

# **ASTRONET: Infrastructure Roadmap Update**

**Ian Robson**



The ASTRONET Science Vision and Infrastructure Roadmap were published in 2007 and 2008 respectively and presented a strategic plan for the development of European Astronomy. A requirement was to have a light-touch update of these midway through the term. The Science Vision was updated in 2013 and the conclusions were fed into the Roadmap update. This was completed following the outcome of the ESA decisions on the latest missions. The community has been involved through a variety of processes and the final version of the update has been endorsed by the ASTRONET Executive.

**ASTRONET** was created by a group of European funding agencies in order to establish a strategic planning mechanism for all of European astronomy. It covers the whole astronomical domain, from the Sun and Solar System to the limits of the observable Universe, and from radioastronomy to gamma-rays and particles, on the ground as well as in space; but also theory and computing, outreach, training and recruitment of the vital human resources. And, importantly, ASTRONET aims to engage all astronomical communities and relevant funding agencies on the new map of Europe.

<http://www.astronet-eu.org/>

**ASTRONET** has been supported by the EC since 2005 as an ERA-NET. Despite the formidable challenges of establishing such a comprehensive plan, ASTRONET reached that goal with the publication of its Infrastructure Roadmap in November 2008. Building on this remarkable achievement, the present project will proceed to the implementation stage, a very significant new step towards the coordination and integration of European resources in the field.

## Acknowledgements

*I would like to thank all those who contributed to this Roadmap Update, in particular those responsible for Panels A-E (Chapters 3-7) and to the Members at Large for their overview. I would also like to thank the ASTRONET Executive and Board, especially the former for their support and guidance in preparation of this Update, and for organising the two EWASS sessions at Turku and Geneva.*

*Ian Robson, July 2014*

*'It is a pleasure to welcome the publication of this update which builds upon the very successful initial Roadmap. Thanks are due to all those who have contributed, particularly Professor Robson, and to the support of the EU FP7 programme. I hope that the Update will prove a useful and influential baseline for the on-going development of the European Astronomy and space science programme.'* Dr Denis Mourard, ASTRONET Coordinator and Dr Ronald Stark, Chair ASTRONET Board



Cover image of the Flame Nebula in Orion taken with the VISTA telescope. Image courtesy of ESO/J.Emerson.  
Acknowledgement: the Cambridge Astronomical Survey Unit



# **ASTRONET: Infrastructure Roadmap Update 2014**

## **Executive Summary**

Excellent progress has been made on implementing the recommendations of the original ASTRONET<sup>1</sup> Infrastructure Roadmap<sup>2</sup> that was issued in 2008. Furthermore, great progress has been made on answering the questions posed in the original Science Vision<sup>3</sup> document, which guided the infrastructure selections. The Science Vision, which was published in 2007, has also been updated and published<sup>4</sup> and again, has guided the update of the Infrastructure Roadmap.

The economic downturn at the end of the last decade has had an impact on progress, but gratifyingly, most of the ‘large’ projects have continued with relatively little impact apart from delays. On the other hand, where the financial climate has had a serious impact is the ongoing annual support of astronomical research; i.e. research grants (staffing and training), support for operations of existing facilities and support for small-to-medium instrumentation projects. However, in the midst of the downturn, the International Year of Astronomy 2009 (IYA2009)<sup>5</sup> proved to be a spectacular success and provided a springboard for many initiatives that have followed. The explosion of new media into the communication toolkit has also provided another huge boost for the subject.

Since the publication of the original Roadmap, excellent science continues to be delivered from space missions such as XMM Newton, INTEGRAL, Cassini, Cluster, Hinode, Mars Express, SOHO and Venus Express. The Rosetta mission, launched in 2004 to study and plant a lander on the comet 67P/Churyumov-Gerasimenko, is about to come to fruition. Since 2008, three new astronomy missions have been launched by the European Space Agency (ESA)<sup>6</sup>. Herschel has provided a truly spectacular far-infrared/submillimetre mapping of the cold Universe, while its launch companion, Planck, has made exquisite maps of the cosmic microwave background, the remnant of the big bang, to unprecedented accuracy. These were launched on an European Ariane V rocket in 2009. The latest mission, Gaia, was launched in December 2013 on its mission to map a billion stars in our Galaxy, thereby revealing how our galaxy was formed and how it has evolved.

In addition to the astounding success of the above, the ESA Cosmic Visions<sup>7</sup> selection process has now set the scene for the following small, medium and large future projects: S1, M1, M2, M3, L1, L2, L3. The last of these (L3) is planned to launch in 2034. The themes cover a wide range of topics: study of the Sun (M1-Solar Orbiter); planetary exploration

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<sup>1</sup> <http://www.astronet-eu.org>

<sup>2</sup> <http://www.eso.org/public/archives/books/pdfsm/astronet.pdf>

<sup>3</sup> <http://www.astronet-eu.org/FP6/astronet/www.astronet-eu.org/spip33fa.html?rubrique27>

<sup>4</sup> <http://www.astronet-eu.org/spip.php?article170&lang=en>

<sup>5</sup> <http://www.astronomy2009.org>

<sup>6</sup> <http://www.esa.int>

<sup>7</sup> <http://sci.esa.int/home/>

searching for biological markers (L1-JUICE), exoplanetary study (S1-CHEOPS and M3-PLATO), the search for dark energy (M2-EUCLID); the study of the hot and energetic Universe (L2-Athena) and the study of the gravitational wave Universe (L3). This process is a clear highlight and Europe can now see its premier space astrophysics research planned out into the distant future. This long-term planning is possible because of the relative stability in funding for ESA (compared to other agencies and nations – see Chapter 8) and is an important principle in being able to maximise returns for the agencies as well as allowing the astronomical community to be in a position to plan their own activities accordingly. Of course more could always be done with more money, or with collaborations with other nations, both of which would allow more missions to be undertaken, or missions to happen sooner. Aside from these ESA flagship missions there is scope for bi-national projects and a number of these have shown that they can be extremely successful and cost effective.

Since 2008, huge scientific progress, along with countless new discoveries, have been made using the suite of ground-based telescopes spanning the radio through to optical (and even gamma-ray) regimes. The VLT suite of 4x8m telescopes of the European Southern Observatory (ESO)<sup>8</sup> continues to set the world-standard for the 8-10m class telescopes. These are now augmented by two new survey telescopes at optical (VST) and infrared (VISTA) wavelengths. Continued provision of new instruments for the VLT as well as the VLT Interferometer (VLTI) is at the forefront of ESO's optical/infrared mandate. The ALMA millimetre/submillimetre array in the Atacama Desert is now essentially complete as far as the initial receiver bands are concerned and while still ramping up to full operation, it is already demonstrating its huge potential with some fabulous, ground-breaking observations.

With regard to the top-priority ground-based project in the original Roadmap, ESO's giant optical-infrared telescope, the E-ELT<sup>8</sup>, progress has been excellent. The project was approved in 2012 and is now firmly established; the design is finalised, the first-light instrumentation agreed, the site has been selected and is now being prepared with ground-breaking and the construction of the access road. Project construction will be boosted as soon as the Brazilian Parliament ratifies the accession to ESO, which is expected in the near future. First-light of the E-ELT is expected in 2024.

The second (and joint) top-priority, ground-based project, the Square Kilometre Array (SKA)<sup>9</sup>, has also progressed in leaps and bounds during the last five years. This is a global collaboration (currently comprising institutions from twenty countries), with Europe aiming to be in the lead position. The SKA Organisation was established as a legal entity in 2011, with headquarters at Jodrell Bank in the UK and now has a Director and an International Board. A major milestone was achieved in 2012 with the selection of the site; in fact a dual location was selected within the two competing countries, Australia and South Africa. The design phase is currently underway and the construction of Phase 1 of the project is planned for completion around 2023.

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<sup>8</sup> <http://www.eso.org>

<sup>9</sup> <https://www.skatelescope.org/>

One of the themes underlined in the original Roadmap was the need for multi-object spectrometers for the current suite of major optical/infrared telescopes and it is very satisfying to see that at least three such projects are now underway in Europe. While good progress has been made on the rationalisation of the ‘small’ optical/IR telescopes through various initiatives, the squeeze on annual operating budgets means that there is still further work to be undertaken here. Likewise for the radio telescopes in Europe; in the realm of ALMA, there is undoubtedly scope for some rationalisation and cash savings to be made, albeit at a potential loss to individual countries. This is currently being addressed by an ASTRONET panel (ERTRC)<sup>10</sup>.

One of the original Roadmap recommendations; to ensure adequate funding is set-aside for technology development that ultimately leads to new instrumentation and facilities, is reiterated. This is particularly important in times of financial pressure. In this context, a push to ensure that Europe has access to its own supply of low-noise, large-format infrared arrays remains a key recommendation that needs pursuing at the highest levels.

The European Solar Telescope (EST)<sup>11</sup> remains a high priority and the flagship project for the Solar Physics community. Good progress has been made since the original Roadmap and while full construction funding has not yet been achieved, the EU FP7 Capacities project SOLARNET<sup>12</sup> received significant funding for 2013-2017. This will assist in preparation work for the EST. A key recommendation from the community is to have the EST established on the next update of the European ESFRI Roadmap<sup>13</sup>, which is due in 2015.

One of the main recommendations from the original Infrastructure Roadmap was to phase the two major ground-based projects (E-ELT and SKA) to prevent an impossible funding bulge. A similar issue is now being faced with regard to the top-two astroparticle physics projects; the gamma-ray Cerenkov Telescope Array (CTA)<sup>14</sup> and the neutrino detector of KM3NET<sup>15</sup>, both of which are listed on the ESFRI Roadmap. The CTA is progressing with a formal organisation being defined and site selection in the south being negotiated, while steady progress is being made with the first detector for KM3NET although construction funding is not yet secured.

With regard to outreach, education and training, great strides have been made in using astronomy as a ‘taster’ for science and technology in a broad range of school ages. The spectacular success of the International Year of Astronomy in 2009 (IYA2009) has led to a huge upsurge in activity in the education and outreach arenas. Furthermore, the explosion of new devices (e.g. smart-phones and tablets) and their applications alongside the dramatic rise of citizen science projects, demonstrate how outreach has expanded its horizons in the past

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<sup>10</sup> <http://ertrc.strw.leidenuniv.nl/>

<sup>11</sup> <http://www.est-east.eu/>

<sup>12</sup> <http://www.solarnet-east.eu/>

<sup>13</sup> [http://ec.europa.eu/research/infrastructures/index\\_en.cfm?pg=esfri-roadmap](http://ec.europa.eu/research/infrastructures/index_en.cfm?pg=esfri-roadmap)

<sup>14</sup> <https://www.cta-observatory.org/>

<sup>15</sup> <http://www.km3net.org/home.php>

six years. However, many of the recommendations from Panel E, specifically regarding education, have progressed little. This is for two reasons: firstly because they involve major policy decisions at national levels across Europe, something that is non-trivial; secondly, because to achieve this there is a requirement for a driving force and staff effort to support it. This is an area where ASTRONET needs to determine how it will progress these issues (or otherwise). In the education and training domain, the economic downturn was bad news for many researchers within Europe, especially those on ‘soft money’. The number of PhD places was cut in many countries and the resulting career progression into postdoctoral positions also declined.

As well as impacting staffing and training the economic downturn also brought annual operating budgets for current facilities into sharp focus. These are now being tensioned against outlays for future projects and their inevitable operating costs. This will be a challenge for the future as astronomy appears to be developing into more ‘global’ projects in the future. In this context, the situation with regard to small and medium-sized optical/IR telescopes will continue to require stark choices, as will the ongoing support for a number of radio telescopes across Europe.

However, looking at the original Roadmap recommendations, virtually all of them have either been met, are in progress, or continue to stand today. Indeed, the picture is incredibly positive in spite of the economic climate. This ‘light touch’, mid-term, update has produced a number of additional recommendations, but not a large number. This is mainly because the original work concentrated on a ten-year span and with the ESA missions now planned out into the 2030’s and the E-ELT and SKA progressing well, much of the urgency for the ‘big projects’ has subsided. However, it is clear that while the big projects are now well defined, the next tier of projects will need additional work for the next Roadmap. It is still too early to define a number of these, but this work will need to start in the next three years.

In conclusion, this Roadmap update has demonstrated that the original plan was extremely successful in laying out the future direction of astronomy activity in Europe. Indeed, it stands up very well with regard to other strategic roadmaps, and Chapter 8 describes the Decadal Surveys of the USA as a comparison. However, what is clear from all current roadmapping exercises is that future project costs and associated risks (and hence cost inflation) need to be very carefully audited at the time of funding, because cost increases without additional funding (or new partners) will require scientific descoping. While these are never palatable, the otherwise damage on the rest of the programme can be enormous (e.g. the situation in the USA with regard to the NASA<sup>16</sup> Astrophysics budget and the cost inflation of the James Webb Space Telescope – JWST).

This document gives an overview and update of the progress since the original Roadmap of 2008. Essentially most of the original recommendations are either still supported, or they have been achieved. A number of new recommendations are summarised in Chapter 9, some

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<sup>16</sup> <http://www.nasa.gov/>

of which are generic in nature and apply across the board for many projects. Astronomy is currently in a very healthy position in Europe, but a continuing squeeze on national funding and the resulting implications is something that needs careful thought in terms of prioritisation and planning and this will be a key theme of the next version of the highly successful ASTRONET Science Vision and Infrastructure Roadmap.

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*A multi-wavelength composite image from ESA's Herschel space observatory showing a sequence of star-forming regions in the molecular cloud W48, some 10 000 light-years away in the constellation Aquila (the Eagle). Courtesy of ESA/Herschel/PACS/SPIRE/HOBYS Key Programme consortium*

# **1. Introduction**

## 1.1 Process

The starting point for the original ASTRONET Infrastructure Roadmap was the Science Vision document published in 2007. This presented the science themes that should be studied over the coming decade and beyond. The outputs from this were mapped onto existing or potential future projects. These were then given a stress-test against potential funding and the final recommendations of the Roadmap were produced and published in 2008.

One of the requirements of the ASTRONET project was that both of these documents should have ‘light-touch’, mid-term updates. This task was the responsibility of the UK’s Science and Technology Facilities Council (STFC)<sup>17</sup>. The Science Vision document was updated with an audit date of February 2013.

The original Roadmap was divided into five areas, each of which was tackled by a Panel of experts. These themes were: High Energy Astrophysics and Gravitational Waves (Panel-A); Ultraviolet, Optical, Infrared and Radio/mm Astronomy (Panel-B); Solar Telescopes, Solar System Missions, Laboratory Studies (Panel-C); Theory, Computing Facilities and Networks, Virtual Observatory (Panel-D); Education, Recruitment and Training, Public Outreach (Panel-E). This theme was retained for the update of the Roadmap and Chapters 3-7 have, in the main, been produced by the Chairs and co-Chairs of the original Panels and the Members at Large (see appendix A).

The purpose of the Roadmap update is not to reiterate the science that can be achieved, this is covered in the update of the Science Vision document, rather it is to highlight where decisions may need to be made between competing projects, resources and timescales. What is really important is to identify in Chapters 3-7 any important gaps in which Europe needs to invest for the future, especially in new technologies or processes. In what follows, in order to retain commonality and ease of comparison with the Roadmap of 2008, the sections and their headings for the five Panels (Chapters 3-7) exactly reflect those in the original document.

While this Update gives a commentary on most of the projects listed in the original Roadmap, it does not provide a compliance matrix of the progress; this is dealt with in a parallel ASTRONET Report on the ‘Implementation of the Roadmap’.

Chapter 9 presents the *new* recommendations from the Update. These are given along with the original recommendations from the five Panels. There were a number of over-riding strategic recommendations from the original Infrastructure Roadmap (such as pacing the E-ELT and the SKA) but these have not been amplified in Chapter 9 but are dealt with in the individual Panel Chapters.

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<sup>17</sup> <http://www.stfc.ac.uk>

The original intention was to complete the Roadmap Update by the end of 2013. However, the announcement by ESA of the timetable for selection of L2, L3 and M3 and the ramifications of these decisions on the overall programme resulted in the completion being intentionally delayed until the spring-summer of 2014, albeit most of the work had been undertaken in 2013.



*Launch of the Gaia satellite on 19<sup>th</sup> December 2013 from the Kourou site in French Guiana. Photo courtesy of ESA-S Corvaja*

## 1.2 Progress since the Infrastructure Roadmap of 2008

Progress has been exceptional across the board and spectacular science has been obtained through a large range of space and ground-based missions and projects. Examples from the space area include the ESA missions<sup>18</sup> of Cassini-Huygens, XMM-Newton, INTEGRAL, Cluster, Mars Express, Venus Express, SOHO, Herschel and Planck, along with other missions with European interest such as SWIFT<sup>19</sup>, Fermi<sup>19</sup>, Hinode<sup>19</sup>, Kepler<sup>19</sup> and AGILE<sup>20</sup>. Indeed, a number of these had not been launched at the time of the original Roadmap. Recently, Gaia<sup>18</sup> has been launched and has just completed commissioning and is starting its operational phase, while Rosetta<sup>18</sup> is about to rendezvous with its comet after its lengthy journey since launch. Also, a number of major space projects have come to fruition in terms of approval. The Cosmic Visions programme for ESA is now in place with the selection of the M1, M2, M3, L1, L2 and L3 missions. The introduction of a ‘small mission’ category has

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<sup>18</sup> <http://sci.esa.int/home/51459-missions/>

<sup>19</sup> <http://www.nasa.gov/missions/index.html>

<sup>20</sup> <http://agile.rm.iasf.cnr.it/>



seen CHEOPS<sup>18</sup> (characterisation of exoplanets) emerge triumphant for S1. These are described in Chapter 2.1.

Huge progress has been made in terms of observations of the Sun as highlighted by missions like Hinode, the two STEREO spacecraft and the Solar Dynamics Observatory, while Solar System studies have benefited by from the continued operation of Cassini-Huygens, Mars Express and Venus Express. In early 2013, the Herschel Observatory ended a truly spectacular mission, opening up the far infrared with data of the highest quality; this will provide astronomers with many years of data for analysis and follow-up. Early in 2013, the Planck mission had its first public cosmology data release, showing the early Universe in unprecedented detail and revealing some new features not readily seen in previous surveys of the cosmic background radiation. The first polarization map was released in May 2014 and the publication of the deeper map is eagerly awaited before the end of the year in light of the recent results on polarization signals from primordial fluctuations.

On the high-energy side, European astronomers have been capitalizing on a very successful suite of X- and gamma-ray missions (e.g. XMM-Newton, Integral, Swift, AGILE and Fermi) that have produced a continuum stream of discoveries.

Progress has also been spectacular from the ground with a huge landscape of new observations emerging; these range from the discovery of extra-solar planets through to deep surveys addressing galaxy formation in the very early Universe. Regarding the two joint top-priority new large facilities from the original Roadmap; the E-ELT project is now making major strides forward, being formally approved by ESO, construction of the access road has begun and recently (June 2014) there was the levelling of the mountain-top. The SKA is now a fully-fledged project with an international project office (located at Jodrell Bank UK), a Director, an International Board and a first significant tranche of funding. Another Roadmap priority, the Cherenkov Telescope Array (CTA) has been awarded European funding to cover its Preparatory Phase and an organisation is being set under the auspices of a Resource Board.

The massive, multi-national, millimetre/submillimetre interferometer on the 16,000ft high Atacama Plateau, ALMA<sup>21</sup>, is now undertaking fantastic new science even though it is not yet complete and so is nowhere near its full potential. The extension to the Plateau du Bure interferometer, NOEMA<sup>22</sup>, (the Northern Extended Millimeter Array) has now entered the construction phase, while the new technology of SCUBA-2<sup>23</sup> on the James Clerk Maxwell Telescope (JCMT) is producing major surveys that will also provide a wealth of data for ALMA follow-up. Exoplanet research has come on leaps and bounds, spearheaded by Kepler. From the ground, instruments such as HARPS<sup>24</sup> (and now HARPS-North) along with WASP

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<sup>21</sup> <http://www.almaobservatory.org/>

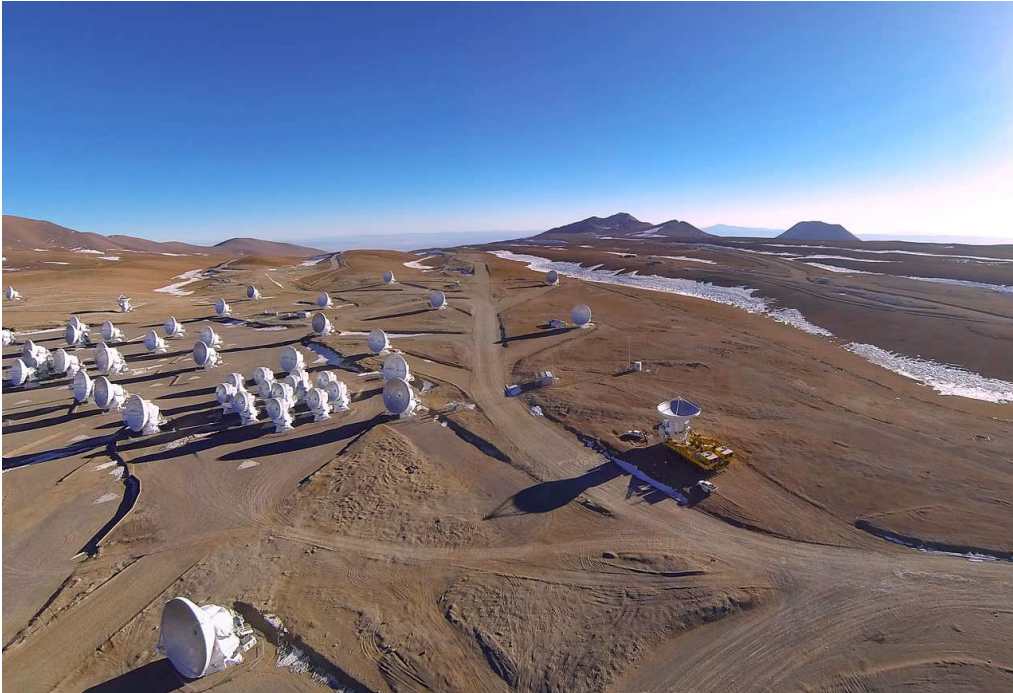
<sup>22</sup> <http://iram-institute.org/EN/noema-project.php>

<sup>23</sup> <http://www.stfc.ac.uk/UKATC/projects/scuba2/whatis/35374.aspx>

<sup>24</sup> <http://www.eso.org/sci/facilities/lasilla/instruments/harps.html>

and Super-WASP<sup>25</sup> are providing further discoveries as well as detailed studies of exoplanet properties.

The unique airborne observatory, SOFIA<sup>26</sup>, with its 4m telescope housed in a Boeing 747SP, is fully operational and making exciting new observations. However, budget cuts in the US and a very recent review panel recommendation have put this mission under threat. The European link lies with Germany.



*The final antenna arriving at the ALMA site on the Chajnantor Plateau in Chile. Photo credit A. Marinkovic/X-Cam/ALMA (ESO/NAOJ/NRAO)*

While the approval of new projects has been very welcome, the economic climate has not allowed any significant uplift of astronomy budgets over the short- to medium-term and the, at best, flat-cash (no inflation increase) annual budgets have put squeezes on current infrastructure and staff. The support for ground-based facilities is one example where a number of world-class observatories are facing difficulties or changes of ownership due to lack of funding (e.g. James Clerk Maxwell Telescope, United Kingdom Infrared Telescope-UKIRT).

The end product of all of these missions and facilities is data and the explosion in the quantity and quality of data from ground- and space-based facilities have presented new challenges for storage, analysis, and distribution. In the realm of the Virtual Observatory (VO)<sup>27</sup>, the efficient and interoperable access to this wealth of data, computed in simulations, and curated

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<sup>25</sup> <http://www.superwasp.org/>

<sup>26</sup> [http://www.nasa.gov/mission\\_pages/SOFIA/](http://www.nasa.gov/mission_pages/SOFIA/)

<sup>27</sup> <http://www.ivoa.net/>

by information services is increasingly important. This is especially the case in this era of multi-wavelength survey science and ‘big data’. The VO is the e-Infrastructure for astronomy that provides the framework for seamless, unified access to standardized astronomy data services. It is embraced as a world-wide community-based initiative, and is transforming the way astronomy research is done. This Roadmap update shows significant progress since 2008 including the successive EC funded projects that have supported the development of the VO, the continued take-up of VO techniques in astronomy data centres, and the current efforts to establish VO as a sustainable component of the astronomy infrastructure. This is not only for past-data, but more importantly for future data-sets, that will be immense and face challenges in data-handling (see Chapter 6)..

While this is mostly a great success story, this is not the time for complacency. In order to remain at the forefront of world astronomical science Europe must ensure that technological developments continue at the right level in order to provide the necessary platforms for future instruments and facilities. These are discussed in the specific Chapters that follow.

### 1.3 The document history

The update process began with a kick-off meeting in Schiphol in February 2013, which included many of those who produced the Science Vision Update. Community input has been provided through a web-based forum and presentations at meetings. Because this is a ‘light-touch’ update, a specific, pan-European, community-based meeting was not deemed necessary and instead special sessions at the European Week of Astronomy and Space Science (EWASS) were used during 2013 and 2014 (see below). This was in addition to national astronomy meetings across Europe.

The first draft of the Update was compiled by the members listed in the Appendix A following the meeting described above. This draft was published on the web for community input in June 2013. Input was also obtained through an on-line forum, communication through members and a one-day presentation at the European Week of Astronomy and Space Science (EWASS)<sup>28</sup> in Turku in July 2013.

As noted above, the document was essentially completed in the late summer of 2013, but it was decided to await the outcomes of the ESA Cosmic Visions L2/L3/M3 deliberations given the importance they have on the field. Following the ESA decisions, the ASTRONET Executive reviewed the next draft in May 2014 and this was subsequently published on the ASTRONET web in early June. This was followed by a special community session at the EWASS meeting in Geneva in July. The on-line forum was closed two weeks later, the final draft was completed by the end of July and the final document was signed off for publication by the ASTRONET Executive.

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<sup>28</sup> <http://www.astro.utu.fi/EWASS2013/>



*The VISTA survey telescope in its enclosure at the Paranal Observatory in Chile. Photo courtesy of Steven Beard/UKATC/ESO*



## 2 Decisions and changes since the Roadmap of 2008

### 2.1 Space

#### 2.1.1 ESA

The Rosetta mission aims to study and attach a lander onto the comet 67P/Churyumov-Gerasimenko, is about to be realised. Launched in 2004 and after a ten-year journey encompassing four orbits of the Sun, Rosetta has just been re-awakened from its deep sleep and will finally arrive at its destination in August 2014. It will then begin more than a year-long study of this ancient world, very recently shown to be a more of a binary body than a single nucleus.



*Artist impression of the Rosetta's lander, Philae, on the surface of comet 67P/Churyumov-Gerasimenko. Image courtesy of ESA/ATG medialab.*

Herschel and Planck were launched in 2009. Both missions have been truly spectacular. The cryogenics for Herschel were exhausted in April 2013 and the satellite was decommissioned a couple of months later. Planck was finally switched off in October 2013.

The Gaia satellite was launched on December 19<sup>th</sup> 2013, entering its operational orbit in January 2014. It has just completed commissioning and is now operational, working extremely well. It is commencing its mission to produce a stereoscopic and kinematic census of about one billion stars in our Galaxy and throughout the Local Group.

For the future ESA missions, the two medium missions (M1 and M2) were selected in October 2011 and they are:

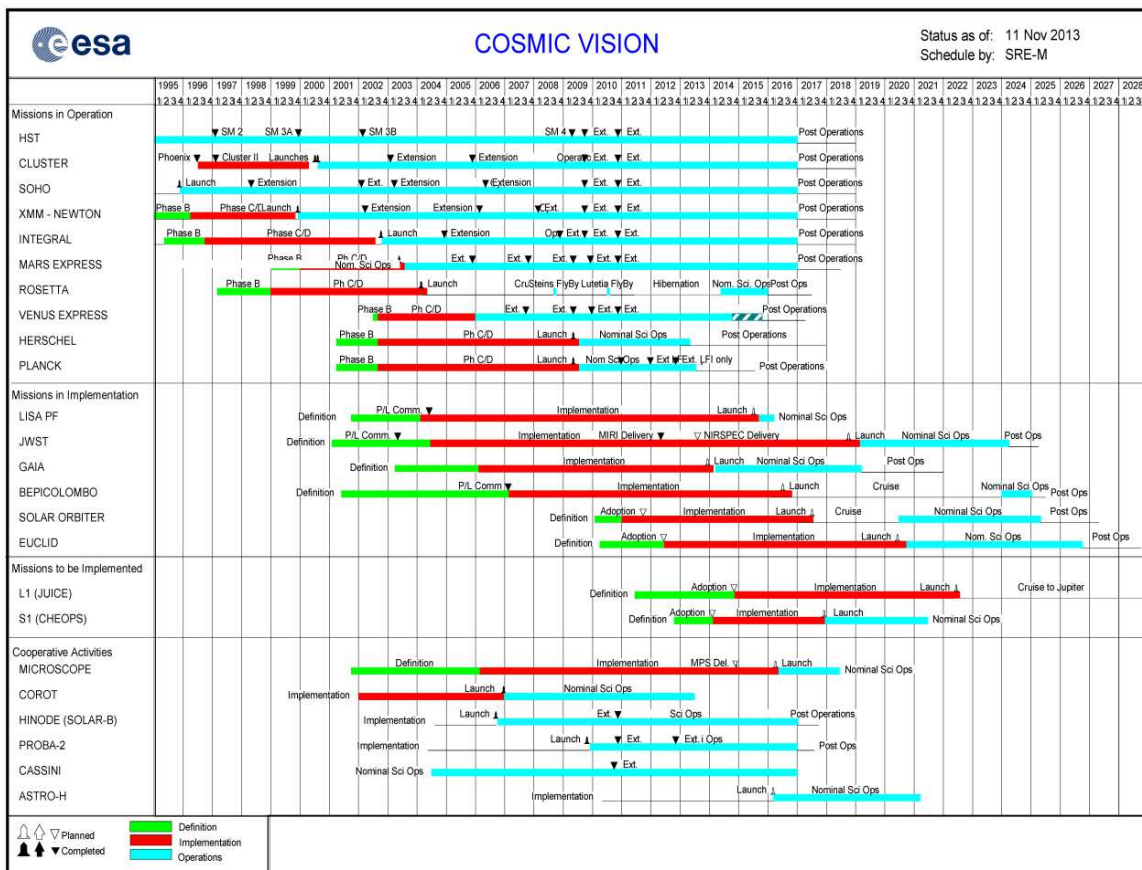
M1: Solar Orbiter, with a planned launch in 2017 – a mission to study the Sun from an out-of-the-ecliptic vantage point and perform the closest-ever in-situ measurements of local near-Sun phenomena

M2: Euclid, with a planned launch in 2020 – to map the geometry of the dark Universe, measuring the distance-redshift relation and the growth of structure by using two complementary Dark Energy probing methods: baryon acoustic oscillations and weak gravitational lensing

The first large mission (L1) of the ESA Cosmic Vision programme was selected in April 2013. The successful candidate was JUICE with a planned launch in 2022 – a mission to study the giant gaseous planet Jupiter and three of its moons, Europa, Ganymede and Callisto in unprecedented detail.

In the midst of this process, ESA introduced a ‘small’ class mission, designated S1, and the successful candidate, CHEOPS, was selected in October 2012. This mission, with a planned launch in 2017, aims at characterising transiting exoplanets around known bright and nearby host stars.

During this period ESA decided to commit to the L2 and L3 missions and asked for suggestions for investigatory themes (rather than specific missions/telescopes). The result of the ‘thematic white papers’ for the L2 and L3 missions was announced in late November 2013. The outcome was that the first mission, L2, to be launched in 2028, will study the hot



ESA Cosmic Visions schedule as of November 2013. Image courtesy of ESA

and energetic universe via a large X-ray observatory, Athena. The following large mission, L3, is the study of the Universe through gravitational waves and will be launched in 2034.



Finally, in the ESA Cosmic Visions programme, the successful M3 project, PLATO, with a launch planned for 2024, was selected in February 2014 to open a new way in exoplanetary science, by providing a full statistical analysis of exoplanetary systems around stars that are bright and nearby enough to allow for simultaneous and/or later detailed studies of their host stars.

### 2.1.2 National, bi-lateral and other missions

The Solar Dynamics Observatory was launched in February 2011 and is part of NASA's Living with a Star Programme. STEREO is another NASA mission and both have European collaborations. Both missions are providing valuable data on our Sun.

NASA's Fermi and SWIFT are making important observations in the high-energy regime and have European collaboration along with the Alpha Magnetic Spectrometer<sup>29</sup> (AMS) which is searching for antimatter in cosmic rays on-board the International Space Station.

The French-Italian X-ray mission, SIMBOL-X, was cancelled in 2009; however, collaboration with Russia and China helps to maintain some new European X-ray astronomy instrument activity (see 3.2.2.1). The Max Planck Institute (MPE) is providing the e-ROSITA<sup>30</sup> X-ray instrument on-board the Russian Spectrum-Roentgen-Gamma (SRG) satellite, which is planned to launch in 2015.

## 2.2 Ground-based

### 2.2.1 Facilities

The ESO VISTA 4m survey telescope with a 67 megapixel infrared camera saw first light on Paranal in late 2009 and has been performing extremely well ever since. The 2.6m VLT survey telescope (VST), with a 268 megapixel optical camera saw first light in 2011 and is also operating very successfully. The William Herschel Telescope (WHT) on La Palma has been given a new lease of life with a new instrument; WEAVE (see 4.2.2.1), which will provide wide-field spectroscopic follow-up to Gaia. Other 4 and 2m class telescopes on La Palma do not have such a clear-cut future (see 4.3.1, 7.5, 8.1). The Spanish-led 10m Gran Telescopio Canarias (GTC)<sup>31</sup> telescope on La Palma has made steady progress since the start of operations in 2009.

The Pierre Auger Cosmic Ray Observatory<sup>32</sup> has been operating successfully for a number of years studying the ultra-high energy cosmic ray events detected through the Cherenkov light in the Earth's atmosphere. It has provided clues on the evolution of their composition with

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<sup>29</sup> <http://ams.nasa.gov/>

<sup>30</sup> <http://www.mpe.mpg.de/eROSITA>

<sup>31</sup> <http://www.gtc.iac.es/>

<sup>32</sup> <http://www.auger.org/>

energy and put new constraints on their origin. Cherenkov light is also used to study very high energy gamma-rays with the MAGIC<sup>33</sup> and HESS<sup>34</sup> suites of telescopes.



*The two 17m diameter gamma-ray telescopes of the MAGIC Observatory on the island of La Palma with the Gran Telescopio Canarias (GTC) in the background. Photo courtesy of Robert Wagner, Stockholm University.*

LOFAR<sup>35</sup> has made major strides since 2008 and is now fully operational with 36 stations in the Netherlands and other stations in Germany, France, Sweden and the UK. It has already made new and innovative observations and in terms of understanding how to operate such an array is an ideal pathfinder for the SKA. The ALMA millimetre/submillimetre synthesis array has made spectacular progress and all of the antennae are now in position at the observing site and first science is already well under way. While nowhere near its full potential, the first scientific discoveries are demonstrating the transformational capabilities of this multinational project. The European participation and access is managed by ESO.

The GREGOR<sup>36</sup> 1.5m solar telescope on Tenerife was inaugurated in 2012 and is currently commissioning a multi-conjugate adaptive optics system in order to achieve the highest possible resolution.

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<sup>33</sup> <https://magic.mpp.mpg.de/>

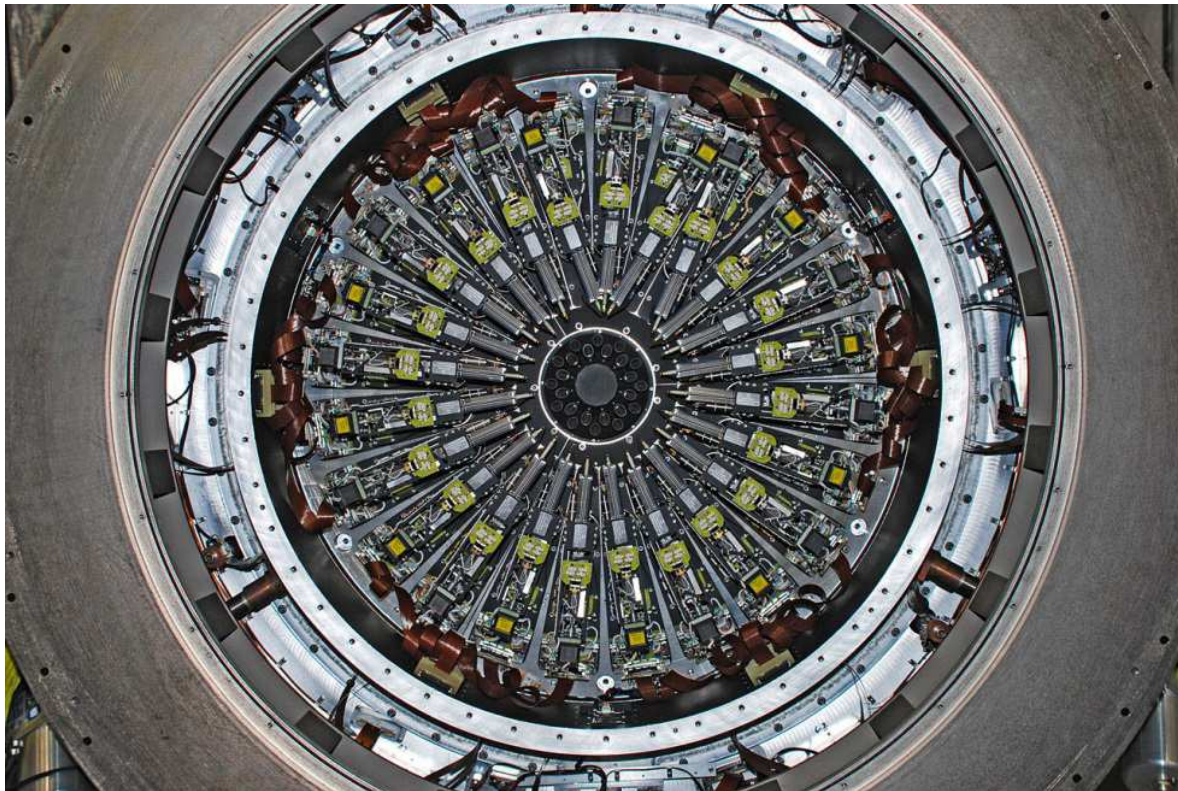
<sup>34</sup> <https://www.mpi-hd.mpg.de/hfm/HESS/>

<sup>35</sup> <http://www.lofar.org/>

<sup>36</sup> <http://www.kis.uni-freiburg.de/index.php?id=163&L=1>

### 2.2.2 Major Instruments

X-SHOOTER, KMOS, MUSE and SPHERE have been introduced to the VLT. Two new instruments have been provided for the VLTI (AMBER and MIDI); while the PRIMA instrument has recently been cancelled in order to focus on ensuring that the facility is ready for the two new instruments of Gravity and MATISSE. Initially installed as visitor instrument, PIONIER is now part of the VLTI suite and permits unprecedented imaging capabilities at the resolution of a milli-arcsecond. Submillimetre arrays are now being delivered; the first and largest being SCUBA-2 on the JCMT, while other large arrays developed within Europe are being deployed on the APEX telescope.



*The 24 arms feeding the multi-object spectrometers of the KMOS instrument on the VLT. Photo courtesy of UKATC/STFC/ESO*

### 2.3 Other

The Stratospheric Observatory for Infrared Astronomy (SOFIA), an airborne platform with a 4m telescope funded by NASA and the German Aerospace Center (DLR) obtained first light in 2010 and has been in operation since that time, recently undertaking the 100<sup>th</sup> flight. However, budget cuts within NASA have recently put pressure on the continuation of this project.



*The SOFIA airborne observatory housing a German-built 2.5m telescope. Photo courtesy of Jim Ross/NASA.*



### **3 Panel-A: High Energy Astrophysics, Astroparticle Astrophysics and Gravitational Waves**

#### 3.1 Introduction

ESA's recent decision to investigate the hot and energetic universe via a powerful, next generation, X-ray observatory (Athena) for its L2 mission changes the future outlook of high-energy astrophysics both in Europe and in the world. The world astronomical community relies on workhorses facilities such as NASA's Chandra and ESA's XMM-Newton, whose continued operations since 1999 provide the essential X-ray astronomy view of the Universe that astronomy needs. In addition, contributions in the form of smaller missions such as JAXA's Suzaku and NASA's NuStar have also proven very important. Activities of the X-ray astronomy community are now focussed on optimising the design of the X-ray telescope, as well as the suite of instruments needed to achieve its ambitious goals. Also, the ESA L3 selection of a mission dedicated to the search for low frequency gravitational waves (inaccessible from the ground) is extremely important and such a mission is clearly needed and will certainly break new ground, ranging from astrophysics to cosmology. However, with a launch projected for 2034 it might be difficult to maintain the necessary teams in place and this is an aspect that will need careful management.

*Recommendation 3.1: ESA and national agencies need to plan for the retention of key skills and key teams for the long lead-time missions of Cosmic Vision.*

While no new space mission dedicated to gamma-ray astronomy is in sight, the field of gamma-ray astronomy continues to move forward through attempts to boost the performances of ground-based Cherenkov telescopes (e.g. MAGIC, HESS, Veritas), which will provide the main observing tool in the coming years.



*ESA's XMM-Newton X-ray Observatory. Image courtesy of ESA*

## 3.2 High Priority New Projects

### 3.2.1 Ground Based Near-Term

#### 3.2.1.1 CTA

While the existing Very High Energy (VHE) gamma-ray experiments, such as HESS, MAGIC and VERITAS continue to operate and to obtain important results, the world community is getting ready for the Cherenkov Telescope Array (CTA) gamma-ray observatory. This is moving forward vigorously and is now completing a three-year preparatory phase of telescope construction prototyping. This is funded by a European grant in conjunction with significant national investments (especially from Germany and Italy). The CTA collaboration now encompasses more than 1,000 scientists from 27 countries and a legal CTA entity was founded in mid-2014. A major milestone was completed in April 2014 with the shortlisting of two observing sites in Chile and Namibia for the Southern site, with on-going discussions on a site for the Northern array.

It should also be noted that the high priority accorded in the original ASTRONET and ASPERA rankings, as well as in the US Decadal Survey, certainly helped to establish CTA as the major instrument in very high-energy astrophysics at global world-wide level. Efforts are currently underway to obtain the funding to commence construction as soon as possible; which would be a decision in mid-2015 and construction to begin in 2016. CTA, which is part of the ESFRI Roadmap, is also one of the two astronomy projects (the other being the SKA-see later) being proposed to the EU's Horizon 2020<sup>37</sup> programme.



*Artist impression of the CTA Observatory. Image courtesy of the CTA-Observatory*

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<sup>37</sup> <http://ec.europa.eu/programmes/horizon2020/>

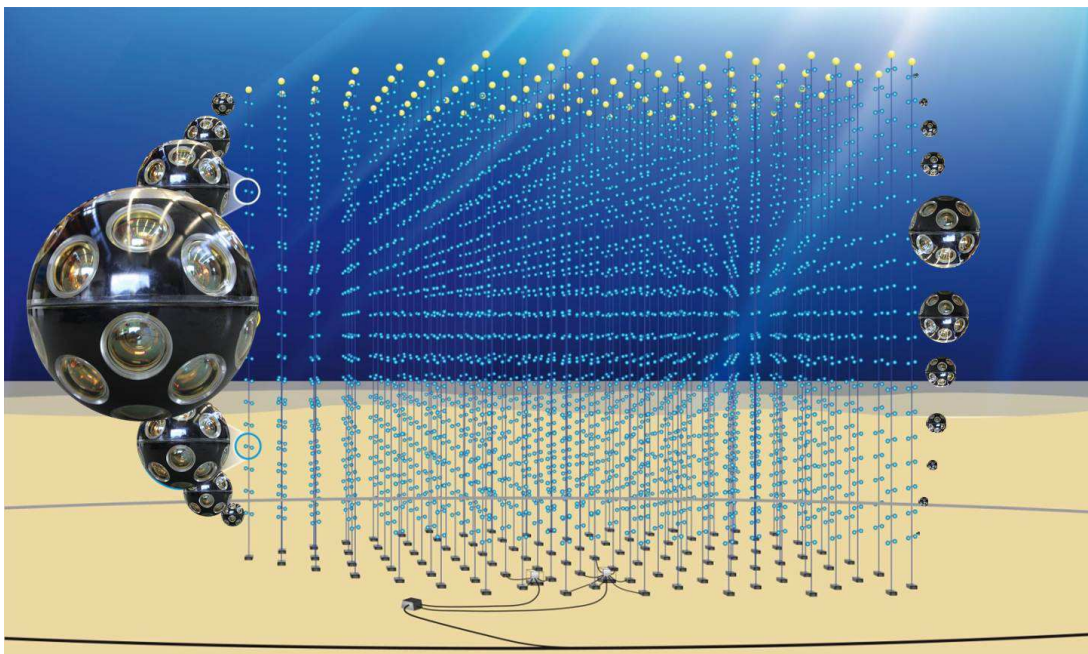


It is also important to note that developments in ground-based, gamma-ray detection are pushing towards lower energy thresholds, with detection of  $\sim 10$  GeV gamma-rays from the ground being a realistic prospect. This will close the present energy gap between satellite detectors and ground-based Cherenkov telescopes and has a potential for major impact in high-energy astrophysics, where no space successor of the Fermi telescope is foreseen. However, since Cherenkov telescopes are pointed observatories (as opposed to scanning ones like Fermi), a vigorous multiwavelength effort is needed to survey the sky pinpointing potentially interesting targets.

*Recommendation 3.2: strengthen multiwavelength collaborations through dedicated programmes and grants*

### 3.2.1.2 KM3NeT

Neutrino astronomy is enjoying more and more attention thanks to the preliminary results of the IceCube Observatory<sup>38</sup> located 1km beneath the ice of the South Pole. Currently KM3NeT has €40M funding for phase-1 and good progress has been made in the Mediterranean Sea with the deployment and operation of the first module (DOM - Digital Optical Monitor) in April 2013. Currently there is an ongoing debate between the particle physics and astrophysics communities regarding the optimisation of the geometry and the size of the final KM3Net. Once phase 1 is complete (in 2014-15) phase 1.5 will commence. This will look to achieve the implementation part of the project and is costed at €90M for which there is currently commitment from France, Italy and the Netherlands. The decision whether to double the size of the array (phase 2) will be made in 2016.



*Artist impression of KM3NeT deployed, courtesy of Marc de Boer/Ori Ginale and the KM3NeT Collaboration*

<sup>38</sup> <http://icecube.wisc.edu/>

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

The origin and composition of cosmic rays of ultra-high energy continues to be one of the least understood phenomena in the Universe. Their study is being pursued from space with the Alpha Magnetic Spectrometer (AMS) on board the International Space Station and from the ground with an international facility such as the Pierre Auger Observatory. The AMS, a NASA-led mission with major European participation, has recently released its first results focused mainly on the precise measurement of the electron-positron ratio in cosmic rays.

The Pierre Auger Observatory, a huge 3,000 km<sup>2</sup> particle array combined with four wide-angle optical telescopes for atmospheric fluorescence light and located in the Southern Hemisphere (Argentina), is now fully operational and its results demonstrate the existence of a statistically significant spectral feature (steepening or cutoff) at around  $5 \times 10^{19}$  eV. The Auger collaboration proposes to build a significantly larger array in the Northern Hemisphere, called AugerNext, in order to increase the statistics at higher energies and to access the whole sky. The AugerNext consortium consists presently of fourteen partner institutions from nine European countries supported by a network of European funding agencies. It was one of three projects whose preparatory work was funded by the Astroparticle Physics European Community (ASPERA), to the tune of €1.8M, and it is a principal element of the ASPERA/ApPEC<sup>39</sup> strategic roadmaps.

### 3.2.2 Space Based Near-Term

#### 3.2.2.1 X-rays

Before the ESA selection of a next generation X-ray telescope for its L2 mission, the X-ray community was facing an uncertain future since, while thriving on the legacy of Chandra and XMM-Newton (supplemented by Suzaku and nuStar) no major mission was in sight. The cancellation of Simbol-X (hard X-ray imaging), highly rated in the original ASTRONET Roadmap, was disappointing but was partially mitigated by the NASA mission nuStar. This is an Explorer (small) class mission, which has a small European participation. In the field of high energy X-ray astronomy, collaborations are underway between Europe and China for the Hard X-ray Modulation Telescope<sup>40</sup>, which will be the first Chinese astronomy satellite. This has a launch planned for 2016.

The German (DLR) e-ROSITA X-ray telescope provided by MPE on-board the Russian Spektrum-Roentgen-Gamma (SRG) platform is planned to perform a sensitive sky survey in low-energy X-rays and is approaching launch, now foreseen to be not before December 2016. The NASA NICER (Neutron Star Interior Composition ExploreR) mission, a soft X-ray instrument to be installed on the International Space Station, is also foreseen for a launch in

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<sup>39</sup> <http://www.appec.org/>

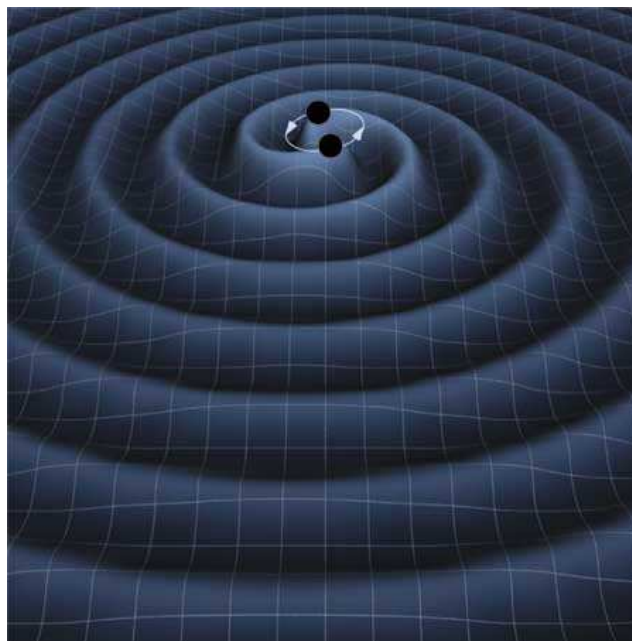
<sup>40</sup> <http://www.hxmt.cn/english/>

2016. Finally, the French-Chinese project SVOM<sup>41</sup>, devoted to the study of Gamma-Ray Bursts on the wake of the success of the SWIFT mission, is now ready to start anew after being on hold for some time and has a launch planned for 2018.

*Recommendation 3.3: Continuing R&D technological research activities remains of paramount importance to maintain European leadership in the field of high-energy astrophysics*

### 3.2.3 Gravitational Waves

The selection of a gravitational wave observatory for the ESA L3 mission provides a clear roadmap in the field of low-frequency gravitational wave observations from space, albeit with a lengthy timespan before the planned launch in 2034. In the meantime, the long-delayed proof-of-concept LISA Pathfinder will test the concept of low-frequency gravitational wave detection by putting two test masses in a near-perfect gravitational free-fall, while controlling and measuring their motion with unprecedented accuracy. The launch is currently scheduled for 2015.



*Artist's impression of gravitational waves from two orbiting black holes. Image courtesy of: T. Carnahan (NASA GSFC)*

### 3.2.4 Ongoing Space Missions

The ongoing missions of XMM-Newton and INTEGRAL are performing well and recently their operations have been extended by ESA up to 2016 with a mid-term review in 2014. This has certainly been aided by the strong recommendations that were in the original ASTRONET Reports.

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<sup>41</sup> <http://smc.cnes.fr/SVOM/>

Furthermore, the very good performances of a number of high-energy missions, either European-led, or with an important European contribution should be highlighted. Apart from XMM-Newton and INTEGRAL, some teams of the European astronomical community can access data collected by SWIFT, AGILE and Fermi, making this decade a golden one for high-energy astrophysics. While AGILE has been extended up to mid-2015, SWIFT and Fermi received a very good rating in the previous NASA Senior Review and their funding is secured up to 2016 with an intermediate review in 2014.

*Recommendation 3.4: In view of the excellent health of the XMM-Newton and INTEGRAL missions, this panel feels confident to strongly endorse, yet again, their continuation. Moreover, this panel welcomes the outcome of the recent NASA Senior Review, which has approved the continuation of SWIFT and Fermi operations for between 2 and 4 years.*

### 3.3 Conclusions

The conclusions remain valid and there are very exciting developments on the horizon for the high-energy community, but in space the ambitions required by the Science Vision can only be realised by a carefully planned, long-term strategy of the space agencies, for which they probably need to act jointly. Should funding and national priorities permit, there is clearly time for NASA (and other agencies like JAXA) to become involved with the two L-class missions (L2 and L3) to enhance their capability. The lengthy timescale for L2 and L3 needs careful thought in terms of maintaining teams and adequate career progression and reward, especially on the research front as noted in the recommendation above.

Although not mentioned above, it should not be forgotten that on the ground-based gravitational wave front, progress continues with the VIRGO<sup>42</sup>, GEO600<sup>43</sup> and the LIGO<sup>44</sup> projects. Furthermore, the European FP7-funded conceptual design study for the Einstein Telescope<sup>45</sup> has now been completed.

There is one area in which prioritisation will most likely need to be made and this is in the astroparticle physics domain, where the CTA and KM3NET are essentially competing for available funding. One possibility is that one of the projects might be phased more downstream, hence removing immediate competition (as was the recommendation for the E-ELT and SKA funding from the original Roadmap). This is something that is under vigorous discussion by the European Astroparticle Physics Consortium (ApPEC) and no further actions are needed.

A note in passing is that a number of dark matter direct detection experiments are being conducted but these general fall outside the sphere of astronomy.

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<sup>42</sup> <http://www.ego-gw.it/index.aspx>

<sup>43</sup> <http://www.geo600.org/>

<sup>44</sup> <http://www.ligo.caltech.edu/>

<sup>45</sup> <http://www.et-gw.eu/>

## **4 Panel B: Ultraviolet, Optical, Infrared and Radio/mm Astronomy**

### 4.1 Introduction

Since the publication of the Roadmap the situation regarding current opportunities and future perspectives for the European astronomical community has evolved substantially in many of the wavelength regimes covered by Panel B. In the optical/near-infrared domain, where Europe has taken the worldwide lead with the four Very Large Telescope (VLT) units, the Very Large Telescope Interferometer (VLTI) and their associated suite of focal plane instruments (which is still evolving), the top-priority – the European Extremely Large Telescope project (the E-ELT) – is now approved, albeit not quite yet fully funded.



*ESO's Observatory at Paranal in Chile showing the four VLTs the VST, the Ancillary Telescopes of the VLTI and in the background, the VISTA telescope. Photo courtesy of ESO/G.Hüdepohl*

In the (sub)-millimetre, the construction of the Atacama Large Millimetre Array (ALMA) project, in which Europe is a partner through ESO together with the US National Science Foundation and Japan's National Institutes for Natural Sciences (both parties representing further institutions in Canada and Taiwan), is almost complete and scientific operations have already started. Indeed, given that all initial ALMA bands will be completed in 2014, it seems timely to start work on adding additional (missing) bands. Europe's role in this wavelength range will be further enhanced as the construction of 4 more antennas for the Plateau de Bure Interferometer progresses. This first phase of the approved NOEMA project is due for completion by 2016. During Phase 2 a further 2 antennas will be added, but currently this is not yet funded.



In the longer wavelengths radio domain, LOFAR has started operations and has produced the first significant science results. The preparation of the world-class future project, the SKA, has now moved into a well-defined project with site selection decided as discussed below.

Thanks to ESA's Horizon 2000 and 2000+ and Cosmic Vision programs, Europe continues the exploitation of the Hubble Space Telescope (HST), whose lifetime has been prolonged. The follow-up mission, the James Webb Space Telescope (JWST), to which Europe contributes in a significant manner, is now delayed to a launch in 2018. Continued European participation in the project is seen as a very important mid-term priority. Europe's leading position in astrometry, which had been established through ESA's HIPPARCOS mission, will be greatly enhanced by the much more powerful Gaia mission, which was successfully launched in December 2013. Exploiting Gaia data is an important near- and mid-term priority for European astronomy and requires significant funding.

Planck and Herschel have both produced a wealth of data before running out of cryogenic coolant. Both missions have already strongly impacted fields like cosmology, galaxy evolution and star formation, and will continue to do so through extensive data analysis that will continue for at least 5-10 years. This is another important mid-term priority for Europe.

As noted earlier, the Dark Energy mission, EUCLID, which was given top priority in the previous Roadmap was selected for the ESA M2 slot, while CHEOPS, a mission to characterize exoplanets by ultrahigh precision photometry was selected for the S1 launch slot in 2017. The recent decision for the M3 mission resulted in success for PLATO, an exoplanet transit and asteroseismology mission that will be launched in 2024.

As emphasized in the previous Roadmap (Chapter 7), the 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, nor available funding, and such funding comes from an ad-hoc mixture of national support and EC-sponsored scientific networks. An enlarged and better structured European support for scientific exploitation of large infrastructure is urgently needed and would significantly enhance their scientific productivity. This applies immediately to Herschel/Planck and GAIA and in the future the JWST.

*Recommendation 4.1: ESA, the EU and national agencies should address the potential for a more coherent funding arrangement for the exploitation of scientific data from space missions.*

## 4.2 High priority new projects

### 4.2.1 Ground-based, near-term (-2015)

#### 4.2.1.1 Development of wide-field, multiplexed spectrometers for 8m-class telescopes

A very strong scientific case for the development of wide-field, multiplexed spectrometers has existed for many years and was a high priority recommendation of the Roadmap and of

the updated Science Vision. The term ‘wide-field’ here means a field-of-view (FOV) of at least 1.5 degrees (with a goal of 3 degrees) in order to provide simultaneous spectroscopic observations of thousands of objects over a FOV matched to the scientific requirements, comparable to that envisaged for the next generation wide-field imagers, e.g. the Large Synoptic Survey Telescope (LSST).

In the last 5 years, wide-field imaging has grown beyond expectation, and will continue to grow with the availability of new ground-based survey telescopes like the VST and VISTA at ESO, or later in space with EUCLID. The Gaia satellite needs to be complemented by a ground-based, wide-field spectrometer to measure radial velocities and stellar parameters ( $T_{\text{eff}}$ , detailed abundances, etc.) of thousands of stars fainter than magnitude 16.5, which cannot be observed by the Gaia on-board spectrometer. Furthermore, wide-field X-ray surveys by e-ROSITA, and in the far infrared with Herschel will be, or are already, creating large samples of objects that can be looked at with wide-field spectrometers to study very faint and distant starburst galaxies, AGNs and QSOs.

Currently, on the international stage, ground-based facilities tend to focus on imaging surveys, i.e. MEGACAM<sup>46</sup> at the Canada France Hawaii Telescope (CFHT), the VLT Survey Telescope (VST) and the Visible & Infrared Survey Telescope for Astronomy (VISTA) at ESO, the Panoramic Survey Telescope And Rapid Response System (Pan-Starrs)<sup>47</sup> and in the future, the LSST<sup>48</sup> in the USA. These will provide insights into the Dark Energy through weak lensing measurements, supernova measurements, and by revealing the distant galaxy distribution. The same is true for space projects, Gaia and EUCLID (see Section 4.2.4) in Europe which will have spectroscopic capabilities either limited to bright objects, or optimized for complementary (low resolution, near-infrared) wavelengths. Multi-object spectroscopy is a natural and much needed complement to existing wide-field imaging surveys such as those mentioned above.

The good news is that excellent progress has been made in this area following on from the original Roadmap recommendations. In 2010, ESO issued a call among its community for a wide-field spectrometer. Two concepts, MOONS<sup>49</sup> and 4MOST<sup>50</sup> were reviewed in 2013 and selected to proceed to a design and construction phase with MOONS scheduled for first-light in 2018 and 4MOST in 2019.

MOONS is a multi-object spectrometer in the visible and the near IR for the VLT. It will provide a field-of-view of 25 arcmin and 500 fibres for objects and 500 for sky references. This instruments aims to study faint and distant galaxies. The 4MOST instrument is designed for a 4m class telescope, initially this was either VISTA or the NTT and VISTA has been selected. The field-of-view is projected as 3 degrees with 3000 fibres. It will have two

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<sup>46</sup> <http://www.cfht.hawaii.edu/Instruments/Imaging/Megacam/>

<sup>47</sup> <http://pan-starrs.ifa.hawaii.edu/public/>

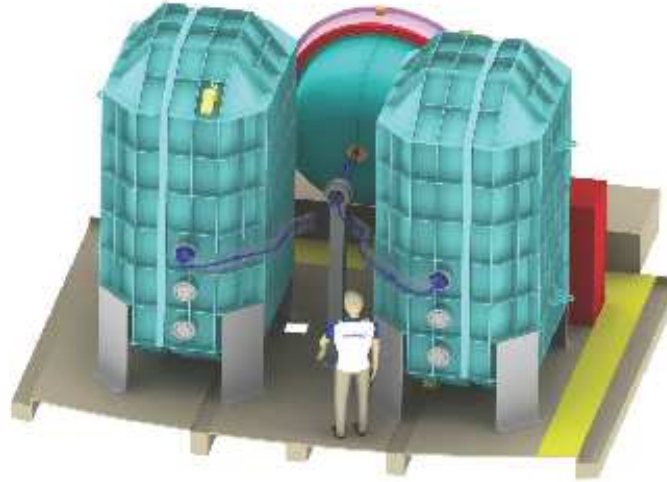
<sup>48</sup> <http://www.lsst.org/lsst/>

<sup>49</sup> <http://www.roe.ac.uk/~ciras/MOONS/VLT-MOONS.html>

<sup>50</sup> <http://www.aip.de/en/research/research-area-ea/research-groups-and-projects/4most/>



operating modes: a low and a high spectral resolution mode. Scientific targets are the follow-up of targets too faint to observe with the Gaia spectrometer (see next), a ground-based optical follow-up of targets for the e-Rosita X-Ray mission and large coverage spectroscopic programme following the Euclid mission.



*Design outline of the MOONS instrument as it will reside on the Nasmyth platform of the VLT. Image courtesy of Michele Cirasuolo/UKATC and the MOONS Consortium*

A third project, WEAVE<sup>51</sup>, is designed to exploit Gaia's scientific legacy and is a prime focus spectrometer for the William Herschel Telescope (WHT). It will have a field-of-view of 2 degrees and about 1000 fibres. It will provide a low-resolution survey for radial velocity measurements of stars that are too faint to be observed by the Gaia spectrometer, along with a high-resolution survey to make accurate determinations of the metallicities and temperatures of the bright stars observed by Gaia. The instrument PDR took place in early 2013, and the start of the surveys should be in 2017, provided adequate funding is secured by all partners (UK, Netherlands, Spain, France and Italy).

The three projects nicely complement each other (northern hemisphere, southern hemisphere, wide coverage, deep exposures), as recommended by the corresponding ASTRONET working group. All these projects should be ready between 2017 and 2020 and their individual costs are estimated at about 40 to 50 M€

These projects also have a notable industrial relevance as several concepts require industrial-scale replication of precision optical, opto-mechanical, electronic, and/or photonic modules, thereby pushing the limits of current industrial practice.

Other projects are under study or in a development phase elsewhere; such as the Dark Energy Spectroscopic Instrument, (DESI-formally Big BOSS) on the 4m Mayall telescope at Kitt Peak. This has a field-of-view of 3 degrees and 5000 fibres. These other projects present

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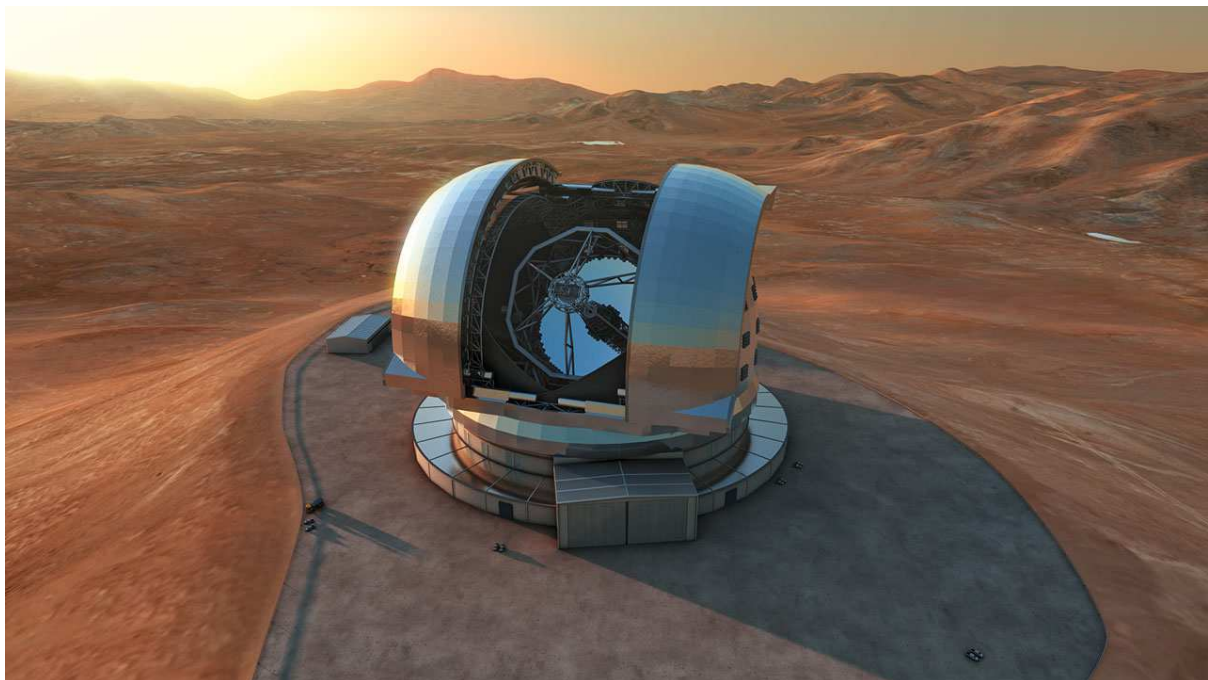
<sup>51</sup> <http://www.ing.iac.es/weave/>

opportunities for bi-lateral collaboration from European countries, while within Europe, the CALIFA<sup>52</sup> survey of galaxies in the local Universe is underway on the Calar Alto 3.5m telescope. To conclude, the landscape is now far better than the situation at the time of the writing of the initial ASTRONET roadmap, with well advanced projects and a well-defined path to have several wide-field spectrometers in operation in the next 5 years.

#### 4.2.2 Ground-based, medium-term (2016-2020)

##### 4.2.2.1 The European Extremely Large Telescope (E-ELT)

The E-ELT project, one of the top-two priorities for Panel B in the original Roadmap, has matured since then. It is now a 39m diameter, filled-aperture phased telescope with an internal Adaptive Optics system designed to provide near diffraction-limited angular resolution in a 5 arcminute (scientific) to 8 arcminute (technical) diameter field-of-view over 80% of the available sky (through the use of multiple natural and laser guide stars). The wavelength domain is from 0.4 $\mu$ m to 21 $\mu$ m. This instrument-friendly facility should accommodate at least six large focal stations with fast switchover in order to optimize its scientific output.



*Artists impression of the E-ELT on Cerro Amazonas in Chile. Image courtesy of ESO/L.Calcada*

A major milestone was achieved in late 2012 when the ESO Council confirmed approval of the E-ELT Programme. As of June 2014, ESO had obtained firm commitments to support this project from all of its member states and once Brazil has ratified its accession agreement to ESO (currently progressing in Brazil's Congress) the E-ELT construction will commence in

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<sup>52</sup> <http://califa.caha.es/>

earnest. In the intervening time, preparatory construction work on the site is being undertaken and long, lead-time items are being procured in order to maintain the project timeline. The construction cost is estimated to be €1.083M (2012 financial conditions), including the costs for the first generation of instruments. First light is expected around 2024.

In the USA there are two main giant optical/IR telescope projects: the Thirty Meter Telescope<sup>53</sup> (TMT), a collaboration of universities in California with Canada, Japan, China and India, to be located on Mauna Kea; the Giant Magellan Telescope<sup>54</sup> (GMT), a collaboration of 8 US universities, Australia and the University of Sao Paolo, Brazil. The construction costs for these two projects will be financed by large private funds. See also Chapter 8.2.1.

#### 4.2.2.2 The Square Kilometre Array (SKA)



*Artists impression of the low-frequency aperture array of the SKA to be based in the Australian Murchison region. Image courtesy of the SKA Telescope Organisation*

Excellent progress has been made on this joint top-priority project, which is now in a preparatory development phase. The concept is for an aperture synthesis radio telescope achieving a sensitivity of at least 50 times that of upgraded existing radio arrays and survey

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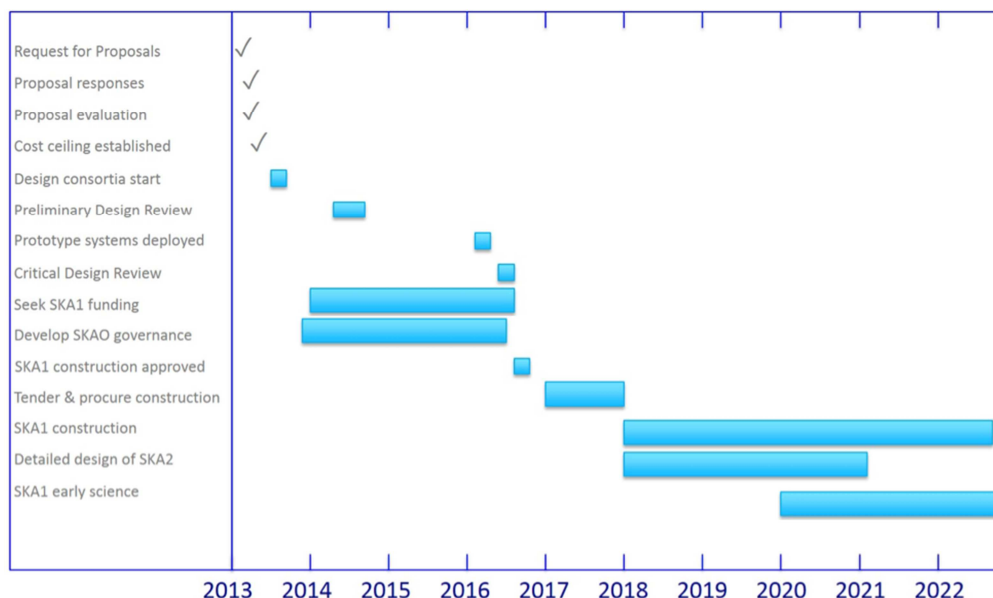
<sup>53</sup> <http://www.tmt.org/>

<sup>54</sup> <http://www.gmto.org/>

speeds 10,000 times faster. The frequency coverage will extend from ~50 MHz to 25 GHz (~50 MHz to ~14 GHz during Phase 1 of the development). There will be a central condensation of antennas, with remote groups of antennas located at distances up to at least 3,000 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.

The SKA is a global collaboration, with Europe aiming to be in the lead position. In 2011 the SKA Organisation was established as a legal entity and currently has its Project Office in a new building at Jodrell Bank in the UK. The project currently comprises institutions from 20 countries: Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, Malta, Netherlands, New Zealand, Poland, Portugal, Russia, South Africa, South Korea, Spain, the UK and US. The project now also has a Director and a major milestone was achieved in 2012 with the selection of the site. A dual location has been chosen; these are in Western Australia, which will host the low-frequency SKA using the aperture array technology, and South Africa, which will host the mid-frequency SKA employing relatively small dishes.

The SKA is in a preparatory development phase. Engineering R&D has been carried out via specifically funded design studies and will continue in an international collaborative fashion in workpackages defined by the SKA Organisation and focusing on all aspects of the SKA design. Regarding the timeline for the project, the years 2014-2016 are foreseen to be a detailed design and pre-construction phase. This will be followed in the years 2018-2023 by the Phase 1 construction activity; the initial deployment (15-20%) of the array at low to mid-band frequencies. Early science operations will commence around 2020. In parallel, during 2018 to 2021 the Phase 2 design work will be undertaken. Phase 2 will provide the full collecting area of the array at low to mid-band frequencies (~70 MHz to ~10 GHz). Full science operations are projected to commence no sooner than 2024.



*Timeline for the SKA Project, courtesy of the SKA.*

The target construction cost for the SKA is €1,500M. The SKA Board has decided that Phase 1 will have a €650M cap to the capital cost of construction. Operational costs of the array are expected to be ~€100M/year. The European contribution to the construction and operational costs will depend on the number of European countries engaged in the project, but is expected to be in the range of 50-60% overall. The Phase 1 design process, which is currently underway, is supported through cash and in-kind contributions from the Member States of the SKA Organisation.

It now appears that the potential serious clash for funding of the SKA and E-ELT that was a major concern for the Roadmap in 2008 has been avoided through a combination of delaying work (through natural causes for the SKA) and seeking additional partners for funding (both). In addition, both projects have benefitted from significant EU funding.

#### 4.2.3 Space-based, near-term (launch until 2015)

##### 4.2.3.1 Gaia Data Analysis and Processing

Europe has taken the worldwide lead in astrometry through its very successful HIPPARCOS mission. Gaia is a follow-up mission with greatly enhanced capabilities and was successfully launched in December 2013. 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. The community participation in the Gaia mission is almost entirely in software and data processing, rather than the hardware instrumental provision typical of ESA missions.

The direct Gaia data will be generated by the Data Analysis and Processing Consortium (DPAC), and will form a crucial data set for all future studies of stellar, solar system, planetary system, and galactic astrophysics, as well as providing the distance scale for large-scale structure and cosmological research. Some 300 individuals in 15 European countries are involved in the processing, calibration and reduction of the raw Gaia data, before it becomes available for scientific analysis by the whole community. As noted earlier, it is vital that this very substantial data analysis and processing effort must be sustained both during the lifetime of the mission (up to 2020) and beyond, probably for another three to four years.

To exploit Gaia's potential to the maximum, the satellite's orbital position needs to be known much more precisely than normal satellite tracking will deliver. To overcome this problem, ground-based observations of the satellite's position need to be organized throughout the mission. This was a key recommendation from the original Roadmap and arrangements have now been put in place by ESA for the immediate future but not yet for the whole mission lifetime.

*Recommendation 4.2: it is important that the determination of Gaia's precise position from ground-based observations should be secured for the total lifetime of the mission.*

The main mission costs (€673.M in 2012 costs) are covered in the ESA Science budget. However, to this the cost for the data reduction and analysis and for ground-based



observations needs to be added and this is not provided by ESA. ESA has subcontracted a significant part of the data processing and analysis activities to an international consortium (DPAC), which is funded by national funding agencies that have signed a long-term multilateral agreement. The currently predicted total costs to the national agencies for data reduction and analysis amounts to about €15M/year (190 FTEs/year) over 14 years.

*Recommendation 4.3: it is vital that national agencies ensure that adequate funding is provided for data analysis to ensure that Europe is best placed to maximise scientific return from the Gaia mission*

#### 4.2.4 Space-based, medium-term (launch 2016-2020)

##### 4.2.4.1 CHEOPS

CHEOPS (CHaracterizing ExOPlanets) was selected by ESA in 2012 as the first S-class mission in the Cosmic Vision 2015-2025 program. It will search for exoplanetary transits by performing ultrahigh precision photometry on bright stars already known to host planets. It will build on previous work, like ground-based searches for exoplanets and space missions like COROT and Kepler and will determine accurate radii for planets known to be in the super-Earth to Neptune mass range. It will also allow the study of the mass-radius relation in a planetary mass range for which currently few data exist. It will furthermore identify planets with significant atmospheres over a range of planetary masses, distances from the host star and stellar parameters. It will place constraints on possible planet migration paths, and probe the atmospheres of known hot-Jupiters. Finally it will provide targets for future ground-based studies and space observatories.

As a ‘small’ ESA mission, CHEOPS will be a small spacecraft with a total launch mass of about 200kg in a low-Earth orbit (800 km). CHEOPS is a low-risk technology project and launch is planned for the end of 2017, with a 3.5 years lifetime. The estimated cost is €90M, with a €50M ceiling for the ESA contribution.

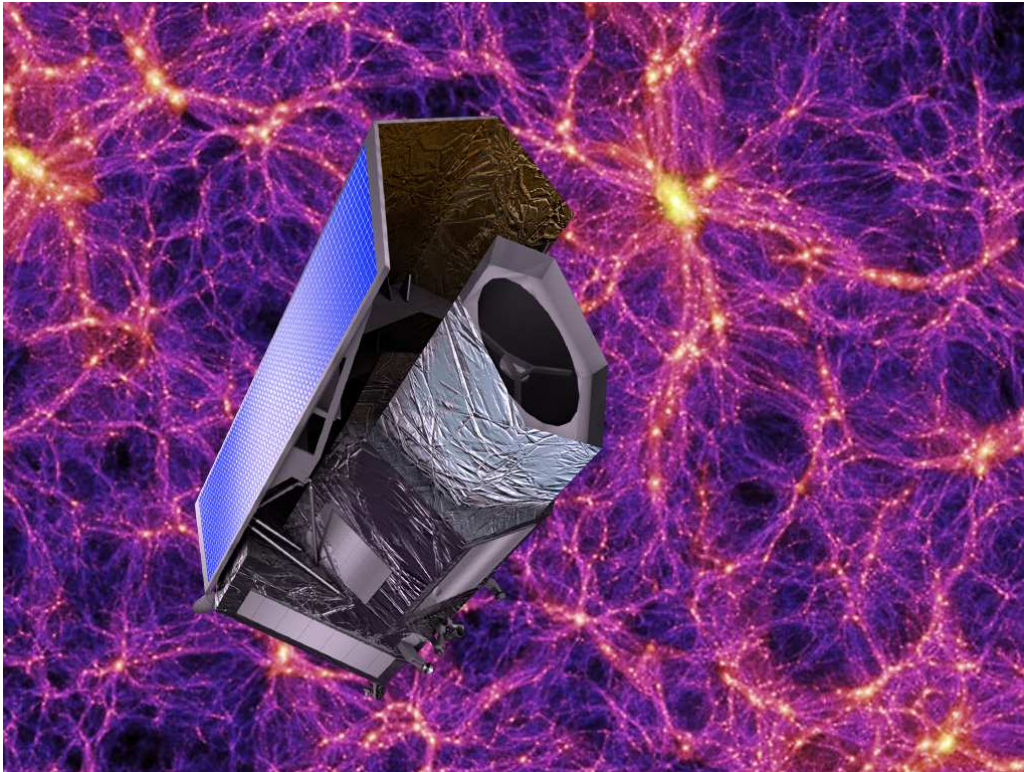
##### 4.2.4.2 EUCLID

The search for Dark Energy was a high priority for the original Science Vision and Roadmap and it was gratifying to see EUCLID selected as the ESA M2 mission for launch in 2020. It operates with a visible imager and near-infrared imager/spectrometer and will combine the Weak Lensing approach with the Baryonic Acoustic Oscillations (BAO) method. EUCLID will have a 1.2 m telescope with a  $\sim 0.5 \text{ deg}^2$  field-of-view, providing optical (550-920 nm) images, near-IR (Y, J, H band) photometry and low resolution ( $R = 400$ ) 0.8-1.7  $\mu\text{m}$  spectroscopy. Over the 6 year mission duration, it will accumulate sub-arcsec resolution images and photometry of  $\sim 1$  billion galaxies and near IR spectra of a subset of about  $10^8$  galaxies down to  $H = 22$  magnitude.

Technically, the key components of the mission build on a significant heritage from other missions and the technological risk appears generally low except for the Ground Segment, where the total amount of data and its processing represent one of the main challenges of the

mission. The other technological challenge is to develop an attitude control system able to achieve 0.1 arcsec pointing stability over long periods of time.

While EUCLID is ESA funded to the sum of €606M, additional funding is anticipated from national agencies to about €150M. Recently NASA has announced that it will contribute to the EUCLID mission as a minority partner, providing the IR detectors. This is an area where Europe remains in need of urgent technology development, to ensure its own capability and to foster European industry building on the excellent heritage of optical detectors (e.g. Gaia, LSST).



*Artists impression of the EUCLID satellite set against the background of the Cosmic Web. Courtesy of ESA*

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

SPICA is a Japanese-led mission with a cooled ( $\sim 5\text{K}$ ) 3.5m telescope to follow-on from Herschel, mainly undertaking spectroscopy over a five-year lifetime. This project was in ESA's program as a 'Mission of opportunity' and ESA's contribution would be the Telescope Assembly and a European Ground Segment. In addition, a nationally funded consortium would provide the SAFARI instrument, a cryogenically cooled Fourier Transform Spectrometer operating over the 30-210  $\mu\text{m}$  range. However, following a 'Mitigation Review' in 2013 the resulting cost increases have pushed the ESA requirement into the M-class category and so a new proposal for an European contribution to SPICA will be presented for the next Medium Class Mission call, M4, which should be issued in late 2014.

The development of the SAFARI instrument involves 49 institutes from 11 countries (7 of which are European). The key new technologies lie in the detectors (Transition Edge Sensors)

and their coolers (Adiabatic De-magnetisation Refrigerator), both of which have a low Technology Readiness Level (TRL) and still require significant development.

#### 4.2.5 Space-based, longer-term - M3 candidates (launch 2021-2025)

##### 4.2.5.1 PLATO – Planetary Transits and Oscillations of Stars

PLATO was submitted to ESA for the M2 launch but was not selected. It was then resubmitted as a candidate for the M3 mission and was successful. It will be a follow-up to the COROT and Kepler missions but with enhanced capabilities allowing the detection of a significant sample of earth-size planets and smaller ones. PLATO will perform high-precision monitoring in visible photometry of a sample of  $> 100,000$  relatively bright ( $V \leq 12$ ) stars and another 400,000 down to  $V=14$ , and will meet stringent requirements: a field-of-view larger than about  $300 \text{ deg}^2$ ; a total duration of the monitoring of at least 3 and preferably 5 years; a photometric noise  $< 8 \times 10^{-5}$  (goal  $2.5 \times 10^{-5}$ ) in one hour for stars of  $V=11-12$ . This data set will allow the detection and characterization of exoplanets down to Earth-size and smaller by their transit in front of a large sample of bright stars, while getting detailed knowledge of the parent stars thanks to asteroseismological measurements. The ability to detect planets around bright and therefore close-by stars will provide targets for more ambitious imaging and spectroscopic missions in the future. PLATO, therefore, can act as a pathfinder for a downstream DARWIN-like mission (see 4.2.6) or the Terrestrial Planet Finder (TPF). As an M3 mission, PLATO will have a cost cap of €508M from ESA and the launch is planned for 2024.

#### 4.2.6 Space-based, long-term (launch beyond 2025)

Several ambitious missions were in competition for the first round of implementation of ESA's Cosmic Vision Large Mission, the L1 mission. Among them, two were based on space interferometers, DARWIN for the study of terrestrial extra-solar planets, and FIRI, a submm interferometer to study star formation and primordial galaxies. Despite the excellence of the scientific programs, they were not selected for assessment as part of the L1 competition. Nevertheless, in response to ESA's call for scientific themes that might be implemented through L-class missions two proposals based on the scientific aims of DARWIN and FIRI were submitted for the L2/L3 slots. However, again neither was successful and the next revision of the Science Vision and Infrastructure Roadmaps will need to assess their scientific priorities.

A third mission was proposed for the L2/L3 slot in the Panel-B area; this was to carry out a survey of the microwave to far infrared sky in both intensity and polarization, and, in addition, measure its absolute spectrum. The same comment applies with regard to future prioritisation.

*Recommendation 4.4: long-term missions usually require considerable study and technical development and it is important that adequate funding needs to be provided by ESA and National Agencies to support the preparatory R&D activities in the future. Areas that require*

*special attention are e.g. the development of large, low-noise detector arrays, and the development of techniques that will allow high precision formation flying.*

### 4.3 Continuing Facilities

#### 4.3.1 2-4m-class Optical Telescopes

While the small & medium size facilities (SMFs) are not part of the large infrastructures addressed by ASTRONET, they do have a role to play on their own in supporting the programmes of the Science Vision (see Section 4.3.1.2 below). Optimisation of their scientific impact and cost effectiveness was a key recommendation of the original Infrastructure Roadmap along with the urgent need to define a strategy for 2-4m telescopes at the European Level. Accordingly, the European Telescope Strategy Review Committee (ETSRC) was appointed by the ASTRONET Board in coordination with the OPTICON Executive Committee to identify how Europe's medium-size telescopes can best contribute to the delivery of the Science Vision goals, and to propose how a suite of existing telescopes can do so in a cost optimized manner. This panel delivered its final report in March 2010<sup>55</sup>.



*The cluster of telescopes on the Island of La Palma. Photo/image/video courtesy of the Isaac Newton Group of Telescopes, La Palma*

The ETSRC identified the most important classes of observational capabilities to be in the domain of wide-field astronomy, combining multiplex multi-object spectroscopy and wide-field imaging in the near-IR and visible (as noted above also for the 8m telescopes). To obtain a better definition of the scientific specifications for the wide-field spectrometers, the

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<sup>55</sup> [http://www.astronet-eu.org/IMG/pdf/PlaquetteT2\\_4m-final-2.pdf](http://www.astronet-eu.org/IMG/pdf/PlaquetteT2_4m-final-2.pdf)

ASTRONET board, in co-ordination with the OPTICON Executive Committee, set up a European Wide-Field Spectroscopy Working Group (WFS-WG) and the report was published in September 2011<sup>56</sup>. The recommendations of this working group have been translated into several projects as discussed above (MOONS, 4MOST and WEAVE).

Facilitating international access to these medium-size telescopes was another recommendation of the ETSRC. This took place in the framework of the OPTICON Transnational Access program. Today, a single international time allocation process offers about 150 nights spread on 13 2-4m telescopes in both hemispheres. Time has been reserved on the smaller (2m) telescopes to organize training sessions for undergraduate and graduate students. This was organised, in the framework of the OPTICON NEON schools (see also Panel E).

Indeed, recent years have seen the start of a more coordinated approach to utilise European (or partly European) mid-size facilities in astronomy, with specialisation of the 4m class telescopes, open time for training young astronomers and transnational access to most of these facilities (see Chapter 7). There is, however, still room for more coordination and optimisation and the situation is still far from an effective pan-European organization of the small and medium-sized facilities. Nevertheless, important steps have been taken in the right direction and the first results are encouraging.

While this is a positive step, it is also clear that a number of telescopes in this class are under threat of closure or transfer of ownership. UKIRT has been transferred to the University of Hawaii and negotiations are currently underway to transfer ownership of the JCMT.

*Recommendation 4.5: the future optimisation of the 2-4m class optical/IR telescopes in Europe requires further and ongoing work in order to maximise overall efficiency and cost effectiveness.*

#### 4.3.2 8-10m-class Optical Telescopes

The Roadmap recommended that a study be established, under the auspices of ASTRONET with OPTICON, within the next 3-5 years to develop a long-term strategy for the scientific exploitation of the 8-10m class telescopes and for further investments into their instrumentation. This is still awaited. Most of the energy at ESO and in the European community has been spent on the delivery of the second generation instruments for the VLT (X-Shooter, KMOS, MUSE, SPHERE), which should be completed by 2016 with the arrival of ESPRESSO, the end of the ALMA construction (end of 2014), and the consolidation of the E-ELT design phase. Once the construction of the E-ELT has started in earnest, the landscape will be well defined for the next 15 – 20 years. An ASTRONET working group addressing the question of the 8-10m telescopes has begun work.

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<sup>56</sup> <http://www.astronet-eu.org/IMG/pdf/D26-Vsdef-2.pdf>



### 4.3.3 Optical-IR interferometry

Slow but steady progress has been made on the incredibly challenging technique of ground-based optical-IR interferometry through the VLTI. However, as the programme has met significant challenges and new facilities have emerged (e.g. Gaia) the decision was taken to cancel the PRIMA facility and instead focus on ensuring that the VLTI is ready for the two new instruments, Gravity and MATISSE. The current ESO strategy is to ensure the success of these second-generation VLTI instruments and to continue with PIONIER for imaging capabilities in the short-term. The longer-term development, such as additional ancillary telescopes and/or extended wavelength coverage, are supported by unique science programmes but will likely depend on the success of the second generation instrumentation.

*Recommendation 4.6: A coherent long-term plan should be established under the auspices of ESO and the European Initiative for Interferometry during the coming two years. It should be built on the realizations of Gravity and MATISSE and prepare the future plans for enhanced high angular resolution capabilities in the ELT era and in complement to exoplanets and stellar physics space missions.*



*A view along the Interferometric Tunnel, with the rails for two of the VLTI Delay Lines. Courtesy of ESO.*

### 4.3.4 Millimetre and Submillimetre Telescopes

The millimetre and sub-millimetre wavelength ranges play a key role in studying the ‘cold universe’. The entire millimetre and sub-millimetre wavelength ranges can only be observed from space. From the ground, the observations are restricted to the atmospheric windows at 3, 2, and 1mm, and a number of sub-millimetre windows extending to below 0.3mm. Water

vapour absorption lines are the primary cause for the opacity of the Earth's atmosphere in these wavelength ranges, which are therefore best exploited from dry, high altitude sites.

With Europe's significant participation in ALMA, which is now essentially complete, and has already produced outstanding scientific results, European astronomers have access to the world-leading instrument for high resolution observations in the southern hemisphere that will address most if not all of the pertinent SV questions.

In addition, astronomers from France, Finland, Germany, the Netherlands, Spain, Sweden and the UK, are presently operating a number of millimetre and submillimetre facilities, most of them at high altitude sites in Europe, Hawaii and Chile, with several of them ranked as world-class. These facilities have been built to serve the needs of the scientists in the countries involved, but they also accept observing proposals from all across Europe and indeed worldwide on a scientific merit basis. Within Europe, access to these facilities is supported by the EC under the RadioNet Trans National Access (TNA) scheme. These facilities, owned by European institutions, comprise a number of single dishes, namely the APEX telescope in Chile, the JCMT on Hawaii, the IRAM Pico Veleta telescope, the Metsahovi and Onsala telescopes and the Yebes telescope, all in Europe. In addition, there is the Plateau de Bure Interferometer with its six 15m-diameter telescopes, to which four more telescopes will be added in the coming 4 years. This is Phase 1 of converting the PdB array into NOEMA (Northern Extended Millimeter Array). NOEMA will have twice the current number of antennas and the length of the baselines will also be doubled as well as the number of spectral channels. This situation compares favourably with the situation elsewhere in the world.



*The IRAM 30m telescope at the Pico Veleta site in Spain. Image courtesy of IRAM*

With Germany's participation in the SOFIA airborne observatory, which is now fully operational, observations can be performed across the submillimetre and far-infrared range. This is an important option for Herschel follow-up observations and as a complement to ground-based deep surveys and single dish observations. However, this facility is now under

threat because of recent reductions on the NASA budget. For the future, the planned CCAT telescope offers potential for European participation; currently only institutions in Germany are members of this US-led consortium.

At millimetre and submillimetre wavelengths there is still a lot of room for further improvements by installing e.g. more sensitive, wider-bandwidth receivers, bolometric and heterodyne receiver arrays with larger numbers of pixels (like e.g. SCUBA-2), large format arrays based on new technologies (e.g. Kinetic Inductance Detectors–KIDs), and much more powerful spectral backends. Also, the software tools for data reduction and analysis need to be developed further, especially in view of a growing user community of non-specialists. Institutes in France, Germany, the Netherlands, Spain, Sweden and the UK are actively engaged in such development work, which is partially supported by the EC-funded RadioNet project. However, although this sounds very positive, there is a cloud firmly on the horizon with the pull-out of the Netherlands and the UK STFC from the JCMT, leaving the sole European submm facility as APEX. A number of UK universities are attempting to buy-back into the JCMT to maintain access to the array suite of instruments and to complete the SCUBA-2 surveys currently underway.

*Recommendation 4.7: a coherent long-term plan should be established under the auspices of ASTRONET and RadioNet during the coming two years. It should outline the scientific role of each of the facilities mentioned above in the ALMA era, develop an access strategy beyond the current Trans National Access (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. This is very urgent as the future funding for some of these facilities is currently under discussion/threat.*

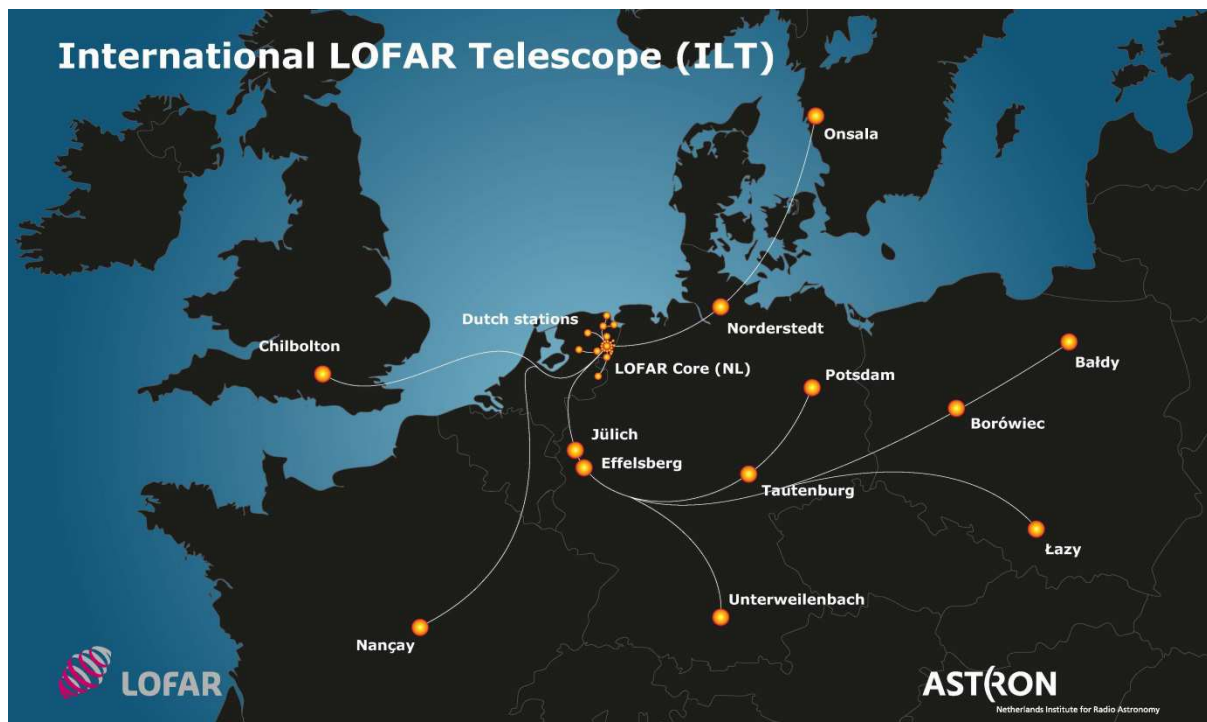
#### 4.3.5 Radio Observatories

European groups own and operate more than a dozen radio telescopes with collecting areas larger  $> 500\text{m}^2$ , and a number of smaller solar radio telescopes. These facilities are located in France (Nancay), Finland (Metsahovi), Germany (Effelsberg+5 LOFAR stations elsewhere), Italy (Medicina, Noto, Sardinia), Latvia (Irbene), the Netherlands (Westerbork), Poland (Torun), Portugal (Pampilhosa), Spain (Yebes), Sweden (Onsala), United Kingdom (Manchester, e-MERLIN). The European VLBI Network (EVN) and LOFAR facilities both involve several of these countries in addition.

Some of these dishes operate for some fraction of time as part of Europe-wide networks. This holds for LOFAR (section 4.1) and the EVN. with participating telescopes in the Netherlands, France, Germany, Sweden, Italy, Poland, Finland and the United Kingdom and in Puerto Rico, China, Russia and South Africa respectively. For VLBI, a central correlator facility has been developed in Dwingeloo, and is operated by JIVE, the Joint Institute for VLBI in Europe, currently moving to an ERIC structure. The LOFAR data also requires a dedicated, high performance central computing facility (recently upgraded) because of the unprecedented amount of radio astronomical data to be treated. A few of the facilities like Metsahovi and Medicina are engaged in systematic monitoring work, which is particularly

important in view of the time variability of many radio sources, including some that served as flux calibrators.

A particular role for existing European radio facilities arises in connection with the preparation of the SKA. The European radio community is actively developing and testing the new technologies that will be needed for the SKA. LOFAR is, of course, one of the prime examples of an SKA pathfinder for low frequencies. In addition, there is the phase array feed (PAF) technology demonstrator project APERTIF (fully funded via two NWO grants) that will be installed on the Westerbork array. One prototype is already in place in one of the telescopes and has delivered first data. Three telescopes will be equipped with PAFs in 2014, with installation of the remaining nine PAFs expected in 2015. 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. 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.



*Locations of the International LOFAR Telescope. Image courtesy of ASTRON*

Following the recommendation in the original Roadmap to review the overall situation of European radio astronomy with regard to its international competitiveness, and the options for future developments, a review is underway under the auspices of ASTRONET in coordination with RadioNet (ERTRC). Its findings will become available in late 2014. Similarly, the FP7-funded RadioNet3 project includes a workpackage to reflect on future developments, the results also being due in 2014. Key issues for the radio astronomy community will be (i) how to maintain and even strengthen Europe's current position in radio astronomy by new technical developments like those mentioned above, (ii) how to foster even more cooperation between the existing groups in order to optimise the use of existing

radio telescopes, and (iii) how to attract and involve an even larger fraction of the European astronomical community in radio astronomical research. The necessary tools, including access to the facilities and data reduction and analysis support clearly need improved coordination, and new organisational and funding schemes will most likely have to be invented for this, in addition to the funding needed for Europe's participation in the SKA project.

#### 4.4 Perceived Gaps and Technology Development for Future Facilities

At present, there is no consolidated database where ongoing conceptual design activities, pre-development work, prototyping and testing of new technical developments are registered. Most of the ongoing activities become more widely known only when consortia are formed to respond to an opportunity that opens up, e.g. by the EC for Joint Development Activities, or through Announcements of Opportunities (AOs) issued by ESO or ESA.

*Recommendation 4.8: before considering in any systematic manner perceived gaps and technology developments, it seems desirable to consider the creation of such a database, e.g. through ASTRONET. This should cover developments both for instrumentation and for software.*

In general, it seems clear that the technical readiness of new projects at component, sub-system and system level needs to be carefully analysed before taking the final decision to go ahead with the construction phase. Pushing the TRL to high standards obviously creates a cost at a stage when the project is not yet fully confirmed, and may indeed not be selected as the next project to build, or at least be significantly delayed. This risk should be taken. The advantages of having established a high level of technical readiness before confirming a project and starting its construction outweigh by far the potential financial losses.

*Recommendation 4.9: the preparatory studies for new projects should include a verification of an advanced stage of technical readiness (TRL). This will help to reduce the risk of significant cost-overruns during the construction phase.*

As noted above, the need to continue very active R&D work to improve the performance of existing devices, e.g. in the area of infrared detectors and detector arrays, and to develop enabling new technologies can only be emphasized again. The funding mechanisms mentioned are still limited and need to be developed further. As it comes to full-scale projects, it seems that many (if not all) of the next generation facilities will require enormous investments. Even if they are conceived from early on as global projects, Europe's share will be in the order of hundreds of millions of Euros. In some cases this is inherent to the project, in others there may be room for economies of scale, and by new approaches to risk management.

*Recommendation 4.10: it is critically important that these technology developments needed for the future in terms of key parameters (e.g. large-scale detector arrays) and high-tech solutions are explored in close collaboration with industry.*



In the broader context there is one area in which there will soon be a global gap, and this is in the area of UV astronomy (from space). Currently this is supported by the HST, but this has a limited lifetime as no future repair/service missions will be possible. Furthermore, apart from the World Space Observatory (WSO-UV)<sup>57</sup>, there are no UV missions on the near-term horizon and so this is an area in which the science requirements needs to be tensioned across the opportunity and cost. This will be an area of focus for the next version of the Science Vision and Infrastructure Roadmap.

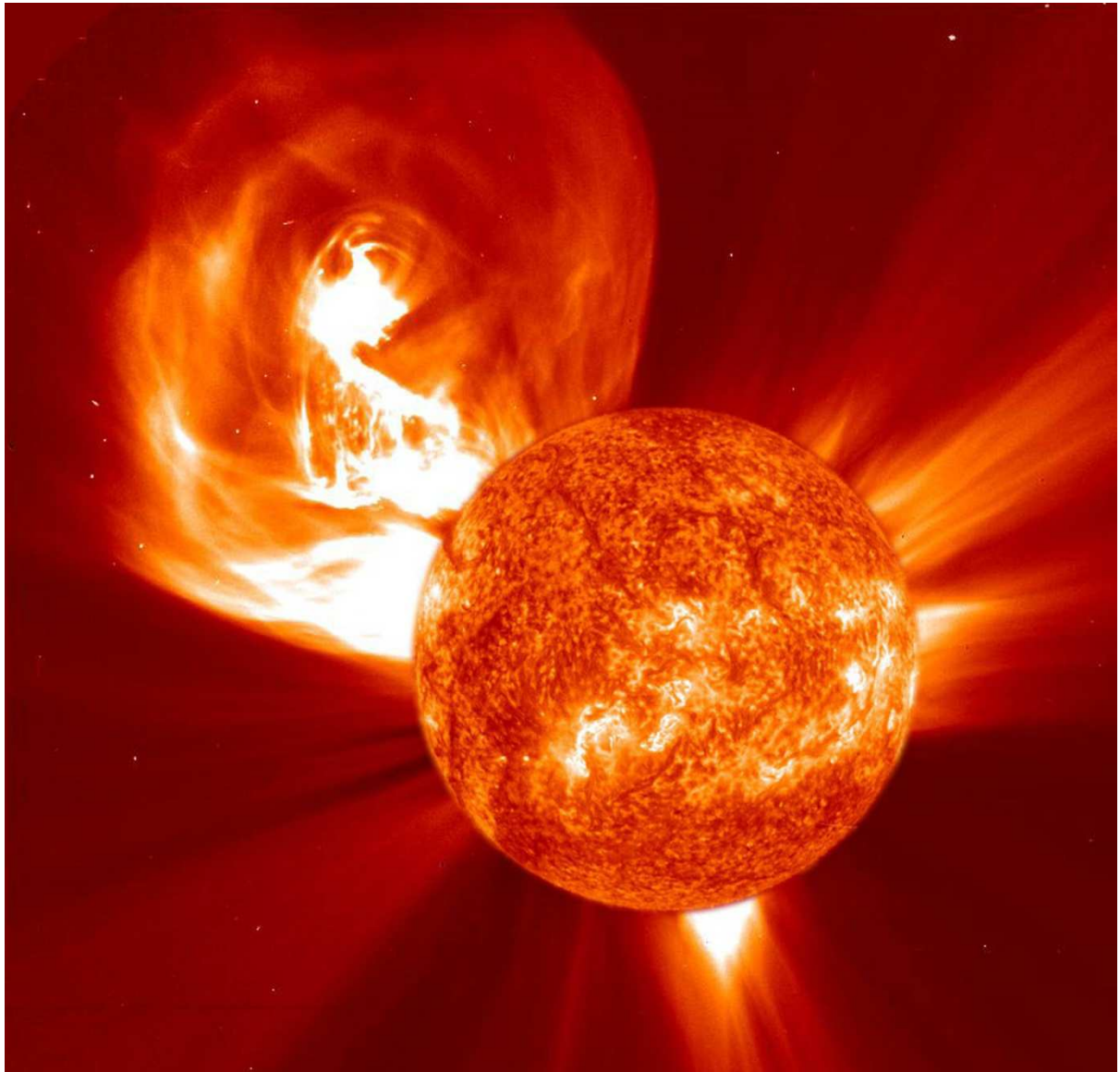
#### 4.5 Concluding Remarks

As described above, it can be seen that the landscape for Panel B has changed significantly since the initial Roadmap. Several of the projects that Panel B had identified as high priority projects that must be implemented in a timely manner have either occurred (like Herschel, Planck and Gaia), or their construction is nearing completion and first science operations have started - as in the case of ALMA and LOFAR. Projects that were still in a preparatory/study phases in 2007/2008 have in the meantime been approved (like the E-ELT), or they have come significantly closer to full approval and funding (like the SKA). For space projects, ESA's selection of the tranche of missions to be implemented in the framework of the 'Cosmic Vision' programs has significantly clarified the picture.

However, some of these missions stretch into the next two decades before launch and therefore agencies and communities need to develop strategies to deal with potential long gaps. This also goes for long-timescale ground-based projects. It is very important for all future projects that adequate funds be spent on preparatory activities, even at the risk that some of them may fail or the respective projects never be implemented. Given that the final approval of projects has severe consequences for 5-10 years into the future, scientific excellence must remain the primary selection criterion, but technical readiness should follow closely behind. This is mandatory for a realistic implementation plan; both timewise and moneywise (see also Chapter 8.2).

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<sup>57</sup> <http://www.wso-uv.org/wso-uv2/index.php?lang=en>



*Stunning composite image of a coronal mass ejection from the Sun as seen by the SOHA satellite. Image courtesy of ESA*

## **5 Panel C: Solar Telescopes, Solar System Missions, Laboratory Studies**

### 5.1 Introduction

The introductory text is still valid and much of the description of the near future has become reality in the intervening years.

Ulysses has now ceased operation and the Solar Dynamics Observatory (SDO) was launched in 2011. Partial archives for SDO data have been established in Brussels (mainly AIA- Atmospheric Imaging Assembly data) and Lindau (mainly HMI- Helioseismic and Magnetic Imager data). These will become more generally available in Europe through the EU funded SOLARNET project (see 5.2.1.1). Among the achievements of the Cassini mission, a new result is the unexpected discovery of many complex hydrocarbon and nitrile species of very high atomic masses in the ionosphere of Titan. The MSL/Curiosity rover, launched by NASA in November 2011, has been successfully operating on the Martian surface since August 2012, analysing the elemental composition and the mineralogy of the Martian surface and searching for possible traces of past life. The JUNO mission was launched by NASA in August 2011 to approach Jupiter in 2016, with the prime objective of probing its interior and better understanding its origin.



*Spectacular image of the Martian surface taken by MARS Express. Image courtesy of ESA/DLR/FU Berlin*

The mission extensions recommended in the original Roadmap have all been realised and all missions in operation have been extended until the end of 2014 at least. The ESA Science Programme Committee (SPC) has also awarded extensions to the operations of Cassini-Huygens, Cluster, Hinode, Mars Express and SOHO from 1<sup>st</sup> January 2015 to 31<sup>st</sup> December 2016 subject to a mid-term review and subsequent SPC confirmation in November 2014. Separately, Venus Express operations have also been extended into 2015 subject to a mid-term review in 2014 as the fuel is expected to run out sometime within 2015. The originally

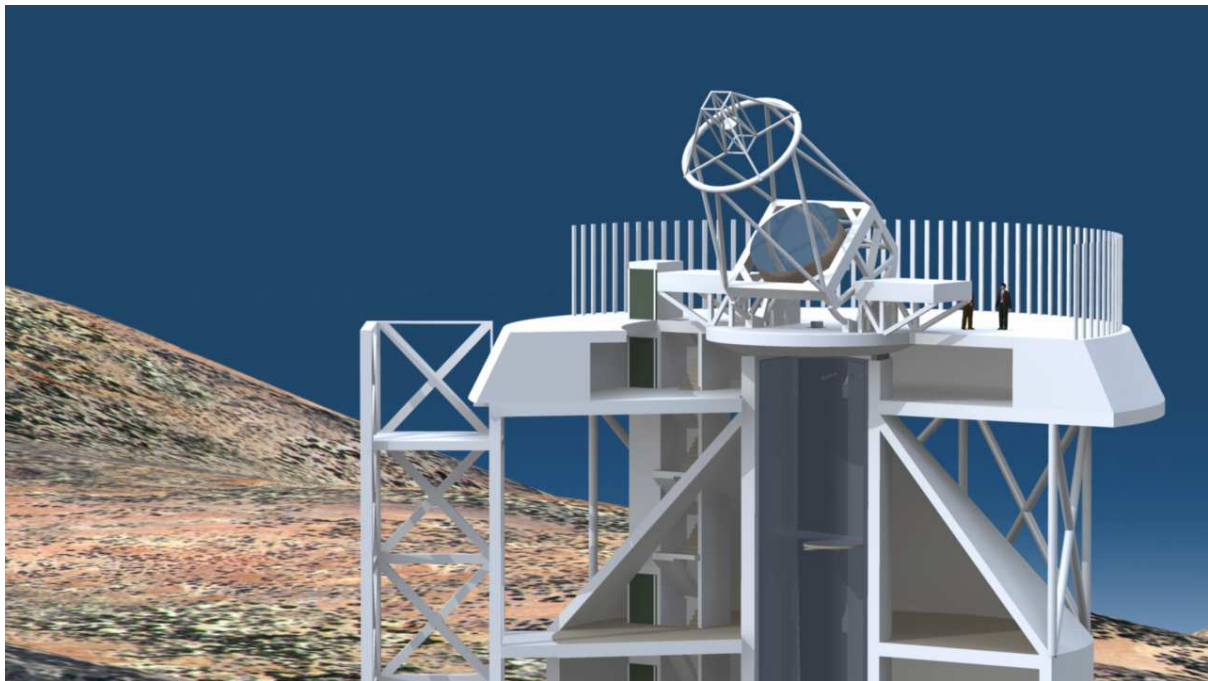
planned launch dates for the future missions have slipped somewhat and currently the launch of BepiColombo is not before 2016.

## 5.2 High Priority New Projects

### 5.2.1 Ground-Based, Medium-Term

#### 5.2.1.1 European Solar Telescope (EST)

This is still the flagship and highest priority project for European Solar Physics. The conceptual design study was completed in 2011. Funding for the design and construction phases is not yet secured but the EST project is moving forward in spite of a difficult funding climate in Europe. The EU FP7 Capacities project SOLARNET has received funding (€6M) for 2013-2017. SOLARNET provides access to the existing solar observing facilities on the Canary Islands for countries not owning the facilities. There is also funding for technological development work and for streamlining data reduction pipelines and providing data in a form suitable for a solar virtual observatory; all in preparation of EST. The US equivalent project, the ATST (see Chapter 8.2.3), is now under construction. The recommendation in the original ASTRONET Roadmap that EST should be included in the ESFRI list in the next revision is again supported by Panel C.



*Concept design for the EST. Image courtesy of the Instituto de Astrofísica de Canarias<sup>58</sup>*

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<sup>58</sup> <http://www.iac.es/>



## 5.2.2 Space-Based, Near-Term

### 5.2.2.1 Solar Orbiter

Solar Orbiter has been selected by ESA as the M1 mission for launch in 2017. This mission is high priority for solar physics; it combines imaging and spectral capabilities, in situ and remote observing from the close vicinity of the Sun.

### 5.2.2.2 ExoMars

The exploration of Mars is the top priority for the European planetology community and ExoMars is an essential part of it. However, the ExoMars project has been reshaped several times since 2007, not the least after the withdrawal of NASA from the project. The project is now led by ESA and Russia. The first phase will include an orbiter and a descent lander and is planned for launch in 2016, while a rover, devoted to exobiology studies, is to be launched two years later. The objective is to search for past or present signs of life by obtaining and analyzing sub-surface samples extracted with a drill. In parallel, the NASA mission InSight, to be launched in 2016, will be devoted to the study of the internal structure of Mars, in particular by seismology. As a next step, NASA is currently preparing a new rover mission to Mars, Mars-2020. This mission is designed as a preparatory phase for a future Mars sample return mission, which remains the ultimate science objective of planetary exploration.



*Artist impression of ExoMars Rover on the surface of Mars. Image courtesy of ESA*

## 5.2.3 Space-Based, Medium-Term

### 5.2.3.1 Cross-Scale



Cross-Scale has not been selected by ESA for further consideration. The science remains important but there is no European mission to achieve this. In the USA, MMS is under development by NASA for a launch in 2014.

#### 5.2.3.2 Marco-Polo

Returning samples of extraterrestrial matter to Earth is among the major objectives of the planetology community for the decades to come. Among the possible targets, near-Earth asteroids (NEAs) are of major interest for better understanding the origin and evolution of the solar system, but also in view of potential hazard associated with them. They are also attractive targets in terms of feasibility. The Marco-Polo mission, devoted to this objective, was competing for selection as M3 in ESA but was not selected. Nevertheless, a sample return mission from a NEA, like Marco-Polo-R, remains a high priority for solar system science.

#### 5.2.3.3 Titan and Enceladus Mission (TandEM)

Following the spectacular discoveries achieved by the Cassini-Huygens mission, defining a follow-up mission devoted to the exploration of Titan and Enceladus was fully justified. However, in the competition for the planetology L1 mission, Laplace was selected instead of TandEM, ultimately leading to JUICE. The concept, however, should appear again among the long-term flagship projects.

#### 5.2.3.4 LAPLACE

LAPLACE was selected to compete for L1 but was reworked into the JUICE project when NASA pulled out. JUICE has been selected as ESA's L1 mission for launch in 2022. The mission will approach the Jovian system in 2030. It will include two flybys of Europa, several flybys of Ganymede and Callisto and will finally orbit Ganymede in 2032. JUICE will address a broad range of planetary objectives including an exobiology perspective.



*Artist impression of the JUICE mission in the Jovian system. Image courtesy of ESA/AOES*

#### 5.2.3.5 Other solar system missions to be considered in the frame of an L-class mission

Several solar-system missions were submitted in response to the ESA call for ideas for selecting concepts for the L2 and L3 missions of the Cosmic Vision program. Although none was selected, in addition to the above-mentioned missions several concepts were highly ranked. The first is the exploration of the icy giant planets, which was perceived by ESA's Senior Survey Committee (SSC) as a first priority in view of both our present limited knowledge regarding Uranus and Neptune (only explored by the Voyager missions in the 1980s) and the fast increasing number of Neptune-size exoplanets discovered around other stars. Another important mission concept selected by the SSC is the exploration of Venus, with special emphasis on its surface and interior.

#### 5.2.4 Space-Based, Long-Term

##### 5.2.4.1 PHOIBOS

Probing Heliospheric Origins with an Inner Boundary Observing Spacecraft. This was not selected for further study but many of the scientific objectives are covered by the NASA SolarProbe Plus mission.

#### 5.2.5 Ongoing Space Missions with Probable Applications for Mission Extensions

Ongoing ESA-led space missions within the remit of panel C (Cluster, Hinode, MarsExpress, SOHO, VenusExpress) have all been extended to the end of 2014 with extensions for 2015-2016 being in the budget but in need of confirmation in November 2014.

#### 5.3 Perceived Gaps

*Radio spectral imaging of the Sun at centimetre to metre wavelengths.*

This is still a perceived gap even though solar imaging with LOFAR and ALMA will go a certain way towards fulfilling the science goals.

*A medium-aperture (1-2 m) (extreme-) ultraviolet satellite facility with X-ray capabilities.*

The Japanese Solar-C (1.5m) mission fulfils most of the science requirements of such a mission. Following the 2010 ESA call for M-class Missions, a team of scientists from Europe, the US, and Japan proposed that ESA should lead the development of a large EUV/FUV high-throughput telescope feeding a scientific payload of high-resolution imaging spectrographs and cameras. This scientific payload is to be provided by an international consortium with European, US and Japanese partners funded by their respective national agencies and institutes. In the proposed scheme, the integration and test of the instrument payload should be led by ESA with support from the international consortium. This instrument, proposed as LEMUR (Large European Module for solar Ultraviolet Research), received a very positive evaluation by the ESA scientific advisory structure in the M-missions evaluation.

#### 5.4 Concluding Remarks and Priorities

The original conclusions are still mostly valid but see the above for the update of individual space missions. CrossScale and Marco Polo are no longer in the competition but the science these missions were to address is still of high priority.

In the near-term, ExoMars is the high priority mission for the European planetology and exobiology community, whilst in the long-term, the selection of JUICE, which deals with all aspects of planetology (internal structure, surface and atmosphere, planetary environment, solar system formation and evolution, exobiology) meets the priorities of a very large community.

## 5.5 Recommendations

The original recommendations are still valid (and some are already implemented). The process of updating the ESFRI roadmap was launched in April 2014 and the recommendation that EST should be included in the ESFRI roadmap in the next revision is therefore, especially important, given the current funding climate in Europe, but it is clear that this will not be an easy process.

For the space missions, the above updates need to be propagated into a new recommendation.

*Recommendation 5.1: the European Solar Telescope (EST) should be included in the ESFRI Roadmap in the current revision process.*

## 5.6 Laboratory Astrophysics

There is a separate ASTRONET exercise addressing this field and so an update is therefore not included here in detail. In summary, a twelve-member European Task Force for Laboratory Astrophysics (ETFLA) has been established and a mid-term report to ASTRONET on the establishment of a European Laboratory Astrophysics Network was completed in November 2013<sup>59</sup>. It includes a major survey of laboratory astrophysics activity in Europe. The field is growing rapidly in capacity, impact and coherence driven by strong demand for the best possible data for analysis of astronomical results and their interpretation. However, it remains in need of significant investment. Notably, the Horizon 2020 programme ‘Integrating and opening existing national and regional research infrastructures of European interest’ has identified European Laboratory Astrophysics as one of four key *Starting Communities* in the *Physical Sciences*.

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<sup>59</sup> <http://www.labastro.eu/>

## **6 Panel D: Theory, Computing Facilities and Networks, Virtual Observatory**

### 6.1 Introduction

This remains generally valid and good progress has been made on a number of broad fronts.

The need to be able to analyse massive spectroscopic data sets is being reinforced with the new ground-based survey instruments of 4MOST, MOONS and WEAVE as well as the current ESO VLT surveys in support of Gaia. Regarding the requirement for supercomputers; in addition to the actual hardware there is now the recognition that the requirement for complex and efficient algorithms has become even more pressing in order to make use of the exascale computing facilities anticipated for 2018. With the clock-speed of individual CPUs basically being constant over the past decade, increase of computing power goes along with multicore vector-like structures. Exascale performance is anticipated to require parallelization over more than 1 Million cores.

Considering the size of the current multi-dimensional simulation data sets, parallel, non-data local algorithms also for data visualisation and analysis are required. It is also foreseeable that in the field of simulations, even running individual simulations may become less and less the task of individual people or groups. The trend may be that joint analysis of a few, very big simulations, is undertaken by the community at large.

### 6.2 The Virtual Observatory

The importance of ‘open data’ and e-Infrastructures continues to be recognized by high-level European and International bodies. Governments and funding agencies are promoting ‘open data’ policies requiring that data obtained with public funds be, in general, publically accessible. The G8 Science Ministers have stated a set of principles for open scientific research data<sup>60</sup> emphasising that data should be ‘easily discoverable, accessible, assessable, intelligible, useable and wherever possible interoperable to specific quality standards’, which is in line with the recommendations of the ASTRONET Roadmap.

The EC formed a High-Level Expert Group on Scientific Data, which produced the influential report in 2010 entitled ‘Riding the wave – How Europe can gain from the rising tide of scientific data’. The EC supports a Digital Agenda Strategy<sup>61</sup>. The International Council for Science<sup>62</sup> (ICSU) World Data System, founded in 2008, concerns the long-term stewardship of data for the international science community. The Research Data Alliance<sup>63</sup> (RDA), founded in 2013, is a major initiative for sharing research data across borders and

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<sup>60</sup> <https://www.gov.uk/government/news/g8-science-ministers-statement>

<sup>61</sup> <http://ec.europa.eu/digital-agenda>

<sup>62</sup> <http://icsu-wds.org>

<sup>63</sup> <http://rd-alliance.org>

disciplines. Astronomy e-Infrastructures are prominent in these organisations and astronomy is recognized as being at the forefront for data sharing and re-use in this fast evolving field.

The architecture of the Virtual Observatory (VO) system is now well established with a set of core standards. It has progressed from an early deployment phase in 2008 to an operational phase, whereby the basic interoperability building blocks have been defined and are being implemented.

The relevance of the VO to European data centres is well established via the 2008 and 2010 Data Centre Census (conducted by EuroVO-DCA and EuroVO-AIDA). This provided a snapshot of European astronomy data centres, identifying 69 data centres across Europe covering all areas of astronomy. The census shows a high level of intent to implement the International Virtual Observatory Alliance<sup>64</sup> (IVOA) protocols, and this is verified by the European entries in VO registries. VO usage is high as measured by service query statistics, although impact metrics are difficult to define when services are being accessed transparently via multiple tools and interfaces.



*Members of the International Virtual Observatory Alliance. Image courtesy of IVOA*

IVOA remains the international coordinating body for VO, and now comprises twenty-one organisations and VO initiatives. IVOA has matured as an alliance with established procedures for setting scientific and technical priorities for development of standards aligned with global member project priorities. Euro-VO continues to coordinate activities at the European level.

### 6.2.1 Future Development of the VO

The Euro-VO AIDA project was completed successfully in 2010 and was followed by a bridging project EuroVO-ICE (2010-2011).

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<sup>64</sup> <http://www.ivoa.net/>



The EuroVO-CoSADIE (2012-2014) project is currently defining the medium-term requirements to establish a sustainable European Virtual Observatory. The activities include support to science users and data centres, continued technological development of standards and tools, and forming an education network. CoSADIE supports the Euro-VO Science Advisory committee, which continues to play an important role with the capacity to define European science priorities that are transmitted to the international level through the IVOA Standing Committee on Science Priorities.

Elements of the sustainability study include the need to maintain VO registry support, VO publishing tools, support to coordinated technological development, and support for professional engagement via schools and workshops. Governance and support models for a sustainable VO are being developed in coordination with Astronet.

Interoperability of tools via VO protocols has proven to be a major step forward leading to significant improvements since 2008. This includes access to images, catalogues across multiple distributed archives, the ability to perform billion-object cross matches, and complex queries on large tables.

#### 6.2.2 VO Compliance

Publishing tools and advice are collected by the IVOA and include VO ‘layers’ and other approaches. Critically, support for publishing need to be made sustainable through ongoing funding.

Another aspect of growing importance is the development of VO-like projects in several sub-disciplines of astronomy, including planetary and heliospheric physics, and the interest of the high energy community, in particular CTA, for implementing their data in the VO. The development of the Virtual Atomic and Molecular Data Centre, which includes atomic and molecular data of high astronomical interest, also takes advantage of the astronomical VO framework.

#### 6.2.3 Computing within the VO

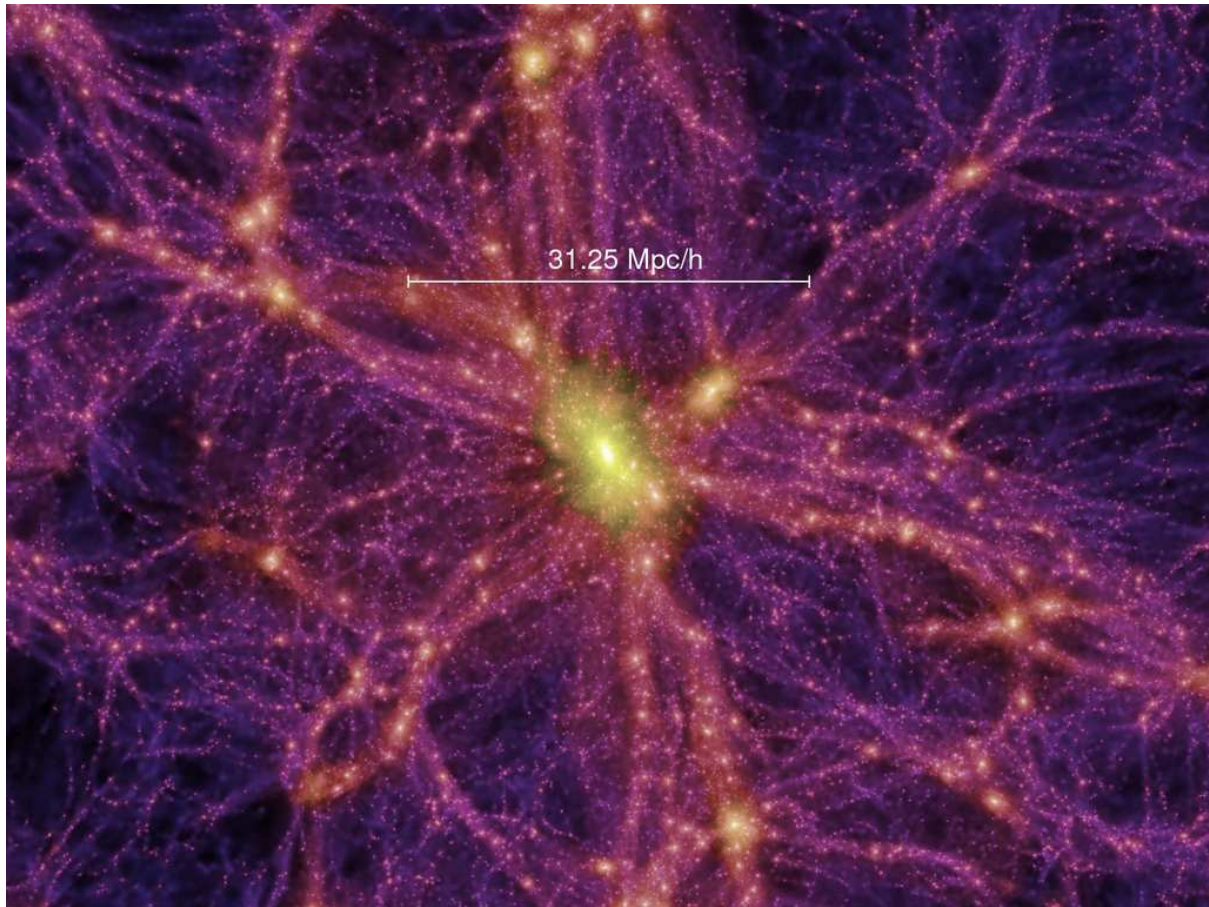
Computing within the VO is now more often described in terms of cloud computing. VO interfaces for asynchronous queries and remote job execution are in place and various implementations of VOSpace provides remote storage.

One of the new developments is the requirement for supercomputing to operate some of the big observational facilities of this and the next decade. For example, LOFAR, SKA and LSST all depend on near-site, supercomputer-like performance for their data reduction and data management.

#### 6.3 Impact of the VO on Theory

The original statement that VO is both a challenge and an opportunity for the development of theory still stands in the regime of VO-compliant data-bases. However, there has been definite progress; large, structured, and VO-compliant data-bases are very good examples of

the increased usage of such theory VO-Tools. An example is in the area of simulations of the large-scale structure of the Universe in the Millennium<sup>65</sup> and Multidark<sup>66</sup> data-bases.



*Image from the Millennium simulation of the Dark Matter in the Universe at the current epoch. Courtesy of the Millennium Simulation Project*

The challenges of matching theoretical modelling with observational data will become even more challenging with the increased availability of large, medium-to-high resolution spectroscopic data from surveys like Gaia, MOONS, 4MOST and WEAVE, featuring millions to tens of millions of spectra. This is not just because of the size of the data-set, but the differing instrumental characteristics and ‘metadata’.

#### 6.4 Astrophysical Software Laboratory (ASL)

Good progress has been made in this area and a working group has been established (PI Steinmetz 2011-2012, Klessen 2012-) in order to make a census of the codes used by a substantial subgroup of the community. A total set of some 40 codes has been identified that are currently used by the astrophysical community in Europe for high-performance simulations in various fields of astrophysics. About eight of these are sufficiently modular in

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<sup>65</sup> <http://www.mpa-garching.mpg.de/millennium/>

<sup>66</sup> <http://www.multidark.org/MultiDark/>

design that they can be seen as major international framework for simulation studies in the field of astrophysics. Furthermore, there are a considerable number of modules that are designed to be incorporated in various applications. Each of these libraries and framework needs continuous maintenance and updating, so a structure like the one proposed here is desperately needed.

A plan for a future ASL has been proposed to the ASTRONET board. This foresees the key role of a Director, in the function of a CEO, as the main coordinator of the ASL. The Director is supported by a project office. The projects supported by the ASL are selected by an international peer review system for a limited amount of time (a few years). Support is at the level of 1-2 FTE per project. Funding purpose and evaluation criteria include documentation, optimization, portability, further development and assistance to users. A regular reporting is required for each project.

*Recommendation 6.1: the ASTRONET Board needs to determine the status of the Astrophysical Software Laboratory in the near-future*

## 6.5 Computational Resources

This continues to be a high requirement in order to remain competitive and within Europe this has led to the establishment of the PRACE infrastructure (Partnership for Advanced Computing in Europe), networking, coordinating and optimizing the use of the major European tier-0 supercomputer centres.

### 6.5.1 Major Computers

On the high performance computing end, China has developed as a major player, currently operating the fastest supercomputer worldwide. In general there is a certain diversification visible, indicating the fundamental need of high performance computers for an internationally competitive research infrastructure. Five of the top ten machines are currently outside of the USA (with 2 in Europe, 2 in China, and 1 in Japan). Indeed, 16 of the top 50 machines are located in Europe. An interesting trend is that the total performance becomes more and more dominated by the highest performance machines. In 2013, 50% of the total performance of the top 500 was provided by the fastest 11 machines, while in 2008 (and the years before), the top 60 machines were required on average.

However, one of the developments that is now of critical importance is the infrastructural support, where power consumption is a critical aspect of further development. The top 10 supercomputers have 5-folded their power consumption in the past 5 years (a factor of 3 for the top 50 as well as the top 500). Along with power consumption comes the problem of heat dissipation and further infrastructural requirements.

### 6.5.2 Data Networks and Data Grids

Progress continues to be made in this area and as an example LOFAR is using dedicated high-throughput, point-to-point, links between the stations and the centralized computer facilities. The trend for observatories and instruments to produce ever larger datasets from

surveys in the petabyte category continues and there is a need for dedicated data facilities distributed throughout Europe to provide access. While some activities in this direction are underway (e.g. in UK and in Germany) there is need for further development to keep pace with the data increase.

*Recommendation 6.2: there is a need for continued investment in dedicated data facilities across Europe to keep pace with the data increase.*



*The BULL Tera 100 supercomputer for the French Atomic Energy Commission. Image courtesy of Bull*

### 6.5.3 Grid Computing

One of the developments is that the EU Commission-funded EGEE has developed into the European Grid Infrastructure (EGI) and its national contacts (NGI). Further resources are available through various providers in the area of cloud computing, some of which are operated by research institutions.

The existing 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 have been meanwhile developed and optimized. Nowadays these not only cover supercomputing needs but also provide high-performance data-bases and data servers (e.g. the GrayWulf design).

### 6.5.4 Screensaver Science

The original idea of ‘screensaver science’; using the idling cycles accessible via the internet to undertake data analysis for a project, has been expanded in a number of ways, especially in the area of ‘citizen science (see also Chapter 7). Now, rather than pure remote data analysis use of the host pc, the non-scientist users of these home computers are employed for mass-analysis of astronomical, and now many other types of data. The data are made available to a



community much larger than the core science group and this is especially useful where the pattern recognition of the human brain comes into play. A prime example is Galaxy Zoo but there are now a number of projects where classification of astronomical (and other) objects from a large survey is undertaken by the ‘citizen scientist’ on a home-pc (see Chapter 7.1).

## 6.6 Recommendations

Comments on the original recommendations are listed below, while new recommendations following from these have been listed above in their respective sections.

### (i) Relevant to the VO

The original recommendations 1, 2, 3, 4 remain highly relevant for the implementation and sustainability of the VO with recommendation 3 (The infrastructure established with EC support will need to be sustained by the national funding agencies to allow continuity of the VO) being especially critical. Recommendations 5 and 6 highlight the need for support of modelling and simulation codes in particular for the interoperability of theoretical and observational data.

### (ii) Relevant to the ASL

All the original recommendations (1-6) remain highly relevant. Connections with other fields of sciences and the experiences in applied mathematics and computer sciences need to be further fostered, in particular considering various initiatives in the area of Exascale computing. A funding and support model needs to be established in order to set up the initial ASL infrastructure and issue the first calls for proposals.

### (iii) Relevant to High Performance Computing and Grids

All the five recommendations remain highly relevant. Regarding recommendation 2, the increasing gap between the top-tier and the next level systems (see above) needs careful monitoring. In this context, the power consumption combined with rising energy costs will be of key importance. Furthermore, this is not limited to top-level computers, but also for those systems further down in the pyramid of services. Larger mid-scale compute clusters already put a considerable strain on the budget of universities and research institutions.

For recommendation 4, state-of-the-art data links are of increasing fundamental importance for the next generation of astronomy facilities as well as for the accessibility and efficient use of the various data sources.



THE UNIVERSE  
YOURS TO DISCOVER



INTERNATIONAL YEAR OF  
ASTRONOMY  
2009

*Logo of the hugely successful International Year of Astronomy 2009 (IYA2009). Courtesy of the IAU*

## **7 Panel E: Education, Recruitment and Training, Public Outreach**

### 7.1 Introduction

Since the ASTRONET Roadmap was published in 2008 the area of education and public outreach has changed dramatically. As predicted, the International Year of Astronomy 2009 (IYA2009) provided enormous opportunities for the community. IYA2009 involved 148 countries and reached more than 800 million people. Star parties, public talks, exhibits, school programmes, books, citizen-science programmes, science-arts events, astronomy documentaries and parades honouring astronomy and its achievements made IYA2009 the largest science event so far in this century. IYA2009 positively changed astronomy education and public outreach in Europe. The community became more organised and more connected, enabling pan-European collaborations and projects.

Additionally, the media landscape has also changed dramatically; mainly in the form of a broadening of the available communication vehicles. Social media networks like Facebook, Twitter, Google Plus and Instagram are proliferating. Furthermore, there has been a notable shift in the profile of the information gatekeepers from being a select group of scientists, authors, journalists and editors to the new curators of knowledge: the crowd. Social media tools have grown from obscurity to almost uniform adoption with incredible rapidity and popular services like Facebook and Twitter are the favoured knowledge sharing tools among the new information gatekeepers.

In the new communication landscape there has been a shift both upwards to high-bandwidth video channels and to lower bandwidth mobile devices like smartphones and tablets.

The difficulties of launching and sustaining pan-European projects have been clearly exposed and result from: different languages; different cultures; different curricula and a lack of sustained funding for operations (as opposed to the more available seed-funding). Some of these difficulties have been addressed, while others have not. The translations issue for instance has been partly addressed by the ESA Country Desks<sup>67</sup> and ESA ESERO Network<sup>68</sup> along with ESO's Science Outreach Network<sup>69</sup>, which, in the case of the latter translates material such as press releases to the majority of the EU Member States. It is, however, worth noting that there is a considerable overlap of efforts and resources and that each solution is meant to address the needs of a given agency and not the bigger European-wide problem.

Other changes have taken place. The demographics of the target groups have – for natural reasons – changed over the period. The so-called millennials (or generation Y) are now an important target. They are accustomed to demanding co-ownership of the communication and the process, and they want to be involved on their terms and be able to co-create during the communication process.

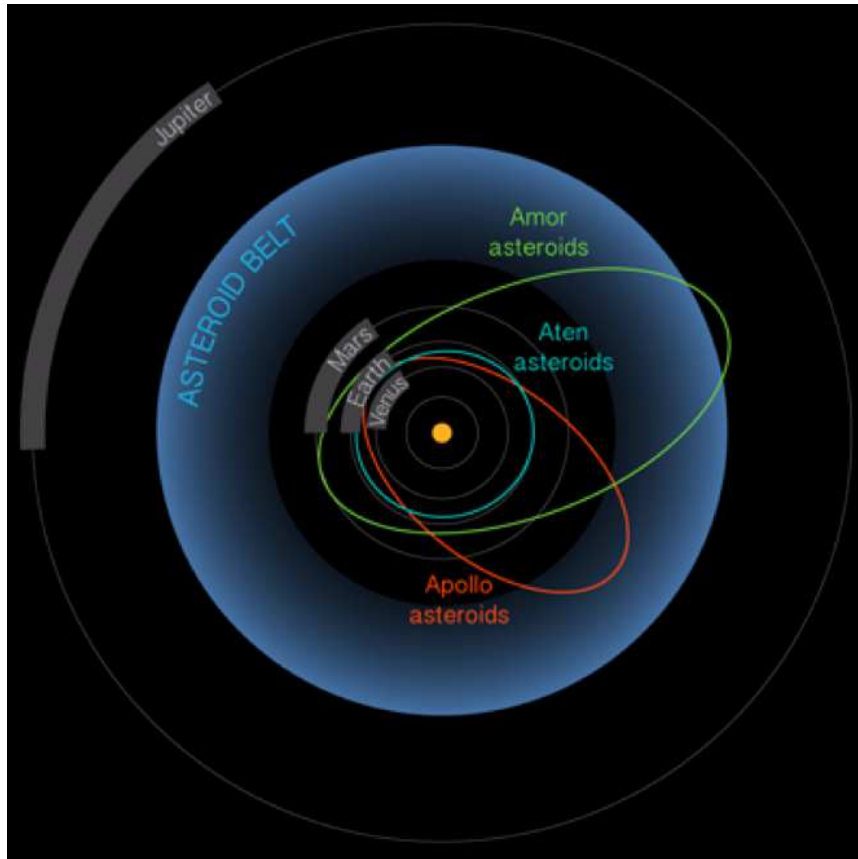
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<sup>67</sup> [http://www.esa.int/ger/ESA\\_in\\_your\\_country/Germany/ESA\\_headquarters](http://www.esa.int/ger/ESA_in_your_country/Germany/ESA_headquarters)

<sup>68</sup> <http://www.esero.org.uk/>

<sup>69</sup> <https://www.eso.org/public/outreach/eson/>

An example of this is the hugely successful citizen science projects that involve the target audience in the scientific process and allow them to partake in the discovery process. An analogy to this is the equally successful crowdfunding initiatives. The overwhelming success of ‘Galaxy Zoo’ (see Chapter 6.5.4) has spawned a wealth of new projects and is one of the most spectacular impacts in the citizen science that has been seen. The all-up project, called Zooniverse<sup>70</sup> now encompasses science areas from astronomy to the natural environment and climate to biology.



*Part of the tutorial about identifying asteroids from the ASTEROID ZOO, which is part of the ZONIVERSE. Image courtesy of ASTEROID ZOO*

If one could count the number of astronomy EPO resources available on the web one would be overwhelmed. Unfortunately, these resources are not available in different languages or cultural adaptations. However, some efforts have been made to fill this gap. The ESO Outreach Network translates and adapts news items, documents, brochures, educational material and presentations, specifically to promote and disseminate astronomy. ESA, Universe Awareness (UNAWA)<sup>71</sup> and the Network for Astronomy School Education (NASE)<sup>72</sup> are using their own networks to translate their own resources. Indeed, ESO, ESA, UNAWA and NASE are setting an example for others to follow in the future.

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<sup>70</sup> <https://www.zooniverse.org/>

<sup>71</sup> <http://www.unawe.org/>

<sup>72</sup> <https://www.iau.org/education/commission46/nase/>

Built on the success of IYA2009, the European-led educational programme Universe Awareness (UNAWE) received a large grant under the EU Framework Programme 7, which enabled the project to support the implementation of some of the Panel E recommendations (1, 2 and 4). However, a sustainable funding model needs to be identified to maintain or even keep community-driven projects. UNAWE is now in its final year before closing down a hugely successful operation; delivering another blow to already operational projects. NASE was born also in 2009 inside Commission 46 (Education and Development) of the International Astronomical Union (IAU). This programme is integrated by IAU members with the support of approximately 1,000 volunteers and is giving support to some of the recommendations of panel E (1, 2, 3 and 4), however, it is also facing serious difficulties in obtaining financial support for its actions.

*Recommendation 7.1: in order to achieve a pan-European educational activity using astronomy as a theme for Science and Technology requires ongoing coordinated funding streams in addition to start-up funds.*

Recent initiatives from the European Commission<sup>73</sup> have been pushing for an open and flexible learning experience through the use of Information Communications Technology (ICT) to improve education and training systems, aligning them with the current digital world. In parallel, the EC has been demanding a more open publication process for research (Open Access) and for the production of educational resources (Open Educational Resources). This will have an impact on future astronomy education initiatives. These initiatives will need to provide easy and open access to the resources and training, like Massive Open Online Courses (MOOCs).



*The Universe in a Box; a project from UNAWE. Image courtesy of UNAWE*

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<sup>73</sup> <http://ec.europa.eu/education/policy/strategic-framework/education-technology.htm>

It now seems clear that the need for a Europe-wide coordination and consolidation of efforts in education and public outreach is stronger than ever before. In addition to the ongoing funding concerns there are the general pan-European aspects discussed above. Specific ideas for the implementation (see also ASTRONET Task 5.3) are listed below and comprise a new recommendation.

Recommendation 7.2:

1. *Creation of a European-wide translations agency that can serve as a service to agencies and national entities*
2. *Creation of a European-wide Educational material repository (see 7.3.2.4 below)*
3. *Creation of a European-wide Teacher Training agency*
4. *Creation of standards for a ‘Top-10’ list of astronomical topics/concepts/ phenomena that students need to get acquainted with at some point during their primary or secondary studies. Some examples might include: seasons; Lunar phases; eclipses; tides; gravity; the Sun as a star; etc.*
5. *Creation of a European-wide standardised educational resources (kits that can be mass-produced and localised)*
6. *Creation of open access resources for images, videos, and planetarium content*

The development of the next generation of instruments, missions and infrastructures will be one step further towards global astronomy. These projects will allow Europe to maintain its leadership position in optical and near IR (OIR) based facilities and its competitiveness at other wavelengths and in space. Efficient training programmes between the agencies and the community will allow Europe to optimize its expertise and use its collective IQ for the development and operation of these facilities. Mechanisms for ‘fast-track’ funding of science programs using the large European facilities should be implemented. Access to small (2-4m class) telescopes to graduate and PhD students should be facilitated through efficient training programmes and schools. Astronomical Institutes are also encouraged to promote and develop university nanosatellite programmes that enable professional training on high technology programmes encompassing a broad range of scientific and technical skills.

## 7.2 Background

The original Panel E report contained ten specific recommendations that can be divided into two groups: those that seek to change the cultural behaviour and those that require specific funding initiatives. It has already been noted that implementing both types have been very difficult, the first because of the difficulty of pan-European working and the second due to lack of funding. Nevertheless, this update report reflects the changes that have taken place in the overall field, which have been especially dramatic in the areas of communication and outreach. As well as new recommendations, the original recommendations are discussed in 7.6. As such it is also anticipated that this Chapter, in common with others, has significant overlap with the ASTRONET Workpackage 5.3 – implementation of the Roadmap.



Importantly, it should be noted that the new recommendations all require actions, but these will only take place if ‘champions’ are identified to lead the activity and funding is made available to undertake these tasks. This is particularly the case for pan-European initiatives. Otherwise, one is left with the situation that while having great merit, many of these recommendations will show little progress given the inertia that is experienced when trying to change cultures and systems.

### 7.3 Education

#### 7.3.1 University Education and Recruitment

There is little to add to this section since the original Roadmap publication. Astronomy continues to be a popular course at university degree level although it is interesting to see the resurgence of recruitment into physics courses. A number of universities offer special study course or secondments to observatories, but this is far from the norm. The debate about the use of visits to facilities and observatories for recruitment and the use of facilities for training of PhD students continues. Other points regarding this section are picked up in the remainder of the Chapter.

#### 7.3.2 Primary and Secondary Schools

Currently innovation in education is moving in the direction of teaching and learning through the use of projects. Many institutions and schools are reworking their curricula in the direction of involving students in specific projects to achieve a much more generalist education. In this, astronomy offers a very special opportunity to introduce students to the scientific thinking as a consequence of its appeal to students and also its intrinsic interdisciplinarity.

Schools departments and teachers can use astronomy as a transversal relation to mix different subjects in a common project in a natural way. Also, astronomy is a very ‘visual’ science and offers the opportunity to introduce science to students in a simpler way than for other topics. Finally, students are naturally interested and motivated in astronomical content and this provides a good opportunity for teachers. All of those that have had the experience of working in astronomy with students have reinforced the view that young people are especially motivated by astronomy and space science.

As an example, in 2002 ESO and the European Association for Astronomy Education (EAAE) launched the ‘Catch a Star’ programme<sup>74</sup>. In this, students, with a teacher guide, choose an object or astronomical phenomena and begin a research project to learn more about it. They decide the direction of their research, the kind of activities and when to finish the work. It is a real research experience in the classroom. Simultaneously, in 2002, the Spanish version of this contest was initiated, called ‘Adopta una Estrella’. This was run by the ‘Ciencia en Acción’ Association (CEA), which opened a similar contest to Spanish and

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<sup>74</sup> <http://www.eaae-astronomy.org/cas/>

Portuguese speaking countries in Europe and the world. This initiative introduced on-line contacts between students from different countries using their native language to explain their researches. This opportunity is very useful for youngest students in primary schools.

Catch a Star and Adopta una Estrella offer students the opportunity to enhance their learning through project work to enable more autonomy in their activities and to connect with students of other European countries.

### 7.3.2.1. Teacher Training

Some progress has been made on teacher training for the career and professional development of teachers (theory, practical observations). Several initiatives have implemented teacher training programmes at the European level (and even at the global level). At the Primary education level, the UNAWE project developed and implemented a comprehensive teacher training programme in 5 European countries (Italy, Germany, the Netherlands, Spain and the UK). In total, 1,800 primary school teachers have been trained by UNAWE from 2011-2013. At the secondary level, the IAU programmes Galileo Teacher Training Programmes (GTTP)<sup>75</sup>, NASE and EAAE have been training hundreds of teachers in Europe.



## Galileo Teacher Training Program

A LEGACY OF THE INTERNATIONAL YEAR OF ASTRONOMY 2009

*The GTTP is a legacy of the International Year of Astronomy 2009 and is supported by the IAU*

The GTTP is now part of an important research and policy support project towards innovative methodologies for science teaching and the introduction of real research experiences in classrooms broadening the impact of the program to over 2,000 schools in Europe<sup>76,77,78</sup>. The EAAE Association has been organising international courses and summer schools from 1997, initially in cooperation with ESO. These courses had been taught in English but materials have been offered in the language of the host country. Currently EAAE, in cooperation with NASE, has begun to organise national courses in the host country in their national language and to generate resource materials in these languages.

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<sup>75</sup> <http://www.galileoteachers.org/>

<sup>76</sup> [www.opendiscovery.space.eu](http://www.opendiscovery.space.eu)

<sup>77</sup> [www.inspiringscience.eu](http://www.inspiringscience.eu)

<sup>78</sup> <http://www.go-lab-project.eu/>

At the national level, several ongoing initiatives have been training teachers to use astronomy in the classroom (e.g.: Haus der Astronomie<sup>79</sup> or the National STEM Centre in the UK<sup>80</sup>). Hands-on research is now becoming a reality in many schools. The International Astronomical Search Collaboration is an extraordinary example of involvement of students in such activities, since 2009 over 40 countries enrolled in this project and more than 300 asteroids have been discovered by students. In the field of radio astronomy, a network of radio antennae have been built, solely devoted to education by the European Hands-on Universe Consortium.

However, a consolidation of these teacher training efforts across Europe is necessary to maximise the reach and impact. The establishment of a European-wide agency to coordinate these initiatives could provide the necessary network, framework, resources, expertise and evaluation methodology for a sustainable European-wide teacher training programme.

*Recommendation 7.3: a European-wide agency should be established to coordinate teacher training initiatives and to provide the necessary network, framework, resources, expertise and evaluation methodology for a sustainable European-wide teacher training programme.*

Beyond the support to these teacher training efforts investment in creating innovative and sustainable solutions of science teaching is urgent. Tablets and smart-phones are now common in student's hands and will certainly be part of their future. Preparing students for the world of work will necessarily mean being skilled in the use of such devices. Furthermore, the existence of large repositories of data, available to be used in classroom, and the possibility of real research experiences in classrooms opens a very interesting framework of possibilities for schools (see Chapter 6). Training teachers to embrace this methodology is a demanding task but an urgent and necessary one. Astronomy is multi-disciplinary in its essence and is therefore the perfect choice to engage schools, educators and students in a new trend towards contextualized and significant teaching and learning. Indeed, this is the specific main aim of the international Catch a Star contest.

#### 7.3.2.2 Sky-observing Experiences

One of the main goals of IYA2009 was to promote widespread access to the universal knowledge of fundamental science through the excitement of sky-observing experiences. Several countries have initiated programmes to reconnect children and teenagers with nature<sup>81</sup>. Initiatives like Dark Skies Parks<sup>82</sup> or the IYA2009 Galileoscope project are promoting a widespread access to sky-observing experiences by students (and the general public). Moreover the UNawe programme created the Playground Human Orreries in schools in Northern Ireland (UK) and the Celestial Sphere Playground Models in Spanish

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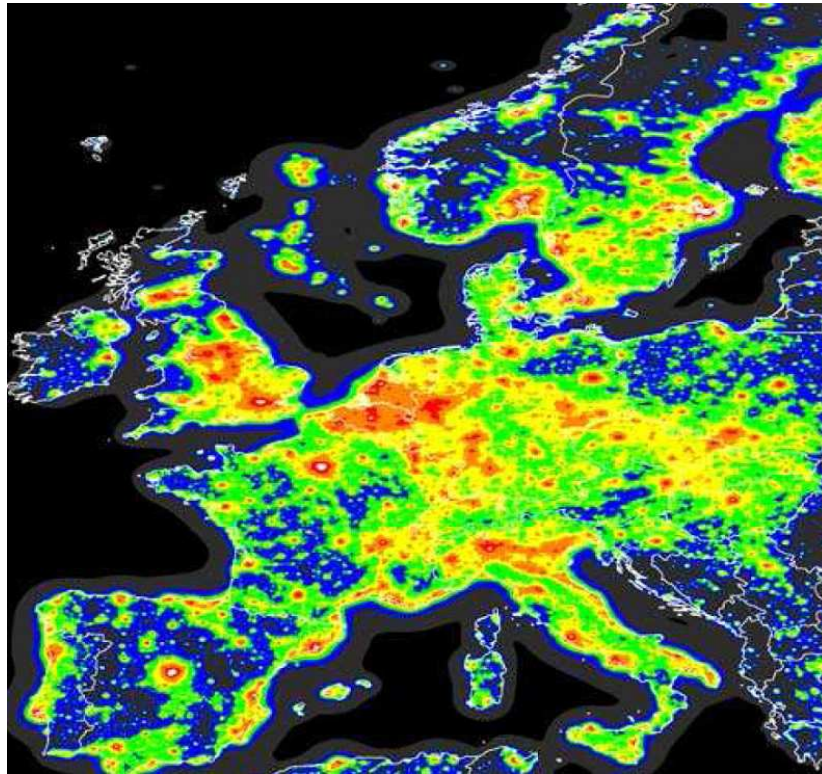
<sup>79</sup> <http://www.haus-der-astronomie.de/en/>

<sup>80</sup> <http://www.nationalstemcentre.org.uk/stem-in-context/professional-development>

<sup>81</sup> <http://www.childrenandnature.org/> and <http://projectwildthing.com/>

<sup>82</sup> [http://www.darkskydiscovery.org.uk/dark\\_sky\\_places/](http://www.darkskydiscovery.org.uk/dark_sky_places/)

primary schools. The use of robotic telescopes (LCOGT<sup>83</sup>, PIRATE<sup>84</sup>, National Schools' Observatory<sup>85</sup>, etc.) in the classroom is now easy and accessible for most of the European schools. Support in other languages is, however, necessary for these initiatives to reach the widest European community.



*Light pollution across Europe but showing there are some dark sky areas good for astronomy. Image courtesy of P. Cinzano, F. Falchi (University of Padova), C. D. Elvidge (NOAA National Geophysical Data Center, Boulder). Copyright Royal Astronomical Society.*

### 7.3.2.3 Consolidation of Astronomy Education in Europe

Small progress has been made in consolidating experiences, lessons and best practices for astronomy education across Europe. Some steps should be made towards this. A study on best practices for astronomy education across Europe should be made. This study should also identify anchor points to introduce astronomy in non-science-related subjects like history or arts. Defining standards in astronomy education is also essential to create a common framework to develop educational programmes, resources, curricula and evaluation strategies. It is recommended to create a standard 'Top-100' list of astronomical topics/concepts/phenomena that students need to get acquainted with at some point during their studies (topics like the Sun as a star, Seasons, Lunar phases, Tides, Gravity, etc.).

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<sup>83</sup> <http://lcogt.net/>

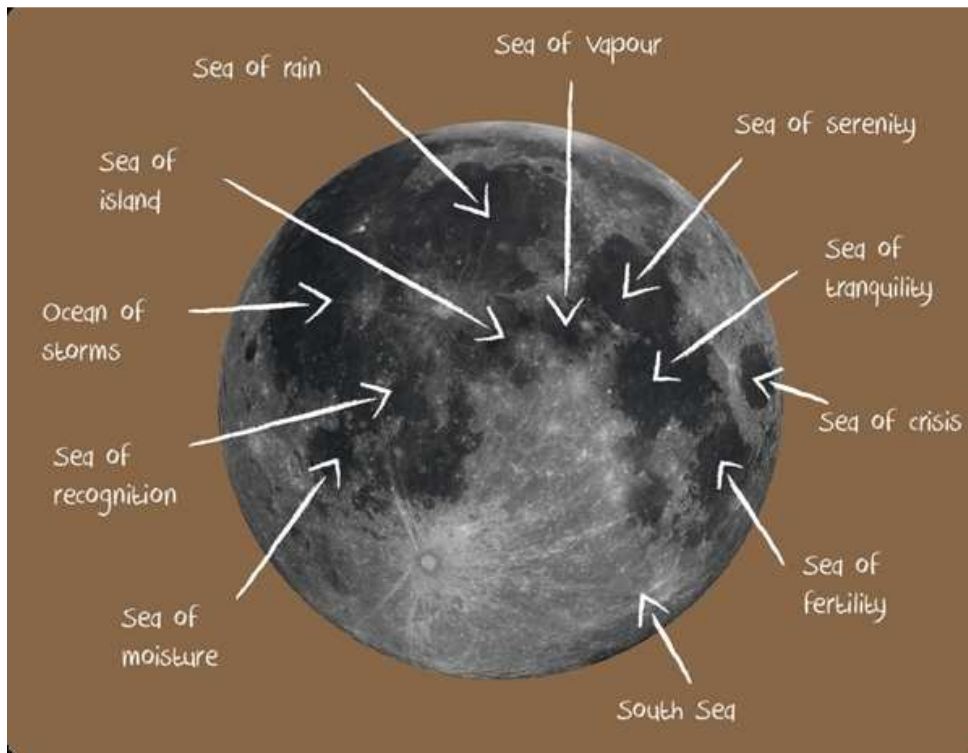
<sup>84</sup> <http://pirate.open.ac.uk/>

<sup>85</sup> <http://www.schoolsobservatory.org/>

#### 7.3.2.4 Web-based Distribution System for Educational Material

Considerable progress has been made on this topic. Recently, the IAU launched an open-access platform for peer-reviewed astronomy education activities, astroEDU<sup>86</sup>. This is a platform that allows educators to discover, review, distribute, improve and remix astronomy education activities, and offers a free peer-review service by professionals in education and science. AstroEDU also links its educational content with existing European educational repositories like Scientix. At the moment the platform is only available in English; it will be necessary to allocate financial resources to expand the platform to other European languages (the costs are estimate to around 0.2 FTE per language). Funding is also needed for promotion to gain the necessary momentum and support from the community.

*Recommendation 7.4: funding needs to be provided to enable AstroEDU to be expanded to cater for the entire European educational community (extension of the original recommendation 1).*



*Exercise learning about lunar cratering from astroEDU. Image courtesy of Gregory H.Revera / graphic: C. Provot (UNAWA)*

### 7.4 Communication

#### 7.4.1 Science Museums and Planetariums

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<sup>86</sup> <http://astroedu.iau.org/>



There has been significant progress in this area: ESA and ESO have each published 2 planetarium shows. It is worth noting that all of these were done in collaboration with commercial partners as there was insufficient funding available to enable free use. ESO provides some limited materials for free use in planetariums and is ramping up to develop a system for innovative distribution that allows other planetariums to use open access content from agencies and observatories. This is one of the foundations for the philosophy of the planned ESO Supernova Planetarium in Garching (planned for 2017).

*Recommendation 7.5: ASTRONET and funding agencies should agree and push for open access content to be made available for museums and planetariums (extension of original recommendation 6).*

The selected software will provide a ‘menu’ that allows the planetarium presenter a daily selection of interesting news and dataset previews downloaded overnight — planetary maps, images of sky objects, tabular data, event data etc. — and mark the full datasets and metadata (descriptions, web URLs, licensing etc.) up for download and for possible inclusion in show segments during the day. Earlier ESO developments with this philosophy include the web-based Portal to the Universe (see below) and the ESO News Kiosk.

#### 7.4.2 Public Communication and Outreach

##### 7.4.2.1 Funding for Public Communication and Outreach

Despite the recession it appears that the level of outreach funding has only decreased marginally. There is still a need to provide strategic long-term support for public communication and education in Europe, especially operational funding for existing and new projects, and not only seed-funding (as in the case of UNAWWE).

There is still a need to organise communication departments that operate in a professional fashion, i.e., by professional science communicators, working with active scientists.

Funding agencies must increase the expenditure on public outreach activities to accompany the research activities (STFC being a good example of this).

##### 7.4.2.2 Recognition for scientists involved in public outreach

Little has happened to ensure clear, career-relevant recognition for scientists who become involved in public communication and to offer media training course. The IAU Commission 55 Washington Charter<sup>87</sup> covers the former but not much has been done to promulgate it in Europe and thereby gain recognition for the field of outreach in general. One of the problems is the need to provide evaluation processes and criteria to assist career development, peer esteem and measurement of ‘impact’. PLOS Article-Level Metrics (ALMs)<sup>88</sup> is providing a mechanism to measure the impact of published research articles, including social media

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<sup>87</sup> [http://www.communicatingastronomy.org/washington\\_charter/index.html](http://www.communicatingastronomy.org/washington_charter/index.html)

<sup>88</sup> <http://article-level-metrics.plos.org/>

impact. But there is a need to develop metrics for other Education and Public Outreach (EPO) initiatives.

One form of recognition for researchers and also astronomy teachers could be a form of certification, and perhaps this is something to consider in the future for a pan-European approach.

*Recommendation 7.6: 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 (extension of original recommendation 7).*

#### 7.4.2.3 Creation of a standardised European science communication portal for media, educators, interested laypeople

There has been significant progress in this area. The IYA2009 cornerstone project, Portal to the Universe (PTTU)<sup>89</sup>, was created in mid-2009 to address this exact recommendation, but has not yet managed to attract the necessary funding from the agencies for promotion, marketing and further development to gain the necessary visibility and momentum.

PTTU enables real-time access to content by aggregating (pulling) from providers of dynamic content like blogs, images, news, etc. and distributing (pushing) to users, as well as indexing and archiving, collecting and maintaining a central repository of useful information. Technology such as RSS feeds and standardised metadata make it possible to tie all the suppliers of astronomy information together with a single, semi-automatically updating portal. The result is a technologically advanced site that brings together strands of astronomy content from across the Internet. This enables anyone with a web connection to stay up-to-date with cutting-edge astronomy and space science breakthroughs.

#### 7.4.3 Relationships with Industry

The construction of any major facility or instrument relies heavily on industry. At one level in the construction, this may not involve cutting-edge technology, but in the area of control and instrumentation, it absolutely will. It is in this latter area that there is a clear dependence on a close link and working relationship between cutting-edge (beyond the state-of-the-art) research, mainly carried out in university and government laboratories and the high-tech industries that will often be required to take these low-value TRLs (Technology Readiness Level) to a production capability. The ability to forge a good working relationship with industry is therefore vital for these new facilities.

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<sup>89</sup> <http://www.portaltotheuniverse.org/>

There is another area in which industry has an important part to play and that is the strategic value of certain components, so that Europe is not beholden to a foreign party that can dictate the availability and price of components. Infrared detectors for space (and to some extent ground) is a clear example where currently Europe is dependent on the US, who can then leverage scientific influence (e.g. EUCLID) and also set the price and availability of provision of components. While this has not been a real problem so far, nevertheless, being self-sufficient in this area is something that Europe has been striving for through various EU initiatives. It is important that this concept is continued through to a successful conclusion (see recommendation in Chapter 5).



*Integration of the hugely successful European e2v Technologies CCDs onto the support structure for the focal plane of the Gaia satellite at Astrium in Toulouse. Image courtesy of Astrium.*

## 7.5 Exploitation of Facilities and the Impact on Recruitment and Training

The 2008 ASTRONET Roadmap recommended that ‘fast-track’ funding mechanisms be implemented to support the scientific exploitation of the large European facilities, enabling young astronomers to be more internationally competitive in large collaborations. Little progress has been seen on this score as this is a structural issue that requires inter-agency (e.g. ESO, ESA, national agencies) agreements to be overcome. Clearly a balance needs to be struck between individual peer-assessed programmes and major programmes that are potentially world-beating but need access to a wide variety of facilities to make the maximum impact. ASTRONET remains the appropriate body to promote this important recommendation and make it happen.

It has long been recognised that small-class telescopes (1 to 2m) in regional observatories have considerable value for the training of graduate and PhD students. The 2008

ASTRONET Report by the European Telescope Strategic Review Committee (ETSRC) recommended that formal graduate schools be maintained, in addition to resorting to graduate and PhD students for carrying out the observations in places where there are no telescope operators. End-to-end projects, from instrument development or characterization, observation and calibration, to data analysis allow students to get hands-on professional experience. Summer schools (usually 1-week long) organized by EC networks and science programmes can complement regular training sessions from university programmes. Continued access to these facilities should be maintained and encouraged by the agencies, enabling the training of hundreds of students every year.

The past years have seen the development of university nanosatellite programmes for the training of students in high technology projects. These projects require expertise in a broad range of domains, from project management to orbitography, electronics, mechanics, thermal control, etc. Student projects can be easily developed at moderate costs in specialised labs, and can in addition provide valuable research opportunities, e.g. to raise the TRL of specific components. Indeed, Europe is lagging behind the US in this domain, and astronomy institutes with instrument development capabilities could play an important role in promoting and developing such projects.

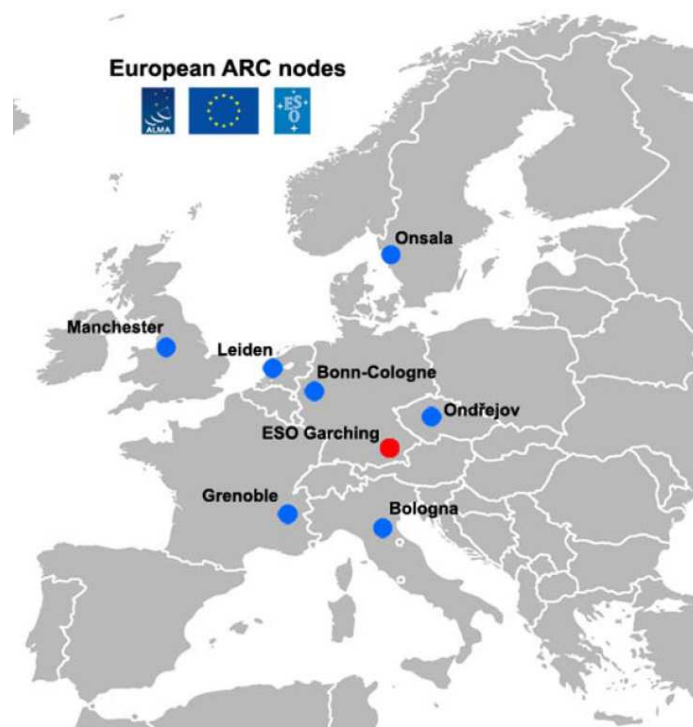
The new large-scale projects discussed in the preceding Chapters of this document will require the intellect and the expertise from the whole astronomical community across Europe. The organisation of the community to work efficiently on these projects remains to be consolidated. As an example, the VLT instrumentation plan had a tremendous impact on the ground-based astronomical community across Europe, raising the level of technical and managerial expertise across Europe. However, this expertise in the OIR domain could be consolidated and optimized, for instance through regional centres of well-defined areas of expertise, somewhat similarly to the situation at mm and radio wavelengths (cf the ALMA Regional Centres<sup>90</sup>) or for space labs, which have highly complementary capabilities and domains of expertise. Cross-training between these centres of expertise and the main agencies (ESO, ESA) would be highly beneficial to the community as a whole, raising the level of expertise in the community and optimizing the development of the European projects and missions. A better organisation of the community by the agencies on technical matters remains an endeavour that would benefit the whole community, avoiding unnecessary competition (as was the case for the selection of the M1 and M2 ESA Cosmic Vision missions) while still allowing innovation to blossom and excellence to prevail.

One must not forget the potential of using ‘old’ telescopes and facilities as educational devices. Even better is the use of visits to active facilities but as these are often quite remote, time and cost become obvious barriers to seeing what a ‘real’ observatory can do (in this context radio telescopes have an obvious advantage being located across mainland Europe). There are a number of initiatives and competitions that allow a very small group of undergraduate students and school children to visit a front-line observatory but these remain

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<sup>90</sup> <http://www.eso.org/sci/facilities/alma/arc.html>

an extreme minority and in many respects should not detract from the mainstream educational ethos.



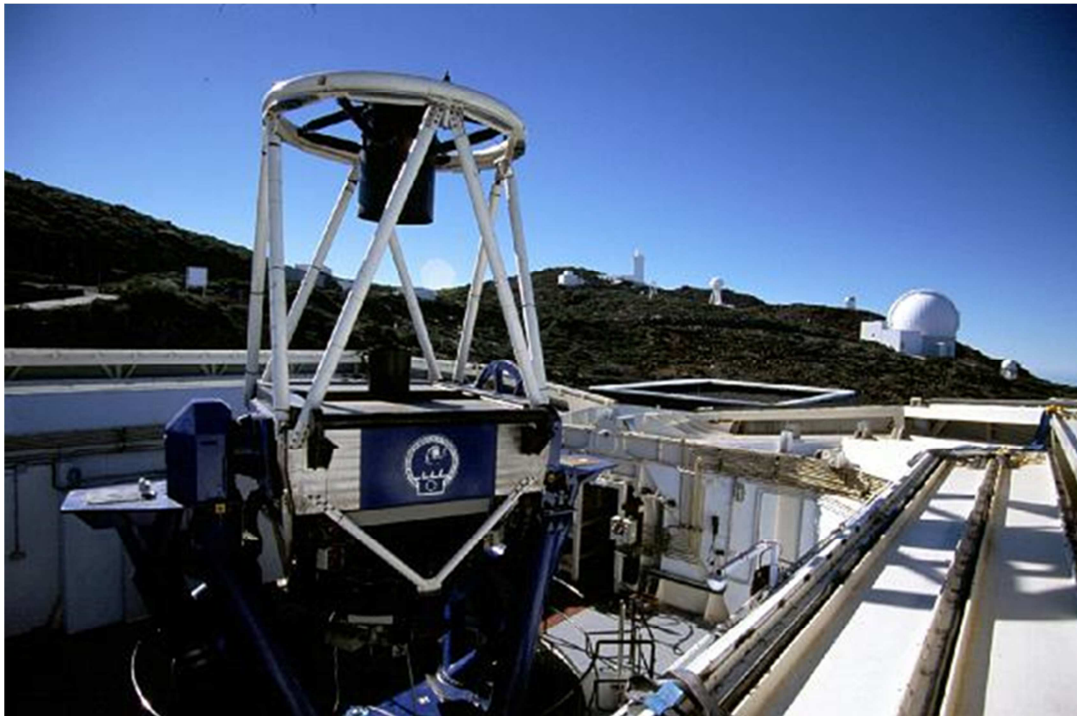
*The European nodes for the ALMA Regional Centres (ARC) providing local help and support. Image courtesy of ESO*

The use of actual visits, secondments and use of telescopes remains one of the key themes in recruitment, both to undergraduate courses and also to some extent in the postgraduate career. It has long been recognised that the ‘excitement’ of working at a real observatory and undertaking real-time observations gives a real ‘buzz’ and studies have shown that this is an effective tool in recruitment. The use of robotic telescopes, often aimed at secondary schools, gives that early edge to propel students into science at university, perhaps even astronomy degrees. However, robotic telescopes also have a cutting-edge place in observational astronomy, being able to undertake a number of projects, usually of a long-term or monitoring nature, that are very hard to gain time for on main-stream, staffed and scheduled facilities.

Following on from this theme an interesting concept to note is that more large-scale facilities (space and ground) are now scheduling observing on an essentially queue-based process; scientifically ranked but executed according to availability or specific conditions (e.g. seeing or water vapour content for ground-based facilities). The ‘observer’ then need not be present for their observations, a position long held for space-based observations. This has an impact on the staffing of the observatories and also on the training of students. As the drive to make facilities as productive as possible, this ‘remote’ trend is unlikely to diminish and this raises questions as to the type of training that might be required. The ability to distil a scientific question into an observational programme through an algorithm that lends itself to a queue-based and remote-user peer review application system is something that pedagogy will need



to consider, rather than the long-distance travelling and the luck of the prevailing weather at the telescope (albeit granted that this is one of the most exciting aspects of ground-based observational astronomy).



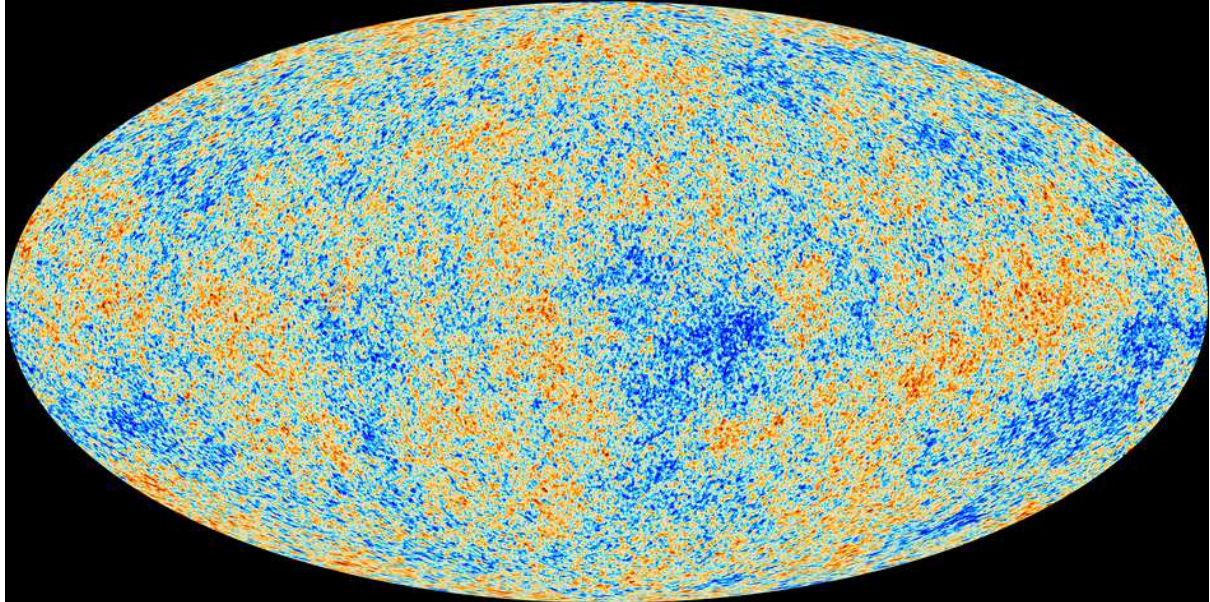
*The robotic Liverpool Telescope<sup>91</sup> on La Palma offers opportunities for research, outreach and educational programmes. Image courtesy of R. Smith and the Liverpool Telescope.*

## 7.6 Summary and Implementation

All of the original recommendations still stand; however, it is clear that progress on implementing them has been less than ideal for reasons expressed earlier. While progress in the overall field has been huge, the pan-European aspect has made little progress, with brilliant beacons from individual nations, organisations or agencies shining out from an otherwise bland landscape. It is clear that without ‘champions’ to take these ideas forward along with supporting funding, these ideas will remain just that. The new recommendations listed above are designed to assist in the future implementation.

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<sup>91</sup> <http://telescope.livjm.ac.uk/>



## The Anisotropies of the Cosmic Microwave Background as seen by ESA's Planck satellite

*The CMB is a snapshot of the oldest light in our Universe, imprinted on the sky when the Universe was just 380 000 years old. It shows tiny temperature fluctuations that correspond to regions of slightly different densities, representing the seeds of all future structure: the stars and galaxies of today. Credits: ESA and the Planck Collaboration*

## **8 Funding for astronomy in Europe**

### 8.1 Comparison with the previous Roadmap

One of the most difficult tasks facing the authors of the original Roadmap was determining the available funding for the programmes under consideration. This was for a variety of reasons: multiple agencies in any one country; private organisations; lack of information; concern about providing medium-term forecasts that might have a political impact. Nothing has changed and so a different approach is taken here.

The assumption is that the ESA and ESO programmes are essentially fully funded for the lifetime of this strategy. For ESO, the picture is clear for the bigger projects: construct and operate the E-ELT, operate and upgrade ALMA; operate and continue to upgrade the VLT and VLTI; operate the two survey telescopes on Paranal along with ‘other’ facilities and instrumentation. The Cosmic Vision strategy is now set with S1, M1, M2, M3 and L1, L2 and L3 missions approved. This stretches out the programme well into the 2030’s as far as L3 is concerned. A future M4 is the only new mission that will be considered in the timescale of this Roadmap Update.

The SKA is a major, multi-national project and so for the moment it is up to the individual nations whether to participate. Securing an appropriate participation by European nations in SKA and guaranteeing the most productive access to European astronomers to that facility depends to some extent on the structure and governance model that the observatory ends up adopting. This needs to be borne in mind by the European nations involved.

In the realm of astroparticle physics, the two top ranked projects (CTA and KM3NET) currently do not have adequate funding for both to proceed. These projects are funded by a variety of sources, but national agencies being one of the key areas. Extensive work is currently being undertaken to prioritise the projects and to seek additional sources of funding.

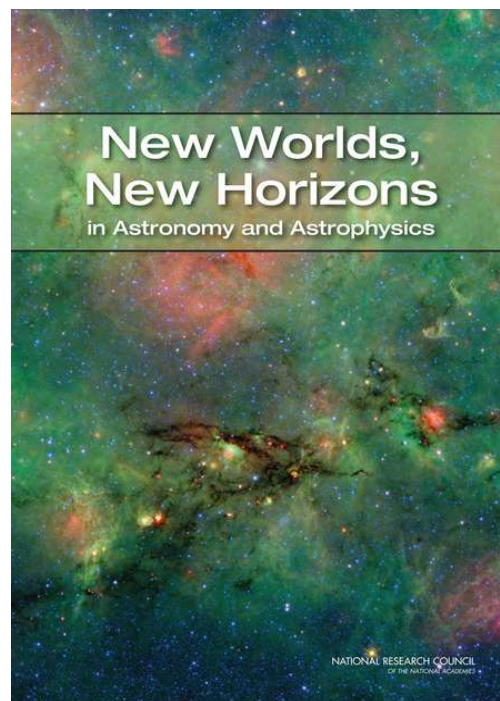
Therefore, moving away from the large-scale European projects of ESA/ESO, the choices for individual European nations boil down to opportunities to contribute to projects on the order of a ‘few-millions of euros’ scale. This opportunity might be for self-contained, single nation projects, pan-European projects, or contributions to multi-national, major projects (e.g. SKA, LSST, CCAT). While this situation continues to look healthy in terms of capital investment, the ongoing (and rising) cost of non-capital provision – research grants, training, facility running costs etc, in the era of flat-cash budgets is causing concern. As has been noted earlier in this report, the need to close world-class facilities to maintain within flat-cash could easily result in a decline in European competitiveness on the global stage over the next few years. The hope is that the new facilities coming on-line (e.g. ALMA) will more than compensate. However, this may require some strategic direction to be undertaken within Europe to maximise overall scientific productivity at the expense of some national ‘treasures’. This will not be an easy task.

In space, the rising costs of missions have led to the concept of ‘small’ (or Explorer-class) missions. These offer more opportunities for bi-lateral collaborations and with both India and

China seeking to increase their space involvement, which includes research satellites, therein lies a further opportunity for Europe. An example of which is the Millimetron<sup>92</sup> project, a Russian-based mission to undertake spectroscopy in the far-IR region.

## 8.2 Comparison with other Strategic Surveys of Astronomy and Space Science

The yardstick by which any astronomy roadmap is judged is the so-called ‘US Decadal Surveys’<sup>93</sup>. The survey for Astronomy and Astrophysics has been ongoing for over fifty years since the first was published in 1960. The last survey was released in 2010, entitled ‘New Worlds, New Horizons in Astronomy and Astrophysics (2010)’. There are also two further ‘decadal surveys’ pertinent to that of the ASTRONET Science Vision and Roadmapping. These are for the planetary and for the solar and space communities and are respectively: ‘Vision and Voyages for Planetary Science in the Decade 2013-2022 (2011)’; ‘Solar and Space Physics: A Science for a Technological Society (2013)’. Although other countries have produced strategic surveys (e.g. Canada with ‘Unveiling the Cosmos: A Vision for Canadian Astronomy 2010-2020 - Report of the Long Range Plan 2010 Panel’<sup>94</sup>) for comparison of scale we shall only discuss those from the USA, and even then, focus more on the Astronomy and Astrophysics area.



*The latest ‘Decadal Survey’ from the USA of 2010.*

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<sup>92</sup> <http://www.asc.rssi.ru/submillimetron/mm/>

<sup>93</sup> <http://aas.org/resources/decadal-surveys>

<sup>94</sup> [http://www.casca.ca/lrp2010/11093\\_AstronomyLRP\\_V16web.pdf](http://www.casca.ca/lrp2010/11093_AstronomyLRP_V16web.pdf)



It turns out that the ASTRONET Infrastructure Roadmap has, in fact, done exceedingly well in comparison. The Decadals have always strictly been science-led (like the ASTRONET Science Vision) but a recurrent problem with previous Decadals (especially in Astronomy and Astrophysics, which is used as a generic survey in what follows) was that the programme turned out to be significantly more ambitious than the funding available, especially in the NSF and NASA domains. This was for two principal reasons: a general under-estimate of project costs (and lack of rigorous assessment of these); an over-estimate of available funding. Either of these would not be helpful to a strategic plan, but when both are present, the outcome is that a significant number of projects remain unfunded at the end of the decade. This led to a number of large projects being ‘carried-over’ into the next Decadal, hence curtailing the number of potential new projects. Furthermore, while NASA fared much better in this light, the very significant rise in the cost of the JWST has led to severe problems in the astrophysics space area (see below). Of course when funding is strong, as it was in the US in the 1990s, it is almost incumbent to propose a programme that exceeds the funds to some extent. The ASTRONET process was well aware of these problems and so attempted to recommend a programme that would fit within the available resources, or at least would be a very modest over-projection.

Indeed, the 2010 Astronomy and Astrophysics Decadal Survey attempted to counter the trend of unstarted recommended projects and a *huge* amount of work was expended in the USA in producing the final recommendations. Firstly, extensive community consultation and town-hall meetings were undertaken to agree the scientific themes and priorities. Following this, specific projects were then subjected to very extensive reviews in terms of costs, timescales and risks. The results from these were then fed back into the recommendations in order to attempt to have a programme that would fit within the anticipated resources. Nevertheless, some four years into the programme, it is clear that there are still problems in terms of finding sufficient funding to support the programme timeline. As noted above, one of the major problems was always out of the control of the Decadal Panel; namely the large over-run in the cost and timescale for the James Webb Space Telescope (JWST), which surfaced relatively late in the mission and which has had a significant impact on astrophysics space missions. Therefore, it is clear that projects need to meet, or almost meet, their predicted budget envelopes. Should they begin to exceed these significantly, then unless additional resource can be identified (e.g. through other partners) then a scientific descope needs to be considered and weighed against the opportunity cost of delaying other missions (which often results in an increase in cost for them). This, of course, is always easier said than done.

Another problem facing the US Decadal Panels was that having a good handle on what the future budget for their areas might be is far from simple (perhaps especially in the NASA arena). It can be argued that this is an area where Europe (through for example ESA and ESO) is in a much stronger position; where the political process and resulting changes do not usually have huge impacts on programmes, but rather ‘delta swings’ in the overall funding profiles. This is contrasted with the USA, where recently the annual budgets have been delayed notably – making long-term planning exceedingly difficult. A very interesting



document to read is the ‘Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop ( 2013 )’<sup>95</sup>.

### 8.2.1 Decadal Survey recommendations - Astronomy and Astrophysics

The recommendations from the latest round of Decadal surveys in terms of projects and technological developments were:

Large Space-based projects (in priority order):

1. Wide-Field Infrared Space Telescope (WFIRST)
2. New Explorer Missions – two medium, two small and at least four missions of opportunity in the coming decade
3. Laser-Interferometer Space Antenna (LISA)
4. International X-ray Observatory (IXO)

Large Ground-based projects (in priority order)::

1. Large Synoptic Survey Telescope (LSST)
2. Mid-scale innovation programme (projects and instrumentation)
3. Giant Segmented Mirror Telescope (GSMT)
4. Atmospheric Cerenkov Telescope Array (ACTA)

Other recommendations (medium-scale funding):

- New Worlds (exoplanets) Technology Development for a 2020 Decade mission
- Technology development for a mission to study the epoch of inflation (cosmic background polarisation)
- Cerro Chajnantor Atacama Telescope (CCAT)
- Small-scale projects

In terms of the ASTRONET Roadmap, a number of these projects have parallel European counterparts, suggesting the potential for downstream collaboration as the projects and budgets pan out. WFIRST is a space-based, wide-field, infrared survey telescope fitted with a low-resolution spectrometer, performing some of the same science as EUCLID but in the infrared as opposed to the optical. The current baseline for the mission is called WFIRST-AFTA, utilising an existing 2.4m telescope (larger than the original design anticipated for WFIRST) to save costs and reduce risk due to previously tested hardware. This concept has recently been endorsed<sup>96</sup>. LISA and IXO (with no timescale for launch or approval) can be seen as counterparts to the ESA L3 and L2 missions respectively.

The top ground-based project, the LSST, does not have a European counterpart, but the VISTA (albeit a significantly smaller telescope) facility has a number of years head-start on

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<sup>95</sup> [http://www.nap.edu/openbook.php?record\\_id=18434&page=1](http://www.nap.edu/openbook.php?record_id=18434&page=1)

<sup>96</sup> [http://www.nap.edu/openbook.php?record\\_id=18712](http://www.nap.edu/openbook.php?record_id=18712)

this project, and other survey facilities include the SDSS, DES and PanSTARRS. The LSST is expected to receive construction funding sometime in 2014. Recently, there was a LSST conference in Cambridge (UK) to assess interest in European participation and the use of the LSST for EUCLID follow-up is an attractive option and the enhancement of current plans for data-centres in Europe is one of the ideas being pursued. The call to set-aside funding for instrumentation and project studies is interesting in that it demonstrates the need to maintain ‘headroom’ in programmes to allow technological developments to be undertaken. This is something that is echoed in the ASTRONET Roadmap (see Chapters 5 and 7). The GSMT is an attempt to settle on governmental funding and support for a giant telescope (e.g. the Giant Magellan Telescope slated for a Chilean site and the Thirty Meter Telescope for Mauna Kea). The ESO E-ELT is larger and more advanced in terms of funding but the GMT and TMT are confident of securing their construction funding and if this pans out, the GMT (the smallest) may beat the E-ELT to first light. The ACTA telescope is closely linked to the CTA proposal from Europe but its future is also dependent on funding.

The theme of technology development is again promoted with regard to a new exoplanet mission in the 2020’s as well as to study the epoch of inflation, through Explorer-type missions, balloons and technological developments for a future potential satellite cosmic microwave background polarisation experiment. The CCAT project (a 25m diameter submillimetre telescope on Cerro Chajnantor) does not have a European counterpart, but some of the Germany community are heavily involved in the project and the opportunity is available for others to join as funding for construction has still not been obtained (but see 8.2.4).

### 8.2.2 Decadal Survey recommendations – Planetary Science

A key recommendation is to increase the cost of medium-scale missions to \$1B excluding the launch costs and that NASA should select two missions in the decade 2013-2022 to pursue the following questions:

- Comet Surface Sample Return,
- Lunar South Pole-Aitken Basin Sample Return,
- Saturn Probe,
- Trojan Tour and Rendezvous, and
- Venus In Situ Explorer

The next mission in the series should address:

- Io Observer,
- Lunar Geophysical Network.

In terms of large missions, the highest priority in the decade was for the Mars Astrobiology Explorer-Cacher (MAX-C), which is part of the NASA-ESA Mars Sample Return programme (including the ESA Mars Exo-Rover). However, this programme is very expensive and there is a strong recommendation that this should be cost-capped and that if these cannot be verified, then the mission should be deferred or cancelled. Negotiations with ESA in overall cost reductions form a strong recommendation of the Panel.

The second priority for the decade is a Jupiter-Europa Orbiter (JEO), but again, the projected cost is very high and the Panel essentially re-iterate their recommendations for MAX-C above, the costs need to be reduced or alternative decisions taken. The third priority mission is the Uranus Probe and Orbiter missions and again, it should be cost-capped.

The above shows the tremendous pressure that the NASA budget has come under and that projects ‘at any cost’ can no longer be approved and that hard decisions (through descopes or collaborations) need to be taken in order to maximise the overall programme and opportunities. The committee also recommended other projects to be included should the budgets be increased, or funding becomes available.

### 8.2.3 Decadal Survey recommendations – Solar and Space Physics

This survey took a more strategic approach and addressed themes rather than specific missions, although individual missions are noted. Therefore, it is much harder to compare to the Roadmap and the other Decadal surveys. Interestingly, the top priority on NASA and the NSF was to complete the current approved programme of experiments and missions, this includes the collaborative Solar Orbiter (ESA) mission to be launched in 2017 and the Solar Probe Plus (a 2018 launch), which will make the first visit to the solar corona to discover how the corona is heated, how the solar wind is accelerated, and how the Sun accelerates particles to high energy.

The second priority was to implement what is called the ‘DRIVE’ mission. This stands for Diversify, Realize, Integrate, Venture, and Educate) and is aimed at both NASA and the NSF. Specifically it means that the agencies should Diversify observing platforms with microsatellites and mid-scale ground-based assets, Realize scientific potential by sufficiently funding operations and data analysis, Integrate observing platforms and strengthen ties between agency disciplines, Venture forward with science centers and instrument and technology development, and finally to Educate, empower, and inspire the next generation of space researchers. These themes were also very much in-line with those expressed in the ASTRONET Science Vision document, albeit not so lucidly expressed. There are two specific recommendations within DRIVE: fund the Advanced Technology Solar Telescope (ATST) – a US counterpart to the European Solar Telescope; and to create a new competitively selected mid-scale project funding line in order to enable such projects and instrumentation for large projects. The ATST is now funded and is in the advanced stage of construction on Haleakala, Hawaii and has some European (UK) involvement.

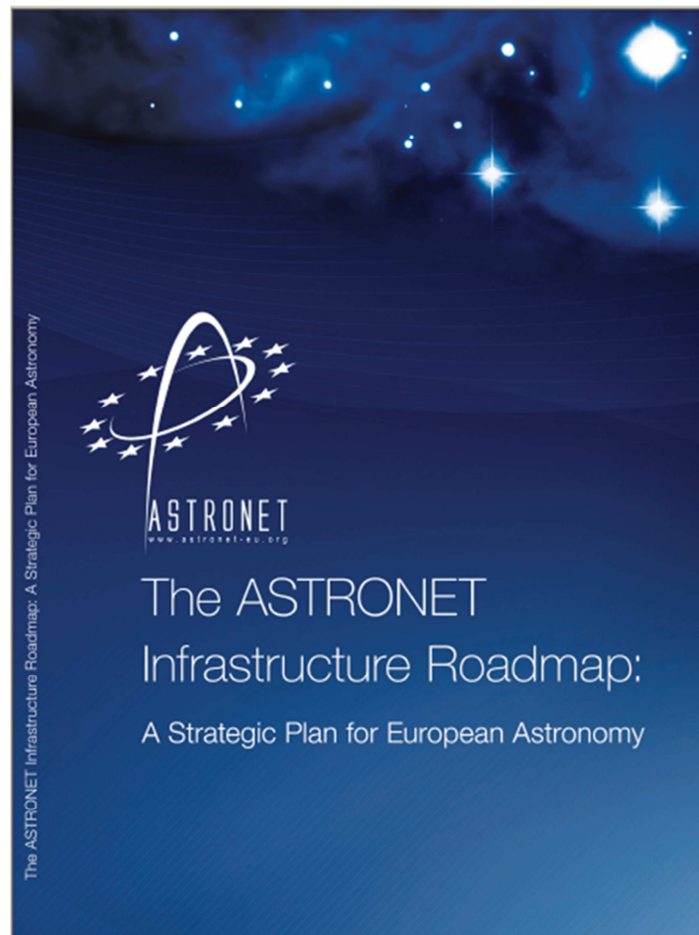
The third priority was to accelerate and expand the heliophysics Explorer programme to allow a better mix and more frequent deployment of small and mid-size Explorer missions. The Report also makes a number of recommendations with regard to space-weather but these are not reproduced here.

### 8.2.4 Decadal recommendations – progress

Because the latter two Decadals have just been completed, it is more instructive to focus on the Astronomy and Astrophysics Survey, being released just two years after the ASTRONET

Roadmap. It is clear that things have been difficult in the USA due to the squeeze on budgets following the economic crash of 2008 and the difficult political situation in the government. In terms of the major ground-based projects, good progress has continued on the LSST and construction funding is expected sometime in 2014 as it is in both the NSF and DOE budgets. The same is true for the funding of the GSMT; while both the GMT and TMT are progressing with design work and fund-raising, how the NSF will contribute to a single large optical/IR telescope remains unclear. The design work continues for CCAT, but again, the construction costs have still not yet been found. However, a proposal for this funding has recently (March 2014) been submitted to the NSF Mid-Scale Innovations Program (itself a recommendation from the Decadal Review). As noted previously, the large increase in costs for the JWST has hit the NASA astrophysics programme hard; however, the Solar System and planetary programmes seem to be in a relatively better shape, especially with the small and medium missions.

### 8.3 How has the ASTRONET Roadmap fared – conclusions



*The original ASTRONET Infrastructure Roadmap published in 2008 has stood the test of time well.*

The conclusion is that for a number of reasons the Infrastructure Roadmap has been very successful in comparison with those previously from the USA (i.e. before the latest Decadal Survey). This is not because the Roadmap was under-ambitious in its scope, but because of

two points: the programme was costed to be ‘do-able’; and more importantly, the political situation and funding has been more stable in Europe than in the USA. This latter point has had bigger impacts in the USA, especially where many of the missions are not as international as those in which Europe is involved. This is highlighted by the fact that ESA and ESO essentially have control over the financial envelope of their programmes (which are expected to be stable over the medium- to long-term due to the political process within Europe). The key is then matching the scientific missions espoused through their own processes as well as the ASTRONET Science Vision and Infrastructure Roadmap processes. It is interesting to note how the ESA Cosmic Visions programme has now set the path for long-term planning for missions, especially the really major (large-scale) missions, well into the 2030 window. However, it should also be noted that a major perturbation to the NASA astrophysics programme was the massive cost over-run of the JWST – see later.

Where programmes do not fit within the ESA/ESO fields, then the situation is much more akin to the USA, where multi-national European funding needs to be obtained (always a slower process to match national aspirations and budgets) or EU specific funding (another slow process). This is an area where the fluctuations in annual national budgets for capital and recurrent costs along with the inherent instability of the process accompanied by a higher degree of risk take a toll on longer-term planning.

The astroparticle physics field is an area, which, in a number of nations, does not have an individual and separate ‘home’ within the funding agencies. While to some extent this has been compensated for within Europe by having a pan-European organisation (ASPERA/ApPEC), nevertheless, the competition for funding between the top-two projects (CTA and KM3NET) means that either significant additional funding needs to be identified, phasing introduced, or competition will see one of them fall by the wayside.



## **9 The Roadmap Update conclusions and recommendations**

### 9.1 Introduction

As can be seen from the preceding work, the original Infrastructure Roadmap has been extremely successful in identifying the medium and large projects and giving some order of priority and timescales so that the funding envelope allows the maximum number of projects to be undertaken. The Roadmap compares extremely favourably with the equivalent from the USA because of the financial and political stability of the two major pan-European organisations, ESA and ESO. This light-touch update generally confirms all that was said in the original Roadmap and presents an up-beat report on the general state of the new facilities.

The economic downturn at the start of the decade generally slowed the pace of the new projects but had a more marked impact on the non-capital budgets of nations. The need to fund research grants and personnel, maintain training and provide additional funding for new facilities has meant that there is a squeeze on the ‘on-going’ national programmes. This has manifest itself in reduced research grant awards (hitting research activity, personnel, experiments and instruments) and a tension against funding to maintain existing facilities. The ASTRONET review of the small and medium-size optical/IR telescopes has produced some clear recommendations and a strategic overview is now urgently needed of the radio and submillimetre regimes through the ASTRONET process.

Below we present the *original* recommendations from the Infrastructure Roadmap and the *new* ones from this Update. The numbering sequences for the recommendations correspond to that in the original Roadmap and this Update.

### 9.2 Panel-A

#### 9.2.1 Original Recommendations

1 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.

#### 9.2.2 New Recommendations

*3.1: ESA and national agencies need to plan for the retention of key skills and key teams for the long lead-time missions of Cosmic Vision.*

*3.2: strengthen multiwavelength collaborations through dedicated programmes and grants*

*3.3: continuing R&D technological research activities remains of paramount importance to maintain European leadership in the field of high-energy astrophysics*

*3.4: in view of the excellent health of the XMM-Newton and INTEGRAL missions, this panel feels confident to strongly endorse, yet again, their continuation. Moreover, this panel*

*welcomes the outcome of the recent NASA Senior Review, which has approved the continuation of SWIFT and Fermi operations for between 2 and 4 years.*

### 9.3 Panel B

#### 9.3.1 Original Recommendations

1 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.

2 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.

3 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.

4 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.

5 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.

6 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

7 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.

### 9.3.2 New Recommendations

*4.1: ESA, the EU and national agencies should address the potential for a more coherent funding arrangement for the exploitation of scientific data from space missions.*

*4.2: it is important that the determination of Gaia's precise position from ground-based observations should be secured for the total lifetime of the mission.*

*4.3: it is vital that national agencies ensure that adequate funding is provided for data analysis to ensure that Europe is best placed to maximise scientific return from the Gaia mission*

*4.4: long-term missions usually require considerable study and technical development and it is important that adequate funding needs to be provided by ESA and National Agencies to support the preparatory R&D activities in the future. Areas that require special attention are e.g. the development of large, low-noise detector arrays, and the development of techniques that will allow high precision formation flying.*

*4.5: the future optimisation of the 2-4m class optical/IR telescopes in Europe requires further and ongoing work in order to maximise overall efficiency and cost effectiveness.*

*4.6: a coherent long-term plan should be established under the auspices of ESO and the European Initiative for Interferometry during the coming two years. It should be built on the realizations of Gravity and MATISSE and prepare the future plans for enhanced high angular resolution capabilities in the ELT era and in complement to exoplanets and stellar physics space missions.*

*4.7: a coherent long-term plan should be established under the auspices of ASTRONET and RadioNet during the coming two years. It should outline the scientific role of each of the facilities mentioned above in the ALMA era, develop an access strategy beyond the current Trans National Access (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. This is very urgent as the future funding for some of these facilities is currently under discussion/threat.*

*4.8: before considering in any systematic manner perceived gaps and technology developments, it seems desirable to consider the creation of such a database, e.g. through ASTRONET. This should cover developments both for instrumentation and for software.*

*4.9: the preparatory studies for new projects should include a verification of an advanced stage of technical readiness (TRL). This will help to reduce the risk of significant cost-overruns during the construction phase.*

*4.10: it is critically important that these technology developments needed for the future in terms of key parameters (e.g. large-scale detector arrays) and high-tech solutions are explored in close collaboration with industry.*

## 9.4 Panel C

### 9.4.1 Original Recommendations

1 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.

2 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.

3 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.

4 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.

5 We also strongly recommend development of 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.

#### 9.4.2 New Recommendations

*5.1: the European Solar Telescope (EST) should be included in the ESFRI Roadmap in the current revision process.*

### 9.5 Panel D

#### 9.5.1 Original Recommendations

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.
7. 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.
8. 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.
9. 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.

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

11 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.

12 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.

13 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.

14 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.

15 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.

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

17 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.

18 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.

## 9.5.2 New Recommendations

*6.1: the ASTRONET Board needs to determine the status of the Astrophysical Software Laboratory in the near-future*

*6.2: there is a need for continued investment in dedicated data facilities across Europe to keep pace with the data increase.*

## 9.6 Panel E

### 9.6.1 Original Recommendations

1 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.

2 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.

3 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.

4 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.

5 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.

6 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.

7 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.

8 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.

9 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.

10 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.

#### 9.6.2 New Recommendations

*7.1: in order to achieve a pan-European educational activity using astronomy as a theme for Science and Technology requires ongoing coordinated funding streams in addition to start-up funds.*

- 7.2:
1. *Creation of a European-wide translations agency that can serve as a service to agencies and national entities*
  2. *Creation of a European-wide Educational material repository (see 7.3.2.4 below)*
  3. *Creation of a European-wide Teacher Training agency*
  4. *Creation of standards for a ‘Top-10’ list of astronomical topics/concepts/ phenomena that students need to get acquainted with at some point during their primary or secondary studies. Some examples might include: seasons; Lunar phases; eclipses; tides; gravity; the Sun as a star; etc.*
  5. *Creation of a European-wide standardised educational resources (kits that can be mass-produced and localised)*
  6. *Creation of open access resources for images, videos, and planetarium content*

*7.3: a European-wide agency should be established to coordinate teacher training initiatives and to provide the necessary network, framework, resources, expertise and evaluation methodology for a sustainable European-wide teacher training programme.*

*7.4: funding needs to be provided to enable AstroEDU to be expanded to cater for the entire European educational community (extension of the original recommendation 1).*

*7.5: ASTRONET and funding agencies should agree and push for open access content to be made available for museums and planetariums (extension of original recommendation 6).*

*7.6: 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 (extension of original recommendation 7).*

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