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Editors: Isobel Hook, Dimitra Rigopoulou, Steve Rawlings and Aris Karastergiou

The ASTRONET Infrastructure Roadmap: Europe's Strategic Plan for Astronomy

M. F. Bode

Astrophysics Research Institute, Liverpool John Moores University, Birkenhead, CH41 1LD, UK

Abstract. The ASTRONET Infrastructure Roadmap represents a community-based, comprehensive plan that aims to maintain and strengthen Europe's rôle in astronomy internationally over the next 10-20 years. In this review, I first describe the background to ASTRONET. This is followed by an outline of the development of the Roadmap itself. Details are given of the working methods used and the conclusions reached, which include not only those regarding future facilities (encompassing several of the 'Megastructures' that are the theme of this conference) but also areas such as theory, computing and public engagement. Gaps and opportunities in our proposed provision are outlined before addressing the proposed next steps for the ASTRONET programme as a whole.

1. What is ASTRONET?

ASTRONET is an ERA-Net financed by the European Commission Framework 6 programme, under the initiative 'Integrating and Strengthening the European Research Area' (ERA). ASTRONET was founded by the major European funding agencies and funded at the level of 2.5M euros over 5 years from September 2005. It is co-ordinated by CNRS/INSU, with Jean-Marie Hameury as project manager, and the ASTRONET Board is chaired by Johannes Andersen of NOTSA. At the time of writing, it comprises 10 primary Contractors (mainly national funding agencies, plus ESO) together with 16 Associate member organisations from 14 countries (plus ESA) and a further 4 nations represented by Forum members. The list is still growing. Further information, publications and updates on progress of the initiative can be found on the project's website at <http://www.astronet-eu.org/>.

ASTRONET was founded for the following over-riding reason. Large projects proposed for the next 10-20 years in astronomy and astro-particle physics constitute several billion euros. The EU only provides for a few percent of this cost - the funding agencies and other government organisations would be expected to meet the rest. ASTRONET was thus established to help national funding agencies to take science-based, rational, coordinated decisions for the long term benefit of European astronomy - and, at a higher level, to help unlock further necessary resource for our science in Europe. We are therefore effectively prototyping a counterpart of the US Decadal Surveys for Europe, but with a wider remit and in a rather more complex environment. Hence this is a very ambitious undertaking.

Activities within ASTRONET since 2005 have fallen under five main headings:

- Agreement on a common Science Vision for the next 20 years (published in September 2007 - de Zeeuw & Molster 2007).
- Establishment of a Roadmap of infrastructures to address the Science Vision (published in November 2008 - Bode, Cruz & Molster 2008 - see below).
- Networking, including the integration of new participants (ongoing) and the production of a Report on the Management of European Astronomy (published by ASTRONET in July 2007).
- Coordinated Actions, which required work towards launching a common call for proposals with a common or joint budget (launched, and successful proposals underway under the title 'Common Tools for Future Large Sub-mm Facilities').
- Implementation, including specific actions arising (to December 2010). Planning for the long-term future is well advanced (see last section).

2. Developing the Roadmap

Here, the brief was to assemble a plan for the infrastructures that will enable European astronomy to deliver the Science Vision, with the STFC of the UK as the lead agency and the current author as the Roadmap Task Leader. We therefore naturally took the Science Vision as the point of departure. Our remit was very broad, covering both ground and space-based facilities, plus the Virtual Observatory, (super)computing, theory, human resource issues, outreach, education and training and industrial links. We were to incorporate existing plans (of ESO, ESA etc.) as far as possible, and have a global perspective. Overall, we were to attempt to fit this within reasonable budgetary envelopes and schedules. The process of developing the Roadmap got underway in earnest in the

Autumn of 2006. The motivations and modes of operation are described in detail in Chapters 1 and 2 of the final report (Bode et al. 2008), which, together with an Executive Summary, is available from the ASTRONET website.

As with the Science Vision, the task of developing the Roadmap was undertaken by specialist Panels, reporting to a Working Group. The panels were organised under the following headings (with the relevant chapters of the final report indicated in each case): *A.* High energy astrophysics, astro-particle astrophysics, gravitational waves (Chapter 3); *B.* UVOIR and radio/mm astronomy (Chapter 4); *C.* Solar telescopes, solar system missions, laboratory studies (Chapter 5); *D.* Theory, computing facilities and networks, virtual observatory (Chapter 6), and *E.* Education, recruitment and training, public outreach, industrial links (Chapter 7).

The first three Panels effectively covered facilities and the latter two some additional critical underpinning infrastructure in its widest sense, and the broader impact of our work on society in general. The Panels comprised up to 12 members each, with selection being based primarily on relevant expertise, but bearing in mind a reasonable spread of nationality and gender. Each Panel reported to the Working Group whose membership comprised the chair and co-chair of each Panel together with 10 members at large who assisted the Panels with their work. Overall however, the task of the Working Group was to synthesise the recommendations of the Panels into the final Roadmap, ably aided and abetted by the Assistant Scientists (Maria Cruz of Liverpool JMU and Frank Molster of NWO) and chaired by the current author. Altogether, over 60 scientists, plus educators and journalists on Panel E, were members of the Panels and Working Group.

3. Working Methods

From March 2007 until October 2008 around 40 meetings of the Panels and Working Group were held. Most of these were face-to-face, but Panel D in particular, rather fittingly, held several virtual meetings via teleconference. Panels A to C identified well over 100 facilities which might be evaluated in the roadmapping exercise. As part of this, a questionnaire was sent to all of them, generating an almost complete return by early July 2007 (the full list of facilities surveyed can be found in Appendix IV of the final report). An evaluation template was formulated and then completed by each assigned Panel rapporteur for each facility. Evaluation criteria were developed to give first-pass rankings, then each facility was further discussed, further information gathered as appropriate, and initial judgements refined (for example in the light of the ESA Cosmic Vision results which were available to the Panels in October 2007). In parallel with this, the ASTRONET Science Vision was launched in September 2007.

The main focus of the Roadmap is of course on future facilities (but well-defined major upgrades and significant operational prolongations were also included). Only fa-

ilities with a significant European content (in terms of a likely funding requirement) and well enough developed to be able to be judged adequately were included. We had to set some lower bound to the 'scale' of projects to be scrutinised, and decided upon a European funding requirement of greater than 10M euros capital cost and/or greater than 10M euros operational cost over 5 years (unless there were a special reason to lower this limit in a particular case). Finally, only those facilities where a major European funding decision was expected to be required from 2009 onwards were included.

Broad categories of prioritisation were used for initial ranking of facilities: High, Medium and Low, with only High priority projects normally discussed in detail in the final report; other facilities were included for 'context' and some smaller scale current facilities have been grouped. It was recognised that a large facility may on average address more Science Vision questions than a smaller-scale example, but the smaller one may very cost-effectively address a sub-set of important science questions. Therefore projects were sub-divided into cost categories: Small (10M-50M euros); Medium (50M-400M euros), and Large (greater than 400M euros). These mapped to some extent onto the previous US Decadal Survey for ground-based projects (the latest Survey just being published at the time of writing) and the original ESA Cosmic Vision 'M-class' and 'Flagship (L-class)' designations for space-based missions, including instruments. We also utilised a timescale division (to full operation) as follows: Short-term (<2015); Medium-term (2016-2020); Long-term (2020+) and assigned each project a current Technology Readiness Level. The evaluation criteria we used (in decreasing weight) were Scientific Impact (particularly in relation to delivering the Science Vision), Competition/Uniqueness, European Involvement, User Base and Industrial Relevance. This evaluation gave us a first-pass ranked list of projects in each of Panels A-C.

The terms of reference for Panels D and E were naturally somewhat different from Panels A, B and C. Specific questions from these Panels were included in the questionnaire sent to facilities, but D and E also undertook considerable additional information gathering as detailed in Chapters 6 and 7 of the final report. Panel D then gave members responsibility for specific areas within their remit and Panel E sub-divided into several task groups. Information exchange with other Panels took place throughout the process, both directly and through the Working Group.

The roadmapping process was not without cognizance of, and inputs from, other organisations and initiatives with an important role in the future shape of astronomy in Europe. For example, the Working Group included representatives of ESO and ESA, plus the EC-funded Integrated Infrastructures Initiatives (I3s) OPTICON and RadioNet. In addition, the Europlanet initiative had representation on Panel C (and on the Working Group in the initial phases). Information exchange with the astro-particle ERA-Net, ASPERA, included round-table meetings with ASTRONET. Finally, links with the European

Strategy Forum for Research Infrastructures (ESFRI) were gradually strengthened as the ASTRONET initiative progressed.

In order to meet the deadlines set at the start of the project, activity was intense between the constitution of the Working Group and Panels in early 2007 and the delivery of the final report in November 2008. An important milestone was then a meeting with the Agencies in London in February 2008 where our initial findings were presented for a 'sanity check' in terms of, for example, funding envelopes and competing national aspirations. Further work ensued on the draft, which was then released for public consultation in early May 2008, at which point a web-based forum was also made available to the community to post their comments. As with the Science Vision, the centrepiece of the consultation was an open symposium, held over 4 days in June 2008 in Liverpool, which was attended by around 300 participants. The consultation period then ended in July 2008. The final Panel and Working Group meetings were subsequently held to amend their conclusions in light of the consultation. Responses to all comments made on the web forum were posted following the launch.

4. Priorities and Recommendations

4.1. Ground-based projects

Among the *large scale* ground-based infrastructure projects, two emerged as clear and equal top priorities due to their potential for fundamental breakthroughs in a very wide range of scientific fields, from planetary systems (including our own) to cosmology:

- *The European Extremely Large Telescope* (E-ELT) and the *Square Kilometre Array* (SKA).

Both of these projects (and others below) are covered in detail elsewhere in these proceedings of course. 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, as detailed in Chapter 4 of the report.

Three outstanding projects were identified in the *medium scale* category. In descending order of priority these comprise:

- The 4m *European Solar Telescope* (EST) to be built in the Canary Islands; the *Cerenkov Telescope Array* (CTA), a high-energy gamma-ray 'true' observatory, and finally the proposed underwater neutrino detector, *KM3NeT*.

In addition, in terms of the highest priority *small scale* project, a working group has been established to study the options for the provision of a *Wide-Field Multiplexed Spectrograph* for massive surveys on a 4-8m-class optical telescope. This group will provide its report later this year.

4.2. Space-based projects

The Working Group and Panels independently agreed with ESA's initial selection of Cosmic Vision missions, all recognized to be of high scientific value. The final choice of missions by the standard ESA procedure, 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, roadmap priorities, including some non-ESA missions, are set out below.

Among the *large scale* missions:

- The gravitational-wave observatory *LISA* and the X-ray observatory *XEUS/IXO* were ranked together at the top. Next in priority were the proposed *TandEM* and *LAPLACE* missions to the planets Saturn and Jupiter and their satellites. Of these, *LAPLACE* became the Europa Jupiter System Mission (EJSM - jointly with NASA and JAXA) and was selected to proceed to the next stage by ESA in early 2009; it will now compete with *IXO* or *LISA* for the next L-mission 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 within ESA (*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:

- *GAIA science analysis and exploitation* (an approved Horizon 2000 Plus astrometric mission) was judged most important.
- Among proposed new projects in this category, the dark energy/dark matter mission *Euclid* was ranked highest, followed by *Solar Orbiter* (a joint project with NASA). At the ESA Space Science Advisory Committee (SSAC) in January 2010, both were selected for further study, with *Euclid* ESA's initial first choice.
- Next in the ASTRONET rankings, with equal rank but different maturity, are *Cross-Scale* (magnetosphere), *Simbol-X* (a non-ESA X-ray project), *PLATO* (exoplanet transits) and *SPICA* (a far-infrared observatory - led by JAXA). Of these, *PLATO* has now been selected for further study by ESA as being of equal priority to *Solar Orbiter* in the M-class missions and *SPICA* has also been endorsed to proceed to the definition study phase, but as ESA is a minor partner to JAXA, it is being treated separately from the other approved Cosmic Vision missions. However *Cross-Scale* was not selected and funding for future development of *Simbol-X* was not secured by its international partners.

- Below these in the ASTRONET rankings was *Marco Polo* (a near-Earth asteroid sample return), which was also not selected by ESA to go forward to the next stage of the Cosmic Vision process, but may be pursued within the framework of a 'Mission of Opportunity' with ESA as a minor partner should such partnership opportunities arise.

By their nature, there were no small scale space projects under consideration for inclusion in the Roadmap.

4.3. *The rôle of existing facilities*

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, however, 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. Recommendations on mission prolongations are summarised in Chapter 8 of the final report.

On the ground, the existing set of small to medium-size night-time optical telescopes is a heterogeneous mix of national and common user instruments, equipped and operated without overall coordination. This is inefficient in the era of 8-10m telescopes and ASTRONET therefore appointed a committee (the European Telescope Strategy Review Committee - ETSRC) to review the future rôle, organisation, and funding of the European 2-4m optical telescopes within the context of the Roadmap. The final ETSRC report is now available via the ASTRONET website. A review of Europe's existing radio telescopes is now underway as SKA development gathers pace. That for mm/sub-mm facilities 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, and the rationalisation of ground-based solar telescopes as we move into the EST era. These reviews will help Europe to establish a coherent, cost-effective complement of medium-size facilities.

4.4. *Theory, computing and data archiving*

It is acknowledged that 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. The Roadmap therefore proposes continued development of the Virtual Observatory, including recommend-

ing planning for the provision of a public, VO-compliant archive with any new facility.

The Roadmap also proposes that a 'virtual' European Astrophysical Software Laboratory (ASL - a centre without walls) be created to accelerate developments in this entire area on a broad front. The ASL would coordinate and raise funds for software development and support, user training, postdoctoral positions within a programme of pan-European networks, and set standards. It is proposed that the ASL would select a few highly competitive astrophysics projects per year to send proposals to the top-tier, pan-European high performance computing centres to help ensure a significant share of CPU hours at the petascale level for astronomy. The report also makes recommendations on the development of novel data grids by exploiting the popular appeal of astronomy in order to get CPU owners to donate spare CPU cycles, or by initiating a classical market in such cycles. The ASL could have a rôle in coordinating this activity. An ASL Committee has now been established which is due to report to the ASTRONET Board in September 2010 on the initial steps required.

4.5. *Laboratory astrophysics*

The report stresses the need to enhance support for laboratory astrophysics - including the curation of solar-system material returned by space missions in a proposed European Analysis and Curation Facility. The report also proposes the establishment of a Technical Fellowship Programme and of new European networks stimulated by Joint Calls between the agencies, as pioneered by the call undertaken in the current ASTRONET project. To take these initiatives forward, a European Task Force for Laboratory Astrophysics is being formed.

4.6. *Education, recruitment, outreach and industrial links*

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. The proposed initiatives include among others:

- Enhanced training of teachers in astronomy - this has now been taken up in IAU Commission 46 for implementation in 2010-2011.

- Inclusion of astronomy more widely in national curricula - this is an action likely to be followed up in the proposed next stage of ASTRONET (see below).
- New or enhanced educational portals - these will now be created and hosted on the IAU Commission 46 website in several languages.
- Establishment of a standardised European communication portal for media, educators, interested people and others - this has now been implemented as <http://www.portaltotheuniverse.org/>.
- Appropriate funding and recognition of outreach activities - again something that should be followed up in the proposed next stage of ASTRONET.
- Creation of an international network of experts in technology transfer - there has been some subsequent progress on the national scale, but the international initiative still needs pursuing.
- Enhanced scientific exploitation of facilities - the issue has already been taken up with the European Research Council, but also requires the attention of the various national funding agencies to ensure that Europe maximises the scientific output of its facilities.

4.7. Technology development and industrial spin-off

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 the Roadmap 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 R&D programme centred on promising future facilities and in concert with industry is therefore an important priority across all areas of the Roadmap. The required technology development and industrial applications are summarised in Chapter 8 of the final report.

5. Gaps and Opportunities in Europe's Future Observational Capability

Inevitably, the roadmap process revealed several gaps in future provision, and we briefly outline these here:

- Small-scale and fast-track space missions - while our prioritisation of facilities naturally focussed on the medium to large scale space missions, we recognise the opportunities afforded by smaller projects as a crucial part of a balanced future programme.
- High Energy Astrophysics - Panel A identified various 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. One such area is 0.1-10 MeV imaging and spectroscopy and another is all-sky monitoring in both X-rays and γ -rays.
- UV Astronomy - there is a pressing need for a successor to IUE in terms of a dedicated FUV/EUV astronomy

mission. Panel C also identified the need for an (E)UV Solar mission with X-ray capabilities.

- Optical/IR ground-based interferometry over kilometric baselines - this is a natural successor to VLTI.
- mm-submm Astronomy - European access is required here to a large aperture single dish with array detectors on an extremely high site. There is also a requirement for further CMB polarisation studies post-Planck.
- Radio spectral imaging of the Sun - such imaging at centimetre to metre wavelengths is essential in particular in furthering our understanding of physical processes in the solar corona.
- Arctic and Antarctic sites - these offer special opportunities for the development of astronomy and their further exploration and development are encouraged.

6. Next Steps and Concluding Remarks

The current ASTRONET project finishes at the end of 2010. However, funding has now been secured under the Framework 7 programme of the EC to continue the project for a further 4 years. This will allow several of the initiatives mentioned above to come to full fruition, with ASTRONET acting as a facilitator and champion, and also enable the updating of the Science Vision and the Roadmap. Towards the end of this period, preparations will start for a full revision of the Roadmap.

The Roadmap is a pioneering venture for Europe, and a complex and challenging task. Its implementation will however help to maintain and enhance Europe's leading rôle in addressing what are foreseen as the major questions in our area of science. It will also enhance the scientific and technical capability of Europe at all levels and aid collaborations with our wider international partners on some of the largest-scale, global projects over the next two decades. We have a job to do to persuade our political masters to provide adequate funding to realise our goals, but we have some powerful and compelling arguments in our favour to help them to decide to do so.

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