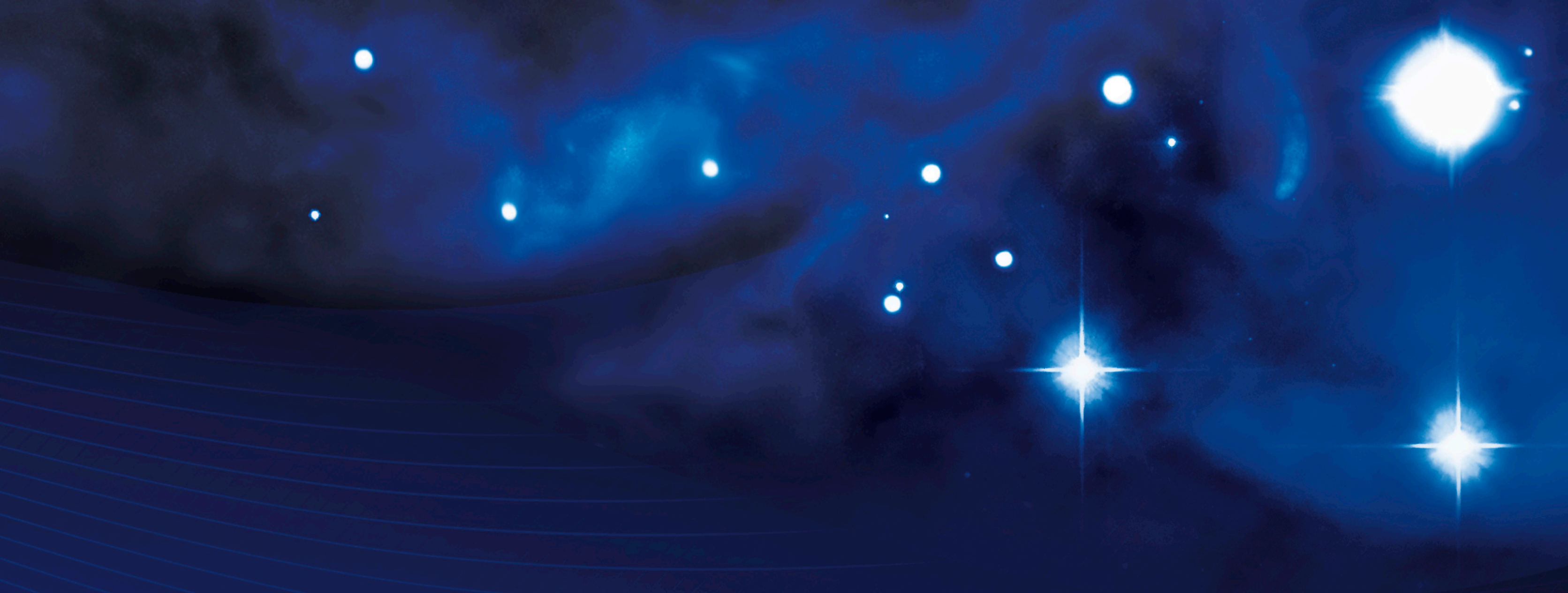

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The ASTRONET Infrastructure Roadmap:

A Strategic Plan for European Astronomy

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The ASTRONET
Infrastructure Roadmap

This document has been created by the Infrastructure Roadmap Working Group and Panels under the auspices of ASTRONET, acting on behalf of the following member agencies: ARRS (SI), BMBF and PT-DESY (DE), IA CAS (CZ), CNRS/INSU (FR), DFG (DE), ESA (INT), ESO (INT), ESF (EE), FWF (AT), GNCA (GR), HAS (HU), SAS (SK), INAF (IT), LAS (LT), MICINN (ES), MPG (DE), NCBiR (PL), NOTSA (Nordic), NWO (NL), RSA (RO), SER (CH), SRC (SE), STFC (UK), UAS (UA).

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Executive Summary

Background: The Global Context

Astronomy is experiencing a golden era. Just the past few years have brought epochal discoveries that have excited people from all walks of life, from the first planets orbiting other stars to the accelerating Universe, dominated by the still-enigmatic dark matter and dark energy. Europe is at the forefront of all areas of contemporary astronomy. The challenge before us is to consolidate and strengthen this position for the future.

In a world of ever-fiercer global competition, European astronomy has reached its current position by learning to cooperate on a multilateral basis, especially through the European Southern Observatory (ESO) and the European Space Agency (ESA). However, the backbone of European astronomy remains the scientists and research programmes at national universities and research organisations.

The scientific challenges of the future will require an effective synergy of financial and human resources all across Europe, based on a comprehensive long-term strategy and underpinned by vibrant national scientific and technological communities — in short, a true European Research Area in astronomy. This approach is also needed for Europe to be a strong partner in the largest, global projects.

ASTRONET was created by the major European funding agencies and research organisations to meet this challenge. Supported by the European Commission, ASTRONET aims to prepare long-term scientific and investment plans for European astronomy for the next 10–20 years. The Infrastructure Roadmap represents the core of this effort and is unique in the history of European astronomy, for several reasons:

Firstly, the Roadmap includes the whole of astronomy, from the remote borders of the Universe to the Solar System. Secondly, it considers observational tools on the ground and in space, covering gamma-ray to radio wavelengths as well as subatomic particles and gravitational waves. Thirdly, it also encompasses theory and computing, laboratory studies, and technology development. Fourthly, it recognises the power of astronomy to excite young people about the study of science and technology, and the need to train and recruit the human resources that are the *sine qua non* for the scientific outcome. Finally, it involves all of Europe, including the new EU member states.

Science-Driven Prioritisation

Scientific planning must be based on scientific goals. Accordingly, the ASTRONET process began with the development of a Science Vision for European Astronomy, published in October 2007[1]. It reviewed and prioritised the main scientific questions that European astronomy should address over the next 10–20 years under four broad headings:

- Do we understand the extremes of the Universe?
- How do galaxies form and evolve?
- What is the origin and evolution of stars and planets?
- How do we fit in?

In doing so, the Science Vision identified generic types of research infrastructure that would be needed to answer the key questions under each heading, but did not assess specific projects. The Roadmap builds on the Science Vision. It aims to develop a matching set of priorities for the material and human resources needed to reach these goals, and a plan for phasing the corresponding investments so that the bulk of the Science Vision goals can be reached within realistic budgets.

The ASTRONET Roadmap thus complements that of the European Strategy Forum on Research Infrastructures (ESFRI) — which covers *all* sciences — by analysing, comparing, and prioritising the flagship projects in all of astronomy in technical and financial detail, and by addressing directly the hard facts of the implementation phase.

The Roadmap was developed primarily on scientific grounds by a Working Group appointed by the ASTRONET Board. Existing and proposed infrastructure projects across astronomy were reviewed by three specialist Panels of top-rank European scientists. Two other Panels considered (i) the concomitant needs regarding theory, computing and data archiving, and (ii) human resources, including education, recruitment, public outreach and industrial involvement. Overall, over 60 European scientists were directly involved in this effort. Feedback from the community at large was invited through both a web-based forum and through a large, open symposium held in June 2008.

The Panels worked by assessing projects requiring new funds of €10M or more from European sources and on which spending decisions are required after 2008 — well over 100 in all. They examined each project for potential scientific impact, uniqueness and level of European involvement, as well as size of the astronomical community that would benefit from it and its relevance to the advancement of the European high technology industry.

The Working Group and Panels were mindful of existing national and international strategic plans, including those of ESFRI, ESO and ESA. They also considered the global context, including the plans of our major international partners. Close contacts were maintained with the infrastructure networks OPTICON, RadioNet, EuroPlaNet and ILIAS, and with the ERA-NET ASPERA. However, the Working Group has sole responsibility for the final report.

Three aspects of the Roadmap are notable. Firstly, it emphasises the need to include the entire electromagnetic spectrum — and more — in the study of most cosmic phenomena, from young stars and planets to supermassive black holes. Secondly, although the priorities of proposed new space missions were reviewed independently by the ASTRONET and ESA Cosmic Vision panels, the conclusions very largely agree. Finally, the Roadmap identifies a number of gaps in current planning. The most notable of these are the need for technology development in several areas, the inconsistency between resources devoted to major projects and to their scientific exploitation, and the coordination of space projects and matching ground-based efforts to secure the full scientific returns from the overall investment.

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[1] http://www.astronet-eu.org/-Science-Vision-

Financial and Human Resources

A useful roadmap must include realistic estimates of costs, technological readiness and available resources. Independent advice as well as information provided by the projects themselves has been used to assess their cost and maturity, but the reliability of these data varies from project to project. For future space missions in particular, projects have been changing and merging, either internally or with global projects, while this report was being prepared.

Resource estimates and scientific capabilities described here should therefore be regarded as a snapshot of the current situation, based on the best information available to date. Known or estimated costs for operations are included throughout.

More surprisingly, despite a dedicated effort to obtain an overview of the present financial and human resources for European astronomy, this information remains quite incomplete. Budget numbers for ESO, ESA and the national funding agencies are easy to collect, but including universities and projects in individual nations as well as multilateral collaborations is far more difficult. The demarcation between astronomy and other natural sciences such as physics or biology is another source of uncertainty. This report can therefore only give approximate total figures, but does present the best pan-European estimates available today.

While ground-based and space-based projects are considered separately in the following, as the funding sources and project selection procedures are often different, the Roadmap recommendations are all based on the global scientific perspectives of the Science Vision.

Ground-Based Projects

Among ground-based infrastructure projects, two emerged as clear top priorities due to their potential for fundamental breakthroughs in a very wide range of scientific fields, from the Solar System and other planetary systems to cosmology:

- The European Extremely Large Telescope (E-ELT), a 40 m-class optical-infrared telescope being developed by ESO as a European or European-led project. A decision on construction, based on a detailed design and cost estimate, is planned for 2010.

- The Square Kilometre Array (SKA), a huge radio telescope being developed by a global consortium with an intended European share of up to 40%. The plan is to develop the SKA in phases of increasing size and scientific power. Construction of Phase 1 could be decided in 2012 and Phase 2 around 2016.

It was concluded that although the E-ELT and the SKA are very ambitious projects requiring large human and financial resources, they can both be delivered via an appropriately phased plan.

Three other projects were considered scientifically outstanding in areas with European leadership, but in narrower fields and with lower budgets than the E-ELT and SKA. These have been grouped together in a separate list comprising, in descending order of priority:

- The European Solar Telescope (EST), an advanced 4 m solar telescope to be built in the Canary Islands. The EST will enable breakthroughs in our understanding of the solar magnetic field and its relations with the heliosphere and the Earth; when ready, it will replace the existing national solar telescopes in the Canary Islands.

- The Cerenkov Telescope Array (CTA), an array of optical telescopes to detect high energy gamma rays from black holes and other extreme phenomena in the Universe. Building on existing successful European experiments, the CTA — the first true observatory at such energies — is expected to bring a breakthrough in our understanding of the origin and production of high energy gamma rays.

- The proposed underwater neutrino detector, KM3NeT, was also considered of great scientific potential, but ranked lower than the CTA because of the more proven astrophysical discovery capability of the latter.

A smaller project, but again of high priority, is a wide-field spectrograph for massive surveys with large optical telescopes. A Working Group is being appointed by ASTRONET to study this in detail. Finally, the report identifies a need to incorporate and support laboratory astrophysics — including the curation of Solar System material returned by space missions — more systematically than now.

Space Missions

Important national and multinational space projects are being developed outside the ESA structure. The Roadmap includes them as appropriate and encourages the continued development of smaller, fast-track missions.

However, the development of major scientific space missions in Europe is dominated by ESA's strategic planning — most recently the Cosmic Vision exercise. Regardless of scientific merit, only a couple of new L-class (large-scale) and a few M-class (medium-scale) missions are likely to be selected for implementation in the next decade within the Cosmic Vision plan due to budgetary constraints; mission proposals submitted in answer to the first call for projects are currently undergoing major changes and transformations before the final selection is made. Their overall impact depends on maintaining a strong science programme at ESA.

The Roadmap Working Group and Panels independently agreed with ESA's initial selection of Cosmic Vision missions, which were all judged to be of high scientific value. The final choice of missions by the standard ESA review and down-selection procedures that track changes in mission scope and cost and possible mergers with or replacement by other European or international projects, is therefore broadly supported. Within this framework, our priorities, including some non-ESA missions, are as follows:

- Among the large-scale missions, the gravitational-wave observatory, the Laser Interferometer Space Antenna (LISA) and the International X-ray Observatory (XEUS/IXO) were ranked together at the top. Next were the Titan and Enceladus Mission (TandEM) and the LAPLACE mission to the planets Saturn and Jupiter and their satellites. One of these will likely be selected in early 2009; it will then compete with IXO or LISA for the next L-slot. ExoMars was ranked highly as well, just below TandEM/LAPLACE, but does not compete directly with the other science missions as it belongs to a different programme (Aurora). The longer-term missions Darwin (search for life on "other Earths"), the Far Infrared Interferometer (FIRI; formation and evolution of planets, stars and galaxies), and the Probing Heliospheric Origins with an Inner Boundary Observing Spacecraft (PHOIBOS; close-up study of the solar surface) were also deemed very important. However, they still require lengthy technological development, so it was regarded as premature to assign detailed rankings to these three missions at this stage.

- Among medium-scale investments, science analysis and exploitation for the approved Horizon 2000 Plus astrometric mission, Gaia was judged most important. Among proposed new projects in this category, the dark energy mission EUCLID and then Solar Orbiter were ranked highest. Next, with equal rank but different maturity, are Cross-Scale (magnetosphere), Simbol-X (a non-ESA X-ray project), the Planetary Transits and Oscillations of Stars mission (PLATO; exoplanet transits) and the Space Infrared telescope for Cosmology and Astrophysics (SPICA; far-infrared observatory). Below these is Marco Polo (near-Earth asteroid sample return).

The Role of Existing Facilities

The scientific role and operating cost of existing and approved facilities are also considered in the Roadmap. In space, several current missions are so successful that an extension of their operational lifetimes beyond those already approved is richly justified on scientific grounds. In a constrained environment, the selection of the missions that can be extended within available funds should be based on the scientific productivity of the mission and, for ESA-supported missions, the overall balance in the ESA programme.

On the ground, the existing set of small to medium-size optical telescopes is a heterogeneous mix of national and common instruments, equipped and operated without overall coordination. This is inefficient and, for example, impedes effective ground-based support for space missions. ASTRONET has therefore appointed a committee to review the future role, organisation and funding of the European 2–4 m optical telescopes within the context of the Roadmap, to report by September 2009.

Reviews of Europe's existing millimetre–submillimetre and radio telescopes will be undertaken shortly after, followed later by a review focusing on the optimum exploitation of our access to 8–10 m-class optical telescopes as we enter the era of the E-ELT. Together, these reviews will enable Europe to establish a coherent, cost-effective complement of medium-size facilities.

Theory, Computing and Data Archiving

The development of theory and computing capacity must go hand-in-hand with that of observational facilities. Systematic archiving of properly calibrated observational data in standardised, internationally recognised formats will preserve this precious information obtained with public funds for future use by other researchers, creating a Virtual Observatory (VO).

The Virtual Observatory will enable new kinds of multiwavelength science and presents new challenges to the way that results of theoretical models are presented and compared with real data. Along with other initiatives, the Roadmap proposes that a European Astrophysical Software Laboratory (ASL), a centre without walls, be created to accelerate developments in this entire area on a broad front.

Education, Recruitment and Outreach

Ultimately, the deployment of skilled people determines which scientific facilities can be built and operated, as well as the scientific returns that are derived from them. Recruiting and training the future generation of Europeans with advanced scientific and technological skills is therefore a key aspect of any realistic Roadmap for the future.

Conversely, astronomy is a proven and effective vehicle for attracting young people into scientific and technical careers, with benefits for society as a whole, far beyond astronomy itself. The Roadmap identifies several initiatives to stimulate European scientific literacy and provide European science with the human resources it needs for a healthy future, drawing on the full 500-million-strong population of the new Europe.

Technology Development

Technological readiness, along with funding, is a significant limiting factor for many of the proposed projects, in space or on the ground, and key areas for development are identified in each case. However, astronomy also drives high technology in areas such as optics and informatics. Maintaining and strengthening a vigorous and well-coordinated technological research and development (R&D) programme to prepare for the future, in concert with industry to ensure technology transfer, is therefore an important priority across all areas of the Roadmap.

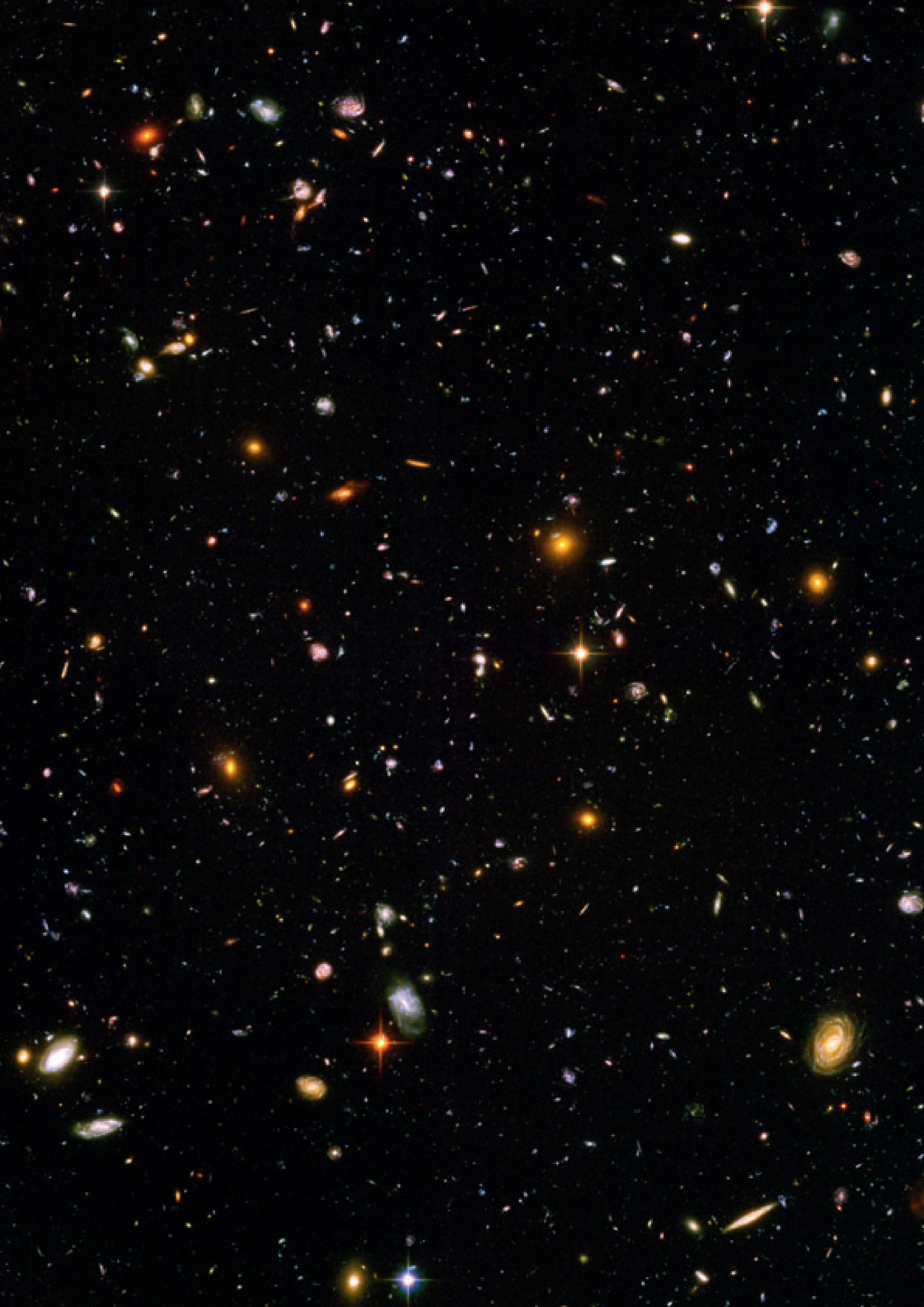
Conclusion and Perspectives for the Future

The Roadmap can be fairly represented as a community-based comprehensive plan that addresses the great majority of the Science Vision goals. Implementing it will maintain and strengthen the role of Europe in global astronomy within realistic budget limitations.

In order to achieve this in a timely manner given the stiff international competition, a budget increase of order 20% over the next decade will be required. However, the coherent plan proposed here will make this a very cost-effective investment for Europe. Moreover, such a plan, with its integrated view of the global context, will also be a strong asset in negotiating international partnerships for the largest projects.

“Plans become useless, *but planning* is essential!” The context for the Roadmap has kept evolving while it was being developed, and will continue to do so. ASTRONET, in concert with ESFRI, will monitor progress on implementing the proposals of the Roadmap over the next 2–3 years, whether small or large in financial terms. The entire European astronomical community awaits the outcome with keen anticipation.

Finally, we foresee that a fully updated Roadmap will be needed on a timescale of 5–10 years. Whether the Science Vision then needs to be updated as well will depend on scientific and financial developments on the international scene in the meantime.



Chapter 1 Introduction

1.1 Context

Science has provided the technologically advanced and comfortable existence that the majority of Europeans enjoy today compared with that of previous generations. At least as importantly, it lets us predict future events with increasing accuracy (for example, the weather) and to understand our place in the Universe in time and space. Astronomy is the oldest science and arguably the one with the greatest long-term impact on civilisation. For example, the revolution in scientific thought that occurred at the end of the Middle Ages was driven by the revelation that the Earth goes around the Sun. This was followed by the realisation, via observations of a comet and two supernovae at the end of the 16th and beginning of the 17th centuries, that the western orthodoxy that everything above the Moon was unchanging, with the planets fixed to crystal spheres, was totally wrong. Furthermore, it was realised that planetary motion could be understood in terms of physical laws that could also be applied to objects on the Earth. The greatest technology-led breakthrough came in 1609, when Galileo Galilei first pointed a telescope at the night sky and recorded in detail the wonders it revealed.

Europe was home to this scientific revolution, and since then our continent has maintained a strong astronomical community working across a diverse range of fields. Today they study everything from the interaction of the solar wind with the Earth's upper atmosphere to cosmology. We are now living in exciting times for our science and are on the brink of truly fundamental breakthroughs in understanding. In turn, Europe is becoming an increasingly dominant player in this field. With appropriate resources targeted in a coordinated pan-European way, it can be the world leader in many of the most important areas of astronomy.

The dramatic progress of astronomical discoveries over recent decades is intimately connected to advances in technology. Ever since that fateful day in 1609, telescopes have increased steadily in power. In the middle of the last century, our ability to detect radio signals from space provided the first new window on the Universe, while our ability to launch satellites provided observing facilities that now cover the entire electromagnetic spectrum and gave us the ability to visit other worlds. The challenging requirements of sensitivity and precision for astronomical measurements have in turn often driven the pace of technological advance, cross-fertilising basic research and commercial applications.

The fundamental questions that we now wish to answer include: What is the nature of the dark energy and dark matter that appear to be the dominant components of our Universe? Is there life elsewhere in the Universe? How common are Earth-like planets that may harbour life and allow it to evolve into complex and perhaps intelligent organisms? What are the underlying mechanisms of solar variability and transient activity and how do these affect the Earth's atmosphere, including its climate? Addressing these questions, and many others, requires us to push the boundaries of the latest technology at our disposal. We must also have gifted technologists and scientists to design, build and operate the facilities that we develop and to analyse the results they produce.

A great strength of our area of science is that the public is fascinated by astronomy and space. Our species is innately curious and humans wish to understand their origins and place in the Universe. Astronomy is also accessible. Everyone is aware of objects in the heavens, be it only the Sun and the Moon, and astronomy is one of the few sciences where amateurs still make a valuable contribution, by, for example, discovering comets and monitoring variable stars. Importantly, astronomy can be used as a vehicle to harness the enthusiasm of our young people for the study of science, mathematics or technology. These subjects are recognised as vital to maintaining our civilisation, but they have all suffered from a decline in the numbers of students studying them in recent decades.

Recognising its importance, the national funding agencies in Europe have been supportive of astronomy and space science over many years. In order to address some of the most important and fundamental questions in contemporary science, our future plans for astronomy are ambitious. Within Europe, they require a collective investment of several billion euros for new facilities and their associated operations, spread out over the next two decades. Some funding will be pursued through programmes of the European Union, which have proved invaluable in providing "seed corn" funds for initial development. But the bulk of the support required will only

Image Credit: NASA/ESA, S. Beckwith (STScI) and the HUDF Team

be accessible from the national funding agencies. This is why the agencies established ASTRONET, an ERA-NET with support from the European Union, to formulate a coherent pan-European plan with a 20-year horizon.

The first stage of development of the plan was the formulation of a Science Vision[2], this was completed and published in September 2007. The Science Vision captures the key astronomical questions that we expect to be addressed over the next 20 years. These were gathered together under four main headings:

A. Do we understand the extremes of the Universe?
B. How do galaxies form and evolve?
C. What is the origin and evolution of stars and planets?
D. How do we fit in?

The current document now provides a scientifically motivated Roadmap of infrastructures necessary to deliver the Science Vision.

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[2] http://www.astronet-eu.org/-Science-Vision-

1.2 Astronomy in Europe Today

The multi-wavelength approach. In days gone by astronomers divided themselves into those working in the radio, optical infrared, X-ray or gamma-ray wavelengths. But today, most astronomers use information from across the electromagnetic spectrum — and in addition from particles — that allows the fullest possible understanding of the phenomena they are studying. This means that more often than not several facilities work together in a complementary fashion to enhance our understanding. We illustrate this by briefly considering two examples.

Gamma-Ray Bursts (GRBs) give unique insights into physical processes in some of the most extreme conditions in the Universe. They were first observed in 1967 by the Vela satellites launched by the US military to monitor the international nuclear test ban treaties. These astronomical discoveries were a by-product. It was not until 1973 that the existence of these unpredictable flashes of gamma rays was announced to the international scientific community, once their cosmic origin had been established. A plethora of theories arose for the origin of these mysterious events, placing them at distances ranging from the edges of our Solar System to the distant cosmos. In the 1990s, the BATSE instrument on the Compton Gamma Ray Observatory satellite excluded many of these theories, but distances ranging from the edge of our galaxy to the edge of the observable Universe remained possible until 1997. In that year the Italian–Dutch satellite BeppoSAX was able to locate the position of a burst more accurately than ever before, and within hours of its occurrence, by virtue of the X-ray emission it detected from the burst and its “afterglow”. This allowed ground-based optical telescopes of the Isaac Newton Group on La Palma in the Canaries to search for and find an optical counterpart around a day later. This, in turn, was followed up by the Hubble Space Telescope (HST), whose observations showed that the burst was associated with a distant galaxy. For a substantial fraction of the bright GRBs subsequently observed, the afterglow emission was even detected at radio frequencies.

It soon became evident that all observed GRBs are far beyond our own galaxy, at cosmological distances. This showed that the energy involved was at the boundaries of plausible physical models. In fact, GRBs are the most luminous events since the Big Bang itself. One solution was that the emission might be in the form of a beam. Indeed, simple models of the interaction of relativistic jets with an ambient medium led to spectral evolution of the resulting afterglow that has now been observed from the gamma ray to the radio. The launch of the Swift satellite in late 2004 proved to be the next watershed. Using a combination of the wide-field Burst Alert Telescope (BAT) together with the higher spatial resolution of the X-ray Telescope (XRT) and UV-Optical Telescope (UVOT) Swift has detected and provided accurate positional information on several hundred GRBs. Gamma-ray observatories such as INTEGRAL, AGILE and Fermi (formerly GLAST) have often teamed up with Swift in detecting and finding positions for an increasing number of GRBs. This information has been fed automatically to ground-based telescopes. Robotic telescopes on the ground have followed up very many bursts within a few minutes, providing optical and infrared photometry and in one case so far, polarimetry. Larger conventional telescopes have then provided spectroscopic follow-up in particular.

This effort means that we now know of two main types of burst. The “long-duration bursts” (long here meaning typically just tens of seconds for the duration of the GRB itself) appear to arise from the collapse of a supermassive star of at least 30 times the mass of the Sun. The “short bursts” (durations shorter than 1–2 seconds) have been much harder to associate with particular progenitors, largely in the past because of the additional challenges of rapid follow-up compared to the long-duration bursts. However, the favoured theory is that they are due to the coalescence of two compact objects (neutron stars or black holes) in a binary system. Without the multi-wavelength approach, using facilities operating across the electromagnetic spectrum both on the ground and in space, GRBs would still remain the mystery they were 30 years ago. A major future challenge is to explore and exploit the use of GRBs as cosmological probes. This again will require a combination of advanced space-borne and ground-based facilities across the electromagnetic spectrum.

GOODS. In ten consecutive days around Christmas 1995, the Hubble Space Telescope accumulated an exposure of a region of the sky in the constellation Ursa Major that was then the deepest optical image ever taken, termed "The Hubble Deep Field" (HDF). The data were so spectacular that they were immediately made available to the astronomical community around the world. This in turn spurred a large number of follow-up observations across the electromagnetic spectrum with the most powerful ground- and space-based telescopes, most of which were made public in the same spirit. The HDF thus became a landmark in observational cosmology, providing invaluable resources of public data for studying the distant Universe. Later, other deep fields were added, using the powerful telescopes in the southern hemisphere, most importantly the Chandra Deep Field South (CDF–S).

The Great Observatories Origins Deep Survey (GOODS) followed these footsteps, building on existing surveys and using three of NASA's "Great Observatories", HST, Chandra and Spitzer, as well as many of the world's great ground observatories (ESO's Very Large Telescope [VLT], Keck, the Very Large Array [VLA], etc.). The programme centres on the two Chandra Deep Fields, each of which is much larger than the original HDF, and is intended to combine the best deepest data across the electromagnetic spectrum. GOODS incorporates 3.6–24 μm observations from a Spitzer Legacy Program, four-band HST Advanced Camera for Surveys (ACS) imaging from a Hubble Treasury Program, deep X-ray observations from Chandra and the X-ray Multi-Mirror Mission (XMM-Newton) and extensive near-infrared and optical imaging and spectroscopy from the largest ground-based telescopes, as well as highly sensitive radio and submillimetre measurements. The data have been used, among other things, to study the mass assembly history of galaxies up to very early cosmic times, the cosmological evolution of active galactic nuclei, the distribution of dark and luminous matter in the distant Universe, cosmological parameters derived from observations of distant supernovae, and the extragalactic background light. In the meantime more than 250 papers with primary GOODS data have been published in refereed journals and more than 700 papers mention the survey in their abstract.

The southern GOODS field has also been selected as the site of the Hubble Ultra Deep Field (HUDF) and the wider Hubble Galaxy Evolution from Morphology and SEDs (GEMS) survey. Even wider surveys with a similar multi-wavelength coverage from the largest telescopes available have been performed in recent years, most importantly the Cosmic Evolution Survey (COSMOS) centred around the largest Hubble Treasury Program, and designed to survey a two square degree field. Among other results, it yielded the first three-dimensional map of the large-scale distribution of dark matter in comparison with normal matter in this region of the sky by combining weak lensing measurements with galaxy and X-ray maps. Projects such as GOODS, COSMOS, and others illustrate beyond any doubt the importance of having matched capabilities across the spectrum available in the same time interval, proving the success of the Great Observatories concept.

Figure 1 illustrates the fact that the major future projects we discuss in this document also span the spectrum with a good match of sensitivities for the study of the distant Universe. Although limited budgets mean that they will not all happen at once, it is important to provide as much operational overlap as possible. The scientific return that would come, for example, from having the Cherenkov Telescope Array, the International X-Ray Observatory, the Laser Interferometer Space Antenna, the James Webb Space Telescope (JWST), the Atacama Large Millimeter/submillimeter Array (ALMA), the European Extremely Large Telescope and the Square Kilometre Array operating at the same time would be vastly greater than the return if they operated sequentially.

The development of the Virtual Observatory also promises to enhance the ability of researchers to conduct multi-wavelength astronomy in an efficient and effective way. It calls for a structured archiving system, and the tools with which to extract data simply and reliably.

Observing facilities on the ground and in space.

Europe's astronomers have access to many optical and infrared telescopes in a range of sizes and capabilities, including solar telescopes, and to a large number of radio telescopes, both single-dish and interferometers. They are also participating in ground-breaking missions to objects in the Solar System. Figure 2 illustrates some of these facilities.

The largest optical/infrared telescopes are equipped with state-of-the-art instruments, including many that take advantage of recent progress in adaptive optics. Some are even being linked interferometrically to obtain milliarcsecond resolution. Many in the 2–4 m-class now concentrate on tasks such as performing wide-field imaging surveys, obtaining radial velocities for millions of stars in the Galaxy using multi-fibre spectroscopy, seeking exoplanets, or participating in rapid reaction and long-term monitoring programmes. The European Southern Observatory is a major player in the continent's vibrant ground-based programme, operating the world's premier optical facilities.

The major astronomical space observatories that are currently active include the HST in the optical and ultraviolet, the Spitzer Space Telescope in the infrared, the Chandra and XMM-Newton in the X-ray domain, and the INTEGRAL and Fermi missions at higher energies. Astronomy missions dedicated to specific topics include the Rossi X-Ray Timing Explorer (RXTE), Swift, AKARI, Suzaku, AGILE and the Convection, Rotation and planetary Transits (CoRoT) satellite. The Solar and Heliospheric Observatory (SOHO), Ulysses, Cluster, the Solar Terrestrial Relations Observatory (STEREO) and Hinode are studying the Sun, its surroundings, and the Earth's magnetosphere. In the field of planetary exploration, Cassini is active in the Saturn system, Rosetta is on its way to comet 67P/Churyumov–Gerasimenko, orbiters are probing Venus and Mars, and the Mars rovers *Spirit* and *Opportunity* continue to provide stunning science and remarkable images, supplemented by the arrival of the Phoenix lander in May 2008. Europe has a coherent space research programme orchestrated largely, though not entirely, through the European Space Agency.

Figure 2 (bottom) illustrates some of the observational facilities currently under development or about to be launched. These include space missions such as Herschel/Planck, Gaia, BepiColombo and the JWST. On the ground, the 10.4 m optical telescope Gran Telescopio CANARIAS (GTC) is entering full operation, as are other large optical telescopes in which Europe has a significant share. New survey telescopes such as the Visible and Infrared Survey Telescope for Astronomy (VISTA) and the VLT Survey Telescope (VST) in Chile are being completed. Various new radio telescopes are under construction, including e-MERLIN and the Low Frequency Array (LOFAR). LOFAR will provide a major advance in the study of objects that emit extremely long radio waves. The next decade will also see the full power of the 8–10 m-class optical/infrared telescopes exploited, with second generation instruments and interferometric links, and the completion of ALMA, the ground-breaking (sub)millimetre telescope array in the Atacama desert.

Step change in capabilities. The facilities just described, both current and about to be deployed, will play an important role in addressing some of the most fundamental questions astronomers face today. The Planck satellite, which is soon to be launched, will make important contributions towards our understanding of dark matter and dark energy. The James Webb Space Telescope, with launch scheduled for 2013, will help in pushing the boundaries towards the detection of the first stars, black holes and galaxies, and will provide information on the reionisation of the Universe shortly after the Big Bang. Herschel, which will be launched together with Planck, and ALMA, which will be completed in 2012, will peer through dust to help us understand how stars and planets form. And Cassini is still orbiting Saturn, studying its complex and diverse system, helping our understanding of astrobiology and the possible emergence of life in the outer Solar System.

But the currently funded facilities will not provide definitive answers to the questions in the Science Vision. For example, the JWST will detect the first "luminous" galaxies and quasars in the Universe. But smaller galaxies

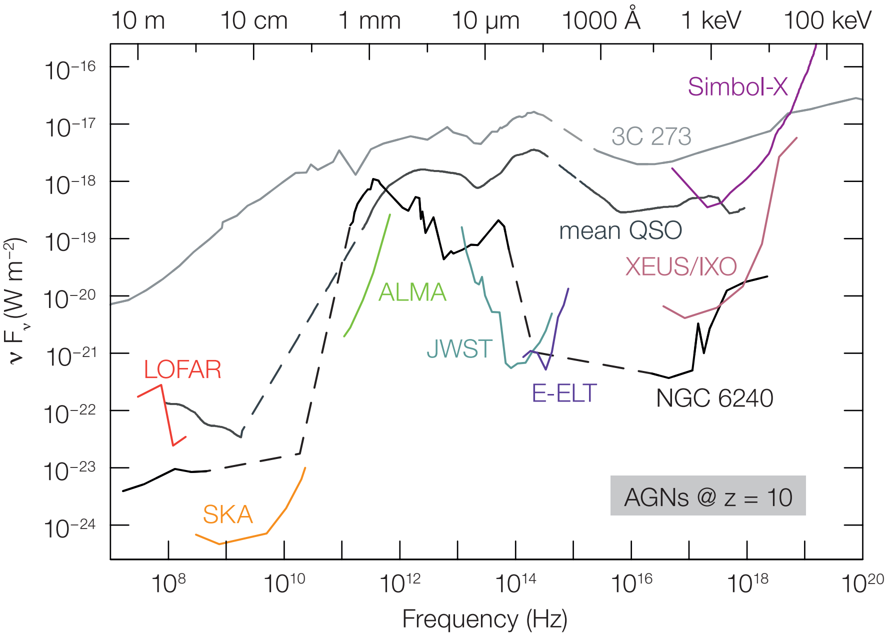

Image Credit: Marc Türler, INTEGRAL Science Data Centre, Geneva

Figure 1: Comparison of sensitivities of major future facilities. Spectral energy distributions for 3C273, for an average QSO template, and for the obscured star-forming galactic merger NGC 6240 are shown at a redshift of z = 10. Sensitivities assume 12-hour 1-σ detections for all instruments apart from the X-ray observatories XEUS/IXO and Simbol-X where an equivalent 5-σ detection in 1 Ms is assumed.

will require a new class of 30–40 m optical telescopes now under development and known collectively as extremely large telescopes (ELTs). Planck will undoubtedly shed light on the nature of the dark matter in the very near term, but in the medium term, more detailed information on what dark matter and dark energy really are will come from large, dedicated deep imaging surveys in optical and near-infrared wavelengths, followed by massive spectroscopic surveys. Future radio telescopes with very large collecting areas will also play a role in the longer term via surveys of the distribution of neutral hydrogen in the Universe. In the very long term, space-borne instruments designed to measure the polarisation of the cosmic microwave background (CMB) and detect primordial gravitational waves may shed light on processes in the early Universe beyond the knowledge of present day physics. In the search for life elsewhere in the Universe, we need to develop far more

Sample of Astronomical Observatories

Present

Under Construction

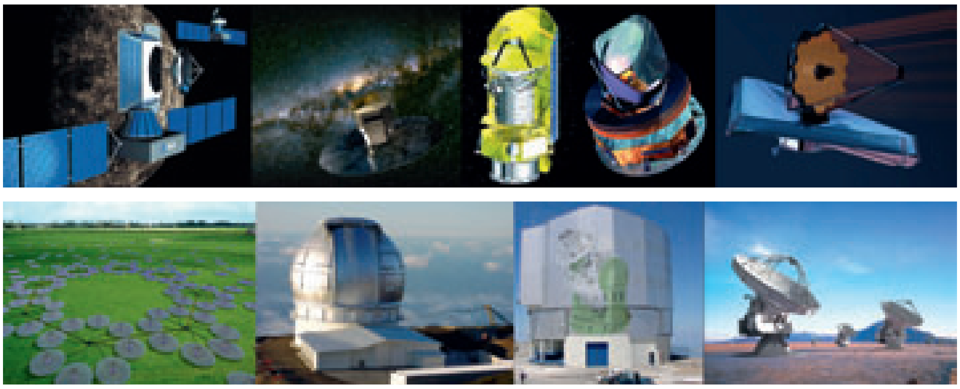

Image Credit: ESO

Figure 2: A selection of observatories from top to bottom and from left to right. (Top) Present space-based observatories: XMM-Newton, INTEGRAL, Mars Express, Venus Express, CoRoT, SOHO, HST; (Middle) Present ground-based observatories: Westerbork Synthesis Radio Telescope (WSRT), Roque de los Muchachos, Swedish 1 m Solar Telescope (SST), Major Atmospheric Gamma-ray Imaging Cherenkov Telescope (MAGIC) Telescope, Effelsberg 100 m Radio Telescope, JCMT, La Silla, VLT(I)/Paranal, Plateau du Bure; (Bottom) Observatories under construction or about to be launched: BepiColombo, Gaia, Herschel, Planck, JWST, LOFAR, the GTC, VST, ALMA.

capable planetary probes, with some able to operate in the challenging environments of the outer planets and their moons. In order not only to find, but also to characterise Earth-like planets around other stars, we require high sensitivity and high resolution facilities on the ground and in space, well beyond the capabilities of anything we have at our disposal today.

These very brief examples illustrate that step changes in capability are unavoidable if we are to address the formidable series of questions set in the Science Vision. These steps include, among others, the development of: extremely large optical/infrared telescopes, large collecting-area (km^2) radio telescopes, large collecting-area X-ray observatories, large volume (km^3) neutrino telescopes, and challenging space missions to the outer Solar System. Their scientific and technological development go hand-in-hand.

The role of technology. Continuing improvements in semiconductor sensors, electronics, telescopes and computing have maintained an impressive doubling in the detection sensitivity of radio telescopes every three years over the past 70 years (Figure 3, bottom). The sensitivity of radio telescopes has improved by twelve orders of magnitude since Karl Jansky's pioneering work in the 1930s. Further improvements in digital technology and computers, and the mass production of cheap, commercial radio dishes, are expected to lead to another two orders of magnitude improvement over the next two decades. Similar dramatic advances have occurred at X-ray and optical/infrared wavelengths. Continued progress in detector technology and telescope collecting area can also be expected in these wavebands in the foreseeable future, leading to correspondingly large gains in sensitivity for instruments in these fields.

Energy-resolving detectors represent another area of transformational technology. Such devices have been used successfully in X-ray and gamma-ray astronomy. Current progress in superconducting devices will soon allow the development of very capable energy-resolving imaging detectors for the optical and the infrared as well.

Substantial improvements in capabilities can be expected in the angular resolution of astronomical measurements. Figure 3 (top) shows the development of angular resolution in optical/near-infrared astronomy over the past 70 years. While the adverse impact of the Earth's atmosphere prevented significant improvement of optical imaging until the middle of the twentieth century, dramatic advances have occurred since that time. They will almost certainly continue for the next one or two decades. The development of the Hubble Space Telescope was one key stepping stone toward much

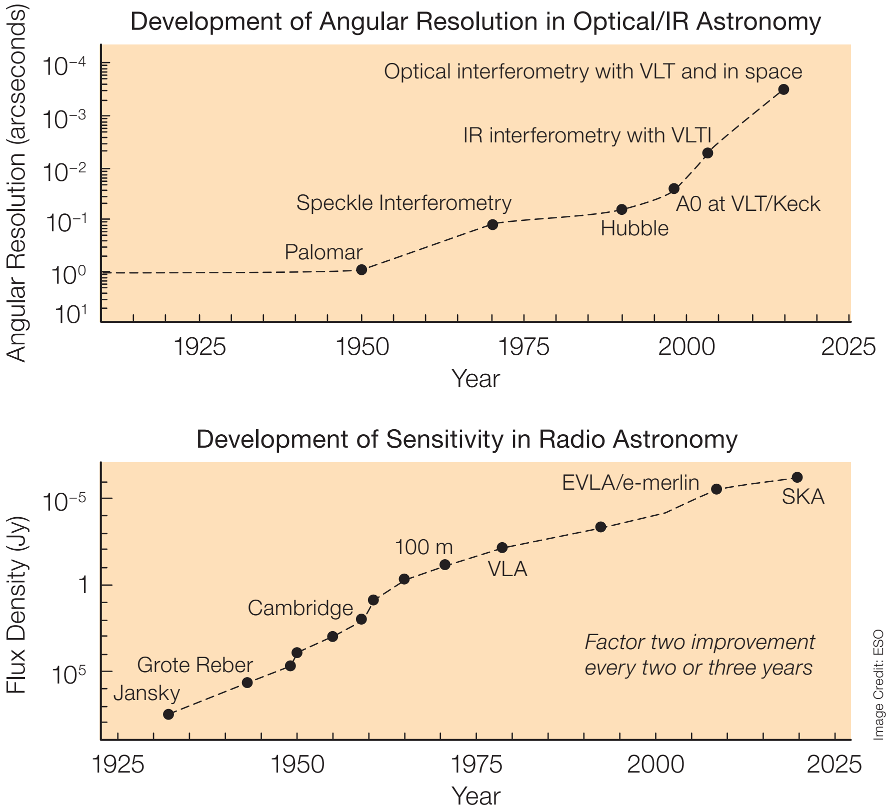

Image Credit: ESO

Figure 3: Top: Improvement in angular resolution with time in optical/infrared astronomy. Bottom: Improvement in sensitivity with time in radio astronomy.

higher angular resolution by placing an optical telescope above the Earth's atmosphere. Another was the development of techniques such as speckle and adaptive-optics imaging that correct for the blurring of the atmosphere from the ground. The combination of adaptive optics with large, lightweight optical mirrors has led to the dramatic improvement in ground-based angular resolution shown in Figure 3. Modern adaptive-optics systems routinely allow diffraction-limited imaging — matching the limits set by optical theory — on 8–10 m telescopes in the near-infrared. The next decade should see the application of this technique to 30–40 m-class telescopes as well as to shorter wavelengths.

Spatial interferometry between several individual telescopes is another key development. This technique was pioneered in radio astronomy, but during the past decade wide-bandwidth interferometry has become feasible at infrared and optical wavelengths, resulting in milliarcsecond resolution. While infrared-optical interferometry is presently a challenging and somewhat experimental technique, further progress in single-mode optical fibres, integrated optics, lasers and fast control systems is expected to make sub-milliarcsecond-imaging interferometry routine in the next ten years for more complex and fainter objects than is possible at present. A longer-term application will be precision interferometry from space, with enormous added benefits in wavelength range, stability and sensitivity. In the first instance, this will require the development of "formation flying" by groups of satellites, an area of wide interest and one where Europe has a technological lead.

Future progress in spectroscopic capabilities can be expected both in terms of multiplexing, and in spectral resolution and precision. Large, integral-field spectrometers and energy-resolving devices, in combination with ever-larger imaging detectors, will allow very significant progress in spatial and spectral multiplexing across all wavebands. The combination of very high resolution spectroscopy with ultra-stable laser clocks will enable a new generation of fundamental time and frequency measurements.

Advances in remote sensing instruments, solar electric and micropropulsion technology, radiation-hardened electronic circuits, digital instrumentation, high bandwidth communications, on-board processing, advanced optical ceramics and interplanetary navigation have led to an equally remarkable surge in missions to explore the Solar System. Landing on Saturn's moon Titan, flybys and impacts of asteroids, and rovers operating on the surface of Mars, were implausible even two decades ago. Now plans and capabilities exist to explore the inhospitable surfaces of Mercury at one extreme of temperature, and the icy crust of Jupiter's moon Europa at the other.

Finally, there has always been a close coupling between astronomical research and industrial development. A prime example is in computing, where astronomy, along with other disciplines, has always been pushing the boundaries of technical possibilities. Large astronomical simulations in cosmology, hydrodynamics and gravity have been among key test cases for the fastest computers of each generation. The requirement of larger and more realistic simulations in astronomy, its vastly larger data rates and its complex data processing needs have strongly motivated the development of yet faster and more capable services. Physics and astronomy have led to imaging algorithm development now used in medical diagnosis, industrial process control and in security. They have also exploited the internet and grid revolutions. These developments, along with many instances of industrial spin-off across a wide range of fields, are expected to continue into the future.

1.3 About this Document

The Infrastructure Roadmap now builds on the Science Vision to provide a comprehensive and prioritised plan for the development of astronomy and space science in Europe. In the next chapter of this document, we describe in more detail the process by which the Roadmap has been formulated, including the close working relationships there have been with other organisations and initiatives within Europe. Chapters 3–7 then contain the reports of each of the five Roadmap Panels. Chapter 8 distils these into a prioritised set of recommendations and considers the funding, technology development, industrial and human resource implications. Finally, the Appendices contain further details and background on various important aspects of our work.

Over 60 scientists from across Europe have taken active and demanding roles in the extensive and lengthy roadmapping process. As with the formulation of the Science Vision, a very important aspect has been the involvement of the astronomical community. The draft of this document was therefore subject to open consultation at the Infrastructure Roadmap Symposium in Liverpool in June 2008, and via a web-based discussion forum that was open for several weeks before and after the meeting.

Chapter 2 Approach and Scope

2.1 How We Worked

As emphasised in Chapter 1, the primary role of the Roadmap is to provide a comprehensive and consistent plan for the development of an optimised infrastructure for European astronomy[3], with a 20-year horizon. The plan focuses on delivering against the science goals described in detail in the Science Vision document[4]. In doing so, it not only considers the facilities that are required to attain these goals, but also the theoretical, computational and laboratory efforts that are needed, and the task of enhancing the wider impact of work on our communities through technology development, scientific education, recruitment and outreach.

The task of developing the Roadmap began in earnest in September 2006, mid-way through completion of the Science Vision. With the mandate and the approval of the ASTRONET Board, a supervising Working Group and thematic Panels were established. Several members of the Science Vision team were associated with the Roadmap development to ensure continuity. In addition, appropriate contacts were established to help to guarantee that the Roadmap would, as far as possible and appropriate, build on the long-range plans developed by ESA and ESO, the ERA-NET ASPERA, and the infrastructure coordination networks OPTICON, RadioNet, and ILIAS, to the mutual benefit of all parties.

The development of the Roadmap has been supervised by the Working Group. This comprises the Task Leader, Chairs and Co-Chairs of the Roadmap Panels that report to it, plus ten Members at Large who have assisted the Panels in their task and helped to ensure thoroughness and consistency. Working Group meetings were also regularly attended by a representative of the Science and Technology Facilites Council (STFC. the lead agency for the Roadmap), the Chair of the ASTRONET Board and representatives of the ASTRONET Project Management Office. The whole process of Roadmap development has been overseen by the ASTRONET Board.

There were five Roadmap Panels, comprising between seven and twelve members each. Working Group and Panel members were chosen as far as possible to provide the required breadth of expertise, whilst fulfilling the need to provide a reasonable balance of national representation and gender. Nominations were sought widely and benefited from the assistance of related projects including OPTICON, RadioNet and ASPERA. The five Panels worked under the following headings:

Panel A: High energy astrophysics, astroparticle astrophysics and gravitational waves
Panel B: Ultraviolet, optical, infrared and radio/mm astronomy
Panel C: Solar telescopes, Solar System missions, laboratory studies
Panel D: Theory, computing facilities and networks, Virtual Observatory
Panel E: Education, recruitment and training, public outreach

Their conclusions form the basis of Chapters 3–7 of this document. Full details of Working Group and Panel membership are given in Appendix II. Each Panel was supported in its work by an ASTRONET Assistant Scientist (Dr Maria Cruz or Dr Frank Molster), both of whom assisted with the tasks of the Working Group.

The Working Group and each Panel were provided with terms of reference detailing the task they had to complete (see Appendix III for details). For Panels A–D, their work firstly entailed assembling an overview of facilities in their area that might be of relevance. This included, where possible, timelines, costs and technological readiness, taking into account necessary research and development. They then proceeded to assess which facilities, or part of them, would be capable of delivering relevant aspects of the Science Vision before (in the case of Panels A–C) proceeding to use the criteria detailed in Section 2.4 below to provide a prioritised list. Panel D considered in particular the supporting "e-infrastructure" necessary to ensure the most effective delivery of the targets set by the Science Vision (see Chapter 6 for further details). After its initial meeting, Panel E split itself into Task Groups (see Appendix VI.A) to consider the relevant aspects of its remit, for which the Science Vision could not be used as a guide. These groups helped to gather information on such diverse topics as European initiatives to utilise astronomy to enhance school-age education; university education in astronomy and astrophysics; science museums and planetaria; industrial links, and primary sources of publicity and the dissemination of our work to the general public

Image Credit: ESA

(see Chapter 7). All the Panels were required to highlight any areas of industrial relevance and then compile a report for initial consideration by the Working Group. Panels exchanged information with, and provided input to, one another throughout the process. The Task Leader and at least one of the Scientific Assistants were present at all meetings of the Panels and Working Group to help to ensure consistency of approach.

The Working Group was then tasked with receiving and reviewing the reports of the Panels and synthesising them to optimise the delivery of the Science Vision. This was assisted by interaction with the funding agencies, which included an intermediate-stage workshop.

There were a total of 26 face-to-face or teleconference Roadmap Panel meetings interleaved with six Working Group meetings before release of the initial draft of the Roadmap in May 2008 for community consultation. This consultation was carried out by means of the Infrastructure Roadmap Symposium in June 2008 and via the online forum, which ran for several weeks either side. There were three subsequent Working Group meetings, plus additional meetings of each of the Panels, to address comments received on the draft, and consequently revise and finalise the Roadmap that is presented here.

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[3] Here astronomy is interpreted in its widest context, encompassing observational and theoretical work on the constituents of the Universe from the near-Earth environment to the distant cosmos, and including laboratory studies, education and outreach.

[4] See http://www.astronet-eu.org/-Science-Vision- and Appendix I for a list of the Science Vision's key questions and respective specific goals.

2.2 Interrelationships

The Roadmap cannot be developed or implemented in isolation. As well as the national funding agencies themselves, and large pan-European organisations that are responsible for the development of facilities of particular relevance to ASTRONET, there are several EU initiatives that seek to enhance the planning and implementation of different aspects of our subject. The ASTRONET Roadmap team sought to foster cooperation and coordination between our project and all the other relevant organisations and initiatives.

Both the European Southern Observatory and the European Space Agency are formal founding partners on the ASTRONET project; ESO as a Contractor and ESA as an Associate. Both are represented at ASTRONET Board level and have participated in the formulation of the Science Vision and now the Roadmap. ESA's representation was especially valuable on the Roadmap Working Group (see below), particularly through the period in 2007 when ESA was considering submissions for missions to fulfill its Cosmic Vision[5] ambitions. ASTRONET was not privy to the ESA selection process, but performed its own independent evaluation of the proposed projects. The outcomes of the two parallel exercises are discussed in the Panel reports in the subsequent chapters. Good working relations were established to ensure mutual understanding of any differences in outlook and perspective.

The ASPERA initiative[6] is another ERA-NET comprising national agencies and funded by the EU under the Framework Programme for Research and Technological Development (FP6). Its primary objective is to provide coordinated planning for the future of astroparticle astrophysics in Europe. Its remit overlaps with ASTRONET's Roadmap Panel A, and to a lesser extent with Panel B. The work of both Panels has benefited from a regular interchange of information on progress. This has included the participation of ASTRONET in ASPERA open meetings as the ASPERA Roadmap was being developed, and taking part in both videoconference and face-to-face meetings, In this way, excellent working relations have been established with ASPERA.

ESFRI[7] brings together representatives of EU Member and Associated States, appointed by the Ministers in charge of Research, plus one representative of the European Commission. The role of ESFRI is to support a coherent approach to policy-making on research infrastructures in Europe, and to act as an incubator for international negotiations about well-specified initiatives. Several of the largest infrastructures considered by ASTRONET are on the ESFRI roadmap and several of the founding agencies of ASTRONET are central to the work of ESFRI.

The OPTical Infrared COordination Network for astronomy (OPTICON)[8] is an Integrated Infrastructure Initiative (I3), initially funded under FP6, which brings together all the international and national organisations that fund, operate and develop Europe's major optical and infrared astronomical infrastructure, together with several world-class facilities for solar astronomy located in the Canarian Observatories. OPTICON incorporates networking, transnational access (TNA) and Joint Research Activities (JRA) to foster collaboration and development of facilities within its remit. RadioNet[9] is another I3 funded under FP6. It has pulled together all of Europe's leading radio astronomy facilities to produce a focused, coherent and integrated project whose goal is to enhance the quality and quantity of science performed by European astronomers significantly. Both OPTICON and RadioNet are represented on the ASTRONET Infrastructure Roadmap Working Group and links between the three initiatives are very strong.

Finally, EuroPlaNet[10] is an I3 network linking planetary scientists from across Europe, again funded under FP6. The aim of EuroPlaNet is to promote collaboration and communication between partner institutions and to support missions to explore the Solar System. The EuroPlaNet coordinator was a member of the ASTRONET Roadmap Panel C. Similarly Euro-VO[11] aims to deploy an operational Virtual Observatory in Europe. ASTRONET Panel D included a leading member of this initiative.

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[5] http://esa.int/esaSC/SEMA7J2IU7E_index_0.html
[6] http://www.aspera-eu.org
[7] http://cordis.europa.eu/esfri
[8] http://www.astro-opticon.org
[9] http://www.radionet-eu.org
[10] http://www.europlanet-eu.org
[11] http://www.euro-vo.org/pub

2.3 Boundaries and Information Gathering

Panels A–C: The main focus of ASTRONET's roadmapping activity is in considering future facilities. In some instances current facilities were considered where, for example, it was already clear that a decision would be made after 2008 on a well-specified major upgrade or operational prolongation. For space missions, prolongation of operations beyond current approval was only considered for those missions already launched at the time of evaluation. Only facilities with a significant European content (and likely funding requirement) are included, with Europe being defined by the nations represented as ASTRONET Contractors or Associates. Small facilities where, for example, single nations might reasonably provide the whole of the funding were not within our purview. On advice from the funding agencies, a lower limit of €10M development and construction cost, and/or €10M operational cost over five years was set, unless there were special reasons to consider less expensive projects. Finally, only those facilities where a major funding decision was considered to be required in the period from 2009 onwards are included in the rankings. When there was any doubt about whether any of the above applied to a specific project or facility, it was included in the information-gathering process, using the maxim that it is better to have too much than too little information.

Lists of potentially relevant projects were gathered from a variety of sources, and included, for example, the whole of the ESA Cosmic Vision submissions. The completeness of these lists was debated at both Working Group and Panel level and a questionnaire to be sent out to all the projects on the agreed list in June 2007 (see Appendix IV for the questionnaire and the complete list of projects surveyed) was formulated. In total 112 projects received questionnaires and the return rate was greater than 90%. The information returned then formed part of the evaluation process that is described in more detail below.

During the evaluation process, facilities were divided into the following categories:

- Cost

Small	€10–50M;
Medium	€50–400M;
Large	> €400M

- Timescale (to full operation)

Short-Term	(–2015);
Medium-Term	(2016–2020);
Long-Term	(2020+).

The Cost categories were aligned to some degree with the last US Decadal Survey on the one hand and, on the other, the ESA Cosmic Vision (Medium and Large equating to ESA "M" and "Flagships", when instruments were included).

Panels D and E: Specific questions relevant to Panels D and E were included as part of the form that was sent to facilities. These questions included archiving requirements, relationship to the Virtual Observatory, and plans for outreach activities. However, both Panels also conducted their own information gathering as detailed in Chapters 6 and 7 respectively.

2.4 Evaluation

For Panels A–C, each project or facility was assigned a rapporteur. An evaluation template was developed that the rapporteur used to produce an independent evaluation of the facility and this was shared with the rest of the Panel, as was each questionnaire response.

Evaluation criteria were formulated and iterated with the Working Group and Panels before being applied to particular facilities. The criteria used were Scientific Impact; Competition/Uniqueness; European Involvement; Scientific User Base, and Industrial Relevance. Within each criterion, marks of 0–3 (high) were assigned via subcriteria, except for User Base where marks were on a 0–2 scale. Each main criterion was given a different weight, with Scientific Impact (as related to the Science Vision) of highest weight and Industrial Relevance the lowest. Separately from this scoring, an assessment was made of Technology Readiness Level (TRL) on a four-point scale for each facility.

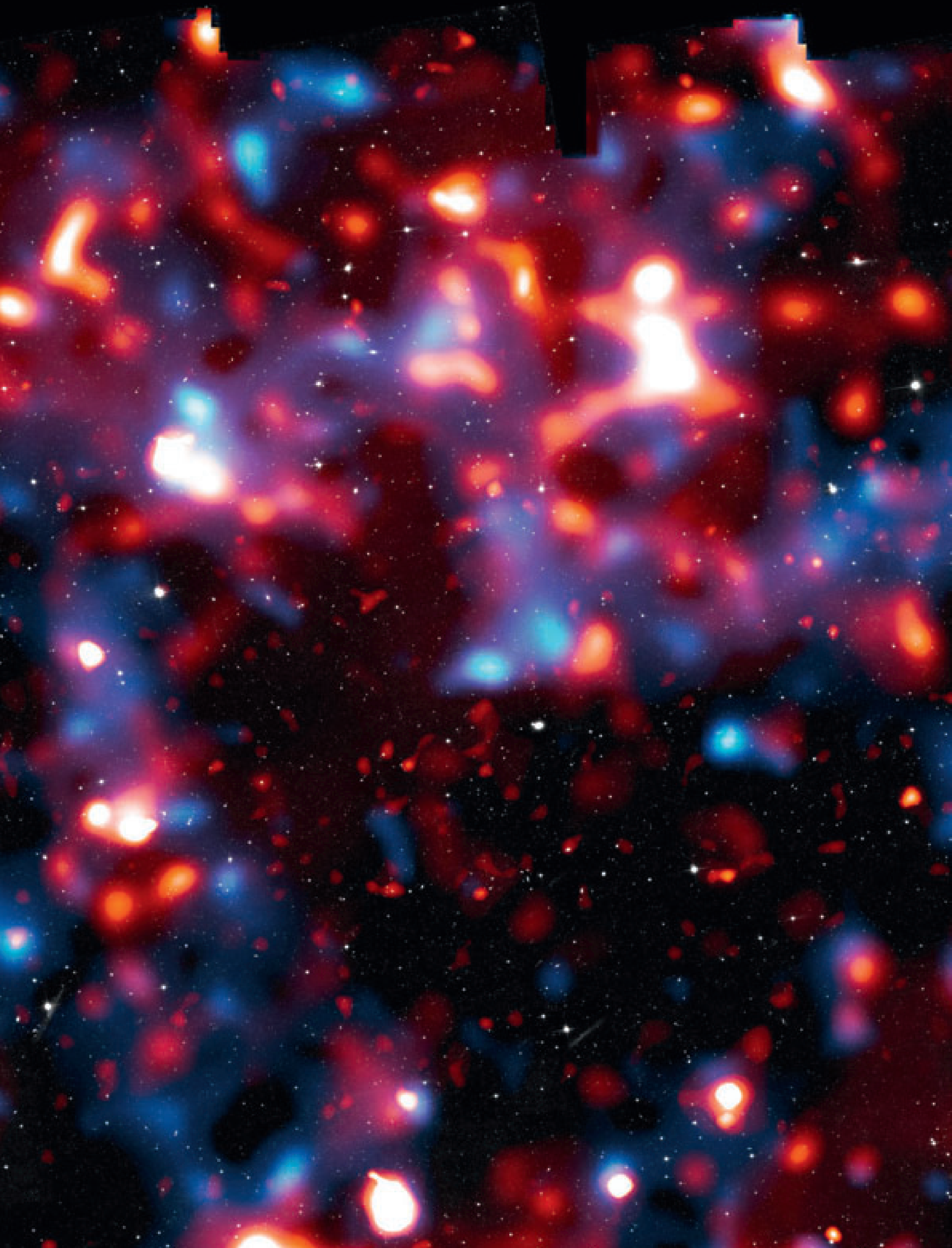
Each of Panels A–C then discussed and scored each project in turn against the above criteria and produced an initial ranked list on which facilities were divided into High, Medium and Low Priority categories. The Panels then revisited the rankings before passing them to the Working Group for consideration at each of two meetings in late 2007. Points of disagreement or clarification were passed back to the relevant Panel for further discussion each time. In general, only High Priority facilities are discussed in detail in the final report, but other facilities are mentioned when appropriate.

The first full draft report was considered by a meeting of the Working Group and the agencies in London in February 2008. The purpose of this meeting was primarily to ensure that the Roadmap was tempered with a degree of realism regarding likely costs and funding envelopes, and national aspirations. Its main conclusions were referred back to the Panels for further discussion as appropriate and prompted the Working Group to meet again, in particular to address priorities across Panels A–C.

It is apparent that despite running largely independent processes, there are no significant discrepancies between for example ESA's Cosmic Vision outcomes and the ASTRONET Roadmap, or between the ASPERA Roadmap and our own. As discussed in the relevant parts of the main text of this document, any residual discrepancies can easily be accounted for.

Of particular relevance for the Agencies is setting clear priorities for projects that are, of course, competing for human and monetary resources. This has been done in this document throughout the entire spectrum of promising new facilities, but must be taken with a strong caveat: ASTRONET priorities as expressed here are a snapshot of the projects, based on their currently perceived science potential, feasibility, cost and risks. All projects throughout their various development phases, from concept to study, construction and deployment, will go through very thorough formal external reviews to reassess periodically their value and will be pursued only if still fully competitive. ASTRONET priorities are thus not a blank cheque for going ahead with any project, only an impetus for the Agencies to try hard to develop some specific and important new capabilities for the benefit of our science in Europe.

The following five chapters give the detailed reports of the individual Panels. These are followed by a chapter that summarises the synthesised Infrastructure Roadmap for European astronomy.



Chapter 3 High Energy Astrophysics, Astroparticle Astrophysics and Gravitational Waves

(Panel A)

3.1 Introduction

Before examining the European projects proposed for future implementation in the fields of gravitational waves, very/ultra-high energy particles, gamma-ray and X-ray astronomy, both ground-and space-based, it is worthwhile to review briefly the state of the art in those branches of astronomy

High energy astrophysics is providing an extraordinary discovery rate thanks to a very successful series of space missions and ground-based facilities that have enabled astrophysicists to address the most energetic phenomena taking place in our Universe. The behaviour of compact objects is under close scrutiny at all wavelengths. Accretion into black holes, be they "stellar" in binary systems or supermassive at the core of remote active galactic nuclei (AGN), is being investigated with unprecedented detail. Gamma-ray-burst science is actively and very successfully being pursued with the aim of clarifying the basic physics involved as well as the progenitor classes. The formation of the elements is being mapped throughout our Galaxy. On a larger scale, X-ray observations are essential to constrain the structure and mass content of clusters of galaxies and their underlying dark matter, as well as in studying the formation of the earliest black holes. In European space science, such a bonanza of results in recent years has been enabled by a suite of ESA missions, such as XMM-Newton and INTEGRAL, complemented by national missions, such as the Italian AGILE, and projects with significant European contributions, such as the NASA Swift mission. The capabilities in the higher energy region ($E > 100$ MeV) have been further enhanced in 2008 with the launch of the NASA-led Fermi Gamma Ray Space Telescope with significant European participation. The European involvement in high energy space astrophysics will continue in the near future with missions devoted to X-ray astronomy that are already approved for launch early in the next decade. The Russian Spektrum-Roentgen-Gamma (SRG) platform will perform a new sensitive X-ray all-sky survey with key instrument contributions from European countries, most importantly Germany and the Netherlands. One of the main goals of SRG is to study dark energy through X-ray observations of around 100 000 clusters of galaxies. The Space multi-band Variable Object Monitor (SVOM) is a French-Chinese collaboration aimed at continuing the investigation of gamma-ray bursts. The next generation high energy astrophysics observatory, formerly called XEUS in Europe and Constellation-X in the USA, is planned in a global cooperation as the International X-Ray Observatory (IXO)[12].

During the last few years, very high energy (VHE) gamma-ray astronomy has emerged from the pioneering Whipple era as a truly observational discipline, largely driven by the European-led High Energy Stereoscopic System (H.E.S.S.) and the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescope. More than 70 VHE (TeV) gamma-ray sources have been detected, representing different galactic and extragalactic source populations such as young shell-type supernova remnants, pulsar wind nebulae, giant molecular clouds, Wolf-Rayet stars, binary pulsars, microquasars, the Galactic Centre, AGN and large numbers of unidentified galactic objects. These results and especially the future observations with the next generation of ground-based detectors such as the Cherenkov Telescope Array will have a strong impact on the development of astrophysics, cosmology and astroparticle astrophysics. Over several decades, high energy neutrino astronomy has remained essentially a theoretical discipline with many exciting ideas and predictions, but without the detection of a single VHE neutrino source. However, high energy neutrino astronomy is currently reaching a state of experimental maturity, as demonstrated by the ANTARES and AMANDA experiments. It is expected that, with the arrival of the next generation of cubic-kilometre-scale detectors like IceCube and KM3NeT, the first high energy sources will be detected, and thus the status of the field will be transformed dramatically.

With the first, long run of the Laser Interferometer Gravitational-Wave Observatory (LIGO) at full design sensitivity and the gravitational-wave detectors, the German-British GEO600 and Virgo, coming some time later, the joint global ground-based gravitational-wave observatory, though not likely to be in the discovery phase yet, is already putting astrophysically important limits on some of the candidate source classes. All these detectors are now moving through a phase where the sensitivity is enhanced towards the "advanced" generation, due to start observations around 2014. At that level of sensitivity the global observatory will cover a fraction of the Universe some 300 Mpc across for neutron star binaries and up to $z = 0.4$ for stellar mass black hole binaries. In this volume, the interesting event rate should be high enough

Image Credit: ESA/NASA, R. Massey (California Institute of Technology)

to allow the start of astrophysical observations at sizeable signal-to-noise ratios. These observations will have an impact on the study of the gravitational waves themselves, on the dynamics of the collapse of compact objects and will reach out to cosmological distances if the signal-to-noise ratio is high enough to allow the location and ranging of the source with interesting precision. If such an observational phase is indeed reached by this class of detectors, then the astrophysical case for a third generation of detectors, the objective of the design study for the Einstein Telescope (ET), will become of the highest priority. LISA, planned as a joint ESA–NASA endeavour, is the future space project for the observation of low frequency gravitational waves that are inaccessible from the ground. In that frequency range, several populations of astrophysical sources are expected, with a large impact from astrophysics to cosmology.

The list of space missions and ground-based facilities discussed in Panel A is shown in Appendix IV. The Panel has reviewed all the high energy space missions with significant European involvement that already exist or are approved for a near-term launch (XMM-Newton, INTEGRAL, Swift, Fermi, SVOM, SRG), as well as the existing ground-based TeV–gamma-ray, cosmic-ray and gravitational-wave facilities. We judge them vital to maintaining and strengthening the substantial European effort in high energy astrophysics. Apart from XMM-Newton and INTEGRAL they have, however, not been ranked in our final recommendations, because according to the information we have received, they do not require a European unsecured expenditure of more than €10M (after 2009), which we have considered as our threshold (see Section 2.3 for more details).

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[12] In May 2008, the XEUS project studied by ESA and the Japanese Space Exploration Agency (JAXA) was merged with the corresponding NASA project Constellation-X into the International X-ray Observatory IXO (see section 3.2.3.1). In the context of this Roadmap we will refer to it as XEUS/IXO.

3.2 High Priority New Projects

3.2.1 Ground-Based, Near-Term (–2015)

3.2.1.1 *Cherenkov Telescope Array (CTA)*

The CTA is a very powerful multi-functional tool for spectral, temporal and morphological studies of galactic and extragalactic sources of very high energy (maximum range considered: several tens of GeV to 100 TeV) gamma rays. The motivation is twofold: (i) to obtain an order of magnitude improvement of the flux sensitivity in the currently explored energy band between 100 GeV to 100 TeV, and (ii) to extend significantly the energy domain of ground-based gamma-ray astronomy down to several tens of GeV. The current plan for the CTA consists of two observatories, one in the northern and one in the southern hemisphere, and each including two sub-arrays aimed at energies of 100 GeV–100 TeV and at around 10–100 GeV detection, respectively (Figure 4). For the higher energies, sub-arrays consisting of tens of 10–15 m-diameter class imaging atmospheric telescopes, an angular resolution within 1–3 arcminutes, an energy resolution as good as 15%, and a sensitivity (minimum detectable flux) at the level of 10^{-14} erg cm^{-2} s^{-1}, can be predicted with confidence. Current sites at altitudes of about 2000 m are fully adequate. The lower energy sub-arrays, which would explore new scientific territory and could bridge the gap to space-based gamma-ray astronomy, are more of a technological challenge, as they may require larger (30 m-diameter class) reflectors equipped with a new type of high quantum efficiency (> 50%) focal plane detectors and higher altitude sites.

Scientific Discovery Potential. Within the context of the Science Vision, the CTA is an important tool towards the resolution of the questions A.5, A.6, and A.7 (see Appendix I for full definitions), and in particular investigations of the origin of galactic cosmic rays, of the physics of relativistic outflows on different scales, from pulsars and microquasars to AGN, of the physics of black holes close to the event horizon, indirect measurements of the extragalactic background light and indirect searches for dark matter. The CTA may also be relevant for other topics, e.g., goals within key question C, given the recent discovery of VHE gamma rays emitted by a stellar association. As with all new windows, surprises are in store. For example, it has been suggested that due to the fact that this will be the largest planned collecting area for optical light it could also break new ground for the observation of fast temporal phenomena.

For the high energy sub-array, given the considerable enlargement of the detection area and the improvement in background rejection compared to the most sensitive current telescopes, H.E.S.S., MAGIC and the Very Energetic Radiation Imaging Telescope Array System (VERITAS), a conservative expectation for the increase in the number of sources is a factor of ten or probably more, allowing meaningful source population studies. Most Galactic VHE sources are extended, and with the

CTA their morphology can be studied with high resolution and flux sensitivity. Moreover, larger photon statistics should allow detailed studies of spectra and cut-off regimes, which serve to characterise acceleration mechanisms. The CTA will provide a sensitive probe of high energy non-thermal processes; for extended sources with angular size larger than 1 arcminute it will be competitive with XMM-Newton in X-rays through emission of synchrotron radiation by multi-TeV electrons.

Perhaps an even more dramatic increase in the number of gamma-ray sources could be achieved by deploying the lower energy sub-array. First steps towards lower energy thresholds have already been taken by the MAGIC telescope and are planned for H.E.S.S.-2. This concerns, first of all, extragalactic objects, because a 10 GeV threshold instrument would allow exploration of the Universe up to or perhaps beyond $z = 5$. The visibility of the Universe around 100 GeV is limited to $z < 1$ by the absorption of gamma rays interacting with the extragalactic background light. Such a detector would combine two advantages of the current ground-based and satellite-borne gamma-ray domains — large photon fluxes, typically 10^{-8} ph cm^{-2} s^{-1} at GeV energies (versus 10^{-12} ph cm^{-2} s^{-1} typical at TeV energies) and huge detection areas of 10^5 m^2 allowed by the atmospheric Cherenkov technique (versus the 1 m^2 area of Fermi at GeV energies). This would provide very high detection rates (e.g., the typical GeV of the Energetic Gamma Ray Telescope [EGRET] and Fermi sources can be detected in exposure times from seconds to minutes), and thus would make the CTA a unique gamma-ray timing explorer with a potential not achievable in any other gamma-ray energy band.

At this stage, the CTA community sees the most promising approach to build, on a timescale to around 2015, an instrument with an energy threshold of around several tens of GeV and extending to 100 TeV.

User Base. The CTA is expected to enter the realm of an observatory-type astrophysics telescope, making the data publicly available to the community, and will therefore have a very broad user base.

International Context. The CTA is currently a collaboration between all the European laboratories involved in this subject. The current plan foresees two sites, one in the northern and one in southern hemisphere, with the northern site emphasising low energies and the southern one providing complete coverage of both low energy and high energy bands. Given that the southern site provides the best galactic coverage and comparable extragalactic coverage, deployment of the southern observatory should be given highest priority.


Image Credit: TASPERA/ D. Rouable

Figure 4: Illustration of a possible configuration for the CTA showing a combination of sub-arrays of telescopes of different sizes in order to cover the full energy range.

Technology Readiness. The high energy sub-array can be constructed using existing technologies. For the low energy sub-array novel high quantum efficiency photodetectors and larger telescope diameters will be required.

Timeline and Cost[13]. The cost of a full-range southern array is estimated at €100M (plus Full Time Equivalents [FTEs]) and the cost of the low energy northern array at €50M (plus FTEs). These target costs require development towards cost-effective large-scale production of telescopes. The costs will also depend on the yet to be determined location and its available infrastructure. In the case of a limited budget, a trade-off analysis between the different energy ranges is required by the community, and this forms part of the ongoing CTA design study. Operational costs are estimated at €7M/yr (including FTEs).

3.2.1.2 *KM3NeT*

Over several decades neutrino astronomy has remained essentially a theoretical discipline, with many exciting ideas and predictions, but without a detection of a single high energy neutrino source. In the TeV energy regime, the most effective approach to registering high energy neutrino signals is established as the transformation of huge volumes of natural water or ice into detectors of the Cherenkov light of secondary muons or electrons. Currently, the feasibility of this technique is demonstrated by several small or medium-scale detectors. However, it is expected that only with the arrival of km^3-volume detectors, namely IceCube, a neutrino telescope at the South Pole, and the KM3NeT water Cherenkov telescope in the Mediterranean Sea (Figure 5), will the astronomical potential of the field eventually be realised.

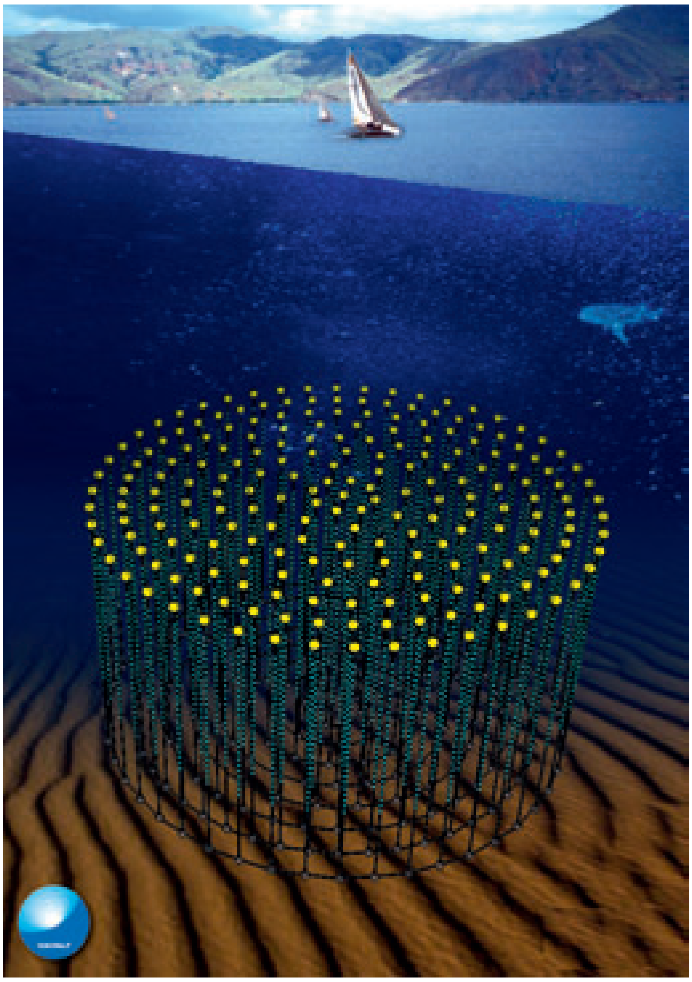

Image Credit: ASPERA/NIKHEF/M. Kraan

Figure 5: Artist's impression of KM3NeT, the kilometre-sized undersea observatory that will search for neutrinos emitted by distant astrophysical sources.

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[13] The cost profile for the CTA is being revised in the ASPERA roadmapping process.

Scientific Discovery Potential. Presently, extragalactic objects like AGN and sources of GRBs are believed to be detectable as neutrino sources, and are therefore the driving motivations of VHE neutrino astronomy. The current models of AGN and GRBs indeed contain many attractive components concerning the conditions of particle acceleration and their interactions that make these objects potentially detectable sources of VHE neutrinos. Independent verification of these models through, e.g., measurement of TeV gamma rays, would remove much of the freedom and uncertainty in these models, but due to absorption at high redshift this information is unfortunately lacking.

On the other hand, models of potential galactic neutrino sources, in particular shell-type supernova remnants, pulsar wind nebulae, star-forming regions and related molecular clouds, are better constrained by gamma-ray observations. In many cases, the expected fluxes from these objects are below the detection thresholds of IceCube and KM3NeT. However, the recent H.E.S.S. discoveries of several TeV gamma-ray sources at the flux level of “1 Crab”, which can be interpreted within the hadronic models of gamma-ray emission, sustain a hope that the first TeV neutrino sources will be detected in the foreseeable future. In particular, one may predict (marginal) detections of TeV neutrinos from a few H.E.S.S. sources located in the inner Galaxy with KM3NeT (but not with IceCube because of its location in the southern hemisphere).

Finally, KM3NeT has a significant discovery potential concerning “hidden” astrophysical objects, i.e., regions from which only neutrinos can escape because of their weak interaction with ambient gas, radiation and magnetic field. Concerning the Science Vision goals, the topics relevant to KM3NeT are A.2, A.5, A.6 and A.7.

User Base. KM3NeT, unlike classical particle physics experiments, envisages running as an open user facility similar to astronomical observatories.

International Context. KM3NeT is complementary to IceCube in sky coverage and detection technique. Note that the KM3NeT telescope has some advantages, compared to the IceCube detector, mainly because of its better (almost by a factor of two) angular resolution. This may provide somewhat better sensitivity compared to IceCube.

Technology Readiness. KM3NeT can be constructed using conventional photomultiplier techniques.

Timeline and Cost[14]**.** The total cost of construction of KM3NeT is estimated at around €250M, with economies/innovation likely used to increase the volume rather than reduce the total cost. In this regard one of the highest priority tasks of the collaboration should be a technological study aimed at reducing the cost of basic units of detectors (strings of photomultipliers). The KM3NeT consortium has recently started its preparatory phase with funding from the EC FP7. The annual operation costs are estimated at €8M.

Priorities. *Panel A sees both the CTA and KM3NeT as having high priority, the latter due to its potential proof of principle of detecting and diagnosing TeV neutrino sources, and the former having somewhat higher priority due to its more proven capability for astrophysical discovery.*

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[14] The cost profile for KM3NeT is being revised in the ASPERA roadmapping process.

3.2.1.3 *A Comment Concerning the Future of Ultra-High Energy Cosmic-Ray Facilities*

Cosmic rays of ultra-high energy remain one of the least understood phenomena in the Universe. A new international facility, the Pierre Auger Observatory, a huge 3000 km^2 particle detector array combined with four wide-angle optical telescopes for detecting atmospheric fluorescence, located in the southern hemisphere (Argentina), is now delivering its first, highly tantalising results. These results demonstrate the existence of a statistically significant spectral feature (steepening or cut-off) at around 5×10^{19} eV. Also, a possible correlation between the arrival directions of the highest energy cosmic rays, above ~ 6×10^{19} eV, and the positions of nearby AGN have been reported. Much more can be expected with more statistics. The Auger collaboration is proposing to build a significantly larger array in the northern hemisphere in order to increase the statistics at higher energies and to access the whole sky. A further increase in detection rates might be achieved with space experiments like the Extreme Universe Space Observatory on JEM/ISS (JEM-EUSO). The relative merits and feasibility of these options are being actively debated in this very fast-moving field.

3.2.2 Space-Based, Near-Term (–2015)

3.2.2.1 *Simbol-X*

Hard X-ray imaging with focusing optics (> 10–100 keV) represents an important development for the next decade, resulting in a 100–1000-fold increase in angular resolution and sensitivity with respect to INTEGRAL, allowing a wide range of questions relating to black hole physics, particle acceleration and nucleosynthesis to be addressed. Simbol-X (Figure 6) is a hard X-ray imaging mission led by France and Italy, with the participation of Germany, planned for a launch in 2014. It is a short-term, medium-size space project and will serve as a first demonstrator for the technique of formation flying. The long focal length (20 m) afforded by the separation of the mirror and instrument spacecraft provides the unique opportunity in high energy astrophysics to fly a focusing telescope operating in the hard X-ray (10–80 keV) regime, with a wide field of view and a wide energy range, a high angular resolution, spectroscopic capabilities, accurate timing and an orbit such that long integrations will be possible. Simbol X will both be a pathfinder for, but also complementary to XEUS/IXO. Because of its enhanced capabilities, and above all its higher angular resolution, Simbol-X will significantly outperform NuStar (NASA) and NeXT (Japanese Space Exploration Agency/Institute of Space and Astronautical Science, JAXA/ISAS), which are planned in the 2011–2013 time frame.

Scientific Discovery Potential. In relation to the Science Vision, Simbol-X is required in order to fully address the key question A. In particular Simbol-X will be very important for addressing questions A.5 and A.6. Together with H.E.S.S. and/or a future CTA facility, Simbol-X will also provide an excellent opportunity for advancing our understanding of question A.7.

User Base. The user base of Simbol-X will, in the first instance, comprise the high energy astrophysics communities of France, Italy and Germany. The extent to which the programme is further internationalised will be governed by the fraction of the mission time set aside for open competition.

International Context. NuSTAR and NeXT are planned for the 2011–2013 time frame and represent significant steps forward in hard X-ray imaging with capabilities similar to Simbol-X. However, Simbol-X is the most sensitive among these projects and has the highest angular resolution, uniquely enabling it to resolve a significant fraction of the extragalactic hard X-ray background.

Technology Readiness. The project is in the preliminary design phase. The major technical challenge for Simbol-X is the development of the requisite formation-flying technology. Issues related to the Attitude and Orbit Control System (AOCS) with respect to formation flying will require detailed ground testbed development and verification. The chosen orbit drives the formation flying requirements and thus the specification of a ground testbed system. Mirror design and development is also still in a preliminary design phase.

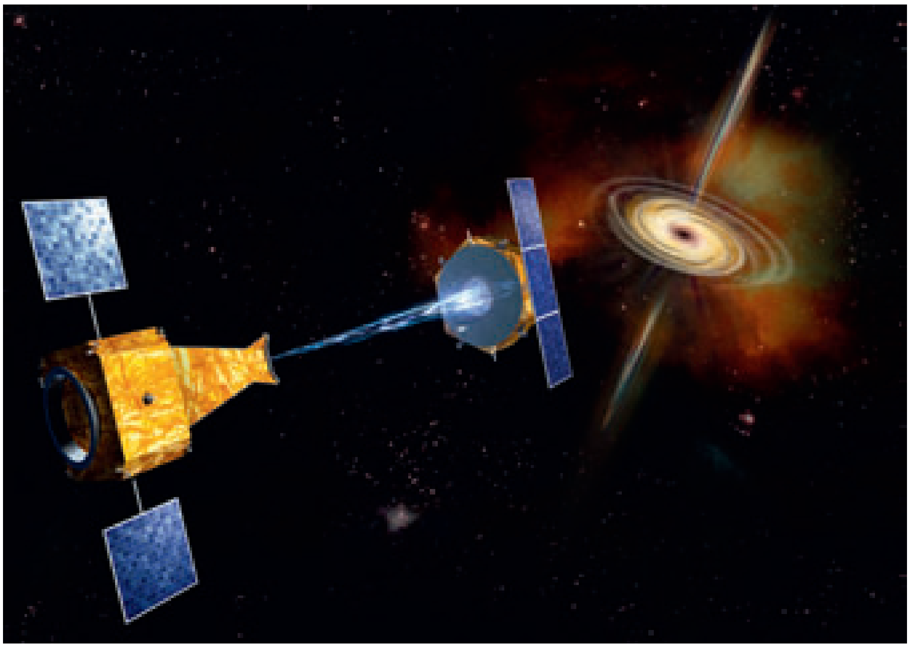

Image Credit: Copyright CNES

Figure 6: Artist's impression of Simbol-X, which will have a 20 m focal length and will be the first focusing telescope operating in the hard X-ray (10–80 keV) regime.

Industrial Relevance. Formation flying is recognised by industry as an important future space technology with many potential applications. As such Simbol-X has attracted strong interest from European industry and also the support of national space agencies (specifically the Italian, Agenzia Spaziale Italiana [ASI], and the French, Centre National d'Etudes Spatiales [CNES]).

Timescale and Cost. Simbol-X is currently in a Phase A Study that is due for completion in 2008. Mission final approval in France and Italy is expected in the 2008–2009 time frame. The launch date is currently envisaged as mid-2014. The cost of the mission will be determined by the end of the phase A study — current rough estimates suggest a total cost of ~ €300M. The bulk of the mission funding would be provided by France and Italy on a shared basis, with significant German contributions to the focal plane and the mirror development.

3.2.3 Space-Based, Medium-Term (2016–2020)

3.2.3.1 *X-ray Evolving Universe Spectroscopy (XEUS) / International X-ray Observatory (IXO)*

XEUS is one of the three large missions selected for study by ESA within the ESA Cosmic Vision programme. It represents ESA's next generation X-ray observatory and will provide a facility for high energy astrophysics fully complementary to other major future observatories operating across the electromagnetic spectrum such as the SKA, ALMA, JWST, the E-ELT and the CTA. In May 2008, ESA and NASA established a coordination group involving ESA, NASA and JAXA, with the intent of exploring a joint mission merging the ongoing XEUS and Constellation-X studies into developing an International X-ray Observatory. A single merged set of top-level science goals and derived key science measurement requirements were established. The starting configuration for the IXO study will be a mission featuring a single large X-ray mirror and an extendable optical bench with a 20–25 m focal length, with an interchangeable focal plane. The instruments to be studied for the IXO concept will include an X-ray wide-field imaging spectrometer, a high spectral resolution non-dispersive X-ray spectrometer, an X-ray grating spectrometer, plus allocation for further payload elements with modest resource demands. The study will explore how to enhance the response to high energy X-rays. This plan establishes an IXO study, which will be the input to the US decadal process and to the ESA selection for the Cosmic Vision plan. The IXO study supersedes the XEUS and Constellation-X activities. An observatory such as XEUS/IXO will also be synergetic with planned future developments in the spheres of gravitational-wave and neutrino astronomy (LISA and KM3NeT respectively).

Scientific Discovery Potential. Within the context of the Science Vision, the capabilities of XEUS/IXO map onto the first three key science questions A, B and C. In particular XEUS/IXO will be very important in addressing questions A.2, A.5, A.6, B.2, B.5, B.6, C.1 and C.3 fully. While the XEUS concept envisaged a pair of spacecraft in a formation-flying configuration, the IXO approach is based on single spacecraft with a deployable structure in order to achieve the focal length needed to meet the scientific goals of the mission in which an X-ray telescope of novel design and unprecedented collecting area feeds a suite of state-of-the art instruments. The huge improvement in sensitivity compared to current X-ray telescopes, coupled with a high spatial and spectral imaging capability, will make XEUS/IXO a unique facility for studying high energy phenomena and processes over the full span of the observable Universe.

User Base. The XEUS/IXO user base will be the entire world astronomical community. The capabilities of XEUS/IXO are such that it will be relevant to almost all branches of modern astrophysics.

International Context. The IXO mission is a common effort by ESA, NASA and JAXA, building on the technological studies carried out both for XEUS and Constellation-X.

Technology Readiness. Some of the major technical challenges for XEUS/IXO include the design, fabrication and baffling of the lightweight X-ray mirrors and the development of a fully dry cryogenic system for the high resolution spectrometer. The project will now enter the assessment and technology development phase. The mirror development is at such a stage that assumptions on collecting area and resolution will require substantive verification. The development of large format Transition Edge Sensors, maintaining energy resolution performance across a wide energy range is also in an early stage. Other elements of the model payload (e.g., the Deeply Depleted Field Effect Transistor; DEPFET arrays) are already further advanced.

Industrial Relevance. The XEUS/IXO project with its range of advanced technology will provide a strong driver for European industry in areas such as spacecraft design, cryogenic systems, X-ray detector arrays and X-ray mirrors. Both mirror and detector technologies have a wide range of terrestrial applications, e.g., in material diagnostics and medicine.

Timeline and Cost. Key future milestones for XEUS/IXO include the selection of the two (from three) L-class missions to enter the definition phase (late 2009) and the eventual selection of the first L-class mission to enter the implementation phase (late 2011). Within the current ESA programme, the launch of the first Cosmic Vision L-class mission is scheduled for 2018. Present estimates including five years of operations suggest XEUS would cost ~ €1260M, of which €650M and ~ €200M could be financed by ESA and the member states, respectively. The remaining costs would have to be funded through a global partnership. The decision to pursue a joint IXO study between ESA, NASA and JAXA now allows for a more capable and less risky mission implementation.

3.2.3.2 *Laser Interferometer Space Antenna (LISA)*

LISA (Figure 7) is a gravitational-wave astronomical observatory aimed at opening the 0.1 mHz–0.1 Hz low frequency range inaccessible from the ground (question A.4 within the context of the Science Vision). In that range several populations of astrophysical sources are expected, namely binary systems of compact objects (white dwarfs, neutron stars, black holes) within the Milky Way. The best known of these have “guaranteed” detections and will serve as high signal-to-noise ratio calibration sources. LISA will produce the most complete census of compact binary objects throughout the galaxy, detecting several thousands of such systems, including those not optically visible. LISA will also discover tens to hundreds of black hole binaries with masses between 10^4 and 10^7 solar masses, detectable with high signal-to-noise ratios at redshifts up to 30. For most of them, LISA will detect signals during the long in-spiral phase, the merger and the final ringdown and will independently measure the luminosity distances. Finally, many tens of extreme mass-ratio black hole binary in-spiral events per year are expected up to about $z = 1$, as well as mergers of binaries involving at least one black hole with mass of 10^2 to 10^4 solar masses out to $z = 20$.

Scientific Discovery Potential. With this observational potential, LISA will help in understanding the formation and the growth of massive black holes, determine the merger history of galaxies, and explore stellar populations and dynamics in galactic nuclei. It will accurately map the spacetime geometry around collapsed objects and test general relativity in the strong-field regime. LISA will thus be essential to address the Science Vision questions A.5, A.6, B.2, B.3 and B.7. It will also be complementary for the Science Vision questions A.1, A.2 and A.3 by studying cosmic expansion history, geometry and dark energy using gravitationally calibrated distances in cases when redshifts are available from electromagnetic measurements and by giving new constraints on cosmological backgrounds. In particular, it will allow the parameter *w* of the dark energy equation of state to be constrained with 2% accuracy.

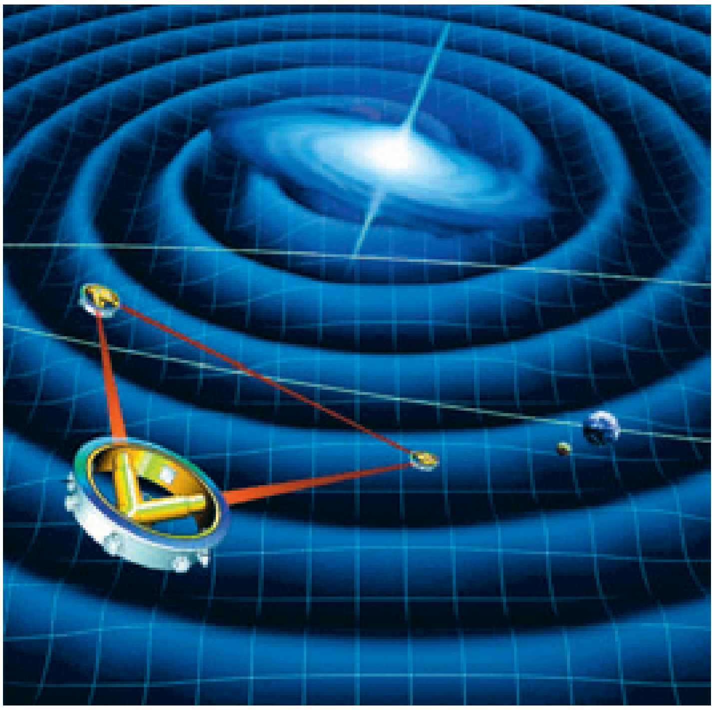

Image Credit: ESA

Figure 7: Artist’s impression of LISA, a joint ESA–NASA mission aimed at detecting gravitational waves from astrophysical sources such as white dwarfs, neutron stars and black holes. LISA’s observations will have impact all across astrophysics as well as fundamental physics.

User Base. The impact of LISA observations will be outstanding all across astrophysics, general relativity, fundamental physics and cosmology. Data will be almost immediately in the public domain for broad exploitation. Since the whole sky is observed all the time, the challenge lies in the extraction of the signals and on the ability to perform meaningful correlations with astrophysical phenomena independently observed.

International Context. LISA is a cooperative ESA–NASA mission. It is included within the Beyond Einstein Program in NASA and has been strongly endorsed in the 2007 Beyond Einstein Program Assessment Committee (BEPAC) review. Within Cosmic Vision, LISA is a competitor for the L1/L2 slot with XEUS/IXO and the mission to the giant planets (see Chapter 5 for more details). LISA is the sole mature low frequency gravitational-wave observatory. Ground-based detectors are sensitive in the high frequency range and will therefore address completely different sources (typically stellar mass objects). The Panel notes the enormous discovery potential that lies in the advanced LIGO and Virgo detectors. This potential, when realised, will clearly raise the priority of the third generation Einstein Telescope.

Technology Readiness. LISA is preceded by LISA Pathfinder, already in implementation for a launch in 2010/2011. LISA Pathfinder is a significant step towards demonstrating the feasibility of geodesic motion at the level required by LISA. It will space-qualify a substantial fraction of LISA technologies, in particular all the hardware needed for local measurement (inertial sensors, microthrusters, picometre test-mass tracking with interferometers, gravitational balancing, thermoelastic distortion control, optical bench manufacturing, etc.). The LISA laser has direct flight heritage from that successfully flown on Terrasat. Outstanding items like phase meters or telescopes are being developed with ESA, NASA and European national funds.

Industrial Relevance. LISA is based on highly innovative technologies, most of them never flown before (picometre tracking of distant bodies, inertial platforms, space interferometry, drag-free navigation, etc.). It is playing and is expected to continue to play an enabling role for the development of these space technologies, with potential spin-offs into terrestrial high precision measurement devices.

Timeline and Cost. LISA is in the running for the ESA Cosmic Vision L1 launch slot in 2018 with the decision points described above. The flight of LISA Pathfinder in 2010/2011, which has to be regarded as an integral part of the LISA programme, is another key milestone. Regarding costs, the NASA and ESA envelopes are roughly $800M and €650M (L-class mission cost cap), respectively, plus €247M for LISA Pathfinder. The last costing exercise done by the project was more or less in the same ballpark, though NASA's accounting is not directly comparable with ESA's. A refined cost assessment is in progress as part of the ongoing formulation. An essential element of the cost is the continuity of the European effort between LISA Pathfinder and LISA with a substantial transfer of teams and technologies from one phase to the following.

Priorities. *Both LISA and XEUS/IXO are ranked by Panel A at the highest priority among all projects discussed. Ideally they should fly in close conjunction to each other in order to exploit the important synergies between the two projects. The implementation sequence will mainly be determined by technological readiness and the international collaboration context.*

3.2.4 Ongoing Space Missions

3.2.4.1 *XMM-Newton*

The XMM-Newton Observatory is one of the cornerstone missions of ESA's Horizon 2000 programme with an emphasis on high-throughput astrophysical X-ray spectroscopy and imaging. Since its launch in December 1999, XMM-Newton has, along with NASA's Chandra Observatory, provided a key international resource for studying the most exotic astrophysical objects currently known, including supermassive black holes at the centres of galaxies, the hot gas that fills the space between the galaxies in clusters, active stars with hot coronae, the aurorae of planets, binary systems powered by accretion onto a neutron star or black hole, and the shock-heated gaseous remnants of supernova explosions. The XMM-Newton catalogue encompasses more than 200 000 sources, the largest number so far in high energy astrophysics. The XMM-Newton Observatory is operated by ESA, with the support of the four nationally funded teams, to enable the community to take advantage of its unique scientific capabilities. Although XMM-Newton has been in orbit for almost nine years, it continues to provide superb data and its observing time remains very heavily oversubscribed. The 2007 oversubscription factor, for example, was 7.8. The number of applicants, the number of registered archive browsers and the number of users downloading the data processing software, consistently indicate that between 1550 and 2000 astronomers routinely use XMM-Newton data. This is approximately 20% of all astronomers worldwide. In 2007 alone, data from XMM-Newton resulted in 323 refereed articles. A 2007 analysis by Trimble and Ceja[15] shows that, with 31.4 citations per article, XMM-Newton has the highest impact ratio of all space observatories. ESA funding of XMM-Newton operations, in conjunction with those of INTEGRAL, seems secure until 31 December 2012, albeit at a significantly reduced level of resources. Beyond that date, however, it will have to compete with other ESA missions. This is despite the fact that XMM-Newton will be the only European-led general purpose X-ray observatory in orbit at the time and, barring unforeseen circumstances, technically capable of delivering world-class science. In particular, in its extended mission phase XMM-Newton will be able to carry out a series of large programmes aimed at either high sensitivity (through long integrations) or more comprehensive coverage of specific source samples or identified sky areas. Such programmes will provide significant input in the near-term (up to 2015) to the Science Vision goals A.5, A.6, B.3 and C.3.

3.2.4.2 *INTEGRAL*

After six years of operations, INTEGRAL is providing the international high energy community with a powerful tool to map the high energy emission from hundreds of sources both in the Galaxy and in the distant Universe. Although the first years in orbit were devoted mainly to the study of our Galaxy, the percentage of observing time on extragalactic targets is increasing, leading to the discovery of numerous distant AGN (up to a redshift of 3.7). With about 100 refereed papers per year, INTEGRAL is an extraordinarily productive mission in the challenging domain of hard X-rays / soft gamma rays. The INTEGRAL catalogue encompasses several hundred sources and the number is steadily growing. Significant galactic diffuse emission is detected above 50 keV, once the point sources have been subtracted. Moreover, thanks to the long integration time now available, the spectrometer is starting to detect the ^{60}Fe line besides the classical ^{26}Al and e+e- lines from the inner regions of the Galaxy. More lines, revealing spots of recent nucleosynthesis, could be within reach in the coming years. The end of the core programme is now opening up the totality of the available observing time, which is always significantly oversubscribed by a large and diverse community of users. With no comparable (or better) mission foreseen in the near future, INTEGRAL data will remain an important asset for the whole high energy community and the Panel members applaud ESA's decision to grant a mission extension up to 2012. If the financial boundary conditions allow, it would definitely be worthwhile to continue the mission even beyond 2012. INTEGRAL observations are considered very important in the near term for the Science Vision goals A.5, A.6, C.3, and complementary for B.7.

The combined cost of one year of XMM-Newton and INTEGRAL operations is €19.4M (2007 EC).

3.2.4.3 *Other Facility Continuations and Technology Preparation*

Panel A is fully aware that important and extremely productive missions such as Swift, as well as Fermi (possibly also AGILE and SVOM) will remain vital and are expected to deliver excellent science well into the next decade. However, individually the amount of European unsecured funds for their operation appears to be below our funding threshold (see Section 2.3). Similarly, the ongoing ground-based facilities will require continuing support for operating costs as well as scientific exploitation, such that the overall costs for facility extensions are not negligible.

3.2.5 Perceived Gaps and Technology Development for Future Facilities

3.2.5.1 *National and Bilateral Missions*

Examples from the past, e.g., GINGA, the Roentgen Satellite (ROSAT), the Advanced Satellite for Cosmology and Astrophysics (ASCA), BeppoSAX, Swift, etc., show that medium-size national and bilateral missions are a crucial and fruitful ingredient to keep the community alive and develop the knowhow and technology in the relevant laboratories. They are essential to bridge the gap between the large flagship missions in the individual wavebands, which are getting more and more rare, with larger time intervals in between. Specialised smaller niche missions or instruments, addressing a focused scientific aim have often been very successful.

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[15] Trimble, V. & Ceja, J. A. 2007, *Productivity and impact of astronomical facilities: A statistical study of publications and citations*, Astronomische Nachrichten, 328, 9, 983–994

While our prioritisation of the facilities in this Roadmap naturally focused on the large, observatory-type, multinational facilities, we consider the opportunities afforded by smaller projects as a crucial part of a balanced programme. Several of the excellent concepts that did not enter into our final prioritised list (see Appendix IV.A), as well as new ideas, may well evolve into such opportunities.

3.2.5.2 *Specific Gaps Identified from the Science Vision*

Our Panel has identified some capabilities that are strongly called for in the Science Vision, but are not yet programmatically ready and/or do not yet provide large improvements over existing experiments at affordable cost. Further development of existing and new technologies should be encouraged in these areas in order to fully address the challenges set out in the Science Vision.

One such area is imaging and spectroscopy in the very difficult 0.1–10 MeV photon energy range. The spectroscopy of nuclear and annihilation lines and the correct identification of the sources of these lines requires considerable progress in sensitivity and resolution in this energy range, in order to make progress in the understanding of the outputs of black hole sources and of the chemical evolution of the Universe through enrichment from various stellar processes.

Another area is all-sky monitoring (ASM) of instantaneously large solid angles for transient and variable sources, in all X- and gamma-ray energies. Some missions are still ongoing or planned for the next decade, but there is a clear threat of lack of continuity in this area in the long term and a need for new concepts to enable the next generation of ASMs. Since many of the high energy sources we need to study are transient or highly variable, the Science Vision calls for continued capability in sensitive all-sky monitoring (e.g., for GRBs, outbursts of black hole sources, XRBs, etc).

The follow-up of large numbers of GRBs to find and study in detail the highest redshift events as cosmological probes is also an important goal in the Science Vision, for which future projects need to be further developed.

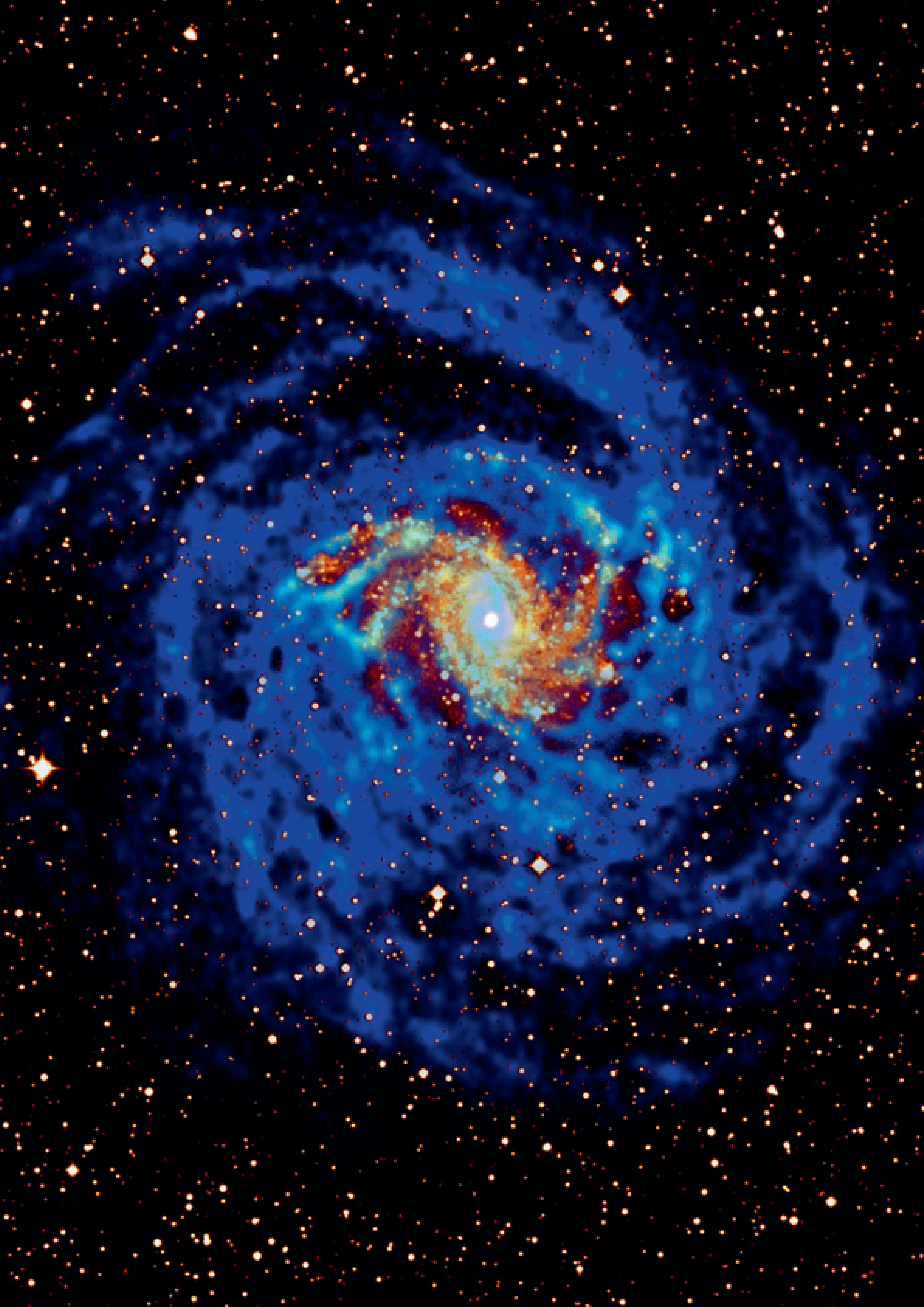
3.2.5.2 *Technology Development*

Technological development is at the heart of any of the future capabilities. Flagship facilities like XEUS/IXO, LISA, the CTA, KM3NET, also owe their high priority to a long history of development. Smaller-scale projects as well as future concepts (e.g., the ET, MeV observatories, massive electronics and computing, etc.) require vigorous technology development in the next decade that Europe must support in order to maintain its success in scientific and technological leadership.

3.3 Conclusions

The impressive suite of space- and ground-based instruments currently available to the astronomical community has fostered dramatic improvements in our understanding of high energy phenomena occurring in all temporal and spatial scales throughout the Universe. Small-, medium- and large-scale instruments have delivered (and continue to deliver) precious data, whose potential is multiplied by the ever-increasing use of astronomical archives. The interplay between results gathered with different methods at different wavelengths and between theory and observations has proven to be an essential tool for all of astronomical research. Thus, in defining our priorities, we have maximised the interplay between ground and space instruments, considering their timing, their maturity (from the instrumental point of view) and their promise for astrophysical discovery.

The purpose of our recommendations is twofold: on the one hand we have selected instruments we deemed able to provide a level of astronomical resources up to the (very demanding) standards we have foreseen for the future. On the other hand, we have strongly endorsed the opening of new astronomical windows, such as neutrino and gravitational-wave astronomy. Balancing between known technologies and promising developments, our programme offers a view that we hope will be shared by the astronomical community.



Chapter 4 Ultraviolet, Optical, Infrared and Radio/mm Astronomy

(Panel B)

4.1 Introduction

Panel B was charged with looking at projects in the ultraviolet, optical, infrared, submillimetre, millimetre, decimetre and metre wavelength range, both on the ground and in space. These wavelength bands carry a very high potential for answering many of the Science Vision questions over the entire range from cosmology to Solar System studies.

As far as current opportunities and future perspectives for the European astronomical community are concerned, the situation varies across the different wavelength regimes. Radiation at optical/near-infrared and radio wavelengths can be observed from ground-based observatories. In the optical/near-infrared domain, Europe has taken the worldwide lead with the four units of the Very Large Telescope and the Very Large Telescope Interferometer (VLTI), and the associated suite of focal plane instruments. In addition, a number of European groups/countries are involved in the Large Binocular Telescope (LBT), Gemini, the GTC and the Southern African Large Telescope (SALT), demonstrating the potential of multinational initiatives. These achievements are the basis for proposing a European Extremely Large Telescope (the E-ELT) as the logical next step.

In the (sub)millimetre range, Europe has constructed and operates world-class ground-based telescopes in high altitude observatories, and, on this basis, is sharing — with North America (the US and Canada) — the lead of the ALMA project, which also has an important contribution from East Asia. A similar situation prevails in the longer wavelength (radio) domain where Europe maintains a number of major facilities, many involved in Very Long Baseline Interferometry (VLBI) experiments coordinated by the European VLBI Network (EVN)/Joint Institute for VLBI in Europe (JIVE), and looks forward to a leading participation in the world-class future project, the Square Kilometre Array.

Thanks to ESA's Horizon 2000 and 2000 Plus programmes, Europe is a key player in space science, but not in all of the wavelength domains. In the ultraviolet, there is only limited access through ESA's minority participation in the Hubble Space Telescope, and there is presently no mission with major European participation that would give access to the far-ultraviolet and the extreme-ultraviolet regions. The HST follow-up mission, the James Webb Space Telescope (JWST), to which Europe contributes in a significant manner, will indeed shift the emphasis to the near- and mid-infrared wavelengths. JWST will be launched in the first half of the next decade. At optical wavelengths, Europe has established a leading position in astrometry through ESA's Hipparcos mission, which will be followed up in 2012 by the much more powerful Gaia mission. For the first time, this mission will chart out a six-dimensional map of our galaxy, the Milky Way. In the infrared domain, European astronomers are looking forward to the launch of the ESA far-infrared missions Planck and Herschel in 2009, which follow ESA's very successful Infrared Space Observatory (ISO).

Panel B considered a total of 43 projects and looked in detail at 38 of them, based upon the information provided by the Principal Investigators (or other project representatives) in response to a questionnaire that was sent out (cf. Appendix IV). About one third of these projects concern upgrades and/or enhancements of facilities that exist or are under construction. Others concern projects that are actively being prepared, mostly with international partners, to bring them forward for a final decision within the next 3–4 years. The remainder are projects that have been recently proposed to ESA in response to the first call for proposals for the implementation of the Cosmic Vision programme. Their state of definition and preparation varies. The list of all projects considered by Panel B is shown in Appendix IV.

First answers to the questions posed in the Science Vision (SV) document will come from the existing facilities and those currently under construction. They will play a very important role, especially if they can be completed and/or upgraded in a timely manner. This concerns in particular the instrumentation of the 8–10 m-class telescopes to which European astronomers have access (see Section 4.3.2), the ALMA and LOFAR (Low Frequency Array) projects, ESA's space missions Herschel and Planck, and also Gaia (see Section 4.2.3.1) and JWST.

ALMA is an outstanding global project in (sub)millimetre astronomy with totally unprecedented sensitivity and angular resolution due to the large number of 12 m-diameter telescopes that will work together as an interferometer, the long baselines that can be realised, and

Image Credit: Tom Oosterloo & Rense Boomsma

the excellent quality of the high altitude site in northern Chile. ALMA is built jointly by Europe, the US, Canada and Japan, with a further contribution from Taiwan. The first telescopes for ALMA are just being delivered to Chile, where they will be assembled and tested, while the necessary receivers and backends are at the same time being constructed in Europe, in the US, Canada and in Japan. As soon as a significant number of the 50 telescopes that are currently funded in Europe through ESO and in North America by the National Radio Astronomy Observatory (NRAO) become operational, together with the telescopes provided by Japan, ALMA will start to address many of the scientific topics listed in the SV document. When fully operational, ALMA will be very important for SV questions B.2, B.6, C.1, C.2 and C.3, and it will contribute to A.6, B.1, B.4, C.5, D.1, D.5 and D.7 (see Appendix I for full definitions). Panel B notes that there is a potential for significant performance upgrades in the future, e.g., by adding more antennas (during the initial European-American discussions 64 antennas had been foreseen), by adding more receiver bands (in the initial discussions ten bands had been foreseen), and/or by installing improved (next generation) receivers and backends. Although Panel B noted these potential upgrades, it was felt premature to include them in the ranking process at this stage. These should be revisited in a few years time when the current Roadmap is updated and with the benefit of significant operational experience with ALMA. In the meantime, Europe must focus its scientific and technical capacities in this field on the commissioning of the instrument, the preparation of its scientific exploitation, and continuing R&D work in the laboratories to prepare for future upgrades. These tasks will require more financial support from national funding agencies and at the European level than has so far been secured.

The LOFAR project is currently under construction and will be operational in 2010. It comprises about 40 stations in the Netherlands and the equivalent of about 16 stations, mostly in the planning phase, distributed in Germany, France, Poland, Sweden, the UK and Ukraine. Construction funds for this so-called “baseline LOFAR” have either already been granted, or are currently being secured. LOFAR will address a large number of SV themes — it is very important for questions A.6, A.7, B.1, B.2, D.2, D.3, D.5 and complementary for B.3, B.6, C.3, C.5, D.1 — and it is a major preparatory step in Europe towards Europe’s participation in the international SKA project. Panel B took note of the plans that exist to improve the u,v coverage of this low frequency array for highest sensitivity, highest dynamic range imaging by building 40 more stations within and outside of the Netherlands after 2010, thereby turning LOFAR into Extended LOFAR (E-LOFAR). The enhanced capabilities of E-LOFAR would allow even more SV questions (A.1) to be addressed, and others more efficiently (A.6, A.7, B.2, B.3 and B.6), thereby further increasing LOFAR’s already high scientific value. The extension was therefore considered as very interesting. Given the fact that the baseline LOFAR project is still in its early construction phase, and that major scientific returns are still to come, as with possible ALMA extensions, Panel B considered it too early to include E-LOFAR in the Roadmap now, but expects that this project will be reconsidered when the current Roadmap is updated in a few years’ time.

The Herschel Space Observatory and the Planck Surveyor should be launched by ESA at the beginning of 2009. Herschel will provide the first direct look into protostars and the first insight into the properties of primeval galaxies, as well as clues to understanding the physical mechanism responsible for far-infrared emission in nearby galaxies. Planck Surveyor will provide an order of magnitude better map of the cosmic microwave background, and the first accurate maps of its polarisation. Both missions are flagships for the European astronomical community in the next five years.

The JWST is the natural successor to both the HST and Spitzer, providing extremely high imaging and low resolution spectroscopic sensitivity at near- to mid-infrared (mid-IR) wavelengths. Its four main science themes are: First Light and Reionisation; The Birth of Galaxies; The Birth of Stars and Protoplanetary Systems; and Planetary Systems and The Origin of Life. In addition, the JWST instrument suite will have wide applicability across a broad range of other scientific topics. Europe is making substantial contributions by leading two of the four science instruments, providing the launch vehicle, and participating in operations support at the Space Telescope Science Institute (STScI) and in Europe. Launch is scheduled for 2013 and continued European participation in the project is seen as a very important near-term priority.

In terms of the present status of these three projects, no more major investment is required. But the European astronomers who have access to guaranteed or open time key projects on the Herschel Observatory and the JWST or to the Principal Investigator time of Planck Surveyor need strong support to ensure a scientific return in Europe commensurate with the major investment during the construction and operation phase of these missions. As emphasised elsewhere in this document (Chapter 7), financial support for the scientific exploitation of space missions is very different in the US and in Europe. In the US, it is part of the NASA budget. In Europe, there is no equivalent ESA mandate and such funding comes from an *ad hoc* mixture of national support and, to a lesser extent, EC-sponsored scientific networks. Enlarged and better-structured European support for scientific exploitation of large infrastructures in general is urgently needed and would significantly enhance their scientific productivity. Herschel and Planck Surveyor should be the first space missions that will benefit from such support, with Gaia and JWST to follow suit.

The HST is another existing facility that can make a contribution towards addressing the Science Vision goals. Being one of the most productive astronomical facilities ever built, ESA should continue to support its operation for as long as NASA will extend its support.

Amongst the future projects, two are outstanding because of their scientific potential and scope in connection with the SV goals; the E-ELT and the SKA, and they are considered in detail in the next Section. Similarly ambitious space projects such as Darwin and FIRI have also been considered by the Panel. Technical development activities are underway for both. If the enabling technologies mature quickly enough, a launch at the end of the period covered by this report may be possible for one of these missions.

Amongst the small and medium-size projects (as defined in Section 2.3) there seem to be many interesting opportunities, but it is clear that only a limited number of them can be pursued. With their relevance to addressing the SV goals as the key criterion, some of them are highly recommended by Panel B for rapid execution as explained below.

4.2 High Priority New Projects

4.2.1 Ground-Based, Near-Term (–2015)

4.2.1.1 *Development of Wide-Field, Multiplexed Spectrographs for Large Optical Telescopes*

There are compelling and fundamentally important scientific cases for the development of wide-field, highly multiplexed spectrographs, and consequently such a project was given very high scientific priority. It should enable massive spectroscopic surveys of a million or more objects at a speed and on timescales compatible with the next generation of wide-field imagers, e.g., the Large Synoptic Survey Telescope (LSST).

Scientific Discovery Potential. The primary science drivers are the determination of the equation of state of dark energy, the study of stellar populations over a large fraction of the history of the Universe, and the study of the structure and formation of the Galaxy and Local Group by determining in a quantitative manner the kinematical and chemical signatures of the different stellar components.

A direct measurement of baryonic acoustic oscillations requires accurate spectroscopic redshifts for millions of galaxies over a significant fraction of the whole sky, and therefore a very wide-field, multiplexed spectrograph is needed to achieve this objective in an efficient manner. Indeed, a very wide-field optical spectrograph is a mandatory complement to the imaging surveys. The same multiplexing requirements — but at different spectral resolution — arise for stellar population studies in our own Galaxy and the Local Group, complementing the Gaia programmes. For galaxy evolution studies, one must measure radial velocity and stellar parameters (T_{eff}, detailed abundances, etc.) of 10^5–10^6 stars fainter than $V = 16.5$ that cannot be observed by the Gaia on-board spectrograph.

In summary, very wide-field spectrographs will be very important in addressing SV questions A.1, A.2, B.3, B.4, C.2 and C.3, and complementary for SV questions A.6, B.6, B.7 and C.1.

User Base. Given the fact that such an instrument has the potential to tackle many different scientific questions, the user base will be very large and the European community should have access to such a facility.

International Context. Currently, ground-based facilities focus on imaging surveys, i.e. MEGACAM at the Canada France Hawaii Telescope (CFHT), the UKIRT Infrared Deep Sky Survey (UKIDSS), the VST and VISTA at ESO, the Panoramic Survey Telescope And Rapid Response System (Pan-Starrs) and in the future, the LSST in the US. These will provide insights into dark energy through weak lensing measurements, supernova observations and by revealing the distant galaxy distribution. The same is true for the space projects, Gaia and EUCLID (see Section 4.2.4.1) in Europe, or the Joint Dark Energy Mission (JDEM) in the US, which will have spectroscopic capabilities either limited to bright objects, or optimised for complementary (low resolution, near-infrared) wavelengths.

Very wide-field optical spectrographs could go to several of the existing large (with apertures greater than or equal to 4 m) optical telescopes, albeit with some significant rebuilding.

Technology Readiness. Such a wide-field instrument was proposed during the workshop on Science with the VLT in the E-ELT era, which took place at ESO in October 2007. A project along these lines, WFMOS (Wide-Field Multi-Object Spectrograph), is currently undergoing a conceptual design study by the Gemini Observatory. A preliminary concept, the Smart Fast Camera has also been proposed for the VLT as an alternative solution. However, none of these projects was judged mature enough to be included specifically in the Roadmap. A prime focus is the best location for such a spectrograph, but with the exception of Subaru and the LBT, 8 m-class telescopes do not have a useable prime focus without significant rebuilding. At the VLT, the implementation of such a wide-field instrument would require a significant redesign and modification of the telescopes, in particular the top-end; although an essentially dedicated facility at one Nasmyth focus could be competitive in development cost and schedule.

Industrial Relevance. Several concepts for this facility require industrial scale replication of precision optical, opto-mechanical, electronic, and/or photonic modules, thereby pushing the limits of current industrial practice.

Timeline and Costs. The projects considered here are at the conceptual design stage, but preliminary design phases might be started in the near future. The total project costs are estimated at about €40M—€50M.

Recommendation. *Considering the enormous scientific value of wide-field spectrographic surveys and their under-representation compared to imaging initiatives, we recommend setting up a working group, under the auspices of ASTRONET, with OPTICON, with the task of (i) developing the top-level requirements of the surveys, (ii) identifying implementation options on a European scale, (iii) establishing the merits of these options with a trade-off analysis and proposing an implementation plan to provide a facility for the whole European community in the 2015–2020 time frame.*

4.2.2 Ground-Based, Medium-Term (2016–2020)

4.2.2.1 *European Extremely Large Telescope (E-ELT)*

This is one of the two outstanding medium-term projects that Panel B has considered (the other is the SKA, 4.2.2.2). The E-ELT (Figure 8) project envisions a 42 m-diameter filled-aperture phased telescope with an internal adaptive optics system designed to provide near diffraction-limited angular resolution in a 5’ (scientific)–8’ (technical) diameter field of view over 80% of the whole sky (through the use of multiple natural and laser guide stars). The minimum wavelength domain is 0.4–21 μm. This instrument-friendly facility should accommodate at least six large focal stations with fast switchover in order to optimise its scientific output.

Scientific Discovery Potential. The E-ELT is a unique tool to address the following questions raised in the Science Vision: A.2, A.6, B.1, B.6, C.1, C.2, C.3, C.4, C.5, C.6, D.6, D.7. In addition it will contribute to studies of questions A.1, B.2, B.3, B.4 and B.7. The most fundamental issues are the following:

Do we understand the extremes of the Universe? One of the most exciting goals of an E-ELT is the possibility of making a direct measurement of the acceleration of the Universe’s expansion. Such a measurement would have a major impact on our understanding of the Universe. By probing the most distant objects the E-ELT will provide clues to understanding the formation of the first shaped objects: primordial stars, primordial galaxies and black holes and their relationships. Studies of extreme objects like black holes will benefit from the collecting power of an E-ELT to gain more insight into time-dependent phenomena linked with the accretion-ejection mechanism around compact objects.

How do galaxies form and evolve? This is one of the two areas where the expected impact of the E-ELT is of paramount importance. The E-ELT is designed to make detailed studies (imaging and spectroscopy) of the first galaxies and to follow their evolution through cosmic time. Today, the preferred scenario of hierarchical merging is facing a major difficulty with the existence of large galaxies early in the history of the Universe. Observations of these early galaxies with the E-ELT will give clues that will help understand how these objects form and evolve. In addition, the E-ELT will be a unique tool for making an inventory of the heavy element content in the Universe over time, and to understand star formation history in galaxies.

What is the origin and evolution of stars and planets? The discovery and the characterisation of exoplanets is the second major topic for the E-ELT. With a 42 m diffraction-limited telescope, it will become possible to image exoplanets in the habitable zone. Apart from its scientific interest, this would represent a major breakthrough for humankind. In addition, the E-ELT will be used to characterise the atmospheres of most of the exoplanets known so far and to study the details of protoplanetary discs. These results will be invaluable for our understanding of the origin and evolution of planetary systems, and their links with the parent stars.

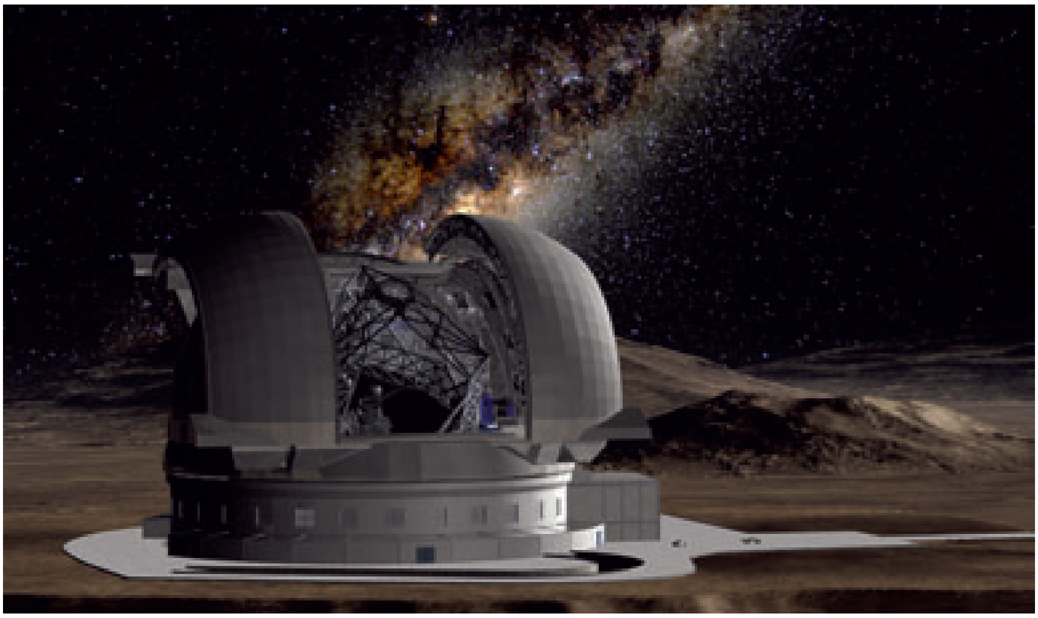


Figure 8: Artist's impression using a rendering of an engineering model of the E-ELT during observations

How do we fit in? For studies of the Solar System, and in particular of trans-Neptunian objects and comets, the E-ELT can be used to make very accurate measurements of the main physical and chemical properties of these objects and to get direct information about the formation of the Solar System.

The main scientific drivers for the E-ELT design are the detection and characterisation of exoplanets, and the detailed study of very distant galaxies. For these domains, an ELT is an essential tool to take advantage of the expected outcome from the JWST, which should be launched around 2013.

User Base. The E-ELT, with its foreseen suite of instruments, will undoubtedly attract a very large fraction of the ESO user community.

International Context. ESO, with the approval of the ESO Council representing the fourteen member states, has set the E-ELT as its first priority after the completion of ALMA, with the aim of maintaining its lead in optical/near-infrared astronomy.

Similar projects are under development in the US. The two main projects are the Thirty-Meter Telescope (TMT, from Universities in California and Canada), and the Giant Magellan Telescope (GMT, from eight US universities and Australia). The construction costs for these two projects will be financed largely by private funds[16]. Both projects have schedules similar to or in advance of the E-ELT. The decision for the construction of the European ELT cannot be deferred later than 2010 in view of this competition, and of the JWST launch date. Overall, Europe aims to build the E-ELT on a timescale competitive with the US projects.

Technology Readiness. The E-ELT is currently going through a Phase B study that will end with a Final Design Review of the whole facility in 2009/2010. This Phase B study includes contracts with industry to design and manufacture prototypes of key elements like the primary mirror segments, the adaptive fourth mirror or the mechanical structure. It also includes concept studies for eight instruments.

Industrial Relevance. The project represents a major challenge to industries working on structural mechanics, electromechanics, very high precision optical and metrology systems (fabrication of the segmented primary and the 6.5 m secondary mirrors), real-time control etc.

Timeline and Cost. The decision to go ahead with the construction is expected to take place in 2010. The construction period is estimated to be 5–6 years, leading to first light around 2016. The design phase (€57M) is fully funded within the ESO budget. The construction cost is estimated to be €960M (including first generation instruments), with a peak of expenditure between 2012 and 2016. About €350M for the construction phase are available within the existing budget integrated over a period of ten years. One of the goals of the preparatory phase is to study the possibilities for additional funding. Additional activities on the organisation of the project and the mission design are supported through a €5M FP7 grant.

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[16] The California Institute of Technology and the University of California received a $200M commitment over nine years in December 2007 from the Gordon and Betty Moore Foundation toward the further development and construction of the Thirty-Meter Telescope.

4.2.2.2 *The Square Kilometre Array (SKA)*

The SKA, like the E-ELT, is seen as an outstanding medium-term project by virtue of its scientific potential and scope. The SKA project (Figure 9) envisages an aperture synthesis radio telescope achieving a sensitivity 50 times that of upgraded existing radio arrays and survey speeds 10 000 times faster. The frequency coverage will extend from ~ 70 MHz–25 GHz and will be attained in three phases: Phase 1 will be the initial deployment (15–20%) of the array at mid-band frequencies (100 MHz–10 GHz); Phase 2 will be the full collecting area at low to mid-band frequencies (~ 70 MHz–10 GHz); Phase 3 entails the implementation of higher frequencies up to ~ 25 GHz and is beyond the timeline of the current Roadmap exercise (see below). This broad coverage includes some frequencies that are not specifically protected for radio astronomy, but are actively used for commercial and other applications. The interference from these terrestrial sources with those from astronomical objects represents a special challenge and requires the SKA to be located in a remote area of the world; short-listed sites are in western Australia and southern Africa. There will be a central concentration of antennas, with remote groups of antennas located at distances up to at least 3000 km from the core and connected to the central data processor via a wide-area fibre network. Constituent technologies include phased arrays and dish reflectors used in various combinations across the operating frequency band.

Scientific Discovery Potential. The SKA has the natural advantage of a synthesis radio telescope in that it will be able to deliver science in a phased manner. SKA Phase 1 will conservatively comprise a few hundred small (~ 15 m diameter) dishes, each with a wide-band (0.5–10 GHz) single-pixel feed, yielding more than ten times the sensitivity of the Extended VLA (EVLA), alongside a 100–500 MHz sparse aperture array, which will be more than ten times as sensitive as LOFAR. If, as is hoped, phased-array feed and dense aperture technologies have matured, their inclusion in Phase 1 will transform its mapping speed.

SKA Phase 2 will eventually deliver the additional order of magnitude increase in sensitivity and significantly greater surveying speed to obtain the full, transformational science capability that maps very well onto the principal Science Vision scientific goals. As of now, the three principal topics are:

Do we understand the extremes of the Universe? The SKA will have a unique capability to map hydrogen emission in a wide variety of environments at a huge range of redshifts, and free from dust obscuration. With its extremely large field of view, the SKA will allow effective surveying and identification of galaxies over a large cosmic volume, and provide the three-dimensional data required for studies of baryonic acoustic oscillations as a function of redshift. This information can be used to constrain the equation of state of dark energy. The SKA will make direct imaging of the high redshift intergalactic medium (IGM) possible at the epoch of reionisation as the IGM is progressively ionised by the first stars and galaxies. The SKA will also be a unique tool for testing the laws of physics in extreme conditions, in particular in

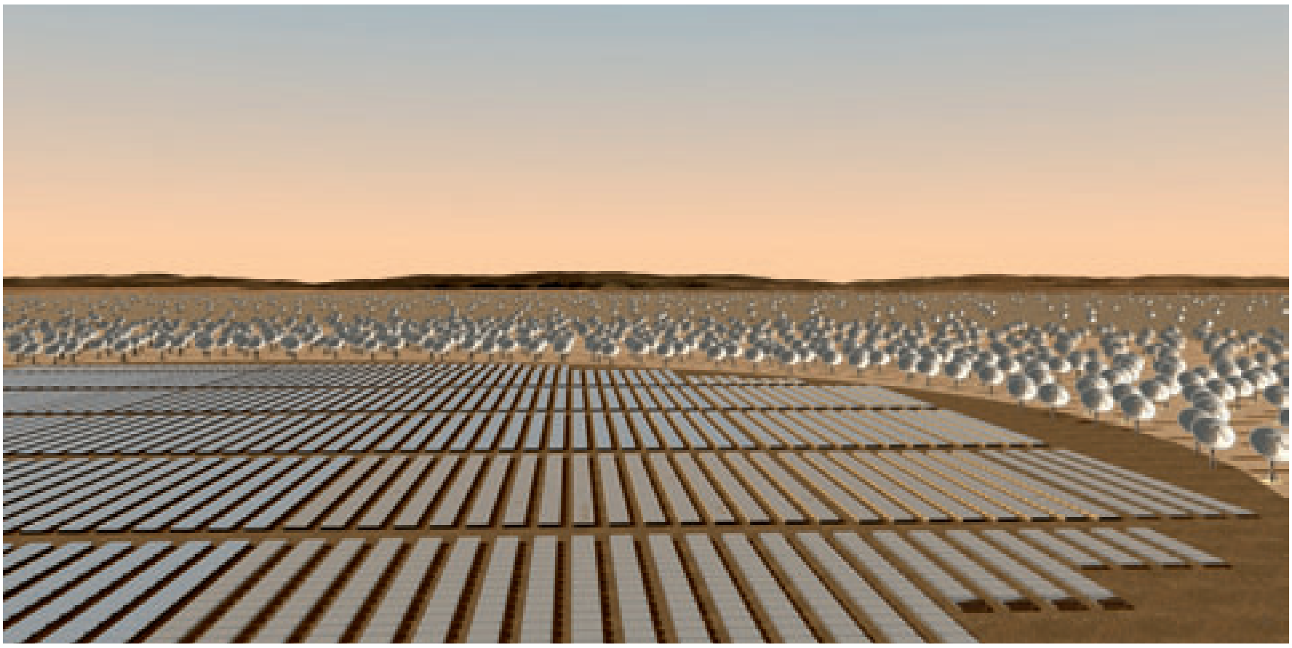


Image Credit: Courtesy SKA Project Office

Figure 9: Artist's impression of the small dishes and focal plane arrays planned for the SKA.

the strong gravity fields of pulsars and black holes, using the SKA as a timing array for cosmic gravitational-wave emission, or for timing pulsars orbiting black holes.

How do galaxies form and evolve? One of the major unknowns about the physical processes that govern galaxy and star formation is the role of magnetic fields. The SKA will have the unique ability to reveal the role such fields may play in the evolving Universe, through all-sky observations of radio polarisation and Faraday rotation. In addition, it will be able to watch galaxies form and evolve across cosmic time through observations of hydrogen emission, its enormous radio continuum sensitivity and spatial resolution.

What is the origin and evolution of planets? The frequency range and very high angular resolution of the SKA will allow it to observe discs where planetary formation is ongoing, to observe potential bio-molecules and also to search, commensally, for signals of extraterrestrial origin. The latter point directly addresses the Science Vision key question: *How do we fit in?*

The science achievable with the conservative SKA Phase 1 addresses a substantial part of these science goals including: a deep survey of HI galaxies to z ~ 2, yielding the first measurements of cosmic evolution of HI; an all-hemisphere HI survey of 10^7 galaxies to z ~ 0.5, placing initial SKA constraints on dark energy and the mass-scale of neutrinos; a significant increase in the number of known pulsars and an order of magnitude increase in pulsar timing precision that will yield fundamental tests of general relativity and, it is hoped, a robust detection of the gravitational-wave background due to supermassive black holes; all-hemisphere Faraday rotation surveys, enabling the first measurement of the cosmic evolution of the magnetic field in galaxy clusters to z ~ 2; direct observation of giant Strömgren spheres around quasars at z ~ 7, establishing how supermassive black holes contribute to the reionisation of the Universe and new classes of transient sources.

In summary, the SKA Phase 1 will address the following high priority topics listed in the Science Vision document: A.1, A.2, A.4, B.2, B.6 and C.3; it will provide complementary information on A.7, B.3, D.1, D.3 and D.4. The extension to Phase 2 will address, with considerably greater capability, the following areas: A.1, A.2, A.4, A.6, B.1, B.2, B.6, C.1, C.3 and C.4; and will provide complementary information on: A.3, A.5, A.7, B.3, B.4, B.7, C.2, C.6, D.1, D.2, D.3 and D.4.

User Base. The SKA will serve not only the classical radio astronomy community, but also the wider astronomical community through pipeline-processed and ready-to-use archived data. ALMA will spearhead this new paradigm for the use of radio astronomical facilities.

International Context. The SKA is conceived as a global collaboration with Europe aiming to be in the lead position. Through the EC 7th Framework Programme (FP7), €5.5M funding has been allocated to conduct a Preparatory Study for the SKA (PrepSKA); this is being matched by ~ €20M of national funds. The PrepSKA consortium, a global partnership of eight funding agencies and twelve universities and astronomy organisations, is investigating the options for the SKA governance structure and legal framework, the procurement model and the funding model. In addition, PrepSKA is funding the SKA's Central Design Integration Team, whose task is to integrate all of the design knowledge gained through the global R&D effort to produce a detailed, costed design for Phase 1 of the SKA.

Technology Readiness. The SKA is in a preparatory development phase. Engineering R&D is being carried out via specifically funded design studies in Europe (SKADS and now PrepSKA), the US (National Science Foundation [NSF] Technology Development Program) and via Pathfinder telescopes under construction in the Netherlands and several other European countries (LOFAR), in the US, Australia (ASKAP), and South Africa (MeerKAT). Other key technologies for the SKA are being developed in Europe through the e-VLBI effort led by EVN/JIVE, the e-MERLIN project and the APERture Tile In Focus (APERTIF) project on the WSRT. The design knowledge generated worldwide will be integrated by the Central Design Integration Team funded by the EC 7th Framework Programme, PrepSKA.

Industrial Relevance. The SKA provides several significant challenges to industry, for example, the need for low-cost mass production of antennas, receivers and chips; the provision of green energy for the remote SKA stations; and the efficient transport of huge quantities of data over thousands of kilometres. Another challenge will be the development of appropriate hardware and software solutions for processing the data once it has arrived at the central processor and then in transmitting it to scientists around the globe.

Timescale and Cost. The governance structure and legal framework for the SKA should be established in 2011; the selection of the site is also scheduled to occur at that time. The plans for SKA construction take full advantage of the opportunity offered naturally by interferometers to allow a phased approach to funding, construction and science. It is anticipated that the construction of the SKA will take place in the three phases defined above. Preliminary, but detailed, cost estimates are that Phase 1 will cost ~ €300M and the full array (Phases 1 and 2) will require €1.5B. Phase 3 is beyond the timeline of the current Roadmap exercise; its costs have not yet been investigated. Operational costs of the array are expected to be ~ €100M /year. The European financial contribution to the construction and operational costs is expected to be in the range of 33–40% overall.

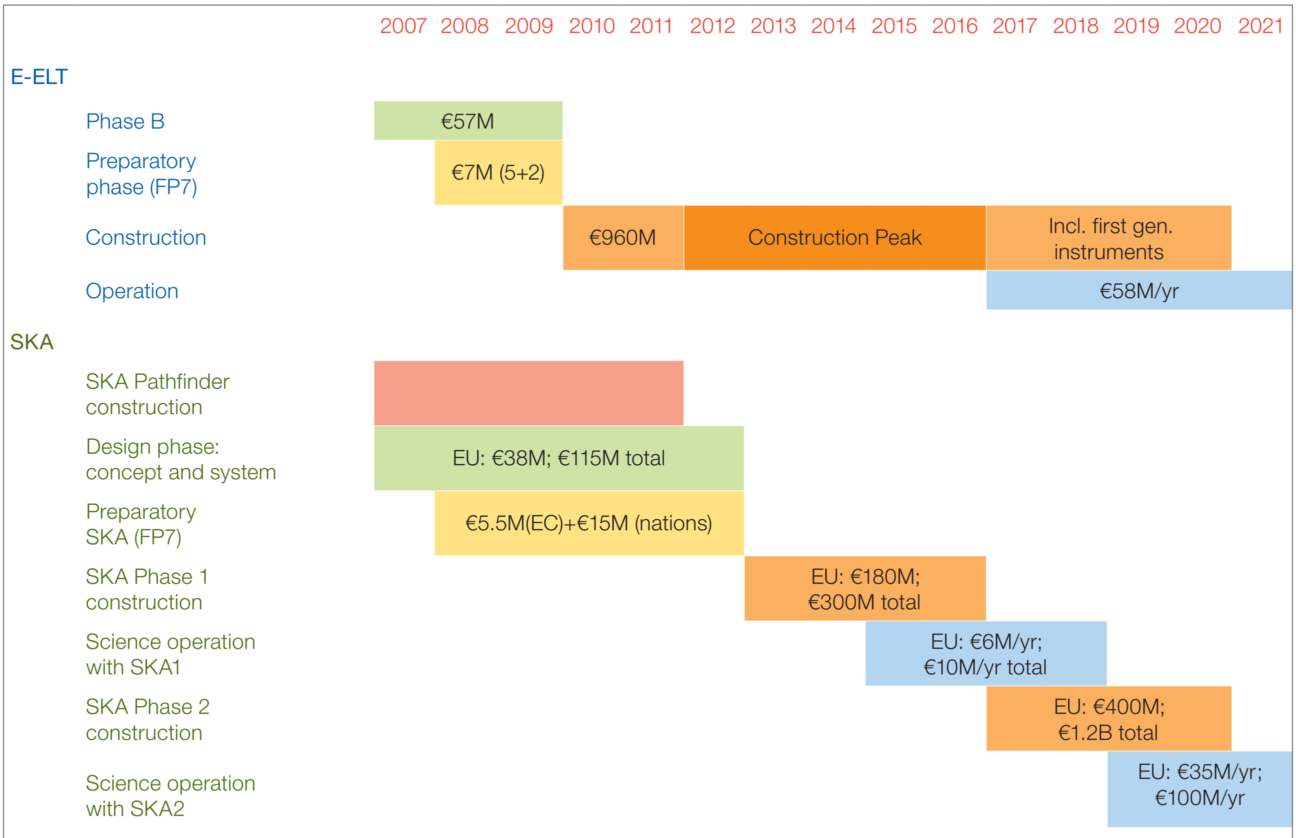
The planned timeline calls for the case for Phases 1 and 2 to be made to governments in early 2012. It is expected that Phase 1 will be funded initially; once the technical validity has been fully established and early science delivered, the funding for Phase 2 will be appropriated. The goal is to complete Phase 1 by 2016. Phase 2 will extend up to 2020.

4.2.2.3 *Timeline for the E-ELT and SKA Decision Process — Recommendation*

These two projects, the E-ELT and the SKA, are the two flagships for ground-based astronomy in the future. Both of them have exceptional capabilities, with performances orders of magnitude better than existing facilities. New windows will be opened up in prominent domains such as, for example, direct imaging of exoplanets with the E-ELT, or the measurement of the equation of state of dark energy with SKA. Both of them are therefore included in the European Roadmap at the highest priority level.

If the ongoing Phase B study is successfully completed according to schedule, all elements will be there to decide on the construction of an E-ELT in 2010. Postponing the decision much longer would weaken the project in view of the competition with the two other privately funded US projects, and the complementary research possible with the JWST. The ESO VLT is now the best observatory in the world in the optical domain. The E-ELT, if decided on in time, will ensure the continuation of this leadership. While possibilities for finding external partners should be actively pursued, a strong European leadership should be maintained, with ESO as the central organisation.

Being a global project, with a very strong involvement of southern hemisphere countries, the European contribution to the SKA will be proportionately less than for the E-ELT. As stated above, the present goal is for Europe to contribute at a level of between 33–40% overall. The governance and the management structure of the project and the full design of Phase 1 of the array will be finalised by 2011. A decision should be taken in 2012 for the first phase, and later, in 2015/2016, for Phases 2 and 3. The spending profile for the SKA envisages



All costs indicated are costs for Europe only. For the E-ELT we have assumed that Europe will fund the whole project, including the instruments. While for the SKA, we have assumed that Europe is supporting 60% of Phase 1 and 40% of Phase 2. We have assumed operation costs at 6% per year of the capital investment

Figure 10: Indicative timeline for the E-ELT and the SKA.

€300M being required from 2012–2016, with a peak in 2015; with Europe providing ~ 60%, this will ensure European leadership at a crucial stage of the SKA. Phase 2 funding of an additional €1.2B will then be required from 2016–2020, peaking in 2017/18, and with Europe providing ~ 25–30%. Phase 3 funding will follow after 2020.

It therefore appears possible to establish a phasing plan with significant spending on the E-ELT through ESO starting in 2010; SKA Phase 1 funding will then ramp up from 2012 and both telescopes should achieve early science around the middle of the decade. Then, at the end of the E-ELT construction peak in 2016, SKA Phase 2 will begin and the full array will take shape (see Figure 10).

The phased approach outlined above will, however, only be feasible if significant additional funds become available soon after 2010. This is a necessary condition for the timely construction of the E-ELT, and even more so when the construction phases of these two big projects overlap. In total, an additional amount of at least €600M seems to be required between 2012 and 2018 above the level of funds available on the basis of a projection of current funding levels. The exact amounts required, and the associated spending profiles, will be key results from the two ongoing design phase studies that include the development of viable funding schemes as a major task. We emphasise that this phased approach is required in order to keep the necessary momentum and expertise to achieve successful European participation and leadership for both projects.

4.2.3 Space-Based, Near-Term (–2015)

4.2.3.1 *Gaia Data Analysis and Processing*

Europe has taken the worldwide lead in astrometry with its very successful mission Hipparcos. Currently, a successor mission with greatly enhanced capabilities is being prepared for a launch in 2012: Gaia. In this section, we want to underline the need to sustain the very substantial data analysis and processing effort for this mission during the entire period until 2022.

Gaia is unusual not only for its many orders of magnitude improvement in performance compared to the current state of the art, but also for the mission structure. Community participation in the Gaia mission is almost entirely in software and data analysis, rather than the hardware instrumental provision typical of ESA missions. This mission structure is driven by the extreme stability specifications for the satellite, which require that the payload be a single integrated optical bench.

The basic satellite structure is a pair of telescopes with a shared focal plane that will deliver three complementary datasets. First, photometric data that allows a complete sky survey, with a precision measurement of each object position (two coordinates) at each observation. With time, as Gaia (and the Earth) orbit the Sun, its changing location allows each object's parallax (providing geometric distances), and the two time derivatives of the position (proper motion, plus higher order motions induced by planetary systems, binarity, etc) to be determined. The second dataset is, for every object, low dispersion spectro-photometry, allowing first order identification of the target's astrophysical nature. The third dataset comprises, for brighter objects, high dispersion spectroscopy, delivering radial velocities and fundamental astrophysical stellar parameters. These and other complementary data (e.g., on metallicities and abundances) for objects fainter than V = 16.5 need to be obtained from the ground with a dedicated very wide-field spectrograph on an 8 m-class telescope (see Section 4.2.1.1).

Scientific Discovery Potential. Gaia will chart a six-dimensional map of our galaxy, the Milky Way, in the process, revealing the structure, composition, and evolutionary history of the Galaxy. The mission will provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematical census of about one billion stars in our galaxy and throughout the Local Group. This amounts to about 1% of the galactic stellar population. Combined with astrophysical information for each star, provided by on-board multicolour photometry, these data will have the precision necessary to quantify the early formation, and subsequent dynamical, chemical and star formation evolution of the Milky Way. Additional scientific products include detection and orbital classification of tens of thousands of extrasolar planetary systems, a comprehensive survey of objects ranging from huge numbers of minor bodies in the Solar System, through galaxies in the nearby Universe, to some 500 000 distant quasars. It will also provide a number of stringent new tests of general relativity and cosmology. In terms of the SV questions, Gaia will be very important in addressing questions B.7, C.2, C.4 and C.5, and complementary for C.1.

User Base. Astrometry provides the fundamental calibrations that underpin quantitative analyses in every branch of astronomy. The direct Gaia data will be generated by the Data Analysis and Processing Consortium (DPAC), and will form a crucial dataset of stellar, Solar System, planetary system and galactic astrophysics for all future studies, as well as providing the distance scale for large-scale structure and cosmological research. Some 300 individuals in fifteen European countries are involved in the processing, calibration and reduction of the raw Gaia data, preparatory to its availability for scientific analysis by the whole community.

International Context. This is a unique project that follows up on ESA's very successful Hipparcos mission, albeit with greatly enhanced capabilities that no other mission can offer.

Technology Readiness. The Gaia mission and its associated software challenges are on schedule for satellite launch in 2012. Gaia will deliver 100 TB of data, and require some 10^{21} floating point operations to reduce and calibrate the data, preparatory for science analysis.

Timeline and Cost. The main mission costs (€582M at 2007 values) are covered in the ESA Science budget. The issue here is the required cost for the data reduction and analysis effort, which is an integral part of the mission, and required in order to produce the huge dataset that will be the basis for the research work of the user community. ESA has subcontracted a significant part of these data processing and analysis activities to an international consortium (DPAC). This is intended to be funded by national funding agencies that have signed a long-term multilateral agreement with ESA that runs for ten years after launch or until 31 December 2022, whichever comes first. The agreement specifies the deliverables without setting cost figures. The consortium has estimated that an effort of about 190 FTEs/year is needed to produce the deliverables. This translates into a cost of about €15M/year for each year until the Gaia catalogue is completed.

4.2.4 Space-Based, Medium-Term (2016–2020)

4.2.4.1 *EUCLID (formerly DUNE and SPACE)*

Dark energy studies are undoubtedly the major new challenge in modern astrophysics. The determination of the nature of dark energy and its evolution with time will require the combination of several observational approaches, associated with large efforts in theory and numerical simulation.

So far, most of the progress in this domain has been achieved through wide-field imaging: measurements of temperature fluctuation of the CMB, use of distant supernovae to obtain a direct measurement of distances, and measurements of dark matter structure by the weak lensing of foreground galaxies. The combination of these independent approaches has been essential in constraining the possible values of the cosmological parameters.

Several major new projects are now planned, both on the ground and in space. Among the most prominent US-led projects that we should note are the Large Synoptic Survey Telescope on the ground and the Joint Dark Energy Mission in space (although neither is fully approved and funded as yet). The LSST is an 8 m telescope with a very wide-field imaging camera in the extended visible (0.4–1 μm) spectral range. Several concepts have been proposed for JDEM, for a selection in 2009.

Amongst the new mission proposals submitted to ESA in response to the Cosmic Vision Announcement of Opportunity (AO), and realisable in the medium term, the Dark UNiverse Explorer (DUNE) and the SPectroscopic All-sky Cosmic Explorer (SPACE) were ranked very highly by Panel B. They represent two different approaches to address the nature of dark energy and dark matter with

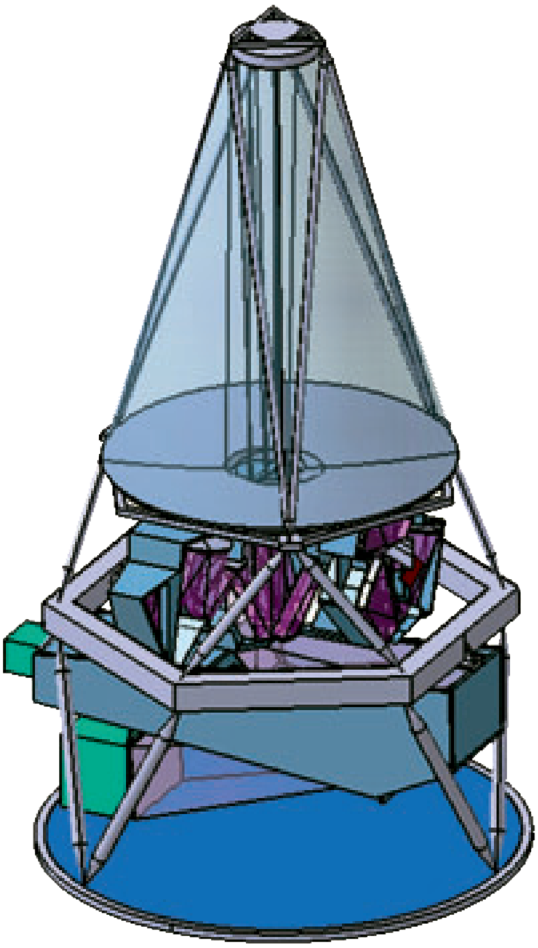


Image Credit: ESA

Figure 11: The proposed EUCLID mission. Image taken from a study based on the ESA CDF Integration Design Model

unprecedented precision, and have been combined by ESA for further studies under the name EUCLID (Figure 11). Panel B, fully in line with the ESA Space Science Advisory Committee (ESA-SSAC) recommendation, emphasises the need to carry out a European study of such a dark energy mission and ultimately to implement it in ESA's strategic plan.

With such a mission and an associated wide-field spectrograph, as recommended in Section 4.2.1 above, the European astronomical community will have two flagship facilities that should ensure an excellent scientific return. Panel B therefore strongly recommends the development of these two facilities with European leadership and following a timely schedule compared to other projects, in particular the LSST or JDEM. This does not preclude looking for collaboration between the US and Europe on EUCLID and JDEM to avoid duplication of effort and overlapping missions, but it is mandatory that Europe maintains a highly visible role in a dark energy space mission. Small-scale European participation in the LSST might also be appropriate.

Scientific Discovery Potential. DUNE was conceived as a visible/near-infrared wide-field space imager that would use weak gravitational lensing to map out the distribution of dark matter in the Universe. It would be very important in relation to SV questions A.1, A.2, and complementary for B.1, B.2, B.3, B.6, B.7.

SPACE was conceived so as to be able to produce the largest three-dimensional map of the Universe over the past ten billion years by taking near-IR spectra of half a billion galaxies over the three-quarters of the sky unobscured by the Galaxy. It would be very important for SV questions A.1, A.2, B.1, B.3 and complementary for B.2, B.4, B.6, B.7, C.1, C.3, D.5.

EUCLID will combine the weak lensing approach of DUNE with the baryonic acoustic oscillations of SPACE. The concept currently under study includes a 1.2 m telescope with a ~ 0.5 deg^2 field of view (FOV) providing optical (550–920 nm) images, near-IR Y-, J-, H-band photometry and low resolution (R = 400) 0.8–1.7 µm spectroscopy. During the four-year mission, it will accumulate sub-arcsecond resolution images and photometry for about one billion galaxies and near-infrared (near-IR) spectra of a subset of about 10^8 galaxies down to magnitude H = 22.

User Base. The mission is optimised to address specific scientific questions, but a vast community will further use the large database that will be made available in an open archive, compliant with Virtual Observatory requirements.

International Context. NASA has assigned a high priority to a dark energy mission in its strategic plan. Three mission concepts are under review, and a final choice will most likely be made in 2009. Preliminary discussions have already taken place between NASA and ESA to establish the possibilities for cooperation on such a mission.

Technology Readiness. Technically, the key components of the mission build on a significant heritage from other missions and the technological risk appears generally low. The digital micromirror devices needed for multiplexing the acquisition of spectra need to be space-qualified and this represents a significant uncertainty at this stage. The other technological challenge is to develop an attitude control system able to achieve 0.1 arcsecond pointing stability over long periods of time.

Timeline and Cost. ESA could launch such a mission in 2017. The ESA cost is capped by the budget allowed to medium-size missions: €300M (2006 EC). National contributions will come in addition to this. The announced total cost for SPACE is €274M to ESA plus €42M to NASA, and €33M to national agencies. For DUNE, the total cost quoted in the proposal is €300M to ESA and €134M to the national agencies. Until the ongoing assessment study is completed, the above cost estimates should be regarded as uncertain by a factor of 1.5 at least. Although the total mission cost may exceed our nominal €400M threshold, here we retain EUCLID in the Medium-size project category for consistency with ESA.

4.2.4.2 *Planetary Transits and Oscillations of Stars (PLATO)*

This proposal, also submitted to ESA in response to the 2007 Cosmic Vision AO, received a high ranking from the ESA advisory bodies and has been selected by ESA for further assessment. Although highly rated, Panel B ranks PLATO at a somewhat lower level than the previously mentioned project because of the fundamental importance of understanding the nature of dark energy.

PLATO (Figure 12) will perform high precision monitoring in visible photometry of a sample of > 100 000 relatively bright ($V \leq 12$) stars and another 400 000 stars down to V = 14, and will meet stringent requirements: a field of view larger than about 300 deg^2; a total duration of the monitoring of at least three and preferably five years; a photometric noise < 8×10^{-5} (goal 2.5×10^{-5}) in one hour for stars of V = 11–12. This dataset will allow the detection and characterisation of exoplanets down to Earth-size and smaller by their transit in front of a large sample of bright stars, while obtaining a detailed knowledge of the parent stars, thanks to asteroseismological measurements.

Scientific Discovery Potential. PLATO will be a follow-up on CoRoT and Kepler, but with enhanced capabilities to enable the detection of a significant sample of Earth-sized and smaller planets. Another unique feature is the ability to detect planets around bright, and therefore close-by, stars, which will be the targets for more ambitious imaging and spectroscopic missions. PLATO can therefore be considered as the necessary pathfinder for Darwin or the Terrestrial Planet Finder (TPF), and it will be very important to address the SV questions C.2, C.5 and C.6, and complementary for C.4 and D.5.

User Base. PLATO will be exploited by the community interested in finding and studying exoplanets, as well as the community interested in asteroseismology studies.

International Context. The PLATO proposal is supported by a large consortium spread over 50 different institutes, both within Europe and in the US. As explained above, PLATO is the next logical step after NASA's Kepler mission, due for launch in early 2009.

Technology Readiness. All PLATO subsystems are at a level where a prototype has been demonstrated in the relevant environment.

Timeline and Cost. A launch date for PLATO has been proposed for the second half of the next decade (probably not before 2017). The total cost quoted in the proposal is €368M: €305M from ESA, and €63M from national agencies. As for all other Cosmic Vision (CV) missions, these cost figures are highly uncertain at this stage.

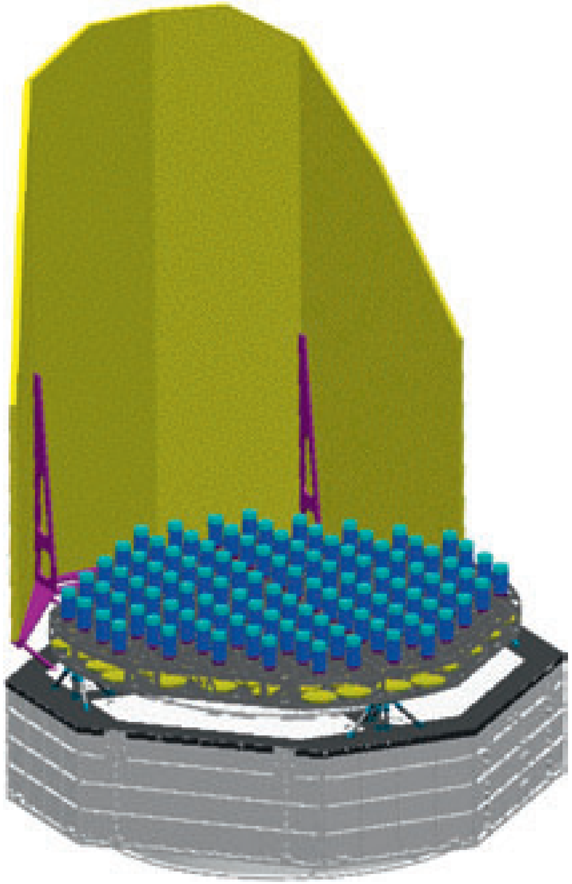


Image Credit: Thales-Alenia-Space

Figure 12: One of two designs for PLATO that were submitted in 2007 as proposals to the ESA Cosmic Vision programme. The design is under revision.

4.2.4.3 *Space Infrared Telescope for Cosmology and Astrophysics (SPICA)*

SPICA (Figure 13) is a Japanese-led mission to which Europe could make a significant contribution. It was submitted to ESA in the frame of the Cosmic Vision and has been selected for further studies. Panel B ranked it very highly in view of its scientific discovery potential.

SPICA is a space-borne, mid- to far-infrared observatory with a 3.5 m-aperture telescope cooled to ~ 5 K. This gives it an enormous sensitivity advantage over current and future (Herschel, Spitzer) facilities in the 30–210 μm range where cold dust and gas emit most of their energy. SPICA's core operational wavelength range will be from 5–210 μm with uninterrupted, wide-field capabilities for imaging and spectroscopy. A coronagraph will allow direct imaging and spectroscopy of, among other things, Jupiter-like exoplanets and protoplanetary discs.

Scientific Discovery Potential. SPICA will be very important in relation to SV questions B.6 and C.3, and complementary for B.2, B.4, C.1, C.4 and C.5.

User Base. SPICA will be an observatory open to the scientific community at large. An ESA-provided Science Operations Centre will guarantee rapid access to the data for European scientists. SPICA will provide a unique, multi-purpose database that will be used by a large community of users spanning most of the astronomical disciplines (cosmology, extragalactic astronomy, galactic astronomy, Solar System studies). The access to observing time and to the data archive will be similar to that of HST.

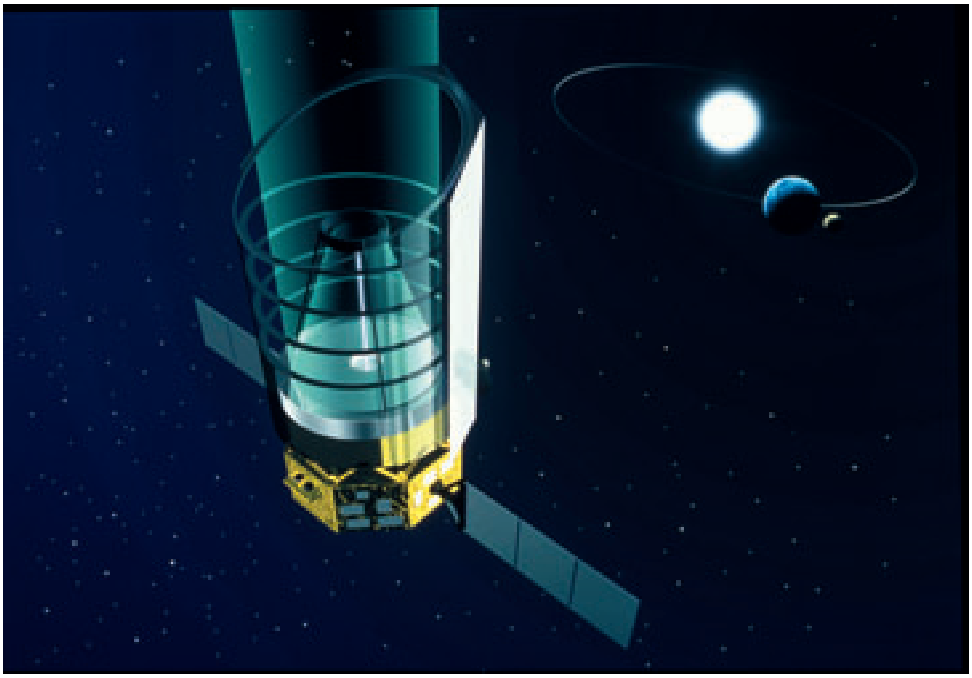


Image Credit: ISAS/JAXA

Figure 13: Artist's impression of the proposed SPICA infrared astronomy mission

International Context. This is an international mission led by JAXA. ESA's contribution will be the 3.5 m-diameter Telescope Assembly and a European Ground Segment. In addition, a nationally funded consortium will provide the SAFARI instrument, a cryogenically cooled Fourier Transform Spectrometer operating over the 30–210 µm range.

Technological Readiness. The SPICA telescope builds upon the heritage from Herschel and its development does not entail significant risks. The development of the SAFARI instrument involves 49 institutes from eleven countries (seven of which are European) with relevant experience. The technology readiness is high for most mission subsystems, with the exception of the detectors (Transition Edge Sensors) and their sub-Kelvin coolers (Adiabatic Demagnetisation Refrigerator), which have a low TRL and still require significant development.

Industrial Relevance. The development of the main European parts for SPICA (the primary mirror and the Far-Infrared Imaging Spectrometer) will generate commercial contracts, mostly with European industries.

Timeline and Cost. Pending approval by JAXA, and the continuation of the project within the ESA–CV process (it has been approved for the initial study phase of the CV), SPICA is expected to be launched in 2017 and will have a mission duration of about five years. The total estimated cost of the mission is €419M, and the estimated European participation is €157M (shared between ESA and member-state contributions). The cost of the SAFARI instrument, €82M out of the €157M, is very uncertain at this stage and should be considered a lower limit.

4.2.5 Space-Based, Long-Term (2020+)

4.2.5.1 *Darwin and the Far Infrared Interferometer (FIRI)*

Despite the fact that these proposals have been submitted for the first round of implementation of ESA's Cosmic Vision programme, i.e. for the period 2015–2020, Panel B considered it more realistic that these missions could only be realised after 2020. They are, however, considered as scientifically very important, and that is why some comments are offered here. We note that the ESA-SSAC has taken a very similar approach.

Darwin has been proposed as an L-type mission whose primary goal is the study of terrestrial extrasolar planets and the search for life on them.

Scientific Discovery Potential. Darwin is designed to detect rocky planets similar to the Earth and perform spectroscopic analysis of them at mid-infrared wavelengths (6–20 µm), where the most advantageous contrast ratio between star and planet occurs. The spectroscopy will characterise the physical and chemical state of the planetary atmospheres and search for evidence of biological activity. The baseline mission lasts five years and will investigate approximately 200 individual target stars. Among these, 25–50 planetary systems can be studied spectroscopically, searching for gases such as CO_2, H_2O, CH_4 and O_3. Darwin will be very important in addressing SV questions C.1, C.4, C.5, and complementary for A.5, B.2, B.6, C.2, C.3, C.5, D.5.

User Base. The community interested in the detailed study of extrasolar planets and the search for life. Other communities will certainly use Darwin for other applications that need its extreme angular resolution capabilities.

International Context. The projected costs are so high that it is a primary candidate for international collaboration. Mission concepts have already been studied by ESA and by NASA, and talks about a possible joint mission have started.

Technology Readiness. From a technological point of view, Darwin is very challenging. It requires ultra-high contrast (> 10^6) nulling interferometry in cryogenic conditions, and high precision formation-flying capabilities still to be developed, but supported by a long term R&D programme. Considerable efforts are already being made. Indeed, precursor missions to Darwin, e.g., Prisma, are in the planning stage. In the US, a mission with similar science goals and technological solution, the Terrestrial Planet Finder (TPF-I), is under study.

Industrial Relevance. The involvement of industry for the solution of all the open issues mentioned above is crucial.

Timeline and Cost. A realistic timeline cannot yet be defined. The total cost will be (at least) €1.2B, to which Europe could contribute 50%, corresponding to the cost of an L-class mission.

FIRI, the Far-Infrared Interferometer, will study the formation and evolution of planets, stars and galaxies. The FIRI mission concept comprises three cold, 3.5 m-aperture telescopes, orbiting a beam-combining module, with separation of up to 1 km, free-flying or tethered, operating at 25–385 μm. It will use the interferometric direct-detection technique to ensure μJy sensitivity and 0.02" resolution at 100 μm, across an arcmin^2 instantaneous field of view, with a spectral resolution $\lambda/\delta\lambda \sim 5000$ and a heterodyne system with $\lambda/\delta\lambda \sim 10^6$. In the FIRI wavelength range it will be possible to peer through dusty regions to unveil the earliest formative stages of planets, stars and galaxies, unperturbed by the confusion experienced by its precursors, Herschel and SPICA.

Scientific Discovery Potential. FIRI will disentangle the cosmic histories of star formation and accretion onto black holes and will trace the assembly and evolution of quiescent galaxies like the Milky Way. Perhaps most importantly, FIRI will observe all stages of planetary system formation and recognise Earth-like planets that may harbour life, via its ability to image the dust structures in planetary systems. Specifically, it will be very important for addressing SV questions A.5, C.1, C.3, C.4, and complementary for B.2, B.3, B.6, C.2, C.5.

User Base. The spatial resolution and sensitivity of FIRI are totally unprecedented and will undoubtedly attract a broad user community.

International Context. The projected costs are so high that it is a primary candidate for international collaboration (possibly ESA–NASA).

Technology Readiness. FIRI requires two major breakthroughs. The first is related to achieving a tuneable baseline interferometer. Even though several options have been described, none of them has been demonstrated. Further progress in this direction might come from other missions that require formation flying, such as Simbol-X (see Chapter 3) and Darwin. The second breakthrough is linked to the requirements on the detectors. Existing bolometer arrays are one or two orders of magnitude away from the FIRI requirements in terms of size or sensitivity. It should be mentioned that very similar detector specifications are also mandatory for a further mission aiming to measure the polarisation of the CMB, and which might be a first priority after Planck Surveyor.

Timeline and Cost. The total cost for FIRI will probably exceed the level of €1.4B. If Europe wants to contribute 50% of this, the current cost envelope for an "L-class mission" would have to be waived.

Recommendation. *It is clear that longer-term missions such as Darwin and FIRI will require considerable further study and technical development. More substantial funding than is available today must be provided to support the preparatory R&D activities in the future. Areas that require special attention are, for example, the development of large, low noise bolometer arrays and the development of techniques that will allow high precision formation flying.*

4.3 Existing Facilities

4.3.1 2–4 m-class Optical Telescopes

4.3.1.1 *Background*

Although the small- and medium-size facilities (SMFs) are not part of the large infrastructures addressed by ASTRONET, they do have a role to play in supporting the programmes of the Science Vision (see Section 4.3.1.2 below). There is, however, clearly room for optimising their scientific impact and cost effectiveness by strategic planning and coordination at the European level.

The number count of the 2–4 m facilities with European participation is:

- Nine telescopes in the range 3.5–4.2 m (WHT, AAT, VISTA, UKIRT, 3.5 m Calar Alto, CFHT, 3.6 m ESO, TNG, NTT). Europe has only a share in some of these facilities (e.g., AAT, CFHT), sometimes with only one participating European country (AAT, UKIRT, CFHT, TNG). Note that the UK will withdraw from the AAT in 2010, and the future of some of the other facilities is under discussion.

- Twelve telescopes in the range 1.9–3.5 m (NOT, INT, VST, Aristarchos, 2.2 m Calar Alto, 2.2 m La Silla, Liverpool, Pic du Midi, Observatoire de Haute-Provence, 2 m Rhozen (Bulgaria), 2 m Ondrejov (Czech republic), 2 m Terskol (Ukraine). Many of these facilities are "national" in the sense that they are owned by a single country.

- There are 20–25 telescopes between 1.0 m and 1.8 m in diameter, many of them no longer in operation.

OPTICON has estimated the cost of operation for each of these facilities, amounting to at least €8–13k/night for the 4 m telescopes, and €2–4k/night for the 2 m telescopes, corresponding respectively to operating costs of €3–5M/yr and €0.7–1.5M/yr per facility. The total operating costs borne by Europe for the 4 m-class telescopes alone is therefore likely to be in the range of at least €30–40M/yr.

The telescope time pressure on these facilities is likely to range from less than one to around three or even five for the most competitive facilities offering instruments not available elsewhere.

We note that 18 of these SMFs (diameter between 1.5–4 m) are now part of the OPTICON/FP6 transnational Access Programme, where of the order of 200 nights per year are distributed across these facilities, supported by EC funding; however the future of this support beyond 2010 is uncertain. Access is contingent on telescope time being granted through the regular time allocation procedure in place at each telescope. In addition to the Access Programme, OPTICON has a related networking activity, a Director's Forum reviewing "all aspects of the management, exploitation, and development of the European observing facilities included in the OPTICON access programme".

4.3.1.2 *Science Vision*

The Science Vision document mentions the SMFs several times, mostly in reference to their role as survey instruments. There are at least four possible areas where SMFs have a role to play:

- Wide-Field Imaging Surveys (e.g., VST, VISTA);

- Telescope networks for continuous photometric, spectroscopic or temporal coverage (including the possibility of discovering and following up on near-Earth asteroids);

- Support to space missions (e.g., GRB follow-up, CoRoT follow-up, Gaia, etc.);

- Training and education of students and young astronomers (see also Chapter 7).

4.3.1.3 *Towards a Pan-European Organisation of SMFs*

A review committee — the European Telescope Strategy Committee — has been appointed by the ASTRONET Board in coordination with the OPTICON Executive Committee to consider the issues listed below. Its remit is to deliver, by September 2009, a short- and medium to long-term strategy to optimise the use of 2–4 m class optical/infrared telescopes by the European astronomical community. Special attention will be paid to developing this strategy in close interaction with the telescope owners — especially through the OPTICON Director's Forum — and with extensive feedback from the community at large. To fulfil its remit, this committee will, in particular:

1. Identify those goals of the ASTRONET Science Vision that are more effectively delivered by 2–4 m-class optical/infrared telescopes.

2. Identify which observational capabilities (site, field of view, instrumentation capabilities and operational modes) are required.

3. Establish an appropriate balance between the scientific, technological and educational goals of 2–4 m-class telescopes, taking into account contributions from both larger and smaller facilities.

4. Consider the appropriate balance among the scientific tasks between large-scale survey-type efforts, including complementary ground-based programmes in support of European space missions, and free access by individual researchers.

5. Develop a realistic roadmap, including technical developments and upgrades, and organisational/financial arrangements that would enable a set of European 2–4 m-class telescopes to deliver the best scientific output for European astronomy in a cost-effective manner.

6. Analyse major needs and opportunities for collaboration on the global stage, e.g., with the US system proposed by the ReSTAR committee (see Section 4.3.1.4 below).

7. Propose arrangements for open access to all data, e.g., through the Virtual Observatory (see Chapter 6).

4.3.1.4 *Situation in the US*

Finally, we note that the National Optical Astronomical Observatory (NOAO) has set up a committee to "develop a prioritized, quantitative, science-justified list of capabilities appropriate to telescopes with apertures less than 6 meters". Note the title of the committee: Renewing Small Telescopes for Astronomical Research (ReStar)[17].

4.3.2 8–10 m-class Optical Telescopes

At present, European astronomers have full or partial access to 8–10 m-class telescopes in both hemispheres; the VLT, Gemini, the LBT, SALT and the GTC, plus some others at a level that falls below our threshold. All these facilities are playing a very important role in addressing a large number of the scientific topics in the SV through observations both in the northern and in the southern sky. These facilities will remain very important for European astronomers at least up to the end of the next decade, provided their capabilities are further enhanced/upgraded. Various options are currently under discussion for all of the 8–10 m-class telescopes.

We focus in the following on the ESO VLT/VLTI as the only such facility to which most European astronomers have full direct access. With the VLT/VLTI, Europe has established the lead in ground-based optical/near-infrared astronomy. It is, therefore, important to put/keep the VLT/VLTI at the astronomical scientific forefront up to about 2018. The long-term goal is to optimise its science output in the ELT era from 2019 to around 2032.

Ten instruments are currently in operation at the four ESO VLTs, and a major so-called second generation VLT instrument development programme is well underway, as well as the construction and commissioning of the full VLTI infrastructure. This phase will end in 2011, followed by a second phase during the period 2011–2020 where

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[17] The charge to the committee and a record of its work, plus its final report and an implementation white paper can all be found at http://www.noao.edu/system/restar/.

existing instruments will be upgraded, and a full complement of VLT/VLTI second generation instruments will be completed. For the latter, it should again be noted that the VLTI would still have a large angular resolution advantage (a factor ~ 5 in size) in the ELT's era, albeit for much brighter objects.

The second generation VLT instruments that are already funded and under construction are:

- X-Shooter, a point and shoot wideband (UV, optical and near-IR) single object spectrometer;

- SPHERE, a high spatial resolution with extreme contrast spectro-imager/polarimeter;

- KMOS, a multi-integral field unit cryogenic near-IR spectrometer;

- MUSE, a wide-field optical integral field surveyor.

Ideas for additional third generation VLT instruments, to be exploited during the E-ELT era, have been discussed at a dedicated workshop in October 2007. However, the final choices still have to be made and the funding secured.

For the VLTI, the infrastructure development is ongoing. The goal is to achieve good imaging capability as well as 10 micro arcsecond astrometry on relatively faint targets, using either the four 8 m Unit Telescopes or at least two (and possibly all four) 1.8 m Auxiliary Telescopes. This is to be accomplished with the PRIMA dual feed facility and four-way fringe tracking. With PRIMA one can expect the first astrometric survey for extrasolar planets and the study of Galactic Centre dynamics.

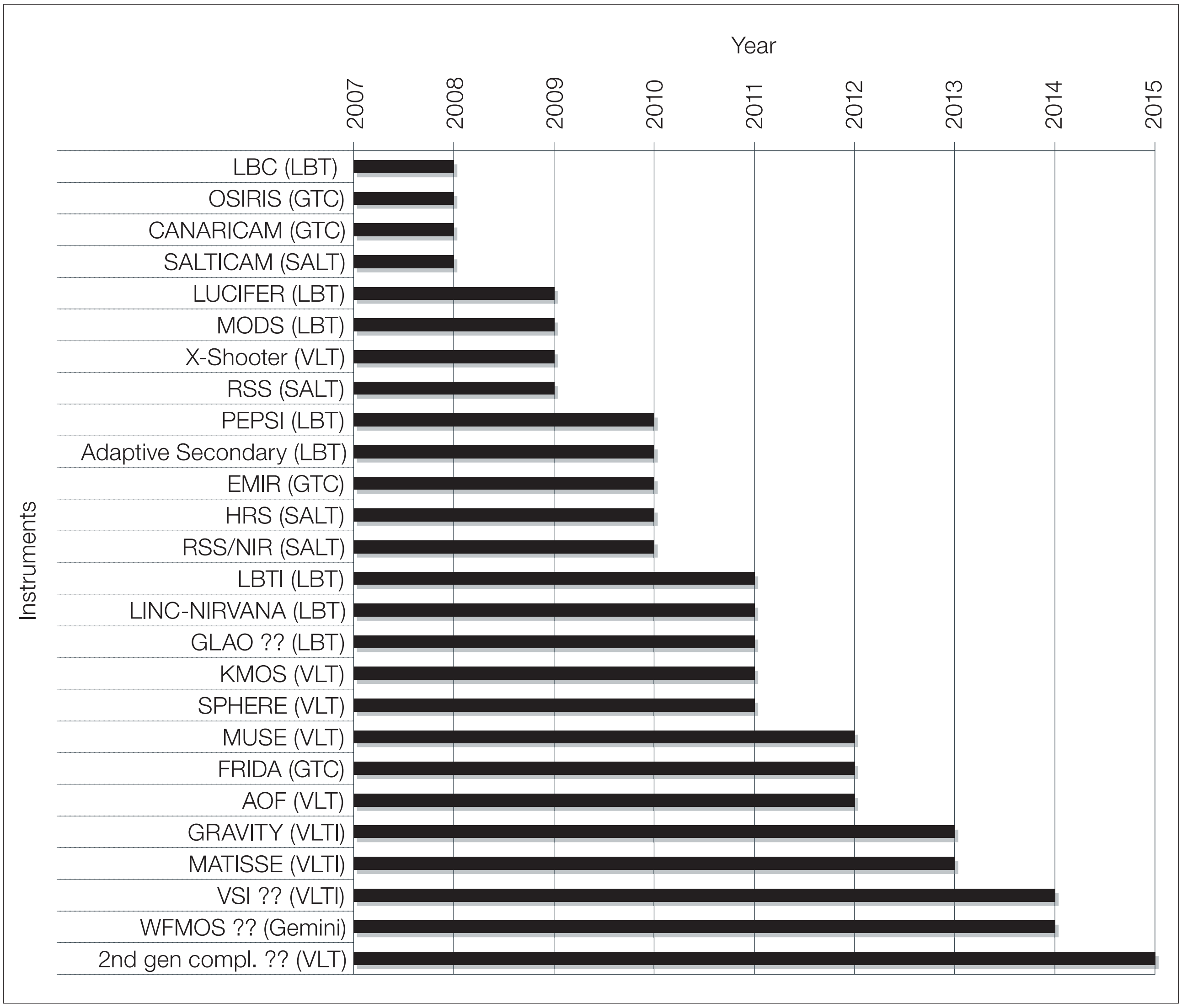

Figure 14: Instruments that are currently under construction for the five 8–10 m-class telescopes to which European astronomers have access. The solid bar represents the development and construction period for each of the instruments, and ends at the predicted start of operations (marked with ?? when this is unclear).

ESO has now decided to start the construction of three second generation VLTI instruments:

- MATISSE, a four-beam mid-IR spectro-interferometer with full image reconstruction. It will allow the study of the near-nuclear environment of active galactic nuclei; the formation and evolution of planetary systems; the birth of massive stars, and observations of the high contrast environment of hot and evolved stars.

- GRAVITY, an adaptive optics assisted, near-IR imager for precision narrow angle astrometry and phase-referenced imaging of faint objects for tests of general relativity in the strong field limit through motions of stars near the event horizon of the Galactic Centre black hole; the detection of intermediate mass black holes throughout the Galaxy, and the direct determination of the masses of exoplanets and brown dwarfs.

- VSI, a 4–6-beam spectro-interferometer for high dynamic range imaging at high angular resolution at near-IR wavelengths. It will probe the initial conditions of planet formation in the environments of young stars; image convective cells and other phenomena on the surfaces of stars; map the chemical and physical environments of evolved stars, stellar remnants and stellar winds; study the central regions of active galactic nuclei and supermassive black holes.

The Gemini observatory (25% UK) presently operates five and nine instruments for the northern and the southern telescope, respectively. Two more instruments are in preparation. The LBT (25% Italy, 25% Germany) is progressively entering into operation. Regular scientific observations with the two prime focus cameras have started in early 2008, and during 2008–2010 other first generation instruments will be commissioned. The issue of second generation instruments is a matter of discussion within the communities involved. The Spanish-led GTC (90% Spain) will have two commissioned instruments at first light, and a first second generation instrument (EMIR) is under construction. SALT (20%: Poland, Germany and UK) is in its commissioning phase and will begin full operation in 2009. It has three first generation instruments and one further instrument under construction. The overall situation is summarised in Figure 14.

The scientifically useful lifetime of instruments at large telescopes is typically 5–10 years. Assuming a "steady-state of innovations", this means that substantial funds will be needed throughout the next decade for upgrades and replacements. The funding for the construction of the third generation instruments that will be decided in the coming years at ESO is estimated at about €60M (based on the cost of the existing first and second generation instruments). More generally, it can be stated that the development and construction of future generation instruments for the 8–10 m-class telescopes to which European astronomers have access, will require an investment of about €10M/yr throughout the next decade in order to stay at the forefront of science and to maintain the present high level of scientific productivity.

However, in the E-ELT era, the question must be asked if the full complement of instruments can be maintained or if some specialisation is not needed. The answer to this question has to take into account the fact that for the E-ELT itself an ambitious and demanding instrument development programme will be required.

The future scientific role and the related suite of instruments for the 8–10 m-class telescopes in the ELT era should be discussed during the next three to five years between the organisations and institutes involved in the operation and further development of such facilities. We note that a similar study is proceeding in the US under the Access to Large Telescopes for Astronomical Instruction and Research survey[18].

Recommendation. *That a study be established, under the auspices of ASTRONET with OPTICON, within the next three to five years to develop a long-term strategy for the scientific exploitation of the 8–10 m-class telescopes and for further investments in their instrumentation.*

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[18] http://www.noao.edu/system/altair/

4.3.3 Millimetre and Submillimetre Telescopes

The millimetre and submillimetre wavelength ranges play a key role in studying the "cold universe". The cosmic microwave background peaks at millimetre wavelengths, and line transitions from atoms and molecules, as well as the continuum emission from dust particles in very low temperature environments ($T < 100K$) determine the characteristic shapes and signatures in the spectral energy distributions observed at these wavelengths. The measurements yield information about the physical properties of the dust and neutral gas in the most distant objects seen in the Universe, and equally about the physical and chemical properties of star-forming regions and of Solar System objects (planets, comets, asteroids and Kuiper Belt objects). These topics figure prominently amongst the SV themes.

The entire millimetre and submillimetre wavelength ranges can only be observed from space. From the ground, the observations are restricted to the atmospheric windows at 3, 2 and 1 mm, and a number of submillimetre windows, extending below 0.3 mm. Water vapour absorption lines are the primary cause of the opacity of the Earth's atmosphere in these wavelength ranges, which are therefore best exploited from dry, high altitude sites.

European groups from France, Germany, the Netherlands, Spain, Sweden, the UK and ESO are presently operating a number of world-class millimetre and submillimetre facilities on high altitude sites in Europe, Hawaii and in Chile including:

- **Millimetre-wave facilities.** The Plateau de Bure mm-array interferometer (IRAM-PdB) with six 15 m-diameter telescopes is the only one of its kind in Europe and currently the most sensitive in the world. It is operated by the Institut de Radioastronomie Millimétrique (IRAM), which also operates the 30 m-diameter mm-wave telescope on Pico Veleta in Spain (IRAM-PV). This telescope offers both single- and multi-pixel heterodyne receivers at 1, 2 and 3 mm, as well as bolometer arrays. The Onsala Space Observatory (OSO) operates a mm-wave 20 m-diameter telescope in Sweden, and the IGN has recently commissioned a new 40 m-diameter single dish in Yebes near Madrid.

- **Submillimetre-wave facilities.** The UK, together with the Netherlands, is running the James Clerk Maxwell Telescope (JCMT) in Hawaii. The JCMT is equipped with heterodyne receivers in the range 230–800 GHz, a 16-element heterodyne array at 850 µm and the next-generation TES bolometer array, SCUBA-2. More recently, the Atacama Pathfinder Experiment (APEX) telescope (located very near the ALMA site in Chile), a joint project between ESO, the Max-Planck-Institut für Radioastronomie (MPIfR) and OSO, started operation, offering direct access to European astronomers in the same way as the optical ESO telescopes. APEX is equipped with a suite of single-pixel heterodyne facility receivers from 230 GHz into the THz frequency regimes, heterodyne arrays, and several bolometer arrays, including the 870-µm bolometer camera, LABOCA.

These facilities have been built to serve the needs of the scientists in the countries involved, but they have also accepted observing proposals from all across Europe, and from around the world, on the basis of scientific merit. Such access has been partially supported under the EC-funded TransNational Access (TNA) scheme as one of the RadioNet activities since 2005. This is motivated by the wish to prepare the astronomical community in Europe for the ALMA project that has recently entered the construction phase and, according to current plans, will start scientific operations in 2010.

Up to now each of the existing facilities (APEX, JCMT, IRAM-PdB, IRAM-PV, OSO, Yebes) has undergone and continues to undergo upgrades that enhance their scientific potential. At millimetre and submillimetre wavelengths there is still a lot of room for further improvements to telescope efficiencies, e.g., by:

- adding more telescopes to an existing interferometer like the IRAM Plateau de Bure six-element array;

- installing more sensitive receivers, bolometric and heterodyne receiver arrays with larger numbers of pixels (e.g., SCUBA-2), and much more powerful spectral backends;

- improving the software tools for data reduction and analysis further.

Institutes in France, Germany, the Netherlands, Spain, Sweden, the UK as well as ESO are actively engaged in such development work, which is partially supported by EC funds given to the RadioNet consortium and to ESO.

For ALMA, the software tools for data reduction and analysis must be brought up to much higher levels than exist at present. Furthermore, special attention is required to support astronomers who want to collect and use ALMA data without being specialists in the field of millimetre and submillimetre interferometry. The idea is to create a network of support centres distributed across Europe with ESO as the central node, and work has started in various places, but in many cases the long-term funding of such activities has not yet been secured and it is important that this activity is properly supported.

ALMA will not only open the field of millimetre and submillimetre astronomy to many more scientists, but it will also change the role of the existing facilities. This must be reflected in future development work and investment planning. At the current time there were, however, no detailed proposals for Panel B to rank and evaluate. Therefore the following recommendation is made.

Recommendation. *A coherent long-term plan for the existing European mm—sub-mm facilities should be established under the auspices of ASTRONET together with RadioNet during the coming three years. It should outline the scientific role of each of the current facilities in the ALMA era, develop an access strategy beyond the current TNA scenario, and it should define the future investments to be made on the basis of the scientific excellence of the projects that can be carried out. Also, this plan should give a comprehensive answer to the question of how the European astronomical community can best be supported through software development, training courses and other activities to optimise the scientific exploitation of ALMA.*

4.3.4 Radio Observatories

A large fraction of the existing radio telescopes in Europe will continue to operate independently and as part of the European (and global) VLBI network. New and upgraded facilities such as LOFAR, e-MERLIN and the Yebes 40 m dish are being commissioned; the Sardinia Radio Telescope is under construction and expected to deliver first light towards the end of 2009; broadband e-VLBI is moving from test system status to being operational on the EVN/JIVE.

A particular role for existing European radio facilities arises in connection with research on technologies required for the SKA. The European radio community is actively developing and testing the new technologies that will be needed for the SKA. LOFAR is one of the prime examples of an SKA pathfinder for low frequencies. In addition, there is the phased array technology demonstrator project APERTIF (partly funded via an NWO grant) that will be installed on the Westerbork array. One prototype is already in place in one of the telescopes and delivering its first data. In the UK the technology to enable time and phase transfer across a fibre optic network, essential for the operation of the SKA, is being developed and tested on e-MERLIN; the network will also test high speed data transmission to the limit with its 210 Gb/s fibre network. A similar development is being tested on the long (on a global scale) baselines of the EVN/JIVE. These efforts have clearly begun to attract and foster a new generation of radio astronomers in many countries and provide a solid basis for European interest and involvement in the SKA.

Furthermore, the European SKADS project is intended to prove the aperture array technology. The first prototype will be installed next to one of the telescopes in Westerbork in 2009, a second system will be erected at the Nançay Radio Telescope, while a third, all-digital prototype is under construction at Jodrell Bank. SKADS is a cooperative venture between many European countries: France, Germany, Italy, the Netherlands, Russia, Poland, Portugal, Spain, Sweden and the United Kingdom, with other partners in Australia, Canada and South Africa.

Many of the larger single dish radio telescopes in Europe will continue operation for a variety of scientific projects. Panel B has not yet undertaken a systematic survey of plans that may exist for their future exploitation. However, such a survey and the development of a preliminary plan to optimise the use of existing radio telescopes is underway in RadioNet.

Recommendation. *That the full plan for the future optimisation and use of existing radio facilities in Europe is developed by ASTRONET in conjunction with RadioNet during 2010.*

4.4 Perceived Gaps and Technology Development for Future Facilities

To maintain the vitality and competitiveness of European astronomy well into the next decade and beyond, it is necessary to provide funding for the research and development of basic enabling technologies. Progress in optics, photonics, micromechanics, large-scale computing and other areas will permit the construction of advanced instruments and observatories that are beyond the horizon of present technical capabilities, or too expensive when realised with today's approaches.

Several areas with demonstrated European accomplishments and leadership are not represented among the high priority projects for the next decade, largely because key enabling technologies need to be brought to maturity before a large facility can be planned in detail. Among these are major new facilities for ultraviolet (UV) astronomy, optical/IR interferometry from the ground and in space, and measurements of CMB polarisation. Investing in R&D in all these areas will enable Europe to play a leading role in astronomy well into the future.

Europe's central role in the International Ultraviolet Explorer (IUE) and subsequent UV missions has created a vital community eager to pursue a next-generation UV mission, whose feasibility will depend strongly on the availability of large space optics with superb surface quality. The IUE satellite was jointly built by ESA, SERC and NASA, and operated extremely successfully for eighteen years (1978–1996). Europe has not implemented another dedicated far-UV/extreme-UV follow-up mission since then and there are also currently no significant plans to do so, despite the emphasis that is put on such a mission in the Science Vision document. Important topics where such a project could contribute are structure of the IGM/ISM (intergalactic medium/interstellar medium), extrasolar planet studies and hot/evolved stars. Panel B considered this situation as very unsatisfactory. This might be remedied to a certain extent by the World Space Observatory (WSO) project, led by Russia, and in which several western European countries have shown an interest. However, a true next generation UV/optical mission will require a capability an order of magnitude or more beyond both HST and WSO.

There are now studies taking place in the US under the Astrophysics Strategic Mission Concept Studies (ASMCS) programme. These include the Theia mission, comprising a 4 m monolithic telescope with a wide-field near-UV/optical imager, a high resolution UV spectrograph and an exoplanet imager. Theia will make significant gains in effective area through the development of optical coatings (Al+MgF_2 for the primary and Al+LiF for the secondary) and improved detectors. It will also be able to utilise the existing Atlas V launcher. More ambitious ideas include 8–16 m-aperture telescopes that take advantage of the new Ares V launch vehicle capabilities associated with the Return to the Moon programme. While there is no UV mission included in the current ESA Cosmic Vision programme, these studies will be concluded in early 2009 and it is important that options remain in the Roadmap for European contributions to NASA initiatives in this area that might be included in subsequent Cosmic Vision calls.

In ground-based optical/IR interferometry, Europe has assumed a leading position by building the VLTI, an operating facility still in a strong growth phase. The next major step beyond this facility will require the construction of an array with kilometric baselines, good image fidelity and high sensitivity. Affordable large telescopes equipped with adaptive optics, optical fibres for beam transport and integrated optics are among the key technologies needed. Space-based interferometry will also benefit from the development of optical components for beam transport, modal filtering and beam combination. In addition, technologies needed for formation flying have to be developed.

Analogous to the need for powerful survey telescopes in combination with the 8–10 m-class telescopes and the future ELTs, observations with a mm–sub-mm interferometer like ALMA need to be prepared for by surveys in this wavelength domain. This needs large aperture single dish telescopes equipped with multi-pixel array detectors and development of these devices is a critical area in which Europe needs to advance further. With the JCMT, APEX and multi-pixel bolometric and heterodyne receivers, Europe already has made steps in this direction. However, it will be necessary to decide on the long-term role for these two facilities, and to weigh future investments in them against the capabilities offered by a larger diameter single dish telescope placed at an extremely high altitude (> 5000 m). Such a project, the Cornell Caltech Atacama Telescope (CCAT), is currently under study in the US, and some European groups have shown an interest in participating. The evaluation of these different options should be one of the outcomes of the long-term planning exercise recommended above (Section 4.3.3).

ESA's Planck satellite will characterise the CMB with unprecedented sensitivity, wavelength coverage and angular resolution; however, Planck's ability to measure CMB polarisation — a topic that has been strongly highlighted in the SV document — will be limited. Based on the results from Planck, ground-based, balloon-borne and, potentially, satellite experiments aimed at better measurements of CMB polarisation have to be developed. This calls for sustained R&D activities in preparation for such future facilities.

Essentially all branches of observational astronomy depend strongly on the availability of ever better detectors; none of the high priority projects in this Roadmap would be possible without state-of-the-art devices such as high performance CCDs, large-format infrared arrays, or low noise sub-mm receivers. Promising developments for future projects include advanced versions of these established technologies, but also, for example, superconductor devices capable of providing energy discrimination for each detected photon in the infrared, visible and X-ray ranges. Europe should continue to engage in R&D on detector technologies, not least because, at present, many projects have to rely on a single source — in some cases with delivery restrictions — capable of manufacturing their detectors.

Most of these preparatory activities for future instruments, facilities and missions require collaborative research involving scientific institutions with specific expertise in their respective areas of astronomy, as well as industry on all levels from small and medium-size enterprises with high technology portfolios to large companies capable of acting as prime contractors for major space missions. In the past, the EC Framework Programmes have been exceedingly successful in fostering pan-European cooperation in important areas such as the development of adaptive optics for large telescopes, the preparation of the Square Kilometre Array, and the construction of sophisticated instrumentation for planned and existing telescopes and interferometers, but the first round of infrastructure contracts in FP7 indicates a drastic drop in this type of support.

Recommendation. *That upcoming FP7 calls and subsequent Framework Programmes provide similar opportunities for forward-looking collaborations between academia and industry in the preparation of advanced observing facilities.*

These EU-funded programmes should be complemented by coordinated activities of the national funding agencies, as exemplified by the recent joint call for proposals on Common Tools for Future Large sub-mm Facilities initiated by ASTRONET. Such joint calls can address specific technology needs and national priorities flexibly within the framework of agreed-upon European strategies.

Finally, another issue that deserves attention at the European level is the possibility of exploiting the very special conditions for optical/infrared/millimetre astronomy on the high Antarctic and Arctic plateaux.

The high Antarctic plateau holds great potential for optical/infrared/millimetre observations which would benefit from one or more of the site characteristics: extreme cold, very low water vapour, highly stable atmosphere and the long uninterrupted winter night. The US South Pole station at an altitude of 2840 m has hosted a significant number of astronomy and astroparticle experiments, but even better conditions are to be found at the higher Dome C (3250 m) and Dome A (4200 m) sites, both of which are now under serious investigation for astronomy.

In particular, the potential of the Franco-Italian Concordia winter-over base at Dome C is under study by the EC-funded coordination activity Antarctic Research, a European Network for Astrophysics (ARENA), involving seven European countries plus Australia. ARENA will report its conclusions regarding scientific possibilities, logistical requirements and financial implications at the end of 2009. This will take the form of a roadmap from the current small national and bilateral projects (e.g., the International Robotic Antarctic Infrared Telescope [IRAIT] 80-cm IR telescope), through medium-scale facilities to fully validate the potential of the site on a 5–10-year timescale (e.g., a 2–3 m wide-field/high resolution optical/IR telescope and/or a 10 m submillimetre telescope), up to large facilities (e.g., an 8 m-class telescope or a large optical/IR interferometric array) in the more distant future.

At the same time, the higher, and potentially better, Dome A site is also undergoing testing by Chinese, Australian, US and UK astronomers. While it currently lacks the winter-over capability found at Dome C necessary to support larger-scale facilities, it may nevertheless be the right choice for smaller, wholly robotic experiments that take full advantage of the improved transmission at THz frequencies, for example. Finally, there is also interest in exploring the properties of complementary sites in the northern hemisphere, particularly the US/Danish Summit camp at 3200 m on the Greenland icecap.

Recommendation. *Given the growing interest in the potential of polar plateau astronomy, Panel B urges that further European studies be carried out that build on the current detailed focus of ARENA on Dome C and broaden the picture to include complementary opportunities at Dome A and Greenland. The aim would be not only to identify those scientific questions that would benefit most from a suitable facility placed on a polar plateau, but would also further explore the logistical and financial implications, as well as liaise with the appropriate national and international polar operators.*

4.5 Concluding Remarks

From a long list of very good projects, Panel B has identified those that should be implemented with priority and in a timely manner because they are the most promising ones to achieve the science goals outlined in the Science Vision document. The next steps differ from project to project, but they all should be seen in the wider context to develop a consistent and balanced programme that meets the aspirations of the astronomical community in Europe.

The massive response to ESA's call for proposals for the implementation of the Cosmic Vision programme is but one proof that the needs of the community are high. ESA has already made a heavy down-selection and will be forced to make a further down-selection at the end of the current study phase. Even then special efforts will be required to finance at least the majority of the highest priority projects considered by this Panel and by all the other Panels.

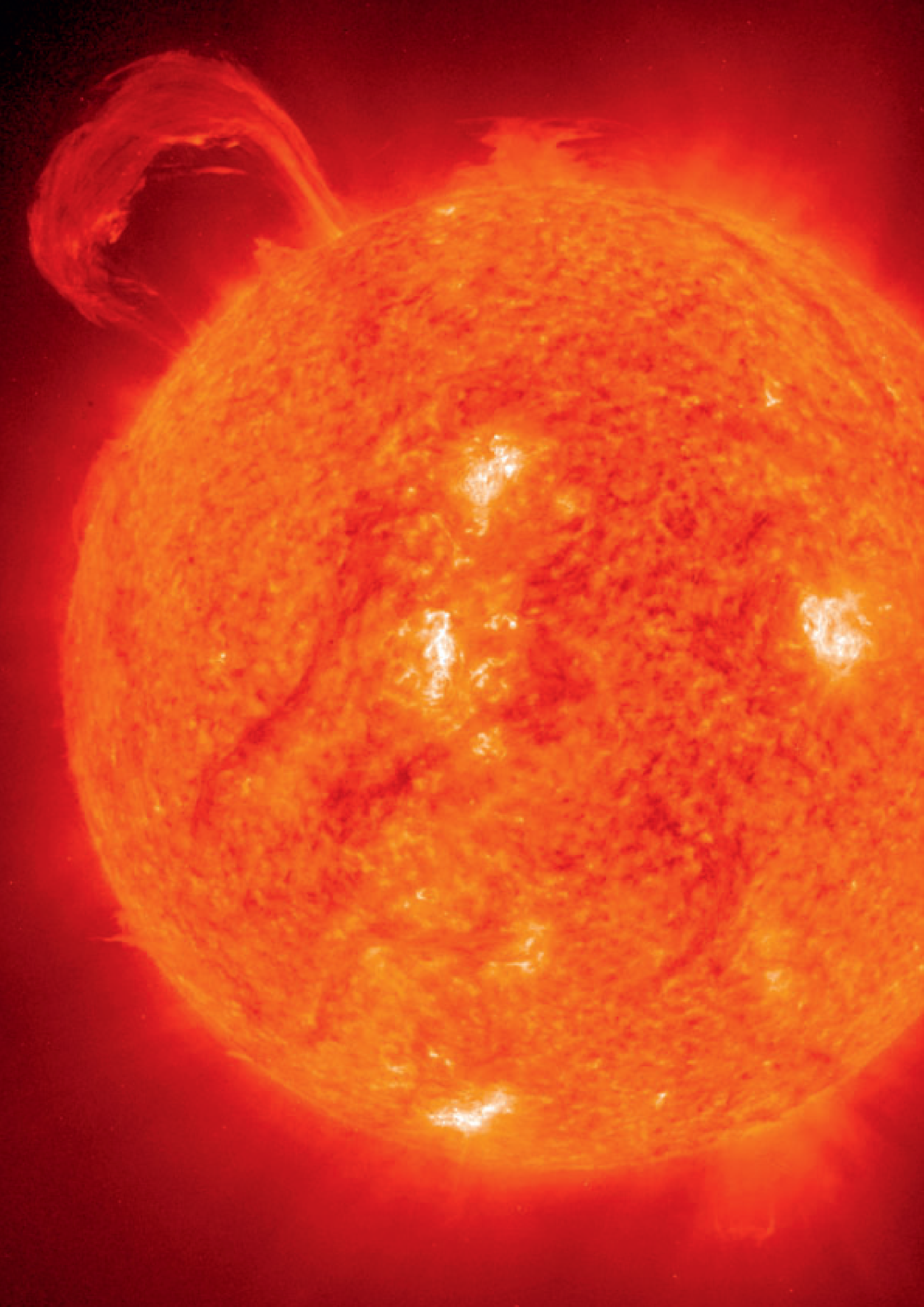
Through the investments made during the last three decades, Europe has taken the leadership in certain fields, both in ground-based and in space-based astronomy. Naturally, the respective communities strive to maintain that leadership position by embarking on the next generation projects in a timely manner. Space projects like Gaia and the ground-based E-ELT and SKA projects are outstanding examples.

The technical specifications that are put on the next generation facilities are such that, often, long lead times are required to develop the enabling technologies. It is for this reason that projects like the E-ELT and the SKA are presently undergoing extensive preparatory phases, and that no final decision about their implementation will be taken before 2010/11.

It is very important for all future projects that adequate funds are spent on such preparatory activities, even at the risk that some of them may fail or the respective projects are never implemented. Scientific excellence must always be the primary criterion, but technical readiness should follow closely behind as a key consideration when deciding on the implementation of a new project. This is the only way to have a realistic implementation plan, both time-wise and money-wise.

Given the fact that the construction of major new facilities absorbs the bulk of the available new funds for periods of five to ten years, projects that are not selected now will have to wait many years until new opportunities arise. The consequence of this is that there will always be “gaps” between successful missions and the next generation experiment, and some observing capabilities may not exist at all for many years to come.

Even if these “gaps” remain gaps for the decade to come, the implementation of the projects that have been classified as having the highest priority by Panel B, and described in this Chapter, is clearly a very big challenge. Many of the projects are, however, crucial for maintaining European leadership in their respective areas of astronomy. Their timely implementation is therefore of paramount importance.



Chapter 5 Solar Telescopes, Solar System Missions, Laboratory Studies

(Panel C)

5.1 Introduction

Panel C was charged with looking at current and future solar telescopes and Solar System missions. It also investigated the more cross-disciplinary field of laboratory astrophysics.

Europe has a strong track record in solar instrumentation. Four of the leading ground-based solar telescopes are European: the Swedish 1 m Solar Telescope, the French/Italian Themis, the German Vacuum Tower Telescope (VTT), and the Dutch Open Telescope (DOT), all of which are situated on the Canary Islands. A 1.5 m solar telescope (Gregor) is close to completion. With regard to space-based solar instrumentation, the first ESA cornerstone of the Horizon 2000 programme included the Solar and Heliospheric Observatory, launched in 1995. SOHO has been a great success and is still providing excellent science. Ulysses has studied the solar wind from all latitudes and is about to cease operation. The NASA-led STEREO mission and the Japanese-led Hinode mission were launched in 2006 and have strong European involvement.

The NASA-led Solar Dynamics Observatory (SDO) will be launched in 2009. The satellite will continuously monitor the Sun with high resolution full disc imaging in several wavelengths producing 3 TB of data per day. The mission will provide a synoptic dataset of unprecedented quality and is crucial for space weather studies and research into possible forecasting. Several partial data archives are foreseen in Europe for specific applications (e.g., helioseismology and space weather) and these should be coupled together with Virtual Observatory and data-grid technologies to facilitate wider usage (see Chapter 6). The data will also be used by a very large community as supporting data, providing a large field-of-view context for high resolution facilities.

Europe has a strong position for *in situ* measurements of fundamental plasma properties through the other half of the first ESA cornerstone mission: Cluster. The four formation-flying satellites were launched in 2000 and the mission is currently in its second extension. This has been augmented by a set of near-Earth probes such as Double Star, Polar and Wind, which have had strong European scientific and, in some cases, operational inputs, and by ground-based instruments such as ionospheric radar facilities, including, for example, the European Incoherent SCATter radar system (EISCAT).

Thanks to the strength of ESA's Horizon 2000 and 2000 Plus programmes, Europe has become a strong player in Solar System exploration. Great successes include Huygens, Mars Express and Venus Express. The Cassini–Huygens mission, launched in 1997, is a joint ESA–NASA programme for the exploration of Saturn's system, with a NASA-led orbiter and an ESA probe, Huygens, which successfully landed on Titan's surface on 14 January 2005. The Cassini–Huygens mission has led to many outstanding discoveries, including the complex dynamics of Saturn's atmosphere, evidence for lakes in the north polar region of Titan, and evidence for outgassing at the south pole of Enceladus. The Mars Express mission, launched in 2003, has been in operation in Mars orbit since January 2004 and has provided us with new perspectives about the Martian atmosphere, the mineralogy of the Martian surface, the nature of its subsurface, and the water history of the planet. Venus Express, launched in 2005, has been operating in Venus orbit since 2006 and has given us spectacular results about the atmospheric dynamics of Venus, and in particular its polar vortex. A two-year mission extension (2010–2011) has been requested for Mars Express and Venus Express. This is fully justified in terms of scientific return, but has not been considered in this report, as the decision is going to be taken before 2009. In the same way, a new extension of the highly successful Cassini–Huygens mission is likely to be considered over the next decade and will be fully justified in terms of science, but it is not considered here, as most of the cost will be covered by NASA.

Furthermore, we are looking forward to the data-gathering phase of the cometary mission Rosetta that is underway to comet 67P/Churyumov–Gerasimenko, arriving at the comet in 2014. Rosetta, the planetary cornerstone of the ESA Horizon 2000 programme, will investigate the origin of the Solar System by studying the origin of comets through the global characterisation of a comet nucleus, the determination of its chemical and isotopic composition and thermal properties. Rosetta will also contribute to the characterisation of main-belt asteroids through the fly-by of two asteroids, 2867 Steins in September 2008 and 21 Lutetia in July 2010.

BepiColombo, the planetary cornerstone of the ESA Horizon 2000 Plus programme, will be devoted to the

Image Credit: ESA/NASA/SOHO

exploration of Mercury. The in-depth monitoring of the closest planet to the Sun will bring information about the composition of the solar nebula and planetary formation in the vicinity of the Sun. The mission will also address the enigma of Mercury's internal structure and the origin of its magnetic field, and will explore Mercury's magnetised environment, unique in the Solar System. The launch of BepiColombo is currently planned for 2013–2014. The mission was being re-examined at ESA at the time of the preparation of the Roadmap and the final conclusions will be known after its publication.

To maintain and strengthen the European position and address the key questions in the Science Vision, some of the existing facilities can play an important role and the extension of current space missions in operation was also evaluated. It is, however, clear that new infrastructure is necessary to fully address the Science Vision questions.

For the evaluation of solar telescopes and Solar System missions, the Panel methodology was similar to that of Panels A and B (as described in Chapter 2), and a large number of infrastructure projects were considered (eleven ground-based, 36 space-based, see Appendix IV). Many projects were not ranked, either because the European funding requirement falls below our threshold (e.g., Solar Dynamics Observatory and mission extension for SOHO) or because all major decision points are anticipated before 2009 (e.g., mission extensions for Mars Express and Venus Express). For the remaining projects (five ground-based, 26 space-based) brief commentaries are given below for the projects that have the highest priority, followed by identified gaps in the project portfolio compared with the Science Vision goals, concluding remarks, priorities and recommendations. For the laboratory astrophysics part, a special report is given in Section 5.6.

5.2 High Priority New Projects

5.2.1 Ground-Based, Medium-Term (2016–2020)

5.2.1.1 *European Solar Telescope (EST)*

The EST is a 4 m-class solar telescope to be located on the Canary Islands (Figure 15). It will be equipped with a suite of post-focus instruments designed to operate together.

Scientific Discovery Potential. The EST has a diameter four times larger than any existing high resolution solar telescope. It will enable observations at unprecedented spatial resolution and sensitivity to magnetic fields. The post-focus instruments will measure fundamental astrophysical processes at their intrinsic scales in the Sun's atmosphere to establish the basic mechanisms of magnetic field generation and removal, and detect and identify the mechanism by which energy is transferred from the solar surface, heats the upper solar atmosphere and eventually accelerates the solar wind. As such, the EST is likely to provide the definitive observations to (i) understand the intrinsic influence of magnetic fields on the Sun's energy output, (ii) establish the nature of the instability that leads to sudden releases of energy and mass that eventually influence life on Earth, (iii) identify the mechanisms that generate and also remove magnetic flux from the Sun, and (iv) pinpoint the non-thermal processes that heat the upper atmosphere of the Sun and other stars. The EST is very important for addressing Science Vision questions D.1, D.2 and D.3.

Image Credit: G. Pérez, Multi-Media Service (IAC)

Figure 15: The artistic concept for the European Solar Telescope, a 4 m-class solar telescope to be located on the Canary Islands.

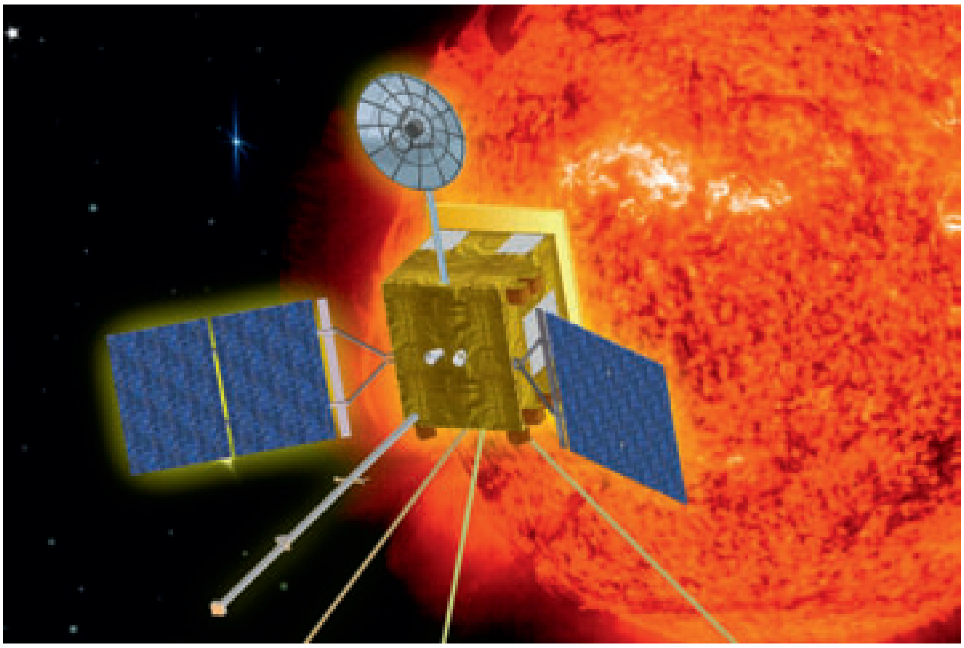


Image Credit: ESA

Figure 16: Artist's impression of the Solar Orbiter spacecraft that will explore the Sun and the heliosphere uniquely from close range and from a vantage point out of the ecliptic.

User Base. Once operational, the pan-European EST will replace the existing national solar telescopes on the Canary Islands (see concluding remarks in Section 5.4) and will be the main observing tool for ground-based European solar physics. As such, a large fraction of the overall solar physics community will use EST. *All* European countries with well-established solar physics communities are represented in the EST and will form the core of the EST user community. Indeed, only the EST will be able to provide the access to a large solar telescope that the European solar community needs to stay at the scientific forefront.

International Context. The EST is complementary to the US-led 4 m Advanced Technology Solar Telescope (ATST) in terms of longitude coverage and focus: the ATST is an all-purpose solar telescope for observations from the UV to the thermal IR as well as off-disc coronal observations, while the EST is focused on the scientifically critical issue of magnetic field measurements at visible and near-infrared wavelengths on the solar disc with an on-axis design optimised for minimum telescope polarisation.

Technology Readiness. Large solar telescopes have been studied over the last 20 years. The Large Earth-based Solar Telescope (LEST) design effort led to the latest generation of national solar telescopes, and the ATST effort is progressing well towards a critical design review. All of the critical technical issues of a 4 m-class solar telescope such as heating of the optics are now well understood and adequate technical solutions have been found. The EST project with its EAST (European Association for Solar Telescopes) consortium has been selected for a three-year preliminary design study (started in February 2008) within the Design Study programme of the Capacities–Research Infrastructures FP7 call.

Industrial Relevance. Much of the EST design will be similar to the design of current night-time telescopes. However, particular attention will have to be paid to the local environment to minimise unwanted heat sources close to and inside the telescope. As such, cooling of the large primary mirror is feasible but challenging, and solutions developed for it may well be of interest to industry.

Timeline and Cost. The conceptual design study (funded with €3.2M from the EU FP7 Design Study programme and €3.5M in matching funds from the participating partners) will be carried out from 2008 to 2010 and will provide a detailed cost study along with a preliminary technical design. Preparation for construction includes the detailed design of all subsystems and the creation of a legal international consortium capable of managing funds from different national sources. This phase is expected to take place in the period 2011–2013 and will require about €7M. Most of the funds will be devoted to subcontracts to private industry. Construction is expected between 2014 and 2019 with an estimated cost (based on a detailed cost breakdown) of €80M. The anual operation costs are estimated at €7.5M/yr.

5.2.2 Space-Based, Near-Term (–2015)

5.2.2.1 *Solar Orbiter*

Solar Orbiter (Figure 16) is a mission going close to the Sun and reaching heliographical latitudes of 30 degrees to enable studies of the solar polar regions.

Scientific Discovery Potential. The principal scientific objectives are to determine the properties, dynamics and interactions of plasmas, fields and particles in the near-Sun heliosphere, to investigate the links between the solar surface, corona and inner heliosphere, to explore, at all latitudes, the energetics, dynamics and fine-scale structure of the Sun's magnetised atmosphere, and to probe the solar dynamo by observing the Sun's high latitude field, flows and seismic waves. Solar Orbiter has become a key component of the joint ESA–NASA HELEX (Heliosphysical Explorers) programme, broadening further the scientific scope towards an in-depth investigation of how the Sun determines the inner heliospheric environment.

The mission objectives have high priority in the Science Vision and the mission is very important for addressing Science Vision questions D.1, D.2, and D.3.

Solar Orbiter is the only mission currently planned with imaging and spectroscopic capabilities from a vantage point out of the ecliptic plane. *In situ* and remote observing from the Sun's close vicinity is another unique aspect of the mission.

User Base. Solar Orbiter addresses key questions in solar and heliospheric physics and thus has a broad user base.

International Context. Solar Orbiter has recently been redefined such that it is now part of a joint ESA–NASA programme called Heliophysical Explorers that comprises ESA's Solar Orbiter and NASA's Solar Sentinels.

Technology Readiness. Going close to the Sun requires heat-shielding technology similar to that being developed for BepiColombo.

Timeline and Cost. Solar Orbiter is the next solar-heliospheric mission in the ESA's science programme. The AO for instruments was released on 18 October 2007. Solar Orbiter has been provisionally selected by ESA with a cost cap of €300M. Launch was scheduled for 2015, but with the cost overruns of the ESA science programme, the programme is being reworked and both the costs and the decision process are now uncertain and launch can probably not be before 2017. The estimated European cost for instruments is €100M.

5.2.2.2 *ExoMars*

ExoMars is the first mission planned by ESA in the framework of the Aurora programme. Its ultimate goal is to establish whether life ever existed or is still active on Mars today. It is designed for robotic exploration of Mars, including a rover devoted to exobiology research (the Pasteur payload) and a Geophysics and Environment Package (GEP) to be accommodated on the landing platform for meteorological and internal structure *in situ* studies. ExoMars will rely on a heavy launcher (Ariane 5 or Proton M), which will launch both the carrier and the descent module. After the lander descent, a rover will be deployed. Both the rover and the GEP will have nominal lifetimes of 180 Martian days. Mission extensions will be possible provided the surface elements are operating properly. The ExoMars prime contractor is Thales Alenia Space — Italy.

Scientific Discovery Potential. The rover will travel several kilometres, searching for traces of past and present signs of life by collecting and analysing samples from within surface rocks and from the subsurface, down to a depth of 2 m (Figure 17). In addition, engineering sensors necessary for the ExoMars Entry, Descent and Landing System will provide an opportunity to perform vital "descent science" measurements. ExoMars is very important for adressing key science questions D.6 and D.7.

User Base. ExoMars is a near-term, top priority for the European planetology and exobiology community. Its main objective is to determine whether life ever existed on Mars or is still active on Mars today. This mission is also a necessary prerequisite to preparing for future, more ambitious missions, in particular a Mars Sample Return mission. All data will be made publicly available in the ESA Planetary Science Archive (PSA), six months after acquisition by the scientific instruments.

International Context. Contributions by NASA (instruments and data relay capability) and Russia (Radioactive Heating Units) are planned.

Technology Readiness. A number of new technologies, particularly for descent and landing, will be developed and used in space for the first time with ExoMars. Many instruments of the Pasteur payload been demonstrated in the laboratory, while other subsystems of the Geophysics and Environment Package are still at the concept level.

Image Credit: ESA

Figure 17: Artist's impression of the ExoMars Rover, which will search for traces of past and present signs of life by drilling into the Martian surface down to a depth of 2 m.

Timeline and Cost. ExoMars is a large-scale, near-term mission. Its total cost is estimated to be a minimum of €950M (possibly more), of which €650M have been secured by a decision of the last Inter-ministry Conference. The remaining funding will be requested at the next Inter-ministry Conference (end of 2008). ESA member states will provide the scientific instruments, estimated to cost €150–200M. The launch of ExoMars is planned for 2013.

5.2.3 Space-Based, Medium-Term (2016–2020)

5.2.3.1 *Cross-Scale*

Cross-Scale will study fundamental properties of the physics of astrophysical plasmas — namely the interactions between the plasma processes that operate simultaneously at different physical scales, essentially electron gyroradius, ion gyroradius and fluid scale (i.e. >> ion gyroradius). The vital role of these interactions has been demonstrated for the first time by Cluster (and is a key result of that mission). Their proper scientific exploration requires simultaneous three-dimensional plasma measurements on the three physical scales and hence simultaneous measurements at twelve points in space (Figure 18, left).

Scientific Discovery Potential. The processes to be studied by Cross-Scale are fundamental to the understanding of the behaviour of astrophysical plasmas throughout the Universe. Cross-Scale will make these studies in the near-Earth environment (magnetosphere and solar wind), which is the only place where high data rates are possible. But the Cross-Scale results will illuminate studies of other magnetospheres (planetary, cometary, stellar, pulsar, etc.) and the many other astrophysical objects in which plasma physics plays a key role (stellar winds, accretion discs, etc.). Cross-Scale will improve our understanding of the microphysics behind key plasma processes such as plasma turbulence, magnetic reconnection and particle energisation — and thus enable the richness of plasma physics to be better represented in models of astrophysical objects. Cross-Scale is very important for addressing Science Vision questions D.1 and D.2.

Cross-Scale extends the European leadership in space plasmas established by Cluster. Its twelve-spacecraft concept offers insights into fundamental plasma processes that are not possible with existing and planned

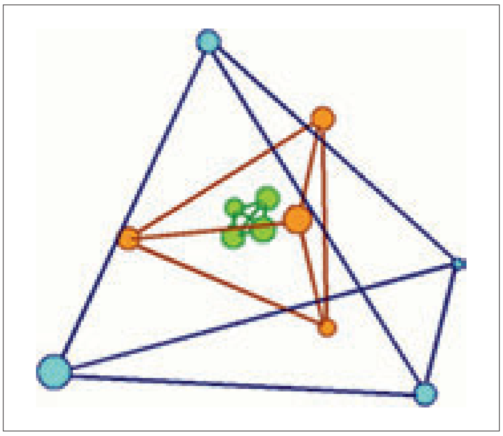


Image Credit: ESA

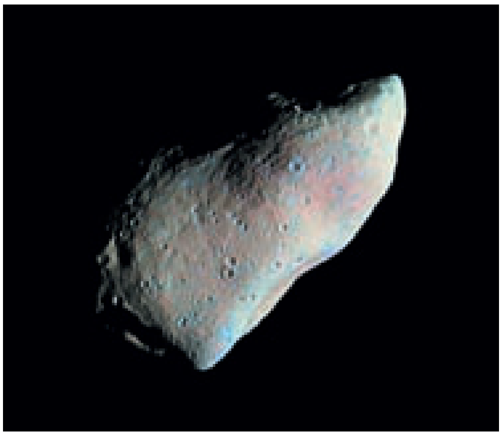


Image Credit: Galileo Project/NASA

Figure 18: Left: The three-nested tetrahedra configuration concept for the twelve Cross-Scale spacecraft. Cross-Scale will quantify the properties of simultaneous, multi-scale interactions in space plasmas. Right: A picture of asteroid 951 Gaspra taken by the Galileo spacecraft during its approach to the asteroid on 29 October 1991. Marco Polo will bring a sample from a primitive near-Earth object in order to improve our understanding of the origin and evolution of the Solar System.

missions. As a result, Cross-Scale has drawn significant interest from Japan and the US. There is no doubt that a European lead on Cross-Scale could draw in technical and financial resources from outside Europe. Europe already has considerable experience in managing shared resources (e.g., on Cluster and Double Star). Thus there is a good understanding of the risks and how to mitigate them.

User Base. Cross-Scale has a large, potential user base in Europe as evidenced by the strong interest in Cluster from many countries. The many young scientists who are today working on Cluster will provide the core of the future user base for Cross-Scale.

International Context. Cross-Scale is a project in partnership with Japan with equal share of costs.

Technology Readiness. The measurement technology needed for Cross-Scale is already well established — namely instruments to measure fields and particles, as on Cluster. One major technical challenge is to reduce instrument mass and power so that the instruments can fit on small spacecraft. This miniaturisation is an active research and development area in which advances have already been made since Cluster was designed twenty years ago. Thus Cross-Scale already has a high technical readiness in terms of instruments. The other major technical challenge is to operate the twelve-spacecraft constellation. This is again an active research area and one where Europe already has relevant experience from Cluster.

Timeline and Cost. The ESA cost is estimated at €300M; an additional €60M is estimated as the European cost for instrumentation. Cross-Scale was selected for further study in Cosmic Vision for possible launch in 2017.

5.2.3.2 *Marco Polo*

Marco Polo is a joint European-Japanese sample return mission to a near-Earth object (Figure 18, right). Its target is a primitive near-Earth object (NEO) whose constituents are unlike known meteorite samples; the target NEO will be scientifically characterised at multiple scales, and samples will be brought back to Earth. Marco Polo thereby contributes to our better understanding of the origin and evolution of the Solar System. Current exobiological scenarios consider the possibility of an exogenous delivery of organic matter to the early Earth, possibly through primitive NEOs. Moreover, collisions of NEOs with the Earth pose a finite hazard to life. For all these reasons, the exploration of such objects is particularly interesting and urgent.

Scientific Discovery Potential. The principal scientific objective of Marco Polo is to return unaltered NEO materials. Samples will be analysed in terrestrial laboratories, preferably including the recommended new European Sample Return Facility (see Section 5.6.3), allowing, in particular, the dating of their histories. Key characteristics of the mission include (i) determining the physical and chemical properties of the target body, (ii) identifying the major events that influenced its history, (iii) searching for pre-solar and organic material and (iv) understanding the role of minor body impacts in the origin and evolution of life on Earth. Marco Polo is very important for Science Vision key questions D.4, D.5 and C.4, and is complementary for C.3.

User Base. The Marco Polo project has attracted wide interest and the project proposal is backed by several hundred scientists from Europe. A total of 436 scientists from countries all over the world support the proposal.

International Context. The mission is based on a collaboration between ESA (providing the launcher and the lander), and JAXA (providing the main spacecraft).

Technology Readiness. A joint ESA–JAXA study is starting the development of a high speed re-entry capsule. Several possible options are presently under study. The current thermal protection technology of the Hasabuya mission is probably sufficient, but with super-lightweight ablators, now being developed, it will be possible to reduce the heatshield mass.

Timeline and Cost. Marco Polo has been submitted to ESA in the frame of Cosmic Vision and has been selected for a pre-assessment study. The ESA cost of Marco Polo is €280M (not including the payload); its total cost is estimated to be €560M. The total cost of the payload, to be supported by the national agencies, is in the range of €40–50M. For ESA, Marco Polo is thus a mid-class, mid-term mission.

5.2.3.3 *Titan and Enceladus Mission (TandEM)*

TandEM[19] is an ambitious project aiming at the *in situ* exploration of Saturn's satellites Titan and Enceladus (Figure 19). TandEM is proposed as a follow-up of the Cassini–Huygens mission, still in operation in Saturn's system, which has led to new discoveries and has raised new questions. The baseline mission concept of TandEM is for two moderately sized spacecraft, to be launched by one or two launch vehicles, which will carry an orbiter, a Titan aerial probe, Titan mini-probes and Enceladus penetrators/landers. The strawman payload provides a strong set of observational capabilities, including cameras, spectrometers, magnetometers, radar, radio-science, seismometers as well as new conceptual instruments scanning all spectral ranges. VLBI tracking of the spacecraft is planned, as was done in the case of the Huygens mission.

Scientific Discovery Potential. The scientific objective of TandEM includes the understanding of cryo-volcanism of Titan and Enceladus, the cycle of methane on Titan (which shows some analogies with the terrestrial water cycle on Earth), the photochemistry and ionospheric chemistry of Titan, and the interaction between Enceladus and Saturn's E-ring, presumably fed by the satellite. TandEM is very important for addressing Science Vision questions D.6 and D.7.

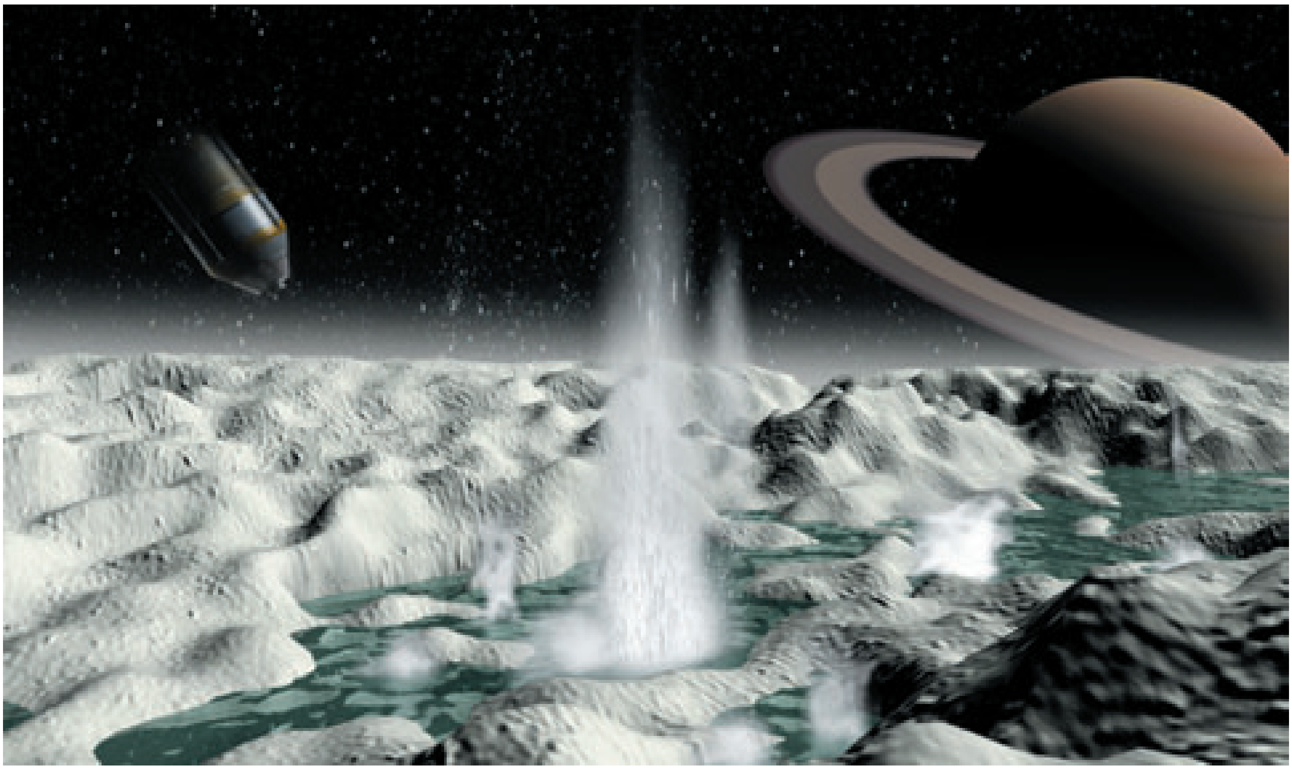


Image Credit: Cnudde@Signal (LESIA)

Figure 19: TandEM is a new mission to Saturn, Titan and Enceladus. It has been proposed to ESA in the frame of the Cosmic Vision and has been selected for a pre-assessment study together with LAPLACE.

User Base. The TandEM mission covers all aspects of planetology science (internal structure, surface, atmosphere, planetary environment), and is thus a top priority for the whole planetology community.

International Context. Collaboration with NASA will be a requisite. The Canadian Space Agency (CSA) is also identified as a partner.

Technology Readiness. The mission will benefit from the Cassini–Huygens and ExoMars heritages, but will also require new technology developments, especially for the Enceladus landers/penetrators, and the Titan balloons and mini-probes. Insertion options like aerobreaking and aerocapture will also be studied. Other critical issues include long-distance communications. A technology implementation plan will be developed during the pre-Phase A study.

Timeline and Cost. TandEM has been submitted to ESA in the frame of Cosmic Vision and has been selected, together with LAPLACE, for a pre-assessment study of one year. The cost of the full mission is estimated to be about €1900M. The ESA part of the budget is €650M, the cost limit for an L-class mission. Assuming the cost of the payload to be about 20% of the cost of the total mission, the anticipated cost of the payload for ESA member states is about €130M. The launch is foreseen around 2021.

5.2.3.4 *LAPLACE*

LAPLACE[20] is an ambitious multi-platform mission to the system of Jupiter and its Galilean satellite Europa (Figure 20). It is building on the in-depth reconnaissance of the Jupiter system by Voyager and Galileo. These missions have revealed, in particular, the uniqueness of Europa, which could shelter a water ocean between its icy crust and its silicate mantle, and might be a good candidate for extraterrestrial life.

The LAPLACE mission will deploy a triad of orbiting platforms in the Jovian system to perform coordinated observations of Europa, the Jovian satellites and the Jovian atmosphere and magnetosphere. One spacecraft will be injected in a polar circular orbit around Europa for a period of at least a few months; the inclusion of a small European impactor in the payload will be studied as an option. A second spacecraft will be placed in an orbit resonant to Europa to serve as a relay for data storage and transmission. A third spinning spacecraft will monitor the Jovian magnetosphere. The payload will include a large range of remote sensing instruments (cameras, spectrometers from gamma ray and X-ray to radio, as well as radar, laser altimeter, magnetometer, micro-gradiometer, dust analyser, mass spectrometer, radio and plasma wave instruments). VLBI tracking of the spacecraft is planned.

Scientific Discovery Potential. The main scientific objectives of LAPLACE are (i) to understand the formation of the Jupiter system, (ii) to understand the physical processes that govern this system, and (iii) to explore Europa's internal structure and its potential habitability. LAPLACE is thus very important for addressing Science Vision questions D.6 and D.7. It is also complementary to addressing D.1 for the study of Solar System plasmas.

User Base. Like TandEM, LAPLACE will address a broad range of planetary objectives and is thus a top priority for the whole planetology community.

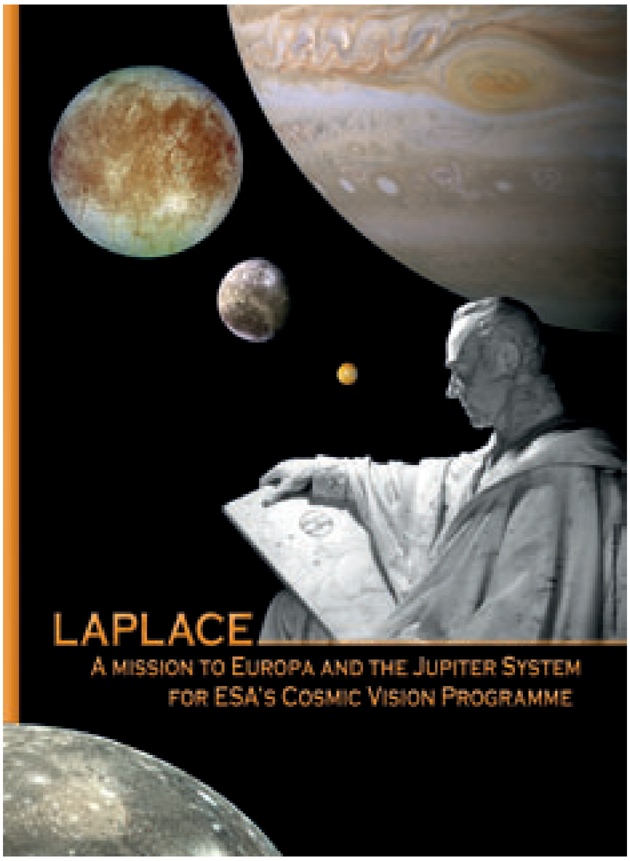


Image Credit: CESR

Figure 20: The LAPLACE mission proposes to carry out an in-depth study of Europa and the Jupiter system. As with TandEM, it has been proposed to ESA in the frame of the Cosmic Vision and has been selected for a pre-assessment study.

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[19] TandEM was submitted to ESA in June 2007 in the frame of Cosmic Vision. Since March 2008, it has been studied in collaboration with NASA under a new name — Titan Saturn System Mission (TSSM). In the context of this document we will keep using the name TandEM as this was the mission concept originally evaluated by Panel C.

International Context. Different options have been proposed for the mission scenario involving the participation of NASA, and other possible partners such as JAXA, at different levels.

Technology Readiness. The Galileo mission and the JUNO mission, presently under development, demonstrate that US technologies are suitable for the Jovian environment. For Europe, a number of specific key technologies will have to be developed, particularly for overcoming the radiation issue and planetary protection aspects while keeping the mass low, and achieving the high accuracy navigation required for science.

Timeline and Cost. LAPLACE has been submitted to ESA in the frame of Cosmic Vision and has been selected, together with TandEM, for a pre-assessment study. Different options have been proposed for the mission scenario, ranging from €650M to €800M with an ESA cost of €650M. Assuming the cost of the payload to be about 20% of the cost of the total mission, the anticipated cost of the payload for ESA member states is about €130M. The mission scenario implies a six-year long Venus–Earth–Earth swingby trajectory, with good launch opportunities in 2017, 2020 and 2023.

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[20] LAPLACE has been submitted to ESA in the frame of Cosmic Vision in June 2007. Since March 2008, it has been studied in collaboration with NASA under a new name — Europa Jupiter System Mission (EJSM). In the context of this document we will keep using the name LAPLACE as this was the mission concept originally evaluated by Panel C.

5.2.4 Space-Based, Long-Term (2020+)

5.2.4.1 *Probing Heliospheric Origins with an Inner Boundary Observing Spacecraft (PHOIBOS)*

PHOIBOS is a mission of exploration and discovery designed to make comprehensive measurements in the never-observed region of the heliosphere from 0.3 AU to as close as three solar radii from the Sun's surface.

Scientific Discovery Potential. The primary scientific goal of PHOIBOS will be to determine how magnetic field and plasma dynamics in the outer solar atmosphere give rise to the corona, the solar wind and the heliosphere. Reaching this goal is a Rosetta-Stone step for all of astrophysics, allowing the understanding not only of the plasma environment generated by the Sun, but also of the space plasma environment of much of the Universe, where hot tenuous magnetised plasmas transport energy and accelerate particles over a broad range of scales. Moreover, by making the only direct, *in situ* measurements of the region where some of the deadliest solar energetic particles are energised, PHOIBOS will make unique and fundamental contributions to our ability to characterise and forecast the radiation environment in which future space explorers will work and live. The mission is very important for addressing Science Vision questions D.1-D.4.

User Base. This is not a facility for general use (in the sense of a general observatory facility), but the data gathered will be available for the wide community.

International Context. Similar missions have been proposed in the NASA system (Solar Probe) and a collaboration is recommended.

Technology Readiness. Going so close to the Sun is technically very challenging and more studies are needed before the mission is technically mature enough for detailed consideration.

Timeline and Cost. PHOIBOS was not selected in the first round of Cosmic Vision, but technology development was recommended. The estimated total cost is €1075M.

5.2.5 Ongoing Space Missions with Probable Applications for Mission Extensions

Mission extensions normally receive a lower score on Scientific Impact than new missions since the "discovery" aspect will normally have been fulfilled in the nominal part of the mission. Extensions can, nevertheless, get high priority because of large supporting value for other missions, because an extension will enable the full coverage of a natural timescale (like the solar cycle) and/or because an extension may give much additional science for a modest cost. Mission extensions mean extending the operations beyond the design lifetime and the decision will depend on the health-status of the spacecraft with the decision point thus close to the start of the extension period. Panel C rated three probable mission extensions highly.

5.2.5.1 *Cluster*

Cluster is the second half of the first ESA cornerstone mission (the other is SOHO). Cluster was launched in 2000 and is in its second extension (until end of 2009). The aim of the Cluster mission is to study small-scale structures of the magnetosphere and its environment in three dimensions. To achieve this, Cluster comprises four identical spacecraft that fly in a tetrahedral configuration. The separation distances between the spacecraft are varied between 20 km and 10 000 km, according to the key scientific regions. Mission operations and archiving at ESA amount to €7.5M/yr and 39 FTEs/yr. This does not include instrument operations in the eleven institutes where at least 1–2 FTEs are used. The cost of operations is relatively high, but the user community is also large. A mid-term review of the present extension was conducted in November 2007. All systems were found to be in good condition and completion of the second half of the second extension was recommended (until end of 2009). There is new science to be conducted during this part of the extension period with the Cluster satellites visiting new magnetospheric regions never studied before by four spacecraft. A third extension to the end of 2012 has been proposed and would provide new scientific possibilities. It is, however, unclear whether the Cluster mission can be extended much beyond the end of 2009; in the mid-term review the end of orbital lifetime (re-entry) for the first spacecraft (Cluster 2) was predicted for June 2011.

5.2.5.2 *STEREO*

STEREO is a NASA-led mission with two spacecraft that orbit the Sun in near-Earth-like orbits, one ahead of the Earth, the other lagging, with the distance increasing with time. STEREO was launched in October 2006. The objective is to get stereoscopic imaging of the outer solar atmosphere and coronal mass ejections (CMEs), observing Earth-bound CMEs all the way from the Sun to the Earth. Europe has contributed about 50% of the instrumentation. The primary mission ends in January 2009 and the first two-year extension has been approved. As the STEREO spacecraft separate, tracing out the Earth's orbit, the mission will move into different phases; a mission extension to 2011 (four years of operation) will allow a detailed study of the three-dimensional Sun and inner heliospheric CME activity, including those directed towards Earth, as we move from solar minimum significantly in the rise towards maximum. A further extension will provide a novel, complete view of the solar sphere (from both sides) coupled with continued observations of CMEs in the heliosphere, including those directed towards Earth. This would be especially valuable in the solar maximum period, from 2012–2014. European costs for a prolongation beyond 2011 are estimated at €3M/yr.

5.2.5.2 *Hinode*

Hinode is a Japanese-led space-based solar observatory with a 50-cm optical telescope, an Extreme UV Imaging Spectrometer (EIS) and an X-ray telescope. Hinode was launched in September 2006. Through a contract with the Norwegian Space Centre, ESA provides a downlink at the Norwegian Svalbard station and a European Data Centre in Oslo at an annual cost of €1.7M. In addition there are the UK running costs for EIS of €0.4M. The ESA contribution provides 80% of the downlink capacity and, since the observing is limited by the downlink capacity, a rather modest contribution makes a great impact on the science return. European funding runs until 2011. A mission extension for an additional five years is a high priority in order to cover a full solar cycle.

5.3 Perceived Gaps

There are several areas of instrumentation that are strongly called for in the Science Vision, but where there are no major new projects in Europe or where the projects are not programmatically ready. International collaboration and further development of existing and new technologies in these areas should be encouraged in order to fully address the challenges set out in the Science Vision. In particular, Panel C has identified the following areas:

- Radio spectral imaging of the Sun at centimetre to metre wavelengths is essential for measuring magnetic fields in the corona, to identify sites of particle acceleration and to track travelling disturbances through the corona. There is a wide range of expertise in solar radio astronomy in Europe, especially at decimetre and metre wavelengths that should be retained.

- A medium-aperture (1–2 m) (extreme-)ultraviolet satellite facility with X-ray capabilities, incorporating subarcsecond resolution imaging and spectroscopy, cadences down to seconds and wavelength selections appropriate to the temperature range of the solar atmosphere — up to relativistic electrons — including, for the first time, (extreme-)ultraviolet magnetic mapping of the solar transition region and corona, to study fundamental solar processes that cannot be studied from the ground, is very important for SV question D.1 and complementary for D.2 and D.3. Technological development is needed in the areas of UV polarisation optics and large-format UV detectors. Furthermore, the mission concepts proposed within Cosmic Vision require formation flying with optical components mounted on different spacecraft. This has not been done to date and such capability needs to be developed and demonstrated.

5.4 Concluding Remarks and Priorities

Current ground-based solar telescopes on the Canary Islands (VTT/Gregor, THEMIS, SST, DOT) were included in the survey to get an overview of the operating costs. It is important to provide adequate access to modern solar telescopes for the European community until the EST is completed to address the Science Vision key questions D.1–D.3. The technical expertise in the groups currently operating on the Canary Islands also plays an important role for the design efforts of the EST. It is foreseen that much of the current operating costs (about €2.5M/yr) can be transferred to the EST and most of the present facilities will then be closed down.

Two ground-based radar projects (SuperDARN and EISCAT_3D) were surveyed. Although it is crucial to study the full Sun-Earth system, and it was recognised that these radar facilities are key to addressing some of the key questions in the Science Vision, such large, multipurpose facilities with a main scientific emphasis in other areas fall partly outside the ASTRONET remit. Thus, we note their value to the Science Vision and encourage support for such activities.

Some of the goals in the Science Vision are best accomplished with smaller facilities that fall below the cost limit of this Roadmap. An important example is a global network of ground-based, synoptic instruments that continuously monitor magnetic and velocity fields as well as spectrally resolved radiative output over the full solar disc with sufficient spatial resolution. Small facilities are also important in studying the Sun-Earth system as the terrestrial response to solar activity/space weather is best characterised by making simultaneous measurements at many different locations around the Earth. Small facilities and small instruments on strategic spacecraft also provide key measurements in understanding space weather and indeed longer-term space climate issues. To ensure the scientific productivity of these smaller facilities/instruments, it is vital that their development, construction, and operation are well coordinated among one another and with space missions.

During some of the work on the Roadmap, it seemed as if all major decision points for Solar Orbiter would be in 2008 and it would thus be outside the scope of this document. With the cost overruns in the ESA science programme this is not likely to be the case any more and Solar Orbiter is therefore now included in the prioritised Roadmap. At the time of evaluation, Solar Orbiter was a near-term project with a planned launch in 2015. It is kept in the near-term category to emphasise the project maturity and its status as a selected project, although a launch in 2017 now seems more probable for budgetary reasons. Among the medium-cost, space-based projects, Solar Orbiter is the top priority project of Panel C.

Again, among the mid-term, medium-cost, space-based projects Cross-Scale was ranked above Marco Polo using our evaluation criteria. This was based on the large discovery potential of Cross-Scale, the importance for the understanding of astrophysical plasmas in general and thus the larger user community.

TandEM and LAPLACE were both given the highest ranking. We do not prioritise between these two projects because they will both have to be modified in the next year during negotiations with other agencies. They are kept in the mid-term category since they were submitted to the Cosmic Vision call in that time perspective although the probable launch date will be after 2020.

5.5 Recommendations

To keep the European leadership in solar physics and properly address key questions in the Science Vision it is important that the EST is implemented as early as possible. Given the previous design efforts (LEST, ATST and the ongoing FP7 pre-design project) the technology readiness is high and the EST should also be included in the ESFRI roadmap in the next revision.

Among the medium cost, space-based projects, we recommend the implementation of Solar Orbiter, Cross-Scale and Marco Polo, in this order of priority.

A medium-aperture (1–2 m) (extreme-) ultraviolet satellite facility with X-ray capabilities to study fundamental solar processes that cannot be studied from the ground is a long term goal of high priority. Necessary near- and mid-term steps towards such a future mission are technology studies of UV polarisation optics and large-format UV detectors and the application of the relevant technologies in small-scale space projects demonstrating the scientific capability of solar UV magnetometry.

Finally, one should emphasise the key role played by Europe in the field of planetary space exploration, which has emerged over the past decade. This is illustrated in particular by the success of Cassini–Huygens, Mars Express and Venus Express, as well as the first round selection of several planetary missions following the Cosmic Vision Announcement of Opportunity. In the near term, ExoMars is the high priority mission for the European planetology and exobiology community. In the mid- to long-term, both TandEM and LAPLACE are top priority missions devoted to the outer planets and their environments. Both missions (one of which is to be selected for further consideration by ESA in 2009) deal with all aspects of planetology (internal structure, surface and atmosphere, planetary environment, Solar System formation and evolution), and also have implications for exobiology. They are strongly supported by the whole planetology community.

5.6 Laboratory Astrophysics

5.6.1 Introduction

Investment in laboratory astrophysics (Figure 21) is highlighted in the Science Vision recommendations as a high priority for all of astronomy. It is identified as a cross-disciplinary requirement that appears in most if not all of the main themes. However, research in Europe is significantly under-funded, fragmented, and does not generally feature in national astronomy roadmaps.

Current astronomical observations and missions are yielding datasets of increasing size, depth and complexity, but these advances have not been matched by growth in knowledge of fundamental physical properties and processes at nuclear, atomic and molecular levels. This knowledge is crucial for the interpretation and exploitation of data and for use in probing conditions in astronomical environments. Forthcoming programmes promise further acceleration in data acquisition and the risk of an even wider gap developing.

The Panel, with input from Panels A, B and D, reviewed current research ranging from dedicated laboratory-based groups to large facilities. Present activity is conducted largely through response-mode national funding of independent university or institute-based groups, in

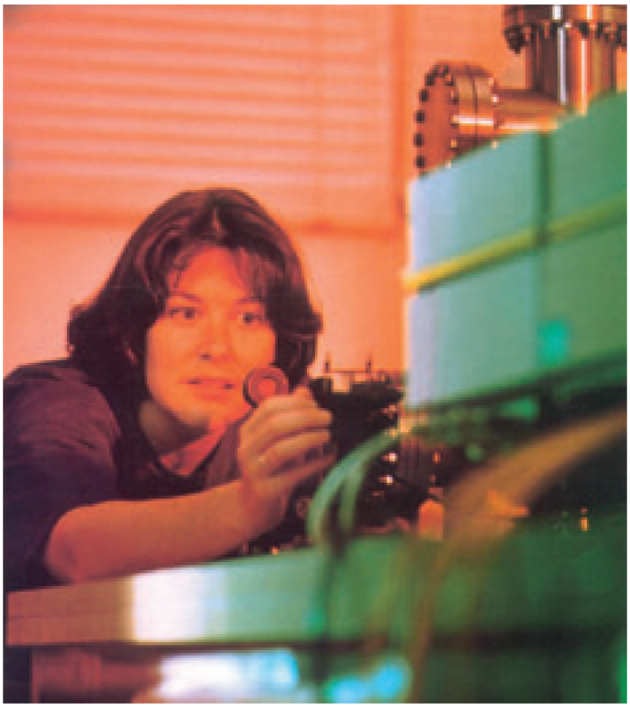

Image Credit: Peter Sarre

Figure 21: An illustration of laboratory astrophysics: aligning the optics for a laser spectroscopic measurement.

part through EC FP6 networks, and as a small component of research at facilities such as synchrotrons. The study gave less emphasis to astroparticle astrophysics which, while of great importance (see discussion of the Science Vision Panel A in section 2.2.2 and 6.2. of the Science Vision) and includes e.g., underground nuclear recoil facilities, is the subject of the ERA-NET ASPERA Programme[21] for which the Roadmap Phase I has been published. The Panel adopted a definition of laboratory astrophysics/studies as "laboratory physics, chemistry and biology, and theoretical calculations and modelling, of atomic, molecular, nuclear and solid-state properties, processes and associated astrophysical phenomena that are required to ensure the success of current and future research programmes in European astronomy". A complementary priority in the Science Vision recommendations is the need for computing resources, which are essential for the delivery of theoretical, dynamical and simulation calculations at an atomic and molecular level, and of astronomical phenomena, environments and feedback mechanisms. With the exception of a proposed sample return facility, no one element of the proposed programme exceeds €10M capital cost and/or €10M operational cost over five years, but the cumulative cost across Europe does so. The Panel was also mindful of relevant activity outside Europe such as the NASA Herschel Science Center Call for research proposals in Laboratory Astrophysics, Data Analysis and Theoretical Research.

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[21] http://www.aspera-eu.org

5.6.2 Relation to the Science Vision

The Panel considered current and future laboratory astrophysics requirements under the themes of Observational Astronomy (extrasolar), Planetary and Solar Astronomy, and Sample Return and Meteorite Analysis, with reference to four broad laboratory topics: Collisions, Plasmas, Reactions and Simulations; Spectroscopy; Earth-Based Sample Analysis and Detectors, and Computational Modelling and Data Analysis. In terms of key questions in the Science Vision Report, the Panel highlights the need for support particularly for the following:

In understanding the extremes of the Universe, there is a clear requirement for dark matter (A.2) and gravitational-wave detection experiments (A.4). High precision measurement of atomic spectral lines and their excitation is a high priority for current missions and XEUS/IXO (Section 3.2.3.1); time, frequency and fundamental constant studies should be explored using ultra-stable laser clocks and high resolution spectroscopy (section 2.2.3 of the Science Vision). In the field of galaxy formation and evolution, we identify the need for laboratory studies of dust and molecules as observed at high redshift through current multi-wavelength ground and space observations including Spitzer, and new facilities including ALMA, Herschel, JWST and the SKA (B.6).

Laboratory and theoretical effort is required to refine nuclear reaction parameters, stellar opacities and the equation of state of stellar matter in order to understand stellar structure and evolution (C.2). Investigating the origin of stars and planets formed from molecular clouds, and the lifecycle of the interstellar medium and stars, requires a wide range of laboratory measurements and calculations (C.1, C.3). These include atomic, molecular and solid-state transitions and oscillator strengths, particularly at long wavelengths in connection with Spitzer, Herschel, ALMA and the SKA, which will yield a wealth of new and largely unidentified spectral lines. A key goal is to provide the database to enable exploitation of atomic, molecular, ice and dust features as diagnostics of the processes associated with forming stars and planets. Measurement, theory and modelling of collision cross-sections, gas-phase and grain surface chemical reactions, photo-processes and plasmas, together with chemistry induced by energetic processing, radiolysis and photolysis of ices, is required. Spectra of "hot" molecules are needed to interpret data on the late stages of stellar evolution and dwarfs (C.3). High energy density laboratory astrophysics embraces extreme conditions of pressure, temperature, velocity and radiation flux; it is essential for studies of the microphysics of stellar and planetary interiors and of violent events such as occur during star formation, including outflows, jets and shocks (C.1–C.3).

For studies of planetary system formation and evolution, coagulation experiments are required for a range of particle size and composition, together with numerical modelling of the aggregation of larger sized particles (C.4, D.4). A particular objective is to chart experimentally and theoretically the transition from simple to prebiotic molecules that may form the basis for life in other planetary environments (C.4). In the search for evidence for life on exoplanets, chemical and spectroscopic modelling of atmospheres, including biosignatures, is needed as a prerequisite for observational studies (B.6).

Concerning *How do we fit in?* (D), studies of the Solar System inform us about astrophysical processes when coupled with experimental and theoretical research on solar/stellar physics including winds, magnetospheres, high energy atomic lines, cometary and asteroid composition and charged particle interactions with the atmospheres and surfaces of planetary environments (D.1–D.5).

For Solar System exploration, techniques and infrastructure for sample return, interplanetary dust and meteorite analysis are crucial. Laboratory work on planetary analogue materials is required: measurements of optical properties (indices of refraction, reflectance, emittance, extinction efficiencies) and physico-chemical analysis of minerals and their mixtures, rocks, dust/aerosols and ices, analysis of the structure of materials (amorphous *v.* crystalline) and processes inducing amorphisation cf. crystallisation (D.4, D.5).

In searching for evidence of life in the Solar System, there is a clear need for a major dedicated European facility for sample analysis and curation, particularly for sample return missions with potentially biologically significant samples from e.g., Mars, but also more generally for asteroid, cometary, meteoritic and Solar System/interstellar dust samples (D.5). Astrobiological (e.g., appearances of extremophiles) and planetary simulation experiments linked with numerical modelling are needed to explore fully the prospects for life elsewhere.

Finally in this section we address two important general points. First, it is crucial that the value and use of all laboratory and theoretical data be secured long term through establishment of a European database with active scientific quality assurance, scientifically informed documentation and easy web-based access. This can be provided in a network-based framework and linked with the Virtual Observatory (Chaper 6). Secondly, it is emphasised that while new observations and missions have clear requirements, there already exist numerous astronomical observations and mission data that demand laboratory studies to allow full exploitation. These include, for example, high energy spectral lines, cometary data and unidentified dust-related spectroscopic features of the ISM; these studies are also integral to the programmes proposed here.

5.6.3 Recommendations

It is proposed that laboratory astrophysics programmes outlined above be accomplished in practice through:

(i) New European Laboratory Astrophysics Networks specifically dedicated to fundamental laboratory experimental, interpretative and computational research and modelling, and database provision for spectra, cross-sections, reaction rates, analogue materials etc. This includes provision of funding to cover running costs for experiments and postdoctoral researchers. Part of the implementation could be through ASTRONET joint calls.

(ii) Individual laboratories in Europe funded through competitive awards including funding for laboratory astrophysics instrumentation.

(iii) Introduction of a European Research and Technical Fellowship programme of jointly held positions that will enhance contact between laboratories and will complement the objectives described by Panel E (see Chapter 7).

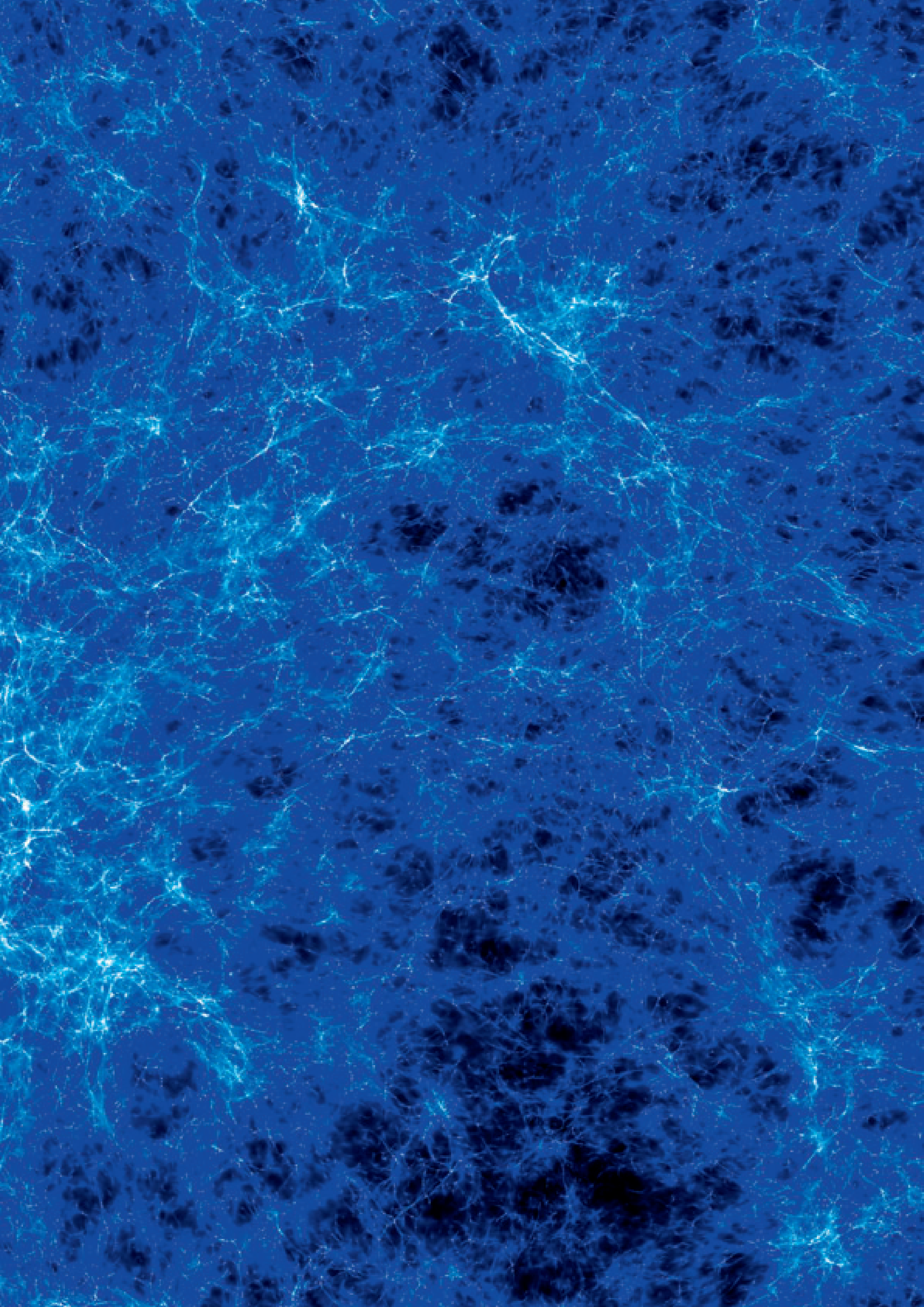
These three initiatives constitute a strategic plan to coordinate and synchronise joint efforts of separate laboratories, the principal objective being to increase the size and efficiency of research in laboratory astrophysics for the benefit of European astronomy.

We also strongly recommend development of:

(iv) A major dedicated European facility for analysis and curation, particularly for sample return missions. Samples returned from, e.g., Mars need to be quarantined until their biological nature and safety has been determined. A thorough discussion of these factors and risks is presented in the 18328/04 ESA Report, reference CR(P4481). Given the precious nature of such samples, it is essential that the most up-to-date analytical techniques are available in the facility. Coordination on a European scale is vital to the success of the facility.

5.6.4 Costs, Training and Industrial Relevance

The Panel recommends a step change in coordinated European-wide funding for laboratory experiments, associated theory and computational modelling, as well as training of skilled personnel in close conjunction with European astronomy facilities and missions. As a core fundamental element, and as a guide, it is recommended that funding provision for laboratory astrophysics be included in the planning of all astronomical and space mission research programmes at a level of the order of 2% of overall budgets, with each programme taking "ownership" and peer-review of this part of the project. Significant European coordination of laboratory astrophysics is essential to keep this activity as an active research subject at the interface between astrophysics, physics and chemistry. In addition, for (i), (ii) and (iii) the step change requires expenditure of *c.* €10M/yr with (iv) being *c.* €80M capital building and instrumentation and €6M/yr running costs (with reference to the costings in the ESA Report CR(P4481), see the summary in Table 4, Chapter 8). A particularly attractive aspect of laboratory astrophysics is its intimate link with the training of research and technical personnel who will be well equipped to contribute to European industry across a wide range of technologies.



Chapter 6 Theory, Computing Facilities and Networks, Virtual Observatory

(Panel D)

6.1 Introduction

Proper return on public money invested in observational facilities requires that theory is also adequately funded, both to ensure that the observational programmes are formulated as incisively as possible, and generally to maximise the scientific return on the data taken. There cannot be a roadmap for "pure theory", which is unpredictable and transcends all individual instruments, but, nevertheless, proper support of computing facilities and competitive means to transfer and handle datasets, both from the observations and from simulations, is of great importance, and the purpose of this document.

It is widely recognised that a new era of observational astronomy is opening: an era dominated by large/deep surveys (2MASS, GOODS, SDSS, VISTA, VST, LOFAR, RAVE, Gaia, etc.) with extended multi-wavelength coupling and exploding data rates. The new observational products are changing the way the community works: much work is now done by multi-institute collaborations, service observing is becoming standard, and formerly isolated colleagues now have access to cutting-edge data in archives.

The Virtual Observatory is a global effort, launched in 2000, that is driven by these developments. It aims to give any astronomer access to all the astronomy data in the world as if they were installed on her/his local computer. As we realise this vision, the number of people working at the frontier of astronomy increases and multi-wavelength studies become much easier. The current effort is already having an impact, with notable increases in data access via VO protocols, the first set of VO-based papers, and the adoption of VO infrastructure by several upcoming space- and ground-based large surveys. Moreover, VO opens access to simulated data (TVO, or theoretical VO).

The way theorists work, and the infrastructure that supports them, has to evolve in parallel with the changes in observational astronomy that are driving, and will be driven by, the VO. Relevant considerations include:

- Complex datasets require complex models.

- More powerful computers make such models feasible.

- Several key problems can only be realistically tackled when a large dynamic range is achieved; for example, turbulent mixing in evolved stars or star formation in a cosmological context.

- State-of-the-art supercomputers (which have only short lifetimes) must be purchased on national or even continental scales.

- Producing code that runs on massively parallel, distributed-memory machines requires a different range of skills from those normally acquired by physicists and astronomers.

- Similarly, specialist skills are needed to produce the kinds of graphical user interfaces that make codes easy to use.

- Given the complexity of the datasets, and the power of the models, it is better to resort to forward modelling, i.e. include observational biases in the models rather than correct the data.

- New layers of code are then required to "observe" models and to compare them with large datasets.

These considerations are increasing the complexity and expense of theoretical work (Figure 22). In addition, there is the tendency for codes to become more complex as fields mature. For example, 30 years ago a student could write a competitive N-body code in a couple of months. Now the state-of-the-art is defined by codes that have been refined over years and employ a range of technologies developed over three decades. Hence, a student or post-doc who wants to work on galactic dynamics will usually download one of a handful of standard codes. The same situation applies in hydrodynamics, or cosmology (for a list of such codes, see Appendix V.C). While every effort should be made to keep innovation alive by breaking down barriers to the development of entirely new codes, we have to recognise that much work is going to be done with a restricted number of widely used codes that are the theoretical analogues of major observational instruments. The vitality of the field and the health of smaller institutions will be best served

Image Credit: Horizon Project/Mare Nostrum

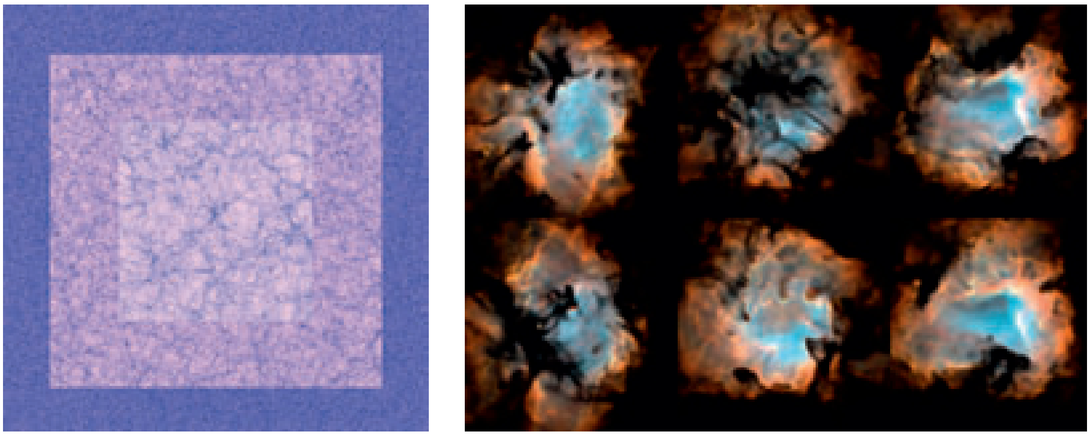


Image Credit: Project Horizon

Image Credit: Garrelt Mellema

Figure 22: Examples of two state-of-the-art simulations. Left: The Horizon-4pi simulation (multi-scale view) — the largest N-body simulation of the evolution of the large-scale structure of the Universe ever performed. Right: Six views into a three-dimensional radiation hydrodynamical simulation of an ionised region inside a turbulent molecular cloud.

if an infrastructure exists that facilitates and encourages wide access to standard codes and encourages their continual evolution.

Thirty years ago the results of a theoretical study could be published in a few graphs. Massive computers, simulating complex systems in three or six dimensions, produce vast outputs, which can be only very partially characterised within a paper. For example, even the reduced results of the Virgo cosmological simulations include a vast database of dark halos, which colleagues around the world can analyse in many different ways.

These considerations do not imply that simple theoretical models will not continue to play an important role in astronomy. They will, and some of them will spawn a family of new standard codes. But while small-scale modelling will continue to flourish regardless of strategic action taken now, large-scale modelling of the type that is essential for the development of astronomy will flourish fully only if we now put in place appropriate supporting e-infrastructure. In the following sections we consider elements of this infrastructure.

6.2 The Virtual Observatory (VO)

The necessity of e-infrastructures has been recognised — e.g., by the European e-Infrastructure Reflection Group (e-IRG) — across many disciplines (biology, geoscience, meteorology). Common requirements include the preservation and management of distributed digital data archives, access to electronic resources, support of virtual communities and use of network, grid and computational capacities. The Virtual Observatory is the e-science initiative for astronomy.

Like the World Wide Web, the VO is not a monolithic system, but relies on a set of standards. The core components of the VO infrastructure are standards for "publishing" data and services, metadata standards for describing data, interoperability standards for tools, and standards for distributed storage and for access to computational and grid resources. A registry of the available VO resources is dynamically updated for the end user. These components are implemented as "interoperability layers" on top of data repositories and yield a scalable system suitable for publishing datasets of any size.

The VO is in the early stages of deployment, thus much of the software that is currently being written is infrastructure software. However, 84% of the facilities surveyed by Panels A, B and C (see Appendix IV) indicated plans for a public data archive, and 53% of those are committed to publishing datasets and resources to the VO. Since these include the majority of the large data providers (e.g., ESA, ESO, LOFAR, etc.), this implies VO compliance of a much higher percentage of the actual data volume. VO projects are now ramping up support to data centres as they implement VO standards, and there is little doubt that by the end of the next decade most astronomical data will be VO compliant. Indeed a growing number of refereed papers are already being published using early VO capabilities.

The development of VO standards is coordinated by the International Virtual Observatory Alliance[22] (IVOA), which was formed in June 2002 and now comprises sixteen VO projects (Figure 23). European VO initiatives are coordinated via the EURO-VO consortium, which comprises ESO, ESA and six national research organisations and VO initiatives. The status of the VO in Europe is described in Appendix V.A. About 100 FTEs have been involved in VO projects in Europe over the past four years or so. The Organisation for Economic Co-operation and Development (OECD) has recognised the importance of the VO and the progress of the IVOA, and that the support of data and data service access cannot be separated from the support of new scientific capabilities (see Appendix V.A).

As for quality assessment, the VO is an open system, where users must take into account the suitability and quality of the available resources for a given purpose. VO metadata describes the provenance of data and links to its documentation, but the data centres themselves control the quality of the data and services they publish to the VO. Registries offer a flexible mechanism for grouping VO resources so that institutes or communities may curate registries for a given theme, or as a set of "trusted" resources. Journal refereeing ensures scientific quality, and the VO may enable new aspects to this such as publishing workflows alongside the scientific results they produced. As well as easing simultaneous access to multiple resources, both observational and theoretical, the VO promises to open up new areas of parameter space in coming years and enable new science.

The IVOA has developed a first set of core standards, and many projects have used prototype systems and tools to demonstrate the capabilities of VO systems. Scientific results have already been obtained, and the flexibility and new capabilities of VO systems is stimulating innovation in the way distributed data are delivered and used.

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[22] http://www.ivoa.net

Image Credit: IVOA

Figure 23: The sixteen members of the International Virtual Observatory Alliance. Starting from the top and going clockwise: EURO-VO, China-VO, VO-India, Canadian VO, Spanish VO, Vobs.It (Italy), Armenian VO, French VO, GAVO (Germany), Hungarian VO, Japan VO, Korean VO, US VO, Russian VO, AstroGrid (UK), Australian VO.

6.2.1 Future Development of the VO

The immediate future for VO projects in Europe will see a transition to operational systems. The national VO projects have implementation plans geared towards the priorities of their communities. EURO-VO activities will be guided by the Astronomical Infrastructure for Data Access (AIDA), a three-year integrated infrastructure initiative starting in 2008 that ranges across all areas of EuroVO. AIDA will:

- Build a community of science users through its Science Advisory Committee and science workshops.

- Assist the large-scale deployment of IVOA protocols and standards by data centres, especially by providing tools and tutorials on the use of the VO.

- Maintain and develop the VO technical infrastructure.

Synergy with European initiatives addressing similar issues (e.g., EuroPlaNet) is being pursued.

While AIDA and national projects will provide support for the implementation of protocols, the onus of operating the physical systems that store the data, building and maintaining the archives and services, is on the data centres and research institutes. Furthermore, the infrastructure already established with EC support will need to be sustained to allow continuity of the VO. This would naturally fall within the scope of the national funding agencies.

The tools that astronomers will use to access data and services in the VO are rapidly maturing. The current strategy is to prototype tools in step with the development of VO standards, so that both the tools and standards meet the expectations of scientific users. The near term (five years) should usher in a new generation of astronomy tools that combine and use distributed multi-wavelength data in an efficient, interoperable manner. This also includes VO interfaces to legacy applications and familiar astronomy software and common scripting languages. In this respect, it would be important to establish standards for interfacing software applications and reference architecture to enable easy integration and sharing. This is currently being addressed by the OPTICON FP6 Network 3.6, Future Astronomical Software Environments.

In the longer term (ten years) the development of the VO is expected to merge into the standard practices for delivery of astronomy data. The scientific development is expected to be rich in innovations as VO leverages on data mining and semantic technologies. The VO is expected to open up new capabilities for multi-wavelength combination of data across archives and processing of large data volumes. Also, in concert with rapid whole sky surveys, the VO will open up new discovery windows in time domain and event-based astronomy.

6.2.2 VO Compliance

Making an archive or service VO-compliant with the core VO standards is intended to be no more difficult than current web publishing methods. VO standards do not dictate in any way the architecture, database system or language of archives. Existing databases are typically made VO-compliant by a translation layer that converts incoming requests from VO systems into the local commands that run a query on the database. Data from future instruments will likely be published to the VO as a matter of course. VO publishing of legacy material can present challenges due to missing metadata or the need for additional curation. The effort required depends on the complexity and intended function of the archive. The provision of content in the VO is a current priority, and uptake of the standards and translation layer tools is ongoing at many data centres, with the EuroVO Data Centre Alliance (DCA) providing workshops and materials in order to coordinate these efforts across Europe.

The combination of data across the spectrum with the VO works best when advanced (science-ready) data products are provided by data centres. Moreover, many of the facilities in the Roadmap will require complex data processing that will necessarily be done by dedicated pipelines. Finally the production of scientific products suitable for ready consumption by the public and educational bodies is an important aspect for facilities as highlighted by Panel E (see Section 7.4.2). Many data centres are actively pursuing the creation and collection of science ready products, and such activities should become the norm for data providers.

6.2.3 Computing within the VO

The vision for the VO requires significant computational resources, for example, to cross-match archives, to apply data mining algorithms, or to compute a theoretical model on the fly. Given the diversity of uses for the VO, there is no single favoured computational architecture. Instead, the VO standards provide, via the IVOA Grid and Web Services working group, very basic interface descriptions for communication of remote executive tasks.

The VO relies on the development of the grid-computing infrastructures described below. In a very general sense the VO concept may be considered as a domain-specific example of a service and data grid.

6.3 Impact of VO on Theory

The VO is both a challenge and an opportunity for the development of theory. At the simplest level, groups that produce bodies of theoretical data, such as atomic oscillator strengths and electron-collision cross-sections, or stellar isochrones, need to publish these data to the VO. This should be as straightforward as making observational data VO-compliant. Groups that simulate astrophysical systems face a much more complex task because their simulations need to be reduced to VO-compliant pseudodata, preferably at many different wavelengths so that the models can be tested against all current datasets. Theory-specific aspects of VO infrastructure are under consideration in the IVOA Theory working group.

At a still deeper level, the VO provides a paradigm for the use of standards to connect a wide range of complex objects that could transform programming styles in a way that would enormously enhance the power of the VO and thus the rate of progress in astronomy.

A requirement to project the results of models into the observational domains of several instruments is extremely challenging: each instrument will have its own biases, and the radiation it measures is likely to be produced by different physical processes. Consider, for example, what will be involved in testing a model of galactic evolution. UV to near-IR rest-frame colours will be needed to compare with the VISTA Hemisphere survey; these must be obtained by combining a population-synthesis code with a code that handles radiative transfer (line excitation and dust scattering). The dust model will use very different physics to predict far-IR fluxes for comparison with ALMA data. Continuum radio fluxes measured by LOFAR and the SKA will be predicted from both the population-synthesis model (which governs the rate of production of supernova remnants) and a model of the interaction of AGN in interstellar and intergalactic gas. These in turn yield X-ray fluxes, which again involve absorption, line emission and the population-synthesis model (which must predict the stellar X-ray emissivity). In principle the VO will enable us to achieve a high degree of rigour by simultaneously fitting to all relevant datasets simultaneously, but the software challenge involved in attaining this goal is formidable.

Overwhelming challenges are best addressed by the subdivision of labour: if subproblems can be identified, and standard interfaces between them specified, individual work packages can be made small enough for a single theorist or theory group to make progress on a reasonable timescale.

The argument here is that the VO poses challenges at two levels. The relatively straightforward challenge is to produce pseudodata outputs that are VO-compliant in the sense that they can be searched by the same engines as real datasets. Individual theory groups could produce such VO-compliant pseudodata themselves simply by reading and encoding the relevant VO specifications, but there are clear economies to be made by sharing the relevant software throughout the community. Moreover, relevant software is usually written when an instrument is being designed, so significant economies might be made by publishing this software in VO-compliant form as part of the instrument-building process.

A much harder, but potentially more rewarding, challenge is to borrow the idea of standards for interoperability from the VO and to use it to build codes that are made up of modules that couple together in standard places and in standard ways. For example, within the galaxy evolution code above one can immediately identify modules to do stellar dynamics, gas dynamics, radiative transport, and population synthesis. The stellar dynamics module is made up of a Poisson-solver and a particle mover, while the hydrodynamics code might include a grid generator, a Riemann solver and a star-formation simulator. Modularisation along these lines has many advantages: smaller code segments make version control and debugging easier and reduce the range of expertise required to contribute to cutting-edge simulations, while the effects of changing numerical methods or input physics can be readily tested by changing one module at a time.

6.4 Astrophysical Software Laboratory (ASL)

To achieve these goals, several steps need to be taken. First, the authors of powerful codes need to be motivated to make their codes generally available, and helped to support and develop them. Second, potential users of these codes need to be helped to understand their structure, limitations and use. Third, the community needs forums in which to establish standard modules and their interfaces.

The Panel believes that a European centre, dubbed the Astrophysical Software Laboratory could make these things happen. The ASL would be a laboratory without walls: guided by a Director and an expert steering committee, it would allocate funding for software support, user training and the establishment of modular standards. The Director of the ASL would probably have about a half-time appointment of limited duration.

Authors of codes could apply to the ASL for funds to be spent on code development and/or training and support of users. In return for this funding, the authors would commit themselves to both the open-source model and compliance with ASL modular standards. Funding would be granted only to outstanding codes, and the level of funding of the modest number of codes supported would be generous. The funding would be for a limited period of three to five years, but could be renewed after a successful review. While one goal of the ASL would be to keep existing codes at the cutting edge, it would also aim to encourage the emergence of new codes by identifying future leaders and supporting their work.

Code development could involve either the extension of the code’s capability (for example, adding magnetic fields to a hydro code), work to achieve modularity, or work on user interfaces; consequently the personnel employed might be postdoctoral astrophysicists or professional programmers. Training and support could consist of running workshops for users and developers, writing documentation, or maintaining a website/wiki, etc.

The ASL would convene meetings of knowledgeable people to develop a set of modular standards. The Panel emphasises that the ASL should work in both directions: encourage the development of new codes from scratch, and to extend and improve existing codes, and also to optimise and adapt them to new architectures.

It is likely that the activities of the ASL would, over time, have a positive impact on the European software industry, both through its drive for modularity, and through its training activities.

6.4.1 Collaborative Networks

Just as observational astronomers form large collaborations to get a big survey done, so collaborations of theorists have arisen to get large simulations run — the Virgo and Horizon collaborations are two examples of such consortia (see e.g., Appendix V.D). Not only are such consortia likely to encourage modularisation, but also they are more likely to command the resources needed to model large observational datasets and properly to exploit the VO. Hence funding arrangements should facilitate the formation of pan-European consortia and the ASL would provide an appropriate coordinating and/or funding body.

Networks might be of two types. Some would focus on particular scientific problems, such as general-relativistic simulations, or star formation, while others would focus on computational techniques, such as model evaluation or magneto-hydrodynamics. Some networks might comprise users of a particular piece of software, such as GADGET2. These networks could play an important role in the development of the ASL’s modular standards, and they would facilitate cross-fertilisation between fields and the spread of best practice.

6.4.2 ASL Structure and Role

Postdoctoral positions would play an important role in making a network a reality. We estimate the manpower required in the ASL at 50 FTE. For a large part, this number relies on researchers already there at the national levels. But some additional funding is required to create the dynamics of the ASL and to build the steering committee. The positions required will essentially be scientists, but there could also be specialised engineers to help the researchers in the parallelising and optimisation of the codes. However computer scientists are not included, because the astrophysics research should lead the work, and not the research in computational science.

A question may arise for the future career of a post-doc working in ASL. Code building and testing is a captivating task, slowing down the writing of astrophysical papers. The same problem arises for people working on instrumentation, or writing packages for an instrument, a pipeline, or data reduction software. In general these young scientists join consortia to collaborate in publications, and the ASL should provide an environment for them to have these opportunities.

The ASL (its steering committee and Director) should make proposals to the European pan-science top-tier computers (e.g., through DEISA, the Distributed European Infrastructure for Supercomputing Applications or DECI, the DEISA Extreme Computing Initiative, Appendix V.B), to have significant ranges of CPU hours reserved for their projects, that they have expertise in, and have judged as highly competitive. It is well known that only a few large projects need to run on the petascale machines (smaller ones are run more cost efficiently on the middle tiers). This will ensure or increase the astronomy share in pan-science computing.

6.5 Computational Resources

State-of-the-art computers have been vital for astronomy since the start of the electronic age half a century ago, when numerical calculations led to an understanding of stellar evolution, and there is no prospect of a decoupling of advances in astronomy and computational facilities. It is now useful to identify three distinct areas in the computational landscape: major computers, high speed networks and massively parallel computations and grids. We consider each area separately.

Problems such as star and galaxy formation, numerical general relativity, and atomic structure calculations involve intensive calculations with large sets of numbers. The scientific return of such work increases with the scale of the available computer, so, to be competitive, European theorists need access to top-ranking machines.

6.5.1 Major Computers

Europe has consistently lagged the US in the provision of supercomputers (see Appendix V.B): in the November 2007 TOP500 census, only three of the top ten machines were outside the US, and only two of these were in Europe, and of the top 50 supercomputers just thirteen were in Europe (one of which is depicted in Figure 24 as an example). Given the importance of high performance computing right across science and engineering, this situation is a matter of wide concern. It clearly arises because the top US machines are funded at a continental level, while European machines are funded at the national level.

The importance of introducing machines at the pan-European level is enhanced by two factors: (i) the pace of technical development is such that machines do not stay at the cutting edge for long, and individual countries may not always budget for sufficiently rapid renewal of their leading machines; (ii) 81% of the top 500 machines now have cluster architectures, and such machines show considerable diversity in terms of memory per processor, processors per block of memory and speed of interconnects between memory blocks. A given scientific problem is best handled by a particular architecture, which might not be that of the machine that is closest to hand. Hence scientific output will be maximised if European scientists have access to machines throughout the continent.

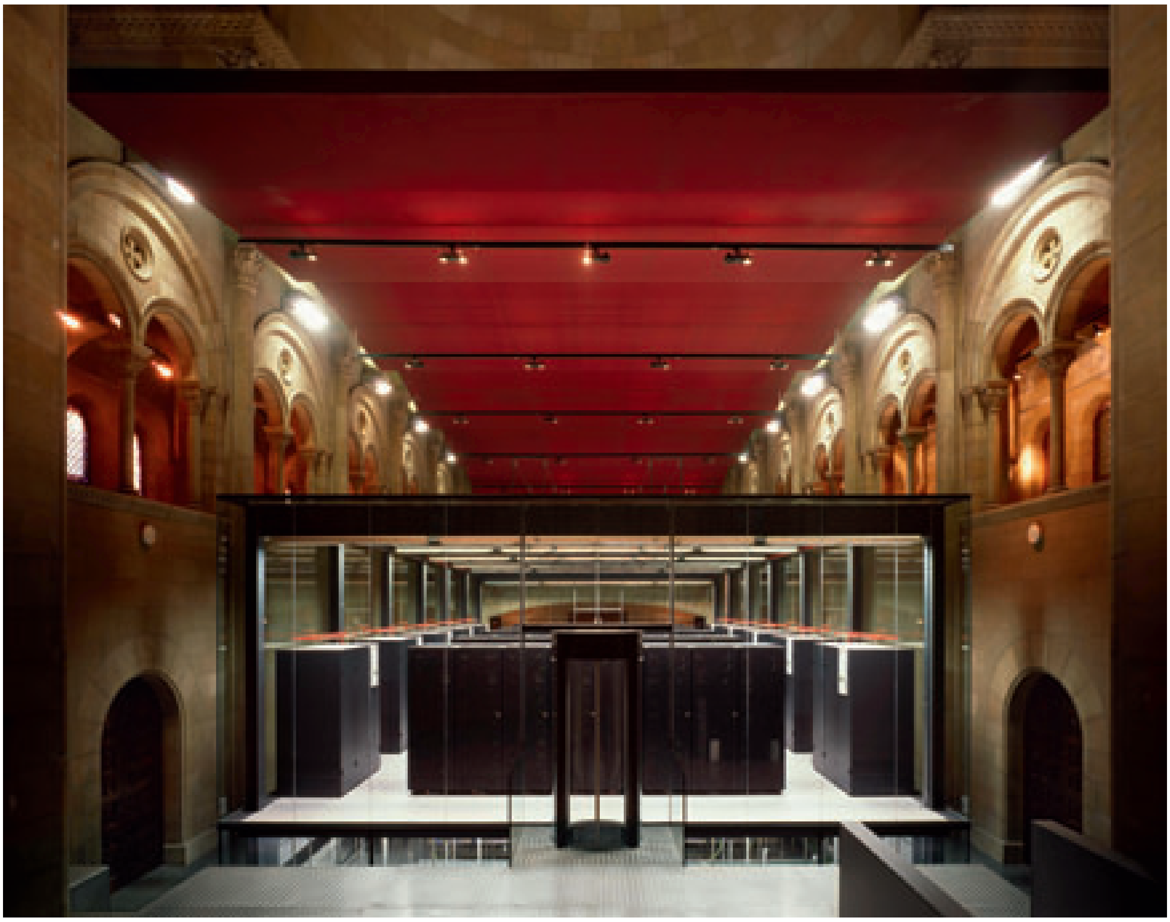

Image Credit: Barcelona Supercomputing Center/MareNostrum

Figure 24: The Barcelona supercomputer in the Torre Girona Chapel (Mare Nostrum), by courtesy of Barcelona Supercomputing Center[23]. Mare Nostrum is one of Europe's most powerful supercomputers and is thirteenth on the TOP500 list[24].

The European strategic approach to High Performance Computing (HET, or HPC European Taskforce[25]) is to concentrate the resources in a limited number of world-level top-tier centres, in an overall infrastructure connected with national, regional and local centres, forming a scientific computing network, for the best use of the top-tier machines. This can be represented as a pyramid, where local centres form the base of the pyramid, national and regional centres are the middle layers, and the high-end HPC centres constitute the top.

6.5.2 Data Networks and Data Grids

Huge volumes of data are already produced by current instrumentation and supercomputers, and the size of datasets will continue to increase rapidly. Fast networks are essential for the distribution of these data to the institutes in which science is extracted from them. Fortunately, significant networks are already available in Europe: GÉANT2, co-funded by the European Commission and Europe's National Research and Education Networks (NRENs), began officially on 1 September 2004, and will run for four years. It connects 34 countries through 30 NRENs, using multiple 10 Gb/s links. GÉANT2 links the European backbone to North America (NASA, and the research networks Internet2 Network, ESnet and CA*net 4), and Japan (SINET). Twenty five Points of Presence in Europe and one in New York are linked by 44 routes. These links are important for extracting science from the Large Hadron Collider (LHC) in Geneva, so the particle-physics community has taken the lead in establishing fast links within Europe and to North America.

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[23] http://www.bsc.es

[24] as of November 2007; http://www. top500.org

[25] http://www.hpcineuropetaskforce.eu/

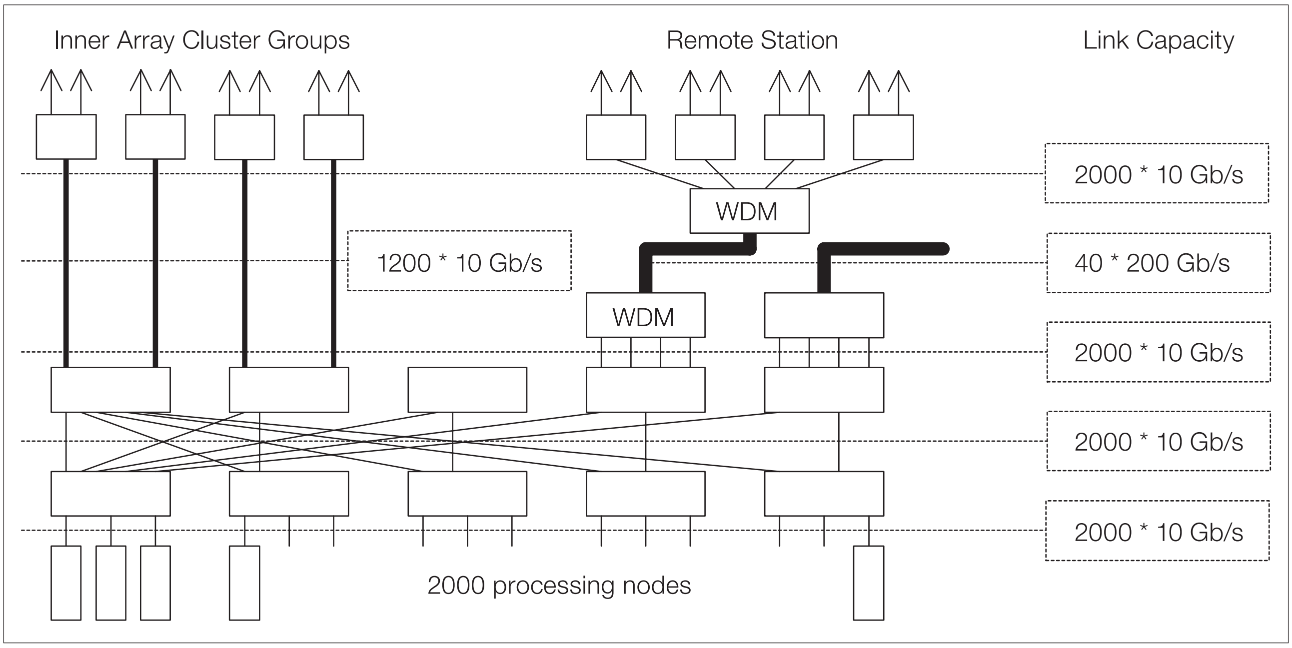

Image Credit: J. Bregman

Figure 25: Network architecture for LOFAR, with WDM (Wavelength Division Multiplex). Thousands of optical fibres of 10 Gb/s must be used, over distances of dozens of kilometres. The rate of data processing is 25 Tb/s. The foreseen computing power required in the final structure (before 2010) poses a serious problem of data processing. There will be 90 stations, for wide-field imaging of 5 degrees in the sky, with 1000-km baselines, at 150 MHz wavelengths. The Blue Gene/L (STELLA installed in Groningen) is 34 TFlops at 1 Tb/s IO, while the required power is at least 200 TFlops.

The European VLBI network, led by JIVE, uses GÉANT2 to track rapid transient events. Thanks to GÉANT2, the radio telescopes at Jodrell Bank and Cambridge in the UK, Effelsberg in Germany, Westerbork in the Netherlands, Onsala in Sweden, Medicina in Italy or Torun in Poland can be used as a single telescope as large as Europe. Up to sixteen telescopes are to join the network in the near future, to form an instrument of global proportions. The next generation of radio telescopes (e.g., LOFAR, SKA, cf., Figure 25) will have even larger needs.

The European DataGrid — an EU-funded initiative, active from 2001 to 2004 — focused on datasets described in databases where bulk data storage is widely distributed. Areas like particle physics or astronomy provide the testbeds to develop the associated software and middleware. The project paved the way for the studies on data access picked up by the Enabling Grids for E-sciencE (EGEE) project. Its main contractors were: Centre National de la Recherche Scientifique (CNRS, France), European Space Agency ESA/ESRIN (Italy), Instituto Nazionale de Fisica Nucleare (INFN, Italy), STFC (UK), European Organization for Nuclear Research CERN (Geneva, coordinator) and NIKHEF (The Netherlands).

In the coming decades a new generation of survey telescopes, such as the VST, VISTA, LSST, LOFAR and the SKA will each produce petabytes of raw observational data, which will have to be calibrated, processed and archived. Given the complexity and dedication required to calibrate and pipeline process this data avalanche, several agencies operating observatories (e.g., ESO, Astron) have decided to place this activity in the astronomical community, in order to actively involve the research astronomer in the process.

ESO's public surveys will be processed in the European astronomical community; the analysis and post-processing of the key science projects of LOFAR will be done at various institutes scattered over Europe. This requires a modern network and e-science infrastructure with distributed resources, which allows teams spread over Europe to jointly collaborate on the data production, as detailed in Appendix V.A.

6.5.3 Grid Computing

The grid-computing concept is that, in the 21st century, the web should provide users with almost unlimited computing power on demand, just as in the 20th century the electrical grid provided electricity on demand. The challenge of realising this vision was enthusiastically taken up by the particle physics community, which was aware that from 2008 onwards data from the LHC would pose a formidable computational challenge.

The grid concept attracted political backing extremely quickly, and the field has been challenged to spend money rather than having to fight for funding. In Europe we have EGEE[26] funded by the EU Commission, and several national programmes (see Figure 26 for a map of grid sites in Europe and beyond). In April 2008 the Gstat global grid-monitoring programme[27] reported around 40 000 CPUs running 15 000 jobs with 135 000 jobs queued. These CPUs are located at 250 nodes with a few hundred to ~ 1000 CPUs per node. Significant sums have been spent on constructing and manning these nodes, and upgrading links between many of them. Similar programmes exist elsewhere, and there is a high level of international cooperation.

The CPUs in a given node could be used to run large parallel jobs, on various architectures. Special middleware is used to schedule multiprocessor jobs, according to their requirement in memory, their ability to run with shared or distributed memory, etc. The middleware scheduler optimises the use of processors, in order to have, at a given time, the smallest possible number of idle processors. In the case of a grid node this problem is compounded by the grid ethos that computing power should be available on demand, like electricity from a socket, which is realistic only if the system automatically has capacity for whatever load a user might realistically present.

Grid computing has been developed by the LHC community because it is well matched to their computational requirement: their four instruments (ALICE, ATLAS, CMS and LHCb) will each experience 40 million collisions per second, and after filtering will spew out ~ 100 events per second that need to be analysed. Each event is a standalone problem, independent of all others, and is encapsulated in more than 1 Mb of data; their recording rate is larger than 1Gb/s. So event processing is ideally suited to grid computing.

Image Credit: GridPP

Figure 26: Grid Real Time Monitor developed by GridPP at Imperial College London.

Astrophysics applications have been part of the EGEE projects since 2004, when the EGEE Applications Panel started its activity: in particular, simulations for the MAGIC Cherenkov telescope and the ESA–Planck mission have been run on the EGEE grid since. Astrophysics has been a part of the Applications Work-Package (NA4) in the EGEE-II project, and an Astronomy and Astrophysics cluster comprising six countries has now been funded within EGEE-III, with the purpose of encouraging the community to be more proactive in exploiting the grid infrastructure.

The VO models that use the grid have to be tightly connected not only to the grid as a high performance computer, but also need to address the challenges of accessing distributed data on the grid. It might be difficult to analyse large blocks of data that are too bulky to send to wherever an idle processor lies; the answers to such questions should be computed by a processor that is attached to the engine that holds the data, as is foreseen for instance by the LSST developments. The problem in particular occurs when comparing observational data with simulations, for in this case two large datasets are involved, and they do not reside in the same place. Hence development of the VO may involve investments in CPU power at data centres and faster data links between data centres, beyond the present infrastructure required by the LHC.

In 2008, there are now successful examples of HPC-oriented regional grid systems where the CPUs and storage systems are connected by Infiniband-4X links making these regional grids resemble a high efficiency medium-sized supercomputer. The ever-increasing speed of the links among high efficiency clusters allows the transfer of large quantities of data much more efficiently, giving hope of solving the challenge of accessing distributed data on the large-scale grid in the future.

Until now there was only partial enthusiasm for grid computing in the astronomical community. For the reasons given above, it was not suited to the computationally intensive projects that have traditionally concerned astronomers (N-body codes, hydrodynamics codes, atomic physics codes). As in particle physics, it seems likely that its main impact will lie in data processing/modelling. Four examples of grid computing in astronomy are given in Appendix V.E.

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[26] http://www.eu-egee.org/

[27] http://goc.grid.sinica.edu.tw/gstat/

6.5.4 Screensaver Science

Once one accepts that grid computing is about running large numbers of compact and independent jobs, it is evident that the hardware model adopted by the LHC is not the only possible one. In the last decade significant results have been achieved by using different software (such as from the Berkeley Open Infrastructure for Network Computing [BOINC], see Appendix V.F for examples) to tap unused CPU cycles on hundreds of thousands of desktop machines. The software provides a client that volunteers install on their machines. A volunteer indicates which projects s/he wishes to support, and the client reports the operating system to the project's server, which then provides the appropriate executable and input data. When the computation is complete, the client sends the output to the project's server and deletes the input data.

In the next decade, the procedure will be simplified, for instance through Java-based software (see Appendix V.F) that could in principle provide access to over a billion CPUs. The major problem that has to be solved to make this dream a reality is to entice the owners of CPUs to subscribe to the system. Projects using BOINC attract volunteer subscribers through websites that advertise their social importance or intellectual excitement. Astronomy can certainly draw in internet users: the GalaxyZoo project[28] to classify a million Sloan Digital Sky Survey (SDSS) galaxy images signed up 85 000 classifiers in its first three weeks. So ESO or ESA could set up a website that signed up subscribers willing to let their spare CPU cycles be used for any astronomy-related work. The resources gathered in this way could then be awarded as research grants by peer review. Another possibility is that a genuine market develops in spare CPU cycles. Machine owners could receive discounts from their ISP or telephone company for every unit of computing resource used on their machines. Such a market might be established either by an existing national research council or by the ASL. If a market could be established, it would be a commercially valuable property.

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[28] http://www.galaxyzoo.org/Default.aspx

6.6 Recommendations

I. *Relevant to VO*

1. Provision of a public VO-compliant archive should be an integral part of the planning for any new facility. We recommend that data centres provide science-ready data.

2. Providers of astronomical tools should make them VO-compliant so they can easily talk to other VO tools and can be accessed within the VO environment.

3. The infrastructure established with EC support will need to be sustained by the national funding agencies to allow continuity of the VO.

4. The development of the VO should be coordinated with evolution of the generic e-infrastructure, and that evolution should reflect the domain-specific needs of astronomy.

5. To prepare for the challenges posed by large surveys, multi-wavelength astronomy and the VO, modelling codes need to be made modular.

6. Substantial investments are required in software that simulates mock data with the observational biases inherent in current and future facilities. Publication of such software in VO-compliant form should become an integral part of the construction of any instrument.

II. *Relevant to ASL*

1. Given the growing importance of sophisticated simulations for the future of astronomy, funding of theory must not fall far behind that provided for observational facilities.

2. Increasingly astronomy will depend on codes that are too complex to be written from scratch by students and post-docs, and astrophysicists throughout Europe must have access to state-of-the-art standard codes. These codes should be regarded as essential infrastructure on a par with major observational instruments.

3. A laboratory without walls called the Astrophysical Software Laboratory should be established to coordinate and fund software development and support, user training, and to set standards. Training and development funding would make it possible for codes to remain at the cutting edge of the field for extended periods. Development funding would also ensure that supported codes conformed to modular standards; the ASL would be the catalyst that enabled the community to establish these standards.

4. Code authors supported by the ASL should be committed to the open-source model.

5. The ASL would have an important role in nurturing the next generation of theorists and codes, both by funding postdoctoral positions within a programme of pan-European networks, and by supporting the development of innovative codes.

6. The ASL committee will select a few highly competitive astrophysics projects each year to send proposals to the European pan-science top-tier computers; this will ensure a significant share of CPU hours at the petascale level for astronomy.

7. The human resources required for the ASL are estimated at 50 FTE/yr. This number includes scientists who are already funded at the national levels, plus a core of researchers (estimated at about 20 FTE/yr) to be funded at European level, and who will be responsible for the ASL's activities and organisation. The ASL should be financed by the national agencies: a specified percentage of each agency budget should be reserved for it.

III. *Relevant to High Performance Computing and Grids*

1. Astronomy should continue to benefit from HPC all-science centres, and share the efforts to develop and increase continuously their performances in order to be at the forefront of the international competition.

2. The development of the top-tier HPC centres should not slow down that of the lower tiers: the whole pyramid of computers at different scales, national and local, is absolutely necessary to satisfy all computing needs.

3. Astronomy must exploit the grid infrastructure more widely, and contribute to the expansion of the capabilities of its middleware, in particular for data processing.

4. Data links within Europe and to the outside world need to be kept abreast of advances in technology. The VO is likely to require a different network architecture from that put in place for LHC science.

5. The possibility of using billions of otherwise idle processors for scientific calculations is now real, and could revolutionise data modelling. Astronomy should lead the way in this area, either by exploiting its popular appeal to get CPU owners to donate spare CPU cycles, or by initiating a classical market in such cycles. The ASL could possibly coordinate this activity, which could have a significant commercial spin-off.

It is recognised that in order for all of the recommendations in this Chapter to be realised, some of them will need to be taken forward by a “champion” that has continuity over several years, and strong connections with the funding agencies and other bodies in Europe. It is proposed that this would be an important continuing role for ASTRONET beyond the current Roadmap exercise. In the case of Panel D, continued involvement by ASTRONET is felt to be particularly important to take forward recommendations I-3 (sustaining VO infrastructure) and II (establishment of the Astrophysical Software Laboratory).

Chapter 7 Education, Recruitment and Training, Public Outreach

(Panel E)

7.1 Introduction

The infrastructures that are built and used for astronomical research are financed by — and therefore must be justified to — our society. Astronomy has an innate appeal for people of all ages, partly because it concerns the fascinating, great questions "of life, the Universe and everything" and partly because much of the data obtained with telescopes can be presented as objects of stunning beauty.

This native advantage that astronomy has over many other sciences does not, however, relieve us of the obligation to explain what we are doing to the public at large. There are many reasons for doing this. They range from attracting bright young people into the subject to fuel future research endeavours to convincing decision-takers to allocate large sums of money to finance increasingly expensive and ambitious projects.

The existence of the International Year of Astronomy in 2009, 400 years after first use of an astronomical telescope by Galileo Galilei, provides a splendid opportunity to boost worldwide awareness of the subject. Organised by the International Astronomical Union (IAU) and endorsed by the United Nations, this global endeavour with over 125 national nodes will reach hundreds of millions of people who will have had little previous exposure to science. Occurring near the beginning of the Roadmap implementation, it should create a groundswell of public support for the ambitious plans we are making.

Panel E is concerned with these aspects of the relationship of our subject with society, from teaching in schools, training in universities and recruitment into astronomy-related jobs to the process of communicating astronomy to the public. It also considers the relationship between cutting-edge research infrastructures with the industries that help build them, hopefully to the benefit of the overall economy of the continent.

In schools across Europe a need has been recognised for the proper training of teachers to present astronomical topics to pupils and to use the resulting enthusiasm to generate a broader interest in science and engineering. Unlike the situation in professional research where English is the working language, school teachers need support in all the European languages, a requirement that has to be addressed by the providers of media and materials.

Young people considering a career in science need to know that, by studying astronomy, their prospects for an interesting and well-paid career are good even if they subsequently leave astronomy for another scientific or technical job or in any job needing analytical and mathematical skills.

At the top level of research activity, where international teams of astronomers, including young post-docs, collaborate to utilise the world's most powerful instruments, there must be sufficient funding available to allow European astronomers to exploit the resulting observations on a competitive timescale, thus reaping the full scientific and training rewards of such large investments in facilities.

It is important that the organisations providing the facilities and also individual scientists recognise the importance of explaining what they do to the people who are, ultimately, paying them to do it. By ensuring that public communication is seen as an integral part of a scientist's job and that it is given clear recognition when done well, a culture of high quality communication can be encouraged.

A common theme among the recommendations we make in this Chapter is an urgent need for steps to improve the organisation and the accessibility of the enormous amount of education and public outreach material in today's information mass market. Tools such as common portals to — and organised repositories of — media and materials for these purposes will bring a fruitful order to the existing rich, but widely dispersed, assemblages of data, images, videos and other information.

Image Credit: ESA/IAU

7.2 Background

People's innate curiosity about the world in which they live draws them towards astronomy, providing rich opportunities for outreach and education. Our task is to gain maximum profit from this situation by stimulating the interest and imagination of people of all ages and backgrounds.

Panel E's report tackles two principal areas:

- **Education**, including primary and secondary schools, university education and research, and recruitment;

- **Communication**, aimed at several different target groups.

A set of recommendations has been derived from the Panel's investigations and they are given and described in the following sections. The Panel membership is given in Appendix II. Each recommendation is supported by some background information, a summary of the work carried out by the Panel and, where possible, some pertinent example.

These recommendations can be divided into two groups (see Section 7.6 below): those that seek to change the cultural behaviour within astronomy and science education and those that will require some financial support provided by government education ministries, national or international funding agencies or individual research institutions. Effects of such spending might be expected to become apparent on timescales of two to three years.

A note on terminology. In this document, we refer to both national and international organisations. Amongst the latter are pan-European organisations like the European Space Agency and the European Southern Observatory for which we use the generic term "agency".

7.3 Education

7.3.1 University Education and Recruitment

There are two aspects of university education considered by Panel E. Firstly, the role of universities as a training ground for future astronomers, and secondly the wider role of astronomy in attracting good students into the study of STEM subjects (Science, Technology, Engineering and Mathematics).

Surprisingly there is little detailed research into either of these two aspects. However, consideration of the destinations of ESO fellows[29] over a 30-year period, and surveys by the UK Institute of Physics[30] and the Particle Physics and Astronomy Research Council (PPARC)[31] into the career plans and paths of graduate and postgraduate physicists allows us to draw some reasonable conclusions.

As expected, at all stages (first degree, PhD, post-fellowship) the fraction of people staying in academic research rises (from about 13% of first degree graduates to about 90% of ESO fellows), nevertheless at all stages some leave academic research for other fields (industry, education etc.). While there may be a variety of reasons why an individual chooses a particular career path, with job availability only being one aspect, these results imply that there is no obvious shortage of qualified people for the jobs in astronomy currently available.

However, there is concern that the early career of many is highly fragmented, involving several short-term contracts, often in a number of different countries. While there are both advantages and disadvantages to this, it is clear that it puts considerable pressure on those with family commitments etc. This problem is much wider than astronomy — it is seen in most science areas — and there is no simple solution, but it is important that it is taken into consideration when planning large projects and their exploitation (see also the comments in Section 8.8). In particular the *Code of Conduct for the European Charter for Researchers*[32] should be followed.

There is also concern over the access to practical observational experience available to early-career astronomers (from undergraduate through to postdoctoral level). With the increase in "remote" observing (robotic, queue-scheduled, satellite, etc.), there are fewer opportunities for hands-on observing, and without such experience remote observing is difficult and prone to error. As noted by Panel B (Section 4.3.1.2), the range of 2–4 m-class telescopes could be used to provide opportunities for training (and motivation at undergraduate level) and will be considered by the ASTRONET/OPTICON review of small and medium-size facilities (Section 4.3.1.3).

It is widely accepted that astronomy attracts potential students towards the physical sciences. A survey carried out by the Istitute of Physics in 2001 of the views of physics undergraduates[33] showed that "Fascination in astronomy/space" was a major motivating factor for students, even for many who were not taking a directly astronomy or astrophysics related degree. (This is also seen at younger ages — see for example the "top rated" science areas chosen by school children in the ROSE report[34]).

In addition, a small survey was carried out by Panel E of a number of universities who have attempted to make use of this attraction to halt a decline in recruitment onto physics degrees by starting or significantly expanding astronomy groups or departments. The details can be seen in Table 1 (Appendix VI.B) but in summary, in almost all cases the potential for improving recruitment was a motivating factor in the change and in all cases there has either been an increase or (at least) a halt in the previous decline of recruitment.

Therefore, while it would be desirable to obtain much stronger evidence from throughout Europe, it is clear that the undergraduate teaching of astronomy plays a valuable role not only in preparing students for astronomical research, but also as a stimulus in wider society and other areas of science.

In the next few years, this role could be strengthened by the Bologna Process[35], which is a Europe-wide process established with the intention of harmonising graduate and postgraduate education across Europe. The primary motivations are to improve workforce mobility by simplifying qualifications and allowing more flexible study by students across institutions and countries.

Currently the progress towards Bologna is patchy across Europe and the impact on each country very different. Nevertheless, since one of the aims of the Bologna Process is to make it easier for students to study part of their degree at a separate institution, this will mean that those universities without astronomy groups will also be able to offer astronomy degrees by collaborating with another institution, which in turn may lead to an increase in the number of astronomy (and physics) graduates. The extent to which this opportunity will be taken up is not clear, but it is important that the astronomical community is ready to make full use of any benefits.

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[29] For (incomplete) lists of former ESO Fellows see http://www.eso.org/sci/activities/ESOFellows-Garching.html and http://www.eso.org/sci/activities/ESOFellows-Chile.html.

[30] *Survey of Undergraduate and Postgraduate Views*, Institute of Physics, March 2001; and *The economic benefits of higher education qualifications*, Commissioned by the Institute of Physics and the Royal Society of Chemistry, 2005.

[31] A 15-year longitudinal career path study of PPARC PhD students, PPARC, 2003.

[32] See http://ec.europa.eu/euraxess

[33] *Survey of Undergraduate and Postgraduate Views*, Institute of Physics, March 2001.

[34] Jenkins E. & Nelson N.W. 2005, Research in Science and Technology Education, 23, 41-57.

[35] http://ec.europa.eu/education/policies/educ/bologna/bologna_en.html

7.3.2 Primary and Secondary Schools

Astronomy introduces the young mind to the idea of working as an individual involved in a wider, European and global large-scale scientific endeavour. This is done in the hope and expectation that it will attract students to the serious study of scientific subjects, not restricted just to astronomy, and create an individual with science-based, transferable skills and personal capabilities that can enhance the European economy. This aim can be justified because the nature of the Universe is an inherently fascinating and attractive subject that is more capable than many other areas of science to stimulate the imagination and sense of wonder quickly and reliably. This aim has motivated projects such as Universe Awareness (UNAWE[36]), which is directed to 4–10-year-old children around the world and particularly within Europe. The programme motivates children through astronomy-related stories, songs and practical activities using materials in their mother tongues.

Later, in secondary school, students become interested in how scientific ideas were developed and they start to ask themselves the great questions of life: Where do we come from? What is the origin of life? Where is the edge of the Universe…? Astronomy can offer them a splendid example of the nature of science and how it has developed. To understand how ideas and theories grew in the past, and are still being developed now, practical observations are an essential tool. Mental models that students build in this way also form a solid basis for understanding the structure of the Universe and the methods of modern astrophysics. Seeing how science has been developed and still is developing in astronomy may also help to counter some anti-scientific attitudes in our society. The usual prescription for dealing with pseudoscience is to teach students the general principles of rational thinking and the scientific method[37].

The actual status of astronomy teaching in European schools is different from country to country. Opinions of 60 teachers from 24 European countries were collected with a questionnaire (Appendix VI.C). In general, astronomy appears in a few lessons associated with another course (Table 6 in Appendix VI.C). Very little astronomy is taught in primary schools and it normally appears as part of environmental or general science. In secondary schools, astronomy generally appears as part of geography or physics. In the majority of European countries there exist optional courses on astronomy for students aged around 16 or 17. In the other cases, astronomy appears only within a few (typically about ten) lessons over the entire duration of secondary schooling. When it is taught in schools, astronomy is always a very popular subject that inspires a real desire amongst the students to know more[38].

The Panel recognised a number of problems that beset the widespread and effective utilisation of astronomy.

- The principal one is the lack of specific training given to the teachers who would carry out this task. Strongly related to this is the position (or absence) of astronomy in the school curricula in the different European countries. The presence of astronomy in the curriculum would do much to ensure the availability of teacher training in the subject.

- It is not normal to have courses organised by the national Ministries of Education. If teachers have a particular interest, they will try to enrol in one of several kinds of astronomy training courses organised by associations of teachers, amateur societies or universities (Table 6 in Appendix VI.C) in their countries or in courses organised by institutions directly connected with astronomy, such as the European Association for Astronomy Education (EAAE), ESA, ESO, planetaria or observatories. It is important to note that attendance of these courses is voluntary and has to come out of the teacher's free time.

- When teachers do not have the opportunity to participate in training courses, they tend to prepare their astronomy classes using course books and fail to convey the excitement generated by modern topics that are the subject of active research (Table 6 in Appendix VI.C).

- Young people are very interested in real, living science, but are uninspired by much of the "school science" that appears to them as an historical relic. Particularly interesting topics for students are exoplanets, life in the Universe, black holes and gravitational lenses[39].

It is advantageous to offer programmes to European teachers that give them the chance to exchange successful and innovative teaching methods and materials. This kind of project enables teachers to improve the quality of teaching and to find new ways to stimulate students to take an interest in science. One of the most interesting programmes in this field in Europe is Science on Stage[40] organised by EIROforum and the associated journal *Science in School*. Science on Stage promotes the exchange of good practice and innovative ideas among Europe's science teachers and provides a forum for a broad debate amongst educators, administrators and policy-makers about the key problems in science education today. The goal of this project is to stimulate good teachers to continue their tasks, to exchange attractive science lessons through the promotion of exciting ideas and to bring together the expertise of the EIROforum research organisations and the European scientific teaching community. By introducing fresh science into the curricula, it is hoped to convey a more realistic image of science to the students.

Recommendation 1

Action. *Create new and support existing training courses for the career and professional development of teachers*, which include practical observations, modern topics and examples. Courses and conferences for teachers from different European countries should be promoted and attendance must be accounted for as teaching time. The Ministries of Education should encourage and facilitate attendance at such events.

Institution. National Ministries of Education and pan-European organisations. ESA, ESO and EAAE have undertaken important actions (Science on Stage, Science in School, the ESO/EAAE summer schools), but these actions can only complement activities by the primary party, the Ministries of Education.

Timescale. One to two years to build up.

Comments.

- Where specific courses do exist, for example the EAAE/ESO summer schools, attendance needs to be increased and awareness of such courses needs to be promoted through the relevant European channels of dissemination.

- Active observation of the sky is basic to the understanding of astronomy. However, in primary as well in secondary school, astronomy is mostly taught in a theoretical way using books, simulated observations on computers etc.

- Students like to have lessons outside and every playground gives access to the sky. It is therefore eminently possible to offer students the opportunity to pursue an observational approach to astronomy, both with the naked eye and with instruments in some cases made by the students themselves[41]. UNESCO has formally

Image Credit: ESO, Catch a Star competition: Kataryna Pospiech

Figure 27: Painting/drawing competitions are a popular method of inspiring children to think about the Universe in which they live.

declared that the dark sky is a right of future generations[42]. The crucial need is for the teacher to have sufficient knowledge of astronomy to be able to organise an observational session.

- Teachers who are not used to working in a practical way are often afraid of taking a class outdoors.

- There is also the widespread feeling that it is essential to have telescopes, which are often not available, to make observations. This is not so.

- A heavily light-polluted sky in a big city can seriously degrade the options for observations. However it does not stop all observations.

- A telescope can be useful for this kind of activity but is not essential that every school has one. Binoculars are excellent for primary and secondary schools. If schools do not have telescopes, it is sometimes possible to contact a group of amateurs to organise a session using their facilities. The rapidly increasing network of robotic telescopes such as the Faulkes Telescope Project[43] and the UK National Schools' Observatory[44], which are available for use by students and teachers, are an exciting new resource with tremendous educational potential. Students are very strongly motivated to obtain results — often including beautiful pictures — for themselves and so achieving a real sense of ownership and discovery.

Recommendation 2

Action. *Encourage schools to use their playgrounds as open-air astronomical observatories equipped with simple devices.* Interested organisations should actively lobby governments and other relevant bodies to minimise light pollution to facilitate the appreciation of the sky throughout Europe. It is important that teachers are properly trained to teach astronomy both in the classroom and (in a hands-on manner) outside during day and night. It is becoming increasingly possible for schools to gain access to robotic telescopes. Such opportunities should be publicised and their exploitation encouraged.

Institution. Ministries of Education.

Timescale. One to two years.

Comments. No additional mechanism required. Use normal Ministry channels.

We have seen that astronomy attracts potential students towards the sciences (Section 7.3.1) and there is plenty of anecdotal evidence to support this statement. This situation should be utilised in order to actively promote science to school students. Of course, by the time that students are at university, it is often too late to invite them to consider a change to science. Therefore, it is at the secondary education level where one might expect the maximum benefit of promoting astronomy.

In secondary curricula in Europe approximately 50% of countries have astronomy as an optional course for students aged 16–18, that is to say one or two years before the start of university studies (Table 2 in Appendix VI.C). It is important to promote this approach and to make sure that it does not decrease. Taking into account that astronomy is a good way to promote science studies to young people, it should be introduced as an optional course for all students. Further, the study of astronomy and astrophysics at school level can also create an individual who is motivated to develop their scientific-based skills further to become an effective contributor to society and European business and industry.

Recommendation 3

Action. *Encourage European stakeholders involved in developing educational programmes and curriculum delivery to realise the inspirational quality of learning using astronomy-related exercises and experiences*, and how this may lead to further engagement in science, technology, engineering, and mathematical endeavour. For pupils in the latest key-stages, dedicated astronomy courses should be offered, at least optionally.

Institution. National Ministries of Education.

Timescale. One to two years to build up.

Comments. Enabling teachers to use astronomy within their general science teaching, or even to conduct dedicated astronomy courses, requires an effort with respect to in-service training as well as the provision of teaching materials.

Therefore, in addition to the need to provide teachers with some specialist knowledge in astronomy, teachers have a need for a range of suitable modern and stimulating materials for their astronomy courses. The linguistic diversity of Europe is a problem for promoting common educational programmes that satisfy good, innovative teachers and passionate students. While professional science can be English-centred, school education must be carried out in the mother tongue. A solely English-centred strategy for science education in Europe will fail.


Image Credit: Carme Alemany

Figure 28: Practical observations are the first step to building mental models. Astronomy offers this possibility to students and, when it is taught in schools, encourages children to want to know more about science.

While there are many excellent materials related to education initiatives already available in different languages for teachers and students at all levels: books, CD-ROMs, worksheets, exercises etc., they are disseminated using a bewildering array of different methods. Examples are those prepared by European agencies, such as ESA and ESO, which are available on the web. The ESA Education Office[45] has developed a website in all the languages of the member states of ESA. The site includes information on space and astronomy in general, European

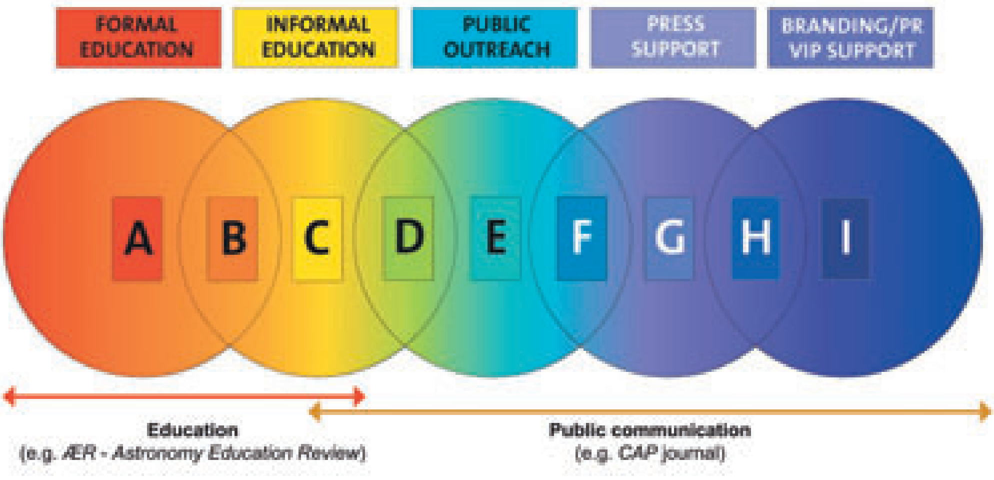

Image Credit: Christensen & Russo (2007)

Figure 29: The entire science communication "space" from education to public communication including "PR"[50].

programmes, educational material for teachers, links to interesting sites and a Question & Answer section.

Recommendation 4

Action. *Implement a centralised, web-based distribution system for educational material in a range of languages.* This system will collect the necessary information, make it universally accessible and help lay the foundation for a common astronomy programme in Europe.

This could be achieved by establishing a dedicated astronomy portal or by exploiting existing portals such as the European Schoolnet (supported by the EU member state ministries of education) or the Science in School website (supported by the EIROforum).

This e-infrastructure should provide access to a range of modern astronomy-related materials for school teachers and students, facilitating enquiry-based science education as recommended in the EU's Rocard Report on Science Education[46]. The portal should promote the exchange of observations made by students and their teachers in cooperative projects. Such a portal could also promote astronomy as an interdisciplinary subject and so catalyse additional inspiring projects in schools.

Institution. Implemented by a pan-European organisation.

Timescale. Two to three years.

Comments. Could involve IAU Commission 46 — Astronomy Education and Development[47] or the European Association for Astronomy Education[48]. The EC-funded COSMOS project[49] may provide a useful prototype.

7.4 Communication

7.4.1 Science Museums and Planetaria

The opinions of the museum and planetarium operators were polled with a questionnaire (reproduced in Appendix VI.D) sent to addresses from the International Planetarium Society[51], the British Association of Planetaria[52], and the European Hands-On Universe[53] network. This list includes various government-funded organisations, non-governmental bodies and privately funded science outreach operations throughout Europe. From a total of 34 responses, the following general conclusions emerged:

- Formal links with the European agencies involved with astronomy and space are scarce. Less than a tenth of responders indicated that they had any link or direct communication with the agencies in Europe.

- The majority of responders would welcome a central repository of visual material relating to astronomy and space. They are especially interested in images and videos.

- The relationship between planetaria and local amateur astronomical societies is common and should be better understood and utilised. Regional astronomical associations and societies are a powerful dissemination mechanism of astronomy related literature and scientific endeavour. The valuable role that amateur astronomers play, both in the role within society as a communication conduit, and also in real scientific endeavour through observation, is recognised by the Panel. Established relationships with professional astronomers are less common.

- Problems with curriculum integration and the sustainability of formal programmes clearly exist.

The responses exposed a richly diverse programme covering many aspects of classical and modern-day astronomy. The interaction with the public clearly benefits

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[36] http://www.unawe.org

[37] Percy J. R. & Pasachoff J. M., *Astronomical Pseudosciences in North America*, Teaching and Learning Astronomy, Cambridge University Press, 2005.

[38] Sjøberg S. 2004, *Science Education: the voice of the learners, Increasing Human Resources for Science and Technology in Europe*, Brussels; Sjøberg S. & Schreiner C. 2007, *Reaching the minds and hearts of young people*, ROSE-project, International Space Science Institute, Bern.

[39] See footnote 38 above.

[40] http://www.eiroforum.org/activities/scienceonstage.html

[41] Lanciano N. 1998, *Teaching/Learning astronomy at the elementary school level*, New Trends in Astronomy Teaching, Cambridge University Press.

[42] Vilches A. & Gil-Pérez D. 2003, *Construyamos un futuro sostenible.* Diálogos de Supervivencia, Cambridge University Press.

[43] http://faulkes-telescope.com/

[44] http://www.schoolsobservatory.org.uk

[45] http://www.esa.int/esaED/

[46] http://ec.europa.eu/research/science-society/index.cfm?fuseaction=public.topic&id=1100

[47] http://iau46.obspm.fr/

[48] http://www.eaae-astro.org

[49] http://www.ea.gr/ep/cosmos/

[50] Christensen, L.L. & Russo, P., 2007, *Communicating Astronomy with the Public*, in Proceedings from Future Professional Communication in Astronomy, ed. André Heck, adapted from Christensen, L. L., 2006, *Hands-On Guide for Science Communicators*, Springer Verlag and inspired by Morrow, 2000, http://www.spacescience.org/education/extra/resources_scientists_cd/Source/Venn.pdf

from the stunning visual appeal that astronomy offers and there is some evidence that this has a direct effect on bringing pupils into science subjects in secondary school, although more tracking is required to verify this effect. Many of the facilities questioned offer a formal astronomy education package linked to the curriculum in their respective regions and it may be that the impact that these centres have on student choice should be further explored. It should also be noted that those that do provide formal stimulus also have difficulty in creating synergy with the curriculum providers and that this is partially addressed in Recommendations 1, 2, 3 and 4.

The planetaria and science centres in Europe are the natural conduits through which the flow of astronomical information is disseminated to the wider public. This leads to our principal recommendation in this area. Although the European Agencies (ESA/ESO) have worked in collaboration with some of the major planetarium associations in Europe, a more systematic collaboration and coherent strategy may be required to further the impact of European astronomy communication to society.

Recommendation 5

Action. *Active steps should be taken to forge links between science museums/planetaria and the European Agencies (ESA/ESO), the principal providers of high quality media and related resources in astronomy.*

Institution. European agency (ESA/ESO) or other stakeholders.

Timescale. Two to three years.

Comment. This could take place via a central portal that could be the same as that referred to in Recommendation 8 below.

It should be noted that the European Space Agency has begun to create a network of European Space Education Resource Offices (ESERO)[54]. The primary task of the European Space Education Resource Offices is to encourage and inspire young people to learn more about science and technology by drawing upon their enthusiasm for space exploration. The ESEROs are intended to be the first ports of call for anyone in Europe requiring educational support related to space activities. A network could be created to promote a synergy between European agencies and science centres and planetaria.

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[51] http://www.ips-planetarium.org/

[52] http://www.planetaria.org.uk/

[53] http://www.euhou.net/

[54] http://www.esa.int/esaED/SEMXH8V681F_index_0.html

7.4.2 Public Communication and Outreach

Here we focus on the astronomy communication activities that are not seen as “formal education”, especially press support, public outreach and activities of a promotional nature (with the aim of elevating the visibility of a scientific organisation). In addition to using the substantial hands-on public communication experience within the Panel, we have distributed a questionnaire to over 40 of the major players in Europe (see Appendix VI.E) and also analysed the answers to the relevant question in the ASTRONET Questionnaire (see 12 in Appendix IV.C and also Section 2.3).

It is widely acknowledged that astronomy can play a key role in raising public awareness of science[55]. A vigorous activity in science public communication and outreach in Europe is an absolutely essential investment in the future health of the subject and, indeed, can significantly contribute to the economic and cultural life of the continent. Differences in the attitude towards public communication between scientists and science management in the US and in Europe are often stark. The Panel has identified a need to bolster public awareness of astronomy (and science in general), to convince scientists of its importance and to equip at least some of them with the knowledge and tools to participate actively in the process.

The European landscape of public communication mechanisms is (not surprisingly) complex and rather fragmented. Different countries have different cultural backgrounds, political systems, technological and scientific levels, and level of general knowledge. The differences naturally make it more difficult to reach the entire continent in an easy way, but the diversity can also be an advantage if taken into account when communicating.

What, from a modern point of view, can only be described as an underdeveloped communication culture and identity in European academia is undoubtedly rooted in its history and linked to the way scientific research has traditionally secured its financial support. Indeed, systematic and sustained public communication about research has not been regarded as indispensable to ensure continued support by public research funders. Public communication is therefore still primarily regarded as a burden on the scientific institutions instead of being seen as a long-term strategic investment. In the US on the other hand the funding loop is much more closed (partly due to federal law) and depends highly on the visibility and results of the individual organisations and research groups.

The claim that Europe has a weak, or in some parts even absent, public communication culture, is strongly supported by the literature and personal experience. As an example Banda (2005) states[56]: "Despite several initiatives in recent years to improve Europe's performance, parts of the research community still do not believe that effective proactive media relations is a priority."

One of the consequences of the Europe/US asymmetry in communication, which is seen over and over again, is that European journalists most frequently quote US sources[57]. One response to the questionnaire states: "European science often appears as second class in the press, even in fields where Europe is leading. The basic communication-cultural differences between the US and Europe are to blame." There may be several reasons for this. Perhaps part of the reason is merely habit with journalists and editors? After all, the media know what they are getting from the US. Perhaps American science stories are more digestible and have a higher standard? Or there are more of them and they are simply more accessible and visible? Most likely all of the above apply, and the best strategy to improve the situation is to consistently produce interesting and high quality communication products in Europe.

This general trend is also apparent in the ASTRONET questionnaire, which provides evidence that there is stronger tendency to include extensive education and outreach programmes in US-dominated facilities. An example is the LIGO Science Education Center in the US (a similar one for GEO600, located in Germany, is not planned as far as we can tell). Naturally there are counterexamples (for instance nearly all radio telescopes in Europe and the US have visitor facilities, as claimed by the European VLBI network).

The lack of communication culture in Europe can also be detected in quite different areas from those discussed so far. An example is the lack of understanding, especially at higher levels, of the scientific hierarchy that astronomical data cannot remain in the ownership of individual scientists or teams beyond a reasonable period. The "ownership" of data streams of potential direct interest to the public by the Principal Investigator of a publicly funded instrument has a destructive impact on the public participation in the science to a degree that should not be underestimated. This is seen for instance for some space-based experiments, with the Mars Express High Resolution Stereo Camera data as a notable example. Instruments operated as "facilities", like most (European) ground-based observatories, tend to have clear data-rights policies. Spacecraft operated as platforms for Principal Investigator experiments produce data that are more under the control of the Principal Investigator.

While most US scientists acknowledge communication as part of their business in order to foster support for future projects, most European scientists don't "get the message". NASA is communicating some of its space missions quite aggressively (actually also quite a few of ESA's and other space agencies' missions) while ESA is very often quite reluctant to communicate the results from its science missions and is sometimes essentially invisible to the press. Without speculating about the detailed reasons for this finding, one conclusion is unequivocal: the difference in the level of funding for public communication per mission between NASA and ESA can be as much as an order of magnitude or more.

Communication could have a huge impact on the general public and on the decision-makers. The fifth servicing mission to the Hubble Space Telescope was saved because of the strong public support, resulting in intense political pressure. The same is true for the New Horizons spacecraft en route to Pluto. NASA's cancellation because of budget problems was withdrawn within months. Could European scientists expect similar public support for their next projects?

The message here is that proper spending on public communication should not be seen as a "cost" but as an "investment" for the future. Returns on this investment may be high. The consequences of not making the investment may be disastrous!

Recommendation 6

Action. *Adequate strategic long-term support must be provided for public communication and education in Europe. Firstly, observatories, laboratories and all facility-funding authorities should allocate sufficient resources for public communication and education.* As a useful benchmark, this would amount to at least a few percent of the overall budget (1–2% is sometimes quoted as a good starting point). For smaller institutes, it should be understood that a threshold investment must be reached to enable a successful communication effort. *Secondly*, public communication of science is subject to the same competitive pressures as all other kinds of public communication. Hence *communication departments must be organised and operated in a professional fashion*, i.e., by professional science communicators, working with active scientists (see recommendation 7). *Thirdly, as strategic management tools, communication departments must be placed at or directly linked to the highest levels of the institutional scientific hierarchies.*

It goes without saying that results from taxpayer-funded experiments must go into the public domain and be accessible as soon as possible. Where research data are subject to proprietary time rights (typically one year), carefully selected elements of the data should be available for presentation in a suitable form for direct public communication at an earlier stage.

Institution. Agencies.

Timescale. One to two years.

Many of the European projects that have answered the ASTRONET questionnaire aim relatively low in their strategy and mainly target science centres, museums, and teachers' organisations. There is a lack of planning of communication targeting press/journalists, stakeholders, political and industrial opinion formers, etc. Furthermore some European education and outreach programmes lack full-time/professional communicators. As one questionnaire responder says, "There is a lack of professionalism and effectiveness in Europe as compared to the US. We need to learn how to get there 'on time' and 'with a splash'."

In terms of recognition of the importance of public communication in general the Washington Charter[58] is a good starting point and we recommend adherence to it at all levels. The questionnaire confirms the claim that the role and importance of public outreach is still not properly understood in many institutes across Europe. This includes assessing and recognising these activities when young people apply for astronomy positions.

Recommendation 7

Action. *Ensure clear career-relevant recognition for scientists who become involved in public communication. Provide, and encourage scientists to utilise, media training courses.* The Washington Charter should be promulgated at all levels. Proper public communication of astronomy entails the allocation of sufficient resources to secure an adequate, sustained effort executed by professional science communicators.

Institution. Employers of research scientists.

Timescale. One to two years.

Public astronomy communication has to develop apace with the other players in the mass market for electronic information (gaming and entertainment industries, etc). The problem today is not so much the availability of excellent astronomy multimedia resources for use in education, outreach and the like, but rather *access* to these (often digital) materials.

Even for an expert user, locating a particular image invariably requires going to a known resource or relying on the vagaries of existing multimedia search engines, such as Google images or YouTube. One questionnaire respondee said: "Even a simple web page with links to the existing outreach material would be a good start."

Another respondee said: "A central repository with illustrations of any kind in astronomy would be very useful. There are a lot of interesting illustrations on the internet. If these were collected in an archive and allowed to be used for talks etc. it would be very helpful!"

Lately, press release portals such as EurekAlert[59] or AlphaGalileo[60] have emerged and seem to have some success amongst journalists. This kind of syndication service, or one-click portal, seems to be favoured in many parts of the community and is a valuable step in the right direction.

In summary, access to digital education and inspiration materials is getting increasingly difficult due to data management issues, not lack of material. The data management issues can be split into standardisation, metadata tagging, and data exchange/communication. Briefly put, we need standards to know how, where, what, etc. to exchange. We need metadata tags to describe the context of the products (images, videos, etc.). And we need well-described methods for exchanging the products. Some of the existing archives, such as at AthenaWeb[61], rely on physical repositories, where the archive centrally stores and distributes the material. Others advocate an aggregator approach where the material stays with the producers (similar to iTunes) and only the metadata and the location of the data is stored centrally. This method has huge advantages over the former as it is community and needs-driven and hence is more efficient once the archive works. The method is however more cumbersome to set up in the initial phase.

Recommendation 8

Action. *Support the creation of a standardised European science communication portal for media, educators, interested laypeople and others.* This portal should promote best practices and requirements for public communication with a particular awareness of the spectacular image material produced by astronomical research activity (and whose production is currently dominated by the US), on multimedia products (animations, video podcasts, etc.) and engage the community in its continuous growth.

Institution. Agencies.

Timescale. Two to three years.

Comments. Involve IAU Commission 55[62]. This could take place via a central portal, which could be the same as that referred to in Recommendation 6.

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[55] Madsen, C. & West, R. M.,2000, *Public Outreach in Astronomy — the ESO Experience*, in Heck, A (ed.): *Information Handling in Astronomy*, Kluwer Academic Publishers; Sjøberg, S. 2002, *Science and Scientists: Cross-cultural evidence and perspectives on pupils's interests, experiences and Perceptions*, Acta Didactica, I,

[56] Banda, E. 2005, Communiqué — *A road map for the establishment of a European research media service.*

[57] Scherzler, D. 2008, *Important for Good Press Relations: Accessibility*, CAPjournal Issue 2, February 2008.

[58] http://www.communicatingastronomy.org/

[59] http://www.eurekalert.org/

[60] http://www.alphagalileo.org/

[61] http://www.athenaweb.org/

[62] http://www.communicatingastronomy.org/

7.4.3 Relationships with Industry

There has always been a close coupling between frontier scientific research and cutting-edge industrial development. The two activities feed off one another. At least in astronomy, however, it is difficult to get an overview of the process and to distil from this an idea about “best practice” methodologies. This area was explored and a questionnaire used (Appendix VI.F) to provide the Panel with pertinent information and suggestions.

From the responses, it is clear that the situation varies from country to country. Regionally, individual authorities or government agencies may host some data on individual projects and the industrial transfer to non-astronomy sectors. Also, individual groups or companies highlight how their own research and development has been successfully transferred outward and some websites and examples are given in the individual responses.

However, it does not appear that many countries have a mechanism within their astronomical community to identify industrial relevance/transfer to other interlocutors or communities as an integral component of their R&D. Or it may be that individual companies and research groups do not display or promote any results of this kind in their main scientific literature or websites. Further, due to copyright or possible intellectual property issues, groups may not, as a result of these restrictions, publicise their work. As a result, even after successful transfer to other sectors, a follow-up public access programme to successful transfer may be overlooked. This is most important to encourage public and industrial engagement with astronomy stakeholders. On the questions of the impact and successful commercial transfer on a regional or EC-wide level, there is strong evidence — even from this extremely limited sample — that there is no central bank or repository easily found or accessible to promote this culture. It is noted by the Panel that the EIROforum has taken the first steps to increase technology transfer among its members and the EC. Also note that ESO and ESA highlight and promote their respective technology transfer programmes[69] as well as EIROforum members.

In acknowledgement to the responses, it would appear that encouragement of the promotion of successful astronomy technology transfer activities would be most helpful in rectifying this situation. Furthermore, the creation of an easily accessible European repository of astronomy technology transfer would greatly enhance visibility of European success stories in astronomy.

Recommendation 9

Action. Create an international network of experts in technology transfer which organises an annual audit of technology transfer activities in order to increase the visibility of the industrial relevance of astronomy.

Institution. Agencies.

Timescale. Two to three years.

Comments. The network could involve existing structures in Europe.

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[63] http://www.eso.org/org/tec/TechTrans/ and
http://www.esa.int/SPECIALS/Technology_Transfer/

7.5 Exploitation of Facilities and the Impact on Recruitment and Training

During its deliberations on recruitment and training, Panel E raised the issue of the problems experienced by European researchers in the timely scientific exploitation of large, multi-facility, multinational research projects. The inevitable trend of tackling major, forefront scientific problems by orchestrating several large observational infrastructures to work together at the limits of their capability has highlighted a structural problem in the funding of research programmes in Europe. The funding mechanisms for scientific exploitation differ from country to country in Europe, but there are few, if any, readily available sources of support that can be accessed rapidly enough to allow researchers to compete effectively with, in particular, their US colleagues.

An example of such a programme is the GOODS[64] survey to study the mass assembly of galaxies etc. This employs large observing programmes with Spitzer, Hubble, ESO VLT, XMM/Newton, Chandra and other facilities to obtain a unique set of data that goes almost immediately into the public domain — making it universally available for analysis. GOODS and other deep field programmes tend to utilise multiple facilities and are known to have a very high scientific impact[65] (see also Section 1.2).

This structural problem was discussed and recognised by the Roadmap Working Group as a whole since it was felt that the importance of the effective exploitation of costly infrastructures was so important that it had to be emphasised in the report.

The issue is that large, potentially high impact, projects in Europe — that may employ multiple facilities — have difficulty in attracting funds soon enough to support a project process that results in the timely publication of results. In a highly competitive international environment, it is essential that the project has access to resources, such as dedicated and well-supported postdoctoral research fellows, early enough and in sufficient quantity. In this way, it can be ensured that the harvest of (observational) material can be turned into scientific results and conclusions that maximise the scientific effectiveness and exploitation of the facilities.

While European astronomers gain access to their major facilities as the result of peer-reviewed selection, they are generally unable to obtain dedicated funding to carry out the associated analysis and publication of results at a speed that is competitive with their non-European colleagues and competitors, the latter often being funded by substantial grants associated with the use of the facilities. Even if funding does eventually become available it is after a delay of about two years following a separate application to a different organisation that can only be initiated after the facility time has been granted. While we appreciate the dangers of assuming that the use of big facilities guarantees the quality and impact of the science, we do believe that the rigorous peer-review processes associated with the major facilities can safely be used as a proxy for the assessment for project funding from a non-facility source (e.g., the EU). A single stage process for the assignment of time and for the support of analysis and research would greatly improve the scientific impact of the work in Europe.

Recognising that large-scale, potentially high impact astronomical research in Europe generally has to go through a "two-hoop" process for the allocation of facility time and the support of analysis and publication, we propose that a way is sought of using the high quality peer-review process already operated by the facilities to provide "fast-track" funding for suitable projects, so enabling them to be internationally competitive. These projects are likely to use multiple facilities and may be pan-European and pan-continental in nature. We recognise also that such programmes provide valuable high quality training opportunities for young postdoctoral scientists that will place them in a strong position for further career development.

Recommendation 10

Action. Large-scale, potentially high impact astronomical research in Europe generally has to go through a "two-hoop" process for the allocation of facility time and the support of analysis and publication. We propose that a way is found of using the high quality peer review process already operated by the facilities to provide "fast-track" funding for suitable projects, so enabling them to be internationally competitive and of high value for training. These projects are likely to use multiple facilities and may be pan-European and pan-continental in nature.

Institution. This would generally need to be pan-European, presumably the EU or one of its delegated bodies.

Timescale. Two years.

Comments. This is a structural issue in Europe that must exist also in the other sciences that employ large, multinational facilities in a competitive, peer-reviewed process.

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[64] GOODS: Giavalisco et al. 2004, ApJ, 600, L93–L98

[65] Meylan, Madrid & Macchetto 2004, PASP, 116, 790–796

7.6 Summary and Implementation

Following an initial collection of some seventy items, Panel E were able to reduce and condense their deliberations to just ten recommendations directed toward the appropriate European and national bodies. A reasonable time to implement these recommendations is considered to be from one to three years. Note that, due to its somewhat broader nature, Recommendation 10 is considered to be an issue of concern to all the Panels and is not addressed further in this section.

It is recognised that in order for the recommendations in this chapter to be realised, they will need to be carried forward and monitored by a "champion" who has strong connections with funding agencies and other relevant high-level bodies in Europe. The need for continuity over at least two to three years, suggests that this is an activity for ASTRONET to follow beyond the current roadmapping exercise.

The recommendations generated by Panel E divide naturally into two categories. The first of these demand a change in mental attitude and methodology — basically a change of culture — and can be implemented at little or no cost over a period of one or two years. Recommendations 1, 2, 3, 6 and 7 fall within this group.

Given appropriate advice, it is possible for the national bodies responsible for school education to implement changes in a relatively simple way at little if any additional cost (Recommendations 1, 2 and 3). Each country has its own structure for teacher training and it is necessary to ensure that these provide opportunities to instruct teachers to present astronomy to their pupils in an exciting and stimulating manner. If this happens, we can be confident that future European citizens will have an appreciation of the Universe around them and can feel excitement about the progress of science in general. Also, the fact that observations of the sky, while being free of financial cost, do require low levels of light pollution, will contribute to an awareness of the need to care for our planet.

The employers of research scientists need to ensure that there is a clear and effective recognition of the efforts that these researchers make to communicate to the public what they are doing and to convey the excitement they feel about the discoveries they make (Recommendation 7). Such recognition should be significant factor in assessing career development.

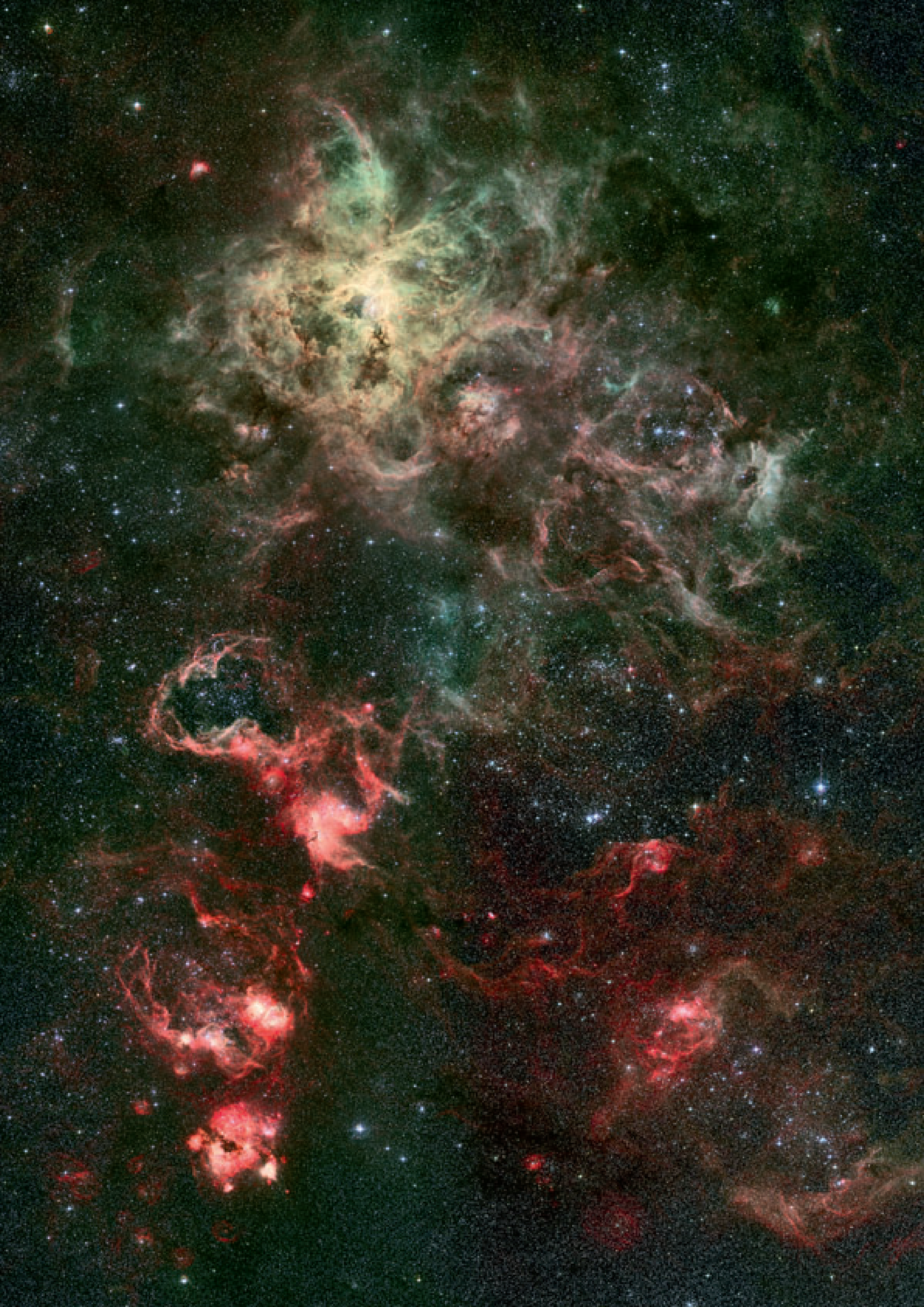
A general guideline reached by the Panel is for funding agencies to arrange to invest some 1–2% of their overall project expenditure into public communication and education and also to ensure that the research results are clearly represented and illustrated in the public domain (Recommendation 6).

The second category, including Recommendations 4, 5, 8 and 9, will require a somewhat longer period (two to three years) to realise and carry some requirements for funding. The development of new capabilities such as portals and repositories needs the clear identification of resources and responsible groups charged with their provision and maintenance. It may be that existing groups with short-term funding can be extended in a way that makes full and continuing use of their existing expertise and capabilities.

Although many professional Europe-wide activities can be effectively carried out in English, the resources aimed at school education have to be made available in the relevant languages. This is particularly pertinent for the portal for primary and secondary schools and for teacher training (Recommendation 4).

A second portal/repository is necessary for non-formal education as recommended in Recommendations 5 and 8. This portal should offer media (including images and videos) for the public and also tailored for science museums and planetaria. While there are already many excellent sources of material, a “one-stop-shop” or aggregator, would greatly increase the efficiency and effectiveness of dissemination.

Many of the contracts offered as part of the development of the cutting-edge facilities in astronomy today are of considerable interest and value to industry in Europe. Some of them can elevate small industries to large ones and/or create new capabilities of relevance to other fields — for example the fabrication of large, high precision optics. The tracking of this process and the recognition of opportunities for technology transfer requires the establishment of an expert group that will increase the visibility of the process (Recommendation 9).



Chapter 8 The Synthesised Roadmap

8.1 Introduction

Europe has a long history of accomplishment in astronomy and space science (see Chapter 1). It now possesses some of the most advanced and capable observational facilities together with some of the world's most talented scientists and engineers. This is an enviable platform on which to build as we seek to answer some of the most fundamental questions in science over the next two decades. However, as discussed in more detail in Section 1.2, for us to make the progress in understanding that is required, needs a step change in our capabilities. In most cases, real progress comes from utilising information across a broad spectral range, and hence requires the use of several distinct but complementary facilities (examples of which are again given in Section 1.2). The costs involved, compared with the likely funding available, inevitably mean that prioritisation has to occur. Nevertheless, as detailed in the introductory chapters, ASTRONET was established not only to facilitate the construction of a prioritised plan, but in so doing, to foster greater pan-European collaboration, enhance the impact that our work has on society in general and to help to secure the resources that our ambitious plans require to bring them to fruition. Overall, Europe has a great opportunity now to lead the way in many of the most significant areas of our work, not least by "getting our act together" and capitalising on those areas where we have special expertise.

This chapter summarises the conclusions of the five Infrastructure Roadmap Panels and brings them together to give an integrated plan for the future of European astronomy spanning the next 15–20 years. In doing so, it has been necessary for the Working Group to address priorities across the Panels, particularly in terms of the observational facilities considered by Panels A–C to be of high priority in delivering the goals of the Science Vision. This chapter also contains summaries of the conclusions of these Panels and those of Panels D and E, where plans for the development of the underpinning theory, modelling and data handling aspects of our science, together with those for enhancing our subject's impact on education, public engagement and industrial links, are also detailed. The priorities as set out below took into account the open debate and consultation with the community that centred around the Roadmap Symposium and web-based forum. They are also of course based on the criteria that governed our process and do not include any wider political issues which may be important in international collaborations or individual national priorities.

The main areas of technical development and potential industrial involvement that are required are outlined. Also stressed is the need to provide sufficient resources across Europe to attract and employ the talented scientists and engineers required to realise the design, construction and effective operation of future facilities, and no less important, to be able to fully exploit them scientifically.

The financial background to all of this is of course of great importance. As can be appreciated, the funding landscape in Europe is very diverse and complex. However, we have attempted to determine the current overall funding envelope with the best accuracy we can (there are still several caveats here but these are noted in Section 8.10 below). On the other side of this picture are the likely costs of the infrastructures to be developed. As detailed in Chapter 2 and the individual Panel Reports that follow it, we have attempted to determine these costs (both capital and operational) as accurately as we can from a variety of sources. However, for projects in the early stages of development in particular, such costs have an inherent degree of uncertainty that means that, as a project progresses, regular reporting and independent monitoring of updated costs must take place. The financial implications again are addressed in Section 8.10 below. Finally, in Section 8.11, the next steps in putting this plan into action are then outlined.

Image Credit: ESO/J. Alves, B. Vandame, Y. Bialetski, R. Fosbury

8.2 Future Observational Facilities

To make their task more tractable, Panels A–C subdivided projects that were to be included in the ranking process (see Section 2.3 for inclusion criteria) into Ground and Space-Based; Near, Medium and Long-Term (in terms of time to full operation), and also into Small, Medium and Large-Scale (in terms of capital cost for design and construction). In producing a synthesised Roadmap it was considered that the most important subdivisions were given by whether a project is Ground or Space-Based and the financial scale of a project (in terms of likely European funding requirement). The financial subdivision has some consistency both with the US Decadal Survey and also with the ESA Cosmic Vision process (note that for space missions, we include likely payload costs, unlike ESA). Retaining the division between Ground- and Space-Based was also thought appropriate as the majority of the space missions covered here will be scrutinised in increasing detail as the Cosmic Vision implementation process progresses over the next few years. Indeed, as emphasised in Chapter 2, our evaluations of all projects are of necessity a snapshot and continued detailed scrutiny of progress is needed in every case.

8.2.1 Ground-Based, Large-Scale

Two projects were seen as being equally high priority under this heading:

European Extremely Large Telescope (E-ELT – see Section 4.2.2.1 for more details). The E-ELT project envisions a 42 m-diameter filled-aperture phased telescope with an internal adaptive optics system designed to provide near diffraction-limited angular resolution in a 5’ (scientific)–8’ (technical) diameter field of view over 80% of the whole sky (through the use of multiple natural and laser guide stars). The minimum wavelength domain is 0.4–21 µm. This instrument-friendly facility should accommodate at least six large focal stations with fast switchover in order to optimise its scientific output.

Square Kilometre Array (SKA — see Section 4.2.2.2). The SKA project envisages an aperture synthesis radio telescope achieving sensitivity 50 times that of upgraded existing radio arrays and survey speeds 10 000 times faster. The frequency coverage will extend from ~ 70 MHz–25 GHz and will be attained in three phases: Phase 1 will be the initial deployment (15–20%) of the array at mid-band frequencies (100 MHz–10 GHz); Phase 2 will be the full collecting area at low to mid-band frequencies (~ 70 MHz–10 GHz); Phase 3 entails the implementation of higher frequencies up to ~ 25 GHz and is beyond the timeline of the current Roadmap exercise. There will be a central concentration of antennas, with remote groups of antennas located at distances up to at least 3000 km from the core and connected to the central data processor via a wide-area fibre network. Constituent technologies include phased arrays and dish reflectors used in various combinations across the operating frequency band. Short-listed sites are remote areas of western Australia and southern Africa.

The E-ELT and the SKA are the two flagships for ground-based astronomy in the future. Both of them have exceptional capabilities, with performance orders of magnitude better than existing facilities. New windows will be opened up in prominent domains such as, for example, direct imaging of exoplanets with the E-ELT, or the measurement of the equation of state of dark energy with the SKA.

If the ongoing Phase B study is successfully completed according to schedule, all elements will be there to decide on the construction of an E-ELT in 2010. Postponing the decision much longer would weaken the project in view of the competition with the two other privately funded US projects, and the complementary research possible with the JWST. The ESO VLT is now the best observatory in the world in the optical domain. The E-ELT, if decided in time, will ensure the continuation of this leadership. While possibilities for finding external partners should be actively pursued, a strong European leadership should be maintained, with ESO as the central organisation.

Being a global project, with a very strong involvement of southern hemisphere countries, the European contribution to the SKA will be proportionately less than for the E-ELT. The present goal is for Europe to contribute at a level of between 33–40% overall. The governance and the management structure of the project and the full design of Phase 1 of the array will be finalised by 2011. A decision should be taken in 2012, for the first phase, and later, in 2015/2016 for Phases 2 and 3. As with the other projects considered here and in Section 8.3, cost profiles (including the cost for both construction and initial operations) etc. are summarised in Section 8.10 below from details given in the relevant Panel report chapter.

An attempt has been made to construct a phased plan to deliver E-ELT and the SKA in a timely fashion (see Section 8.10.2 below).

8.2.2 Ground-Based, Medium-Scale

Three projects were considered to be of highest priority here. They are now summarised in order, with the top priority first.

The European Solar Telescope (see Section 5.2.1.1). The EST is a 4 m-class solar telescope to be located on the Canary Islands. It will be equipped with a suite of post-focus instruments designed to operate together. With a diameter four times larger than any existing high resolution solar telescope, the advent of the EST will thereby enable observations at unprecedented spatial resolution and sensitivity to magnetic fields. The post-focus instruments will measure fundamental astrophysical processes at their intrinsic scales in the Sun's atmosphere to establish the basic mechanisms of magnetic field generation and removal; detect and identify the mechanism by which energy is transferred from the solar surface, heats the upper solar atmosphere and eventually accelerates the solar wind. Once operational, the pan-European EST will replace the existing national solar telescopes on the Canary Islands and will thus be the main observing tool for ground-based European solar physics. The EST is complementary to the US-led 4 m ATST project.

To keep the European leadership in solar physics and properly address key questions in the Science Vision it is important that the EST is implemented as early as possible. Given the previous design efforts (LEST, ATST and the ongoing FP7 pre-design project) the technology readiness is high and we recommend that the EST should also be included in the ESFRI roadmap in the next revision.

Cherenkov Telescope Array (CTA – see Section 3.2.1.1). The CTA promises to be a very powerful multi-functional tool for spectral, temporal and morphological studies of galactic and extragalactic sources of Very High Energy (maximum range considered: several tens of GeV to 100 TeV) gamma rays. The motivation is twofold: (i) to obtain an order of magnitude improvement of the flux sensitivity in the currently explored energy band between 100 GeV to 100 TeV, and (ii) to extend significantly the energy domain of ground-based gamma-ray astronomy down to several tens of GeV. The current plan for the CTA consists of two observatories, one in the northern and one in the southern hemisphere, and each including two sub-arrays, aimed at energies of 100 GeV–100 TeV and at ~ 10–100 GeV detection respectively, with the latter being more technically challenging.

The CTA is judged in particular to be an important tool in investigations of the origin of galactic cosmic rays, of the physics of relativistic outflows on different scales, the physics of black holes close to the event horizon, indirect measurements of the extragalactic background light and indirect searches for dark matter.

At this stage, the CTA community sees the most promising approach to build, on a timescale to around 2015, an instrument with energy threshold around several tens of GeV and extending to 100 TeV. The CTA is expected to enter the realm of an observatory-type astrophysics telescope and will therefore have a very broad user base. Given that the southern site provides best galactic coverage and comparable extragalactic coverage, deployment of the proposed southern observatory should be given highest priority.

KM3NeT (see Section 3.2.1.2). This is a proposed km^3-volume water Cherenkov telescope to be built in the Mediterranean Sea. It will complement IceCube, a neutrino telescope nearing completion at the South Pole, but will have better angular resolution and potentially higher sensitivity. The technological challenges in deploying KM3NeT appear comparatively minimal and there is an ongoing EU-supported study of the project. Although, as described in more detail in Chapter 3, up until now high energy neutrino astronomy has remained a largely theoretical discipline, with these two facilities operating, the astronomical potential of the field should eventually be realised. This includes a significant discovery potential concerning "hidden" astrophysical objects, i.e. regions from which only neutrinos can escape because of their weak interactions with ambient gas, radiation and magnetic fields.

Although KM3NeT was highly ranked due to its potential proof of principle of detecting and diagnosing TeV neutrino sources, the CTA was given a somewhat higher priority due to its more proven capability for astrophysical discovery.

8.2.3 Ground-Based, Small-Scale

Wide-Field, Multiplexed Spectrographs (see Section 4.2.1.1). There are compelling and fundamentally important scientific cases for the development of wide-field, highly multiplexed spectrographs to be placed on an existing 8–10 m-class telescope (see Section 4.3.2), and consequently such a project was given very high scientific priority. It should enable massive spectroscopic surveys of a million or more objects at a speed and on timescales compatible with the next generation of wide-field imagers, e.g., the LSST. The primary science drivers are the determination of the equation of state of dark energy, the study of stellar populations over a large fraction of the history of the Universe, and the study of the structure and formation of the Galaxy and Local Group by determining in a quantitative manner the kinematical and chemical signatures of the different stellar components.

Of two specific proposals surveyed by Panel B, neither was judged mature enough to be included specifically at this stage in the Roadmap. Therefore, considering the enormous scientific value of wide-field spectrographic surveys and their under-representation compared to imaging initiatives, we recommend setting up a working group, under the auspices of ASTRONET, with OPTICON, with the task of (i) developing the top-level requirements of the surveys, (ii) identifying implementation options on a European scale, (iii) establishing the merits of these options with a trade-off analysis and proposing an implementation plan to provide a facility for the whole European community in the 2015–2020 time frame.

8.2.4 Space-Based, Large-Scale

A total of eight projects were placed in this category. Within the ESA Cosmic Vision process, LISA is a competitor for the L1/L2 slot with XEUS/IXO and the mission to the giant planets (TandEM or LAPLACE). ExoMars is part of the separate Aurora programme. Three other projects, submitted in response to the 2007 Cosmic Vision call, were considered to be worthy of continued technological development and further costing and feasibility studies. As with the ground-based projects described above, costs and timescales are summarised in Table 2, with more details in the relevant Panel report Chapters.

X-ray Evolving Universe Spectroscopy/International X-ray Observatory (XEUS/IXO – see Section 3.2.3.1). XEUS is one of the three large missions selected for study by ESA within the current ESA Cosmic Vision programme. It represents ESA's next generation X-ray observatory and will provide a facility for high energy astrophysics fully complementary to other major future observatories operating across the electromagnetic spectrum such as the SKA, ALMA, JWST, the E-ELT and the CTA. In May 2008 ESA and NASA established a coordination group involving ESA, NASA and JAXA, with the intent of exploring a joint mission merging the ongoing XEUS and Constellation-X studies into developing an International X-ray Observatory. A single merged set of top-level science goals and derived key science measurement requirements were established. The starting configuration for the IXO study will be a mission featuring a single large X-ray mirror and a set of powerful imagers and spectrometers. The study will explore how to enhance the response to high energy X-rays. This plan establishes an IXO study, which will be the input to the US decadal process and to the ESA selection for the Cosmic Vision plan. The IXO study supersedes the XEUS and Constellation-X activities. An observatory such as XEUS/IXO will also be synergetic with planned future developments in the spheres of gravitational-wave and neutrino astronomy (LISA and KM3NeT respectively).

While the XEUS concept envisaged a pair of spacecraft in a formation-flying configuration, the IXO approach is based on single spacecraft with a deployable structure in order to achieve the focal length needed to meet the scientific goals of the mission in which an X-ray telescope of novel design and unprecedented collecting area feeds a suite of state-of-the art instruments. The huge improvement in sensitivity compared to current X-ray telescopes, coupled with a high spatial and spectral imaging capability, will make XEUS/IXO a unique facility for studying high energy phenomena and processes over the full span of the observable Universe. The user base will encompass the entire world astronomical community.

Laser Interferometer Space Antenna (LISA — see Section 3.2.3.2). LISA is a space-based gravitational-wave astronomical observatory aimed at opening the 0.1 mHz–0.1 Hz low frequency range inaccessible from the ground. In that range, several tens of thousands of compact object binary systems (white dwarfs, neutron stars, black holes) within the Milky Way should be detectable. In addition, many tens of extreme mass-ratio black hole binary in-spiral events per year are expected up to about $z = 1$, as well as mergers of binaries involving at least one black hole with mass of 10^2–10^4 solar masses out to $z = 20$. With this observational potential LISA will help in understanding the formation and the growth of massive black holes, determine the merger history of galaxies, explore stellar populations and dynamics in galactic nuclei. It will accurately map the spacetime geometry around collapsed objects and test general relativity in the strong field regime and it will also have the potential to act as an additional probe of the nature of dark energy and possibly the very earliest phases of the Big Bang.

LISA represents a true gravitational-wave astronomical observatory serving a wide astronomical community and is a cooperative ESA–NASA mission. It is included within the Beyond Einstein Program[66] in NASA and has been strongly endorsed in the 2007 BEPAC review. LISA is the sole mature low frequency gravitational-wave observatory. Ground-based detectors are sensitive in the high frequency range and will therefore address completely different sources (typically stellar mass objects). Panel A noted the enormous discovery potential that lies in the advanced LIGO and Virgo detectors. This potential, when realised, will clearly raise the priority of the third generation Einstein Telescope.

LISA will be preceded by LISA Pathfinder, already in implementation for a launch in 2010/11. The pathfinder will demonstrate and test the feasibility of key components of the full LISA mission that will in turn have significant industrial spin-off (see Section 8.9).

LISA and XEUS/IXO were ranked together at the highest priority among all projects discussed in this category. Ideally they should fly in close conjunction to each other in order to exploit the important synergies between the two projects. The implementation sequence will mainly be determined by technological readiness and the international collaboration context.

Titan and Enceladus Mission (TandEM — see Section 5.2.3.3). TandEM promises *in situ* exploration of Saturn's satellites Titan and Enceladus. The baseline mission concept is for two moderately sized spacecraft, to be launched by one or two launch vehicles, which will carry an orbiter, a Titan aerial probe, Titan mini-probes and Enceladus penetrators/landers. The scientific objective of TandEM includes the understanding of cryovolcanism on Titan and Enceladus, the cycle of methane on Titan (which shows some analogies with the terrestrial water cycle on Earth), the photochemistry and ionospheric chemistry of Titan, and the interaction between Enceladus and Saturn's E-ring, presumably fed by the satellite. The TandEM mission is seen as a top medium-term priority for the whole planetology community. The mission will take the benefit of the Cassini–Huygens and ExoMars heritages, but will also require new technology developments as discussed in Section 5.2.3.3 (see also Section 8.9 below).

LAPLACE (see Section 5.2.3.4). LAPLACE is a multi-platform mission to the system of Jupiter and its Galilean satellite Europa, which may shelter a water ocean between its icy crust and its silicate mantle, and might be a good candidate for extraterrestrial life. The LAPLACE mission will deploy a triad of orbiting platforms in the Jovian system to perform coordinated observations of Europa, the Jovian satellites and the Jovian atmosphere and magnetosphere. As with TandEM, the LAPLACE payload will include a large range of remote sensing instruments. The main scientific objectives of LAPLACE are (i) to understand the formation of the Jupiter system, (ii) to understand the physical processes that govern this system, and (iii) to explore Europa's internal structure and its potential habitability. As with TandEM, LAPLACE will address a broad range of planetary objectives and is thus a top medium-term priority for the whole planetology community. The Galileo mission and the JUNO mission, presently under development, demonstrate that US technologies are suitable for the Jovian environment. For Europe, a number of specific key technologies will have to be developed, as detailed in Section 5.2.3.4.

A down-select by ESA between TandEM and LAPLACE is anticipated in early 2009. This will, in part, be influenced by decisions within NASA with whom one of these projects will be progressed. Japan may also play a role. Panel C and the Working Group did not place a priority order between these two projects therefore, but the latter gave slightly lower priority to TandEM/LAPLACE compared to LISA and XEUS/IXO, primarily because the potential for fundamental discoveries across a broad front was perceived to be greater for the latter two missions.

ExoMars (see Section 5.2.2.2). ExoMars is the first mission planned by ESA in the framework of the Aurora programme. Its ultimate goal is to establish whether life ever existed or is still active on Mars today. It is designed for robotic exploration of Mars, including a rover devoted to exobiology research (the Pasteur payload) and a Geophysics and Environment Package to be accommodated on the landing platform, for meteorological and internal structure *in situ* studies. In addition to the studies undertaken by Pasteur and GEP, engineering sensors necessary for the ExoMars Entry, Descent and Landing System will provide an opportunity to perform vital "descent science" measurements.

ExoMars is a near-term, top priority for the European planetology and exobiology community. Contributions by NASA and Russia are planned. The necessary technological development is addressed in Section 5.2.2.2 (see also Section 8.9). It is also a necessary prerequisite to prepare for future, more ambitious missions, in particular a Mars Sample Return mission.

Although highly rated, ExoMars was ranked lower then TandEM/LAPLACE in terms of the uniqueness of its contribution to our understanding and the overall size of the potential user base in Europe.

Darwin (see Section 4.2.5.1). Darwin has been proposed as an L-type mission whose primary goal is the study of terrestrial extrasolar planets and the search for life on them. Darwin is designed to detect rocky planets similar to the Earth and perform spectroscopic analysis of them at mid-infrared wavelengths (6–20 μm), where the most advantageous contrast ratio between star and planet occurs. The spectroscopy will characterise the physical and chemical state of the planetary atmospheres and search for evidence of biological activity. The projected costs are so high that it is a primary candidate for international collaboration. Mission concepts have already been studied by ESA and NASA, and talks about a possible joint mission have started. From a technological point of view, Darwin is very challenging because it requires ultra-high contrast ($> 10^6$) nulling interferometry in cryogenic conditions, and high precision formation-flying capabilities still to be developed (see Section 8.9). Detailed timelines and costs are thus yet to be defined.

Far-Infrared Interferometer (FIRI – see Section 4.2.5.1). FIRI will study the formation and evolution of planets, stars and galaxies. The FIRI mission concept comprises three cold, 3.5 m-aperture telescopes, orbiting a beam-combining module, with separation of up to 1 km, free-flying or tethered, operating between 25–385 μm, using the interferometric direct-detection technique to ensure μJy sensitivity and 0.02” resolution at 100 μm, across an arcmin^2 instantaneous field of view, with a spectral resolution, $\lambda/\delta\lambda \sim 5000$ and a heterodyne system with $\lambda/\delta\lambda \sim 10^6$. In the FIRI wavelength range it will be possible to peer through dusty regions to unveil the earliest formative stages of planets, stars and galaxies, unperturbed by the confusion experienced by its precursors, Herschel and SPICA. FIRI would attract a broad user community because it would open up a new wavelength region that has not been explored before at this level of spatial resolution and sensitivity. Again, the projected costs are so high that it is a primary candidate for international collaboration (possibly ESA–NASA). FIRI requires two major breakthroughs in space missions. The first one is related to achieving a tuneable baseline interferometer and the second one is linked with the requirements on the detectors (see Sections 4.2.5.1 and 8.9). Again, total costs and timelines are uncertain.

Probing Heliospheric Origins with an Inner Boundary Observing Spacecraft (PHOIBOS — see Section 5.2.4.1). PHOIBOS is a mission of exploration and discovery designed to make comprehensive measurements in the never-observed region of the heliosphere from 0.3 AU in to as close as three solar radii from the Sun’s surface. The primary scientific goal of PHOIBOS will be to determine how magnetic fields and plasma dynamics in the outer solar atmosphere give rise to the corona, the solar wind and the heliosphere. Reaching this goal is a Rosetta-Stone step for all of astrophysics, allowing the understanding not only of the plasma environment generated by the Sun, but also of the space plasma environment of much of the Universe, where hot tenuous magnetised plasmas transport energy and accelerate particles over a broad range of scales. Moreover, by making the only direct, *in situ* measurements of the region where some of the deadliest solar energetic particles are energised, PHOIBOS will make unique and fundamental contributions to our ability to characterise and forecast the radiation environment in which future space explorers will work and live. Similar missions have been proposed in the NASA system (Solar Probe) and a collaboration is natural. Going so close to the Sun is technically very challenging and more studies are needed before the mission is technically mature. Initial cost estimates are in excess of €1B.

Despite the fact that these three proposals (Darwin, FIRI and PHOIBOS) were submitted for the first round of implementation of ESA’s Cosmic Vision programme, i.e. for the period 2015–2020, Panels B and C considered it more realistic that these missions can only be realised after 2020. They are considered as scientifically very important, and that is why they are included here. We note that the ESA–SSAC has taken a very similar approach.

It is clear that longer-term missions such as Darwin, FIRI, and PHOIBOS will require considerable study and technical development. Although the provision of EC framework funds for initial technical development has been invaluable, and should be continued, more substantial funding than is available today must be provided to support preparatory R&D activities in the future (see e.g., Section 4.5 and also Sections 8.9 and 8.11 below).

8.2.5 Space-Based, Medium-Scale

Gaia Data Analysis and Processing (see Section 4.2.3.1). Europe has taken the worldwide lead in astrometry with its very successful mission Hipparcos. Currently, a follow-up mission with greatly enhanced capabilities is being prepared for a launch in 2012: Gaia. We want to underline the need to sustain the very substantial data analysis and processing effort for this mission during the entire period until 2022 in order for Europe to reap the considerable scientific rewards of this extremely important mission. The data output from Gaia are of importance for the entire astronomical community and the long-term sustenance of the data analysis and processing activity was seen as the highest priority project in this category.

EUCLID (see Section 4.2.4.1). DUNE and SPACE were ranked the most highly by the ASTRONET Working Group amongst the new mission proposals submitted to ESA in response to the Cosmic Visions AO, and lying in the Medium-Scale category. They represent two different approaches to addressing one of the outstanding open questions in astrophysics — the nature of dark

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[66] http://beyondeinstein.nasa.gov/

energy and dark matter — with unprecedented precision. Roadmap Panel B, fully in line with the ESA–SSAC recommendation, emphasises the need to carry out a European study of a dark energy mission and to ultimately implement it in ESA's strategic plan. ESA has started a study of such a mission under the new name EUCLID. Although the total mission cost may exceed our nominal €400M threshold, here we retain EUCLID in the Medium-Scale project category for consistency with ESA.

EUCLID will combine the weak lensing approach of DUNE with the baryonic acoustic oscillations of SPACE. The concept currently under study includes a 1.2 m telescope with a ~ 0.5 deg^2 FOV providing optical (550–920 nm) images, near-IR Y-, J-, H-band photometry and low resolution (R = 400) 0.8–1.7 μm spectroscopy. Technological challenges appear relatively modest. NASA has also assigned a high priority to a dark energy mission in its strategic plan. Three mission concepts are under review, and a final choice will be made most likely in 2009. Preliminary discussions have already taken place between NASA and ESA to establish the possibilities for cooperation on such a mission.

Solar Orbiter (see Section 5.2.2.1). Solar Orbiter is a mission going close to the Sun and reaching heliographical latitudes of 30 degrees to enable studies of the solar polar regions. The principal scientific objectives are to determine the properties, dynamics and interactions of plasmas, fields and particles in the near-Sun heliosphere; to investigate the links between the solar surface, corona and inner heliosphere; to explore, at all latitudes, the energetics, dynamics and fine-scale structure of the Sun's magnetised atmosphere; and to probe the solar dynamo by observing the Sun's high latitude field, flows and seismic waves. Solar Orbiter has become a key component of the joint ESA–NASA HELEX programme, broadening further the scientific scope towards an in-depth investigation of how the Sun determines the inner heliospheric environment. Solar Orbiter is the only mission currently planned with imaging and spectroscopic capabilities from a vantage point out of the ecliptic plane. *In situ* and remote observing from the Sun's close vicinity is another unique aspect of the mission.

During some of the work on the Roadmap, it seemed as if all major decision points for Solar Orbiter would be in 2008 and it would thus fall outside the scope of this document. With the cost overruns in the ESA science programme this is not likely to be the case any more and Solar Orbiter is therefore now included here. At the time of evaluation, Solar Orbiter was a near-term project with a planned launch in 2015. It is kept in the near-term category to emphasise the project maturity and its status as a selected project, although a launch in 2017 now seems more probable for budgetary reasons. Among the medium cost, space-based projects, Solar Orbiter is seen as the top priority project of Panel C and ranked somewhat above Cross-Scale by the Panel. This relative ranking was endorsed by the Working Group, which placed Solar Orbiter below EUCLID in priority, but above the grouping of projects described below that contains Cross-Scale itself.

Cross-Scale (see Section 5.2.3.1). Cross-Scale will perform *in situ* (near-Earth environment – magnetosphere and solar wind) studies of the fundamental properties of the physics of astrophysical plasmas. The vital role of these interactions has been demonstrated for the first time by Cluster. Their proper scientific exploration requires simultaneous three-dimensional plasma measurements on three physical scales and hence simultaneous measurements at twelve points in space.

Cross-Scale has drawn significant interest from Japan and the US, and it is a project in partnership with Japan with a proposed equal share of costs. Cross-Scale has a large potential user base in Europe as evidenced by the strong interest in Cluster from many countries. The remaining technological challenges are discussed in Section 5.2.3.1.

Planetary Transits and Oscillations of Stars (PLATO — see Section 4.2.4.2). PLATO is another project submitted in response to the Cosmic Visions AO and currently under study by ESA. It will perform high precision monitoring in visible photometry of a sample of more than 100 000 relatively bright ($m_V \leq 12$) stars and another 400 000 stars down to $m_V = 14$, and will meet stringent requirements: a field-of-view larger than about 300 deg^2; a total duration of monitoring of at least three and preferably five years; a photometric noise less than 8×10^{-5} (goal: 2.5×10^{-5}) in one hour for stars of $m_V = 11$–12. This dataset will allow the detection and characterisation of exoplanets down to Earth-size and smaller by their transit in front of a large sample of bright stars, while obtaining a detailed knowledge of the parent stars thanks to asteroseismological measurements. It will have the ability to detect planets around bright and therefore close-by stars and can thus be considered as the necessary pathfinder for Darwin or TPF. The technological readiness level is high for this mission.

Simbol-X (see Section 3.2.2.1). Simbol-X is a hard X-ray imaging mission led by France and Italy, with the participation of Germany. Initially, it is expected that the scientific results will be shared among these communities, but there may also be more open competition. It is a short-term, medium-size space project and could serve as a first demonstrator for the technique of formation flying. The long focal length (20 m) afforded by the separation of the mirror and instrument spacecraft provides the unique opportunity in high energy astrophysics to fly a focusing telescope operating in the hard X-ray (10–80 keV) regime, with a wide field of view and a wide energy range, a high angular resolution, spectroscopic capabilities, accurate timing and an orbit such that long integrations will be possible. Simbol-X will both be a pathfinder for, but also complementary to, XEUS/IXO. Because of its enhanced capabilities, and above all its higher angular resolution, Simbol-X will significantly outperform NuStar (NASA) and NeXT (JAXA/ISAS), which are planned in the 2011–2013 time frame.

Space Infrared telescope for Cosmology and Astrophysics (SPICA – see Section 4.2.4.3). SPICA is a Japanese-led space-based mid- to far-infrared observatory with a 3.5 m-aperture telescope cooled to ~ 5 K. This gives it an enormous sensitivity advantage over current and future (Spitzer and Herschel) facilities in the 30–210 μm range where cold dust and gas emit most of their energy. SPICA's core operational wavelength range will be from 5–210 μm with uninterrupted, wide-field capabilities for imaging and spectroscopy. A coronagraph will allow direct imaging and spectroscopy of, among other things, Jupiter-like exoplanets and protoplanetary discs. It will be an observatory open to the scientific community at large. An ESA-provided Science Operations Centre will guarantee rapid access to the data for European scientists. Europe would also provide the 3.5 m-diameter telescope assembly. In addition, a nationally funded consortium will provide the SAFARI instrument, a cryogenically cooled Fourier-transform spectrometer operating over the 30–210 μm range. Panel B ranked SPICA very highly in view of its scientific discovery potential.

The SPICA telescope builds upon the heritage from Herschel and its development does not entail significant risks. The technology readiness is high for most mission subsystems, with the exception of the detectors (Transition Edge Sensors) and their sub-Kelvin coolers (Adiabatic Demagnetisation Refrigerator). Industrial relevance is addressed in Section 4.2.4.3.

Marco Polo (see Section 5.2.3.2). Marco Polo is a joint European-Japanese sample return mission to a near-Earth object with ESA providing the launcher and the lander, and JAXA providing the main spacecraft. Its target is a primitive NEO whose constituents are unlike known meteorite samples; the target NEO will be scientifically characterised at multiple scales, and samples will be brought back to Earth and analysed in terrestrial laboratories, preferably including the recommended new European Sample Return Facility (see Section 5.6). Marco Polo thereby contributes to our better understanding of the origin and evolution of the Solar System. Current exobiological scenarios consider the possibility of an exogenous delivery of organic matter to the early Earth, possibly through primitive NEOs. Moreover, collisions of NEOs with the Earth pose a finite hazard to life. For all these reasons, the exploration of such objects is particularly interesting and urgent. A joint ESA–JAXA study is considering the technological development required (see also Section 8.9).

The Working Group found it difficult to prioritise between Cross-Scale, PLATO, Simbol-X and SPICA. With the advent of the IXO initiative, Simbol-X may not be quite as important in the development of formation flying for the next generation large X-ray mission as it was formerly. However, its capabilities in the hard X-ray compared to the XEUS/IXO concept counteracted any decrease in priority. Finally in this group, Marco Polo was clearly ranked below Cross-Scale by Panel C using our evaluation criteria and therefore is placed below the group of other projects. The relative ranking of the latter two missions was based on the larger discovery potential of Cross-Scale, the importance of the understanding of astrophysical plasmas in general and thus the larger user community compared to Marco Polo.

Not surprisingly perhaps, there were no new Space-Based projects in the Small-Scale, High Priority, category.

8.3 Existing Observational Facilities

8.3.1 Existing Ground-Based Facilities and those in the Late Stages of Development

In several cases, the Panels concluded that certain categories of existing facilities should be treated as a class and recommended specific follow-on actions to enhance their future role. Here we present the main conclusions for each category, together with a brief commentary on particular major projects that are about to come online.

Solar Telescopes (see Section 5.4). Europe has a strong track record in solar instrumentation, operating four of the leading, ground-based solar telescopes: the Swedish 1 m Solar Telescope, the French/Italian Themis, the German Vacuum Tower Telescope and the Dutch Open Telescope, all four situated on the Canary Islands. A 1.5 m solar telescope (Gregor) is close to completion. To address several of the Science Vision questions, it is important to keep providing adequate access to modern solar telescopes for the European community until the EST is completed. The technical expertise in the groups currently operating telescopes on the Canary Islands also plays an important role for EST design efforts. It is foreseen that much of the current operating costs (about €2.5M/yr) can be transferred to the EST and most of the present facilities will then be closed down.

Some of the goals in the Science Vision are best accomplished with smaller facilities that fall below the cost limit of this Roadmap. An important example is a global network of ground-based, synoptic instruments that continuously monitor the Sun's magnetic and velocity fields as well as spectrally resolved radiative output over the full solar disc with sufficient spatial resolution. Small facilities are also important in studying the Sun-Earth system as the terrestrial response to solar activity/space weather is best characterised by making simultaneous measurements at many different locations around the Earth. Small facilities and small instruments on strategic spacecraft (see also Section 8.4) also provide key measurements in understanding space weather and indeed longer-term space climate issues. To ensure the scientific productivity of these smaller facilities/instruments, it is vital that their development, construction, and operation are well coordinated among each other and with space missions.

2–4 m-Class Optical/IR Telescopes (see Section 4.3.1). While small to medium-size facilities (SMFs) have a clear role to play on their own in supporting the European Science Vision, their coordination at European level could certainly optimise their scientific return, while achieving cost savings. A review committee has been appointed by the ASTRONET Board in coordination with the OPTICON Executive Committee. Its remit is to deliver to ASTRONET by September 2009, under the umbrella of Work Package 3.2 (implementation of the Infrastructure Roadmap), a short and medium to long-term strategy to optimise, in concert with OPTICON, the use of 2–4 m-class optical/infrared telescopes by the European astronomical community.

8–10 m-Class Telescopes (see Section 4.3.2). At present, European astronomers have access to 8–10 m-class telescopes in both hemispheres; the VLT, Gemini, LBT, SALT and the GTC, plus some others that fall below our threshold. All are managed by international consortia involving several nations. It is proposed that a review be undertaken, similar to that proposed for the 2–4 m-class telescopes, and again involving ASTRONET and OPTICON, but performed 3–5 years from now. Its main aims would be to look at rationalising access to, and instrument development for, these telescopes in the run-up to the era of the E-ELT.

Millimetre and Submillimetre Telescopes (see Section 4.3.3). The millimetre and submillimetre wavelength ranges play a key role in studying the "cold universe". European groups from France, Germany, the Netherlands, Spain, Sweden, the UK, as well as ESO, are presently operating a number of world-class millimetre and submillimetre facilities on high altitude sites in Europe, on Hawaii and in Chile. While, in principle, access to these facilities is limited to the respective scientific communities, all these facilities have accepted observing proposals from all across Europe, and indeed more widely, under the EC-funded RadioNet TransNational Access (TNA) scheme as one of the RadioNet activities. Training Europe's young astronomers in (sub)millimetre science and techniques (both hardware and software) is also the best way to maximise Europe's return from the involvement in the ALMA project and will be a solid basis for an active European role in future ALMA developments. A coherent long-term plan should be established under the auspices of ASTRONET together with RadioNet during the coming three years. It should outline the scientific role of each of the current facilities in the ALMA era, develop an access strategy beyond the current TNA scenario, and it should define the future investments to be made on the basis of the scientific excellence of the projects that can be carried out. Also, this plan should give a comprehensive answer to the question of how the European astronomical community can best be supported through software developments, training courses and other support to optimise the scientific exploitation of ALMA.

Radio Observatories (see Section 4.3.4). A large fraction of the existing radio telescopes in Europe will continue to operate independently and as part of the European (and global) VLBI network. New and upgraded facilities such as LOFAR, e-MERLIN and the Yebes 40 m dish are being commissioned; the Sardinia Radio Telescope is under construction and expected to deliver first light towards the end of 2009; broadband e-VLBI is moving from a test system to being operational on the EVN/JIVE. A particular role for existing European radio facilities arises in connection with the preparation for the SKA. The European radio community is actively developing and testing the new technologies that will be needed. LOFAR is, of course, one of the prime examples of an SKA pathfinder for low frequencies and other technology development is occurring in relation to e-MERLIN, EVN/JIVE upgrades etc. Panel B has not yet undertaken a systematic survey of plans that may exist for their future exploitation. However, such a survey and a preliminary plan to optimise the use of existing radio telescopes is underway by RadioNet. It is proposed that the full plan is developed by ASTRONET in conjunction with RadioNet during 2010.

Finally, both ALMA and LOFAR are recognised as major projects with potentially very high scientific returns. E-LOFAR and potential upgrades and extensions to ALMA were recommended for consideration in a future ASTRONET process once the current projects have been completed and their scientific capabilities (and limitations) have been fully demonstrated.

8.3.2 Ongoing Space Missions and those in the Late Stages of Development

The Panels and Working Group recognised the importance of several missions that were in advanced stages of development and where the major funding decisions had therefore already been made. These missions include in particular SDO, BepiColombo, JWST, Herschel, Planck, Fermi and SRG. They wished to stress the importance of adequate post-launch support of these costly enterprises and also to urge that adequate resources are provided for science exploitation (see Section 8.7.3 below). In addition, the Panels singled out as high priority the continued operational support of the following ongoing space missions once their current guaranteed operational funding ends. It should be emphasised that the Panels did not consider proposals for mission extensions for those missions (such as Herschel/Planck) that had not been launched at the time of our deliberations. Mission extensions normally receive a lower score on Scientific Impact than new missions since the "discovery" aspect will normally be fulfilled in the nominal part of the mission. Extensions can, nevertheless, get high priority because of large supporting value for other missions, because an extension will enable the full coverage of a natural timescale (like the solar cycle) and/or because an extension may give large amounts of science for a modest cost. Mission extensions mean extending the operations beyond the design lifetime and the decision will depend on the health-status of the spacecraft with the decision point thus close to the start of the extension period.

XMM-Newton (see Section 3.2.4.1). is one of the cornerstones of ESA's Horizon 2000 programme and has provided a key international resource for studying the most exotic astrophysical sources known. ESA funding of continued operations of this mission, and also INTEGRAL (see below) seems secure until 31 December 2012, albeit at a significantly reduced level. As XMM-Newton will continue to be the only European-led general purpose X-ray observatory, continued operation is essential in the near-term (at least until 2015), with the distinct prospect that XMM might continue to be productive and fulfil an important role in the period thereafter, leading towards the launch of XEUS/IXO.

INTEGRAL (see Section 3.2.4.2). continues to provide the international community with a powerful tool to map the high energy emission from hundreds of astrophysically interesting and important sources. If the financial boundary conditions allow, it would definitely be favourable to continue the mission beyond 2012.

The Hubble Space Telescope (see Section 4.1). is one of the most productive astronomical facilities ever built. ESA is urged to continue to support the operation of this mission for as long as NASA will extend its support.

Cluster (see Section 5.2.5.1). was launched in 2000 and is in its second extension (until end of 2009). The aim of the Cluster mission is to study small-scale structures of the magnetosphere and its environment in three dimensions and the mission has been highly successful. There is new science to be conducted during the extension period with the Cluster satellites visiting new magnetospheric regions never studied before by four spacecraft. It is unclear whether Cluster can be extended much beyond the end of 2009 and the prioritisation of such a third extension depends on technical feasibility, scientific plan and cost — issues now being reviewed by ESA.

STEREO (see Section 5.2.5.2). is a NASA-led mission launched in October 2006 with two spacecraft that orbit the Sun in near-Earth orbit, one ahead of the Earth, the other lagging, with the distance increasing in time. The objective is to get stereoscopic imaging of the outer solar atmosphere and coronal mass ejections, observing Earth-bound CMEs all the way from the Sun to the Earth. Europe has contributed about 50% of the instrumentation. The primary mission ends in January 2009 and the first two-year extension is seen as of very high priority. As the STEREO spacecraft separate, tracing out the Earth's orbit, the mission will move into different phases; a mission extension to 2011 will allow a detailed study of the three-dimensional Sun and inner heliospheric CME activity, including those directed towards Earth, as we move from solar minimum significantly in the rise towards maximum. A further extension will provide a novel, complete view of the solar sphere (from both sides) coupled with continued observations of CMEs in the heliosphere, including those directed towards Earth. This would be especially valuable in the solar maximum period, from 2012–14.

Hinode (see Section 5.2.5.3). is a Japanese-led space based solar observatory with a 50-cm optical telescope, an Extreme UV Imaging Spectrometer and an X-ray telescope. Hinode was launched in September 2006. ESA provides a downlink at the Norwegian Svalbard station and a European Data Center in Oslo. The ESA contribution provides 80% of the downlink capacity and since the observing is limited by the downlink capacity a rather modest contribution makes a great impact on the science return. European funding runs until 2011. A mission extension for an additional five years is seen as high priority in order to cover a full solar cycle.

8.4 Perceived Gaps and Opportunities in Europe's Future Observational Capability

Small-Scale and Fast Track Space Missions (see Sections 3.2.5.1 and 5.3). Medium-size national and bilateral missions are a crucial and fruitful ingredient to keep the community alive and develop the know-how and technology in the relevant laboratories. They are essential to bridge the gap between the large flagship missions in the individual wavebands, which are becoming continuously sparser. Specialised smaller niche missions or instruments, addressing a focused scientific aim have often been very successful. While our prioritisation of the facilities in this Roadmap naturally focused on the large, observatory-type, multinational facilities, we consider the opportunities afforded by smaller projects as a crucial part of a balanced programme. Several of the excellent concepts that did not enter into our final prioritised list (see Appendix IV), as well as new ideas, may well evolve into such opportunities.

High Energy Astrophysics (see Section 3.2.4.3). Panel A identified some areas of instrumentation that are strongly called for in the Science Vision, but are not yet programmatically ready and/or do not yet provide large improvements over existing experiments at affordable cost. Further development of existing and new technologies should be encouraged in these areas in order to fully address the challenges set out in the Science Vision. One such area is imaging and spectroscopy in the very difficult 0.1–10 MeV photon energy range. The spectroscopy of nuclear and annihilation lines and the correct identification of the sources of these lines requires considerable progress in sensitivity and resolution in this energy range, in order to make progress in the understanding of outputs of black hole sources and of the chemical evolution of the Universe through enrichment from various stellar processes. Another area is all-sky monitoring of instantaneously large solid angles for transient and variable sources, in all X- and gamma-ray energies. Some missions are still ongoing or planned for the next decade, but there is a clear threat of discontinuity in this area in the long term and a need for new concepts to enable the next generation of ASMs. Since many of the high energy sources we need to study are transient or highly variable, the Science Vision calls for continued capability in sensitive all-sky monitoring (e.g., for GRBs, outbursts of black hole sources, XRBs, etc.). The follow-up of large numbers of GRBs to find and study in detail the highest redshift events as cosmological probes is also an important goal in the Science Vision, for which future projects need to be further developed.

UV Astronomy (see Sections 4.4 and 5.5). Europe's central role in the International Ultraviolet Explorer and subsequent UV missions has created a vital community eager to pursue a next-generation UV mission, whose feasibility will depend strongly on the availability of large space optics with superb surface quality. The IUE satellite was jointly built by ESA, SERC and NASA, and operated extremely successfully for eighteen years (1978–1996). Europe has not implemented another dedicated far-UV/extreme-UV follow-up mission since then and there are also currently no significant plans to do so despite the emphasis that is put on such a mission in the Science Vision document. Important topics where such a project could contribute are IGM/ISM structure, extrasolar planet studies and hot/evolved stars. Panel B considered this situation as very unsatisfactory. This might be remedied to a certain extent by the WSO project, which is led by Russia, and in which several western European countries have shown an interest. However, a true "next generation" UV/optical mission will require a capability an order of magnitude or more beyond both HST and WSO. While there is no UV mission included in the current ESA Cosmic Vision programme, detailed studies currently underway in the US will be concluded in early 2009 and it is important that options remain in the Roadmap for European contributions to NASA initiatives in this area, which might be included in subsequent Cosmic Vision calls.

Similarly, Panel C concluded that a medium-aperture (1–2 m) (extreme-)ultraviolet satellite facility with X-ray capabilities to study fundamental solar processes that cannot be studied from the ground is a long-term goal of high priority. Necessary near- and mid-term steps towards such a future mission are technology studies of UV polarisation optics and large format UV detectors and the application of the relevant technologies in small-scale space projects demonstrating the scientific capability of solar UV magnetometry.

Ground-Based Optical/IR Interferometry (see Section 4.4). Europe has assumed a leading position here by building the VLTI, an operating facility still in a strong growth phase. The next major step beyond this facility will require the construction of an array with kilometric baselines, good image fidelity and high sensitivity. Affordable large telescopes equipped with adaptive optics, optical fibres for beam transport and integrated optics are among the key technologies needed. Space-based interferometry will also benefit from the development of optical components for beam transport, modal filtering and beam combination. In addition, technologies needed for formation flying have to be developed.

Millimetre–Submillimetre Astronomy (see Section 4.3.3). Analogous to the need for powerful survey telescopes in combination with the 8–10 m-class telescopes and the future ELTs, observations with a mm–sub-mm interferometer like ALMA need to be prepared for by surveys in this wavelength domain. This needs large aperture single dish telescopes equipped with multi-pixel array detectors and development of these devices is a critical area of technology development in which Europe needs to develop further. With the JCMT, APEX and multi-pixel bolometric and heterodyne receivers, Europe has made steps in this direction. However, it will be necessary to decide on the long-term role of these two facilities, and to weigh future investments into them against the capabilities offered by a larger diameter single dish telescope placed at an extremely high altitude (> 5000 m). Such a project, CCAT, is currently under study in the US, and some European groups have shown an interest in participating. The evaluation of these different options should be one of the outcomes of the long-term planning exercise recommended above (Section 8.3.1).

Another important project in this wavelength range concerns the detailed study of the polarisation of the CMB. ESA's Planck satellite will characterise the CMB with unprecedented sensitivity, wavelength coverage and angular resolution; however, Planck's ability to measure CMB polarisation — a topic that has been strongly highlighted in the SV document — will be limited. Based on the results from Planck, ground-based, balloon-borne, and potentially, satellite experiments aimed at better measurements of CMB polarisation have to be developed. This calls for sustained R&D activities in preparation for such future facilities.

Radio Spectral Imaging of the Sun (see Section 5.3). Panel C concluded that such imaging at centimetre to metre wavelengths is essential for measuring magnetic fields in the corona, to identify sites of particle acceleration and to track travelling disturbances through this region. There is a wide range of expertise in solar radio astronomy in Europe, especially at decimetre and metre wavelengths, which should be retained.

The Arctic and Antarctic (see Section 4.4). Numerous research stations have by now been established in Antarctica, and astronomy and astroparticle astrophysics are benefiting from the infrastructures that have been put there. There is also a growing interest in developing complementary sites in Greenland. With the long, uninterrupted dark time periods and the low temperatures, Arctic and Antarctic sites offer special opportunities for astronomy that have so far mostly been exploited through small or medium-size national or bilateral projects. Given the growing interest in the potential of polar plateau astronomy, further European studies should be carried out which build on the current detailed focus of ARENA on Dome C in the Antarctic and broadens the picture to include complementary opportunities at Dome A and Greenland. The aim would be, not only to identify those scientific questions which would benefit most from a suitable facility placed on a polar plateau, but also to further explore the logistical and financial implications, as well as liaise with the appropriate national and international polar operators.

8.5 Laboratory Astrophysics

It is proposed that the laboratory astrophysics programmes outlined in Chapter 5 be accomplished in practice through (i) new European Laboratory Astrophysics Networks specifically dedicated to fundamental laboratory experimental, interpretative and computational research and modelling, and database provision for spectra, cross-sections, reaction rates, analogue materials etc. This includes provision of funding to cover running costs for experiments and postdoctoral researchers. Part of the implementation could be through ASTRONET joint calls; (ii) individual laboratories in Europe funded through competitive awards including funding for laboratory astrophysics instrumentation and (iii) the introduction of a European Research and Technical Fellowship programme of jointly held positions that will enhance contact between laboratories and will complement the objectives described by Panel E (see Chapter 7).

These three initiatives constitute a strategic plan to coordinate and synchronise joint efforts of separate laboratories, the principal objective being to increase the size and efficiency of research in laboratory astrophysics for the benefit of European astronomy.

We also strongly recommend development of (iv) a major dedicated European facility for analysis and curation, particularly for sample return missions. Samples returned from e.g., Mars need to be quarantined until their biological nature and safety have been determined. A thorough discussion of these factors and risks is presented in 18328/04 ESA Report, reference CR(P4481). Given the precious nature of such samples, it is essential that the most up-to-date analytical techniques are available in the facility. Coordination on a European scale is vital to the success of the facility.

8.6 Theory, Computing Facilities and Networks, Virtual Observatory

The main recommendations of Panel D can be summarised under the following headings (see Chapter 6 for more details):

8.6.1 Virtual Observatory (VO)

A public VO-compliant archive should be planned for any new facility. We recommend that data centres provide science-ready data in their VO archive. This is of absolute necessity for easy exploitation of large surveys, and multi-wavelength modelling.

Substantial investments are required in software that simulates mock data with the observational biases inherent in current and future facilities. Publication of such software in VO-compliant form should become an integral part of the construction of any instrument.

8.6.2 Astrophysical Software Laboratory (ASL)

Powerful sophisticated codes should be regarded as essential infrastructure on a par with major observational instruments. A laboratory without walls called the Astrophysical Software Laboratory should be established to coordinate and fund software development and support, user training, postdoctoral positions within a programme of pan-European networks and to set standards. Training and development funding would make it possible for codes to remain at the cutting edge of the field for extended periods. Development funding would also ensure that supported codes conform to modular standards, and are provided in the open-source model.

The ASL committee will select a few highly competitive astrophysics projects each year to send proposals to the European pan-science top-tier computers; this will ensure a significant share of CPU hours at the petascale level for astronomy.

8.6.3 High Performance Computing and Grids

Astronomy should continue to benefit from HPC all-science centres, and share the efforts to develop and increase continuously their performance, in order to be at the forefront of the international competition. The development of the top-tier HPC centres should not slow down that of the lower tiers: the whole pyramid of computers at different scales, national and local, is absolutely necessary to satisfy all computing needs. Astronomy must also exploit more widely the grid infrastructure, and contribute to the expansion of the capabilities of its middleware, in particular for data processing.

Data links within Europe and to the outside world need to be kept abreast of advances in technology. The VO is likely to require a different network architecture from that put in place for LHC science.

The possibility of using billions of otherwise idle processors for scientific calculations is now real, and could revolutionise data modelling. Astronomy should lead the way in this area, either by exploiting its popular appeal to get CPU owners to donate spare CPU cycles, or by initiating a classical market in such cycles. The ASL could possibly coordinate this activity, which could have a significant commercial spin-off.

8.7 Education, Recruitment and Training, Public Outreach, Industrial Links

As well as the creation of the guiding Science Vision and the development of the Infrastructure Roadmap that addresses the scientific questions it poses, it is essential to consider some of the associated structural and sociological issues. The purpose is to ensure that the community of astronomers who will actually carry out the research, and the industry that will support the endeavour, are in a healthy state and are being continually and appropriately rejuvenated. The political and organisational decision-makers and the general public must also be kept aware of the work being done and of its crucial importance to our society.

In response to this desire, Panel E has — in a European context — looked at the state of science education in schools and the role that astronomy can play in this to create interest and excitement amongst both pupils and teachers. It has considered the process of the recruitment and training of the researchers who will become the users of the infrastructures and the engineers who will work in industry to build them. It has also examined the processes of outreach and public communication that operate to keep the broader population aware of the results of astronomical research and so create the excitement and enthusiasm without which it will not be possible to obtain funding for our ambitious projects. Finally, the Panel surveyed the relationships with European industry and also made recommendations for changing the scientific exploitation of the continent's astronomical research facilities.

The Panel's deliberations have been distilled into ten recommendations that span its remit and are summarised here (see Chapter 7 for more details).

8.7.1 Education

Panel E recognised that for astronomy to be taught successfully in schools and to act as a magnet to draw students into the sciences in general, it is essential that teachers are ready, willing and able to present the subject to their pupils with confidence and a sufficient degree of background knowledge. Supporting new and existing training courses for teachers that include modern topics — the ones that will excite the students — is strongly recommended to the Ministries of Education in the EU member states. The specific inclusion of astronomy in national curricula is a very direct way of facilitating this process.

Astronomy has the special advantage that its teaching can be dramatically enhanced by just taking students outside and looking at a clear — and preferably not light-polluted — sky. Teachers should be given the confidence and the freedom to do this and they can often be helped to do it by local amateur astronomers.

European stakeholders involved in developing educational programmes and curriculum delivery should be encouraged to realise the inspirational quality of learning using astronomy-related exercises and experiences and how this may lead to further engagement in science, technology, engineering, and mathematical endeavour. Many European countries have the capability to run optional astronomy courses for students in the 16–18-year-old age group. This is very effective for generating an interest in science at a critical moment in the educational process. This possibility should be spread to the countries that do not yet offer it.

There is a vast amount of information available that is suitable for both formal and informal education in astronomy and related sciences. Making this material readily accessible to educators, students and the public at large would greatly enhance its value. For school education in particular, it is necessary to take account of the different European languages and take steps to remove the discrimination inherent in the use of a single dominant tongue. The establishment of a new multilingual central portal for education material, or enhanced exploitation of existing portals, is recommended and seen as catalytic for a wide range of education activities.

8.7.2 Communication

The Panel found that the links between science museums/planetaria and the principal providers of high quality materials, notably the agencies such as ESA and ESO, were not particularly well developed, with the reliance generally being placed on more local contacts. These wider links should be enhanced. The Panel also supports the existence of a Europe-wide portal for the public communication of astronomy that would promote best practice and aggressively exploit the innate advantages of the subject, notably the spectacular image material that is available.

A study of the replies to the questionnaires distributed to a wide range of existing and planned astronomical facilities throughout the world (see Appendix IV) revealed that there are distinct differences accorded to the provisions for public communication between the US — where it is considered to be an essential element in the project — and in Europe — where it usually is not. It is therefore recommended that observatories, laboratories and facility-funding authorities allocate a fraction of their project budgets to peer-reviewed outreach programmes. While it is not a universal problem, there remain some taxpayer-funded projects in Europe that do not place results in a suitable form in the public domain after a reasonable proprietary period. The timely public communication of exciting results from such projects is essential to the long-term health of the subject.

Europe does not have a well-developed culture of the public communication of science by the scientists themselves. It is often considered not to be an essential element in a scientific career to be able to convey the excitement and broader cultural relevance of new results to a public that, while ready to listen, will not actively seek the information. This culture must be countered in a number of ways. One of the most important and straightforward to implement is to provide career-relevant recognition to scientists who do make the effort to do this. While some training courses are available, the scientists should be made more aware of them and encouraged to participate.

While there are notable exceptions, it is difficult in Europe to monitor the process of technology transfer between astronomy and industry. With the increasing scale and technical complexity of the multinational infrastructures outlined elsewhere in this document, it is important that there is a clearly visible process to illuminate the industrial relevance of the subject. The Panel has recommended that a group of international experts be formed to audit the process annually.

8.7.3 Exploitation of Facilities and the Impact on Recruitment and Training

The final recommendation from Panel E is of particular relevance to the Roadmap as a whole and concerns the way in which the scientific exploitation of the results produced from the large facilities is organised and funded. It recognises the rather fundamental difference between the way in which the associated research projects in Europe are funded when compared in particular with the US. The separation between the competition for "facility-time" and that for the assembly of the resources necessary to work up and publish the results leads to delays and a degree of competitive disadvantage. A solution is recommended that would minimise delays and also offer training advantages by allowing postdoctoral researchers to become involved in large-scale, cutting-edge investigations on a level international playing field. This entails the funding agencies seriously exploring the use of the high quality peer review process already in place for facility usage to "fast track" the award of exploitation grants.

The recommendations of Panel E are addressed in general to the relevant intergovernmental agencies in Europe, such as ESA and ESO, to national Ministries of Education and to the European Union. A follow-up of the process on timescales of up to two or three years will be necessary.

As with recommendations elsewhere in this Chapter, there would be a continuing role for a body such as ASTRONET in helping to ensure that those of Panel E are put into practice (see Section 8.11).

8.8 Human Resources

In 2003, ESA and ESO member states spent €461M on astronomical research in these two organisations, and in total about €1280M (Woltjer 2006 — see footnote 71 below).

The satellites launched by ESA and the facilities built up and operated by ESO in Chile are exploited by the astronomical communities in Europe, with a total count of about 4200 post-PhD scientists[67], and about 1900 PhD students (Woltjer 2006). These scientists exploit not only the facilities offered by ESA and ESO, but, in addition, a substantial number of national and international facilities, the latter often operated under bilateral or multilateral agreements with one or more European partners as signatories.

The preparation and the exploitation of the new facilities included in the ASTRONET Roadmap, because of their importance for answering fundamental scientific questions that have been compiled in the Science Vision document, must draw on the existing human resources in Europe as much as possible. The problem in Europe is that the mechanisms that lead to decisions about new investments in new infrastructures are often only weakly coupled to the decision-making processes to deploy personnel and to cover the operating costs. Only in a few European countries are these decisions taken at national level and by the same agency. In many other countries different agencies are involved in decisions about investment and operating costs, and an even larger number of agencies may be involved in covering the staff costs. When it comes to “soft money” sources, the variety is even larger.

A special challenge arises from the fact that big new investment projects take much more than a decade between the submission of the initial proposal and the end of the construction phase of the new facility. This means that at least the core of the scientific and technical team that is responsible for a new facility has to be stable over such long periods of time, often creating a conflict with individual career developments, and often leading to the consequence that the scientists who conceived the project are not the ones who will harvest the results.

ASTRONET has started to analyse this situation by making an inventory of the human resources that currently exist in European astronomy[68]. As the Roadmap is implemented, it will be necessary to find ways to (re-) deploy existing manpower, and the additional human resources that will be required, at least during certain periods, in a coordinated manner. This is a far from trivial task because of the large number of different institutions contributing to the personnel costs; but it is mandatory in order to make sure that neither the existing facilities that are expected to continue for very good scientific reasons, nor any of the new facilities, get seriously understaffed.

As explained in previous sections, data from future large facilities will be collected in large databases, and their competitive scientific exploitation is not in the least a question of the manpower that can be allocated to data reduction and analysis, accompanied by detailed modelling work that is needed for the interpretation of the results. An imbalance between Europe’s participation in major investment projects and the strength of the scientific teams that exploit the data coming from these projects absolutely must be avoided (see also Section 8.7.3 above). This may require new steering processes for the deployment of manpower across Europe. The EU-supported networking activities have gone some way in this direction, but they are by no means enough. In the longer term, ASTRONET could provide a forum for defining and helping to implement such mechanisms, which are needed to underpin the implementation of the Roadmap (see Section 8.11).

Finally, as noted in Chapter 7, there is concern that the early career of many young scientists is highly fragmented, involving several short-term contracts, often in a number of different countries. While there are both advantages and disadvantages to this, it is clear that it puts considerable pressure on those with family commitments etc. This problem is much wider than astronomy — it is seen in most science areas — and there is no simple solution, but it is important that it is taken into consideration when planning large projects and their exploitation. In particular the *Code of Conduct for the European Charter for Researchers*[69] should be followed.

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[67] Although this may be underestimated, see Appendix V.G.

[68] http://lbc.oa-roma.inaf.it/astronet/scenario.html

[69] http://ec.europa.eu/euraxess

8.9 Technology Development and Industrial Applications

8.9.1 Technology Development

Technological development is at the heart of any of the future capabilities. Flagship facilities like XEUS/IXO, LISA, ELT, SKA, TandEM and LAPLACE, also owe their high priority to a long history of technology research and development.

To maintain the vitality and competitiveness of European astronomy well into the next decade and beyond, it is necessary to provide funding for research and development in basic enabling technologies. The funding of these activities should ideally be coordinated at a European level. The continuing availability of framework programme fund is very important. Also, the ASTRONET Joint Call for Proposals on Common Tools for Future Large sub-mm Facilities is a good example of a specific need that can be addressed within the framework of a European strategy.

Technology research and development efforts are not cheap and the expenditure for these takes place at the start of a project (or even before) when it is not yet sure that it will continue. This makes it difficult to find the money to fund these activities. However, it is generally believed that technology research and development efforts in the long run will save money and improve the performance of the facility. The reason for this is twofold, and goes back to the principle that the outcome of research is unpredictable. The outcome of a research and development project seldom fulfils all the criteria posed at the beginning. This in general results in a redesign of the facility or instrument. The later this happens in the project the more costly it will be. Furthermore, an early outcome of the feasibility study of a certain item or aspect of the facility will help to make a well-founded go or no-go decision. Again the earlier in a project this can be done, the cheaper it will be.

It is estimated that about 10% of the budget for large facilities should be spent on technology development programmes. This money should become available early in a project (or more generically, even before the specific project starts). At the same time it should be well understood by all parties that the funding of R&D efforts so early in the project should not be seen as an irrevocable statement of support for the whole project. It will indeed be necessary that R&D programmes will be started for more facilities than those for which the construction can be funded in the end. This can occur for example because the enabling technologies for some of them may not mature as quickly as expected.

An (incomplete) list of the required technology programmes is given below. As is indicated in several cases similar technology advances can be used for more than one facility.

Technology development for high priority projects in the near to mid-term future (in order of appearance in the document):

- Novel high quantum efficiency photo-detectors and larger telescope diameters will be required for the low energy sub-array of the CTA.
- Simbol-X should become a demonstrator mission for the formation-flying technique and the AOCS. If successful (parts of) the technique can also be used for LISA, Cross-Scale and in the further future Darwin and FIRI.
- Lightweight X-ray mirrors will be an essential development for both XEUS/IXO and Simbol-X.
- The development of large format Transition Edge Sensors (TES), maintaining the energy resolution performance across a wide energy range is also a requirement for XEUS/IXO.
- For LISA, all the hardware needed for the local measurement (inertial sensors, microthrusters, picometer test-mass tracking with interferometer, gravitational balancing, thermoelastic distortion control, optical bench manufacturing, etc.) will have to be space-qualified via a demonstrator mission.
- Aiming for an increase in telescope size by a factor 4–5 from the present ground-based optical telescopes requires several new technologies with respect to the telescope and its instruments. Prototypes of key elements for the E-ELT like the primary mirror segments, the adaptive fourth mirror or the mechanical structure are contracted out to industry.
- The design and development of the E-ELT will have a critical influence on its instruments and vice versa and this mutual interaction is ensured by a time-phased development path.
- The multiple identical unit approach from the SKA allows for the prototyping of a single unit before the manufacturing of all the units starts. Pathfinder telescopes are under construction in the Netherlands and several other European countries (LOFAR), US, Australia (ASKAP) and South Africa (MeerKAT).

- For EUCLID, the most important developments lie in the area of the space qualification of the digital micromirror devices needed for multiplexing the acquisition of spectra. The other technological challenge is to develop an attitude control system able to achieve 0.1 arcsec pointing stability over long periods of time.

- The main technological risk areas for SPICA are the detectors (Transition Edge Sensors) and their sub-Kelvin coolers (Adiabatic Demagnetisation Refrigerators).

- Solar Orbiter and PHOIBOS will have to fly close to the Sun and require some innovative heat-shielding technology. They might re-use some of the technology from BepiColombo.

- In addition to heat shielding, shielding from radiation should also be investigated for Solar Orbiter; a mission like LAPLACE could also profit from these R&D efforts.

- Many facilities, especially the space missions, are actively pursuing the miniaturisation of their instruments and spacecraft, because this reduces the volume and thus the mass, and, in general, also the power consumption.

- Heat-shields for entry into the atmospheres of planets or moons can still be optimised in weight and can then be used in missions like TandEM/LAPLACE, ExoMars and Marco Polo.

- Almost all future facilities will have to deal with high data rates. Therefore it will remain necessary to stay at the forefront of computer capabilities and to develop smart methods for compression and to look for possibilities to increase bandwidth.

Technology development for high priority projects in the long-term future (2020+):

- Darwin is very challenging because it requires ultra-high contrast (> 10^6) nulling interferometry in cryogenic conditions. Precursor missions to Darwin, e.g., Prisma, are in the planning stage.

- High precision formation-flying capabilities are required for both Darwin and FIRI, and could be demonstrated by Simbol-X, LISA and Prisma

- Existing bolometer arrays are one or two orders of magnitude away from the FIRI requirements in terms of size, or sensitivity. It should be mentioned that very similar detector specifications are also mandatory for a further mission aiming to measure the polarisation of the CMB, which might be a high priority after Planck Surveyor.

In this Roadmap, several gaps were identified for which a viable facility was proposed. In general this is because the next step in sensitivity and resolution requires new technologies for the detectors and the (mirror) optics. This is especially true for the UV and 0.1–10 MeV photon energies.

Most of these preparatory activities for future instruments, facilities, and missions require collaborative research involving scientific institutions with specific expertise in their respective area of astronomy, as well as industry on all levels from small and medium-size enterprises with high technology portfolios to large companies capable of acting as prime contractors for major space missions. This collaboration will also ensure that enabling technologies can find their way into the commercial market. It is always difficult to predict which will be the winners (although we make an attempt in the next section), but the past has taught us that sooner or later a significant fraction of astronomy-enabled technological breakthroughs find their way to the commercial market.

8.9.2 Industrial Applications

Although not always obvious for the outside world, there has always been a close coupling between frontier astronomical research and cutting-edge industrial development. And this coupling goes both ways with astronomy pushing industry to improve its performance, while adopting inventions from industry at the same time. A prime example is in Information and Communications Technologies (ICT), where the availability of fast computers revolutionised computational astrophysics, while at the same time the demands from astronomy (like EVN and LOFAR) pushed industry forwards. Another field is the radio signal processing developed by radio astronomy, which has often acted as an enabler for industry (e.g., as did solutions for interference problems in the mobile communication industry, precision tracking and global navigation satellite systems). A very effective method of technology transfer is to develop, together with industry, new technologies needed by astronomy. Working together on frontier technical developments is an ideal setting for cross-fertilisation between the scientists and engineers at the universities and research institutes and qualified personnel from major industry and small businesses. Funding for this kind of collaboration may be found in other budgets than those usually available for pure scientific research.

Looking at the list of high priority facilities it is expected that this symbiosis will continue to bring prosperity for both industry and astronomy. Examples of the industrial relevance of the developments necessary for the Roadmap's high priority future astronomical facilities are:

- Issues related to the AOCS with respect to formation flying (necessary for LISA, Simbol-X and others) are recognised by industry as an important future space technology with many potential applications.

- The lightweight X-ray mirrors and X-ray detectors necessary for XEUS/IXO will have a wide range of terrestrial applications, e.g., in material diagnostics and medicine.

- New cryogenic materials and systems necessary for all future IR and X-ray facilities could become advantages for the liquid natural gas, defence, high performance computing and the medical industries.

- Astronomy has always required very high quality optics, which have found their way into industrial applications. New developments within integrated optics, active optics and mirrors etc. will likely follow the same route.

- High performance, low maintenance cooling systems (large and small) will have numerous applications in all places where cooling is required.

- Terrestrial high precision devices could profit from the picometre tracking devices that are required for LISA.

- Celestial reference systems, presently defined from VLBI radio observation of compact extragalactic objects, are essential for spatial navigation (GPS, GALILEO, telecom satellites, probes in the Solar System). Gaia will observe 500 000 such objects at optical wavelengths, which will provide an improvement in the definition of the reference system.

- Future all-sky monitoring databases require very efficient data-mining systems and system configurations, including high speed data exchange and (image) processing. The solutions in this field can be used for numerous other databases and applications outside the sphere of astronomy.

- Many of the future instruments and facilities from the Roadmap will require the mass production of single item procurements. One can think here of detectors, high precision optical elements, receivers, etc. This will not only make the individual items much cheaper and therefore more interesting for the commercial market, but the techniques themselves to scale up the production of these high quality items can be used for other top-end instruments.

- Heat shields developed for re-entry capsules, e.g., for Marco Polo, can be used in high temperature environments like blast furnaces.

- Grid computing using spare CPU time from ordinary users is already used for a few projects, but has the potential to grow significantly. There is the possibility that a genuine market develops in spare CPU cycles. Machine owners could receive discounts from their ISP or telephone company for every unit of computing resource used on their machines.

- New methods for data access, data handling, and data storage need to be developed; methods which will also be applicable in many other areas. The data handling, system monitoring and data distribution of a complex sensor network such as LOFAR pushes the boundaries of information technology and will lead to IT developments that are relevant for a wide range of applications.

- SKA will be located at a very remote place where access to the electricity network is not a given. The project team is pursuing options for environmentally friendly energy production. Since a large-scale solution is required, this could push the alternative energy industry forwards.

- With the increase in the number of units in the facilities, also the connections between the different subsystems multiply significantly. Within the SKA one is looking at the possibilities for connector-less connections. This has attracted the attention of the car, shipbuilding and defence industries.

- All new facilities are complex and need dedicated control systems: lessons learned in astronomy can be used in industry and vice versa.

- LOFAR and the SKA require accurate knowledge of the atmosphere and the ionosphere; this is of interest for the radio and satellite communication industry.

- Astronomical projects are used by industry for their advertising. Participating in these complex systems is generally considered very beneficial for their public relations.

In addition there are less directly related connections. Present and future solar monitoring facilities on the ground and in space deliver valuable information about the activity of the Sun and especially its dangerous outbursts. An accurate early prediction of space-weather can save billions of euros in satellite damage.

As identified by Panel E (see Section 7.4.3), it does not appear that many countries have a mechanism within their astronomical community to identify industrial relevance or technology transfer to other interlocutors or communities as an integral component of their R&D. It would appear that encouragement of the promotion of successful astronomical technology transfer activities would be most helpful in rectifying this situation. Furthermore, the creation of an easily accessible European repository of astronomy technology transfer as recommended by Panel E (see Section 7.4.3.) would greatly enhance the visibility of European success stories in astronomy.

Finally, it should be mentioned that perhaps one of the greatest contributions to industry is ultimately the students. Trained in astronomy, and especially when trained in areas such as instrumentation, laboratory astrophysics or computational astrophysics, they acquire skills that make them well equipped to contribute to European industry across a wide range of technologies.

8.10 Funding, Costs and Major Decision Points in Roadmap Implementation

8.10.1 Funding

As described in detail in the ASTRONET Report on the Management of European Astronomy[70], the funding landscape for astronomy in Europe is very fragmented and complex. Funders are very diverse across different countries and sometimes even inside a single country — ranging from national funding agencies (such as the STFC in the UK or NWO in the Netherlands) to research institutes (e.g., MPG, CNRS/INSU and INAF in Germany, France and Italy, respectively), and from project management agencies (e.g., PT-DESY in Germany) to relevant ministries (such as the BMBF in Germany, the MICINN in Spain and the OCW in the Netherlands). In some countries one single agency funds all the astronomical areas considered by the Roadmap (e.g., the STFC in the UK). For other countries, for example, Italy or France, ground-based astronomy, space science and astroparticle astrophysics are funded through several different channels, including national space agencies. In addition, most countries make a contribution to the international ESA and ESO organisations, which then operate independently from their sources of funding.

With such a complex situation it is not surprising that determining the total investment in astronomical activities in Europe is such a difficult undertaking[71]. Doing so is well beyond the scope of this document. However, in order to understand how our main recommendations fit the current scenario, we have tried to determine the likely funding envelope for astronomy in the next five years. For that we asked all the agencies that were invited to our workshop in London[72] on 12 February 2008 to provide us with their best estimate for the funding likely to be available for the development and operation of new facilities or initiatives in the areas covered by the Roadmap.

In most cases, the answers we received covered only the areas of infrastructure described by Panels A–C in Chapters 3, 4 and 5 (excluding laboratory astrophysics). For that reason, those are the areas where we will be focusing our attention in the remainder of this Section. This is not to mean that investments in the domains of computation and theory (as described in Chapter 6 by Panel D), education and outreach (as described in Chapter 7 by Panel E), and laboratory astrophysics are not important. However, due to the complexities described above, trying to determine the available funding envelope in these areas would require an effort that we could not possibly achieve within our time frame or resources.

Nevertheless, the numbers we did receive from the agencies and will consider in what follows are not without their caveats. First of all, we chose to concentrate on only some of the major European players involved in ASTRONET, namely ESO, ESA, France, Germany, Italy, the Netherlands and the United Kingdom. Even then, it was not always possible to have financial projections covering the next five years. In such cases, we have had to use the latest available budgets (2007 and 2008) and assume they would remain constant in the near term. This will not always be the case, but it can be assumed as a rough approximation. The next proviso — as referred to in the Report on the Management of European Astronomy (see Footnote 70 — is that the numbers might not always be directly comparable, due to different accounting and budgetary systems. Again, as a first approximation, we have assumed that they are comparable however. Finally, we were not always able to quantify the amount currently spent on astroparticle astrophysics facilities, even for the small set of countries considered here.

With all that said, our best estimate for the overall current level of investment in Europe in ground-based infrastructure development and operation is of the order of €100M/yr (considering the countries mentioned above and excluding their contributions to ESO); ESO received in addition just over €160M from all its members in the present year. In space, taking more complete information contained in an ESA report[73], national agencies spend approximately €250–300M/yr overall (excluding their ESA subscriptions), and ESA has an additional annual budget of €400M for its mandatory science programme (we may note that this total European expenditure of €650–700M/yr on scientific space missions represents only 20–25% of that spent by NASA).

Thus the total European budget for the development and operation of ground and space-based facilities is of order €1000M/yr. This is roughly half the estimated total spend on astronomy and space science in Europe of around €2000M/yr. The total figure includes such things as university staff, exploitation, theory, computing, central facilities, outreach, management etc.

8.10.2 Costs and Major Decision Points

8.10.2.1 *Ground-Based Facilities*

E-ELT

The decision to go ahead with the construction is expected to take place in 2010. The construction period is estimated to be 5–6 years leading to first light around 2016. The design phase (€57M) is fully funded within the ESO budget. The construction cost is estimated to be €960M (including first generation instruments), with a peak of expenditure between 2012 and 2016. About €350M for the construction phase are available within the existing budget, integrated over a period of ten years. One of the goals of the preparatory phase is to study the possibilities for additional funding. Additional activities on the organisation of the project and the mission design are supported through a €5M FP7 grant.

SKA

The governance structure and legal framework for the SKA should be established in 2011; the selection of the site is also scheduled to occur at that time. The plans for SKA construction take full advantage of the opportunity offered naturally by interferometers to allow a phased approach to funding, construction and science. It is anticipated that the construction of the SKA will take place in the three phases defined above (see Section 8.2.1). Preliminary, but detailed, cost estimates are that Phase 1 will cost ~ €300M and the full array (Phases 1 and 2) will require €1.5B. Phase 3 is beyond the timeline of the current Roadmap exercise; its costs have not yet been investigated. Operational costs of the array are expected to be ~ €100M/yr. The European financial contribution to the construction and operational costs is expected to be in the range of 33–40% overall. The planned timeline calls for the case for Phases 1 and 2 to be made to governments in early 2012. It is expected that Phase 1 will be funded initially. Once the technical validity has been fully established and early science delivered, funding for Phase 2 will be appropriated. The goal is to complete Phase 1 by 2016. Phase 2 will extend up to 2020.

It now appears possible to establish a phasing plan with significant spending on the E-ELT through ESO starting in 2010; SKA Phase 1 funding will then ramp up from 2012 and both telescopes should achieve early science around the middle of the decade. Then, at the end of the E-ELT construction peak in 2016, SKA Phase 2 will begin and the full array will take shape (see Table 1). The phased approach outlined above will, however, only be feasible if significant additional funds become available soon after 2010. This is a necessary condition for the timely construction of the E-ELT, and even more so when the construction phases of these two big projects overlap. In total, an additional amount of at least €600M seems to be required between 2012 and 2018 above the level of funds available on the basis of a projection of current funding levels. The exact amounts required, and the associated spending profiles, will be key results from the two ongoing design phase studies that include the development of viable funding schemes as a major task. We emphasise that this phased approach is required in order to keep the necessary momentum and expertise to achieve successful European participation and leadership for both projects. Total costs, including operations, are as indicated in Table 1.

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[70] http://lbc.oa-roma.inaf.it/astronet/scenario.html

[71] See also Woltjer, L., 2006, *Europe's Quest for the Universe* (EDP Sciences).

[72] The guest list included representatives of all of the ASTRONET contractors (except the Polish National Centre for Research and Development, which was not formally a contractor at the time) and Associates, plus those of the ASI and the CNES and Ministry of Research and Higher Education, the German DLR (Deutsche Zentrum für Luft- und Raumfahrt), and the Dutch Ministry of Education, Culture and Science and NOVA (Nederlandse Onderzoekschool voor de Astronomie).

[73] Funding of European Space Sciences, 2008, ESSC Report Series, European Science Foundation, Strasbourg (in print)

EST

The conceptual design study concludes in 2010 and will provide a detailed cost study along with a preliminary technical design. Preparation for construction is expected to take place in the period 2011–2013 and will require about €7M. Most of the funds will be devoted to subcontracts to private industry. Construction is expected between 2014 and 2019 with an estimated cost (based on a detailed cost breakdown) of €80M. The annual operation costs are estimated at €7.5M/yr. Panel C also recommended the closing of Europe's smaller solar telescopes as the EST becomes operational, with the subsequent release of around €2.5M/yr of operational funding.

CTA

The CTA community sees the most promising approach to build, on a timescale to around 2015, an instrument with energy threshold around several tens of GeV and extending to 100 TeV. The cost of a full-range southern array is estimated at €100M (plus FTEs, as included in Table 1) and the cost of the low energy northern array at €50M (plus FTEs, again as included in Table 1). These target costs require development towards cost-effective large-scale production of telescopes. The costs will also depend on the, yet to be determined, location and its available infrastructure. In the case of a limited budget, a trade-off analysis between the different energy ranges is required by the community, and this forms part of the ongoing CTA design study. Operational costs are estimated at €7M/yr (including FTEs).

KM3NeT

As with other major projects noted here, the KM3NeT consortium has recently started its preparatory phase with funding from the EC FP7 programme. Construction should start in earnest in 2011. The total cost of construction of KM3NeT is estimated at around €250M, with economies/innovation likely used to increase the volume rather than reduce the total cost. In this regard one of the highest priority tasks of the collaboration should be a technological study towards reduction of the cost of basic units of detectors (strings of photomultipliers). The annual operation costs are estimated at €8M.

Wide-Field Multiplexed Spectrographs for Large Optical Telescopes

The proposed working group will define the scientific requirements, implementation options and provide an implementation plan to deliver such instruments, in the 2015–2020 time frame. The working group will report by the end of 2009 and the total project cost is currently estimated at approximately €40–50M.

Existing Ground-Based Facilities

The proposed reviews will report on the following timescales:

• 2–4 m Optical Telescopes:	September 2009
• Radio Facilities:	During 2010
• mm–sub-mm Facilities:	By end 2011
• 8–10 m Optical Telescopes:	In 2011–2013

Costs associated with these facilities, where known, are given in Table 3.

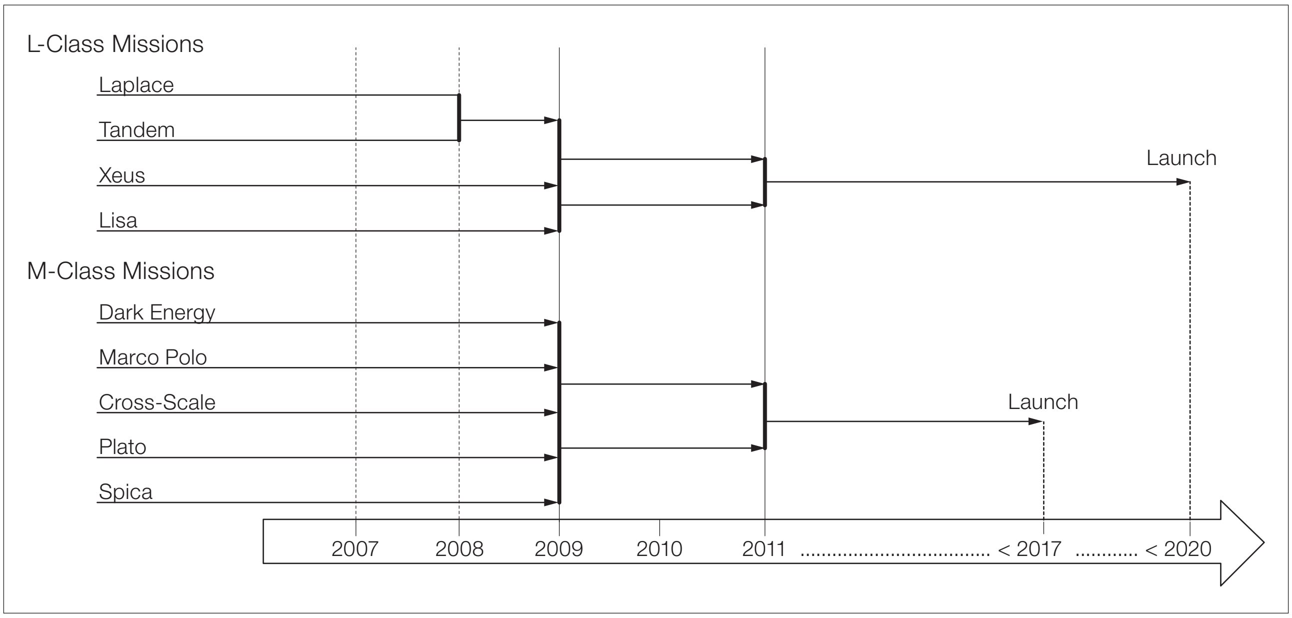

Image Credit: ESA

Figure 30: The selected Cosmic Vision mission candidates and the outline down-selection process leading to one M- and one L-class mission launched in 2017 and 2018 respectively. Following the decision not to cancel BepiColombo, Solar Orbiter will probably be delayed to 2017 and it is thought likely that it will be put in competition with the new Cosmic Vision missions within ESA.

8.10.2.2 *Space-Based Facilities*

Missions within ESA's Cosmic Vision Planning

Cosmic Vision is planned as part of the future ESA mandatory space science programme for 2015–2025. It is subdivided into cycles of competitive mission developments. The first cycle, started in December 2007 following the selection of missions to enter assessment, aims to launch two missions (one Medium and one Large) in the 2017–2018 time frame. During the Cosmic Vision period there is potential for the mandatory programme to support some additional projects e.g., national missions or Missions of Opportunity, but the majority of the programme will be focussed on the Cosmic Vision missions.

ESA plans to select one M-class mission (≤ €300M ESA cost envelope) and one L-class mission (≤ €650M ESA cost envelope) within the first planning cycle of 2015–2018. The ESA advisory structure down-selected nine proposals for competitive study in autumn 2007, i.e. three L-class missions (LAPLACE, Tandem and XEUS/IXO, with LISA to be included later on), five M-class missions (Cross-Scale, PLATO, Marco Polo, DUNE and SPACE; the latter two now combined into a single dark energy mission named EUCLID), with a Mission of Opportunity (SPICA), which is led by Japan. As is apparent from Figure 30, the down-selection will result in two M-class and two L-class missions going into competitive definition study towards the first launches in the programme.

ExoMars

This mission, falling under the Aurora programme, has a total cost estimated to be a minimum of €950M of which €650M have been secured by a decision of the last ESA Interministerial Conference. The remaining funding will be requested at the next Interministerial Conference at the end of 2008. ESA member states will, in addition, provide the scientific instruments, estimated to cost €150–200M. The launch of ExoMars is then planned for 2013.

Simbol-X

Simbol-X is currently in a Phase A Study, which is due for completion in 2008. Mission final approval in France and Italy is expected in the 2008/9 time frame. The launch date is currently envisaged as mid-2014. The cost of the mission will be determined by the end of the phase A study — current rough estimates suggest a total cost of ~ €300M. The bulk of the mission funding would be provided by France and Italy on a shared basis, with significant German contributions to the focal plane and the mirror development.

Gaia Data Analysis and Processing

Gaia is set for launch in 2012. The main mission costs (€582M at 2007 values) are covered in the ESA science budget. The issue here is the required cost for the data reduction and analysis effort throughout the period to 2022 in order for Europe to reap the maximum scientific benefit. ESA has subcontracted a significant part of the data processing and analysis activities to an international consortium (DPAC). This is intended to be funded by national funding agencies that have signed a long-term multilateral agreement with ESA which runs until ten years after launch or until 31 December 2022, whichever comes first. The agreement specifies the deliverables without putting cost figures. The consortium has estimated that an effort of about 190 FTEs/yr is needed to produce the deliverables. This translates into a cost of about €15M/yr until the Gaia catalogue is completed.

Operational Prolongation of Current Missions

Continuing support of several current missions is proposed. Costs are detailed in Table 3. In summary, these missions and suggested mission extensions comprise:

• XMM-Newton:	2013–2015
• INTEGRAL:	2012+
• Cluster:	2010–2012
• STEREO:	2011–2014
• Hinode:	2012–2017

In addition, there was strong support for continued European funding of HST operations alongside that of NASA.

8.10.2.3 *Overall Cost Profiles*

We will now consider the overall European cost requirements for the high priority facilities described in Section 8.2 (and summarised in Table 1 and Table 2 for ground- and space-based projects respectively), compare it to the current funding envelope and discuss some of the implications of our findings. The cost requirements for the facilities described in Section 8.3 are summarised in Table 3; the costs related to the recommendations of Panels D and E, and laboratory astrophysics are summarised in Table 4.

For ground-based facilities, the estimated cost profiles are presented in Figure 31. The total construction cost is €2070M, spread over ten years of significant spend between 2011 and 2021. Of these, €450M are related to astroparticle facilities (CTA, KM3NET), and would in most countries have a different origin than the €1620M devoted to "classical" astronomy facilities, and will not be discussed further. This would thus lead to an average spending of €160M/yr, compared to a total astronomy budget in Europe of order of €2000M/yr, or to a present budget of €250–300M/yr for the construction and operation of ground-based facilities. It is anticipated that €350M would be available in the next decade within the ESO budget after the end of ALMA construction, i.e. an average of €35M/yr. Some savings on existing facilities could be achieved, by reducing when possible the operation costs or by closing some of them, but it is unlikely that this could exceed €10M/yr, since closing existing facilities takes time and costs up to twice the annual operation cost.

The total increase in ground-based astronomy (excluding astroparticle) would thus be of order of €120M/yr, i.e. 40–50% of the present day budget for large-scale facilities, and of order 6% of the total European astronomy budget. This could be reduced to a €90M/yr (35%) increase if a non-European contribution to the ELT is found, and to around €65M/yr (25%) if the total construction period extends over fifteen years instead of ten years.

The total running cost of the new facilities is estimated at €100M/yr plus €15M/yr for astroparticle facilities; this would fit within the large-scale facility budget provided that additional funding is found to build them, of course, and that the increase in the large-scale facility budget is maintained in the long term after the end of the construction phase.

Turning to space-based facilities, the current budget of the ESA mandatory science programme is €400M/yr, which, by design, will allow the launch of three large (L) missions and three medium-size (M) missions before 2025, where the financial envelopes of L- and M-class missions are fixed at €650M and €300M, respectively (2007 Equivalent Currency). This assumes that instruments will continue to be developed and funded mostly by member states and outside of the ESA science budget.

This will enable the launch of all three high priority ASTRONET L-class missions, LISA, IXO/XEUS and TandEM/LAPLACE before 2025, but only as collaborative ventures with NASA and/or JAXA. In that respect, it is somewhat disturbing that Europe has lost the capability to develop purely European flagship missions such as XMM-Newton or ISO. Indeed, at 2008 Equivalent Currency, the cost of XMM-Newton or ISO for instance would be about twice as large as the financial envelope of an L-class mission and well beyond the capability of today's ESA science budget.

Of the seven high priority ASTRONET medium-size missions — EUCLID, Solar-Orbiter, Cross-Scale, Simbol-X, PLATO, SPICA and Marco Polo — only four could be launched before 2025 if the current financial situation holds, three through the ESA science programme plus Simbol-X, which is funded nationally. However, even this limited objective will be difficult to achieve for the following reasons:

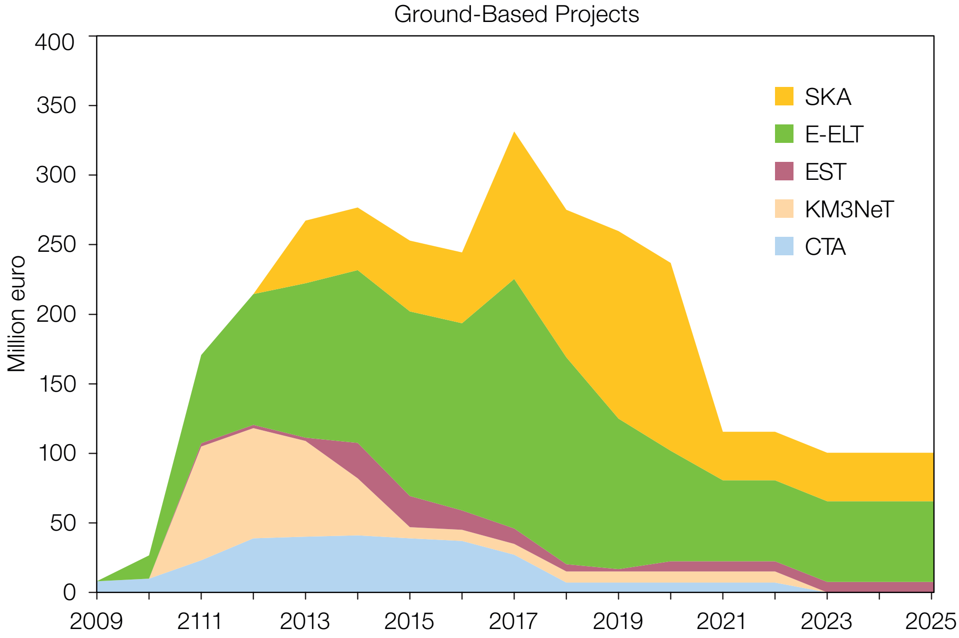

Image Credit: Maria Cruz for the Roadmap

Figure 31: The estimated European cost profiles (including development, construction, operations and manpower) for the future ground-based observational facilities proposed in the Roadmap (wide-field multiplexed spectrographs not included); see Section 8.2 for more details. The profiles presented here are preliminary and are based on the information provided to us by various project representatives, and through ASPERA, in the case of the CTA and KM3NeT (note that cost profiles for these two projects are being revised in the ASPERA roadmapping process).

- Firstly, preliminary indications show that, with the exception of SPICA, all Cosmic Vision M-class missions currently under assessment will substantially exceed their €300M envelope.

- Secondly, funding of the instruments on-board Cosmic Vision missions will put a heavy financial burden on the national budgets of ESA member states. The relative cost of the payload as a fraction of the total project cost varies from project to project. For past missions, it hovered between 20–30%, with a recent upward trend as instrument sophistication increases. Cosmic Vision missions have instruments that are at the forefront of technology and many of them require complex and expensive cryogenic cooling chains (e.g., SAFARI onboard SPICA or NFI on IXO/XEUS). The cost of such instruments is likely to exceed €100M each. Assuming a 30% instrument/project cost ratio implies that European member states will have to disburse nearly €1B over a 10-year period starting in 2012 only to finance Cosmic Vision payloads, i.e. roughly €100M/yr. This comes on top of the financial effort required to support the Gaia DPAC (15M€/yr, which may, however, be an upper limit to the unsecured funding as some agencies will already have elements of this in their planning lines) and the (mostly) French–Italian Simbol-X project (€300M in total or about €60M/yr up to 2014).

Even more uncertain is the budget of the robotic exploration optional ESA programme since it depends on the level of subscription of the member states that are willing to participate. Currently, ExoMars is the only "approved" project in this programme, with a nominal launch in 2013. Its €1.2B cost, however, is only half covered by member states' subscriptions so far. We have assumed that a compromise will be found by ESA's Council of Ministers at its November 2008 meeting such that member states' subscriptions will match a reduced cost of €950M. ESA member states will thus incur additional expenditures of €190M/yr up to 2013 and possibly beyond if robotic exploration continues into the future.

In total, member states will therefore have to spend €365M/yr to support: Cosmic Vision payloads (€100M), robotic exploration (€190M), Simbol-X (€60M) and the Gaia DPAC (€15M). This exceeds the current level of expenditures of all European national programmes combined, which is estimated to be of the order of €250–300M/yr. It is therefore essential that fresh funds be found to finance ExoMars and future robotic exploration missions.

In conclusion, for space missions:

- Either directly or indirectly through ESA, European member states will have to sustain a long-term financial effort of about €500M/yr in support of Cosmic Vision, plus an additional €190M/yr for robotic exploration, and €75M/yr for Simbol-X and the Gaia DPAC.

- This will permit the launch of the three high priority ASTRONET missions LISA, IXO/XEUS and LAPLACE/TandEM, but only as joint ventures with NASA and JAXA.

- This will not however allow implemention of all seven medium-size projects highly ranked by ASTRONET, but at most four of them.

- A modest increase of the ESA science budget — of the order of €60M/yr — would permit the launch of up to six of the seven medium-size ASTRONET high priority projects before 2025. Such an increase will be proposed at the Ministerial Council meeting of ESA in November 2008, and ASTRONET fully supports this.

- Though ASTRONET is fully behind the scientifically exciting ExoMars project, it is essential that the robotic exploration programme be financed with fresh funds and not at the expense of the mandatory ESA science programme. Robotic exploration should not divert funds from the national science programmes either, since the latter will be crucial to finance the sophisticated instruments on-board Cosmic Vision missions.

8.10.2.4 *Laboratory Astrophysics*

Panel C recommends a step change in coordinated European-wide funding for laboratory experiments, associated theory and computational modelling, as well as training of skilled personnel in close conjunction with European astronomy facilities and missions. As a core fundamental element, and as a guide, it is recommended that funding provision for laboratory astrophysics be included in the planning of all astronomical and space mission research programmes at a level of the order of 2% of overall budgets, with each programme taking "ownership" and peer-review of this part of the project. Significant European coordination of laboratory astrophysics is essential to keep this activity as an active research subject at the interface between astrophysics, physics and chemistry. In addition, for recommendations (i), (ii) and (iii) the step change requires expenditure of *c.* €10M/yr with (iv) being *c.* €80M capital building and instrumentation and €6M/yr running costs, with reference to the costings in ESA Report CR(P4481) — see Section 8.5 and summary in Table 4. A particularly attractive aspect of laboratory astrophysics is its intimate link with the training of research and technical personnel, who will be well equipped to contribute to European industry across a wide range of technologies.

8.10.2.5 *Theory, Computing and Networks, Virtual Observatory*

As described in Chapter 6, supercomputing equipment is managed globally for all sciences at the European level. The essential resource where astronomy is involved directly is staff effort. The current level of resources dedicated to Virtual Observatory activities is estimated at 100 FTE/yr over Europe, and will need to increase in the near future in view of the huge increase in data flows expected from major new instruments. As for the new Astrophysics Software Laboratory structure recommended above, the human resources dedicated to this essential activity are estimated at 50 FTE/yr. This number includes scientists who are already funded at national levels, plus a core of researchers (estimated at about 20 FTE/yr) to be funded at European level, and who will be responsible for the ASL's activities and organisation.

The infrastructure established with EC support will need to be sustained by the national funding agencies to allow continuity of the VO. Similarly, the ASL should be financed by the national agencies: a specified percentage of each agency budget should be reserved for it. Costs are summarised in Table 4.

8.10.2.6 *Education, Recruitment and Training, Public Outreach*

The main recommendations of Panel E should be implemented on timescales in the range of 1–3 years and involve a diverse range of stakeholders across Europe. It is recommended that all facility funding bodies should allocate sufficient resources for public communication and education. As a useful benchmark number, this would amount to at least a few percent of their overall budget (1–2% is sometimes quoted as a good starting point). In addition it is estimated that capital costs of approximately €400k and running costs of €100k/yr would be required to establish the communication and educational portals recommended by the Panel (see Table 4).

8.10.2.7 *Conclusions Regarding Funding*

The majority of the funding requirement outlined in the Roadmap naturally relates to that of large observational facilities. We noted in Section 8.10.2.3 that to make sure that Europe's ambitions for the ground-based programme come to fruition would ideally require additional funding at the level of around €120M/yr. Similarly, in order to see the launch of almost the complete set of high priority space missions by 2025 will require an increase in funding through ESA of approximately €60M/yr plus funding for Simbol-X (€60M/yr to 2014) and Gaia DPAC (€15M/yr to 2022). Finally, €190 M/yr of new funds will be needed to develop ESA robotic exploration missions, such as ExoMars. There may be some savings possible in the ground-based programme if international partners fund a significant part of the E-ELT and in addition the whole programme is stretched out over fifteen rather than ten years. For ExoMars, funding should be sought from outside the mainstream astronomy and space science programmes of the agencies and if this can be secured, the requirement for new money within these budget lines would obviously be reduced accordingly. Overall, the required increase in ground- and space-based facilities' budgets is therefore estimated to be between €200M/yr (external partners for E-ELT, construction over fifteen years; ExoMars funding from outside traditional astronomy budgets) and €445M/yr.

Turning to laboratory astrophysics, the proposed sample analysis and curation facility would require funding for capital build and operation spread over ten years of approximately €14M/yr. In addition, it is estimated that the proposed networking, fellowships and other programmes would require a step change of around €10M/yr. Laboratory astrophysics and outreach both propose guidelines on general investment in these areas. For laboratory studies, the guideline is set at the order of 2% of the cost of new facilities. For outreach, the guideline is 1–2%. Taking into account the fact that there is already some spend in these areas, a figure of 3% total uplift might be reasonable, which equates to approximately €30M/yr. The Astrophysical Software Laboratory (estimated 20 additional FTEs) and enhanced Virtual Observatory provision would by contrast only require around €3M/yr of extra, targetted funding. These lines therefore require total additional funding of approximately €57M/yr.

Thus the overall uplift for European astronomy that is required to realise our ambitions as set out in the Roadmap lies in the range of approximately €260M/yr to €500M/yr, or around 13–25% of the estimated total current spend on astronomy and space science in Europe.

8.10.2.8 *Other Issues*

There is a clear need to invest appropriately in R&D and other preparatory activities for future major facilities (see Section 8.9). The funding here comes predominantly from both the EU Framework Programme and the national agencies. Industry often has an important role to play here as well. Overall, the level of funding for such activities may need to be increased in the future.

We have described above the high priority given to Gaia data processing and analysis. More generally, Europe should ensure that adequate data handling resources are available to exploit the output from its major projects, including for example, ALMA.

Allowance should be made in any funding scheme for the development of fast track, relatively low cost projects. A case in point is national or bilateral space projects.

Finally, it should be stressed again that Europe needs to provide adequate resources to employ in a timely fashion the personnel who will scientifically exploit the results of our facilities. Panel E proposes a mechanism for helping to ensure that this happens, and suggests that this be implemented by the funding agencies by 2010.

Project	*Ranking*		*2009*	*2010*	*2011*	*2012*	*2013*
Large Scale[a]							
E-ELT	1	Phase B	Secured				
		Preparatory Phase	Secured				
		Construction		€960M		Construction Peak	
		Operations					
SKA	1	Design Phase	Secured				
		Preparatory Phase	Secured				
		Phase I Construction					€180M
		Phase I Operations					
		Phase II Construction					
		Phase II Operations					
Medium Scale[b]							
EST	1	Preliminary Design	Secured				
		Final Design			€7M		
		Construction					
		Operations					
CTA[c]	2	R&D	€25M				
		Construction			€200M		
		Operations[d]				€4M	€5M
KM3NeT[c]	3	R&D	Secured				
		Construction			€250M		
		Operations[d]				€7M	€9M

Small Scale			
Multiplexed Spectrographs	1	Concept Stage	Costs and timeline yet to be defined.

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[a] The two projects under this heading were seen as being equally high priority.

[b] The three projects under this heading are listed in order with the top priority first.

[c] Cost profiles for the CTA and KM3NeT are being revised in the ASPERA roadmapping process.

[d] These include commissioning costs.

2014	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*
🟥	🟥	🟥	🟧 Incl. first generation instruments	🟧	🟧	🟧					
			🟦 €58M/yr	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
🟧	🟧	🟧									
	🟦 €6M/yr	🟦	🟦	🟦							
			🟧 €400M	🟧	🟧	🟧					
					🟦 €35M/yr	🟦	🟦	🟦	🟦	🟦	🟦
🟧 €80M	🟧	🟧	🟧	🟧	🟧						
						🟦 €7.5M/yr	🟦	🟦	🟦	🟦	🟦
🟧	🟧	🟧	🟧								
🟦 €6M	🟦 €7M/yr	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
🟧											
🟦 €11M	🟦 €8M/yr	🟦	🟦	🟦	🟦	🟦	🟦	🟦			

Table 1: Ranked list of future ground-based observational facilities (prioritised within each category — see Section 8.2 for more details) and estimated European cost requirements. Notes: (i) no attempt is made in this table to reflect the cost profiles, only the amounts and number of years for construction are given — for the cost profiles see Figure 31; (ii) the cost and milestone activity information presented here was provided by the projects' Principal Investigators and/or other representatives and through ASPERA in the case of the CTA and KM3NeT — this information is necessarily uncertain as all projects are undergoing preparatory studies.

Project	*Ranking*		*2009*	*2010*	*2011*	*2012*	*2013*
Large Scale[a]							
LISA (CV)	1	Cost for ESA		€650M			
		Cost for national agencies	Not applicable				
XEUS/IXO (CV)	1	Cost for ESA		€650M			
		Cost for national agencies		€200M (assuming payload costs to be ~ 30% of those of the mission)			
TandEM/LAPLACE	2	Cost for ESA		€650M			
		Cost for national agencies		€130M (assuming payload costs to be ~ 20% of those of the mission)			
ExoMars (Aurora)	3	Cost for ESA	€300M				
		Cost for national agencies	€150M				
Medium Scale[b]							
Gaia DPAC	1	Data Processing & Analysis	€15M/yr				
EUCLID (CV)	2	Cost for ESA		€300M			
		Cost for national agencies		€100M (assuming payload costs to be ~ 30% of those of the mission)			
Solar Orbiter	3	Cost for ESA		€300M			
		Cost for national agencies		€100M			
Cross-Scale (CV)	4	Cost for ESA		€300M			
		Cost for national agencies		€60M			
PLATO (CV)	4	Cost for ESA		€300M			
		Cost for national agencies		€63M			
Simbol-X	4	Cost for national agencies	€300M				
SPICA (CV)	4	Cost for ESA		€75			
		Cost for national agencies		€82M			
Marco Polo (CV)	5	Cost for ESA		€300M			
		Cost for national agencies		€40–50M			

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[a] LISA and XEUS/IXO were ranked together by the Working Group at the highest priority followed by TandEM/LAPLACE, which will be down-selected by ESA to one single mission to the giant planets in early 2009. All three (LISA, XEUS/IXO and the mission to the giant planets) will compete for L1/L2 slot within the Cosmic Vision Process. ExoMars was ranked below TandEM/LAPLACE.

[b] Gaia DPAC was given the highest priority within this category, followed by EUCLID then Solar Orbiter. Cross-Scale, PLATO, Simbol-X, and SPICA came next, but the Working Group found it difficult to prioritise between them. Marco Polo was ranked below this group of projects.

2014	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*
🟥	🟥	🟥	🟥	🟥							
🟥	🟥	🟥	🟥	🟥							
🟦	🟦	🟦	🟦	🟦							
🟥	🟥	🟥	🟥	🟥							
🟦	🟦	🟦	🟦	🟦							
🟥	🟥	🟥	🟥								
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🟥	🟥	🟥	🟥								
🟦	🟦	🟦	🟦								

Table 2: Ranked list of future space-based observational facilities (prioritised within each category — see Section 8.2 for more details) and estimated European cost requirements. Notes: (i) no attempt is made in this table to reflect the cost profiles, only the amounts and number of years for construction are given; (ii) the cost and milestone activity information presented here was provided by project representatives and by ESA (in the case of the Cosmic Vision projects) — this information is necessarily uncertain as all projects are undergoing preparatory studies.

Existing Facility Name	*Cost Description*
Gound-Based	
Solar Telescopes	*Current Operating Costs:* €2.5M/yr
2–4 m-class Optical Telescopes	*Current Operation of the 4 m telescopes:* at least €30–40M/yr
8–10 m-class Optical Telescopes	*Estimated cost for third generation instruments for the VLT:* ~ €60M (2012–2022) *More generally:* €10M/yr development funding required throughout the next decade
Millimetre and Submillimetre Telescopes	*Current Operating Costs:* €11M/yr
Radio Telescopes	*Current Operating Costs:* €26M/yr
Space-Based	
XMM-Newton	*Current combined operations cost:* €19.4M/yr
INTEGRAL	
HST	*Estimated extension cost:* €3M/yr
Cluster	*Current operation costs (ESA):* €7.5M/yr + 39 FTEs/yr
STEREO	*Estimated European prolongation costs:* €3M/yr
Hinode	*European Data Centre (current costs):* €1.7M/yr *UK running costs for EIS:* €0.4M/yr

Table 3: Estimated European costs associated with the existing observational facilities described in Section 8.3 (based on the information provided in Chapters 3, 4 and 5).

Area	*Description*	*Costs*
Laboratory Astrophysics (Section 5.6)	General Recommendation	2% of the cost of a new facility should be invested in laboratory astrophysics
	European facility for analysis and facility curation	Capital cost: €80M Running costs: €6M/yr
	Other Recommendations	Step change in expenditure of €10M/yr
Theory, Computing and Virtual Observatory (VO) (Chapter 6)	Astrophysics Software Laboratory	50 FTEs/yr (approximately 20 FTEs/yr new)
	Supercomputing	Current investment: ~€20M/yr
	VO	Current level of effort: 100 FTEs/yr
Public Communication and Education (Chapter 7)	General Recommendation	Invest 1–2% of the cost of new facilities in public communication and education
	Cost of two portals/repositories of information (Recommendations 4, 5 & 8)	Capital cost: €400K Running costs: €100K/yr

Table 4: Estimated costs associated with the recommendations made in Section 5.6 for laboratory astrophysics (see also Section 8.5) and by Panels D and E in Chapters 6 and 7, respectively.

8.11 Conclusions and Next Steps

This report has built on the work of the Science Vision to provide a science-driven, prioritised plan for the development of astronomy in Europe over the next two decades. It not only incorporates consideration of major facilities, but also addresses the development of important areas such as theory, computing and data handling; education and outreach; technology development and industrial spin-off; scientific exploitation, and the critical area of human resources. Difficult decisions have had to be made along the way about priorities, but we have always endeavoured to do so within the framework of our agreed criteria. In general, our conclusions have been consistent with those of other bodies such as ESO, ESA and ASPERA. However, there may be occasions where other criteria, such as the politics of international collaboration, or varying national aspirations, lead to different priorities being set by other bodies from those we have agreed here.

We have inevitably concentrated our attention on new, relatively large facilities. We have also formulated recommendations for major enhancements to, or the investigation of rationalisation of existing facilities. In the case of some current high priority space missions, we have recommended the funding of mission prolongations where appropriate. Overall, we hope that our work will lead to the enhancement of Europe's lead in several areas of our science and to the impact that it has on society in general.

Our recommendations should not be a straitjacket to innovation and progress however. We have recognised the need for flexibility and enhanced research and development activity in order to bridge the gaps in our ability to address some of the remaining Science Vision questions. It is also important that opportunities continue to exist for the development of relatively small-scale, fast track, but high impact facilities, for example in national or bilateral space missions.

The Roadmap needs, in some sense, to be a living document. In terms of major revisions, these will need to be undertaken in a timely, but efficient fashion. The full exercise should therefore be repeated at intervals of between five and ten years. Between these major revisions however, there is an important continuing role for ASTRONET.

In the immediate follow-on period from the Roadmap exercise through to the current formal end of the project in September 2009, ASTRONET will be leading the reviews that the Roadmap has set in train of the 2–4 m-class optical telescopes and Europe's radio facilities. It will also be establishing a study group to investigate the provision of a wide-field multiplexed spectrograph for large optical telescopes as recommended in this report.

Beyond the current EU funding cut-off, a body such as ASTRONET is required to oversee the implementation of these reviews and then to move on to lead similar activities for the 8–10 m-class optical telescopes into the E-ELT era; the mm–sub-mm facilities alongside the full operation of ALMA, and the rationalisation of our smaller solar telescopes in the run up to the EST.

There are other recommendations that need to be taken forward by a champion who has continuity over several years, and strong connections with the funding agencies and other governmental bodies in Europe. It is proposed that this would be an important continuing role for ASTRONET. In the case of Panel D, continued involvement by ASTRONET is felt to be particularly important to take forward recommendations regarding sustaining the Virtual Observatory infrastructure and the establishment of the proposed Astrophysical Software Laboratory. There is a very similar role envisaged for ASTRONET to carry forward the recommendations of Panel E.

In terms of laboratory astrophysics, it is proposed to establish new European Networks engaged in fundamental laboratory experimental, interpretative and computational research and modelling, and database provision for spectra, cross sections, reaction rates, analogue materials etc. Part of the implementation could be through joint calls by the funding agencies, co-ordinated through ASTRONET. Similar joint calls are seen as an important potential complement to EU Framework Programmes to address specific technology needs within the context of agreed European strategies.

It has been stressed several times in this document that a fundamental resource is the human beings who are required to design, build, operate and exploit the results of our world-class facilities. Specific recommendations in this regard relate to the development of a fast track route to funding posts for scientific exploitation and the introduction of a European Research and Technical Fellowship programme of jointly held positions that will enhance contact between laboratories. More widely, to maintain and enhance our human capital may require new steering processes for the deployment of manpower across Europe to be put in place. EU-supported networking activities have gone some way in this direction, but they are by no means enough. In the longer term, ASTRONET could provide a forum for defining and helping to implement such mechanisms as required to underpin the implementation of the Roadmap.

Our plans are ambitious, and to realise them will at times necessitate tough decisions being made on the continuation or otherwise of existing facilities by the funding agencies. In addition there is no doubt that significant additional funding will be required for our subject over the next two decades to implement our vision and thereby maintain and enhance our world-leading position and the impact our work has on society at large. Perhaps most importantly therefore, a future incarnation of ASTRONET is needed to work with the funding agencies and other organisations to ensure that the recommendations of the Roadmap are implemented and help to enhance future decision making, cooperation and coordination in Europe. In addition, at a higher level, ASTRONET would use the results of our work to emphasise at governmental level the importance and impact of our science, and not least the example we set for collaboration in Europe and beyond. Indeed, most large projects involve international cooperation beyond Europe's borders, and ASTRONET could help promote such global collaborations.

The formulation of the ASTRONET Infrastructure Roadmap has been a pioneering, challenging and complex task requiring the dedication and insights brought to it by a large and distinguished team comprising some of Europe's most talented scientists, educators and scientific administrators. All of them have given their time freely and enthusiastically, and it is due to them, and to the wider community who gave such valuable input to the whole process, that the recommendations of this report are taken from dreams to reality.

Appendices

Appendix I Science Vision Goals

The main scientific goals for each of the four areas in the Science Vision are listed below.

A. Do we understand the extremes of the Universe?

1. Measure the evolution of the dark energy density with cosmological epoch, to search for deviations from a cosmological constant.

2. Test for a consistent picture of dark matter and dark energy using independent and complementary probes, thus either verifying general relativity or establishing the need for a replacement theory.

3. Measure the polarisation of the cosmic microwave background at ten-degree scales, to search for the signature of relic gravitational waves.

4. Directly detect astrophysically-generated gravitational waves to measure strong-gravity effects, in particular arising from black hole coalescence.

5. Make direct studies of regions near the event horizon of supermassive black holes in galactic nuclei, to test strong gravity and to understand how large-scale relativistic jets are launched.

6. Understand the astrophysics of compact objects and their progenitors, particularly the functioning of the supernova explosion and gamma-ray burst mechanisms.

7. Understand the origin and acceleration mechanism of cosmic rays and neutrinos, especially at the highest energies.

B. How do galaxies form and evolve?

1. Map the growth of matter density fluctuations in the early Universe, both during and after the Dark Ages.

2. Detect the first stars, black holes, and galaxies, and thus establish the nature of the objects that reionised the Universe and discern the first seeds of galaxies.

3. Determine the evolution of the galaxy cluster mass function and constrain the equation of state of the dark energy.

4. Make an inventory of the metal content of the Universe over cosmic time and connect its evolution to detailed models of star formation, and the subsequent metal production and ejection from galaxies by superwinds.

5. Measure the metallicity of the warm–hot phase of the intergalactic medium in the local Universe and solve the missing baryons problem.

6. Measure the build-up of gas, dust, stars, metals, magnetic fields, masses of galaxies and thus the evolution of the Hubble sequence with cosmic time and the connection between black hole and galaxy growth.

7. Obtain a comprehensive census of the orbits, ages and compositions of stars in the Galaxy and the nearest resolved galaxies, aiming to produce a complete history of their early formation and subsequent evolution.

C. What is the origin and evolution of stars and planets?

1. Determine the initial physical conditions of star formation, including the evolution of molecular clouds, and the subsequent development of structures in general, and the formation and mass distributions of single, binary or multiple stellar systems and stellar clusters.

2. Unveil the mysteries of stellar structure and evolution, also probing stellar interiors.

3. Understand the lifecycle of matter from the interstellar medium to processing in stars and back into the diffuse medium during the last stages of stellar evolution.

4. Determine the process of planet formation, aiming for a full understanding of the timeline for the formation of planets and the chemical evolution of the material that will eventually end up in exoplanets.

5. Explore the diversity of exoplanets in a wide mass range from giants to Earth-like, to characterise the population of planetary systems in relation with the characteristics of their host stars.

6. Determine the frequency of Earth-like planets in habitable zones and push towards their direct imaging with the long-term goal of spectroscopic characterisation including the detection of biomarkers in their atmospheres.

D. How do we fit in?

1. Utilise the vicinity of Solar System plasmas, in (i) the Sun, (ii) the heliosphere and (iii) planetary environments, to develop a detailed understanding of physical processes which apply to astrophysical phenomena.

2. Develop a unified picture of the Sun and the heliosphere including the planetary environments, including a systems-level view of energy flow from the Sun to the Earth.

3. Understand the underlying mechanisms for solar variability and transient activity, the subsequent variability in the heliosphere and the resulting impacts on the Earth and other planetary environments.

4. Understand the role of turbulence and magnetic fields in the evolution of the primordial nebula, the mechanism of particle growth, and the elemental and isotopic ratios in this nebula, and in Solar System bodies.

5. Determine the dynamical history and the composition of trans-Neptunian objects and asteroids, and the rate of large potential impactors in the near-Earth asteroid population; search for complex molecules in comets and study the link between comets and interstellar matter.

6. Constrain the models of internal structure of planets and satellites and the origin of their internal heat, the surface-atmosphere interactions and the recycling mechanisms in the terrestrial planets and outer satellites.

7. Understand the origin and evolution of Titan's atmosphere, searches for liquid water at the surface and subsurface of Mars, and for liquid water oceans below the surface of Europa and other outer satellites.

Appendix II Contributors

The tables below list the membership of the Infrastructure Roadmap Working Group and its five supporting Panels.

Infrastructure Roadmap Working Group

Mike Bode	Chair	Liverpool JMU	United Kingdom
Guenther Hasinger	Chair Panel A	MPE	Germany
Patrizia Caraveo	Co-chair Panel A	INAF-Milan	Italy
Michael Grewing	Chair Panel B	IRAM	IRAM
Laurent Vigroux	Co-chair Panel B	IAP Paris	France
Mats Carlsson	Chair Panel C	Oslo	Norway
Therese Encrenaz	Co-chair Panel C	Obs. de Paris	France
Francoise Combes	Chair Panel D	Obs. de Paris	France
Paolo Padovani	Co-chair Panel D	ESO	ESO
Rosa M. Ros	Chair Panel E	Technical University of Catalonia	Spain
Robert Fosbury	Co-chair Panel E	ST-ECF	ESA
Xavier Barcons	Member at Large	CSIC-UC	Spain
Jean Clavel	Member at Large	ESA-ESTEC	ESA
Phil Diamond	Member at Large	RadioNet	RadioNet
Gerry Gilmore	Member at Large	OPTICON	OPTICON
Thijs van der Hulst	Member at Large	Groningen	Netherlands
Guy Monnet	Member at Large	ESO	ESO
Hans-Walter Rix	Member at Large	MPIA	Germany
Ian Robson	Member at Large	UK ATC	United Kingdom
Catherine Turon	Member at Large	Obs. de Paris	France
Guy Wormser	Member at Large	CNRS/IN2P3	France
Maria Cruz	Assistant	Liverpool JMU	United Kingdom
Frank Molster	Assistant	NWO	Netherlands
Johannes Andersen	In attendance	NOTSA	Denmark
Simon Berry	In attendance	STFC	United Kingdom
Fabienne Casoli	In attendance	CNES	France
Jean-Marie Hameury	In attendance	CNRS/INSU	France
Eric Quemerais	In attendance	CNRS/INSU	France

Panel A: High energy astrophysics, astroparticle astrophysics and gravitational waves

Guenther Hasinger	Chair	MPE	Germany
Patrizia Caraveo	Co-chair	INAF-Milan	Italy
Felix Aharonian		Dublin	Ireland
Catherine Cesarsky		ESO	ESO
Anthony Peacock		ESA-ESTEC	ESA
Stefano Vitale		Trento	Italy
Bob Warwick		Leicester	United Kingdom
Ralph Wijers		Amsterdam	Netherlands

Panel B: Ultraviolet, optical, infrared and radio/mm

Michael Grewing	Chair	IRAM	IRAM
Laurent Vigroux	Co-chair	IAP Paris	France
Susanne Aalto		Chalmers University	Sweden
Martin Barstow		Leicester	United Kingdom
Jean-Gabriel Cuby		LAM Marseille	France
Roberto Maiolino		INAF-Roma	Italy
Mark McCaughrean		Exeter	United Kingdom
Raffaella Morganti		ASTRON/Groningen	Netherlands
Andreas Quirrenbach		Heidelberg	Germany
Rafael Rebolo		IAC	Spain
Massimo Turatto		INAF-Padova	Italy
Arnold van Ardenne		ASTRON	Netherlands

Panel C: Solar telescopes, Solar System missions, laboratory studies

Mats Carlsson	Chair	Oslo	Norway
Therese Encrenaz	Co-chair	Obs. de Paris	France
Michel Blanc		Ecole Polytechnique	France
Willy Benz		Bern	Switzerland
Maria Blecka		Warsaw	Poland
Richard Harrison		RAL	United Kingdom
Christoph Keller		Utrecht	Netherlands
Rickard Lundin		Swedish Institute of Space Physics	Sweden
Olga Prieto Ballesteros		Centro de Astrobiología-INTA-CSIC	Spain
Peter Sarre		Nottingham	United Kingdom
Oskar von der Luhe		Freiburg	Germany

Panel D: Theory, computing and networks, Virtual Observatory

Francoise Combes	Chair	Obs. de Paris	France
Paolo Padovani	Co-chair	ESO	ESO
Mark Allen		Strasbourg	France
James Binney		Oxford	United Kingdom
Matthias Steinmetz		Potsdam	Germany
Marco de Vos		ASTRON	Netherlands
Aake Nordlund		Copenhagen	Denmark

Panel E: Education recruitment and training, public outreach

Rosa M. Ros	Chair	Technical University of Catalonia	Spain
Robert Fosbury	Co-chair	ST-ECF	ESA
Lars Lindberg Christensen		ESA/Hubble/ST-ECF	ESA/ESO
Jose Carlos del Toro Iniesta		IAA-CSIC	Spain
Leonarda Fucili		SMS Belli Rome	Italy
Robert Hill		Northern Ireland Space Office at Armagh	United Kingdom
Dirk Lorenzen		German Public Radio	Germany
Claus Madsen		ESO	ESO
Andy Newsam		Liverpool JMU	United Kingdom
Alan Pickwick		Manchester Grammar School	United Kingdom
Veselka Radeva		Varna Observatory	Bulgaria

Appendix III Initial Terms of Reference

III.A Panels A–C

- Assemble information on priorities identified by relevant external bodies (e.g., ASPERA, ESO, ESA etc.).

- Assemble an overview of facilities in this area that may be of relevance. This would include, where possible, timelines, costs and technological readiness (including necessary R&D).

- Assess which facilities, or part thereof, would be capable of delivering relevant aspects of the Science Vision.

- Provide a prioritised list (possibly in broad categories of prioritisation) of facilities and other infrastructures identified in this area, for transmission to the Working Group.

- Assess the Human Resource needs of this area.

- Highlight any areas of Industrial Relevance.

- Compile a report (guideline for inclusion in the final report is ten pages plus figures) and any other relevant background information, to be passed to the Working Group.

III.B Panel D

- Assemble information on priorities identified by relevant external bodies (e.g., national and international supercomputer or grid initiatives, ESFRI, European and international VO projects, European infrastructures etc.).

- Assemble an overview of facilities in this area that may be of relevance. This would include, where possible, timelines, costs and technological readiness (including necessary R&D).

- Assess which facilities, or part thereof, would be capable of delivering aspects of the Science Vision. This needs to be done in close collaboration with Panels A, B and C, to make sure that the data processing and archiving requirements or future experiments are captured.

- Provide a prioritised list (possibly in broad categories of prioritisation) of facilities and other infrastructures identified in their area, for transmission to the Working Group.

- Assess the Human Resource needs of their area.

- Highlight any areas of Industrial Relevance.

- Compile a report (format to be discussed, but guideline for inclusion in the final report is ten pages plus figures) and any other relevant background information, to be passed to the Working Group.

III.C Panel E

- Assemble information on initiatives to utilise astronomy and astrophysics to enhance school age education and assess their impact.

- Assemble information on postgraduate recruitment and training in Europe, including numbers of students in different areas (both science and technology development if possible).

- Assemble information on primary sources of publicity for our subject area and assess their impact (via international comparison if appropriate).

- Assess where greater cooperation, additional resources (including human resources) and/or better practise would significantly enhance the above areas in Europe.

- Highlight any areas of Industrial Relevance (particularly in training aspects).

- Compile a report (guideline for inclusion in the final report is ten pages plus figures) and any other relevant background information, to be passed to the Working Group.

III. D Working Group

Following the initial work of the Panels:

- Assemble information on priorities identified by national Funding Agencies.

- Receive and synthesise the priority lists of the Panels to optimise delivery of the Science Vision. This would include consideration of the overall human resource needs.

- Identify areas of synergy and areas where technological development and industrial involvement/relevance needed or appropriate.

- Discuss the draft priority list and other input from the Panels with the Funding Agencies at an intermediate stage Workshop.

- Refine the list following the Workshop to provide a publicly available draft document.

- Organise a Roadmap Symposium for the community to have their input.

- Undertake further refinement, in conjunction with the Agencies, in order to produce the final version for passing to Workpackage 3.2.

Appendix IV List of Facilities

The tables below list the 112 projects that received the ASTRONET questionnaire (see Section IV.D below). In each table, the facilities in the first two columns were evaluated as described in Section 2.4, and ranked as high priority (first column), and as medium and low priority (second column). The facilities in the third column were not ranked because: their European costs fell below our threshold; or no major funding decisions were considered to be required in the period beyond 2008; or they were still at a very early concept stage, where there was not enough information available.

IV.A Facilities Surveyed by Panel A

High Priority Projects	*Also ranked*	*Considered but not ranked*
CTA	Adv-LIGO	AGILE
INTEGRAL	Adv-Virgo	AMS
KM3NeT	Auger North	Argos-X
LISA	EDGE	GLAST
Simbol-X	Einstein Telescope (ET)	IceCube
XEUS	GRI	Spektrum-RG
XMM-Newton	GRIPS	SVOM
	S-EUSO	Swift

IV.B Facilities Surveyed by Panel B

High Priority Projects	*Also ranked*	*Considered but not ranked*
Darwin	B-POL	A New Window to the Universe: Very Low Frequency Astrophysics (VLFA)
DUNE	CCAT	ALMA
E-ELT	EVN	Antarctica
FIRI	H2EX	APEX
Gaia DPAC	IRAM	e-MERLIN
LOFAR	LSST	Far Ultraviolet Space Observatory
SKA	Millimetron	Fresnel Interferometric Imager
SPACE	Pegase	Gemini
SPICA	PLATO	GranTeCan
VLT/VLTI instrument upgrade	SAGE	JWST
Wide-field spectrographs	Sardinia Radio Telescope	KOI
	See-Coast	LBT
		Luciola
		Lunar Radio Explorer/ Lunar Low Frequency Array/ Lunar Dark Ages Mapper
		Measurement of cosmological magnetic fields in Lyman-alpha clouds through the paramagnetic Faraday effect
		Stellar Imager Concept
		The Modern Universe Space Telescope
		The Celestial Exoplanet Survey Occulter
		World Space Observatory (WSO)

IV.C Facilities Surveyed by Panel C

High Priority Projects	*Also ranked*	*Considered but not ranked*
Cluster	ATST	BepiColombo
Cross-Scale	Comet Sample Return	European Moon and Mars Planetary Observatories
European Solar Telescope (EST)	COMPASS	Evolution Surveyor of the Atmospheric Composition
ExoMars	Cutlass/SuperDARN	Dutch Open Telescope
Hinode	DunExpress	Mars Fly
LAPLACE	Dynamics	Methane Imager for Planetary Missions
Marco Polo	EISCAT	Observatoire de Nançay
PHOIBOS	EVE	Research of the liquid water generated via non-stellar energy sources in Enceladus
Solar Orbiter	FASR	Rosetta
STEREO	HIRISE	SDO
TandEM	Interstellar Heliopause	Solar LOFAR station
	KRONOS	Swedish 1 m Solar Telescope
	LunarEx	Themis
	Mars Origins Mission	Venus Troposphere
	MEMO	Virtual Human Spaceflight
	POLARIS	VTT/Gregor
	SARIM	
	SMESE	
	Ulysses	
	WARP	

IV.D ASTRONET Questionnaire (outline)

1. Name of facility/mission/instrument:

2. New facility, major upgrade to existing facility or precursor to major new facility?

3. Principal Establishment(s), including role of each:

4. Other Collaborating Establishment(s), again including role of each:

5. Management Structure (including any relationships with organisations such as ESA, ESO etc.):

6. Please provide a brief textual summary of your facility/instrument/mission, describing:

    - The principal scientific objectives (reference can be made to the Science Vision at http://www.astronet-eu.org/-Science-Vision-)

    - The basic technical specification

    - Its development status (e.g., initial proposal/in detailed development/under construction/in operation/major upgrade ongoing), including as appropriate details of approval and review status

    - Its operational timeline

    - The status and nature of any necessary significant research and development required

7. Future Milestones (type and date):

    - E.g. for Space projects, include the milestones of the normal project Phases

    - For existing facilities, please include any major development/upgrade plans here

    - If the construction will be split into more than one phase, please indicate what will be achieved in Phase 1 and when, and what will be achieved during later phases (and when)

8. Outline Budget and non-industry direct FTE staff on the project
   - All figures should be in 2006 Euros if possible, and from the start of calendar year 2010 onwards
   - Give a total Cost at Completion and non-industry FTE requirement for design and construction (for Space projects, this includes payloads)
   - If possible, provide a cost and FTE requirement to each milestone given in 7. above
   - Provide an estimate of annual operating costs (in the case of a major upgrade, this should be in terms of any additional cost to existing operations)
   - Provide, if possible, an estimate of the FTE scientific staff required to properly exploit the data gathered
   - State what funding is already secured for each phase of the project (noting any funding decisions in the next 6 months that may affect this, and of which ASTRONET should be aware)
   - Give an estimate (can be in percentage terms) of the likely required European funding share of the project from 2010 onwards
   - Please give any details of external verification of figures given and a clear statement of what contingency (if any) is included in future budget estimates.
   - If possible, costings should be direct costs, not including such items as university overheads. In order that meaningful comparisons between projects can be made, give details as appropriate of what your costings include.
   - Again, we do appreciate that the figures given may be approximate, particularly in the medium- to long-term. Any additional information on how the figures given are arrived at will be gratefully received
9. What are the main technical and/or programmatic risks to the development and operation of the facility/mission/instrument? How might these be mitigated?
10. What plans do you have for a Public Data Archive (including corresponding estimated set-up and operational costs, FTE requirements for this and general publicly accessible archive needs)?
    - If you are not planning a public archive, please explain why
    - If planning one, are there any plans to make it “VO-compliant”, and at what additional cost? If not, for what reason: a) not thought important, b) do not know what “VO-compliant means”, c) do not have the resources, d) other (please explain)
11. Please give details of any interaction with industry:
    - What is the nature of any current or future major industrial involvement?
    - Which kind of industry has been, or would be, involved?
    - Please give the names of any existing major industrial partners.
12. Do you have any associated educational and outreach activities, ongoing or planned?
    - Please specify their nature and target audience(s).
    - Do you produce or plan to produce any material for education? If so, is it interactive and who is it aimed at? (e.g. teachers/students; primary/secondary/university education levels)
    - Do you evaluate or plan to evaluate the impact of your educational activities?
    - Do you produce any multimedia material and/or material which is aimed at the media?
13. Please feel free to add any additional information on your facility that you feel may be useful to the ASTRONET Roadmapping exercise.

Appendix V Appendices Relevant to Theory, Computing Facilities and Networks, Virtual Observatory (Panel D)

V.A The VO in Europe

European VO initiatives are coordinated via the EURO-VO consortium[74], which has eight member organisations comprising European intergovernmental (the European Organisation for Astronomical Research in the Southern Hemisphere [ESO] and the European Space Agency [ESA]) and national research organisations and VO initiatives. EURO-VO cooperates with national VO projects in France, Germany, Italy, the Netherlands, Spain, and the UK. EURO-VO started in 2005 and consists of three interacting elements.

- EURO-VO DCA: a network of the European data centres, which populates the system with data, provides the physical storage and computational fabrics, and using VO technologies, publishes data, metadata and services to the EURO-VO;
- EURO-VO Technology Centre (VOTC), a distributed organisation, coordinating a set of research and development projects on the advancement of VO technology, systems and tools;
- EURO-VO Facility Centre (VOFC), that provides the EURO-VO with a persistent, centralised registry for resources, standards and certification mechanisms as well as community support for VO technology take-up and dissemination and scientific programme support using VO technologies and resources. The VOFC provides a public face to the EURO-VO.

EURO-VO followed from the Fifth Framework Programme (FP5) R&D project Astrophysical Virtual Observatory (2002–2004), and the science case experience of the AstroVirtel initiative (2000–2002). Indeed, the European Union has been supporting VO efforts in Europe through four related projects.

- Astrophysical Virtual Observatory (AVO) (2002–2004), a €5M R&D project to investigate the scientific and technological requirements needed to build the VO in Europe, funded at the 50% level by the FP5;
- VOTECH (2005–2008), a €6.6M design study to complete all technical preparatory work necessary for the construction of the EURO-VO, funded at the 50% level by the Sixth Framework Programme (FP6), which relates to VOTC;
- Data Centre Alliance (DCA) (2006–2008), a €1.5M Coordination Action tasked to set up the uptake of the VO framework by the European data centres, funded by the FP6;
- Astronomical Infrastructure for Data Access (AIDA) (2008–2010), a €2.7M Integrated Infrastructure Initiative to lead the transition of the VO in Europe into an operational phase, with emphasis on the science exploitation of the data, funded by the FP7.

VOTECH has made important progress toward completing the technical preparatory work for building the European VO. The VOTECH mid-term review (November 2007) demonstrated important progress in the four domains, Architecture, Intelligent Resource Discovery, New User Tools and Data Exploration. This includes a significant impact on the IVOA standards for querying online archives, virtual data storage, and accessing tabular data. New tools like VOExplorer provide pragmatic use of VO registries for finding data and services. Interoperability and integration of tools is greatly improved by standardised communication between applications. This provides combined scientific capabilities beyond what is possible in the individual tools, as well as minimising duplication and increasing cooperation. VO-TECH integration also includes the framework for data-mining capabilities in the VO, and also for integrating VO with grid technologies.

The DCA is coordinating the first integration of European data centres in the VO framework. The first cycle of the project delivered a major workshop for data centres on how to publish to the VO, including hands-on assistance and tools for mapping databases to VO standard systems. Strong feedback mechanisms in this project are ensuring that the DCA meets data centre needs, and a detailed census of data centres is being prepared. The DCA is also preparing the inclusion of new types of services in the VO in particular theoretical and modelling services. The second cycle of the project, which will end in December 2008, includes another major VO publishing workshop, a workshop on publishing theory services, and a workshop on coordination of the VO development with computational grid projects.

Some Facility Centre activities have begun, initially with support provided solely by EURO-VO partners (plus limited funding from the OPTICON and RadioNet I3s in 2005 for organising the first EURO-VO Workshop, which was held in Garching, Germany, in June of that year). In particular, a EURO-VO Science Advisory Committee has been formed, because it was needed to provide guidance and evaluation; a limited, prototype call for scientific proposals, the EURO-VO Research Initiative, was launched in February 2007, with a second one made in April 2008. EURO-VO–DCA workshops were organised in 2007, including one focussed on a specific topic, "Spectroscopy and the VO".

Parallel and complementary to the Euro-VO effort, the EC has decided to fund the design, construction and qualification of AstroWISE, which delivered a European-wide distributed system in the fall of 2006. AstroWISE is fully operational and involves national data centres and satellite nodes in the Netherlands, Germany, France, Italy and plans to roll out the network further in other European countries, such as Spain, Denmark and beyond (e.g., Chile). AstroWise performs massive data production and analysis, using its own developed compute grid and a direct connection to the EGEE-grid. AstroWISE populates the astronomical archives and facilitates full quality assessment by users by tracking the workflow of data from the raw to the final product.

Much survey data will be pipelined through the AstroWISE system, and will be analysed and quality controlled by teams distributed over Europe connected by a peer-to-peer network. The network is positioned in between the observatories and the EURO-VO and requires maximum connectivity to the various infrastructures. AstroWISE publishes directly into the EURO-VO. In the future, given the high demand on connectivity to processing grids, storage grids and publication grids, AstroWISE will play an important role as a working switchboard between these infrastructures. The requirements of future missions, such as EUCLID, imply that such networks should be further expanded.

ESA has been participating actively in the VO initiative in astronomy at European and international levels. The ESA-VO project aims to be the European VO node for all space-based astronomy and to make sure that all ESA astronomy archives are VO-compliant. In addition to providing data content, ESA-VO develops some VO applications and VO publishing services. ESA has secured dedicated VO funds, besides the archive funding, but within the same team, to make sure that ESA Archive are fully part of the VO. These goals and objectives remain the same for the medium-term future, with special emphasis that upcoming ESA missions (e.g., Herschel, Planck, Gaia) can benefit of the VO in their early phases.

ESO has been a key player in the VO arena from the beginning. ESO's VO activities have been managed by the Virtual Observatory Systems (VOS) Department of the Data Management and Operations Division, whose mission was also to make the ESO Archive into a powerful scientific resource for the community. VOS has been working towards making all ESO data VO-compliant, creating science-ready data products from the ESO archive, and also ingesting such data from ESO and consortium pipelines, from ESO Large Programmes, and, in the near future, from ESO Public Surveys (VST and VISTA). VOS has also been redesigning the archive facility and its interface to be able to publish its data within the VO infrastructure. Finally, VOS has been involved in the development of VO technology, standards, and tools for the archive, also via participation to European VO activities, in particular through the VO-TECH, DCA and AIDA projects. As of 1 June 2008, VO activities at ESO are managed by the Virtual Observatory Project Office.

AstroGrid is a UK national project with global intent. It aims to (i) deliver a working VO service for UK astronomers, (ii) collaborate with European partners in constructing the EURO-VO, and (iii) construct infrastructural software that other projects and data centres worldwide can use — for example tools for deploying datasets; client side middleware; and an application programming interface (API) for tools developers. After an initial period of technology development, during the last two years AstroGrid has operated a working pilot system, and run a series of user workshops to get feedback from real astronomers. Following this experience, the user interface has been radically overhauled, and the project has deployed a full working service in April 2008. This includes deploying key datasets in the UK, and through the AstroGrid registry, establishing access to resources worldwide; providing VO-Desktop tools for exploring and accessing data; providing interoperable science analysis tools written by European partners; and deploying core services such as Registry, MySpace, and Workflow through Python scripting. Funding has come in part from PPARC/STFC and in part from FP5/6/7 projects. The AstroGrid consortium leads the VO Technology Centre (VOTC) arm of EURO-VO. PPARC–STFC have funded AstroGrid in three successive phases. The AstroGrid-1 project (2002–4) made preliminary investigations, and developed new technologies. The AstroGrid-2 (2005–7) project completed technology development and made a pilot working service; AstroGrid-3 (2008–9) is about to deploy the full working service. During 2008 a review by STFC will decide whether to establish a long-term operational service. The membership of the AstroGrid consortium has evolved somewhat during the three projects, but for AstroGrid-3 is: Cambridge, Edinburgh, Leicester, Jodrell Bank, MSSL/UCL, RAL and UCLan.

French participation in the Virtual Observatory endeavour is coordinated by the Action Spécifique Observatoires Virtuel France (AS OV), created in 2004 by INSU. AS OV is funded with seed money from INSU/CNRS and CNES and this effort is spread over several laboratories/observatories. AS OV has working groups in the areas of Spectroscopy, Theory, Workflows, Grid, Geodetics and Fundamental Astronomy, Images, Planetology. The French astronomy community is rather VO-aware, with some 40 different projects identified in the French-VO 2006 census. In addition, the French VO community participates very actively to the definition of VO standards by IVOA and to the European VO projects.

A number of important VO reference services are provided by France such as the CDS, SkyBot, and several others are being made available. Future prospects depend mainly on the continuing support from the laboratories, but the emphasis of these activities will be to coordinate activities in a way similar to the EURO-VO Data Centre Alliance, and that more actions directed towards the scientific community will be developed.

In Germany, the Virtual Observatory and grid are funded via the German Astrophysical Virtual Observatory (GAVO) and by the AstroGrid-D. GAVO is about to enter its third funding phase. While much of the VO effort is concentrated on observational archives, GAVO is active in pursuing the theoretical component. This comprises the publication of theoretical datasets in similar ways to their observational counterparts, as well as the creation of services with a more theoretical flavour. The ultimate goal is to create an environment in which, on one hand, theoretical results can be used for the interpretation of observations, and on the other hand, observations can be used to constrain theoretical models. GAVO develops prototype tools for the analysis of stars and nebulae, providing synthetic spectra to the VO, based on simulation software for the calculation of NLTE model atmospheres. GAVO will also provide a VO interface to the RAdial Velocity Experiment (RAVE) survey. AstroGrid-D, a project funded by the German D-Grid initiative, is more focused on the middleware between the grid and the astronomical application and on the integration in the national and international e-science initiatives, in particular services, metadata and the integration of compute hardware, data archives and astronomical facilities (e.g., robotic telescopes).

Virtual Observatory activities took place in Italy from late 2003–2006, within the DRACO project (Datagrid for Research in Astrophysics and Coordination with the Virtual Observatory), and from 2006 in the VObs.it project. VObs.it aims to provide a unified approach to the archives and databases developed by the Italian community. The first steps in this direction are to foster the adoption of IVOA standards, to provide grid-aware VO applications and to build a national registry containing the list of VO-compliant services available to the international community. Activities include operations of the INAF data centre including data from TNG, the Large Binocular Cameras (LBC) on the LBT and VIMOS reduced data. VObs.it also includes ITVO (Italian Theoretical VO). Emphasis is also placed on three-dimensional visualisation (VisIVO) and data mining techniques (AstroNeural) for the VO. VObs.it also contributes to work to allow the compute-intensive VO applications to run on the grid, and vice versa grid applications to access VO resources, and in particular the possible interactions between EURO-VO and EGEE, in the framework of the VO–DCA project

VO activities in the Netherlands are coordinated by University of Groningen/OmegaCEN. They identify several planned data acquisition facilities that will produce large archives, which are to be made available in the VO. These include LOFAR (notably the wide-field imaging surveys),

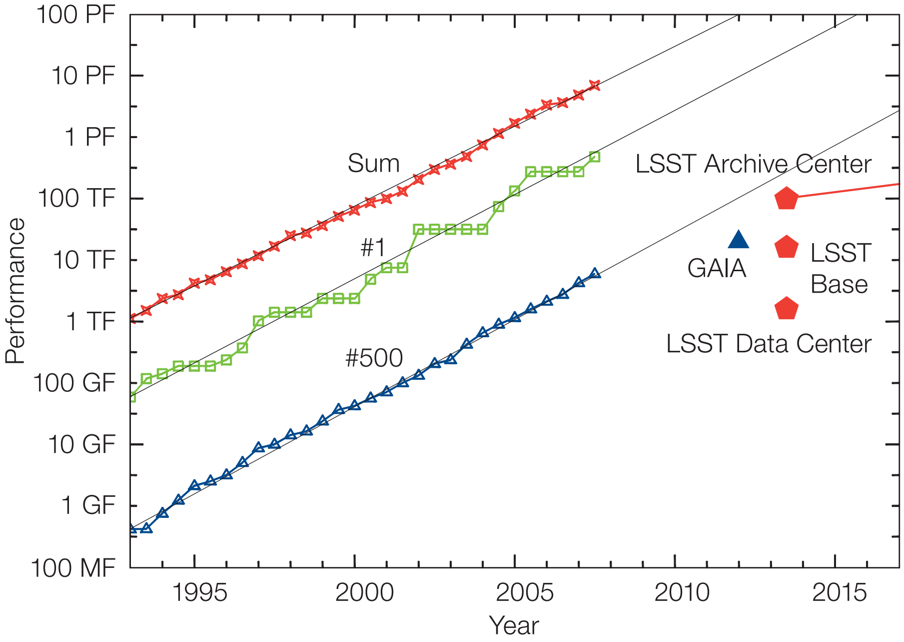

Image Credit: Top500.org

Figure 32: Projected performance development, from TOP500 November 2007. In this linear-log diagram, the line in the middle shows the exponential growth of the computing power of the top first equipment in the world (478 teraflops in November 2007). The bottom line shows the analogue for the number 500 in the list (5.9 teraflops in November 2007). The top line shows the trend for the sum over the 500. Are also indicated are the computing power required for LSST (Large Synoptic Survey Telescope, full pentagons), and Gaia (full triangle).

Westerbork radio surveys, JIVE results, optical wide-field imaging surveys with VST/OmegaCAM and VISTA and large ACS HST surveys such as the Coma legacy survey. VO release of Gaia data can be supported. The results of current and planned large theoretical numerical simulations of cosmological evolution of gas and galaxies using national supercomputers (e.g., Blue Gene in Groningen) are also to be published in the VO.

The Spanish Virtual Observatory (SVO) has funds guaranteed in the mid-term, and has strong local community support. The Spanish ASTRID project focuses on the development and exploitation of astronomical instrumentation, to be used in large international facilities belonging to institutions of which Spain is a member (ESA, GTC, and in the near future, ESO). SVO is active in VO theory developments including the SVO-LAEFF Theoretical Data Server that includes the CoRoT Ground-Based Asteroseismology Archive, the IUE Archive and the INTEGRAL Optical Monitoring Camera (OMC) Archive.

OECD Findings on the VO Initiative

The Global Science Forum of the OECD organised a Workshop on Large Scale Programmes and Projects in Astronomy and Astrophysics in December 2003 in Munich, Germany. The final report addressed the VO explicitly in the following terms:

Findings

The astronomical community has developed the Virtual Observatory concept in response to the challenges of data management and storage. Impressive progress has been made by the International Virtual Observatory Alliance based on support and funding from science agencies. The workshop participants agreed that the global adoption of the IAU resolution and its support by funding agencies, government bodies, and astronomers is critical to the realisation of the VO and the maximal scientific utilisation of new astronomical facilities. In the astronomical research environment of the 21st century, the endorsement and financial support of long-term data and data service access cannot be separated from the support of new scientific capabilities.

Recommendations

New projects and facilities must take data management, storage, maintenance and dissemination into account at the earliest planning stages, consulting potential users in the process. Agencies and governments should consider adopting the IAU resolutions as the basis for progress in this field. Agencies should recognise that this is an important long-term issue and should coordinate plans, provide adequate funding on a long-term basis, and support development and maintenance of the needed infrastructure. Agencies should encourage broadening of existing VO collaboration into a fully representative global activity.

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[74] http://www.euro-vo.org

V.B Computing Centres in Europe

During the last few years, Europe has suffered from a slight loss of competition with the USA, as far as supercomputer equipment is concerned (see Figure 32 and Figure 33). At the last TOP500 census, only two European countries (Germany and Sweden) appear in the top ten high performance computing machines, and 25 in the top 100. The first machine is in the USA (Livermore, California), with 478 teraflops. Cluster architecture is now spreading (81% of the machines)[75].

The performance of computing equipment is not sufficient, however, and many other criteria should be considered in the competition. In astronomy, European teams have powerful post-processing capabilities to exploit the heavy numerical simulations. In cosmology and galaxy formation, for instance, several European groups are at the forefront of research, not only to carry out the simulations, but also for the analysis and exploitation.

Conclusions of the ESFRI Committee

The European Strategy Forum on Research Infrastructures lists a European High Performance Supercomputing Centre in its roadmap (other astronomy-relevant projects in this category are the ELT and the SKA). The proposal aims at concentrating the resources in a limited number of world top-tier centres in an overall infrastructure connected with associated national, regional and local centres, forming a scientific computing network to utilise the top-level machines. This overall architecture will respond both to Capability (high performance) and Capacity (high throughput) Computing needs. Different machine architectures will fulfil the requirements of different scientific domains and applications. This can be represented as a pyramid, with local centres at the base, national and regional centres in the middle and the high-end HPC centres at the top.

The ESFRI proposal made use of an informal report by a task force of HPC Europe. This report has identified astrophysics as a field of research in which high-end supercomputers traditionally play a crucial role, mainly because very often modelling and simulations must replace planned and controlled experiments. Six areas of grand challenges were identified for which modelling on supercomputers is essential. These are (from small to large mass and length scales):

- The Formation of Stars and Planetary Systems;
- Solar and Heliospheric Physics;
- The Evolution and Explosions of Stars;
- Black Hole Physics on Stellar and Galactic Scales;
- Formation and Evolution of Galaxies;
- Cosmology and the Formation of Large-Scale Structure.

For applications to all of these grand challenges, codes are ready for and make use of high-end capability computers. For example, the largest cosmological simulations yet completed by the Virgo consortium (the so-called Millennium Simulation) used up to 400 000 CPU-hours on the IBM Power-4 system and produced several terabytes of data. These numbers are similar to the computer resources used for simulations of two merging black holes in general relativity at supercomputer centres in the US.

It is expected that in most fields of astrophysics, the need for computational resources will increase by a factor of at least ten in the next few years because the spatial resolution of the present simulations is still far from being sufficient to model the interior of stars and their atmospheres, and galaxies and cluster of galaxies in a realistic way. Realistic simulations can only be performed on supercomputers with sustained ~ 100 teraflop/s, but significant progress can be expected with slower machines already. For simulations of planet and star formation, stellar explosions, astrophysical jets and accretion discs, solving the radiation-(magneto)-hydrodynamic problems will ultimately need supercomputers with several hundreds of teraflop/s sustained performance, which might become available past 2010 (with petaflops peak performance).

Overview of Existing Supercomputers, in the Participating Countries (seven countries, including NOTSA, FR, DE, NL, UK, IT, SP)

At this top level of hypercomputers, equipment is always available for several scientific domains, of which the astrophysics share is about 10% on average over the countries. Europe is now preparing several petaflop supercomputers for 2010, and below are the status and comments on the current initiatives in the different countries.

The consortium DEISA[76], has been leading national supercomputing centres and their collaboration to foster the world-leading pan-European computational science research. DEISA1 began in 2002 and was funded by FP6, and DEISA2 is beginning under FP7.

Germany. In order to give Germany the best prospects for adopting a leading role in the future European high performance computing ecosystem, and in particular in the building of a Europe-wide supercomputer

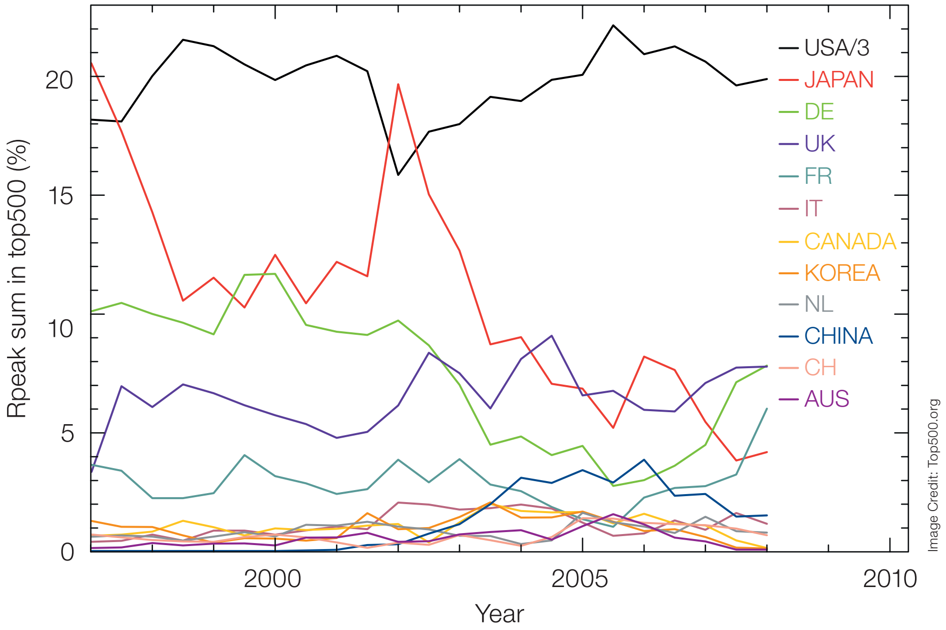

Image Credit: Top500.org

Figure 33: Evolution over time of the accumulated power in each country in terms of theoretical peak performance Rpeak sum of machines in the TOP 500, for the different countries in the world.

infrastructure in the petaflop performance range, as is being planned in the Seventh Framework Programme, the three German national supercomputing centres at Jülich, Garching and Stuttgart joined forces in 2006 and gave birth to the Gauss Centre for Supercomputing (GCS). The GCS offers a state-of-the-art high performance computing and networking infrastructure with machines of different architectures, yet complementary. The two fastest computers are the 220 teraflop Blue-Gene at NIC (the John von Neumann Institute for Computing) and the 126 teraflop machine at the Max-Planck-Institut Computing Centre in Garching. Each one favours special types of applications. In order to promote scientific cooperation between the three centres and in particular between their user communities in the area of high performance computing, the network infrastructure between these computing centres is currently being upgraded to 40 Gb/s, and later striving for 100 Gb/s. Access to the resources is enabled by grid technology, which — together with high speed communication — will also facilitate distributed computing and data storage.

France. GENCI, Grand Equipement National de Calcul Intensif, is a legal entity 50%-owned by the French State, represented by the Ministry for Higher Education and Research, 20% by the Commissariat à l'Énergie Atomique (CEA), 20% by the CNRS and 10% by universities. It was created in January 2007 to promote the use of modelling, simulation and high performance computing in fundamental and industrial research, and to promote the organisation of European high performance computing and to participate in its actions. A strategic Committee is following the HPC computing projects, and the proposed €25M/yr for the budget. After the completion of Tera10 (Bull, 10 teraflops) the CEA is proposing to build a new computing centre by Ter@tec, with the help of the local sponsors, and proposes an extension aimed towards a European HPC machine. The CNRS announced the acquisition of a 200-teraflop IBM machine in 2008, with a combined architecture (40 000 CPU cores, from 0.5Go memory for massive parallel processing and 4000 cores up to 8Go of memory per core for symmetric multiprocessing).

UK. The report[77], *A Strategic Framework for High End Computing (HEC)*, published in 2006, maps out the road to petascale computing for the UK. It recommends training more specialists and proposes investments of at least £26M/yr. At the present time, the focus of UK HEC resides heavily in the physical sciences: the major communities include particle physics, astronomy, condensed matter, chemistry and material science, computational fluid dynamics and geophysics. The UK also has a National Grid Service (NGS) in place, including a set of lower-end nodes, together with the UK national supercomputing facilities.

Spain. Mare Nostrum, based in Barcelona since 2005, is one of the largest supercomputers in Europe. The computer is owned by the Barcelona Supercomputing Center–Centro Nacional de Supercomputación (BSC–CNS), a consortium created by the Research and Education Departments of the national and regional governments and the Polytechnic University of Barcelona. It is used for research in computer architecture, aerodynamics, biology and genetics, and also has industrial applications. It was available to Europe via DECI, in which astronomers had a large share.

The Netherlands. For Dutch academic and research supercomputing in general, the Netherlands Organisation for Scientific Research (NWO) provides support through its National Computing Facilities (NCF). The NCF funds, for instance, one large national supercomputer, currently Aster (replaced by Huygens in 2008) in the SARA centre (including networks like SURFnet, grids, visualisation…). The NCF's policy is to have a new system approximately every six years with a significant mid-life upgrade after three years. This schedule serves the scientific community best: the highest performance, the least number of "changes", best affordability, always on track and a kind of predictability for scientists who continuously invest in their software developments. Stella (the IBM BlueGene to operate LOFAR) is dedicated to LOFAR, and therefore to astronomy for the main part, and has been in Groningen since 2005.

Italy. CINECA in Bologna is the main supercomputer centre for research, operated by a consortium of 31 Italian universities, plus CNR, the Research Ministry and some other institutions, together with industrial partners. CINECA has two machines in the TOP 100, and is twelfth in Europe, and aims to reinforce the connection between universities, key research centres and industry. CINECA has announced the acquisition of a 200 teraflops IBM machine, with 40 000 CPU cores for the end of 2008.

Denmark. The Danish Centre for Scientific Computing (DCSC) provides supercomputing resources to a small number of regional centres. Currently, the regional centres typically have resources of the order of 500–2000 cores; the largest installation is currently of the order of 15 teraflops. While this organisation is ideal for providing low-overhead, mid-range capacity to participating groups, small countries such as Denmark will need to participate in European scale initiatives to obtain access to petaflop computing.

PRACE: The Partnership for Advanced Computing in Europe is preparing a permanent pan-European HPC service, consisting of several tier-0 centres providing European researchers with access to high capability computers and forming the top level of the European HPC ecosystem. PRACE is a project funded in part by the EU's 7th Framework Programme.

All of these supercomputing centres involve all the sciences, and astrophysics participates at a level of about 10% in their use. An exception must be noted here, due to the development of new technologies in radio-astronomy interferometers (such as LOFAR, SKA): their needs in data processing and computer power are such that a supercomputer in the Netherlands has been dedicated to their operation.

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[75] Although the USA have about 60% of the first 500 machines, the European share is now rising slightly from 25% to 30% of the top 500, and is larger than the Asian share. In Europe, the UK now has first place, and Germany second.

[76] http://www.deisa.eu/

[77] http://www.epsrc.ac.uk/ResearchFunding/FacilitiesAndServices/HighPerformance Computing/HPCStrategy/2006StrategicFramework.htm

*v.*c Software and Codes

In addition to a European (super)computer infrastructure, the scientific software developed by the various astrophysics groups is becoming increasingly important from a strategic point of view. Whereas ten years ago every research group could develop its own research codes, nowadays the complexity and sophistication of the codes have grown to such an extent that many groups rely on the general availability of this scientific software. Some of the most powerful packages have been used as “research instruments”, and quoted in the literature as such.

Another point is that the range of users is broadening: they range from theoreticians developing improved algorithms and new types of applications, to experimentalists who need to use simulation to interpret complex data. In addition, it is not sufficient to make free software available: essential elements of the success of a software infrastructure are appropriate training and user support, so the software can be used reliably. This emphasises the importance of networking and building consortia, that are able to distribute the expertise.

Principal Public Software for Theory

In this section, some of the main “power-horses” in the various astrophysical domains are listed. This list is not exhaustive, and the existence of many other useful public codes is acknowledged[78].

- ASH (Anelastic Spherical Harmonic) for solar convection and oscillations, originally based in Colorado, then also developed by European astronomers.

- CESAM (Code d’Evolution Stellaire Adaptatif et Modulaire), stellar evolution code, based in Nice, France, but developed by many Europeans.

- NBODY (1 to 6), Aarseth method for dense stellar systems (UK).

- GADGET for cosmological N-body/SPH massively parallel simulations, Max-Planck-Institut für Astrophysik (MPA), Germany.

- RAMSES for cosmology, Adaptive Mesh Refinement, CEA, France.

- FLASH for hydrodynamics, developed originally to solve for thermonuclear flashes on the surfaces of compact stars such as neutron stars and white dwarf stars, and in the interior of white dwarfs (i.e., Type Ia supernovae); based in Chicago, USA.

- ZEUS, a family of Eulerian (grid-based) magnetohydrodynamic codes (MHD) for use in astrophysics, with radiative transfer (can be used in cartesian, cylindrical or spherical geometries); mainly US, but also European developers.

- PLUTO modular, Godunov-type code for astrophysical applications; supporting classical, relativistic and magneto (Newtonian and relativistic) fluid dynamics modules in cartesian and curvilinear coordinates in multiple space dimensions; based in Torino (Italy).

- PENCIL is a multipurpose code for massively parallel computing. It includes hydrodynamics, magnetic fields, radiation, ionisation, multi-species dust dynamics with coagulation and certain reaction-diffusion equations. Based in Nordita (Denmark).

- CLOUDY, numerical simulation of plasmas and their spectra (UK-based and Canada, USA).

- LORENE, an object language for numerical relativity, (Langage Objet pour la RElativité NumériquE in French) to solve various problems arising in numerical relativity, and more generally in computational astrophysics. Using multi-domain spectral methods, LORENE can implement matrices, tensors, and model astrophysical objects, such as stars and black holes (based in Meudon, France).

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[78] See for instance the websites: http://astro-sim.org/, http://ascl.net/ (Astrophysics Source Code Library).

V. D Networks and Consortia

- CESAM (Stellar Physics) working group, in collaboration with EZ, TYCHO, ASTEC, STARS, TMAP.

- AstroSim (European Network for Computational Astrophysics, from the Solar System to galaxies, computational techniques and multi-scale modelling). AstroSim provides funding for conferences, workshops, training schools, exchange visits and collaborative travel. From 2006–2011, a dozen institutes in European Countries have combined their funding through the ESF.

- Manybody.org NEMO (Software environment for stellar dynamics, galaxies); STARLAB (software package for simulating the evolution of dense stellar systems); with PARTIVIEW as an advanced 4D-visualisation; and MODEST (MOdeling DEnse STellar systems).

- LENAC (Latin-American European Network for Astrophysics and Cosmology): scientific areas of direct interest to the network: computer simulations of the formation of large-scale structure and galaxies, funded by the European Commission's ALFA-II programme.

- Virgo Consortium, for cosmological supercomputer simulations, founded in 1994 in response to the UK's High Performance Computing Initiative. International collaboration between UK, Germany, Canada, the USA and Japan.

- HORIZON consortium for galaxy formation in a cosmological context (2005, France)[79].

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[79] http://www.projet-horizon.fr/

V. E Examples of the Use of Grid Computing in Astronomy

Example 1

Gravitational lens fitting. Gravitational lensing provides an extremely powerful way of probing mass distributions, independent of any assumption about the relation of mass to light. In the case of strong gravitational lensing, the data consist of image brightnesses, parities and time delays, and the model comprises the Hubble constant and the sky-projected mass distribution of the lens. The mass distribution is not, however, uniquely determined even with perfect data. Hence it is necessary to explore a large family of mass models, all perfectly consistent with the data. PixeLens[80] is a program for exploring model ensembles in this way, which is already implemented in Java and applet-capable, which promises a rapid transition to grid implementation. This example illustrates a key point of astronomical modelling: problems with model-degeneracy are common. The strategy of exploring ensembles of models compatible with the data is computationally costly, and rarely adopted so far, but will probably become standard practice in the next decade.

Example 2

Black hole hunting. Most black holes at the centres of galaxies have been detected through their effect on the central surface-brightness profiles and line-of-sight velocity distributions of the galaxies. These data are modelled by Schwarzschild's technique: for a given black hole mass and mass-to-light ratio, non-negative weights are assigned to ~ 2000 orbits so as best to reproduce the measured surface-brightnesses and line-of-sight velocity distributions. The favoured black hole mass is the one that produces the best fit to the data. This procedure is flawed[81]; really the best black hole mass is the one that allows the largest possible number of sets of weights[82], determining which mass satisfies this criterion is computationally expensive and has not been done with real data. Implementing Magorrian's algorithm is perfectly matched to distributed computing.

Example 3

Modelling the Gaia catalogue. A model galaxy might consist of a gravitational potential described by a dozen parameters together with a few thousand orbital tori, each described by 20–50 parameters, and distribution functions (DFs) for 10–100 stellar populations. Each DF would consist of the values it takes on each torus. One wants to know the likelihood of the Gaia catalogue given this model. Errors (especially in distance) blur each star so it has a non-negligible probability density in a volume of phase space, so we have to integrate the DF through this volume. The billion stars in the catalogue could be sent out to N processors, $10^9/N > 1000$ stars per processor, to evaluate the integral.

Example 4

CMB modelling. Planck is the third generation space mission for the mapping and the analysis of the microwave sky. In order to achieve the ambitious goals of this ESA mission, unanimously acknowledged by the scientific community to be of the highest importance, data processing of extreme accuracy is needed. The PlanckSim project has been active since 2004 and is using the EGEE infrastructure to simulate the whole Planck mission several times, on the basis of different scientific and instrumental hypotheses. The mock data are then reduced, calibrated and analysed down to the production of the final products of the mission, in order to evaluate the impact of possible instrumental effects on the quality of the scientific results, and then to refine appropriately the data processing algorithms.

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[80] http://www.qgd.uzh.ch/projects/pixelens/

[81] Merritt & Valluri 2005, ApJ 602, 66

[82] Magorrian, 2006, MNRAS 373, 425

V.F Examples of the Use of Widely Distributed CPU

Examples of projects that are based on BOINC include Climateprediction.net[83], Einstein@home[84], Folding@home[85] and SETI@home[86], which started it all.

However, the procedure is at present quite complex. Since the number of executables that a BOINC project server can provide is limited, the operating system of a participating computer must be on a short list of systems (currently thirteen, but that includes several essentially extinct systems). More crucially, the volunteer's machine is not protected from the project's code, which must be trusted by the volunteer. To gain such trust the project must have its code certified bug-free in the same way that a pharmaceutical company has a drug approved. Thus the BOINC model is not suited to the dynamic scientific computing environment in which a code is modified and recompiled after one or a few runs.

Java, which runs on every PC and most mobile phones, provides an elegant solution to these problems: a Java applet can be written that will run a program compiled for any given processor, such as an x86 (JPC[87]). An applet prevents the executable from doing anything illegal, upon which fact we daily rely as we use our browsers. Thus once a population of machines is running the applet, a researcher can compile experimental code to a legacy executable type such as x86, and send it straight out to N machines, with whatever CPUs, and wait for the results to come straight back to his PC. With this technology, volunteers don't need to trust the incoming software, and projects don't need a dedicated server. Nereus[88] is an implementation of the software that handles (encrypted) intermachine communications and accounting.

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[83] http://www.climateprediction.net

[84] http://einstein.phys.uwm.edu/

[85] http://folding.stanford.edu/

[86] http://setiathome.berkeley.edu/

[87] http://www-JPC.physics.ox.ac.uk

[88] http://www-nereus.physics.ox.ac.uk/

V.G Estimates of Manpower and Computing Power

Orders of magnitude can be estimated for the current status by two different ways. From the present number of astronomers, estimate the fraction involved in theory and computing; or from the total researchers involved in computing, estimate that 10 or 15% depending on the countries are involved in astrophysics.

Manpower

The number of IAU members worldwide[89] is about 10 000. About half of these are from Europe. Assuming all astro-related scientists in permanent jobs are IAU members, and assuming that each permanently employed scientist on the average engages at least one junior scientist (PhD student or post-doc) who is *not* a member of the IAU, one arrives at *a conservative estimate of the number of people engaged in astro-related science in Europe as 10 000* (not counting support personnel and technical staff).

Ideally, about half of these are/should be doing mostly theoretical work, and a fair (and growing) fraction of these should in turn be using substantial computational resources in their work. In addition, a fair and growing fraction of the observationally inclined researchers are, or will soon be, relying on archival (VO/GRID) facilities for their work.

As a (still conservative) estimate, one would then conclude that *of the order of 5000 scientists are engaged in theoretical and/or astro-related computational and/or archival work in the European arena.* Depending on to what extent one includes space science, these numbers could potentially be substantially larger. A smaller number, of the order of 10–20% of these (so of the order of at least 500–1000 scientists in Europe) are doing computationally intensive astro-related work.

From another point of view, about 10 000 people are involved in high performance computing across Europe, according to the users of the main national supercomputers. From the estimated 10% share of astrophysics, this point of view would also converge to *1000 people involved in computationally intensive astro-related work in Europe.*

Computing Power

Combining this estimate with the estimates from the discussion of supercomputing resources, one would conclude that these 5000 scientists are sharing of the order of 10% of 3 Mflops times 400M inhabitants, which leads to *an estimated average resource per scientist of about 25 Gflops.*

Another estimate can be obtained by estimating the typical resources available to the (much smaller number of) astro-scientists that have supercomputing as their main activity. Typical large grants at US and European supercomputing facilities are probably of the order of a few million CPU hours/yr per scientist, which is roughly equivalent to having 24/7 access to 100 CPUs. Current theoretical peak CPU performance is of the order of 10 Gflops (see Figure 34), but actual performance is in many cases at most 10% of that, so about 1 Gflop per CPU.

Both estimates seem at least to some degree consistent: A small fraction of astro-scientists may be using up to *several hundreds of Gflops on the average*, while the theoretical community as a whole in Europe may have access to of the order of *a few tens of Gflops on the average.*

The ratio of these two estimates is consistent with the estimates above of the fraction of scientists involved in computationally intensive astro-related work.

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[89] http://www.iau.org/administration/membership/individual/distribution/

V.H Costs and Budget for the Coming Years (National and Global)

In the discussion below astro-related computing — computational astrophysics as well as VO-related services and archiving — are considered as *an integral part of scientific computing in general.* This is the situation in most countries in the world, and moreover, certainly the most optimal way of allocating resources to astro-related computing.

All kinds of resources associated with scientific computing and archival — CPU power, networking, and disk and archival storage capacity — are subject to (different) variants of Moore's law: exponential growth with very short timescales[90]. This implies very short write-off times for equipment, and very substantial reinvestment fractions per year[91].

Estimated Levels of Costs for Scientific Computing in Europe

Below is an estimate of the order of magnitude of the cost and resources that are available now, and are likely to be available in the future.

A simple overview of resources per capita in the European countries can be obtained from an initiative and periodic report that is attempting to maintain a comprehensive comparison between the European countries. The report in question is *Academic Supercomputing in Europe* (ARCADE-EU) initiated by the NCF, comparing academic scientific computing resources in a number of European countries. The comparison is available online[92], up to 2005.

Some of the most informative figures from the current report are included in Figure 34. They show a comparison of the supercomputing resources per capita (the number of kflops per inhabitant) and a measure of the level of supercomputing investments (the number of kflops per euro GDP). More importantly, however, these figures (and the additional figures available online) provide an excellent order of magnitude estimate of the level of investments in academic supercomputing in Europe. Apparently these were recently of the order of 3 Mflops per inhabitant, and of the order of 100 flops per euro GDP (in the 2003 report the numbers were ~ 1.2 Mflops and ~ 50 flops per euro GDP).

A conservative overall conclusion would be obtained by counting an investment level of €0.5 per inhabitant, but only for the ~ 400 million people living in the five largest European countries, the Nordic and Benelux countries, we arrive at *an estimated European investment level in academic supercomputing of the order of €200M/yr.*

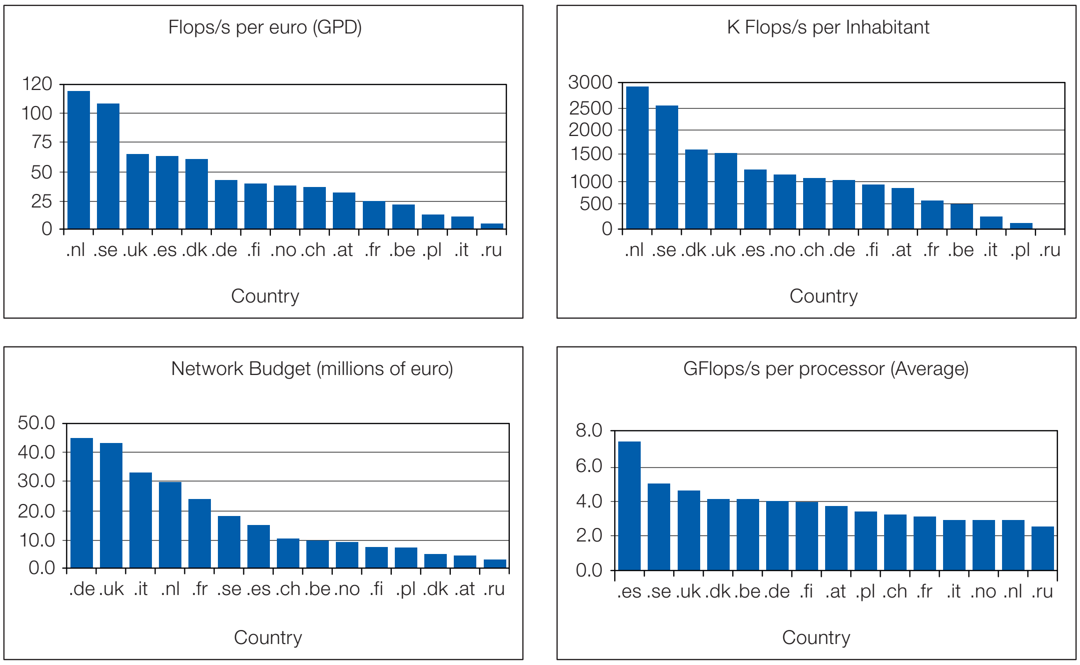

Image Credit: ARCADE-EU

Figure 34: A comparison between the fifteen European countries that are leading in the field of academic supercomputing using the ARCADE (Academic Research Computing Advanced facilities Discussion group Europe) for 2005 (last year of statistics). Top Left: Installed computing power per euro of GDP (Gross Domestic Product). Top Right: Installed computing power per inhabitant. Bottom Left: Average power per processor, in Gflops. Bottom Right: Network budget in M€.

This estimate is supported by the ESFRI conclusions and recommendations:
Due to rapid evolution, the commercially available hardware for HPC has a short lifecycle: therefore large investments need to be carefully planned. The high-end resources should be implemented every 2–3 yrs, with supporting actions in the national/regional centres to maintain the transfer of knowledge and feed projects to the top-tier level.

Cost of high-end infrastructure. Several installations, (where an installation can consist of two different architectures, placed in different locations) €100–200M every 2–3 years, starting 2008–2009; medium level infrastructure €50–100M every two years, starting 2007–2008. *The estimated cost includes several medium-size installations (5–10).*

Maintenance/upgrade cost (€50–100M/yr) total for both top levels. In addition funding for supporting projects like software development and optimisation and training should be conducted in order to obtain the maximum impact and efficiency from the HPC resources. *Estimated need is €30–50M/yr.*

Year	*Peak Performance (Tflops)*	*Disk Storage Capacity (PB)*
2005	400	
2008	3200	250
2010	12 800	1000
2015	409 600	32 000

Table 5: Europe's estimated requirements for HPC resources over the next ten years[93].

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[90] Values often mentioned are factors of two at constant cost in of the order of 18 months for CPU power, 12 months for disk storage, and 9 months for network components.

[91] Any constant reinvestment plan will maintain exponential growth, but maintaining an up-to-date technology level requires that the fraction of the total values reinvested each year is high.

[92] http://www.arcade-eu.info/academicsupercomputing/comparison.html

[93] Source: ESFRI, e-IRG http://www.e-irg.org

Appendix VI Appendices Relevant to Education, Recruitment and Training, Public Outreach (Panel E)

VI. A Task Group Membership

To most efficiently achieve its aims, the full Panel divided into task groups (TG) which focussed on data gathering and assessment in the areas of (i) university education and recruitment; (ii) primary and secondary school education; (iii) science museums and planetaria; (iv) public communication and outreach and on (v) relationships with industry.

Each of the task groups made personal contacts and performed (mostly) web-based searches for existing relevant material and opinions with particular emphasis being placed on well-justified and quantitative data to support conclusions. In addition to existing material, the groups made selective distributions of questionnaires to follow up and expand on certain points. The texts of these questionnaires are given in Sections VI.B to VI.F below. Many documents were consulted during this process and a selection of them is quoted in Chapter 7. Where appropriate, individual experts were contacted for further information.

The report is structured around the five TG subject areas. Within each section, we discuss the identification of problems, the findings based on an analysis of the problems and, finally, the principal recommendations resulting from this process.

The recommendations presented in the body of the report are the result of a global down-select from some seventy or so draft recommendations made by the individual TG. This selection process has necessarily been brutal but we have attempted to identify those tasks that are both important for the long-term health of astronomy (and science in general!) in Europe and are of such a nature that there is a clear possibility of successful action being taken. Where substantial, pertinent initiatives have already been taken or are currently underway, we have attempted to identify them and comment if appropriate.

Task Group Membership

1. University education and recruitment: Fosbury, del Toro, **Newsam**
2. Primary and secondary school education: Ros, Fucili, **Pickwick**, Radeva
3. Science museums and planetaria: **Hill**, Radeva, Ros
4. Public communication and outreach: **Christensen**, Lorenzen, Madsen
5. Relationships with industry: **Hill**

VI. B University Education and Recruitment

In order to assess the effectiveness of using astronomy courses to attract students to take university degrees in science subjects, the following questionnaire was sent to a number of universities in the Netherlands, Germany and UK, selected as having recently made changes in science degree courses.

Questionnaire

1. To what extent was the decision to develop the Astronomy Group at your institution influenced by hopes of increased undergraduate recruitment?

2. In your opinion, was there any effect on recruitment from the change?

3. Do you have any facts or figures to support your opinion?

4. Do you have any other comments that you would like to make concerning the effect of Astronomy and Space on the numbers of undergraduate students studying physics-related subjects?

5. Are you happy for your name to be quoted in any report, or would you prefer your answers to be treated anonymously?

Survey results

In recent years a number of universities have attempted to halt a decline in recruitment onto physics degrees by starting or significantly expanding their astronomy groups or departments. In a small survey, Panel E have contacted departments in the UK, Germany and the Netherlands where there has been such a change in recent years in order to assess the effect.

So far in most cases (5/6), potential for recruitment was a motivating factor in the change in group size and in all cases there has either been an increase or (at least) a halt in the decline of recruitment (in one case the improvement in student numbers was described as "spectacular"). Obviously, it is impossible to demonstrate a direct causal connection between these factors, but against an overall drop in physics recruitment it is certainly encouraging. Respondents also supported the view that the inclusion of astronomy in a degree programme attracted students into normal physics programmes as well.

University Contacted	*Recent Change (reason for contacting)*
University of Bonn, Germany	Significant expansion of astronomy department in recent years
University of Liverpool, UK	Started collaboration with Liverpool John Moores University to offer a suite of astronomy-related degrees
University of Nottingham, UK	Started a large astronomy group from scratch
Radboud University Nijmegen, Netherlands	Reinstated their astronomy group about five years ago
University of Southampton, UK	Name of department changed from "Physics" to "Physics and Astronomy"
University of Warwick, UK	Started and then significantly expanded their Astronomy Group in the past decade

Table 6: List of Physics departments that have recently made a significant change that increases their level of astronomical research and/or teaching.

Summary of responses

To what extent was the decision to develop the Astronomy Group at your institution influenced by hopes of increased undergraduate recruitment?

Strongly/Entirely:	2/6
Partially:	3/6
Not at all:	1/6

In your opinion, was there any effect on recruitment from the change? (Support with figures if possible)

Yes: (Strong effect, >50%)	2/6
Yes: (Small effect, 10–50%)	3/6
No: (No effect)	0/6
Unable to say:	1/6

*VI.*C Primary and Secondary School Education

In order to collect information about astronomy education in Europe the following questionnaire was distributed in the 1st ESO–EAAE Summer School that took place in Garching in July 2007. There were 17 countries represented by their respective delegations.

Several countries information had been added after the summer school. In total 24 countries were represented through 60 teachers.

Questionnaire

1. Are astronomical concepts present in curricula (primary and secondary schools) in different disciplines?

2. Within which disciplines are astronomy concepts taught?

3. Is astronomy an independent discipline?

4. At what age do students start being taught astronomy?

5. How often are astronomical concepts taught?

6. How do teachers get their training in astronomy?

Responses follow in Table 7 below.

Country	*Are astronomy concepts present in school curricula?*	*Within which disciplines are astronomy concepts taught?*	*Is astronomy an independent discipline?*	*At what age do students start being taught astronomy?*	*How often are astronomical concepts taught?*	*How do teachers get their training in astronomy?*
Belgium	Yes	Chemistry, maths, physics and geography	No	9–11 years old	2 years, some lessons (end of primary school and end of secondary school)	Not from Ministry of Education. Only some courses in planetaria.
Bulgaria	Yes	General science (human and natural), physics, geography, astronomy clubs in schools	Not since 2001 Yes, but only in an optional course for 18-year- old students	10–11 years old	4 years, some lessons	Courses in national and regional Pedagogical Centres, courses in public astronomical observatories and planetaria. Conferences.
Cyprus	Yes	Geography, physics and astronomy	Yes, but only in an optional course for 16-year-olds	11 years old	1 year in primary school A few lessons in secondary school 1 year secondary school (optional)	Workshops Lectures
Denmark	Yes	Physics, nature and technology, chemistry	Yes, 1 optional course 10–12 years old	Primary school, typically in years 3 and 4	Astronomy is central in physics in secondary school	Astronomy is part of the teacher training programme.
Finland	Yes	Physics, environmental sciences, geography	Yes, 1 optional course for 16 year olds and in astronomy clubs	8 years old	Some lessons over 10 years.	Special courses for in-service teachers Optional courses and lessons
France	Yes	Geology and physics Earth science	No	6 years old	1–2 hours from 6–10 years old. 3 weeks/yr for 16–18 years old	Amateur associations, Teaching associations, planetaria, observatories
Germany	Yes	Physics, nature and technology	Yes (in last year of secondary school, astronomy is part of the final examination in physics)	11 years old	Some lessons for three years.	Special courses for teachers in some areas of the country.
Greece	Yes	Geography, physics and astronomy	Yes, but only in an optional course for 16 year old students	9 years old	A few lessons in primary school Ten lessons age 12–15 1 optional course at 16 years old	No teacher education. Only some lectures.

Hungary	Yes	Physics, geography	No	13 years old	13 year-old students (10 weeks) 18 year-old students (12 weeks)	1 semester at university for physics and geography teachers
Italy	Yes	Earth science and physics	No	6 years old, not always	At most 3 months in 3 years	Course for beginners and amateur associations
Latvia	Yes	Physics, general sciences, geography	Yes, optional course for 17–18 year olds	8–9 years old	In total 48 hours over 11 years	Not much in university education. Teacher Training courses. Local observatories, Teacher conferences
Lithuania	Yes	Earth science, physics	No	11–12 and 16–18 years old	2 years, some lessons (primary school) 3 years, 10% in physics lessons (secondary school)	Pedagogical university and Physics Departments
Luxemburg	Yes	Natural sciences, geography, physics	No	10 years old	10–13 years: occasionally 17–18 years: some lessons	No special teacher training, conferences and lectures
Malta	Yes	In primary part of science (optional); in secondary physics (predominantly) compulsory	No	13–15 years old	3 years some lessons. From age 13–15	Initiative taken by local groups of teachers and sometimes involving astronomy clubs.
Netherlands	Yes	General sciences, physics	Yes for some students at pre-university course (compulsory)			Training in conferences, workshops but not in teacher education
Poland	No	Science, geography, physics	No (but full name of subject in secondary school is physics and astronomy)	7 years old	11 years, some lessons	Workshops, lectures, observation centres, conferences, cooperation with universities and planetaria
Portugal	Yes	Physics, chemistry, geography and biology Astronomy clubs	No	8 years old	8 years, only some lessons	During pedagogical and didactical training.
Romania	Yes	Physics, geography and mathematics. Extra-curricular activities in some schools	Not since 1997 There is an optional subject in some schools.	11 years old	5 hours/yr for 7 years	Summer schools

Slovenia	Yes	General sciences (human and nature), physics; geography, astronomy clubs and optional courses in primary and secondary schools	Yes, 1 year optional course for 13–15 years and in astronomy clubs	6 years old	6 years of some lessons per year (primary school) 3 years 10% in physics and geography lessons	University for pedagogic, physics and geography teachers, Astronomy association, Observatories
Spain	Yes	Physics, geography, Earth science, design, technology, geology, maths	No In some regions astronomy is an optional subject for students at 16 years old	6 years old, but there are resources available for 3–4 years old	12 years as some isolated lessons	Lectures, workshops, courses in training teacher centres
Sweden	Yes	Physics and geography	No (except in a very few schools)	Around 9 years old	Some lessons for a few years	A short course for future natural science and physics teachers. Special courses arranged by universities.
Switzerland	Yes	Geography, physics and mathematics	No	10–11 years old in geography	Few lessons in primary and secondary school	Through workshops, lectures and special courses for teachers
Turkey	Yes	Astronomy, physics and general science	Yes as optional subject at 16 year old, only 2 hrs per week	8 years old	8 hours per a year during school life	University for teachers of physics
UK	Yes	Science and physics (predominantly) School clubs not commonplace	No Yes, only in an optional course for 16 years old students but not common in schools	7 years old	2 years some lessons. 1 year in an optional course	Conferences, astronomy associations, universities, planetaria, local observatories (not often).

Table 7: Information collected from 24 countries, July 2007–July 2008.

VI. D Science Museums and Planetaria

The following questionnaire was sent to planetaria in the European Union member states. It has been passed on to the International Planetarium Society, British Association of Planetaria representatives and to all European Hands-On Universe members to pass on in their region. Some of the questions do not apply to all planetaria/science centres/museums, but this was a first step at seeing the big picture that is happening worldwide and the crucial contribution that is being made to communicating astronomy with the public. All facilities that replied are included below.

Questionnaire

- Name of facility/organisation:
- Does your organisation operate portable planetaria? How many?
- Web address/es:
- Principal PIO contact name/email:
- Total spend per annum:
- Major source of funding. Government/ non-government, charity etc..

- Number of ‘permanent’ staff employed:
- Number of part-time helpers:
- Number of visitors per year:
- Do you have a formal programme of astronomy education?
- What are the astronomy themes or topics? What are the most popular?
- What is your target age group?
- What are the most urgent problems to address to improve the public communication of astronomy in your area?
- Does your organisation produce its own resources? Eg Presentations, other educational material etc.
- What is the most common source of material that you utilize?
- Do you have a formal relationship with any of the space agencies or related partners?
- How often do you use this relationship? Please specify.
- If a central repository for outreach materials, e.g. a picture library, existed, would you use it?
- Do you work closely with professional astronomers who are responsible for the scientific content of your work?
- Do you work with local amateur astronomical associations? Please specify nature of collaboration

A summary of responses and an analysis of them are given in Table 8 below.

Science Centres	*Astronomy programmes*	*Own resources*	*Agency Contact*	*Use of Repository*	*Professional Contact*	*Amateur Contact*
More than 30 000 visitors Total 12	Yes: 7 No: 5	Yes: 12 No: 0	Yes: 7 No: 5	Yes: 8 No: 3 No reply: 1	Yes: 10 No: 2	Yes: 10 No: 2
Between 30 000 and 10 000 visitors Total 12	Yes: 7 No: 5	Yes: 10 No: 2	Yes: 3 No: 8 No reply: 1	Yes: 8 No: 1 May be: 1 No reply: 2	Yes: 7 No: 5	Yes: 8 No: 2 No reply: 2
Less than 10 000 visitors Total 10	Yes: 4 No: 6	Yes: 7 No: 2 No reply:1	Yes: 2 No: 8	Yes: 5 No:1 May be: 3 No reply: 1	Yes: 6 No: 4	Yes: 9 No: No reply: 1

Table 8: Summary of questionnaire responses from 34 science centres in 16 European countries (Belgium, Bulgaria, Czech Republic, Denmark, France, Germany, Ireland, Lithuania, Netherlands, Norway, Poland, Portugal, Rumania, Sweden, Spain, and UK). In this Table Agencies means ESA, ESO and other institutions like the International Planetaria Society, Observatories or NASA.

VI. E Public Communication and Outreach

The following questionnaire was distributed to a list of 43 public communication and outreach sites in 15 European countries (Belgium, Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, Netherlands, Norway, Poland, Spain, Sweden, Switzerland and the UK).

Questionnaire

- Name of Observatory/facility/organisation:
- Outreach web address:
- Principal PIO contact name/email:

- What do you feel has worked well in the outreach that you do:

- What are the most urgent problems to address to improve the public communication of astronomy in your area?

- What are the most urgent problems to address to improve the public communication of astronomy in Europe in general?

- What is your impression of the “European communication culture” (as opposed to that elsewhere, for instance the US)?

- If a central repository for outreach materials, e.g. a picture library, existed, would you use it?

- Who are the (other) major EPO players in your county, i.e. organisations communicating astronomy with the public?

- What astronomy topics are in your opinion most interesting to the public? For instance what are the most asked questions?

- Do you work closely with scientists who are responsible for the scientific content of your work?

- What could be done to create more collaboration between the astronomy communicators in Europe and elsewhere?

- How do you measure your success?

- Any ideas about how to get the younger generation interested in science?

- How could the science communicators be trained better?

- Any other points you wish to make................

The major players in European astronomy EPO are national observatories and laboratories, planetaria and science centres, funding organisations as well as intergovernmental EPO offices.

VI. F Relationships with Industry

This set of **Key Questions** was addressed to selected individuals in ten European countries (France, Greece, Ireland, Italy, Poland, Portugal, Spain, Sweden, the UK) and two international organisations (ESA and Eurisy).

1. Are there data available nationally on the transfer of astronomy (not space) into industry either through an agency or an industrial contract model/policy? Please supply source of evidence, eg. website or policy document;

2. Can the impact be assessed?

3. Is there information available on profits gained from astronomy Tech Transfer vs. Space sector Transfer?

4. Are the data and knowledge easily accessible? If not, please state why;

5. Are you aware of any kinds of collaborations or cross-pollinations between science, science communication/education and commercial entities? Please state, with website and source(s);

6. Would a central EU site of results and transfers be helpful in assisting future Tech Transfer and knowledge transfer in Astronomy across regions? If so, how would you envisage this?

Summary of responses to questions

From the initial responses, it appears that the answers vary from country to country. Regionally, individual authorities or government agencies may host some data on individual projects and the industrial transfer to non-astronomy sectors. Also, individual groups or companies highlight how their own R&D has been successfully transferred outward and some websites and examples are given in the individual responses. However, it does not appear that many countries have a mechanism within their astronomical community to identify industrial relevance/transfer to other actors or communities as an integral component of their R&D. Or, it may be that individual companies, research groups, other actors, do not display or promote any results of this kind in their main scientific literature or websites. Further, due to copyright or possible intellectual property issues many actors may not publicise their work due to restrictions. As a result, even after successful transfer to other sectors, a follow up public access programme to successful transfer may be overlooked.

On the questions of the impact and successful commercial transfer on a regional or EC-wide level, there is strong evidence — even from the extremely limited sample so far — that there is no central bank or repository easily found or accessible to promote this culture. However, it is encouraging that regionally the UK Astronomy Technology Centre[95] states in its principles: “The

UK ATC should facilitate technology development in industry and universities to meet the needs of the current and future astronomy programme, and promote its exploitation in other research sectors and industry." Also, ESO highlights and promotes technology transfer[96] on a European level. However, it is unclear if the promotion of the methodology or way of thinking has filtered down culturally to all actors involved in each region.

The question "Are you aware of any kinds of collaborations or cross-pollinations between science, science communication/education and commercial entities?" will require an EU-wide effort to collate every example of linkage from science to the wider society. There are many projects (too numerous to mention in this document) and examples in each region involving working separately or with their European counterparts were transfer of all kinds is taking place. Regionally, science centres and planetaria work with educational authorities to increase pupil uptake of STEM (Science, Technology, Engineering and Mathematics) activities and assist teachers in locating partners across Europe at peer level or research mentoring level. (e.g., the Faulkes Telescope Project, European Hands-On Universe). Also, as a means of support, science centres increasingly turn to non-astronomy and space business and industrials to support their activities. It may be that this creative network of science communicators and networks could act as liaison for their research counterparts as an introduction to the wider market?

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[95] http://www.roe.ac.uk/ukatc/principles.html

[96] http://www.eso.org/org/tec/TechTrans/

List of Abbreviations

2MASS: 2 Micron All Sky Survey
http://www.ipac.caltech.edu/2mass/

AAO: Anglo-Australian Observatory
http://www.aao.gov.au/

AAT: Anglo-Australian Telescope (AAO)
http://www.aao.gov.au/

ACS: Advanced Camera for Surveys (HST)
http://www.stsci.edu/instruments/acs/

AGILE: Astro-rivelatore Gamma a Immagini Leggero (Italian gamma-ray satellite)
http://agile.rm.iasf.cnr.it/

AGN: Active Galactic Nucleus

AIDA: Astronomical Infrastructure for Data Access
http://cds.u-strasbg.fr/twikiAIDA/bin/view/EuroVOAIDA/WebHome

AKARI: Japanese all-sky infrared survey satellite (Previously known as ASTRO-F or IRIS - InfraRed Imaging Surveyor)
http://www.ir.isas.jaxa.jp/ASTRO-F/

ALFA: Amérique Latine Formation Académique (EC)
http://ec.europa.eu/europeaid/where/latin-america/regional-cooperation/alfa/index_en.htm

ALICE: A Large Ion Collider Experiment (LHC)
http://aliceinfo.cern.ch/

ALMA: Atacama Large Millimeter/submillimeter Array
http://www.eso.org/projects/alma

AMANDA: Antarctic Muon And Neutrino Detector Array
http://amanda.uci.edu/

ANTARES: Astronomy with a Neutrino Telescope and Abyss environmental RESearch
http://antares.in2p3.fr/

AO: Announcement of Opportunity

AOCS: Attitude and Orbit Control System

APERTIF: APERture Tile In Focus (WSRT)
http://www.astron.nl/~devoscm/rd-wiki/doku.php?id=report_projects_2008#apertif

APEX: Atacama Pathfinder EXperiment.
http://www.mpifr-bonn.mpg.de/div/mm/apex.html

API: Application Programming Interface

ARCADE-EU: Academic Research Computing Advanced facilities Discussion group Europe
http://www.arcade-eu.org/

ARENA: Antarctic Research, a European Network for Astrophysics
http://arena.unice.fr/

AS OV: Action Spécifique Observatoires Virtuel
http://www.france-ov.org

ASCA: Advanced Satellite for Cosmology and Astrophysics (formerly known as Astro-D)
http://heasarc.gsfc.nasa.gov/docs/asca/asca2.html

ASH: Anelastic Spherical Harmonic (computer code)
http://irfu.cea.fr/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=1256

ASI: Agenzia Spaziale Italiana
http://www.asi.it/SiteEN/Default.aspx

ASKAP: Australian Square Kilometre Array Pathfinder
http://www.atnf.csiro.au/projects/askap/

ASL: Astrophysical Software Laboratory

ASM: all-sky monitoring

ASMCS: Astrophysics Strategic Mission Concept Studies
http://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId={13E6324F-F3B8-1D7F-835C-7A2D28B720E1}&path=open

ASPERA: AStroparticle ERAnet
http://www.aspera-eu.org

ASTEC: Aarhus Stellar Evolution Code

Aster: Supercomputer at SARA
http://www.sara.nl/userinfo/aster/index.html

ASTRID: Project to develop and exploit astronomical instrumentation for large international facilities (Spain)
http://www.astrid-cm.org/

AstroGrid: UK Virtual Observatory project funded by STFC and EU FP6.
http://www.astrogrid.org/

ASTRONET: ERA-NET project to establish a long-term planning process for the development of European astronomy.
http://www-astronet-eu.org

ASTRON: Netherlands Institute for Radio Astronomy
http://www.astron.nl/

AstroSim: Astrophysics Simulations (European Network for Computational Astrophysics)
http://www.astrosim.net/

Astro-WISE: Astronomical Wide-field Imaging System for Europe
http://www.astro-wise.org/

ATLAS: A Toroidal LHC ApparatuS (LHC)
http://atlas.ch/

ATST: Advanced Technology Solar Telescope
http://atst.nso.edu/

Aurora: European Space Exploration Programme (ESA)
http://www.esa.int/esaMI/Aurora/index.html

AU: Astronomical Unit, the Earth–Sun distance

AVO: Astrophysical Virtual Observatory (now part of EURO-VO)
http://www.euro-vo.org/avo/

BAT: Burst Alert Telescope (SWIFT)
http://swift.gsfc.nasa.gov/docs/swift/about_swift/bat_desc.html

BATSE: Burst And Transient Source Experiment (Compton Gamma-Ray Observatory)
http://gammaray.msfc.nasa.gov/batse/

BEPAC: Beyond Einstein Program Assessment Committee (NASA)
http://beyondeinstein.nasa.gov/

BepiColombo: An ESA mission in cooperation with Japan that will explore Mercury.
http://sci.esa.int/home/bepicolombo/

BeppoSAX: Italian-Dutch X-ray satellite
http://www.asdc.asi.it/bepposax/

BMBF: BundesMinisterium für Bildung und Forschung
http://www.bmbf.de/

BOINC: Berkeley Open Infrastructure for Network Computing
http://boinc.berkeley.edu/

BSC-CNS: Barcelona Supercomputing Center—Centro Nacional de Supercomputación
http://www.bsc.es/

CAP: Communicating Astronomy with the Public.
http://www.capjournal.org

Cassini-Huygens: NASA-ESA-ASI mission to explore Saturn and its moons.
http://sci.esa.int/cassini

CA*net 4: Canada's Advanced optical Internet research and education Network, also called CANARIE Network
http://www.canarie.ca/canet4/

CCAT: Cornell Caltech Atacama Telescope
http://www.submm.caltech.edu/~sradford/ccat/

CCD: Charge Coupled Device

CDF: Chandra Deep Field (-S) South / (-N) North
http://chandra.harvard.edu/press/01_releases/press_031301.html

CDS: Centre de Données astronomiques de Strasbourg
http://cdsweb.u-strasbg.fr/

CEA: Commissariat à l'Énergie Atomique (CEA)
http://www.cea.fr

CERN: European Organization for Nuclear Research
http://www.cern.ch

CESAM: Code d'Évolution Stellaire Adaptatif et Modulaire (Computer code)
http://www.oca.eu/cesam/

CFHT: Canada France Hawaii Telescope
http://www.cfht.hawaii.edu/

Chandra: NASA's imaging X-ray space observatory Chandra (formerly known as AXAF)
http://chandra.nasa.gov/

CINECA: Consorzio Interuniversitario del Nord est Italiano Per il Calcolo Automatico
http://www.cineca.it/en/index.htm

CLOUDY: Spectral simulation computer code
http://www.nublado.org/

Cluster: Four spacecraft to study the small-scale structure of the magnetosphere and its environment in three dimensions (ESA)
http://sci.esa.int/cluster/

CMB: Cosmic Microwave Background

CME: Coronal Mass Ejection

CMS: Compact Muon Solenoid (LHC)
http://cms.cern.ch/

CNES: Centre National d'Études Spatiales
http://www.cnes.fr/

CNR: Consiglio Nazionale delle Ricerche
http://www.cnr.it

CNRS: Centre National de Recherche Scientifique
http://www.cnrs.fr/

Compton Gamma Ray Observatory: Gamma ray satellite (NASA)
http://heasarc.gsfc.nasa.gov/docs/cgro/index.html

Constellation-X: NASA X-ray mission, now part of IXO
http://ixo.gsfc.nasa.gov/

CoRoT: Convection, Rotation and planetary Transits satellite (CNES led satellite)
http://smsc.cnes.fr/COROT/

Cosmic Vision: see CV
http://www.esa.int/esaSC/SEMA7J2IU7E_index_0.html

COSMOS: 1) HST Cosmic Evolution Survey
http://cosmos.astro.caltech.edu/
2) Advanced Scientific Repository for Science Teaching and Learning
http://www.ea.gr/ep/cosmos/

CPU: Central Processing Unit

Cross-Scale: Satellite Mission concept to study the nonlinear coupling of electron, ion and fluid scale processes (ESA Cosmic Vision)
http://www.cross-scale.org/

CSA: Canadian Space Agency
http://www.space.gc.ca/eng/default.asp

CTA: Cherenkov Telescope Array
http://www.mpi-hd.mpg.de/hfm/CTA/

CV: Cosmic Vision (ESA)
http://www.esa.int/esaSC/SEMA7J2IU7E_index_0.html

Darwin: Multi-spacecraft mission to detect Earth-like planets (ESA)
http://www.esa.int/science/darwin

DCA: Data Centre Alliance
http://www.euro-vo.org/pub/dca/overview.html

DCSC: Danish Centre for Scientific Computing
http://www.dcsc.dk/

DECI: DEISA Extreme Computing Initiative
http://www.deisa.eu/deisa1/applications/

DEISA: Distributed European Infrastructure for Supercomputing Applications
http://www.deisa.eu/

DEPFET: DEpleted P-channel Field Effect Transistor

DF: distribution function

DLR: Deutsche Zentrum für Luft- und Raumfahrt
http://www.dlr.de/

DOT: Dutch Open Telescope
http://dot.astro.uu.nl/

Double Star: A joint project between ESA and the China National Space Administration
http://sci.esa.int/science-e/www/area/index.cfm?fareaid=70

DPAC: Data Processing and Analysis Consortium (for Gaia)

DRACO: Datagrid for Research in Astrophysics and Coordination with the virtual Observatory
http://wwwas.oats.inaf.it/grid/index.php?option=com_content&task=view&id=14&Itemid=27

DUNE: The Dark UNiverse Explorer (now combined with SPACE in EUCLID)

EAAE: European Association for Astronomy Education
http://www.algonet.se/~sirius/eaae.htm

EAST: European Association for Solar Telescopes
http://www.astro-east.org/

E-ELT: The Extremely Large Telescope
http://www.eso.org/public/astronomy/projects/e-elt.html

Effelsberg: 100 m single dish radio telescope at Effelsberg, Germany
http://www.mpifr-bonn.mpg.de/english/radiotelescope/index.html

EGEE: Enabling Grids for E-sciencE
http://www.eu-egee.org/

EGRET: Energetic Gamma Ray Experiment Telescope
http://imagine.gsfc.nasa.gov/docs/features/bios/thompson/egret.html

Einstein Telescope: Gravitational wave detector
http://www.et-gw.eu/

e-IRG: e-Infrastructure Reflection Group
http://www.e-irg.eu/

EIROforum: Partnership of Europe's seven largest intergovernmental research organisations.
http://www.eiroforum.org/index.html

EIS: Extreme UV Imaging Spectrometer (Hinode)
http://msslxr.mssl.ucl.ac.uk:8080/SolarB/Solar-B.jsp

EISCAT: European Incoherent SCATter radar system
http://www.eiscat.se/

EISCAT_3D: Next generation European Incoherent SCATter radar system
https://e7.eiscat.se/groups/EISCAT_3D_info

EJSM: Europa Jupiter System Mission, new name for Laplace mission, under consideration jointly with NASA
http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=42291

E-LOFAR: Extended LOw Frequency ARray
http://www.lofar.org/

ELT: Extremely Large Telescope

e-MERLIN: upgrade of MERLIN
http://www.merlin.ac.uk/e-merlin/

EMIR: Espectrógrafo Multiobjeto Infrarrojo (GTC)
http://www.ucm.es/info/emir/

ERA-NET: European Research Area Network
http://cordis.europa.eu/coordination/era-net.htm

ESA: European Space Agency
http://www.esa.int/

ESERO: European Space Education Resource Offices
http://www.esa.int/esaED/SEMXH8V681F_index_0.html

ESF: European Science Foundation
http://www.esf.org/

ESFRI: European Strategy Forum on Research Infrastructures
http://cordis.europa.eu/esfri/

ESnet: Energy Science network
http://www.es.net/

ESRIN: ESA Centre for Earth Observation
www.esa.int/esaMI/ESRIN_SITE/index.html

ESO: European Southern Observatory
http://www.eso.org/

EST: European Solar Telescope
http://www.iac.es/proyecto/EST/

ET: Einstein Telescope, proposed future gravitational wave observatory
http://www.et-gw.eu/

EUCLID: ESA dark Energy Mission (combination of DUNE and SPACE)
http://sci.esa.int/euclid

EuroPlaNet: European Planetology Network
http://www.europlanet-eu.org/

EURO-VO: European Virtual Observatory
http://www.euro-vo.org/pub/

EVLA: Expanded VLA
http://www.aoc.nrao.edu/evla/

e-VLBI: electronically linked Very Long Baseline Interferometry
http://www.evlbi.org/

EVN: European VLBI Network
http://www.evlbi.org/

ExoMars: Mars exploration mission (ESA)
http://www.esa.int/esaMI/ExoMars/index.html

EZ : Stellar evolution code
http://theory.kitp.ucsb.edu/~paxton/EZ-intro.html

Fermi: Gamma-ray Space Telescope, formerly known as GLAST (NASA)
http://fermi.gsfc.nasa.gov/

FIRI: Far-Infrared Interferometer (ESA)
http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=40090

FLASH: Hydrodynamical code for thermonuclear flashes (computer code)
http://flash.uchicago.edu/website/home/

FP6, FP7: EU Framework Programmes for Research and Technological Development: FP6 — 2002–2006; FP7— 2006–
http://ec.europa.eu/research

FTE: Full Time Equivalent

GADGET: cosmological N-body/SPH simulation (computer code)
http://www.mpa-garching.mpg.de/gadget/

Gaia: Astrometric satellite (ESA)
http://astro.estec.esa.nl/GAIA/

GalaxyZoo: General public based galaxy classification programme
http://www.galaxyzoo.org/

Galileo: Spacecraft that studied Jupiter (NASA)
http://galileo.jpl.nasa.gov/

GAVO: German Astrophysical Virtual Observatory
http://www.g-vo.org/www/

GCS: Gauss Centre for Supercomputing
http://www.gauss-centre.eu/

GÉANT2: Gigabit European Academic Network 2
http://www.geant2.net/

Gemini: An international partnership comprised of two 8.1 m telescopes. One telescope is located on Hawaii's Mauna Kea, and the other on Chile's Cerro Pachón.
http://www.gemini.edu/

GEMS: Galaxy Evolution from Morphology and SEDs (Hubble survey)
http://www.mpia.de/GEMS/gems.htm

GENCI: Grand Equipement National de Calcul Intensif
http://www.genci.fr/

GEO600: German-British Gravitational Wave Detector
http://geo600.aei.mpg.de/

GEP: Geophysics and Environment Package, now alled Humboldt payload (ExoMars)
http://www.esa.int/SPECIALS/ExoMars/SEMSZIAMS7F_0.html

GINGA: Japanese X-ray astronomy mission (also known as ASTRO-C)
http://heasarc.gsfc.nasa.gov/docs/ginga/ginga.html

GLAST: Gamma-ray Large Area Space Telescope (now known as Fermi)
http://glast.gsfc.nasa.gov/

GMT: Giant Magellan Telescope
http://www.gmto.org/

GOODS: Great Observatories Origins Deep Survey (HST, Chandra and Spitzer)
http://www.stsci.edu/science/goods/

GRAVITY: Near-infrared VLTI instrument
http://www.mpe.mpg.de/ir/gravity/index.php

GRB(s): Gamma-ray Burst(s)

Great Observatories: Collective NASA name for the Compton Gamma Ray Observatory Hubble Space Telescope, Chandra and Spitzer

Gregor: 1.5 m solar telescope on Tenerife.
http://www.gtc.iac.es/home.html

Gstat: Global grid monitoring programme
http://goc.grid.sinica.edu.tw/gstat/

GTC: The Gran Telescopio CANARIAS
http://www.gtc.iac.es/pages/gtc.php

Hasabuya: Japanese asteroid exploration satellite
http://www.isas.ac.jp/e/enterp/missions/hayabusa/index.shtml

HDF: Hubble Deep Field
http://www.spacetelescope.org/science/deep_fields.html

HEC: High End Computing

HELEX: Heliophysical Explorers (Report)
http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=41396#

Herschel: Far-Infrared and Submillimetre Telescope, formerly called FIRST (ESA)
http://sci.esa.int/home/herschel/index.cfm

H.E.S.S.: High Energy Stereoscopic System
http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html

H.E.S.S.-2: Upgrade of H.E.S.S.
http://irfu.cea.fr/Phocea/Vie_des_labos/Ast/ast_technique.php?id_ast=2284

HET: HPC European Taskforce
http://www.hpcineuropetaskforce.eu/

Hinode: Japanese solar satellite, formerly known as Solar-B
http://solar-b.nao.ac.jp/index e.shtml

Hipparcos: Astrometric Satellite (ESA)
http://sci.esa.int/hipparcos

HPC: High Performance Computing

HST: The Hubble Space Telescope (NASA, ESA)
http://stsci.edu

HUDF: Hubble Ultra Deep Field
http://www.nasa.gov/vision/universe/starsgalaxies/hubble_UDF.html

Huygens: 1) see Cassini–Huygens (ESA lander)
2) Supercomputer at SARA
http://www.sara.nl/userinfo/huygens/index.html

IAU: International Astronomical Union
http://www.iau.org/

IceCube: Neutrino Detector at the Antarctic
http://icecube.wisc.edu/

IGM: InterGalactic Medium

ILIAS: Integrated Infrastructure Initiative (I3) in the field of astroparticle physics
http://www-ilias.cea.fr/

INAF: Istituo Nazionale di AstroFisica (National Institute for Astrophysics)
http://www.inaf.it/

INSU: Institut National des Sciences de l'Univers (National Institute for the Science of the Universe)
http://www.insu.cnrs.fr/

INT: Isaac Newton Telescope
http://www.ing.iac.es/Astronomy/telescopes/int/index.html

INTEGRAL: INTErnational Gamma-Ray Astrophysics Laboratory
http://sci.esa.int/integral

Internet2 Network: High performance backbone network, formerly Abilene
http://www.internet2.edu/network/

IR: Infra-Red

IRAIT: International Robotic Antarctic Infrared Telescope
http://astro.fisica.unipg.it/coloti/coloti.htm

IRAM: Institut de Radioastronomie Millimétrique
http://www.iram.fr/index.htm

IRAM-Pdb: Plateau de Bure mm-array interferometer
http://www.iram.fr/IRAMFR/index.htm

IRAM-PV: 30 m-diameter mm-wave telescope on Pico Veleta in Spain
https://www.iram.es/IRAMES/index.htm

ISAS: Institute of Space and Astronautical Science
http://www.isas.ac.jp/e/index.shtml

ISM: InterStellar Medium

ISO: Infrared Space Observatory (ESA)
http://www.iso.vilspa.esa.es/

ISP: Internet Service Provider

ITVO: Italian Theoretical Virtual Observatory
http://wwwas.oats.inaf.it/IA2/index.php?option=com_content&task=section&id=12&Itemid=71

IUE: International Ultraviolet Explorer
http://sci.esa.int/science-e/www/area/index.cfm?fareaid=22

IVOA: International Virtual Observatory Alliance
http://www.ivoa.net/

IXO: International X-ray Observatory (ESA, NASA)
http://sci.esa.int/science-e/www/area/index.cfm?fareaid=103

JAXA: Japanese Space Exploration Agency
http://www.jaxa.jp/index_e.html

JCMT: James Clark Maxwell Telescope
http://www.jach.hawaii.edu/JCMT/

JDEM: The Joint Dark Energy Mission (NASA)
http://universe.nasa.gov/program/probes/jdem.html

JEM-EUSO: Japanese Experiment Module for Extreme Universe Space Observatory
http://jemeuso.riken.jp/

JEM/ISS: Japanese Experiment Module for ISS
http://www.jaxa.jp/projects/iss_human/index_e.html

JIVE: Joint Institute for VLBI in Europe
http://www.jive.nl/

JRA: Joint Research Activities
JUNO: Spacecraft for a Jupiter mission (NASA)
http://juno.wisc.edu/
JWST: James Webb Space Telescope
http://sci.esa.int/jwst/
Kepler: Space mission to detect exoplanets by partial obscuration of their host star (NASA)
http://kepler.nasa.gov
KM3NeT: km^3 neutrino detector
http://www.km3net.org/
KMOS: K-band Multi-object Spectrometer (VLT)
http://www.roe.ac.uk/ukatc/projects/kmos/index.html
Kuiper Belt: Region of the Solar System extending from the orbit of Neptune (at 30 AU) to approximately 55 AU from the Sun, consisting mainly of small bodies.
LABOCA: Large Apex BOlometer CAmera
http://www.apex-telescope.org/bolometer/laboca/
LAPLACE: Space mission to Europa and the Jupiter system (ESA)
http://sci.esa.int/laplace
LBC: Large Binocular Cameras (LBT)
http://lbc.mporzio.astro.it/
LBT: Large Binocular Telescope
http://medusa.as.arizona.edu/lbto/
LENAC: Latin-American European Network for Astrophysics and Cosmology
http://www.lenac.dur.ac.uk/
LEST: Large Earth-based Solar Telescope (telescope class)
LHC: Large Hadron Collider
http://lhc.web.cern.ch/lhc/
LHCb: Large Hadron Collider beauty experiment (LHC)
http://lhcb.web.cern.ch/lhcb/
LIGO: Laser Interferometer Gravitational-Wave Observatory
http://www.ligo.caltech.edu/
LISA: Laser Interferometer Space Antenna (ESA/NASA)
http://sci.esa.int/lisa/
LOFAR: Low Frequency ARray
http://www.lofar.org/
LORENE: Langage Objet pour la RElativité NumériquE (Object Language for Numerical Relativity)
http://www.lorene.obspm.fr/
LSST: Large Synoptic Survey Telescope
http://www.lsst.org/lsst home.shtml
MAGIC: Major Atmospheric Gamma Imaging Cherenkov telescope
http://www.mppmu.mpg.de/
Marco Polo: A joint European-Japanese sample return mission to a near-Earth object
http://sci.esa.int/marcopolo
Mars Exploration Rovers: Robots that study the surface of Mars (*Spirit* and *Opportunity*, NASA)
http://marsrovers.jpl.nasa.gov/
Mars Express: Mars orbiter (ESA)
http://www.esa.int/esaMI/Mars_Express/
MATISSE: Multi-AperTure mid-Infrared SpectroScopic Experiment (VLTI)
http://www.oca.eu/matisse/
MeerKAT: Karoo Array Telescope
http://www.kat.ac.za/
MEGACAM: 1 degree x 1 degree wide-field imaging camera (CFHT)
http://www.cfht.hawaii.edu/Instruments/Imaging/MegaPrime/
MERLIN: Multi-Element Radio Linked Interferometer Network
http://www.merlin.ac.uk/
MHD: Magnetohydrodynamics
MICINN: Ministerion de Ciencia e Innovación (Ministry of Science and Innovation, Spain)
http://web.micinn.es/
MODEST: MOdeling DEnse STellar systems (computer code)
http://www.manybody.org/modest/
MPA: Max-Planck-Institut für Astrophysik
http://www.mpa-garching.mpg.de/
MPG: Max Planck Gesellschaft
http://www.mpg.de/
MPIfR: Max-Planck-Institut für Radioastronomie
http://www.mpifr-bonn.mpg.de/
MSSL: Mullard Space Science Laboratory
http://www.mssl.ucl.ac.uk/
MUSE: Multi Unit Spectroscopic Explorer (VLT)
http://muse.univ-lyon1.fr/
NASA: National Aeronautics and Space Administration
http://www.nasa.gov/home/index.html
NBODY: Many-body gravitational interactions simulations (computer code)
http://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm
NCF: Nationale Computer Faciliteiten (National Computing Facilities, NWO)
http://www.nwo.nl/nwohome.nsf/pages/ACPP_4X6R5C
NEMO: Stellar Dynamics Toolbox (software environment)
http://bima.astro.umd.edu/nemo/
NEO: Near-Earth Object
NeXT: New exploration X-ray Telescope
http://www.astro.isas.ac.jp/future/NeXT/
NIKHEF: The National Institute for Nuclear Physics and High Energy Physics (NL)
http://www.nikhef.nl/
NOAO: National Optical Astronomical Observatory (US)
http://www.noao.edu/
NOT: Nordic Optical Telescope
http://www.not.iac.es/
NOTSA: Nordic Optical Telescope Scientific Association
http://www.not.iac.es/general/notsa/
NOVA: Nederlandse Onderzoekschool voor de Astronomie (Netherlands Research School for Astronomy)
http://www.astronomie.nl/
NRAO: National Radio Astronomy Observatory (US)
http://www.nrao.edu/
NREN(s): National Research and Education Network(s) for a list see:
http://en.wikipedia.org/wiki/National_research_and_education_network
NSF: National Science Foundation (US)
http://www.nsf.gov/
NTT: New Technology Telescope (ESO)
http://www.eso.org/sci/facilities/lasilla/telescopes/ntt/index.html
NuStar: Nuclear Spectroscopic Telescope Array
http://www.nustar.caltech.edu/

NWO: Nederlandse Organisatie voor Wetenschappelijk onderzoek (The Netherlands Organisation for Scientific Research)
http://www.nwo.nl/
OCW: Ministerie van Onderwijs, Cultuur en Wetenschappen (Ministry of Education, Culture and Science, NL)
http://www.minocw.nl/english/index.html
OECD: Organisation for Economic Co-operation and Development
http://www.oecd.org/
OMC: Optical Monitoring Camera (Integral)
http://integral.esa.int/integ_payload_omc.html
OmegaCAM: 1 square degree wide-field, optical, camera (VST)
http://www.astro.rug.nl/~omegacam/
Opportunity: See Mars Exploration Rovers.
OPTICON: The OPTical Infrared COordination Network for astronomy
http://www.astro-opticon.org
OSO: Onsala Space Observatory, Swedish Research Council
http://www.oso.chalmers.se/
Pan-Starrs: Panoramic Survey Telescope & Rapid Response System
http://pan-starrs.ifa.hawaii.edu/public/
PARTIVIEW: 4D (space and time) visualisation tool
http://bima.astro.umd.edu/nemo/amnh/
Pierre Auger Observatory: High-energy cosmic rays detector
http://www.auger.org/
PENCIL: High order finite-difference computer code for compressible hydrodynamic flows with magnetic fields
http://www.nordita.org/software/pencil-code/
Phoenix: Mars Lander Mission (NASA)
http://phoenix.lpl.arizona.edu/
PHOIBOS: Probing Heliospheric Origins with an Inner Boundary Observing Spacecraft (ESA CV)
http://www-luan.unice.fr/JeanArnaud/pdf/Phoibos_KI.pdf
PixeLens: Program for reconstructing gravitational lenses from multiple image data.
http://www.qgd.uzh.ch/projects/pixelens/
Planck: Satellite to image the anisotropies of the Cosmic Microwave Background (ESA)
http://www.rssd.esa.int/index.php?project=Planck
PLATO: PLAnetary Transits and Oscillations of Stars (ESA CV)
http://sci.esa.int/plato
PLUTO: Modular, Godunov-type computer code for astrophysical applications
http://plutocode.to.astro.it/index.html
Polar: NASA satellite mission to investigate the Earth's magnetosphere
http://www-istp.gsfc.nasa.gov/polar/
PPARC: Particle Physics and Astronomy Research Council (now part of STFC, UK)
http://www.pparc.ac.uk/home_old.asp
PRACE: Partnership for Advanced Computing in Europe
http://www.prace-project.eu/
PrepSKA: Preparatory study for the SKA
http://www.jb.man.ac.uk/prepska/
Prisma: Technology mission aimed at the demonstration of rendezvous and formation flying in space.
http://www.prismasatellites.se/?sid=9028
PSA: Planetary Science Archive (ESA)
http://www.rssd.esa.int/index.php?project=PSA
PT-DESY: Projektträger Deutsches Elektronen-Synchrotron (D)
http://pt.desy.de/
QSO: Quasi-Stellar object
R&D: Research & Development
RadioNet: An Integrated Infrastructure Initiative, funded under FP6
http://www.radionet-eu.org
RAL: Rutherford Appleton Laboratory (UK)
http://www.scitech.ac.uk/About/Find/RAL/Introduction.aspx
RAMSES: Computer code to study large-scale structure and galaxy formation.
http://irfu.cea.fr/Projets/COAST/ramses.htm
RAVE: RAdial Velocity Experiment (AAO)
http://www.rave-survey.aip.de/
ReSTAR: Renewing Small Telescopes for Astronomical Research
http://www.noao.edu/system/restar/
ROSAT: ROentgen SATellite (D)
http://www.mpe.mpg.de/xray/wave/rosat/index.php
Rosetta: Rendez-vous mission with the comet Churiumov-Gerasimenko (ESA)
http://www.esa.int/rosetta
RXTE: Rossi X-Ray Timing Explorer (NASA)
http://heasarc.gsfc.nasa.gov/docs/xte/xtegof.html
SAFARI: SpicA FAR-infrared Instrument
http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=42283
SALT: Southern African Large Telescope
http://www.salt.ac.za/
SARA: Stichting Academisch Rekencentrum Amsterdam (NL)
http://www.sara.nl/index_eng.html
Science Vision: See SV
SCUBA-2: Submillimetre Common-User Bolometer Array 2
http://www.jach.hawaii.edu/JCMT/continuum/scuba2.html
SDO: Solar Dynamics Observatory
http://sdo.gsfc.nasa.gov/
SDSS: Sloan Digital Sky Survey
http://www.sdss.org/
SED: Spectral Energy Distribution
SFC: Smart Fast Camera (concept for large field of view camera for large telescopes)
Simbol-X: Next-generation formation-flying X-ray telescope (CNES/ASI)
http://www.cnes.fr/web/CNES-en/5853-simbol-x.php
SINET: Japanese Science Information Network
http://www.sinet.jp/
SKA: Square-Kilometre Array
http://www.skatelescope.org/
SKADS: Square-Kilometre Array Design Studies
http://www.skads-eu.org/
SMF: Small- to Medium-sized Facility
SN: SuperNova
SOHO: Solar and Heliospheric Observatory
http://soho.esac.esa.int/
Solar Orbiter: Close range solar mission (ESA), part of HELEX programme with NASA's Solar Sentinel.
http://sci.esa.int/science-e/www/area/index.cfm?fareaid=45

SPACE: SPectroscopic All-sky Cosmic Explorer (now combined with DUNE in EUCLID)
http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=41177
SPHERE: Spectro-Polarimetric High-contrast Exoplanet Research (VLT)
http://www.eso.org/projects/aot/vltpf/
SPICA: Space Infrared telescope for Cosmology and Astrophysics
http://sci.esa.int/spica
Spirit: See Mars Exploration Rovers.
Spitzer: Spitzer Space Telescope (NASA)
http://www.spitzer.caltech.edu/
SRG: Spektrum-Roentgen-Gamma (also known as SXG, Russia)
http://hea.iki.rssi.ru/SXG/SXG-home.html
SSAC: Space Science Advisory Committee (ESA)
http://sci.esa.int/science-e/www/area/index.cfm?fareaid=1
SST: Swedish 1 m Solar Telescope
http://www.solarphysics.kva.se/NatureNov2002/telescope_eng.html
STARLAB: Software package for simulating the evolution of dense stellar systems
http://manybody.org/manybody/starlab.html
STARS: Numerical code to calculate stellar evolution
http://www.ast.cam.ac.uk/~stars/
STEM: Science, Technology, Engineering and Mathematics
STEREO: Solar TErrestrial RElations Observatory (NASA)
http://www.nasa.gov/mission_pages/stereo/main/index.html
STFC: Science and Technology Facilities Council (UK)
http://www.scitech.ac.uk/
STScI: Space Telescope Science Institute
http://www.stsci.edu/institute/
Subaru: 8.2-metre optical-infrared telescope at the summit of Mauna Kea
http://subarutelescope.org/
Super-DARN: Super Dual Auroral Radar Network
http://superdarn.jhuapl.edu/
SURFnet: High speed computer network for research and education (NL)
http://www.surfnet.nl/nl/Pages/default.aspx
Suzaku: Japanese X-ray mission
http://www.isas.ac.jp/e/enterp/missions/suzaku/index.shtml
SV: Science Vision
http://www.astronet-eu.org/-Science-Vision-
SVO: Spanish Virtual Observatory
http://svo.laeff.inta.es/
SVOM: Space-based multi-band Variable Object Monitor
http://www.cesr.fr/spip.php?article251
Swift: NASA mission aimed at gamma-ray burst studies.
http://swift.gsfc.nasa.gov/
SXG: see SRG
TandEM: Titan and Enceladus Mission
http://sci.esa.int/science-e/www/area/index.cfm?fareaid=106
TES: Transition Edge Sensor (new detector technology).
TG: Task Groups
THEMIS: Thermal emission imaging system for Mars Odyssey mission.
http://themis.asu.edu/
TMAP: Tübingen-NLTE-Model-Atmosphere-Package
http://astro.uni-tuebingen.de/groups/stellar/tmap/
TMT: Thirty Meter Telescope
http://www.tmt.org/
TNA: TransNational Access
TNG: Telescopio Nazionale Galileo
http://www.tng.iac.es/
TPF: Terrestrial Planet Finder (NASA), comprising TF-C and TPF-I
http://tpf.jpl.nasa.gov/
TPF-C: Terrestrial Planet Finder Coronograph (NASA)
http://planetquest.jpl.nasa.gov/TPF-C/tpf-C_index.cfm
TPF-I: Terrestrial Planet Finder Interferometer (NASA)
http://planetquest.jpl.nasa.gov/TPF-I/tpf-I_index.cfm
TRL: Technology Readiness Level
TSSM: Titan Saturn System Mission — formerly TandEM
http://sci.esa.int/science-e/www/area/index.cfm?fareaid=106
TVO: Theoretical VO
http://bima.astro.umd.edu/nemo/tvo/
TYCHO: Stellar evolution code
http://chandra.as.arizona.edu/~dave/tycho-intro.html
UCL: University College London
http://www.ucl.ac.uk/
UCLan: University of Central Lancashire
http://www.uclan.ac.uk/
UKIDSS: UKIRT Infrared Deep Sky Survey, the successor to 2MASS
http://www.ukidss.org/
UKIRT: UK Infrared telescope on Mauna Kea, Hawaii
http://www.jach.hawaii.edu/UKIRT/
Ulysses: Space mission that will make measurements of the space above the Sun’s poles. (ESA, NASA)
http://helio.estec.esa.nl/Ulysses/
UNAWE: Universe Awareness for Young Children
http://www.unawe.org/joomla/
UNESCO: United Nations Educational Scientific and Cultural Organization
http://portal.unesco.org/
UV: UltraViolet
UVOT: UV-Optical Telescope (Swift)
http://swift.gsfc.nasa.gov/docs/swift/about_swift/uvot_desc.html
Vela satellites: Satellites designed to monitor worldwide compliance with the 1963 nuclear test ban treaty
http://www.daviddarling.info/encyclopedia/V/Vela_satellite.html
Venus Express: ESA mission to Venus
http://www.esa.int/esaMI/Venus_Express/
VERITAS: Very Energetic Radiation Imaging Telescope Array System
http://veritas.sao.arizona.edu/
VHE: Very High Energy
VIMOS: VIsible MultiObject Spectrograph (VLT)
http://www.eso.org/instruments/vimos/
Virgo: 1) Gravitational wave detector
http://www.virgo.infn.it/
2) Consortium for Cosmological Supercomputer Simulations
http://www.virgo.dur.ac.uk/new/index.php

VisIVO: Visualisation interface to the Virtual Observatory
http://visivo.oact.inaf.it/
VISTA: Visible and Infrared Survey Telescope for Astronomy
http://www.vista.ac.uk/
VLA: Very Large Array (US)
http://www.vla.nrao.edu/
VLBI: Very Long Baseline Interferometry
VLFA: Very Low Frequency Astrophysics
VLT: Very Large Telescope (ESO)
http://www.eso.org/observing/vlt/
VLTI: The Very Large Telescope Interferometer (ESO)
http://www.hq.eso.org/projects/vlti/
VO: Virtual Observatory
VOFC: EURO-VO Facility Centre
http://www.euro-vo.org/pub/
VOS: Virtual Observatory Systems
VOTC: EURO-VO Technology Centre
http://www.euro-vo.org/pub/
Voyager: Giant planet exploration spacecraft (NASA)
http://voyager.jpl.nasa.gov/
VST: VLT Survey Telescope (ESO)
http://vstportal.oacn.inaf.it/
VTT: Vacuum Tower Telescope or Dunn Solar Telescope
http://nsosp.nso.edu/dst/
WFMOS: Wide-Field Multi-Object Spectrograph (Gemini)
http://www.stfc.ac.uk/roadmap/rmProject.aspx?q=128
WHT: William Herschel Telescope
http://www.ing.iac.es/Astronomy/telescopes/wht/
WSO: World Space Observatory for Ultraviolet (Russia)
http://www.oact.inaf.it/wso/index.htm
WSRT: Westerbork Synthesis Radio Telescope (NL)
http://www.astron.nl/p/observing.htm
XEUS: X-ray observatory, now part of IXO (ESA CV)
http://sci.esa.int/xeus
XMM-Newton: X-ray Multi-Mirror Mission (ESA)
http://xmm.vilspa.esa.es/
XRB: X-Ray Binary
XRT: X-Ray Telescope (SWIFT)
http://swift.gsfc.nasa.gov/docs/swift/about_swift/xrt_desc.html
X-Shooter: A point and shoot wideband (UV, optical and near-IR) single object spectrometer (VLT)
http://www.eso.org/instruments/xshooter/
ZEUS: Family of Eulerian (grid based) Magnetohydrodynamic codes.
http://lca.ucsd.edu/portal

SIXTH FRAMEWORK PROGRAMME