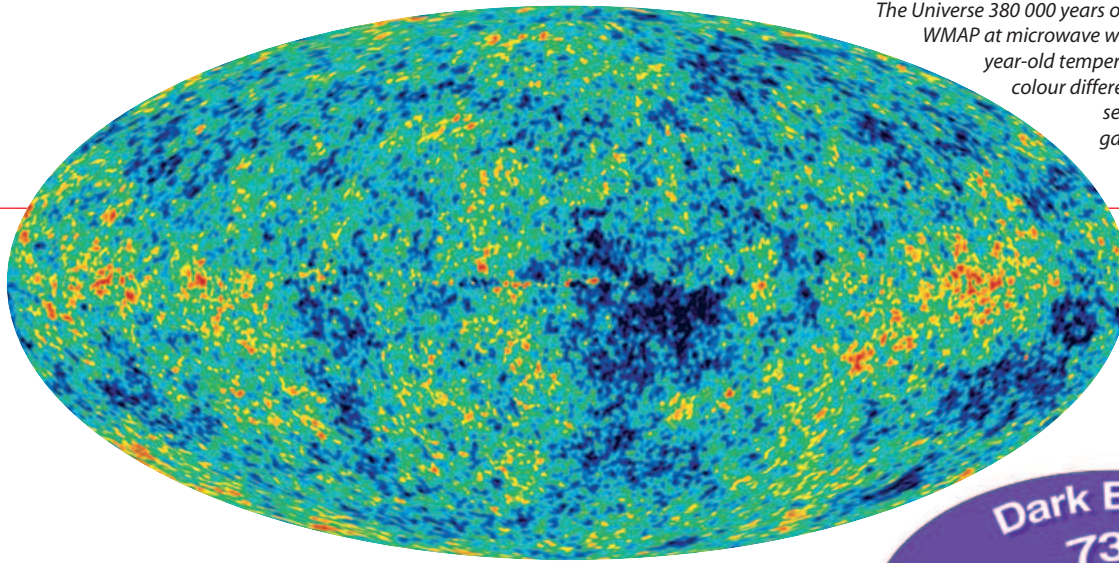
Astronomers have found strong evidence that the Universe underwent a period of very strongly accelerated expansion a split-second after the Big Bang. This is called inflation. But probably the biggest surprise to astronomers in the past decade has been the discovery that the current Universe has entered another period of acceleration, albeit at a much slower pace. The gravitational effect that would normally attract galaxies to each other is being overwhelmed by an apparent repulsion driving galaxies apart faster and faster. Einstein anticipated this possibility with his cosmological constant, which represents an energy density called dark energy and an associated negative pressure that, in effect, converts gravity into anti-gravity, creating the necessary repulsion. But Einstein's constant was an *ad hoc* addition to his equations for which he had no physical explanation (see Chapter 3). It is crucial to measure the amount and time-dependence of today's dark energy in order to obtain clues to what is producing it. This will be as important and urgent a problem in the period 2015-2025 as it is today.

Dark energy is estimated to represent about 70% of the total mass-energy budget in the Universe, and there are two powerful

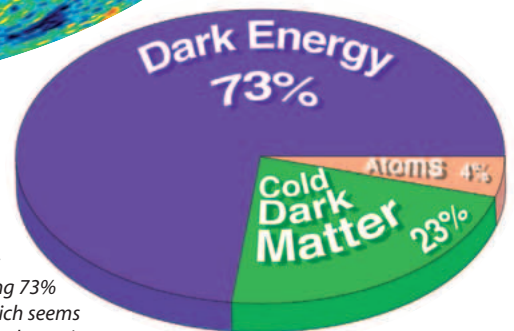
dark matter, which represents about 23% of the mass?

- what is the origin and future of the accelerated cosmic expansion? What is the nature of dark energy which seems to be responsible for it – and which contributes most of the content of the Universe?
- how were the first luminous objects in the Universe ignited? When and how did the very first stars form, evolve and explode? What history of stars and supernovae gave rise to the chemical elements we take for granted?
- how, when and why does a black hole form? How does it grow? What happens when two black holes merge?
- what is the history of the supermassive black holes that we now observe? And how do they interact with their host galaxies?

The most important scientific goals that ESA could set itself, on behalf of Europe, now include: detecting imprints of the very early stages of the evolution of the Universe in radiation observable today; unravelling the nature of dark energy and dark matter; understanding how the observable Universe took shape, and how it evolves



The Universe 380 000 years old. This image, obtained with WMAP at microwave wavelengths, reveals 13 billion year-old temperature fluctuations (shown as colour differences) that correspond to the seeds that grew to become the galaxies. (NASA/WMAP Science Team)



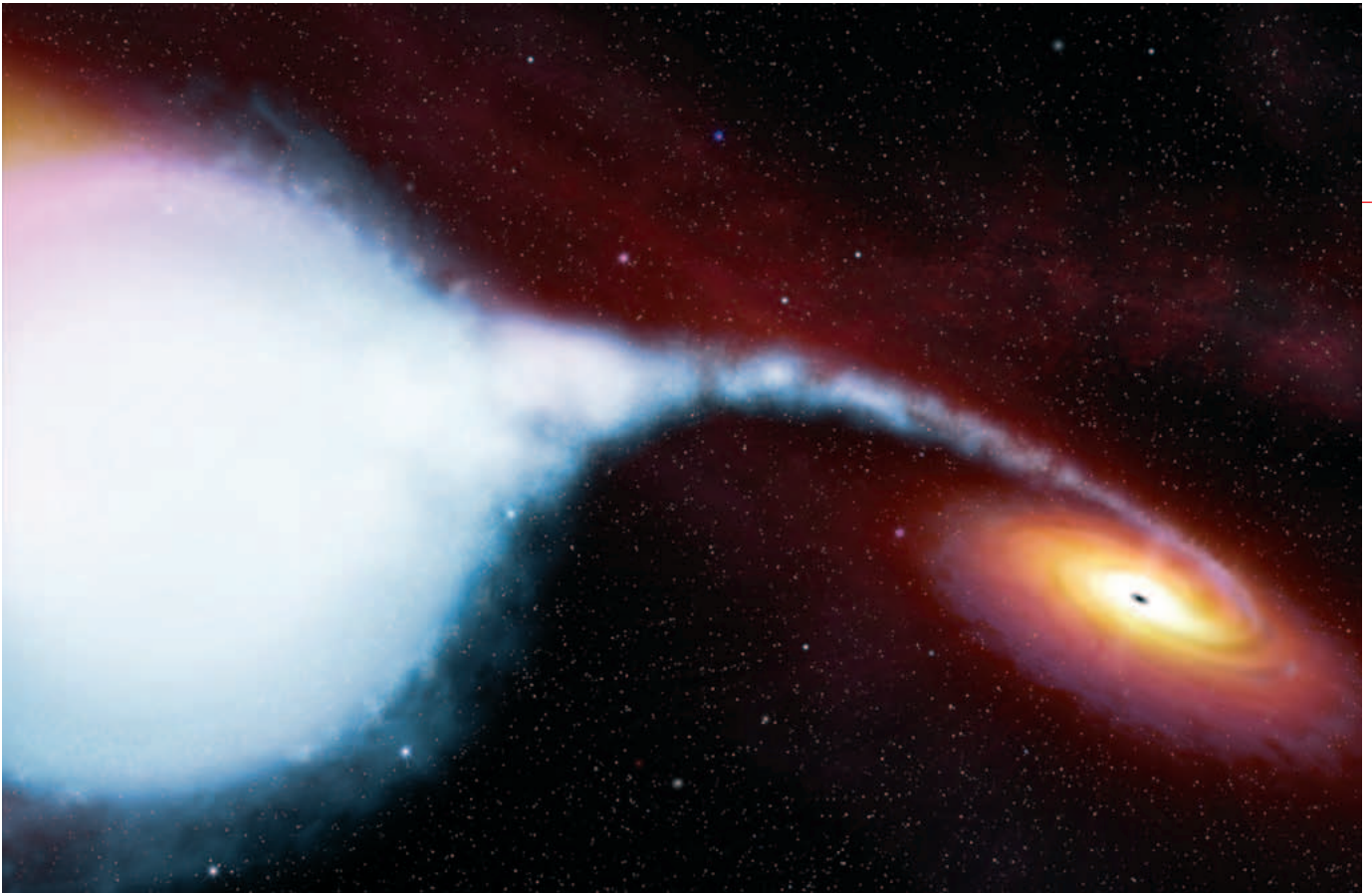
The content of the Universe. Less than 5% of the mass of the Universe has been identified as ordinary matter. 23% is unseen dark matter, detectable only by its gravitational effects. The remaining 73% is the mysterious 'dark energy', which seems to be responsible for the accelerated cosmic expansion observed today. (NASA/WMAP Science Team)

methods for finding and investigating it. One is to study weak lensing, the slight bending of light caused by the gravitational field produced by the large-scale distribution of matter in the Universe. The other is to make precise measurements of the brightness and redshift of large numbers of exploding stars, supernovae of Type Ia, at very large distances, in order to test the cosmic geometry and rate of expansion. Both kinds of measurements require a space-based telescope with a very wide field of view and the ability to make images in visible and near-infrared light. Europe's leading role in wide-field imaging is a major asset in this domain. Observations by such a **wide-field optical-infrared imager** would complement the investigations of gravitational waves discussed in Chapter 3.

Theoretical models predict that the inflation at the origin of the Universe, when it is believed to have undergone a phase of extremely rapid expansion, should be observable in the shape of the initial density fluctuations from which the first stars and galaxies originated. These predictions have been impressively confirmed by recent observations, notably by NASA's WMAP. More subtle information

about inflation will come from the detection of temperature fluctuations in the cosmic microwave background radiation that were caused by primordial large-scale gravitational waves created in the Big Bang. The physical mechanism driving inflation is unclear, and competing theories make different predictions about the amplitude and the shape of the primordial gravitational wave spectrum. Observing such a wave spectrum will provide the key to deciphering the very beginning of the cosmos.

The first possibility is to characterise the primordial gravitational waves indirectly from their imprint on the polarisation properties of the cosmic microwave background. The weakness of the signal makes space-based observations mandatory. An **all-sky mapper for polarisation of the cosmic microwave background** would capitalise on European



Matter spirals into a black hole. Relativistic jets spout from the vicinity of the compact object. X-ray emission is produced as surrounding gas is accreted by the black hole. This high-energy radiation is not just a witness to the existence of black holes but also reveals the rate at which they grow to their huge masses.

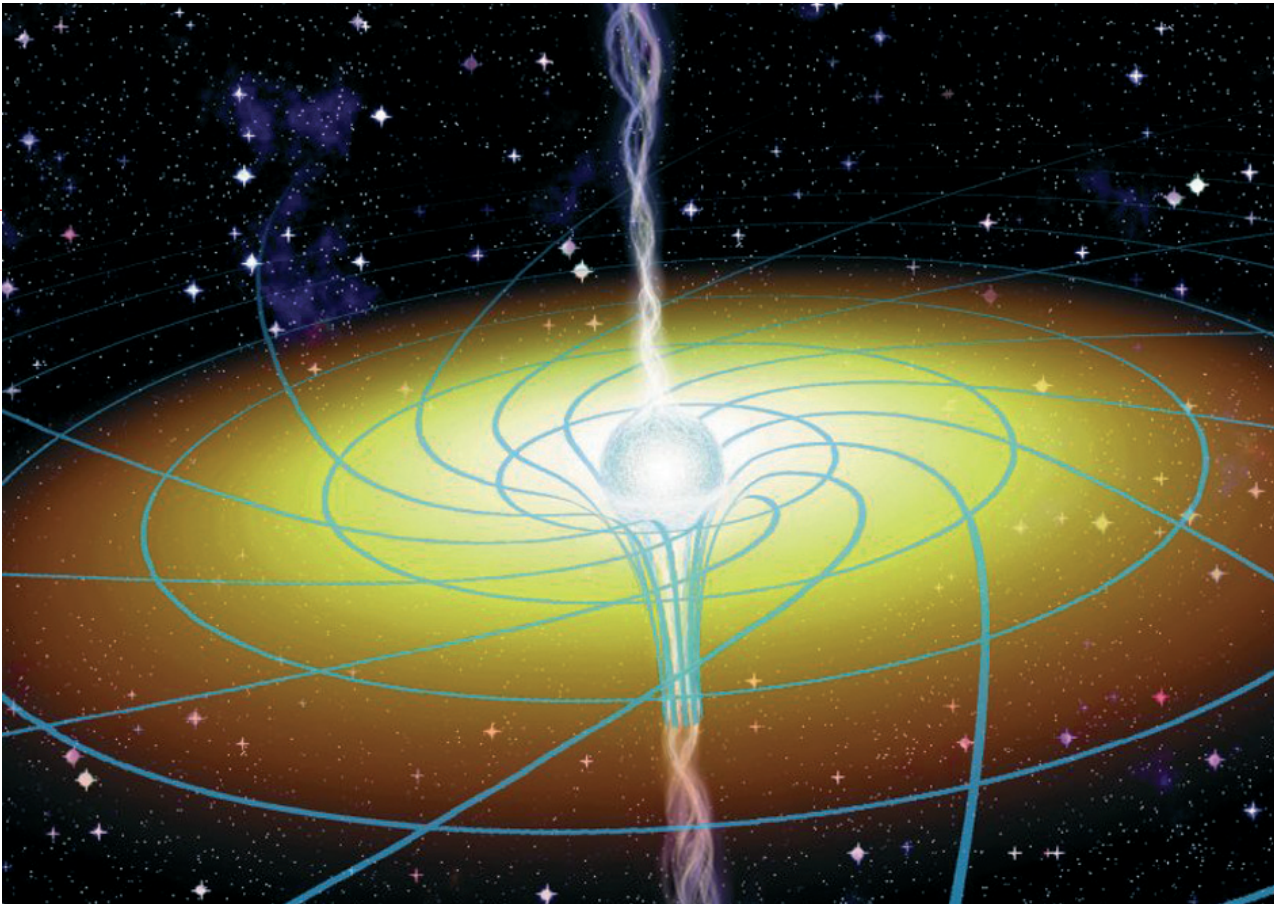
expertise in observing the background. Indeed, ESA's Planck mission (2007) is a first step in this study, as it will produce a multi-frequency all-sky map of the cosmic microwave background, albeit with only a limited sensitivity to polarisation. The follow-up project should generate a multi-frequency all-sky map of much greater sensitivity than Planck, so as to characterise completely the polarisation parameters of the cosmic microwave background radiation.

Another approach to the circumstances of inflation relies on the direct detection of the primordial gravitational wave background, the emission of which marked the end of the inflation era, and which might even contain information about the Universe before inflation set in. This approach, calling for a **gravitational wave cosmic surveyor**, was described in Chapter 3.

4.2 The Universe taking shape

Tracing cosmic history back to the time when the first luminous sources ignited, thus ending the dark ages of the Universe, has just begun. At that epoch the intergalactic medium was reionised, while large-scale structures increased in complexity, leading to galaxies and their supermassive black holes. The merging of galaxies, their star-formation history, their relationship to quasars and their interactions with the intergalactic medium are all processes that we have started to analyse with NASA-ESA's Hubble Space Telescope, ESA's XMM-Newton and NASA's Chandra, and other telescopes observing at complementary wavelengths, back to a time when the Universe was only about 10% of its current age.

Pushing this history back to still-earlier times will be one of the great achievements of



Hubble's successor, the NASA-ESA-CSA James Webb Space Telescope (JWST). The rapid evolution of this research area requires the flexibility provided by observatory-type missions, including ESA's Herschel, and by the ALMA ground-based observatory. But even taking into account the gains of the next 10 years, several questions will be left unanswered. In particular, JWST will miss the first clusters of galaxies and the precursors of quasars, expected to have central black holes with a much lower mass and luminosity than those seen closer in the cosmos. These will be best observed in X-ray.

As observational cosmology necessitates a multi-wavelength approach, no single observatory can complete the cosmic picture. However, a **large-aperture X-ray observatory** will be an early priority. It will

be able to trace clusters of galaxies back to their formation epoch, making possible the study of the early heating and chemical enrichment of the intracluster gas, their relation to black hole activity, and the assembly of the clusters' galaxy population. Such an observatory should also be able to detect and characterise the precursors of quasars and locate the mergers of supermassive black holes expected to be detected by LISA. These objectives will require high sensitivity, with a collecting area above 10 m^2 , and a wide field of view covering at least 5 arcmin for viewing extended objects. A field of 15 arcmin would substantially increase the serendipitous science return and the survey potential for locating the most extreme objects in the high-redshift Universe. High spatial resolution ($< 5 \text{ arcsec}$) will be needed to avoid source confusion. A soft

X-ray spectroscopy capability should make possible the detection of the missing half of the baryons in the local Universe, most likely hidden in the warm-hot intergalactic medium.

Although JWST will register the redshifted visible light from very distant objects (redshifts up to $z \sim 10$) it will miss the star-forming regions hidden by dust. They will be observable, in the longer term, only by a new-generation **far-infrared observatory**. This instrument will be essential to resolve the far-infrared background glow into discrete sources and so locate as much as 50% of the star-formation activity, which is currently concealed from our view by dust absorption. The far-infrared observatory will also resolve star-formation regions in nearby galaxies, both isolated and interacting, and identify through spectroscopy the cooling of molecular clouds with primordial chemical composition. These goals call for a resolution of about 1.5 arcsec at wavelengths around 200 μm .

Other interesting information, especially on the warm-hot intergalactic medium and supernovae of Type Ia at low redshifts, would be obtainable using high-resolution ultraviolet spectroscopy.

4.3 The evolving violent Universe

Nature offers astrophysicists the possibility of observing objects under much more extreme conditions, in terms of gravity, density and temperature, than anything feasible on Earth. On the one hand, black holes and neutron stars are unique

laboratories where the laws of physics can be probed under these extreme conditions (Section 3.3). On the other hand, the same objects were the driving engines of the birth and evolution of galaxies, of the creation of heavy elements such as iron, and more generally, of the transformation of the primordial hydrogen and helium from which stars and galaxies were first being formed.

Recent results show that supermassive black holes exist in the cores of most galaxies and that there must be a direct link between the formation and evolution of the black holes and of their host galaxies. X-ray emission is produced as surrounding gas is accreted by the black hole. This high-energy radiation is not just a witness to the existence of the black holes but also probes the rate at which these black holes grow to their current huge masses. Systematic, high-sensitivity X-ray observations of these growing supermassive black holes along cosmic history will give unprecedented information on the growth of large-scale structures in the Universe and on the formation of galaxies. It is also of the utmost importance to understand the feedback between this process and the formation of stars and the galaxies themselves, for which the X-ray observations will need to be complemented by far-infrared observations of the same objects to map star formation activity (see Section 4.2).

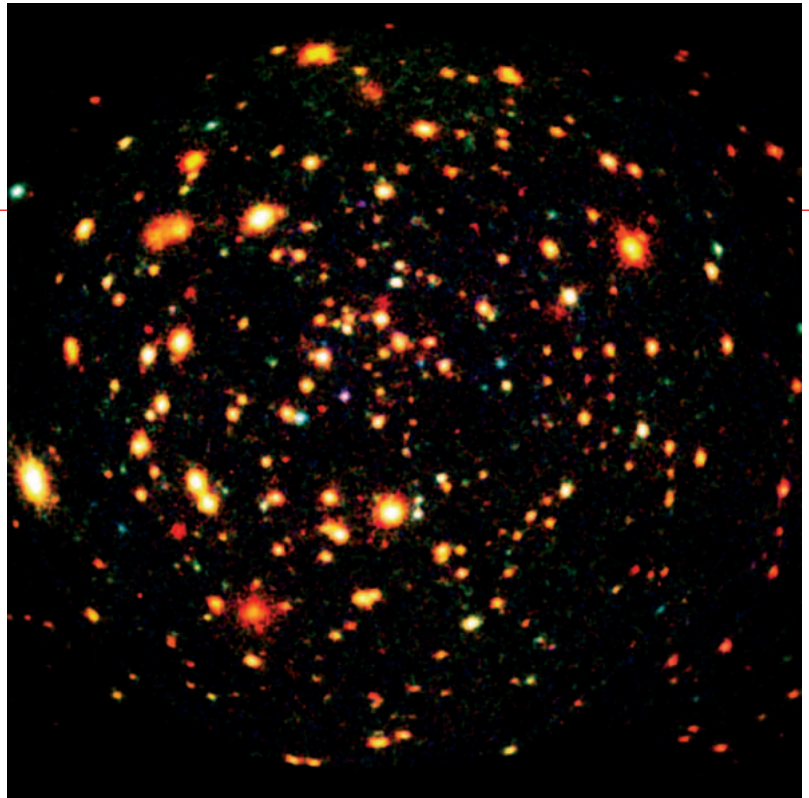
Thanks to another breakthrough of the past 10 years, the extremely bright and brief emissions of gamma-ray bursts are now thought to be produced by a rapid

Observed by XMM-Newton, the Lockman Hole provides the deepest ever X-ray survey of this region where observation of the early Universe is facilitated by the relative absence of intervening, absorbing material. More than 60 new X-ray sources were detected in the 5-10 keV band alone. (G. Hasinger, Max-Planck-Institut für extraterrestrische Physik (MPE), Garching, D).

accretion of gas onto new black holes, resulting from the merging of neutron stars or the dramatic explosion of a high-mass supernova or hypernova. Capture of debris from the explosion results in an extreme rate of mass accretion, which can power an ultra-relativistic jet of matter. This process can be used to probe the formation rate of high-mass stars that give rise to the hypernovae, out to very high redshifts and the epoch of galaxy formation.

Debris escaping from the scene disperses the heavy elements formed by nucleosynthesis in the massive stars, into the interstellar and intergalactic medium. We can witness this process in full detail when it happens very close to us, in the remnants of supernovae in our own Galaxy. The transported energy also heats the gas and suppresses star formation. The chemical abundances in the gas on these large scales can be determined from X-ray line emission, and reflect the supernova rate integrated over time, while nuclear lines at gamma-ray energies from radioactive isotopes give a snapshot of recent activity. Comparison of the abundances in the local and high-redshift Universe will show the evolution of chemical enrichment and the impact of supernova feedback of energy on the growth of large-scale structures in the Universe. Comparison of the abundances of elements in the gas of galaxies, clusters of galaxies and in the intergalactic medium will shed light on the life-cycle of matter in the Universe.

When two supermassive black holes merge in a galaxy, they produce X-rays and



gravitational waves. Simultaneous observations of these events by the X-ray observatory and by the gravitational wave detector LISA, described in Section 3.2, would bring complementary information. By pinpointing the galaxy, the X-ray detection will resolve any uncertainties in direction in the gravitational wave signature, and establish the distance of the event unambiguously.

Most of the topics quoted above build on successes achieved with ESA's XMM-Newton. They are also being addressed by the US (RXTE and Chandra) and Japanese (ASCA and Astro-E2) space observatories. For Europe to maintain its lead in understanding the physics of the violent Universe, the next major step requires a **large-aperture X-ray observatory** of high sensitivity ($\sim 10 \text{ m}^2$ collecting area) over a broad bandpass, ideally 0.1-50 keV, in order to handle the large photon rates of a variety of events. High spatial resolution

(~1-2 arcsec) will be needed to avoid source confusion, and time resolution down to a few microseconds to probe the relevant timescales. These performances would, for example, probe the abundances of clusters and groups of galaxies out to redshifts of 1-2, and track changes in the accretion flows onto black holes. The specifications are compatible with those for a large-aperture X-ray observatory applied to studies of the Universe taking shape (Section 4.2) and of matter under extreme conditions (Section 3.3).

Closer to us, the supernova history of our own Galaxy will soon be much clearer through the spectroscopic diagnostics of MeV lines detected by ESA's Integral mission. By the end of the 2015-2025 period, or soon after, the next-generation detectors at these high energies (bandpass 100-2000 keV) will have a sensitivity two orders of magnitude better than Integral's. They would enable a **gamma-ray imaging observatory** to complete the supernova history of the Milky Way – and then to do the same for all the galaxies in the Local Group.

Toolkit for Theme 4

Tools

4. How did the Universe originate and what is it made of?**4.1 The early Universe****Investigate the nature and origin of the Dark Energy that is accelerating the expansion of the Universe**

Gravitational lensing by cosmic large-scale structures, and the luminosity-redshift relation of distant supernovae are the clues

Wide-field optical-infrared imager

Investigate the physical processes that led to a phase of drastic expansion in the early Universe

Gravitational waves from the Big Bang should leave imprints of inflation in polarisation of the cosmic microwave background

All-sky mapper for polarisation of cosmic microwave background

Directly detect gravitational waves from the first moments of the Big Bang

This means operating in a new frequency window (0.1-1.0 Hz)

Gravitational wave cosmic surveyor

4.2 The Universe taking shape

Find the very first gravitationally-bound structures that were assembled in the Universe – precursors to today's galaxies, groups and clusters of galaxies – and trace the subsequent co-evolution of galaxies and super-massive black holes

Large-aperture X-ray observatory

Resolve the far-infrared background into discrete sources, and the star-formation activity hidden by dust absorption

Far-infrared observatory

4.3 The evolving violent Universe

Trace the formation and evolution of the super-massive black holes at galactic centres – in relation to galaxy and star formation – and trace the life cycles of chemical elements through cosmic history

Large-aperture X-ray observatory

Examine the accretion process of matter falling into black holes by the spectral and time variability of X-rays and gamma-rays, and look for clues to the processes at work in gamma-ray bursts

Understand in detail the history of supernovae in our Galaxy and in the Local Group of galaxies

Gamma-ray imaging observatory



Chapter 5

The fundamental science questions addressed in Chapters 1 to 4 need to be answered through specific experiments on carefully selected space missions. Considerable effort will be required to move forward from embryonic concepts for projects to mission profiles that are technically, fiscally and programmatically feasible. For any suite of potential missions, such as those foreseen in Cosmic Vision 2015-2025, the timely and systematic development of new technologies will be crucial for its success.

While the details of the technologies required will mature as the mission characteristics become clearer, it is still possible to identify at an early stage many of the key developments. Technologies that may be common to a number of possible future missions can also be established. For example, deployable mirror systems with large apertures are a common requirement for various astronomical missions, although the design details differ significantly, depending on wavelength. A common readout technology providing random access for large sensor arrays, at different wavelengths, also merits considerable effort.

For each of the scientific Themes 1 to 4, and their sub-themes, we identify in what follows the investigative approach and the possible technologies that should be developed to address them most effectively. The 'tools' selected by scientific criteria become the basis for identifying embryonic concepts for missions, and establishing a provisional sequence based

Technology Requirements

purely on their levels of technology readiness. Missions currently within the ESA programme need to be considered too, since they will also provide important learning curves in the mission, technology and science areas. For example, the development of a gravitational wave cosmic surveyor, to look for signals from the Big Bang, will clearly need to await the implementation of the ESA-NASA LISA mission. In other cases, such as planetary missions, fixed launch windows governed by celestial mechanics will affect programme planning.

5.1 Theme 1: the conditions for planet formation and the emergence of life

The tools identified in Chapter 1, and summarised in Table 1.1, span a wide range of requirements, from large telescope arrays to miniaturised landers. Here, we discuss them from a technological point of view under the various subheadings into which the main question was divided.

5.1.1 From gas and dust to stars and planets

In order to develop this field further and to build on ground-based capabilities, a **far-infrared observatory** with high spatial and low to high spectral resolution will be required, in the range 25-300 μm . The study of dust and gas in stellar discs and proto-stars in the process of formation will demand an instrument with a spatial resolution of ~ 10 milliarcsec and two ranges of spectral resolution: a low one around 1000 and a high one of about 10^5 . Such an instrument will be based on

Table 5.1.1.1: Technologies required for a far-infrared interferometer.

Technology	Comment
Membrane reflectors	Low-mass system
Adaptive optics	Figure control
Interferometer components	
Constellation control	Metrology, micro-propulsion and control
Thermal shields and cryocooler	Long-life coolers
Far-infrared sensor (bolometer/ semiconductor, photo-con)	High-sensitivity arrays

interferometric principles, similar to those also required at near-infrared wavelengths (Section 5.1.2). The configuration of the multi-spacecraft constellation making up such an interferometer will require detailed study. Although many of the key technologies could be common to other missions, some specific additional technologies, involving low- and high-resolution spectrometers, will need to be developed. Table 5.1.1.1 summarises the key technologies required for such an interferometer. Particular effort will be required in the development of the far-infrared sensors.

5.1.2 From exo-planets to biomarkers

The detection of new planetary systems naturally leads to a desire to search for exo-planets in the habitable zone, followed by characterisation of those planets to detect the spectral tracers of a planet's atmosphere, e.g. water, ozone and carbon dioxide and possibly also methane, which may include signs of life. This will require a high ratio of stellar light rejection (10^5 - 10^6) added to a high sensitivity for detecting the

Figure 5.1.2.1: The near-IR nulling interferometer using a 4-spacecraft constellation at L2. The three beams collected by the telescope spacecraft are brought together on the central beam-combiner. A constellation of four appears to be the minimum required to establish the atmospheric characteristics of terrestrial planets (inset) within the habitable zones of stars within 25 pc.

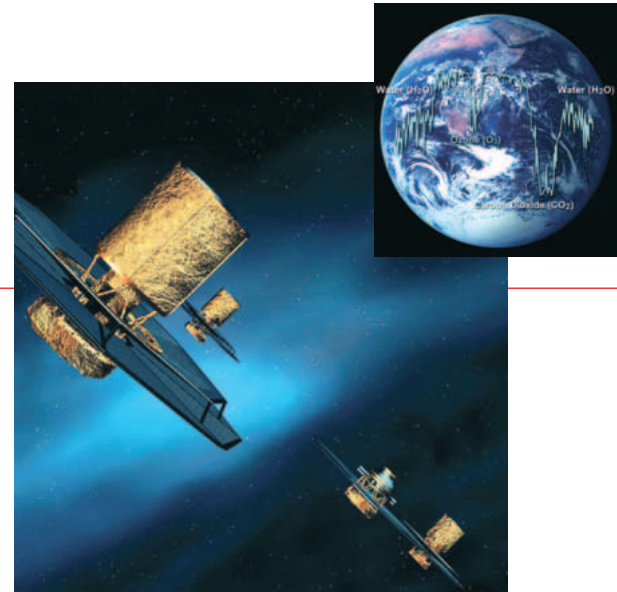


Table 5.1.2.1: Technologies required for a near-infrared nulling interferometer.

Technology	Comment
Single-mode waveguide	Fibre optics or integrated optics
Nulling interferometer components	Optical delay line, phase shifter, etc
Constellation control	Metrology, micro-propulsion and control
Near-infrared sensors and sensor/optics coolers	High-sensitivity arrays + cryocoolers

light emitted by exo-Earths. These objectives would be addressed by a **near-infrared nulling interferometer** with high spatial resolution (images with 10-100 times more detail than will be possible even with instruments such as the JWST) and low-resolution spectroscopy ($R \sim 20-50$).

Such an instrument will require the development of a four-spacecraft constellation with a variable baseline. The challenges with such an optical configuration are significant, particularly for combining the optical beams. Fig. 5.1.2.1 shows one possible mission profile. Three telescopes on three free-flying spacecraft operate together with a separate central beam-combiner spacecraft. The separation between these spacecraft will vary depending on the target star and its associated habitable zone. Such a mission would be capable of observing planetary systems around all stable K, G and F stars out to a distance of 25-30 pc (~80-100 light years) resulting in ~300-500 candidate planetary systems. Further spectroscopic observations with the interferometric

constellation will characterise the planetary atmospheres. The key technologies specific to such a mission are identified in Table 5.1.2.1 (for brevity, some of the generic technologies needed to achieve formation-flying are not listed).

Looking beyond this key step, with the nulling interferometer, the technological prospects for the **terrestrial planet astrometric surveyor** proposed in Section 1.2 can be judged in relation to NASA's Space Interferometer Mission-Planet Quest. This US project, expected in 2011, intends to use interferometry with visible light, on a 10 m baseline, to measure star angular motions to $1 \mu\text{arcsec}$, and so detect the stellar wobbles among the nearest stars due to orbiting planets down to Earth-sized objects. A European mission a decade later, building on Gaia's expertise in global astrometry, could reasonably aim at the nanoarcsec accuracy, and achieve a complete census of terrestrial planets within 100 pc of the Sun.

On the other hand, the goal of eventually imaging terrestrial planets orbiting other stars, mentioned in Section 1.2, would require a large optical interferometer that may be beyond reach in the Cosmic Vision 2015-2025 timeframe.

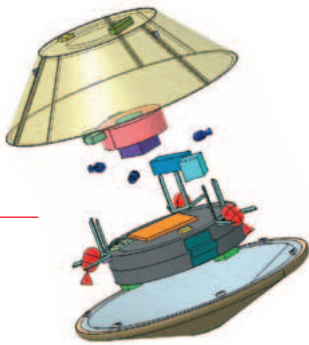


Figure 5.1.3.1: A possible design of a 50 kg lander for Mars with a payload mass of ~12 kg. The complete system including the EDLS would require about 150 kg for a secure landing. Two landers of this class could be accommodated on an orbiter like Mars Express, and inserted into a controlled manner from a highly elliptical Mars orbit. (ESTEC Concurrent Design Facility DemoLander study performed for the Exploration Programme/General Studies Programme.)

5.1.3 Life and habitability in the Solar System

For the theme of life and habitability in the Solar System, Mars is clearly a major target within Cosmic Vision 2015-2025. Naturally, the programme must take account of the major activities envisaged within ESA's Aurora Programme and NASA's planning.

Mars landers with science packages including biochemical and geophysical instrumentation are an important early goal. Key requirements are driving the initial studies:

- to land on rough and high terrain, a challenge for the entry, descent and landing system (EDSL; Fig. 5.1.3.1);
- to penetrate to depths of several metres, for subsurface science;
- to provide mobility for science instruments (Fig. 5.1.3.2).

The technologies and surface science packages needed to meet these requirements are listed in Tables 5.1.3.1 and 5.1.3.2.

The long-term goal is, of course, a **Mars sample return**. The aim would be to gather soil samples and deliver them to the Earth, from a specified set of locations previously

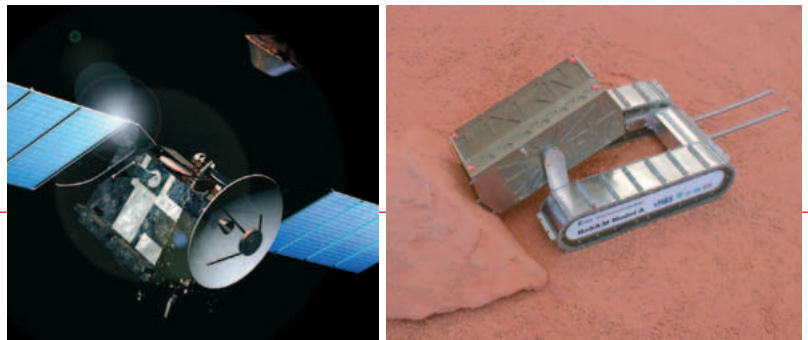


Figure 5.1.3.2: The release of one of two landers from a Mars orbiter before the initiation of the EDLS (left). On the surface, the lander would also require a mobile element (right). Here, a European mini-rover with a range of 50 m and carrying a geochemistry payload of 1 kg is shown.

Table 5.1.3.1: Technologies for the Entry, Descent and Landing System (EDLS) required for an initial secure landing on Mars.

Technology	Comment
Spin-up & eject mechanism	Improved accuracy
Parachutes	Optimisation and extensive tests
Thrusters	Velocity control during descent
Guidance, navigation & control	Descent control by radar/lidar + camera
Airbags	Sizing/pressure optimisation and test
Front heatshield	Increased size and testing
Back cover	Release system and test

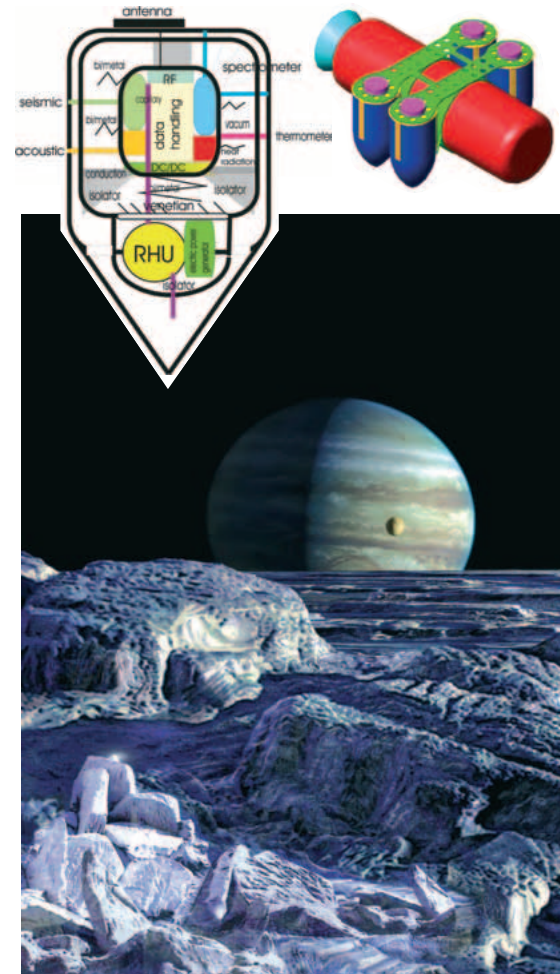
Table 5.1.3.2: Technologies for the surface science packages required to exploit an initial secure landing on Mars.

Technology	Comment
Deep subsurface (5 m) mole	Qualification of existing system
Compact subsurface biochemistry system	Mole packaging and test
Compact subsurface geophysics system	Mole packaging and test
Mini-rover	Test and qualification
Rover geochemistry package	Development and qualification

studied *in situ* by landers or their associated rovers. This further step is a major challenge that needs careful technology preparation. Section 5.2.3 describes a sample return from a low-gravity environment, in this case a near-Earth asteroid.

The Jovian system, often compared to a miniature Solar System, is also a major

Figure 5.1.3.3: An array of four microprobes for Europa with a controlled descent system (top right) together with the distribution of key sensors and subsystems (top left). Adoption of this type of system to perform a controlled landing on the surface of the Jovian moon (below; ©2005 by Don Dixon/cosmographica.com) would require at least 20 kg mass allocation, so taking a major fraction of the resource budget of the payload suite (30 kg) of the Europa orbiter JEO. This should therefore be considered as a later option in the Jupiter exploration programme.



target within Cosmic Vision 2015-2025. It needs to be studied and explored in a coherent and systematic manner through a **Jupiter exploration programme (JEP)**. Those parts of JEP that focus on Jupiter's magnetosphere and interior figure in Sections 5.2.1 and 5.2.2. In the context of the present theme, Jupiter's icy moon Europa is one of the few places where liquid water may be found in the Solar System, making it a prime candidate for the search for life beyond the Earth. Remote sensing from a **Europa orbiter** is certainly an option. The deployment of microprobe **Europa landers** can also be considered, provided that they are technically feasible and the likely science return justifies the effort and resources.

A possible scenario foresees two small spacecraft (400 kg and 600 kg), one acting as a relay spacecraft (JRS1) in a highly elliptical orbit around Jupiter, outside the high radiation zones, while the other (JEO) enters a polar orbit around Europa. There, the orbiter has a maximum lifetime of around 2 months, after which the perturbation by Jupiter's gravity will set the orbiter on an unavoidable collision course with the icy moon. The expected electron radiation is up to 2 Mrads during those 2 months, assuming shielding by 4 mm of aluminium, so this highly hostile environment will require innovative approaches in the spacecraft design.

Global mapping and analysis of the moon's surface can be obtained in 30 days by JEO, with a stereo micro-camera, UV-camera, visible/near-infrared mapping spectrometer,

and a laser altimeter, together with a miniaturised subsurface radar and a low-resource gamma-ray spectrometer. A magnetometer, radiation monitor, radiometer and a low-resource microprobe could complete the core payload of JEO and stay within the available spacecraft resources.

As for Europa landers, a single penetrating microprobe (1 kg) might be considered for an early mission, to perform a local *in situ* analysis of Europa's subsurface. It can be released either shortly before Europa orbit insertion or shortly after. Since there is no significant atmosphere around Europa, the microprobe must survive the shock of a high-speed impact on the icy crust. Currently, this is considered to be unfeasible, although studies continue.

For a later phase in the Jupiter exploration programme, landers making controlled descents from a second Europa orbiter can be contemplated.

In Fig. 5.1.3.3 an illustrative 20 kg microprobe payload consists of a thermometer, spectrometer and seismic and acoustic sensors. The tracking and communication between this very low-power probe and the orbiter will be a significant challenge by itself. Another major challenge will be the attitude control of the probe, since Europa does not have any significant atmosphere to stabilise it.

5.2 Theme 2: how does the Solar System work?

Among the most far-ranging tools for Cosmic Vision 2015-2025 are those that will continue ESA's exploration of the Sun's empire, but now with the additional objective of making better sense of the environments and planets of other stars, and their potential habitability. New technologies to be shared between different kinds of projects will greatly extend the possibilities of exploration at reasonable costs.

5.2.1 From the Sun to the edge of the Solar System

Investigations of plasma physics, and what it can teach us about the complex behaviour of magnetic fields and charged particles throughout the Universe by closer study of those in the Solar System, remain a major goal for ESA in Cosmic Vision 2015-2025. A new opportunity arises in the use of large swarms or small groups of identical micro-

Table 5.2.1.1: Technologies required for a magnetospheric swarm in Earth orbit.

Technology	Comment
Inter-spacecraft control	GNC/autonomy depending on orbits
Highly integrated plasma payload	Low-resource instrument suite
Radiation hardening of LEO spacecraft	Radiation tolerant micro-satellites
Electromagnetic cleanliness tools	Simulation and test tools
Swarm deployment system	Depends on required orbits

satellites for cooperative observations of plasma behaviour in various settings. In particular, Chapter 2 specified the exploration of two very different environments, in the magnetospheres of the Earth and of Jupiter.

In the case of the **Earth magnetospheric swarm**, it is visualised that more than eight spin-stabilised micro-satellites, each of about 50 kg, will be placed at key positions within the Earth's magnetosphere. Although these spacecraft will require only loose formation control to ensure appropriate separation, some developments are needed in key technology areas identified in Table 5.2.1.1. In particular, the swarm deployment and maintenance of the inter-spacecraft distances over potentially small separations, down to less than 1 km, need careful consideration. The level of cooperation between these spacecraft depends on the final number in the swarm. A shepherding spacecraft akin to the HIVE (Hub and Interplanetary VEHICLE) formerly considered in an ESA feasibility study for a Main Belt asteroid mission, might well handle deployment as well as command and control.

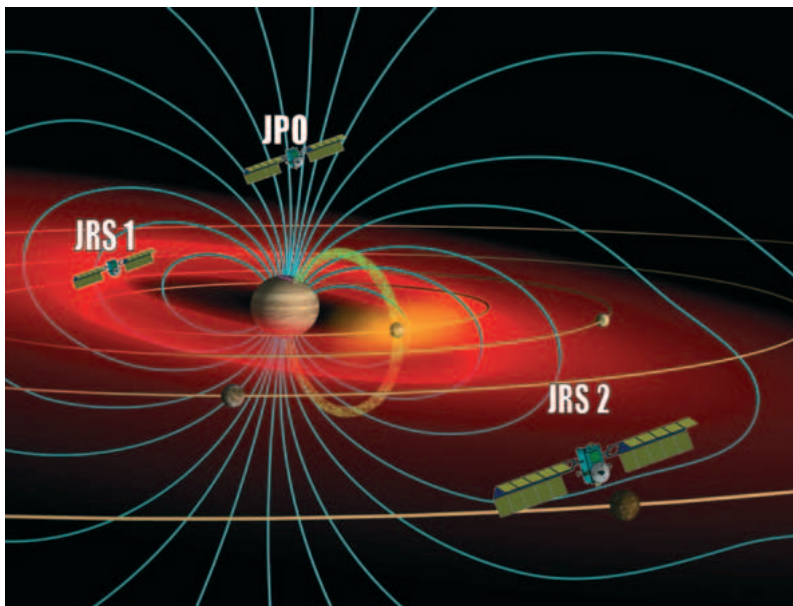


Figure 5.2.1.1: Three small spacecraft including two relay satellites (IRS 1/2) plus a Jupiter polar orbiter (JPO) would carry identical plasma payloads to form a small constellation to study the complex magnetosphere of the Jovian system.

Table 5.2.1.2: The additional technologies required for the development of a small magnetospheric constellation within the Jovian system.

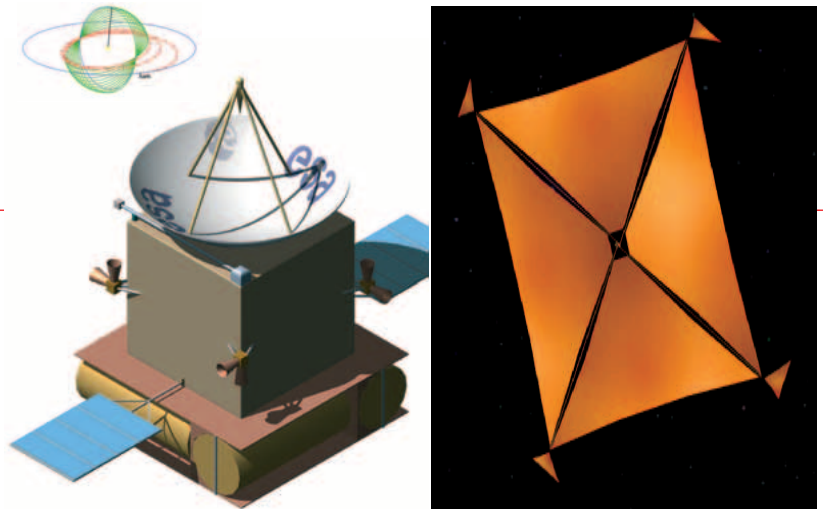
Technology	Comment
Mass memory	Size depends on orbits required
Highly integrated plasma payload	Low-resource instrument suite
Radiation-robust micro-satellites	Radiation levels depend on orbits
Power system	RTG trade-off required depends on spacecraft lifetime and orbits
In system deployment	Depends on orbits and science required
Autonomy	To limit ground control costs

The exploration of the magnetosphere of Jupiter is just one of a number of different themes addressing different scientific objectives within a Jupiter exploration programme. This will involve multiple spacecraft using common facilities and underpinning technologies, as described in Sections 5.1.3 and 5.2.2. All power for the programme is currently based on low-intensity low-temperature (LILT) solar array technology with solar concentrators, rather than radioisotope thermoelectric generators (RTGs). Nevertheless, an RTG development remains desirable for the Jupiter exploration programme and would be essential for the other outer planets beyond Jupiter.

A small multi-spacecraft constellation with trajectories that migrate through the complex system of the Jupiter magnetosphere will build on past experience in Earth orbit with Cluster, and possibly with the Earth magnetospheric swarm described above. It is envisaged that two relay satellites, JRS1/2, needed for the first phase of the Jupiter exploration programme would contain a magnetospheric payload, while a part of the Jupiter polar orbiter (JPO) would be also dedicated to such studies (Fig. 5.2.1.1). A fourth spacecraft, the Europa orbiter (JEO) described in Section 5.1.3, would complete the constellation during its tour through the Jovian system. Technologies specific to these micro-satellites in their magnetospheric role are identified in Table 5.2.1.2.

Beyond the magnetospheric studies of the Earth and Jupiter, the long-term plasma programme involves two extremes: the study of the Sun at polar latitudes at a distance of 0.5 AU, with a **solar polar orbiter** (SPO; Fig. 5.2.1.2) and reaching the heliopause out at 200 AU with an **interstellar heliopause probe** (IHP). Both these tools require spacecraft that can acquire an extremely large change in velocity. This can be achieved through the development of solar sailing as the baseline propulsion system. Solar sails utilise the momentum of the photons of sunlight to obtain a very low but persistent acceleration. Since no propellant is used, the propulsion system is very effective, although very large structures are needed. The acceleration of a solar sail spacecraft will greatly increase as it travels closer to the

Figure 5.2.1.2: The Solar Polar Orbiter with its large sail stowed prior to deployment (left). The fully deployed system (right) allows for a payload mass of 25 kg to be deployed to study the polar regions of the Sun. Inset: the final orbit achieved 0.5 AU above the poles of the Sun.



Sun. IHP in particular will capitalise on this effect by first performing two solar flybys down to 0.25 AU to obtain the required acceleration to travel to the heliopause at 200 AU in a realistic journey time of perhaps 25 years.

The development of a reliable solar sailing system will require great advances from current available technologies. The largest sail deployed so far has been the 20x20 m device in an ESA/DLR ground test. There have been other demonstrations as well, such as a small spinning disc sail deployment, the in-orbit solar sail deployment on the Russian Progress vehicle, and a recent JAXA deployment on a sounding rocket. To turn concepts of the SPO and IHP into realistic projects, several aspects of solar sail technologies will require development, coupled to a technology-demonstration mission in Earth orbit, GeoSail, along the lines of the SMART programme. Such a mission might be able to combine an in-orbit technology demonstration as part of a wider science mission such as the Earth magnetospheric swarm described earlier in this section.

The key technologies specific to the SPO spacecraft and payload are summarised in Table 5.2.1.3. Some other spacecraft technologies such as heatshields will be derivatives of the significant investment in the Solar Orbiter mission.

The second science application of this propulsion technology would be to study the interface between the interstellar medium and the heliosphere by means of

Table 5.2.1.3: The technologies required for the development of the Solar Polar Orbiter based on a solar sail propulsion system.

Technology	Comment
Sail material with Al/Cr coating	2 μm -thick film, loading 8 g m ⁻²
Sail degradation	Material thermal and radiation effects
Sail deployment system	~150 x 150 m ² sail
Spacecraft – sail jettison system	
Lightweight booms	
Sail guidance navigation and control	Spacecraft autonomy
Highly integrated payload	Low-resource instrument suite

Table 5.2.1.4: The technologies required for the development of the Interstellar Heliopause Probe based on a solar sail propulsion system.

Technology	Comment
RTG	~8 W/kg
GNC and autonomy	Autonomous navigation
Analogue-Digital Converter System	Control of large sails
High-temperature sail material	1 μm with Al/Cr coating
Degradation of sail material	Characterisation of candidate materials
Deep-space communications	RF versus optical
Sail sensor integration	Autonomous navigation, health monitor
Long-life components	Applies to all subsystems
Highly integrated plasma payload	Low-resource instrument suite

an interstellar heliopause probe. To reach 200 AU within 25 years would require a 250x250 m x 1 μm sail with characteristic acceleration of 1.1 mm/s², and sail assembly loading of 3.9 g/m². The minimum distance to the Sun is currently set at 0.25 AU, which

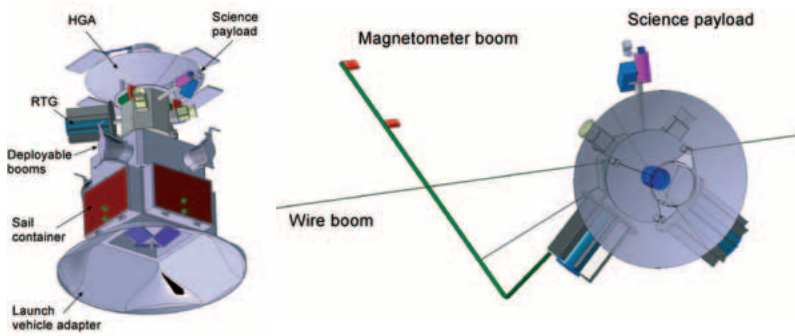
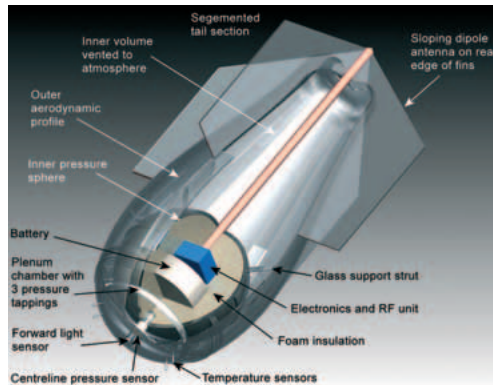


Figure 5.2.1.3: The Interstellar Heliosphere Probe in its launch configuration, with the booms and huge solar sail stowed (left). The sail is jettisoned (right) after 5 years at 5 AU from the Sun. Thereafter, the probe travels out from the Solar System to reach the heliopause in 25 years, and then on into interstellar space.

Table 5.2.2.1: The technologies required for the Jupiter polar orbiter and probes.

Technology	Comment
Thermal protection system	Jupiter atmospheric entry is extremely challenging
Microprobe injection system	Depends on orbit and science
Microprobes including possible mini-aerobot	Capable of withstanding Jovian atmospheric conditions (P,T) depending on required depth
Miniaturised microprobe payload	Requirement is science-dependent
Low-resource communication system	Mission profile-dependent. It should enable communications during the entire entry sequence

Figure 5.2.2.1: A potential design of a microprobe deployed from a local aerobot for probing *in situ* the atmosphere of Jupiter. The microprobe's payload might consist of temperature, pressure and light-level sensors together with infrared flux, wind profile and chemistry instruments. Clearly, the final design will be governed by the probe depth required.



implies that the sail will have to withstand a solar flux 16 times greater than at the Earth. The solar sail will be jettisoned at 5 AU, after about 5 years, during which time it is important that it keeps its optical properties, since the acceleration performance is directly dependent on the reflectivity of the sail material. Clearly, the fulfilment of solar sail technology will be a major challenge in the latter half of the Cosmic Vision 2015-2025 timeframe.

The power system for the interstellar heliopause probe will most likely employ an RTG.

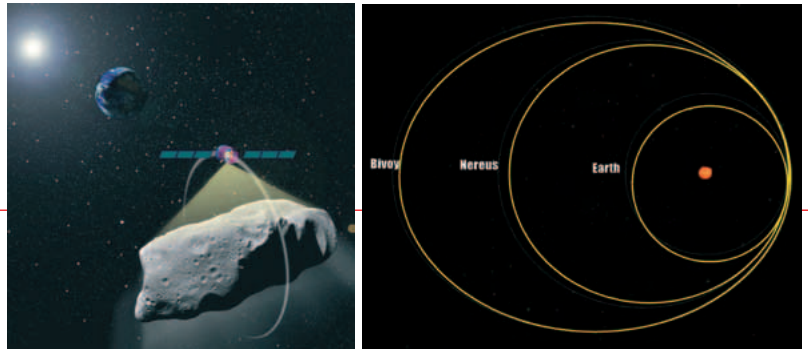
The key technologies specific to the interstellar heliopause probe for both the spacecraft and payload are summarised in Table 5.2.1.4. These are also relevant to one of the fundamental physics explorers, contemplated in Section 5.3.1 for testing gravity at very large distances.

5.2.2 The giant planets and their environments

The study of the giant planets is essential for understanding our Solar System and other planetary systems. The proposed **Jupiter exploration programme** needs to be made in a coherent and systematic manner. This would involve a series of multiple spacecraft entering the system over a number of years. To reduce risks and costs, the programme could consist of small spacecraft with very low requirements of mass and power, enabling the use of relatively low-cost launcher systems. Achieving this result will call for highly miniaturised and integrated systems both for the spacecraft and for their payloads.

Within this proposed Jupiter exploration programme, it is assumed that a dedicated mini-satellite **Jupiter polar orbiter** (JPO) in a low orbit would provide a remote-sensing study of the giant planet's atmosphere. Moreover, *in situ* measurements would be obtained through the injection of a number of microprobes into the atmosphere (Fig. 5.2.2.1). These

Figure 5.2.3.1: The near-Earth sample return spacecraft in orbit about an asteroid (left). The spacecraft trajectory to rendezvous with two near-Earth asteroids (Nerus and Bivoj) is also shown (right). Detailed mission analysis will be required to optimise the targets and route.



could be injected directly from the orbiter, which would require a thermal protection system for each microprobe, or else be released from a mini-aerobot (e.g. a glider or a solar Montgolfier balloon) deployed from a single entry probe capsule. The latter option would require considerable resources for the aerobot and introduce a single-point failure for all probes.

A Jupiter relay mini-satellite (JRS2) is again assumed to handle communications and to contribute to the magnetospheric constellation described in Section 5.2.1. Apart from the technologies discussed in Sections 5.1.3 and 5.2.1, specific technologies for the JPO and probes are summarised in Table 5.2.2.1.

5.2.3 Asteroids and other small bodies

One of the keys to understanding the history and composition of our Solar System lies in investigating its small bodies, such as asteroids and comets. Retrieving a sample from a small, low-gravity body and delivering it to Earth for detailed analysis is significantly different from obtaining a planetary sample. A Mars sample return mission, for example, will require a lander with a fully controlled entry and descent system, and a launcher to send the samples into space. Retrieving a sample from a small body should be simpler (Table 5.2.3.1). A dedicated launch vehicle after sample collection is not necessarily required for such a low-gravity environment, and the descent requirements are also significantly different. It may be possible to consider the collection of samples from multiple sites on an asteroid, or even from multiple targets.

Table 5.2.3.1: The technologies required for a near-Earth object sample return mission.

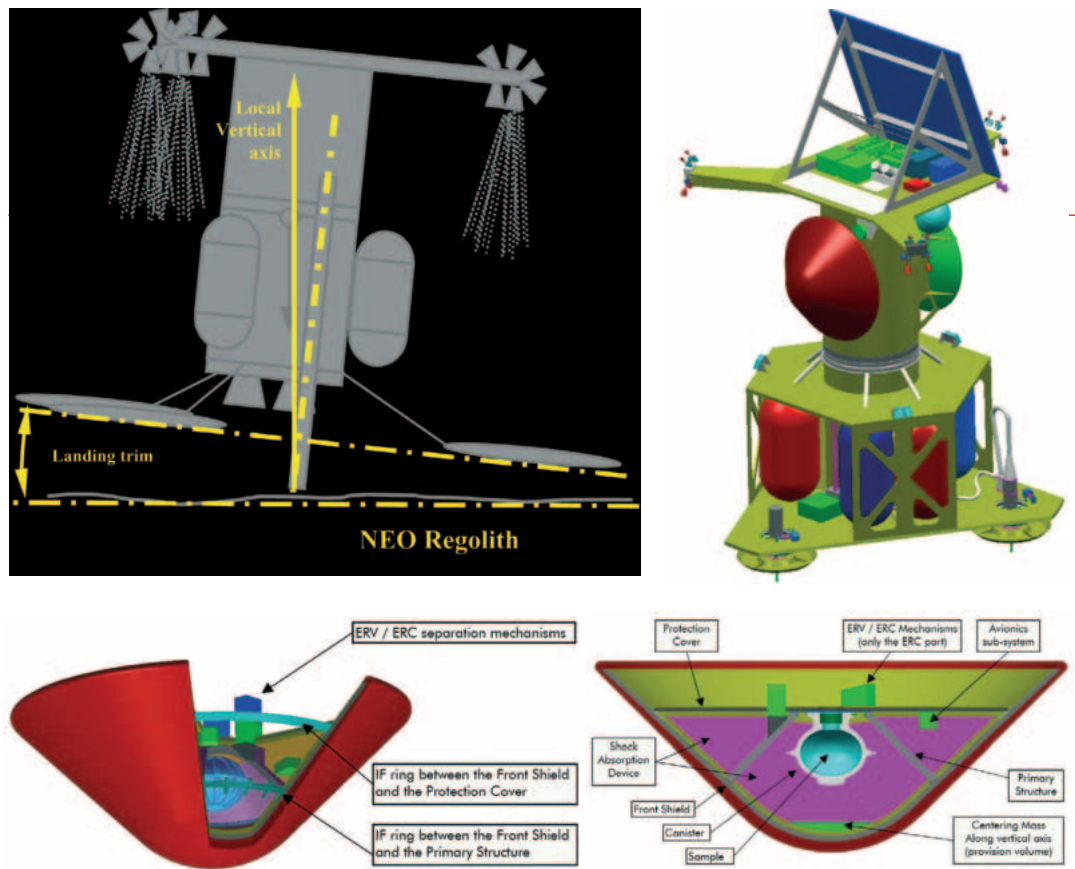
Technology	Comment
Sample mechanism	Touch-and-go multi-site sampler
Sample-transfer mechanism	Transfers sample from sampling device to Earth entry vehicle
Earth entry vehicle	Planetary protection
Guidance and navigation system	Highly autonomous, capable of site recognition and course correction during sampling

Near-Earth asteroids are easily accessible and make attractive targets for a small-body sample return project (Fig. 5.2.3.1). Their orbital lifetimes are short compared to cosmological timescales and they are continuously being replenished from other sources, either from the main asteroid belt or from comets. The goal of a **near-Earth object sample return** is to collect a scientifically significant harvest of the surface material of one or more asteroids and deliver it to Earth.

It is envisaged that a small spacecraft dispatched on a Soyuz-Fregat 2B launch vehicle (or equivalent 'low-cost' launcher) will rendezvous with one or more near-Earth asteroids, perform remote sensing observations and ultimately initiate a series of sampling manoeuvres. Upon completion of sampling, the spacecraft will return to Earth, where the sample canister will make a direct Earth entry.

The amount of material that can be brought back will influence the science that can be

Figure 5.2.3.2: A sample-and-return vehicle performing a touch-and-go manoeuvre on an asteroid (top left). A possible overall spacecraft configuration with propulsion and sampling stage together with the Earth entry vehicle are shown at top right. Schematics of the Earth Entry Vehicle are also shown (lower panels).



performed. Most analytical instruments require much less than a gram of material, and the others only a few grams. However, a greater amount is needed to get a good overview of the sampled area. Some redundancy is also necessary and there should be some additional material in case further research is desired. The objective would therefore be to collect a few hundred grams from each sampling site. Once obtained, the samples will be transferred into a canister inside an Earth entry vehicle (EEV) (Fig. 5.2.3.2).

Several studies have already examined potential designs of entry vehicles for Mars sample return missions. These could help in the design and development of the EEV for the asteroid mission.

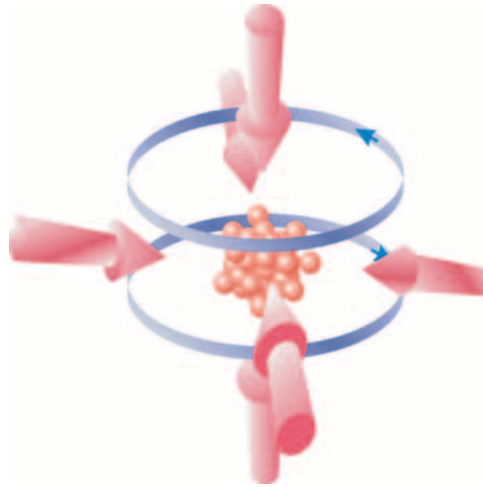
Section 2.3 mentions the long-term aim of

exploring the small bodies of the Kuiper belt, beyond Neptune. Such a project is beyond the scope of Cosmic Vision 2015-2025, yet some of the technologies to be developed for other purposes would clearly be relevant, most specifically those required for the interstellar heliopause probe (Section 5.2.1).

5.3 Theme 3: what are the fundamental physical laws of the Universe?

Fundamental physics became well-embedded in ESA's space science and technology with the adoption of the big ESA-NASA LISA mission to look for gravitational waves. That aspect reappears later in this section, in a discussion of LISA's successor, but there are many other ways of checking the fundamental physical laws with smaller space projects.

Figure 5.3.1.1: The principle of a cold-atom source. Atoms are trapped by a combination of a magnetic field and laser beams. The lasers are adjusted such that the thermal momentum of the trapped atoms is reduced.



5.3.1 Explore the limits of contemporary physics

Unlike Solar System exploration or astronomy, fundamental physics typically requires spacecraft in purely gravitational orbits. That is to say, drag and spurious acceleration effects must be minimised, implying the need for an on-board drag-free control system, comprising an inertial sensor, a charge-control system, a low-thrust propulsion system and drag-free control software. For the candidate projects in the Cosmic Vision 2015-2025 timeframe, two categories of such spacecraft are envisaged. One comprises a series of small, standard, low-cost spacecraft in low-Earth orbit forming the core of a fundamental physics explorer programme (Section 5.3.1.1). The second category consists of individually-designed spacecraft, or even several spacecraft flying in formation in special orbits or trajectories optimised to achieve their scientific objectives. Examples of these, directed to testing gravity at long ranges, appear in Section 5.3.1.2.

5.3.1.1 The fundamental physics explorer programme

Many fundamental physics experiments can be carried out in the weightlessness of spaceflight with an accuracy order of magnitude higher than in ground-based laboratories or on the International Space Station. The optimum environment for these experiments would be on-board a highly stable 3-axis stabilised, drag-free platform. The **fundamental physics explorer programme** would be based on a standard platform that would be reused for

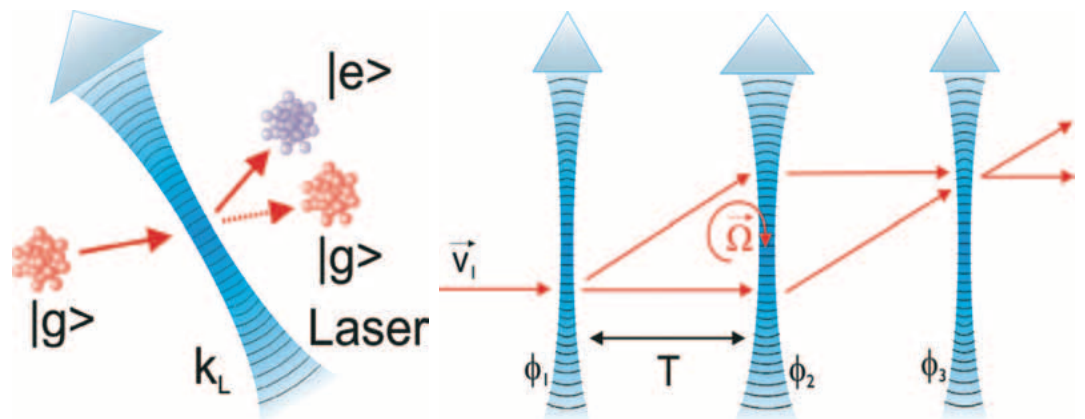
Table 5.3.1.1: Expected improvements in parameters through the use of Bose-Einstein condensates in space in the Fundamental Physics Explorer Programme.

Parameter	Ground Limit	Space Requirement
Free evolution time	< 80 ms	$5 < t < 100$ s
Measurement time	< 100 ms	up to 100 s
Temperature	Typically 100 nK	pK to fK
Dynamics	Trap frequencies > 1 Hz	$0.01 < f < 1$ Hz
Trapped condensate size	100-500 μ m	$100 \mu\text{m} < L < 10$ mm

several missions in low-Earth orbit with only minor modifications in order to reduce the procurement cost. The platform could have the following general features:

- 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.

Several candidate experiments envisage the use of a Bose-Einstein condensate (BEC), which is an ideal gas of identical particles sharing a single quantum state – in effect, a super-atom. Only recently pioneered on the



ground, BECs give a unique insight into a broad range of phenomena in fundamental physics, as well as offering prospects for new quantum sensors based on matter-wave optics. Add the benefits of 'low gravity' and a calm environment in space, and the BECs will become even more amazing.

Table 5.3.1.1 summarises the expected improvements in various experimental parameters when experiments are performed in space. Clearly, space-qualified BEC systems will be an important underpinning technology for many experiments in fundamental physics, and will set the stage for innovative studies, such as:

- phase transitions at ultra-low temperatures (pK–fK range);
- dipolar quantum gases;
- physics of ultra-dilute quantum gases, excitations in the weak trapping regime;
- quantum gas mixtures in a microgravity environment;
- quantum decoherence;
- high-resolution interferometry with coherent matter waves (atom laser).

Fig. 5.3.1.1 shows the technique used to achieve a BEC, using lasers in combination with a strong magnetic field. The absolute temperature of the matter waves has to be

low ($< nK$), and needs to be controlled very accurately (fK range) by Raman coupling, which requires the development of space-qualified Raman lasers with high stability. Integration by nanotechnology would significantly increase the robustness, while allowing a reduction in the required current, and better cooling.

Here, some of the candidates for the fundamental physics explorer programme are briefly considered. All except the first of these examples require BECs; relevant technologies are listed in Table 5.3.1.2.

Test of the equivalence principle using macroscopic objects

The equivalence principle, that everything falls at the same rate under gravity, is tested by a set of proof masses that are in free-fall around the Earth in a drag-free satellite. Disturbances need to be minimal, and therefore the test masses are in a cryogenic environment, well-shielded from stray electromagnetic fields.

Test of the equivalence principle using beams of cold atoms

Using BECs as the samples under test and a matter-wave interferometer as the measurement device, the equivalence principle could be tested with a variety of different atomic species. Such an experiment would yield similar levels of accuracy to those of a macroscopic

Figure 5.3.1.2: Principle of a matter-wave interferometer. The atomic beam passes through a laser, where momentum is added or subtracted depending on the quantum states of the atoms. The suitable orientation of the laser beams allows the control of these atomic waves such that two split beams are routed through separate paths, and recombined. At the recombination point, the atomic beams interfere, thereby the resultant phase-shifts can be measured, which reflect differences in the processes that affected the split beams.

measurement (as in the first example), but would be complementary in extending the measurement to microscopic scales. Additionally, a possible spin-gravity coupling could be investigated.

Searches for deviations from Newtonian gravity at small distances

This would require a specially designed matter-wave interferometer where the atomic trajectories of one arm pass close to a probe mass. The gravitational force felt by the atomic wavepackets is translated by the atom interferometer into a phase shift in the output port of the instrument. By a space-based experiment involving very slow atoms and long interaction times, the effect of small-distance gravity could be measured to micron scales. The same technology as for any matter-wave interferometer would be required (Fig. 5.3.1.2), but the extremely slow atoms represent a further development in technology.

Test of the gravitational inverse square law at several large ranges

This experiment would use a matter-wave interferometer with a BEC as source, in the form of a gravity gradiometer. The essential mission requirement would be to place the drag-free spacecraft in a highly elliptic orbit so as to measure the Earth's gravity field over a wide range of distances. (For another possible gravitational experiment, outside the explorer programme, see Section 5.3.1.2).

Cold-atom clocks of very high precision

The performance of atomic clocks can be improved in space, using cold atoms.

Table 5.3.1.2: Technologies for the fundamental Physics explorer programme.

Technology	Comment
Cryogenic accelerometers	Superconducting test masses and readout (SQUIDS)
Magnetic shielding	Extremely low stray fields
Cold-atom source	Robustness and reliability, low power, lightweight; atom chips
Low-noise cold-atom source	Various elements, e.g. Cs, Rb, H, Mg, Ca, Sr, Ag, Xe, I
Bose-Einstein condensate	High level of integration and nanotechnology
Atom traps	Tight traps, smaller than the de Broglie wavelength; box-shaped potential wells where atoms can be free-floating
Atom laser	Independent cooling and trapping, chip-based atom source, for high brightness
Ultra-stable lasers	Low-amplitude and frequency noise, accurate beam-shaping
Ultra-stable microwave source	For laser control and frequency combs
Ultra-stable Raman lasers	High-frequency stabilisation for narrow atomic transitions

Weightlessness allows very long interaction time between the atoms and the probing electromagnetic field, while the low temperature improves both the accuracy and the stability of the instrument. Means have to be found, both aboard the spacecraft and at the ground station, to transmit the time signal to ground without introducing further uncertainties in the time reference. Correcting for the gravitational shift will require precise orbit determination, to the cm range or better. For the readout of the clock, frequency transitions need to be phase-stabilised by fs laser with 300 MHz to GHz compared to 10^{15} Hz optical frequency, thereby generating a frequency comb.

Table 5.3.1.3: Technology themes for a space detector for ultra-high-energy cosmic rays.

Technology	Comment
Large collecting lens	Large Fresnel lens
Compact fast photodetectors	High time resolution and low power/heat consumption

Table 5.3.2.1: The technologies required for the development of a gravitational wave cosmic surveyor.

Technology	Comment
Phase-locked high power laser	100 W at 1 μm
Large-area mirror based on new materials	Low-mass system. > 1 m
High-sensitivity drag-free control system	Noise < $10^{-16} \text{ m s}^{-2} \text{ Hz}^{-1/2}$
Next-generation inertial sensors	C-couple proof mass
High-precision pointing system over 10^5 km	High-quality GNC to 10^{-6}
Low-frequency GNC	FEEP thrusters and control

Investigation of possible time-dependence of fundamental physical constants

Using high-accuracy clocks based on cold atoms, and by excitations of narrow atomic transitions, the stability of an atomic transition can be measured. This relates directly to the fine-structure constant α , which defines the strength of the electromagnetic force. Measurements under different conditions, or with changes in gravity, should reveal any time-dependence of α .

Tests of quantum measurement theory (entanglement and decoherence)

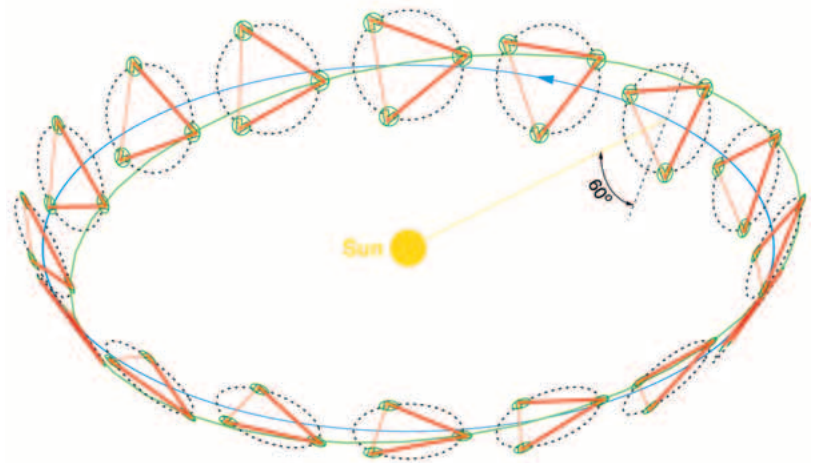
To investigate decoherence, the transition of quantum matter with its statistical behaviour

to matter as perceived in daily life, a high-intensity matter-wave would be released to travel over large distances in an undisturbed manner. The BECs must consist of at least 10^5 atoms. Compensating for magnetic fields will be also necessary, to better than $1 \mu\text{G}$ over 1 m. The same technology can be used for measurements of entanglement.

5.3.1.2 Checking the strength of gravity at long ranges

An anomalous small but constant frequency drift was observed in the tracking data of NASA's Pioneer 10 and 11 probes, consistent with an extra acceleration towards the Sun of $9 \times 10^{-10} \text{ m/s}^2$. This might indicate a breakdown of Newton's law of gravity at large distances and, by implication, Einstein's general relativity. Motivated by these observations, a conceptual mission of the fundamental physics explorer series could be a **deep space gravity probe** that would aim to achieve free-fall (geodesic) motion for a test mass in the Solar System over a distance range from 5 AU to 70 AU, and to monitor this motion precisely with an acceleration resolution of 10^{-12} m/s^2 . If achieved, such a mission would surpass the precision of current data by a factor of 1000, provided that X-band and Ka-band ranging and range-rate measurements can deliver an accuracy of the spacecraft's position to less than 1 m (< $1 \mu\text{m/s}$ for range-rate) in three dimensions. Thrust manoeuvres of all kinds must cease at 5 AU, which rules out planetary flybys at Jupiter and beyond.

Figure 5.3.2.1: The successive year-round positions of the three spacecraft of the ESA-NASA LISA mission (2014), which will trail the Earth in its orbit around the Sun. Very slight changes in the 5 million-km separations, measured with laser beams, will reveal passing gravitational waves.



The deep space gravity probe might be accomplished by solar sailing, which could provide an initial high velocity. In this scenario, the propulsion phase ends with the shedding of the solar sail at 5 AU. Thereafter, the spacecraft will release proof masses of about 5 kg each, which will perform the actual measurement. These objects will be fully passive with homogeneous surfaces, such that the effects of solar pressure and of dust particles can easily be modelled. The free-fall of the proof masses will be monitored via laser ranging by the main craft, which will also carry all necessary communication and power generation equipment.

5.3.1.3 Detection of ultra-high-energy cosmic rays

Matter accelerated to extremely high energies also arrives in the Earth's vicinity. Apart from the commonplace cosmic rays in the 10^{10} eV range, there are astounding cosmic ray particles above 10^{19} eV, more than a million times more powerful than anything produced by accelerators on the ground. If they hit the Earth, they create very extensive showers of particles and make the atmosphere glow by fluorescence and Cherenkov radiation.

Ground facilities, including the large Auger array in Argentina, observe the extensive air showers from the ground, but they are limited by the local horizon. A **space detector for ultra-high-energy cosmic rays** looking down from low Earth orbit could witness the events around a much larger swath. It would need a large-aperture telescope and sensitive light detectors in

the near-ultraviolet and blue region of the spectrum. Table 5.3.1.3 comments briefly on these topics.

5.3.2 The gravitational wave Universe

The search for gravitational waves coming directly from the Big Bang is rated as highly important within Theme 3, but the proposed **gravitational wave cosmic surveyor** will not be easily achieved before the end of the Cosmic Vision 2015-2025 timeframe. The most favourable frequency band for the detection of the Big Bang's gravitational radiation is 0.1-1 Hz, which is well outside the mHz waveband of the ESA-NASA LISA antenna due for launch around 2014.

Fig. 5.3.2.1 illustrates the 5 million km triangle to be marked out by the three LISA spacecraft, and their successive positions as they orbit the Sun in the Earth's wake. Very slight changes in the great distances between the spacecraft, measured with laser beams, will reveal passing gravitational waves.

For the next-generation space antennas, tuned to the 0.1-1 Hz range, the spacecraft separation will be significantly smaller. Clearly, the technologies will build on the LISA mission, and again use a constellation of spacecraft flying in a very extended formation. Key technologies required are identified in Table 5.3.2.1.

Table 5.4.1.1: The technologies required for the development of a wide-field optical-infrared imager.

Technology	Comment
Deployable mirror system	Low mass, large aperture
High-stability optical bench	Low mass in stable environment
Large deployable sunshade	Low-mass system
Active optics	Lightweight smart optics at ~1 arcsec
Closed-cycled coolers	Long life
Large-area near-infrared/optical sensors	Large-format arrays + readouts

Table 5.4.1.2: The technologies required for the development of an all-sky cosmic microwave background polarisation mapper.

Technology	Comment
Deployable antennae	Low mass, large aperture
Large deployable sunshade	Low-mass system
Closed-cycled cooler	Long life
Polarisation-sensitive sensors	Large-format arrays and readout

Table 5.4.2.1: Technologies needed for development of the large-aperture X-ray observatory.

Technology	Comment
Deployable grazing incidence mirror	Low mass, large aperture
High-stability optical bench	Low mass in stable environment
Grazing-incidence mirror coatings	Optimised reflectivity
Formation-flying	Metrology and control laws
Closed-cycled low-temperature cooler	Long life and low temperature
Wide-field semiconductor sensors	Large-format arrays
Cryogenic sensors	Medium-format arrays

5.3.3 Matter under extreme conditions

Here, the requirement is for a **large-aperture X-ray observatory** to probe the hot gas very close to a black hole, with good spectral and temporal resolution. As

this tool is also needed under Theme 4 ‘How did the Universe originate and what is it made of?’, the technology is addressed in Sections 5.4.2 and 5.4.3.

5.4 Theme 4: How did the Universe originate and what is it made of?

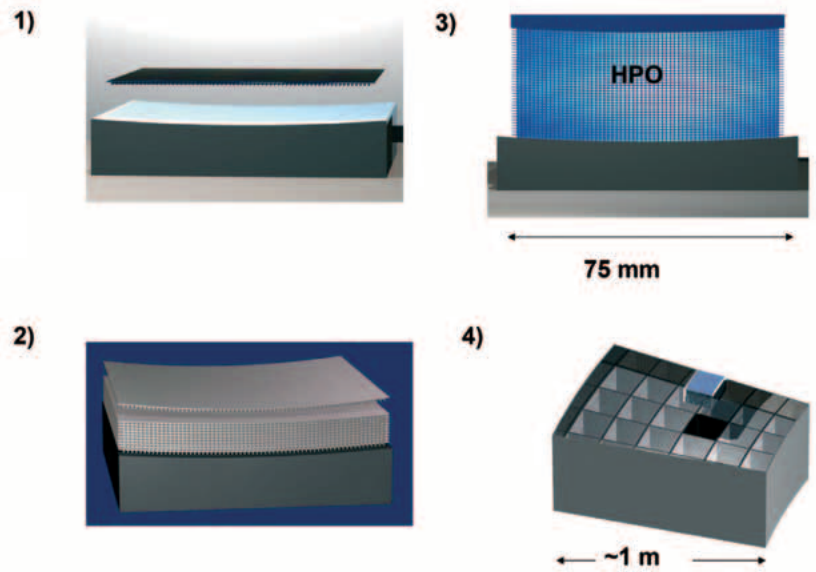
The art of the telescope maker has gradually extended the range of human vision out to the limit of the observable Universe, taking us in time-machine fashion almost back to the very beginning. But there obscurity sets in, because of dust and ionisation, and even large objects look small and confusable in the sky. New generations of telescopes in space are needed to improve the view.

5.4.1 The early Universe

The study of the early Universe centres on the role of dark energy and inflation. Investigations of dark energy could be accomplished through the luminosity-redshift relation of supernovae Type 1a for a large-enough range of redshifts. Another approach is to study the effect of weak lensing – the bending of light by a gravitational field produced by a large-scale matter distribution in the Universe. Precision measurements of both of these effects require a space-based **wide-field optical-infrared imager**, using technologies identified in Table 5.4.1.1.

The sensitivity of any such space observatory will depend on the aperture of the primary mirror which, with current technology, is limited by the launcher shroud and particularly by the mass

Figure 5.4.2.1: The assembly of high-precision silicon wafers into a pore optics stack from which a mirror petal of about 1 m is constructed. Many such petals form the low-mass deployable mirror system needed for a large-aperture X-ray observatory.



constraints. The development of a large, low-mass deployable mirror system with a high resolving power would be required. The imaging performance of such a system will depend on the thermo-mechanical stability of the optical bench carrying the optics (active system). A large primary mirror will impose a commensurate increase in the dimensions of other optical components. The optical bench therefore will be crucial for ensuring the stability of the overall optical system. The focal plane detector of such a wide-field imager requires giga-pixel arrays coupled to the development of low-noise CMOS sensors approaching CCD-type performance.

An advantage of the operation of such wide-field imaging optics in space is the possibility of operating the mirror at the diffraction limit, should this be required scientifically. However, an important feature is the stability of the image point spread function from one observation to the next on the same field. In order to exploit this capability, it will be essential to minimise the relative pointing error and pointing drift of the spacecraft through the parallel development of a high-precision attitude control system. Such a control system would have considerably wider applications within the Cosmic Vision programme.

Considering the role of inflation in the early Universe, observing the polarisation properties of the cosmic microwave background is one of two approaches for characterising the primordial gravitational waves assumed to be left over from the Big

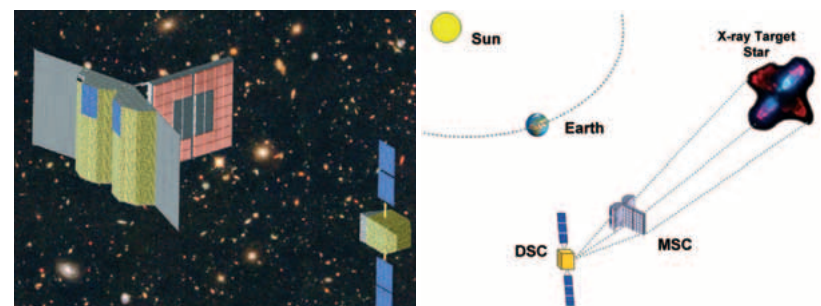


Figure 5.4.2.2: The two spacecraft of the large-aperture X-ray observatory (left). The large mirror spacecraft (MSC) and its 10 m deployable mirror system are in the background; the smaller detector spacecraft (DSC) is in the foreground. The separation between spacecraft will be controlled to ~ 1 mm by the DSC. Deployment will be at L2 (right).

Bang. It requires a multi-frequency **all-sky cosmic microwave background polarisation mapper** with much higher sensitivity than Planck will achieve. Key technologies required are identified in Table 5.4.1.2.

The second approach will be to look for the actual gravitational waves from the Big Bang at frequencies around 0.1-1 Hz, which are uncluttered by more local sources. This gravitational wave cosmic surveyor was discussed in Section 5.3.2.

Table 5.4.2.2: The technologies required for the development of an far-IR facility.

Technology	Comment
Deployable mirror system	Low mass, large aperture, 10 kg/m ²
High-stability optical bench	Low mass in stable environment
Large deployable sunshade	Low-mass system
Active optics	Smart structures operable at low temperatures
Formation flying	Metrology and control, with the ability to fill an interferometric u,v plane
Closed-cycled cooler	Long life
Far-infrared sensors	Large-format superconducting direct detection arrays
Tunable coherent THz receivers	Broadband array receivers approaching quantum-limited performance

5.4.2 The Universe taking shape

Here, the aims are to map cosmic history back to the time when the first luminous sources ignited, and to trace the subsequent evolution of galaxies and their supermassive black holes, together with their effects on the intra-cluster medium. The necessary tool is a **large-aperture X-ray observatory** that is over two orders of magnitude more powerful than current facilities. Timely deployment is essential to maximise the synergies with the LISA gravitational wave observatory, notably in locating the mergers of supermassive black holes expected to be detected by LISA. The key technologies required are identified in Table 5.4.2.1.

Clearly the key to such a mission is the development of a high-resolution large-aperture mirror system. Fig. 5.4.2.1 shows just how such a mirror made up of many mirror petals can be fabricated. These high-precision pore optics based on silicon wafers are a European breakthrough technology, which would allow the

ambitious goals of the large aperture X-ray observatory to be achieved.

It is clear that such a huge mirror system with a collecting area of > 10 m² at 1 keV, a wide field of view, and a resolution of better than 5 arcsec is a major technology challenge, involving novel mirror design with advanced materials. Such a single-aperture mirror system will necessitate a long focal length (~50 m) implying formation-flying of two spacecraft: a mirror spacecraft and a detector spacecraft separated by the focal length. Fig. 5.4.2.2 shows such a possible configuration deployed at the second Lagrangian point L2.

The need for precision formation-flying of two or more spacecraft is a common theme through a number of potential astrophysics missions in Cosmic Vision 2015-2025. In a similar fashion, payload items, including high-stability optical benches and low-temperature closed-cycle coolers, become support technologies of a generic nature.

In addition to such an X-ray facility, another deep-Universe observatory will be required to resolve the far-infrared extragalactic background light into discrete sources and locate the 50% of the star-formation activity in the Universe hidden by dust, to resolve star-formation regions in nearby isolated and interacting galaxies, and to identify spectroscopically the cooling of molecular clouds with primordial chemical composition. These goals require a **far-infrared observatory** to have an angular resolution of about 1.5 arcsec at 200 μm. The major technical challenge will again involve the development of a large-

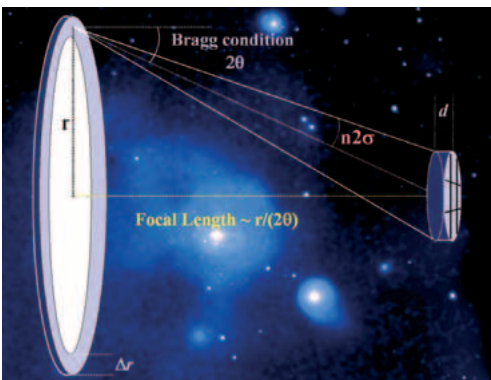
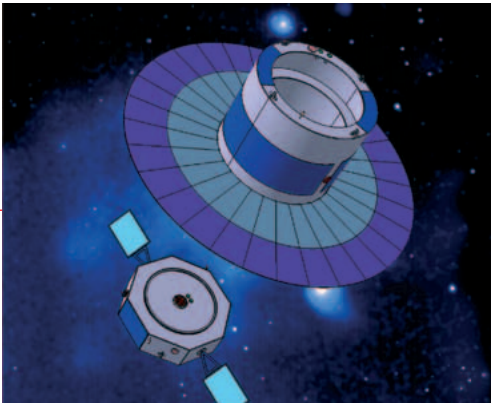


Figure 5.4.3.1: A gamma-ray imaging observatory based on two formation-flying spacecraft separated by 0.5 km (top). The very large-aperture focusing system uses diffractive optics possibly based on the Laue lens principle (bottom) and would study the gamma-ray emission, both spectral and temporal, from matter under extreme conditions of gravity.

Table 5.4.3.1: The technologies required for the development of an X-ray facility focused on the X-ray temporal properties.

Technology	Comment
High time-resolution sensors	Rates > 1 MHz and resolution ~1 μs
Precision clocks	Absolute local time to 100 ns
Higher energy mirror systems	Layered synthetic microstructures
High-energy X-ray semiconductors	Imaging arrays
Spectropolarimeters	High sensitivity

Table 5.4.3.2: Technologies required for the development of a gamma-ray imaging observatory.

Technology	Comment
High-energy focusing optics	High-efficiency photon collection
Large-aperture deployable optics	Mass-efficient deployment system
Long-baseline formation-flying	Metrology and control over ~1 km
High-energy gamma-ray semiconductors	Imaging array and ASIC readout
High-energy reflective coatings	Layer synthetic microstructure

aperture deployable mirror system. Key technologies are identified in Table 5.4.2.2. Particular effort will be required in the development of the far-infrared sensors.

5.4.3 The evolving violent Universe

The study of the evolving violent Universe investigates the role of accretion and ejection mechanisms taking place in the vicinity of black holes and neutron stars, and the crucial interplay between black holes and galaxy evolution. It aims at probing deep inside the gravitational well of black holes and neutron stars, providing a thorough test of general relativity in the strong field limit, and deals with the physics of strong interactions in ultra-dense environments, the virulent processes in hypernova explosions leading to gamma-ray bursts, and binary black hole mergers. These phenomena will best be studied at X-ray wavelengths through the development of a **large-aperture X-ray observatory** as described in Section 5.4.2, but with special attention to the technologies for detecting

extremely rapid variations in emissions, as noted in Table 5.4.3.1.

Sources of explosive nucleosynthesis and electron-positron annihilation are also of major interest. Building on the current ESA Integral mission, the need will arise for a **gamma-ray imaging observatory** that will continue to explore with unprecedented sensitivity the region from 50-2000 keV. It will probably need to rely on diffractive optics with a long focal length. Novel reflective optics could potentially also be used in the region 50-200 keV. Such an observatory will require the development of formation-flying spacecraft similar to those required for the X-ray observatory, but with an order-of-magnitude increase in the focal length. The key technologies required are identified in Table 5.4.3.2.



Chapter 6

Taking account of the scientific and technological perspectives of Chapters 1 to 5, we now develop possible strategies that address the four top questions of Cosmic Vision 2015-2025 with candidate concepts for missions. Appropriate space tools are proposed within each of the selected areas where big progress can be expected in the next two decades. In some cases, the same item appears in more than one scientific context and this obviously enhances its cross-disciplinary value. We also give a few preliminary indications of how the proposals might be sequenced within the timeframe of Cosmic Vision 2015-2025.

6.1 A strategy for Theme 1: stars, planets and life

An intellectually stimulating feature of the present efforts to answer the question 'What are the conditions for planet formation and the emergence of life?' is that they bring to an end a long period in which research on planets seemed to be entirely distinct from stellar and galactic astronomy. Now the aim is to treat the Solar System as a prime exhibit in the much broader context of stellar and planetary formation, aiming at a new science of comparative planetology.

In the early stages of Cosmic Vision 2015-2025, a **Near-Infrared Nulling Interferometer** could be set out to identify Earth-like planets orbiting other stars by finding telltale molecules in their atmospheres. An ingenious interferometric technique using multiple spacecraft would suppress the bright rays from a parent star

Proposed Strategies and Their Implementation

to let its faint planetary companions show themselves sufficiently for spectrographic analysis (Section 1.2).

For in-depth analysis of terrestrial planets within the Solar System, Mars remains an early target, especially in view of the success of Mars Express and the initiation of ESA's Aurora Programme. Examining the planet's surface in greater detail by **Mars Surface Exploration**, including the use of drills and rovers, and eventually by a **Mars Sample Return** would be fitting tasks within Cosmic Vision 2015-2025, as well as, of course, the Aurora Programme (Section 1.3).

Another important aspect of habitability is the characterisation of the magnetic environment. The Sun's magnetic field could be charted by a **Solar Polar Orbiter** (Section 1.3).

The births of stars and planets remains largely mysterious because the events are shrouded in dust. Visualised for the middle of the 2015-2025 period, a **Far-Infrared Observatory** would use a large telescope mirror, kept in shape by 'smart' active optics, to penetrate the dust and observe the birth events in much greater detail than ever before (Section 1.1).

Some Earth-sized planets will be discovered if and when they pass between us and their stars, dimming them slightly, but a full census requires detection of their contributions to stellar wobbles, by ultra-high-precision astrometry surpassing that of ESA's Gaia. A purpose-built **Terrestrial**

Table 6.1: Proposed strategy for Theme 1

What are the conditions for planet formation and the emergence of life?	
First	<p>In-depth analysis of terrestrial planets</p> <p>Search for Earth-like exo-planets with a Near-Infrared Nulling Interferometer with high spatial resolution and low-resolution spectroscopy</p> <p>Explore Mars by Mars Landers and Mars Sample Return</p>
Next	<p>Understand the conditions for star, planet and life formation</p> <p>Trace the formation of stars and exo-planets with a Far-Infrared Observatory with high spatial and low to high spectral resolution</p> <p>Pursue the question of the stellar magnetic environment necessary for life to occur and survive, with a 3-D solar magnetic field explorer – Solar Polar Orbiter</p>
Later	<p>Make a census of Earth-sized planets</p> <p>Detect small planets orbiting stars within 100 parsecs of the Sun, with a Terrestrial Planet Astrometric Surveyor</p> <p>Explore Jupiter's moon Europa as a possible place for life</p> <p>Include a dedicated Europa Orbiter and, if possible, Europa Landers in a Jupiter Exploration Programme (JEP)</p>
Finally (beyond 2025)	<p>Image terrestrial exo-planets</p> <p>To see an Earth-sized planet of another star will require a Large Optical Interferometer</p>

Planet Astrometric Surveyor would take a complete census of the roughly Earth-sized planets circling other stars, out to 100 pc, or more than 300 light-years (Section 1.2).

Jupiter's fascinating moon Europa possesses a subsurface ocean that makes it the next best candidate, after Mars, to harbour alien life in the Solar System. To explore it, a dedicated **Europa Orbiter and/or Lander** would be a strong candidate for inclusion in a Jupiter

Table 6.2: Proposed strategy for Theme 2

How does the Solar System work?	
From the Sun to the edge of the Solar System	
First	Examine plasma processes through the full hierarchy of scales in the Earth's magnetosphere with an Earth Magnetospheric Swarm
Next	Chart the 3-D magnetic field at the Sun's visible surface using a Solar Polar Orbiter
Finally	Send an Interstellar Heliopause Probe towards the outer reaches of the heliosphere
Giant planets and their environments	
First	In a Jupiter Exploration Programme , examine the Jovian environment, including the moon Europa, using a series of multiple micro-spacecraft
Then	Explore the hidden Jovian atmosphere with Jupiter Probes and the surface of Europa with a Europa Lander
Asteroids and other small bodies	
First	For analysis on the Earth, obtain material from a primitive type of asteroid, by a Near-Earth Object Sample Return project

Exploration Programme (JEP). A lander would need to penetrate the icy surface of the moon deeply enough to find nutrients or surviving chemical traces of life, if they exist (Section 1.3).

6.2 A strategy for Theme 2: the best-known stellar system

In the cross-disciplinary spirit of exploration adopted for Cosmic Vision 2015-2025, the question 'How does the Solar System work?' now bears upon our investigations of the planetary systems of other stars, and the environments available for life. Making better sense of the complex behaviour of plasmas in the interplanetary environment

is also essential for improving our understanding of the Universe at large, the ordinary matter of which is almost entirely composed of plasmas of many kinds.

Our own planet's space environment, where the magnetosphere fights dramatic battles with the solar wind, provides an excellent natural laboratory for plasma physics. An early aim would be to create an **Earth Magnetospheric Swarm** consisting of eight or more micro-satellites orbiting the planet in changeable partnerships, to trace the plasma events on much smaller scales than attempted hitherto (Section 2.1).

Comprehensive exploration of the Sun's magnetic bubble, the heliosphere, is also envisaged. Within it, the solar wind blows outwards from the Sun's atmosphere to far beyond the realm of planets, and disturbs the Earth as it passes. After a century of work on solar magnetism, the fundamentals remain elusive. So does the wish to make reliable long-term predictions of Sun-Earth interactions. A **Solar Polar Orbiter** would circle over the north and south poles of the Sun at half the Earth-Sun distance, enabling solar physicists to chart the magnetic fields properly at the visible surface near the poles, for the very first time (Section 2.1).

Jupiter, together with its space environment and moons, continues to invite closer inspection of what is, in effect, a Solar System in miniature. The plasma physics of a huge, rapidly-rotating magnetosphere interacting with the solar wind, and also with local sources of matter, is challenging.

Better knowledge of the planet itself will help astronomers to make sense of the 'hot Jupiters' that they see orbiting close to other stars. The interest of astrobiologists in Jupiter's moon Europa was mentioned in Section 6.1.

With the general aim of improving our understanding of the giant planets and their environments, we envisage a **Jupiter Exploration Programme**. It could consist of mission concepts using multiple micro-spacecraft, to be sent into orbit around Jupiter itself and the moon Europa. Great engineering challenges in a harsh environment are balanced by the promise of rich scientific rewards. Within a framework of international collaboration, launches towards Jupiter and Europa would occur at intervals through much of the period 2015-2025 (Sections 2.1 and 2.2).

The Jupiter programme also calls for probes of highly original kinds. **Jupiter Probes** would plunge deep into the opaque atmosphere of the planet, in a number of selected regions, to send back surer information about the gas giant's internal composition and circulation (Section 2.2). Hopefully, a **Europa Lander** could be included too, although the technical problems are severe (Section 5.2).

An **Interstellar Heliopause Probe** would make a 25-year journey out to 200 times the Sun-Earth distance, in order to reach and explore the frontier where the solar wind of the heliosphere is finally halted by the thin gas that fills the spaces between the stars. The interstellar medium could

then be sampled directly for the first time (Section 2.1).

Solar sails would be the innovative method of propulsion employed to put the Solar Polar Orbiter into its difficult path perpendicular to the plane of the Earth's orbit, and also to propel the Interstellar Heliopause Probe on its long pilgrimage. To provide experience with solar sailing, a small technology mission could be needed early in the post-2015 period.

Completing the Solar System strategy are projects to gather samples from other worlds, including an asteroid, and return them to the Earth so that scientists can analyse the materials in their well-equipped laboratories. That was done fruitfully with the lunar samples returned by the US Apollo and Soviet Luna programmes. A **Near-Earth Object Sample Return** should target one of the most primitive asteroids (carbonaceous-type) passing close to Earth's orbit. Success would bring additional knowledge of the small building blocks of the Solar System to put alongside the results from the comets investigated in past and present ESA missions (Section 2.3)

6.3 A strategy for Theme 3: let's rewrite physics textbooks

Never before has the interplay been stronger between theories of the fundamental forces and particles of the cosmos and, on the other hand, the observations of their handiwork in cosmic space. The Big Bang at the birth of the Universe, gamma-ray bursts of great

Table 6.3: Proposed strategy for Theme 3

What are the fundamental physical laws of the Universe?	
	Explore the limits of contemporary physics
First	For a Fundamental Physics Explorer Series develop a sequence of inexpensive small missions using the same platform, designed for ultra-high-precision experiments that exploit cold atoms and other novel technologies, for which proposals include: testing the nature of space and time; exploring the limits of quantum theory (entanglement, decoherence); looking for signs of quantum gravity
Later	Exploring Solar System gravity for violations of Einsteinian (and Newtonian) gravity at long ranges with a view to resolving anomalies in the tracking of Pioneer-10 with a Deep Space Gravity Probe
Later	Begin particle physics in space with a Space Detector for Ultra-High-Energy Cosmic Rays
	The gravitational wave Universe
Later	Make a key step towards detecting gravitational waves from the Big Bang with a Gravitational Wave Cosmic Surveyor operating in a new frequency window (0.1-1.0 Hz) with orders of magnitude more sensitivity than LISA
	Matter under extreme conditions
First	Probe black holes and ultra-high-energy particle physics Black holes and neutron stars with a Large-Aperture X-ray Observatory

violence, and supermassive black holes that power the fireworks of active galaxies – such phenomena bring space scientists face-to-face with big issues in fundamental physics. The observed conditions far surpass anything within reach of laboratory experiments, and the question ‘What are the fundamental physical laws of the Universe?’ still evades a clear answer. Fortunately, the encounters between fundamental physics and space science are not confined to distant astrophysical events.

Europe has the chance to take the initiative in opening up a completely new field of scientific research, by sending into space novel technologies based on experiments with ultra-cold atoms and Bose-Einstein condensates, where swarms of atoms behave like single super-atoms. In experiments of ultra-high precision, impossible on the ground, Europe’s physicists want to explore the limits of contemporary physics, looking for any flaws in the fundamental theories developed in the 20th Century that may open the door to the most profound discoveries of the 21st Century.

To this end, it is proposed to initiate a **Fundamental Physics Explorer Programme** in the 2015-2025 timeframe. We envisage low-cost missions, using a standard type of drag-free and vibration-free satellites, to carry into space a variety of cold-atom instruments that promise incredibly precise measurement, timing, tracking and pointing (Section 3.1).

So many excellent experiments of this kind have already been proposed by the physics community that selection will not be easy. One general aim is to examine the small-scale nature of space and time, on which theoretical physics rests. Another is the wish to explore the fuzzy boundary between the everyday human-scale world and the sub-atomic realm of quantum mechanics – where ‘entangled’ particles are linked instantaneously across great distances, and yet on the other hand the quantum systems eventually ‘decohere’ and give way to normal macroscopic behaviour. The physicists also want to look for clues that may help to pin

down a quantum theory of the force of gravity, which has preoccupied many theorists for the past 30 years.

If gravity is truly a quantum force, then Einstein's general relativity cannot be exactly correct. The Pioneer Anomaly hints at a possible flaw: NASA's Pioneer-10 probe has travelled a little more slowly than expected on its way out of the Solar System. A custom-designed **Deep Space Gravity Probe** could investigate whether this anomaly really exists; does the inverse-square law of gravity fail over large distances? We hope that such a concept could be implemented in the latter part of the 2015-2025 timeframe.

Black holes and neutron stars provide other examples of matter under extreme conditions, owing to the overwhelming effects of gravity in collapsed objects. Fundamental physics would have much to learn from a **Large-Aperture X-ray Observatory**, which could be expected early in the 2015-2025 period. It would probe gas very close to black holes and examine neutron stars in great detail.

If extreme conditions beyond human reach are likely sources of new physics, the most important tool imaginable just now would be a means of observing directly the extravagantly fierce events in the Big Bang itself. A **Gravitational Wave Cosmic Surveyor** could make a huge step towards penetrating the fog of charged particles that creates the cosmic microwave background at the limit of visibility for light-like rays, but hides what happened earlier.

As gravitational waves can pass freely through the matter, they should reveal what was going on during the first moments of the Big Bang. But their detection calls for instruments operating at frequencies quite different from those of other gravitational-wave experiments, whether existing or under development. A European system in this key waveband would be feasible by 2025. Operating on its own, it would detect every individual gravitational wave source in this band in the entire Universe, returning a wealth of information about the early formation of galaxies and stars. Working with international partners, and developing the technology even further, several LISA-like arrays operating together would finally penetrate the fog and see the Big Bang directly for the first time (Section 3.2).

We also draw attention to the opportunity that arises to study particle physics from space with a **Space Detector for Ultra-High-Energy Cosmic Rays**. Later in the decade, this would complement the large ground-based arrays that register the extensive flashes of light produced when cosmic particles of astounding energy hit the atmosphere in their vicinity.

6.4 A strategy for Theme 4: homing in on the cosmological action

Overlapping with the intense interest in the hidden details of the Big Bang is the effort of astronomers to answer the question 'How did the Universe originate, and what is it made of?' Observatories in space may be the only means of finding out what really happened in the so-called Dark Ages of the

Table 6.4: Proposed strategy for Theme 4

How did the Universe originate and what is it made of?	
The early Universe	
First	Explore the acceleration of the cosmic expansion and the Dark Energy that drives it, both by effects of weak lensing and by the detection of very remote supernovae, with a Wide-Field Optical-Infrared Imager
	Investigate the inflationary phases in the evolution of the Universe by indirectly detecting primordial gravitational waves with an All-Sky Cosmic Microwave Background Polarisation Mapper
Later	Directly detect the primordial gravitational waves from the Big Bang with a Gravitational Wave Cosmic Surveyor
The Universe taking shape	
First	Find the first gravitationally-bound structures and trace the subsequent co-evolution of galaxies and supermassive black holes with a Large-Aperture X-ray Observatory
Later	Resolve the sky background into discrete sources and trace the star-formation episodes hidden by dust absorption with a Far-Infrared Observatory
The evolving violent Universe	
First	Examine the accretion process of matter falling into black holes and trace the life cycle of chemical elements in stars, galaxies and the intergalactic medium with a Large-Aperture X-ray Observatory
Later	Continue this work and also understand in detail the history of supernovae in our Galaxy and in the Local Group with a Gamma-Ray Imaging Observatory

cosmos, meaning the first billion years or so after the Big Bang, beyond the limit of visibility for present instruments.

The very first gravitationally-bound structures assembled in the Universe – the precursors to today’s galaxies, groups and clusters of galaxies – are scarcely known. To find them and to trace the subsequent co-evolution of galaxies and supermassive black holes would be a prime task for a

Large-Aperture X-ray Observatory.

Besides detecting these very early aggregations of matter (Section 4.2), this instrument would also detect and chart the entire course of our violent Universe, including the origin of the chemical elements of which planets and living things are built (Section 4.3). Its role in probing ultra-strong gravitational fields was noted in Section 6.3.

Space telescopes are also needed to reveal more clearly the machinery of the expansion of the Universe. A **Wide-Field Optical-Infrared Imager** would explore the acceleration of the cosmic expansion and the dark energy that drives it, both by the effects of weak gravitational lensing by large early masses, and by the detection of very remote supernovae (Section 4.1).

To investigate the earliest phases of the origin of the Universe, including an inflationary episode very early in the Big Bang scenario, a new approach is needed. This relies on gravitational waves released primordially, which must have affected the polarisation of the radiation in the cosmic microwave background. An **All-Sky Cosmic Microwave Background Polarisation Mapper** could therefore trace the primordial gravitational waves indirectly (Section 4.1). Later, these primordial waves should be directly detectable by the demanding technology of the **Gravitational Wave Cosmic Surveyor** already cited Section 6.3.

A **Far-Infrared Observatory** was noted in Section 6.1 as a means of observing the

birth of stars and planets in our own Galaxy. It would have a very important cosmological role too, in tracing the evolution of the earliest masses by resolving the far-infrared background into discrete sources, and by revealing the star-formation activity hidden by dust absorption (Section 4.2).

To support the detailed examination of black holes by the Large-Aperture X-ray Observatory, and also aiming to understand in detail the history of supernovae in our Galaxy and in the Local Group of galaxies, we envisage a **Gamma-Ray Imaging Observatory**, which may be feasible towards the end of the 2015-2025 period (Section 4.3).

6.5 Implementing the Cosmic Vision 2015-2025 space science plan

The breadth of the investigations represented in the strategies outlined above is enormous. They range from the poles of the Sun to the birth of the Universe, and from gigantic cosmic structures to sub-atomic particles. Also remarkable is the way that very different techniques converge on the same question, whether it be the origin of life or the fundamental physics of the cosmos that makes our existence possible.

Science priorities and programme priorities are not identical. A highly desirable candidate mission may be postponed for technological and/or budgetary reasons. The different themes and their associated projects interact with one another. Some space tools are relevant to more than one of our scientific questions, and overlaps also

occur in the new technologies that need to be developed.

Certain groups of projects require similar innovations, such as the formation-flying foreseen for several telescopes and self-organising associations of micro-satellites in Solar System missions. On the other hand, work towards devising instruments using the novel cold-atom technologies, and adapting them to spaceflight, should probably begin now, with a view to being ready for the first Fundamental Physics Explorer. The same is true of the optics and detectors for X-ray astronomy, a European excellence peak. Solar sailing will take time to master, and so its applications may be deferred until relatively late in the 2015-2025 period.

The space tools nominated in the four strategies should be seen as candidate concepts for missions. More ideas are mentioned than those affordable in the 2015-2025 timeframe. Exactly how much can be accomplished will depend on the Level of Resources of the Science Programme, but also, in part, on what international collaborations can be arranged. However, competition between the candidate concepts is bound to persist up to the time of selection and approval.

Flexibility must remain in the space science programme to allow for unforeseen opportunities or difficulties, whether in the science or in the technology. The readiness of the technology – often highly innovative – will be a decisive factor in the selection and sequencing of the eventual missions. ESA will also wish to maintain a decade-by-

decade balance between Solar System research, astronomy and fundamental physics, and to safeguard Europe's reputation as a reliable partner in international collaborations.

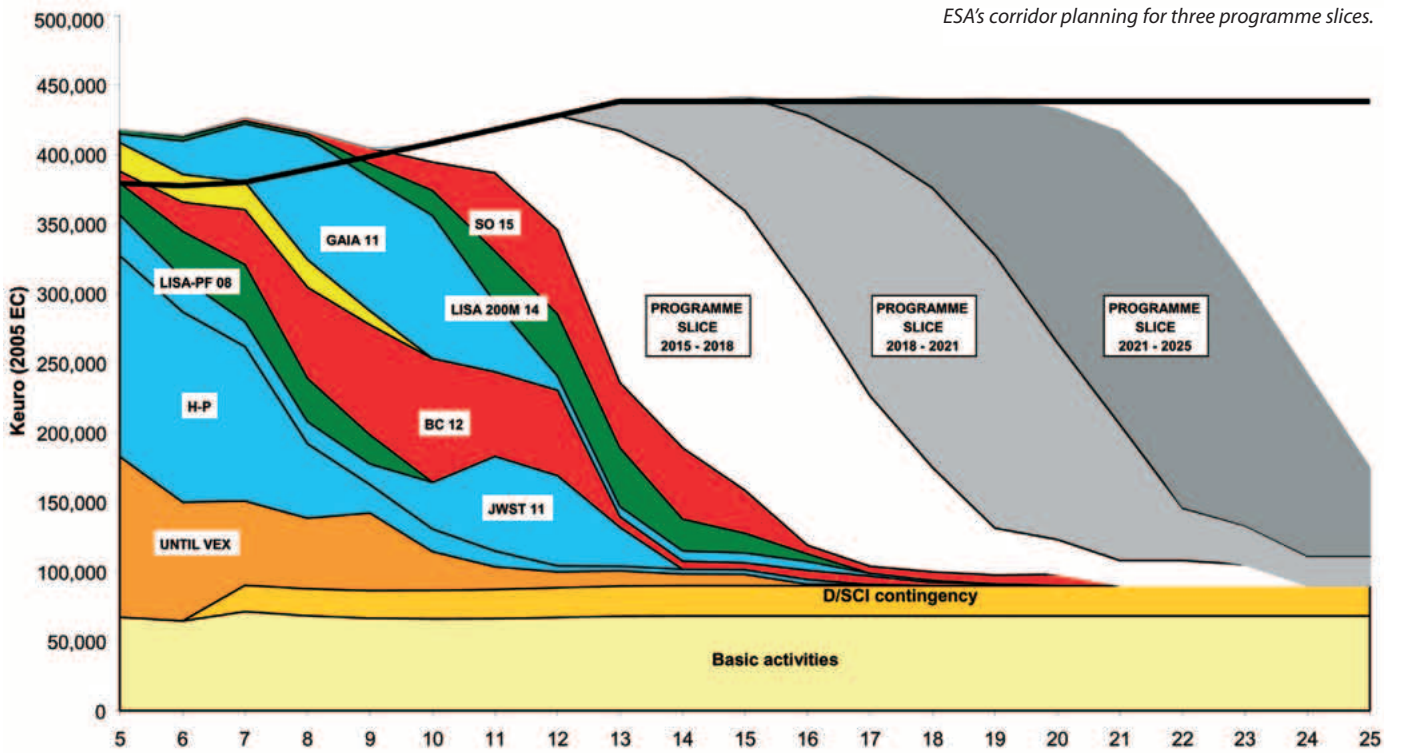
On the basis of the scientific priorities presented in this document, we recommend that ESA's Science Programme Executive issues a succession of Calls for Mission Proposals to implement Cosmic Vision 2015-2025. The pace of implementation should provide for long-sustained, confident work by scientific institutes and industry, which by tradition has enabled Europe to excel in its chosen space science projects despite budgetary limitations.

Implementation could proceed in three 'slices', each providing for several launches during a period of 3-4 years. This approach leads to a policy of corridor planning. Flexibility within each slice will depend on the size, number and sequence of missions, and on the financial and technical payoffs

from international cooperation. The activity for each slice will grow and later decline, over the decade and beyond, while avoiding peaks or troughs in the overall annual expenditures.

An example of such phased corridor planning for three slices is shown in the above diagram, which at the time of writing is only illustrative. As the diagram also makes plain, the rate of early implementation of the new plan will be much affected by the envelopes of actual expenditure on the last major missions of Horizon 2000 Plus, namely Gaia, BepiColombo, JWST, LISA and Solar Orbiter.

If the first major mission of Cosmic Vision 2015-2025 is to be launched in 2015, it should be under construction (Phase-B) by 2008 at the latest. Allowing time for teams to prepare their proposals, and for Phase-A studies and approval to proceed in 2007, the first Call for Mission Proposals ought to happen early in 2006.





Chapter 7

This document, *Cosmic Vision 2015-2025*, exposes the big scientific questions to be addressed by Europe's space science. It proposes the long-term plan that Europe needs in order to remain at the forefront of space science and to improve on the heritage of COS-B, Giotto, Huygens and XMM-Newton, among all other science missions developed by ESA in its first 30 years. In the tradition of Horizon 2000 (1984) and Horizon 2000 Plus (1994-1995), *Cosmic Vision 2015-2025* takes its strength from the massive response by the scientific community to ESA's Call for Themes, issued in April 2004. It has been prepared from the inputs of the space science community by the full ESA science advisory structure – the Astronomy Working Group, the Solar System Working Group, the Fundamental Physics Advisory Group and, at the end, the Space Science Advisory Committee, assisted by ESA's Science Directorate.

For a space science mission, a development time of 10-15 years, preceded by long and intense preparatory work, is the rule. Such an investment cannot be sustained by scientists, technologists, national funding agencies, space industry and international partners without the existence of ESA's long-term plan. The one given here is the logical continuation, into the next decade, of previous ESA science planning cycles. All actors on the European space stage rely heavily on these long-term plans to build confidence in the success of projects that take two decades to develop.

Our plan addresses four broad questions of the utmost importance to understand the

Conclusions

Universe and mankind's place in it. Young scientists and aspiring students are especially fortunate to be living at a time when answers to such basic questions may be within their grasp. What are the conditions for planet formation and the emergence of life? How does the Solar System work? What are the fundamental physical laws of the Universe? How did the Universe originate and what is it made of? Chapters 1 to 4 propose ways of answering these questions and possible space tools to be developed to tackle them. Chapter 5 lists the technology challenges that are raised and suggests the necessary technology development programme. Chapter 6 suggests possible implementation strategies.

To implement Cosmic Vision 2015-2025, it is suggested to ESA's Science Programme to issue Announcements of Opportunities for missions in the coming years. Indeed, for the first mission of the plan, to be launched in 2015, the first Call for Mission Proposals ought to happen early in 2006 if the construction phase is to start by 2008 at the latest. It should be noted that some of the required tools to answer a specific question can probably be fulfilled as a single instrument on a mission. Others will require a full mission development and yet a few more will require a full programme to be defined.

In parallel to all of the above, as outlined in Chapter 5, ESA will have to make substantial efforts on key technological developments, in the frame of its Technology Development Plan, to make Cosmic Vision 2015-2025

feasible. Crucial technologies have already been identified in that chapter that in some cases will benefit several themes. These include lightweight mirror optics, formation flying, autonomous deployment of a swarm of micro-satellites, solar sailing and radiation-tolerant lightweight components. Substantial progress has been made on some of these technological developments under ESA's Payload and Advanced Concepts Office and needs to be actively continued to meet a realistic schedule. In all cases, key technological developments are necessary before missions can be considered for implementation.

We have not explicitly addressed the all-important question of what will have to be done to analyse and exploit scientifically the veritable flood of data to be generated by Cosmic Vision 2015-2025. Already with the current generation of orbiting observatories and probes, ESA and national initiatives are, jointly in some cases, organising *ad hoc* centres and services. An order-of-magnitude increase in the data analysis effort will be required into the next decade, with many missions entering the Terabyte information flow. It goes beyond the scope of the present document to address this issue in detail. However, we want to draw attention to it and we recommend that Europe take prompt initiatives to ensure that the science return of the programme be commensurate with ESA's programmatic effort.

Our plan will be placed in the framework of the worldwide space science context, taking into account possible synergies and

collaborations with science programmes from ESA's international partners (the United States' NASA, the Japan Aerospace Exploration Agency (JAXA), the Russian Roskosmos, the Indian Space Research Organisation (ISRO), the Chinese Space Agency, etc.). Indeed, European space science has a long tradition of collaboration with NASA, with which some of the most successful missions have been developed (Hubble Space Telescope, SOHO, Ulysses, Cassini-Huygens) and others are being developed for the 2005-2015 decade (JWST, LISA). A very close collaboration with JAXA will happen for the first time with the BepiColombo mission to Mercury and collaboration with the Chinese Space Agency was inaugurated with the Double Star mission. Even the most successful ESA-only missions (Giotto, Hipparcos, XMM-Newton, Cluster, Integral, Mars Express, Rosetta, Venus Express, Planck, Herschel, Gaia and Solar Orbiter) have some involvement from international partners.

Cosmic Vision 2015-2025 should also continue to mesh creatively with the national space science and technology programmes in ESA's Member States. Furthermore, several countries in the enlarged European Union that have not yet joined ESA are already participating, through valued co-investigators, in ESA's science missions. They and all other EU members will obviously be welcome to participate in our new long-term programme.

Within Europe, there are other important cultural, scientific and technological

partners with which constructive interactions along the lines of this plan have to be thoroughly explored. The European Southern Observatory (ESO), for example, is pushing ground-based astronomy to the limit. Techniques pioneered at its big observatories in Chile, including interferometry at visible wavelengths, will sooner or later be transferred to space projects. Also directly relevant to the fundamental physics in Cosmic Vision 2015-2025 is the experimental and theoretical work of the European Organisation for Nuclear Research (CERN) in Geneva. Its Large Hadron Collider is due to be switched on in 2007. Experiments on quark-gluon plasmas, for example, produced by colliding nuclei of lead atoms, are complementary to ESA's investigations of 'matter under extreme conditions' in the natural laboratories of neutron stars.

Within ESA itself, added strength and creativity will be gained by the interaction of the science programme with ESA's optional programmes, most notably the 'Aurora' Programme, and other more application-oriented programmes.

ESA's Science Programme is also a strong supporter of European space industry. As much as 80% of ESA's space science budget is channelled, directly or indirectly, to Europe's aerospace industry, and this represents a massive investment in technological innovation. Industrial engineers have played a highly creative part in implementing Horizon 2000 (1984) and Horizon 2000 Plus (1994-1995), putting unrelenting effort into novel hardware and

software and finding ingenious solutions to the difficulties expected in the hostile environments of space. In a word, space engineers enjoy the unprecedented challenges that space science repeatedly throws up. With every novel tool required for ESA's Science Programme, the technological competence of Europe's space-related industries will grow.

Above all, Cosmic Vision 2015-2025 is being presented to the new European Space Council in the context of the institutional European Union presence in space activities. In the European Commission's White Paper *Space: A New European Frontier for an Expanding Union* (November 2003), space science is described as '**essential to Europe's identity and leadership as a knowledge-based society**'. The Commission also notes that the recent erosion of funding for ESA's space science programme has reached a point where it disrupts the balance of the programme and misses the chance to optimise costs and flexibility. The White Paper calls for '**urgent corrective action**'.

Our plan is presented as an act of confidence by a vast and multi-faceted community, who gladly collected in it their best ideas and confidently expects to obtain the necessary support for the timely implementation of an exciting programme aimed at responding to the White Paper call. How much of the promising projects presented in Cosmic Vision 2015-2025 can be accomplished will, naturally, depend on the Level of Resources of the Science Programme.

Last but not least for the future of Europe, ESA's successes in space science is to encourage students to pursue studies and careers in science and engineering. The programme also helps to stem a potentially disastrous brain-drain of scientific and engineering talent to the USA and other parts of the world with active space programmes.

For their part, the European space science community and the ESA Science Programme Executive pledge their continuing effort for the maintenance and reinforcement of Europe's leadership in space science. With the enthusiasm of a space industry which, among many other achievements, has taken us to Saturn and to its moon Titan, this is the right way of realising a knowledge-based and competitive Europe.



Afterword

Space science gives modern society a window on the infinite. Although astronomy from the ground and work in Earth-bound laboratories have their parts to play in decoding how our planet was formed out of the cosmos, indeed how we came to be, only in space can we observe without the disruption of our atmosphere right across the electromagnetic spectrum. Only in space can we experiment outside Earth's gravitational pull and, of course, only by travelling through space can we investigate directly other parts of our Solar System.

This document is proof, if proof were needed, that European scientists have a 'Vision' worthy of the epithet Cosmic. With eyes tuned by a knowledge of what our technical potential can be, the scientists who wrote it start from the peak of present scientific understanding of where we are and, from there, look ahead to a vista of the territories for exploration that lie before us and what is doable. It lays out what scientific questions remain and the paths that need to be followed to obtain answers.

The key, the fundamental driver to the programme proposed, is very simple and can be expressed as '*Science for the sake of science*'; in Latin, '*Scientia gratia scientiae*'. Translated back into English, one would have '*Knowledge for the sake of knowledge*'. A science-based society is a knowledge-based society. A strong programme for exploring the Universe should be part of Europe's 'Lisbon agenda' to become the leading knowledge-based society on the planet.

What is proposed here is not just idle curiosity. What is remarkable at this point is that very basic questions, simple questions that everyone can understand, that scientists would have put on one side a few decades ago, now are coming centre stage for study. Are we alone in the Universe? Why is the Universe the way it is? What is special about the Earth? What were the critical features in determining Earth's habitability (and how long may it remain so)? The discovery in the last decade of extra-solar planets has opened a new perspective and new questions. But it is not just from astronomy that the advances of the last decade or so have come. The reopening of planetary exploration, both Earth's neighbours and the giant planets in the outer Solar System, has provided a cornucopia of issues for research and speculation. This is truly a great time to be a space scientist.

Does Europe deserve such a vision? This question is not one for the scientists to answer. For centuries, Europe did lead the world in astronomy and it has recently regained that lead with the European Southern Observatory's telescopes in Chile. Could Europe also lead in exploring the Universe from space? Technically, it is clear it could; financially, things need to change. European space industry has shown itself up to the most extreme challenges set by the scientists so far. The scientists show here what is the vision. The only issue clouding the speed at which the vision is realised is the budget. The challenge is to the political leaders of Europe to respond in order that at least a substantial part can be realised by 2025.

For now, Cosmic Vision 2015-2025 will serve as a map of the terrain ahead to be tackled by Europe's space scientists. It is not a firm plan. However, using the map as a guide, ESA will make priorities for long-term technology development. Nonetheless, the actual progress and directions taken across the terrain ahead should remain, as far as possible, in the hands of the science community. Because the themes will be the dominant factor, it may well be that missions not foreseen now will materialise before long, that mission foreseen now will vanish, that the sequences outlined here might be changed. The themes outlined here will be realised by the community responding to a phased series of announcements of opportunity. This process, constrained by the budgets available in years to come, will eventually give birth to the actual missions that will build the programme. After a competitive phase, during which several missions will be studied in parallel and the technological requirements will be examined, selected missions will emerge. Probably, as has proved effective in recent years, missions will be grouped to exploit commonality in technical requirements.

Europe will not do it alone. The map will also serve as a guide for seeking future cooperation with the science programmes of the other space-faring nations, such as the USA, Russia, Japan, China, India and Canada. Europe has a greater Gross Domestic Product than any of these and it should aspire to a leading role at the international level.

ESA's Science Programme will not do it alone. Some targets may be met using the International Space Station. Moreover, Mars exploration and, in the future, lunar exploration will fall under the ESA Aurora programme designed to provide infrastructure that scientists can exploit. Hence the priority assigned in particular here to Mars exploration will be accomplished using this additional programme. Similarly, the individual Member States will continue to pursue scientific missions; examples right now are the French-led Corot (Theme 1) and Microscope (Theme 3) missions. It is certain that these should not be the last nationally-led missions, which will fit naturally within the grander plan. The challenge in both cases will be to the national authorities to ensure coherence in their investments.

These control not only the various ESA programmes through their ESA delegations but also the national programmes.

Europe's scientists have seized the initiative and put forward a comprehensive vision appropriate for and fit to inspire a dynamic and outward-looking society. Its realisation depends on budget. The challenge is once more to the political leaders and the national authorities of Europe to respond to make this happen.



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Annex 2: Submitted Themes for Cosmic Vision 2015-2025

In response to ESA's Cosmic Vision 2015-2025 Call for Themes, 150 proposals were received. The proposals are organised in the following way:

- Firstly into one of four main groups: Astronomy and Astrophysics, Solar System, Fundamental Physics, Miscellaneous;
- Secondly, by a category within that group. For example, a specific wavelength or object class;
- Thirdly, alphabetically by surname within a category.

Astronomy and Astrophysics

Title: The Formation and History of Galaxies

Proposed by: Matt Griffin et al.
Contact Email: matt.griffin@astro.cf.ac.uk
Category: Cosmology

Title: POLARIS – POLARization-based Inflation Survey

Proposed by: Per B. Lilje et al.
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Category: Cosmology

Title: Unveiling the Dark Universe with a Wide-Field Imager in Space

Proposed by: Alexandre Réfrégier et al.
Contact Email: refregier@cea.fr
Category: Cosmology

Title: Early Universe and Fundamental Physics

Proposed by: Jean-Loup Puget et al.
Contact Email: puget@ias.u-psud.fr
Category: Cosmology

Title: The Emergence of the Modern Universe

Proposed by: Joseph Silk et al.
Contact Email: silk@astro.ox.ac.uk
Category: Cosmology

Title: The Birth of Stars and Planets

Proposed by: Glenn White et al.
Contact Email: g.j.white@kent.ac.uk
Category: Cosmology

Title: The Hypertelescope Path – Toward Direct Images of Exo-Earths and Other Objects with Micro-arcsecond Resolution

Proposed by: Antoine Labeyrie
Contact Email: labeyrie@obs-hp.fr
Category: Exo Planets

Title: A Large UV-Telescope ('Bio-UV Telescope') for a Deep Search of Biomarkers in Extrasolar Planets

Proposed by: Alain Lecavelier
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Category: Exo Planets

Title: Search for Planets and Life in the Universe

Proposed by: Alain Leger et al.
Contact Email: Alain.Leger@ias.u-psud.fr
Category: Exo Planets

Title: Astrometric Detection of Earth-Mass Planets

Proposed by: Michael Perryman
Contact Email: mperryman@rssd.esa.int
Category: Exo Planets

Title: Understanding the Planetary Population in our Galaxy

Proposed by: Giampaolo Piotto et al.
Contact Email: piotto@pd.astro.it
Category: Exo Planets

Title: Chemical Evolution of Pre-Supernovae, Convection and Cosmic Magnetic Fields

Proposed by: C. Catala et al.
Contact Email: i.w.roxburgh@qmul.ac.uk
Category: Infrared

Title: Stars in the Darkness – Universe: Origin and Evolution and Changing Nature of the Universe

Proposed by: Thibaut Le Bertre et al.
Contact Email: Thibaut.LeBertre@obspm.fr
Category: Infrared

Title: The Universe at Long Radio Wavelengths

Proposed by: Jean-Louis Bougeret
Contact Email: jean-louis.bougeret@obspm.fr
Category: Radio Astronomy

Title: ELR (European Lunar Radiometers) – Radiometers Orbiting the Moon or Landed on the Farside to Measure how Radio-Quiet the Farside of the Moon is

Proposed by: Claudio Maccone
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Category: Radio Astronomy

Title: The Universe at Very Long Wavelengths: Opening the Last Window of the Electromagnetic Spectrum

Proposed by: G.K. Miley et al.
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Category: Radio Astronomy

Title: The Future of Ultraviolet Astronomy

Proposed by: Martin Barstow et al.
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Category: Ultraviolet

Title: Intergalactic Medium Investigation and UV Astronomy

Proposed by: Jean-Michel Deharveng et al.
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Category: Ultraviolet

Title: The Relevance of the UV Window for Modern Astrophysics
Proposed by: Ana Ines Gomez de Castro et al.
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Category: Ultraviolet

Title: The Future of Ultraviolet Astrophysics
Proposed by: Network for UltraViolet Astrophysics (NUVA)
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Category: Ultraviolet

Title: Needs for Ultraviolet Facilities in Astrophysics
Proposed by: Isabella Pagano et al.
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Category: Ultraviolet

Title: Observational Cosmology – The Evolution of Intergalactic Abundances and of the Fluctuating Metagalactic UV Background
Proposed by: Dieter Reimers
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Category: Ultraviolet

Title: Hot Stars and Supernovae as Engines and Tracers for the Chemical Evolution of Galaxies
Proposed by: Klaus Werner et al.
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Category: Ultraviolet

Title: Physics of the Hot Evolving Universe – Science Case for a Large European X-ray Observatory
Proposed by: Xavier Barcons et al.
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Category: X-ray and Gamma-ray Astrophysics

Title: Gravity in the Strong Field Limit and Matter under Extreme Conditions
Proposed by: Didier Barret et al.
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Category: X-ray and Gamma-ray Astrophysics

Title: The Ultimate All-Sky Survey of the X-ray Sky
Proposed by: Sergio Campana et al.
Contact Email: campana@merate.mi.astro.it
Category: X-ray and Gamma-ray Astrophysics

Title: Hard X- and Gamma-ray Polarization: The Ultimate Dimension
Proposed by: Ezio Caroli et al.
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Category: X-ray and Gamma-ray Astrophysics

Title: Opening a New Window to Fundamental Physics and Astrophysics – Science Case for an X-ray Polarimeter
Proposed by: Enrico Costa et al.
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Category: X-ray and Gamma-ray Astrophysics

Title: MeV Gamma-Ray Science
Proposed by: Roland Diehl et al.
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Category: X-ray and Gamma-ray Astrophysics

Title: Exploring the Hard X-/Gamma-ray Continuum Sky at Unprecedented Sensitivity
Proposed by: Filippo Frontera et al.
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Category: X-ray and Gamma-ray Astrophysics

Title: The Global Star-formation History from X-rays: the Large European X-ray Observatory Vision
Proposed by: Ioannis Georgantopoulos et al.
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Category: X-ray and Gamma-ray Astrophysics

Title: Turbulence and Bulk Mass Flow in Energetic Objects: Hot Plasma Dynamics
Proposed by: Jan Willem den Herder et al.
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Category: X-ray and Gamma-ray Astrophysics

Title: Physics behind the Long-term Variability of Interacting Compact Binaries
Proposed by: Juhani Huovelin et al.
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Category: X-ray and Gamma-ray Astrophysics

Title: Nuclear Astrophysics – Gamma-ray Spectroscopy in the MeV Domain
Proposed by: Jürgen Knödseder et al.
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Category: X-ray and Gamma-ray Astrophysics

Title: Probing the High-Energy Universe
Proposed by: François Lebrun et al.
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Category: X-ray and Gamma-ray Astrophysics

Title: The Cosmological Study of Diffuse Baryons: The Role of Low Background Wide-Field X-ray Imagers
Proposed by: Silvano Molendi et al.
Contact Email: borgani@ts.astro.it
Category: X-ray and Gamma-ray Astrophysics

Title: Gamma-ray Bursts Polarisation
Proposed by: Nicolas Produit et al.
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Category: X-ray and Gamma-ray
Astrophysics

Title: The Universe is Changing Every
Minute, We Just Have to Look
Proposed by: Libor Svěda et al.
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Category: X-ray and Gamma-ray
Astrophysics

Title: Unveiling the High Energy
Obscured Universe: Hunting
Collapsed Objects Physics – To
Preserve the ESA Leading Role in
Gamma-ray Astrophysics in the
Next Decade
Proposed by: Pietro Ubertini et al.
Contact Email: ubertini@rm.iasf.cnr.it
Category: X-ray and Gamma-ray
Astrophysics

Solar System

Title: Exobiology and
Micrometeorites: Search for the
Origin of Life
Proposed by: Santi Aiello et al.
Contact Email: pace@arcetri.astro.it
Category: Exo Biology

Title: Search for Planetary Habitability
in the Solar System and Beyond
Proposed by: Jean-Loup Bertaux
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Category: Exo Biology

Title: The Environment for Life: A
Cosmic Vision Theme for ESA
Proposed by: Andrew Coates
Contact Email: ajc@mssl.ucl.ac.uk
Category: Exo Biology

Title: Astrobiological Exploration of
the Solar System and the
Extrasolar Planets
Proposed by: Conseil de Groupement
du GDR CNRS Exobio
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paris12.fr or secretariate:
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Category: Exo Biology

Title: Quest for a Second Genesis of
Life
Proposed by: European
Exo/Astrobiology Network
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Category: Exo Biology

Title: Life on Mars
Proposed by: Dirk Möhlmann et al.
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Category: Exo Biology

Title: Lamarck: An International
Space Interferometer for Exo-Life
studies
Proposed by: Jean Schneider et al.
Contact Email:
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Category: Exo Biology

Title: The Origin and Early Evolution
of Life in our Solar System
Proposed by: Stephan Ulamec et al.
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Category: Exo Biology

Title: A Sample Return Mission to
Near Earth Objects
Proposed by: Antonella Barucci
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Category: Near Earth Objects

Title: Search For and Investigation of
Small Celestial Bodies for the
Protection of Earth
Proposed by: Klaus J. Seidensticker
et al.
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Category: Near Earth Objects

Title: Evolution of Atmospheres and
Ionospheres of Planets and
Exoplanets
Proposed by: Mats André et al.
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Category: Planets

Title: Mars Exploration with
Emphasis on the Ancient Martian
Rock Record as a Proxy for the
Missing Hadean and Earliest
Archaean Record on Earth
Proposed by: Archaean Consortium
Contact Email:
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Category: Planets

Title: Exploring Giant Planets and
their Satellite Systems
Proposed by: Michel Blanc et al.
Contact Email: blanc@oamp.fr
Category: Planets

Title: Comparative Magnetospheres
Proposed by: Stas Barabash et al.
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Category: Planets

Title: Exploration of the outer Solar
System Uranus Orbiter and Probe
Proposed by: Patrick Canu
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Category: Planets

Title: Geochemical Investigation of
the Deep Atmosphere, Surface
and Interior of Venus
Proposed by: Eric Chassefière et al.
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Category: Planets

Title: Study of Atmospheric Escape, Ionospheric Physics and Magnetic Field on Mars

Proposed by: Eric Chassefière et al.
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Category: Planets

Title: Deimos Sample Return Mission

Proposed by: Marcello Fulchignoni
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Category: Planets

Title: Venus Interior and Ionospheric Orbiters

Proposed by: Raphael Garcia et al.
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Category: Planets

Title: In-Situ Exploration of Previously Unexplored Planetary Surfaces (e.g Europa, Io, Titan)

Proposed by: Rob A. Gowen
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Category: Planets

Title: European Planetary Materials Programme

Proposed by: Eberhard Gruen
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Category: Planets

Title: The Evolution of Icy Regions in our Solar System

Proposed by: Günter Kargl et al.
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Category: Planets

Title: Planetary European Network of Geophysical Observatories (PENGO)

Proposed by: Philippe Lognonné et al.
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Category: Planets

Title: Oxygen Circulation of Planetary Atmosphere and Lithosphere

Proposed by: Hans Nilsson et al.
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Category: Planets

Title: Call for a Jovian Satellite Exploration Initiative with Orbiters and Landers

Proposed by: Jürgen Oberst et al.
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Category: Planets

Title: In-Situ Measurements of Venus Atmosphere Properties

Proposed by: Walter Schmidt et al.
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Category: Planets

Title: Planetary Surface & Subsurface Science

Proposed by: Wolfgang Sebaldt
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Category: Planets

Title: Exploring Mercury In-Situ

Proposed by: Tilman Spohn
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Category: Planets

Title: A Multi-Disciplinary Investigation of the Jovian System

Proposed by: Nicolas Thomas et al.
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Category: Planets

Title: The exploration of the Martian Subsurface

Proposed by: Claude d'Uston et al.
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Category: Planets

Title: Magnetic Clouds – A Valuable Tool for Space Weather

Proposed by: A. Geranios et al.
Contact Email: ageran@cc.uoa.gr
Category: Solar Earth Connection

Title: Acceleration and Reconnection in Near-Earth Space

Proposed by: Manuel Grande et al.
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Category: Solar Earth Connection

Title: A Nano-Satellite Constellation to Study the Radiation Belts

Proposed by: Mike Hapgood et al.
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Category: Solar Earth Connection

Title: Surface Research by Space Plasma Instruments

Proposed by: Mats Holmström et al.
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Category: Solar Earth Connection

Title: European Space Weather – Space Science Programme or ‘Multi Space and Time Scale Solar-Terrestrial Study (M-(STS)2)’

Proposed by: François Lefeuve et al.
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Category: Solar Earth Connection

Title: Momentum Transfer from Solar Wind to Planetary Rotation

Proposed by: Rickard Lundin et al.
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Category: Solar Earth Connection

Title: Space Weather Fronts: Tracking and Terrestrial Response

Proposed by: Steve J. Schwartz et al.
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Category: Solar Earth Connection

Title: Helios: The Sun, The Star Close to Earth

Proposed by: Solar and stellar physics group of the Institut d'Astrophysique Spatiale
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Category: Solar Earth Connection

Title: Energetic Solar Cosmic Ray Surveyor and Monitor
Proposed by: Piero Spillantini
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Category: Solar Earth Connection

Title: Conjugate Auroral Spectrographic Telescope Explorer (CASTE)
Proposed by: Johan Stadsnes et al.
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Category: Solar Earth Connection

Title: The 'Star-Sun-Earth' Connection and Cosmic Magnetic Fields
Proposed by: Klaus G. Strassmeier et al.
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Category: Solar Earth Connection

Title: The Scientific Case for Spectropolarimetry from Space
Proposed by: Egidio Landi Degl'Innocenti et al.
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Category: Solar Physics/Ultraviolet

Title: The Sun as a Particle Accelerator
Proposed by: Lyndsay Fletcher et al.
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Category: Solar Physics

Title: Solar/Heliospheric Dynamics and Magnetism
Proposed by: Maxim Khodachenko et al.
Contact Email: maxin.khodachenko@oeaw.ac.at
Category: Solar Physics

Title: Solar Microscopy – Unveiling the Sun's Basic Physical Processes at Their Intrinsic Scales
Proposed by: Eckart Marsch et al.
Contact Email: marsch@linmpi.mpg.de
Category: Solar Physics

Title: Meteoroids and Their Meteor Showers in The Solar System: An Unexplored Realm
Proposed by: Apostolos A. Christou et al.
Contact Email: aac@star.arm.ac.uk
Category: Solar System

Title: SAS – A Comparative Investigation of the ULF-ELF-VLF (to RF) Phenomena, Its Source Activity and Physical Background on Planets, on Interplanetary Space and the Terrestrial Effects
Proposed by: Csaba Ferencz et al.
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Category: Solar System

Title: Origin of Asteroid, Comet, and Other Small Bodies
Proposed by: Yoshifumi Futaana et al.
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Category: Solar System

Title: Origin and Evolution of the Outer Solar System from the Composition of Giant Planets and of Comets of the Oort cloud
Proposed by: Daniel Gautier et al.
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Category: Solar System

Title: Exploration of the Asteroid Belt
Proposed by: Simon Green et al.
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Category: Solar System

Title: Investigation of the Kuiper belt
Proposed by: Harald Michaelis
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Category: Solar System

Title: Exploring Earth's Quasi-Moon and Coorbital Companions
Proposed by: Rainer Riemann
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Category: Solar System

Title: Ice Monitoring in the Solar System and Elsewhere
Proposed by: Alain Sarkissian et al.
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Category: Solar System

Title: Exoplanet Detection and Characterisation
Proposed by: Jean Surdej et al.
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Category: Solar System/Exo Planets

Title: The Formation of Our Solar System
Proposed by: Stephan Ulamec et al.
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Category: Solar System

Title: Heliospheric Explorer – HEX – Beyond the Edges of the Solar System
Proposed by: Robert F. Wimmer-Schweingruber et al.
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Category: Solar System

Fundamental Physics

Title: Investigation on the Origin of Cosmic Rays with the Development of a Stratospheric Airship Platform for Scientific Payloads
Proposed by: Pier Simone Marrocchesi et al.
Contact Email: marrocchesi@pi.infn.it
Category: Cosmic Rays

Title: Opening Particle Astronomy to Probe and Understand the Evolving Universe
Proposed by: Eric Plagnol et al.
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Category: Cosmic Rays

Title: Lunar Observatory for Cosmic Ray Physics
Proposed by: Piero Spillantini et al.
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Category: Cosmic Rays

Title: Investigations of the CASIMIR Force and Vacuum fluctuations
Proposed by: Robert Bingham et al.
Contact Email: N.J.Legge@rl.ac.uk
Category: Fundamental Physics

Title: Matter-Wave Decoherence
Proposed by: Robert Bingham et al.
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Category: Fundamental Physics

Title: The Role of Quantum Fluctuations in Matter-Wave Interferometry
Proposed by: Robert Bingham et al.
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Category: Fundamental Physics

Title: Testing General Relativity by Mapping the Latitudinal Dependence of the Lense-Thirring effect
Proposed by: Philippe Bouyer et al.
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Category: Fundamental Physics

Title: Interferometry with Coherent Ensembles of Atoms (ICE)
Proposed by: Philippe Bouyer et al.
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Category: Fundamental Physics

Title: Novel 'Atom' Optics (NAO) – For Probing Gravity in Space
Proposed by: Philippe Bouyer et al.
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Category: Fundamental Physics

Title: Gravitational Wave Cosmology
Proposed by: Karsten Danzmann / O. Jennrich et al.
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Category: Cosmology

Title: Laser Interferometric Test of Relativity
Proposed by: Hansjörg Dittus et al.
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Category: Fundamental Physics

Title: Determination of the Fine Structure Constant
Proposed by: Wolfgang Ertmer et al.
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Category: Fundamental Physics

Title: Exploring Bose-Einstein Condensates in Space
Proposed by: Wolfgang Ertmer et al.
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Category: Fundamental Physics

Title: Ultracold Atomic Gases – Probes for Ultralow-Energy Phenomena
Proposed by: Axel Goerlitz et al.
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Category: Fundamental Physics

Title: Super-massive Black Holes in the Early Universe
Proposed by: James Hough / O. Jennrich et al.
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Category: Cosmology

Title: Search for an Anomalous Coupling of the Elementary Particle Spin to Gravity
Proposed by: Claus Lämmerzahl et al.
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Category: Fundamental Physics

Title: Deep Space Laser Ranging: Mapping the Solar System and Probing the Fundamental Law of Spacetime
Proposed by: Claus Lämmerzahl et al.
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Category: Fundamental Physics

Title: Observation of the Gravitomagnetic Clock-Effect
Proposed by: Claus Lämmerzahl et al.
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Category: Fundamental Physics

Title: Testing General Relativity with Long-Term Satellite Tracking
Proposed by: Claus Lämmerzahl et al.
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Category: Fundamental Physics

Title: NEWTON B – A Low Cost Space Experiment to Measure the Value of the Universal Gravitational Constant (G) to Greatly Increased Accuracy
Proposed by: Roger Longstaff
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Category: Fundamental Physics

Title: A Breakthrough in Fundamental Physics from Space
Proposed by: Anna Nobili
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Category: Fundamental Physics

Title: Search for an Electric Dipole Moment of the Electron
Proposed by: Achim Peters et al.
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Category: Fundamental Physics

Title: Exploring Gravity in the Quantum Domain
Proposed by: Ernst M. Rasel et al.
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Category: Fundamental Physics

Title: Ultra-Stable Clocks in Space
Proposed by: Christophe Salomon et al.
Contact Email: Andre.Clairon@obspm.fr
Category: Fundamental Physics

Title: Ultra High Precision Measurements of the Equivalence Principle
Proposed by: Michael C.W. Sandford
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Category: Fundamental Physics

Title: Search for Quantum Fluctuations of Space
Proposed by: Stephan Schiller et al.
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Category: Fundamental Physics

Title: Test of Gravity-Matter Coupling and Search for a Time-Variation of Fundamental Constants
Proposed by: Stephan Schiller et al.
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Category: Fundamental Physics

Title: Test of Isotropy of Space for Electromagnetic Wave Propagation
Proposed by: Stephan Schiller et al.
Contact Email: step.schiller@uni-duesseldorf.de
Category: Fundamental Physics

Title: Gödel Mission: Measuring the Rotation of the Universe
Proposed by: Wolfgang Schleich et al.
Contact Email: wolfgang.schleich@physik.uni-ulm.de
Category: Cosmology

Title: Exploring Dark Matter
Proposed by: Bernard F. Schutz / O. Jennrich et al.
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Category: Cosmology

Title: Search for New Short-Range Forces through a Test of the Inverse Square Law of Gravitation at 1μ
Proposed by: C.C. Speake et al.
Contact Email: ct@star.sr.bham.ac.uk
Category: Fundamental Physics

Title: Searching for the Missing Baryonic Matter
Proposed by: Stefano Vitale / O. Jennrich et al.
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Category: Cosmology

Title: Search for Lorentz Symmetry Violation and Spin-Spin coupling Forces
Proposed by: C. Trenkel et al.
Contact Email: ct@star.sr.bham.ac.uk
Category: Fundamental Physics

Title: Investigation of Chirality in Space Environments
Proposed by: Jan-Erik Wahkund et al.
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Category: Fundamental Physics

Title: Test of Isotropy of Space for the Coulomb Potential by Means of Molecular Internal State Quantum Interferometry
Proposed by: Andreas Wicht et al.
Contact Email: andreas.wicht@uni-duesseldorf.de
Category: Fundamental Physics

Title: Electron-Scale and Ion-Electron Hybrid Scale Dynamics
Proposed by: Yamauchi et al.
Contact Email: yama@irf.se
Category: Fundamental Physics

Miscellaneous

Title: Adaptive Grid Measurements of Atmospheric and Ionospheric Parameters in Four Dimensions to Study all Stages of Turbulence
Proposed by: Ulf-Peter Hoppe et al.
Contact Email: Ulf-Peter.Hoppe@ffi.no
Category: Earth Observation

Title: Physics of the Earth's Upper Atmosphere: Studies of Transient Phenomena and Long-Term Climatological Effects
Proposed by: Harri Laakso
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Category: Earth Observation

Title: Establishment of a Cross-Disciplinary Earth and Planetary Systems Laboratory
Proposed by: Hans E.F. Amundsen et al.
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Category: Miscellaneous

Title: Our Laboratory Moon
Proposed by: Roberto Battiston et al.
Contact Email: r.battiston@tiscali.it
Category: Miscellaneous

Title: Multi-Scale Space Physics
Proposed by: W. Baumjohann et al.
Contact Email: baumjohann@oeaw.ac.at
Category: Miscellaneous

Title: A Mission to Test the Pioneer Anomaly and to Probe the Mass Distribution in the Nearby Outer Solar System
Proposed by: Orfeu Bertolami et al.
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Category: Miscellaneous

Title: Multi-Wavelength, Multi-Messenger Approach
Proposed by: Johannes Blümer
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Category: Miscellaneous

Title: Electromagnetic Propulsion
Proposed by: Remi Cornwall
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Category: Miscellaneous

Title: Testing the Pioneer Anomaly
Proposed by: Hansjörg Dittus et al.
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Category: Miscellaneous

Title: Virtual Human Spaceflight: An
Alternative to Human and
Robotic Mission Concepts
Proposed by: Bernard Farkin,
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Category: Miscellaneous

Title: Project Rama – An Interstellar
Probe to Travel Beyond the
Heliosphere
Proposed by: Wing-Huen Ip et al.
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Category: Miscellaneous

Title: Experimental Investigation of
the Pioneer Anomaly
Proposed by: C. Kiefer et al.
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Category: Miscellaneous

Title: Significance of the Pioneer
Anomaly
Proposed by: Claus Lämmerzahl et al.
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Category: Miscellaneous

Title: In-Situ Studies as New Windows
to Astrophysics and Space
Science
Proposed by: Ingrid Mann et al.
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Category: Miscellaneous

Title: Call for a Long-Lived Global
Lunar Geophysical Network
Proposed by: Jürgen Oberst et al.
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Category: Miscellaneous

Title: Space Propulsion by Direct Use
of the Energy of Fission
Fragments
Proposed by: Adinolfi Roberto et al.
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Category: Miscellaneous

Title: LISA Mission and the Pioneer
anomaly
Proposed by: José Luis Rosales
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Category: Miscellaneous

Title: An Artificial Moon as an
Example of the Application of
Precise 'Second Generation' Drag-
Free Technology
Proposed by: C.C. Speake
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Category: Miscellaneous

Title: Space Exploration and the New
Enlightenment
Proposed by: Ian Wright
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Category: Miscellaneous

Acronyms

ADCS: Analogue-Digital Converter System
ALMA: Atacama Large Millimetre Array
ASIC: application-specific integrated circuit
AU: astronomical unit
AWG: Astronomy Working Group (ESA)

BEC: Bose-Einstein condensate

CCD: charge-coupled device
CERN: Centre Européen de Recherches
Nucléaires
CMOS: complementary metal oxide
superconductor
CNES: Centre National d'Etudes Spatiales (F)
Corot: Convection, Rotation and Planetary
Transits
CSA: Canadian Space Agency

DLR: Deutsches Zentrum für Luft- und
Raumfahrt

EDSL: Entry, Descent and Landing System
EEV: Earth Entry Vehicle
ESA: European Space Agency
ESO: European Southern Observatory
ESRO: European Space Research
Organisation
EU: European Union

FEPP: field emission electric propulsion
FPAG: Fundamental Physics Advisory Group
(ESA)

GNC: guidance, navigation & control

HIVE: Hub and Interplanetary Vehicle
HST: Hubble Space Telescope

IHP: Interstellar Heliopause Probe
ISO: Infrared Space Observatory (ESA)
IUE: International Ultraviolet Observatory

JAXA: Japan Aerospace & Exploration
Agency

JEO: Jupiter Europa Orbiter
JEP: Jupiter Exploration Programme
JPO: Jupiter Polar Orbiter
JRS: Jupiter Relay Spacecraft
JWST: James Webb Space Telescope

LEO: low Earth orbit
LILT: low-intensity low-temperature
LISA: Laser Interferometer Space Antenna

MACHO: Massive Compact Halo Objects
Microscope: MICROSatellite à traînée
Compensée pour l'Observation du
Principe d'Equivalence (CNES)

NASA: National Aeronautics & Space
Administration (USA)

RF: radio frequency
RTG: radioisotope thermoelectric generator

SIM: Space Interferometer Mission (NASA)
SOHO: Solar & Heliospheric Observatory
SPC: Science Programme Committee (ESA)
SPO: Solar Polar Orbiter
SQUID: superconducting quantum
interference device
SSAC: Space Science Advisory Committee
(ESA)
SSWG: Solar System Working Group (ESA)
STEREO: Solar-Terrestrial Relations
Observatory (NASA)

VLT: Very Large Telescope

WMAP: Wilkinson Microwave Anisotropy
Probe (NASA)