The ASTRONET

Infrastructure Roadmap

1 *October 2008*

Table of Contents

Executive Summary

Background: The Global Context

Astronomy is experiencing a golden era. Just the past few years have brought epochal discoveries which have excited people from all walks of life, from the first planets orbiting other stars to the accelerating Universe, dominated by 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). Yet, 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 across all of 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:

First, the Roadmap includes the whole of astronomy, from the remote borders of the Universe to the Solar System. Second, it considers observational tools on the ground and in space, covering gamma-ray to radio wavelengths as well as sub-atomic particles and gravitational waves. Third, it also encompasses theory and computing, laboratory studies, and technology development. Fourth, 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. 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? and
- 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 address specific projects. The *Infrastructure 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 by 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 €10 million 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, level of European involvement, size of the astronomical community that would benefit from it, and relevance to the advancement of 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. First, it emphasises the need to include the entire electromagnetic spectrum – and beyond – in the study of most cosmic phenomena, from young stars and planets to super-massive black holes. Second, while 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.

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 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 and other planetary systems to cosmology:

- The *European Extremely Large Telescope* (E-ELT), a 40m-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 per cent. 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 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 4m 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 fast-track smaller missions.

Yet, 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, which tracks 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 LISA and the X-ray observatory XEUS/IXO were ranked together at the top. Next were the TANDEM and LAPLACE missions 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"), FIRI (formation and evolution of planets, stars and galaxies), and 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 Horizons 2000 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), PLATO (exoplanet transits) and 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 2-4m optical telescopes within the context of the Roadmap, to report by September 2009.

Reviews of Europe's existing mm-submm and radio telescopes will be undertaken shortly after, followed later by a review focusing on the optimum exploitation of our access to 8-10m 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 mid-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.

The Virtual Observatory will enable new kinds of multi-wavelength science and present 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, 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 humans determines what 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 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 co-ordinated technological 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.