July 2012

European Astronomical Society Working Group on the Future of Space Astronomy

Report to the EAS Council

Final Report

Document Revision History

Version	**Date**	**Comment**
1.0	28 April 2012	Released to EAS members for comment
2.0	25 June 2012	Final version submitted to EAS Council *Updates to reflect comments from EAS members plus other external developments including the ESA L1 selection, launch of NuSTAR and cancellation of GEMS.*
2.1	24 July 2012	Executive summary added *Minor editorial changes*

European Astronomical Society Working Group on the Future of Space Astronomy

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Executive Summary

For more than five decades, space astronomy missions have made an ever-increasing contribution to our knowledge of the Universe, providing access to wavelengths inaccessible from the ground and to measurements whose precision could not be matched with terrestrial facilities and, perhaps most notably, with access to physical regimes not attainable in terrestrial experiments. Today, space missions continue to provide an integral and crucial contribution to our exploration of the cosmos and to essentially every aspect of astrophysical research.

Over the last few years, however, concern has been mounting over the future of space astronomy, stimulated by the perception that the frequency of mission opportunities may be decreasing. The European Astronomical Society's working group was set up to evaluate the situation from a European perspective, to consider the impact on both the science and the European space astronomy community and to consider what steps could be taken to improve the outlook. There are clear dangers inherent in any decline in opportunities, for example in terms of loss of scientific opportunities and of expertise in the community.

The working group undertook its own survey of space astronomy, examining its scientific context and background and broader connections with ground-based astronomy and assessing the size and scope of the space astronomy community in Europe. It also undertook a survey of the status of space astronomy missions, looking at the record over the last twenty years for past and operational missions, as well as the future plans of both European and worldwide agencies, in order to establish the key trends.

The working group's activities reaffirmed the continued importance of space astronomy as a key component in the future of astrophysical research, noting in particular the ever-increasing synergy between space-based and ground-based studies. The working group identified key issues that need to be addressed to ensure the preservation of Europe's current strengths in space astronomy. The working group's survey of the European space astronomy community demonstrates how large this is, amounting to over 2000 people in more than two dozen institutes, 40% of whom have key technology development roles. Its examination of mission trends reveals an effective decrease in the number of mission opportunities over the next two decades, especially when compared with the last twenty years when the discipline had a relatively 'golden' period. This reduction in opportunities arises from multiple pressures within agency budgets that benefit from only modest growth. The most important pressures include increased mission costs, as new science goals demand ever more complex (and expensive) payloads and place additional requirements on space systems, coupled with new demands for access to space from growing areas such exoplanet studies.

With this background, the working group formulated four recommendations relating to space astronomy in the coming decades. In summary, the recommendations are as follows:

- Planning of the space astronomy program within ESA and other agencies is a complex issue that requires the right balance between stability and predictability on the one hand whilst also allowing for innovation to avoid an uncompetitive program developing. The current approach within the ESA program has problems with the connections between each cycle of the decision-making process and arguably fails to provide the required level of stability. The working group's recommendation in this area emphasizes the importance of stability and predictability of future missions, for example in ensuring that appropriate investments can be made in in technology development.

- International cooperation. The most ambitious space astronomy missions will inevitably only be achieved at a high cost, requiring full cooperation between the one or more of the major space agencies: ESA, NASA and JAXA. The current mismatch between decision-making procedures and timescales, together with several recent collaboration failures, has had a major impact on the future of several planned major missions. The working group stressed the importance of working to resolve this issue if the boldest projects, with the strongest groundbreaking potential, are ever to be realised.

- Mission size. Space astronomy would benefit significantly from having greater flexibility, for example in having access to focused medium/small class missions. Such missions could be provided through ESA or through national initiatives or a combination of these approaches. The working group welcomes the recent S-class initiative (announced by ESA during the final stages of the working group activities), although it notes that the current constraints on this program are rather restrictive if Europe is to emulate the success of the US Explorer program.

- European agenda. The working group noted that space astronomy currently suffers from insufficient coordination at the European level, resulting in a program that can lack coherence and experiences duplication, producing an inefficient program which arguably does not achieve its full European potential. To address this issue, the working group recommends greater and more focused involvement of the EU in stimulating a coordinated development in Europe by providing targeted support such as *integrated activities* specifically for space astronomy.

Section 1: Introduction

1.1 Rationale

The European Astronomical Society Working Group was set up in early 2011 to assess the state of space astronomy in Europe, compare it to the recent past and evaluate its current status and outlook. The Working Group is intended to focus particularly on the prospects for space astronomy missions over the coming decades and assess the dangers inherent in a reduction in missions, for example in terms of loss of major scientific opportunities, expertise in the community and the vitality of European space industry.

1.2 Context and Related Activities

One of the original motivations for setting up the Working Group was the speech made by Roger Bonnet at the 2010 COSPAR assembly noting a concern over "the dearth of forthcoming space astronomy missions and the consequent lack of space astronomy data that is looming on the horizon". These comments stimulated the establishment of a COSPAR working group, under the chairmanship of Pietro Ubertini, who carried out a detailed assessment of the future of space astronomy in the period April 2010 to April 2011, leading to the publication of their report in 2012 (Ubertini et al., *Future of Space Astronomy A global Road Map for the next decades,* J. Adv. Space Res. (2012), http://dx.doi.org/10.1016/j.asr.2012.03.009).

The activities of the EAS Working Group thus overlap considerably with those of the COSPAR Working Group and have benefitted from discussions with Prof. Ubertini and the chance to see draft versions of their report and hear presentations on their activities at the 2011 EWASS in St. Petersburg. Nevertheless we have striven to carry out an independent exercise, focusing on the European perspective, thus, we hope, providing a complementary report. One major difference in our activities is that we have not sought to provide a specific road-map for future space astronomy missions, feeling that this was beyond the scope of what we should attempt given the small size of the Working Group.

In this context we also note the publication last year of a key article by Roger Bonnet and Johan Bleeker on the subject of the future of space astronomy (Bonnet, R.M., Bleeker, J.A.M. *A dark age for space astronomy?* Science 333, 161, 2011). Some of the comments we make in in our conclusions and recommendations echo points made in this publication.

1.3 Terms of reference

1. The Working Group will examine the future of space astronomy from a European perspective, but not be limited to discussion of European-led initiatives. The Working Group will thus include consideration of projects led by non-European agencies (many of which have significant European involvement).
2. The Working Group will cover all aspects of 'cosmic' space astronomy specifically excluding the solar system and solar-terrestrial physics but including gravitational wave astrophysics and extra-solar planet studies. The scope of the Working Group thus matches the remit of ESA's AWG (plus that of the PSWG) but not the SSEWG. It also matches the scope of the US Astro2010 Decadal Review with respect to space missions.
3. The Working Group should consider the next 20 years, ie. a time-frame from now until ~2030, noting of course that the uncertainties beyond the next 5-10 years are very large.
4. The Working Group will present its final report, including its recommendations, to the Council of the European Astronomical Society.

1.4 Membership of the WG

Members of the Working Group are drawn from the wider European space astrophysics community. The group does not aim to be exhaustive in its representation of European countries active in space astronomy or in its coverage of "wavelength" expertise, but to be as effective as possible while representing different views of the European space astronomy community. The membership of the Working Group is:

Chair: Prof. Michael G. Watson, University of Leicester, United Kingdom

- Dr. Jan-Willem den Herder, SRON, Utrecht, Netherlands
- Dr. Hans Ulrik Nørgaard-Nielsen, Technical University of Denmark
- Dr. Jean-Paul Kneib, Astrophysical Laboratory of Marseille, France
- Dr. Roberto Maiolino, Astronomical Observatory of Rome, Italy[1]
- Prof. Martin Ward, Durham University, United Kingdom
- Dr. Sergio Volonté, former Head of the Science Planning and Community Coordination office, ESA
- Dr. Marc Audard, ISDC, University of Geneva, Switzerland.

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[1] Cavendish Laboratory, Cambridge, UK from February 2012.

Section 2: Context and background of space astronomy

2.1 A brief history

The history of space astronomy dates back to early missions in the 1960s with brief sounding rocket flights providing the initial launch opportunities. Space astronomy has since developed into a major component of astrophysics at essentially all wavelengths of the electromagnetic spectrum, from γ- and X-rays to radio band, with operational mission life times rising to years or even decades.

European space astronomy started to take shape with the founding of the European Space Research Organization (ESRO) in 1964 and its subsequent evolution into ESA in 1975. One of the important early milestones was the launch of the COS-B, the first ESRO/ESA satellite dedicated to a single experiment. COS-B was followed in the 1980s by a number of significant missions such as EXOSAT (1983), Hipparcos (1989) and joint observatories (IUE in 1978, IRAS in 1983). The following years saw the launches of the highly successful Hubble Space Telescope (1990), and several other missions dedicated to solar and astrophysical science at all wavelengths.

The European space astronomy landscape over the last few decades has been particularly well-defined thanks to the framework provided by the Horizon 2000 long-term plan for space science, and its Horizon 2000+ successor. The latter plan will end with the upcoming launches of Gaia, BepiColombo, and JWST.

The current European space astronomy scene is now shaped by ESA's Cosmic Vision 2015-2025 program to select missions that should answer four different major scientific questions: "What are the conditions for life and planet formation?", "How does the Solar System work?", "What are the fundamental laws of the Universe?", and "How did the Universe begin and what is it made of?".

Selection of the ESA L- and M-class missions, which form the main elements of the Cosmic Vision program, is ongoing. The first pair of M-class missions (M1 and M2), with nominal launch slots in 2017 and 2019, was selected in late 2011; the successful missions being Solar Orbiter and Euclid. A significant ESA contribution to the JAXA's SPICA mission also remains under consideration. A second set of M-class missions (the M3 candidates: EChO, LOFT MarcoPolo-R and STE-QUEST) are under consideration for a launch in the early 2020s. PLATO (from the first set) will also likely be considered for selection in competition with the other four M3 candidates in 2013.

The potential L-class missions were EJSM-Laplace, IXO, and LISA. However, in March 2011 ESA decided to redefine the L missions as mainly European in scope instead of joint ESA-NASA or ESA-NASA-JAXA ventures. The mission study teams redefined their missions (with some associated name changes). EJSM-Laplace became JUICE, IXO became ATHENA and LISA became NGO. The L-class mission selection took place in May 2012. ESA's SPC chose JUICE for the L1 mission slot. A subsequent call for the L2 and L3 mission slots is anticipated in 2013. ESA is considering changes in the context in which the L2/L3 decisions are made; the outcome will of course depend on the 2012 Ministerial Council meeting.

Outside of the ESA program, several European agencies have continuing national space astronomy programs; past examples include ROSAT, BeppoSax and Agile (German and Italian agencies, with Dutch partnership for BeppoSax) whilst current examples include COROT, led by the French agency CNES and Spektrum-RG, a joint Russian-German project due for launch in the near future. On the international scene, NASA's space program is suffering from significant budgetary issues, which have had a major impact on both space astronomy and planetary exploration missions, many of which are partnerships with ESA. Perhaps the most significant issue is the spiraling cost of JWST, which has both distorted NASA's budget and led to the announcement of the delay of JWST's launch until 2018. Non-European agencies such as JAXA have long maintained strong national programs, now complemented by growing programs led by the Indian and Chinese space agencies.

2.2 Importance of space astronomy: key science areas and priorities

2.2.1 Motivation for space astronomy

The main motivation for space astronomy is, of course, to increase our understanding of the Universe, both through dedicated observational programs and via exploration of new regimes and regions of parameter space, leading to unanticipated discoveries. Space astronomy contributes to every part of astrophysics and plays a key or dominant role in many scientific areas. This is made possible through advanced technological developments, which lead to an increase in capabilities at various wavelengths and at increasing sensitivities. Such progress has been obtained, for example, through the development of higher sensitivity sensors, larger format sensors, or through the use of larger aperture telescopes in conjunction with the unique vantage point of being in space.

Space missions are always based on capabilities that are **uniquely** achievable from space. For example, observing at wavelengths absorbed by the Earth's atmosphere (X-ray, UV, MIR, FIR) is an obvious motivation to go to space. Space observations also provide other unique opportunities: to benefit from high-resolution images over a wide field of view and to achieve high photometric accuracy (in the visible and near-IR: e.g. COROT, *Kepler*, *Euclid*), to benefit from very low sky background (in particular in the near UV and in the near-IR bands) or to monitor transient phenomena, such as supernovae or AGN, on time scale of hours, days or weeks at visible and near-infrared wavelengths (e.g. the SNAP/JDEM concept, *Euclid* and WFIRST). Even at wavelengths not absorbed by the Earth atmosphere, advanced science goals can motivate space missions.

The key science areas where space astronomy mission can make a unique contribution have been identified as part of the Astronet[2] initiative, from a European perspective, and in the US Decadal Survey (Astro2010)[3]. We do not attempt to revisit these here, but emphasize the simple fact that space astronomy is identified as playing a key role in essentially **every** part of astrophysics from cosmology, through the evolution of the Universe, to the origin of stars and planets.

2.2.2 Multi-wavelength astrophysics and Ground/Space synergies

With the constant increase in our understanding of the Universe and the various physical processes at play, it is no surprise that many astrophysical studies are based on multi-wavelength observations, both in imaging and spectroscopy, to interpret distant objects and phenomena. As a consequence, there is a growing synergy between ground and space observations, and an increasing number of research programs combining data from different facilities. Some observations can only be conducted from space due to its unique vantage point, the complementarities and connections are thus developing.

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

[3] http://sites.nationalacademies.org/BPA/BPA_049810

These trends reinforce the importance of a comprehensive space astronomy program. In practical terms they also place additional requirements on space mission science operations, in particular increasing the importance of the expert data centres, which provide the high-level science products needed for full exploitation of the data. Ground-space synergies have also led to the development of a new type of ground-based facility that is dedicated to the detailed follow-up of space discoveries. Examples include robotic telescopes to conduct optical/near-infrared observations of gamma-ray bursts; high-resolution spectroscopy of Gaia-selected stars.

2.3 Ground-based facilities: status, comparisons and connections

To provide the broader context for our discussion of space astronomy, we provide here a brief account of the current status and future directions of ground-based astronomy. Astronomy from the ground is restricted to wavelengths that are not absorbed by the atmosphere, but does not suffer from the stringent mass and size constraints that strongly limit space experiments. Likewise, significant ground-based astronomy facilities can be developed at much lower cost and risk than space facilities. Ground-based facilities often have long lifetimes, measured in decades and the instrumentation used can be continuously updated. It is thus not surprising that ground-based facilities present a richer landscape and that the development of ground-based astronomy follows different patterns.

2.3.1 Current landscape

The main portofolio of ground-based telescopes comprises:

> *Optical/Near-Infrared facilities* (cosmology, galaxies, stars and planets): many telescopes ranging from less than 1m in diameter to ~10m. Around a dozen 8m-class telescopes are currently operational. Small aperture (<2-3m) telescopes are often dedicated to single instruments, with the larger ones (~4-10m) being used as observatories with a much wider range of instruments.
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> *Sub-millimetre facilities* (measuring the CMB fluctuations, clusters through SZ detection, galaxies, stars and planets): large dishes (e.g. the IRAM 30m, the Large Millimetre Telescope (LMT) or interferometers (e.g. the IRAM Plateau de Bure Interferometer, ALMA).
>
> *Radio facilities* (cosmology, reionization, galaxies and stars): a few large dish telescopes exist (GBT, Arecibo), but also many interferometers (VLA, VLBI, GMRT …) that are all used as observatories, although the newest interferometers such as LOFAR are run more like an experiment due to their large sky coverage.
>
> *Other facilities:* other ground-based astronomical facilities include: neutrino detectors such as Ice Cube facility in Antarctica, or Antares in the Mediterranean, and high-energy gamma-ray telescopes which use imaging atmospheric Cherenkov telescopes, eg. HESS, MAGIC & VERITAS.

2.3.2 Trends and future facilities

The last decade has seen the emergence of several important new trends which span much of ground-based astronomy, for example the growing prominence of large-scale survey facilities and projects (SDSS, UKIDSS, PanStarrs) with the science largely enabled by comprehensive software systems to support them. Within specific domains some of the more important developments are summarized below.

Optical/near-infrared: In the last fifty years, multi-purpose visible/NIR observatories were typically designed as "single object" facilities, thus covering a limited field-of view of typically a few square arcminutes. The push to achieve higher spatial resolution with adaptive optics increased the trend to decreasing fields of view due to detector size limitations and the physics of the atmosphere.

The interest of probing deeper in the Universe leads to the building of larger and larger aperture size telescope (Keck, VLT, Gemini), generally at the price of a smaller field of view than the previous generation of telescopes.

However this trend has been counteracted by the development of large format optical and NIR detectors to meet the needs of wide field observations, first on the smaller telescopes (e.g. dark matter searches through microlensing), but now by revamping larger telescopes (e.g. the DECam wide-field imager developed for the Dark Energy Survey) or even with dedicated larger aperture/wide field telescopes (e.g. VISTA, LSST).

A key area in optical, and now infrared, ground-based observations is spectroscopy from low to high resolution with an ever-increasing multiplex capability. The highest resolution (R>10,000) is achieved for stellar physics and exo-planet searches, with lower resolution spectroscopy (R<5,000) being applied primarily for extragalactic astronomy. The large multiplex capabilities that are now being developed focus on mapping the large-scale structures in the Universe, addressing the question of Dark Energy, or on mapping the Milky-Way structure (in particular as follow-up of the Gaia mission).

Sub-millimetre: The last twenty years has seen impressive development of sensors for sub-millimetre wavelengths (both bolometers and heterodyne sensors), leading to a growing number of facilities which utilize these advances (e.g. IRAM, LMT, ALMA, CCAT to name a few). Because these facilities require dry locations to minimize water vapour absorption, high altitude locations and places such as Antarctica are mostly favoured by these facilities.

Radio facilities: The first radio (centimeter to meter wavebands) astronomical facilities developed after World War-II, allowing the first exploration of the sky in the radio band. Interferometers such as the Very Large Area have led to strong progress in topics ranging from studies of star-forming regions in our Milky Way to mapping cosmological distant objects both in their continuum or line emissions.

Radio astronomy has now entered a new era, as technology improves and allows the correlation of signals from an increasing number of radio dishes. The first example is the LOFAR facility, but pre-SKA projects are also being developed with the promise of mapping HI gas at extragalactic scales, thus offering a very efficient way to map galaxies in the Universe to z~1, but also to probe the epoch of re-ionization closer to the Big-Bang.

2.3.3 Facilities in the next decade

Within the next ten years the leading ground-based facilities expected to be operational include:

- *high energy gamma-rays* - CTA (Cherenkov Telescope Array);
- *optical/near-IR* - E-ELT, the European Extremely Large Telescope being developed by ESO together with the Giant Magellan Telescope (GMT) and Thirty Meter Telescope (TMT) being developed by US-led consortia;
- *sub-millimetre* – ALMA (Atacama Large Millimetre Array; already operational);

- *radio* –SKA (Square Kilometer Array)

These facilities, which span the entire electro-magnetic spectrum accessible from the ground, will be complemented in the optical/near-IR/mid-IR by JWST (James Webb Space Telescope; and possibly SPICA) and potentially, by a next generation X-ray observatory such as Athena.

2.4 Current status of European space astronomy community

The European space astronomy community is large and diverse. It includes both scientists mostly involved in theoretical/observational astrophysics, including space astrophysics data analysis and interpretation (hereafter the Space Science community), and scientists and engineers involved in the development of future missions and instruments from space (hereafter the Space Instrumentation community). European space astronomy institutes may employ members of one community or both communities. In some cases, institutes may not directly develop space instrumentation in house but instead undertake a coordination role for the hardware activities carried out by national space industries (e.g. ESA PRODEX-funded projects).

Institutes with a space instrumentation program play a major role in the definition, development, and operation of the space astronomy missions that are crucial to the competitiveness of space astronomy in Europe. Those institutes without a space instrumentation component nevertheless contribute significantly to many areas, for example in taking an active role in the definition of the requirements for new missions. The wider community also participates in the definition of ESA's scientific program through membership of its advisory committees (AWG, SSAC), which are drawn from whole astronomy community, even from traditionally ground-based astronomers with little or no space experience.

Noting these broader considerations, here we focus mainly on the current status of European Space Instrumentation community.

2.4.1 Space instrumentation community: background

New science frontiers require new and advanced instrumentation. Europe has a long history of developing, building and using these instruments over the full electromagnetic spectrum. One of the concerns of the Working Group is the size and preservability of technology development for future astronomy missions in Europe, particularly as the interval between space missions increases, and they become more expensive and more complex. This technology development capability should be of sufficient size to maintain a world-leading role and have sufficient continuity so that knowledge and expertise can be passed on to each new generation.

Historically technology is developed at different levels. In ESA there are various programs to develop technology for space science. The two most relevant programs are the Basic Technology Research Program (*TRP*) which is focused on early development stages across all service and technology domains, taking cutting-edge ideas and testing their suitability for space applications. The other relevant program is the Science Core Technology Program (CTP). These programs have a considerable scope (20 M€ / year), but it should be noted that, increasingly, this funding is not directed to the technology supporting instrumentation. It is the current policy that funding for the payload of missions should come primarily from the member states.

Within member states a variety of funding mechanisms exist. Certain technology is under development for other fields of physics can, with some modifications, be used in space. Often this requires significant extra funding to modify and qualify this technology for space. In addition, for various fields in astrophysics, new instrumental capabilities can be identified and special funding is available for these fields. This ranges from generic technologies to cool missions in space to the mK level, technologies which are more radiation hard or which are smaller and require less power (ASICs) to technologies which are developed with a specific application in mind (detectors covering a certain wavelength band). For this technology funding is available, but this is often linked to flight opportunities in the foreseeable future (typically with a time horizon of 10 years).

The EU framework program (FP7 Space) also provides funding for space-related activities including both science exploration and for technology development. Although there is a clear emphasis in FP7 Space on the GMES program, some funding for space science is available through the program. The current (FP7) funding level for technology with a direct impact on space astronomy is of the order of 10 M€ / year. Within the next framework program (Horizon2020), the allocation for space-related activities is not yet known in any detail, although there are positive indications that support will continue, perhaps at an enhanced level.

2.4.2 Survey of the space instrumentation community

To estimate the size and expertise of the space instrumentation activity, we made a survey of the community working on future instruments for space research in Europe. To assess the scope of the activity is a demanding task, where differences in funding models and organizational structures in different countries make a detailed comparison difficult. Therefore we decided to contact a senior person at each institute to get a fair estimate of the relevant resources per institute and the areas of expertise: (see Appendix A):

- We have approached institutes that have a significant in-house development of instrumentation for future missions at the level of at least 10-20 FTE working on technology or instrumentation. We recognize that we may have missed some institutes but the global picture is realistic.
- We have asked our contact person at each institute to identify the key research areas, the size of the institute (in FTE) and the fraction of the institute primarily working on technology for future missions. (This is not always unambiguous as technology can be relevant to space and ground based observations.)

- We have asked our contact person to identify the key technologies that are under development in their institute (e.g. optics, sensor, data processing, electronics and cryogenics).

The main results of this survey indicate that:

- The community working in institutes contributing to space instrumentation in Europe is large, with more than 2000 people involved. Of these, around 40% have a key role in the development of technology for future missions.

- The number of institutes involved in these activities ranges from one in some of the smaller countries to up to 10 in the larger European nations (note that all Italian institutes are part of a single entity, INAF, but these have different locations and background).

- These institutes cover the full range of technologies (optics, sensors, electronics, cryogenics, antennae …)

- There is a significant overlap in the technology which is being developed in institutes in different countries and sometimes even between institutes in the same country. With a limited number of flight opportunities, only a small fraction of the technology development will make it to a flight instrument.

- When implementing future instrumentation for astronomy, these institutes collaborate to share the load and the resources needed to realize instruments (usually based on technology from one of the participating institutes).

Considering the limited opportunities for the development of space instruments, it is important to note the considerable overlap between activities in different institutes. A better harmonization of these activities would clearly increase effectiveness within Europe, particularly for: (a) the development of cutting-edge technologies; (b) the development of future instruments for space. This calls for a European initiative to create an integrated structure for space instrumentation activities (similar to OPTICON), providing a structure within which the development of related technology can be effectively coordinated. Without such a structure within Europe, seeking to encourage coordination between nationally-funded research programs is unlikely to be productive.

Section 3: Current space astronomy landscape and future plans

3.1 Introduction

As part of its activities the Working Group conducted its own survey space astronomy missions, concentrating on missions operational from 1990 onwards, providing a baseline of 20+ years, complemented by a survey of planned and potential future missions. We classified each mission by its operational status, the primary waveband and the lead and other contributing agencies. We found that classifying missions by size proved to be very subjective; we make some comments about this in later sections. We complemented this with a less detailed survey of other space science fields: heliophysics[4] and planetary science, in order to be able to make some comparisons between disciplines. The full results of space astronomy mission survey appear in Appendix B.

Our survey of space astronomy missions contains a total of 38 past and current missions (16 currently operational), 12 missions under development/study, and we also list a further 3 slots for which the mission selection has not yet been made. In conducting the survey we excluded failed missions and a small number of Space Shuttle and ISS projects (such as BBXRT, MAXI). We also note that it sometimes proved difficult to provide a definitive assignment of the mission status.

Our broader, but less detailed, survey of heliophysics and planetary science missions contains a total of 32 heliophysics missions (five of which are under development and 18 are operational) and 46 planetary missions (including seven under development; 18 of these are operational).

Below we present some summary graphs and comment on some of our findings.

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[4] We adopt the NASA terminology 'heliophysics' which includes both solar studies and studies of the sun-earth connection and related space plasma studies. In ESA terminology such missions are all referred to as planetary. Some missions cannot be uniquely classified in this scheme.

3.2 Past and operational missions

Figures 1 and 2 show the history of the number of space astronomy missions operational by calendar year, broken-down by lead agency and by main waveband. The dominance to date of NASA-led missions is clear from Fig.1, whilst the large fraction of missions devoted to X- and gamma-ray astronomy is evident from Fig.2.

Figure 1 does not, however, reveal an important aspect of these missions, the multi-agency nature of the majority. Indeed, what is evident from the table in Appendix B is that single-agency missions are rare. A few missions have joint agency participation (eg. BeppoSax), several involve both ESA and NASA, but for a large fraction significant contributions come from several agencies in partnership with the lead organisation, with European agencies figuring prominently in the list.

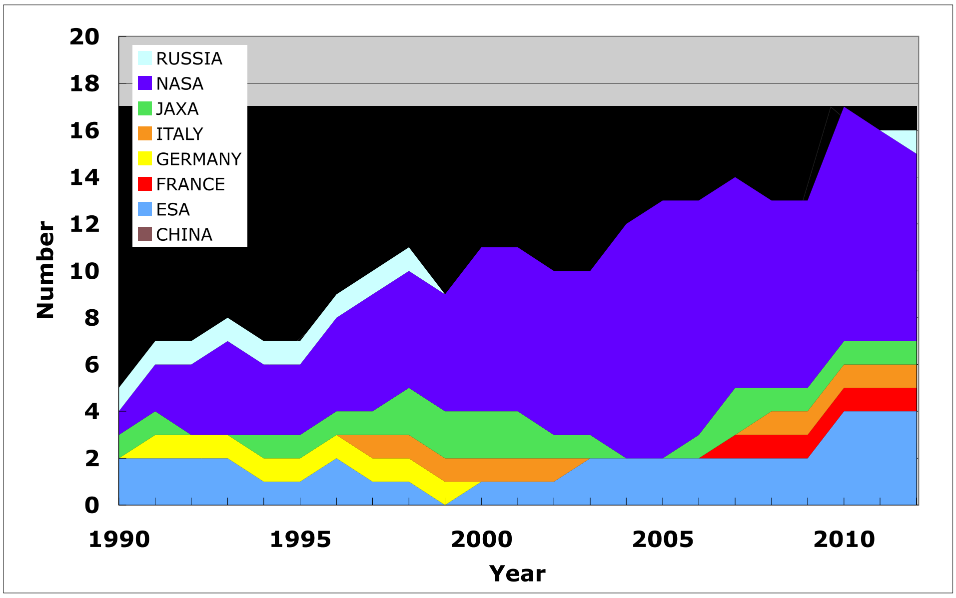

Figure 1: number of operational missions by calendar year, classified by the lead agency.

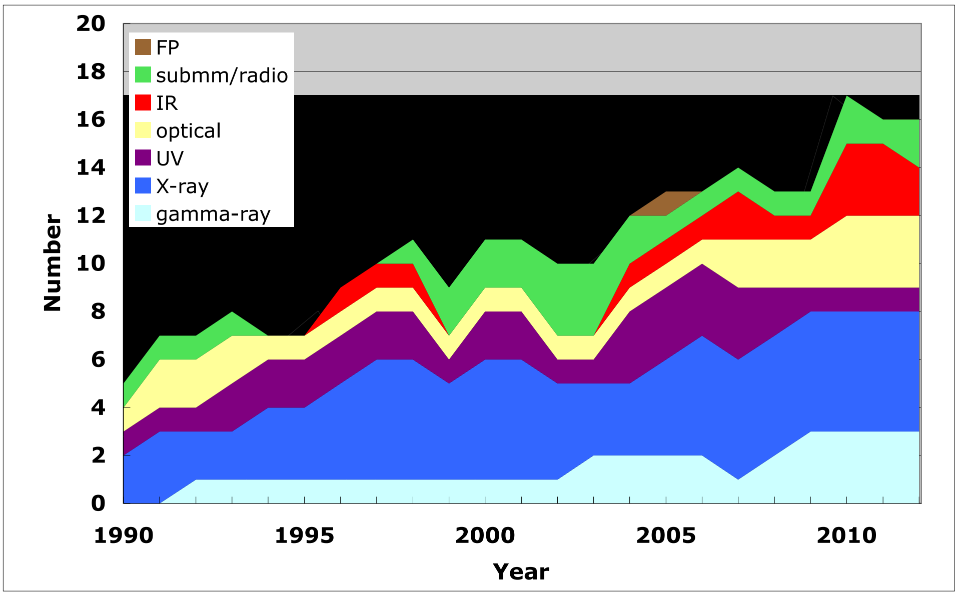

Figure 2: number of operational missions by calendar year, classified according to main observing band. FP is fundamental physics. Subdivision of some adjacent bands is arbitrary.

Overall these figures suggest a very healthy situation with a total of 16 missions currently operational. All that can safely be deduced from these plots is that, until now at least, the rate at which missions are being launched exceeds the rate at which missions are ending. A similar plot for ground-based telescopes would no doubt look even more healthy, as very few ground-based facilities are actually being decommissioned.

These plots do not, by definition, extend into the future and of course the form the graphs would take in future years is critically dependent on: (i) the assumed mission lifetime; (ii) the assumed launch date for future missions, both of which are typically very uncertain. We therefore present a summary of future plans in a separate section.

For completeness, Figure 3 shows the distribution of mission *durations* for past and current space astronomy missions. The median duration for both is ~6 years, but of course this is only a lower limit for current missions. Amongst past missions, RXTE is the longest-lived mission, operational for 17 years until it was recently switched off and thus almost matching IUE's 18 years (not included as it was launched before 1990). The current record holders are HST, Chandra and XMM-Newton.

3.3 Mission size, cost and impact

Our original aim was to classify space astronomy missions by size, but it rapidly became apparent that this was a difficult (and somewhat subjective) task due to different terminology used by different agencies and significant differences in mission cost bases. It is also clear that mission size is not simply correlated with mission impact or importance and is only crudely linked to mission cost.

Nevertheless these are important factors to consider for future missions. Some of the key considerations are as follows:

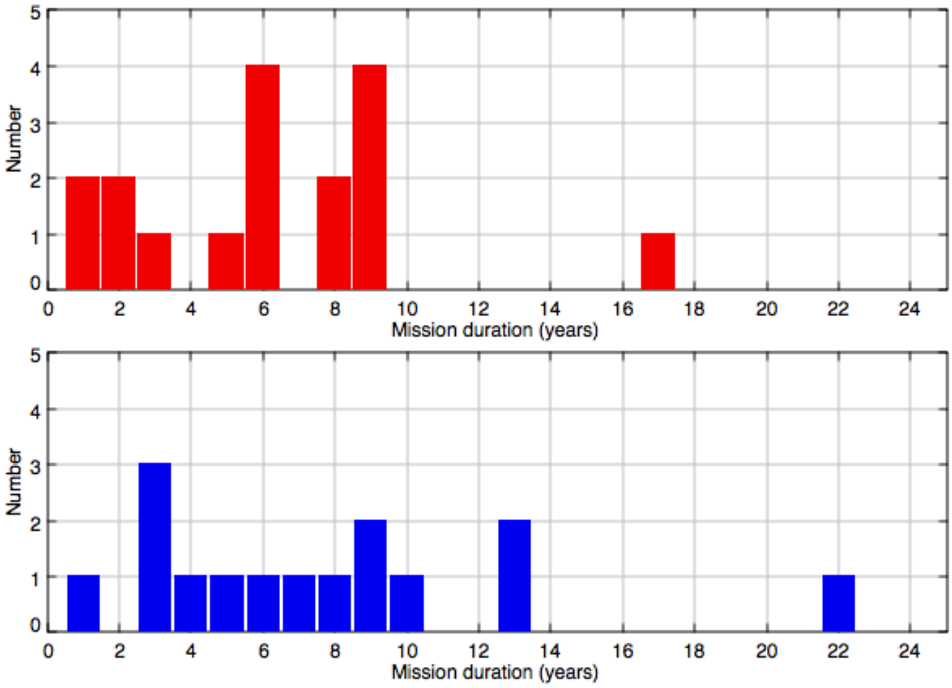

Figure 3: Operational duration of space astronomy missions. Top: past missions; bottom: operational missions (for these the mission duration is of course a lower limit).

- The largest missions (ESA cornerstones, ESA L-class, NASA great observatories) are typically space observatory facilities designed to tackle a wide range of science objectives for a large international community. Large missions typically provide the best possible performance by virtue of having the largest telescopes and the most advanced suite of instrumentation. For the future there are a wide range of scientific objectives that can **only** be tackled by the largest and most costly missions: smaller missions could not hope to provide the required performance. Outside of space astronomy, many planetary missions fall into the large mission category (for obvious reasons), but this is not true for heliophysics missions.

- Mid-sized and small missions (ESA M-class, NASA Explorer Program) have, historically, had enormous impact within space astronomy. In fact over half of all NASA space astronomy missions are part of the Explorer program and the same is true for NASA heliophysics missions. ESA has never had the equivalent of the NASA Explorer program and its missions are typically rather larger (and more costly). Small and mid-sized missions often have a restricted set of scientific goals and may be executed as PI missions, but this is not always the case. There is a general perception that small missions in particular have only a restricted role in the future of space astronomy, but there may still be important niche areas where small missions can play a role – for example in exploring the potential of new techniques or instrumentation. Such missions have an important continuing role for heliophysics, due to the typically lower demands of the relevant instrumentation.

3.4 Future plans

The funding situation in Europe, and for space astronomy worldwide, is determined by a complex set of interacting pressures: the overall level of funding for space science, changing priorities by agencies, eg. redirecting funding out of space astronomy, increasing competition for access to space by new subdisciplines. Coupled to this, mission costs rise inexorably as progress demands ever more complex payloads with longer operational duration. With this background it is not surprising that the funding climate seems to be continuously changing.

ESA funding for space astronomy is healthy, nominally at least, with a total of 465 MEuro allocated to all space science activities in 2011, together with a further 130 MEuro for robotic exploration. This budget is divided between astronomy and solar-terrestrial projects (and also includes fundamental physics missions). Full implementation of the Cosmic Vision program to which ESA is committed is, however, dependent on the level of funding agreed by the ESA Ministerial Council. It is currently unclear whether the 3.5% pa increase sought by ESA will be achievable given the current economic climate. Elsewhere within Europe, the economic climate is having an impact on the budgets of several space agencies, although many countries are committed to protecting their R&D spend against the financial stringencies required to address budget deficits.

In the US, the NASA budget is under increasing strain which seems unlikely to be reduced in coming years. The fraction devoted to astrophysics is relatively stable, but this component continues to be distorted by the escalating and large costs of JWST. In the current NASA budget the biggest problems lie in the planetary program, leading, for example, to NASA's recent decision to pull out of joint Mars exploration ventures with ESA.

To put future plans into the correct context, Table 1 below summarises the launch history distribution for space astronomy missions, together with heliophysics and planetary missions for comparison. This table covers both current, past and future missions. For future missions the names of the missions are also included. It is often difficult to be completely confident of the mission status (ie. 'approved', 'under study', 'proposed') and launch dates are also uncertain. The information we provide is less definitive for heliophysics and planetary missions where we have less insight into the programmatic issues. Figure 4 summarises some of the information presented in Table 1, concentrating on space astronomy missions.

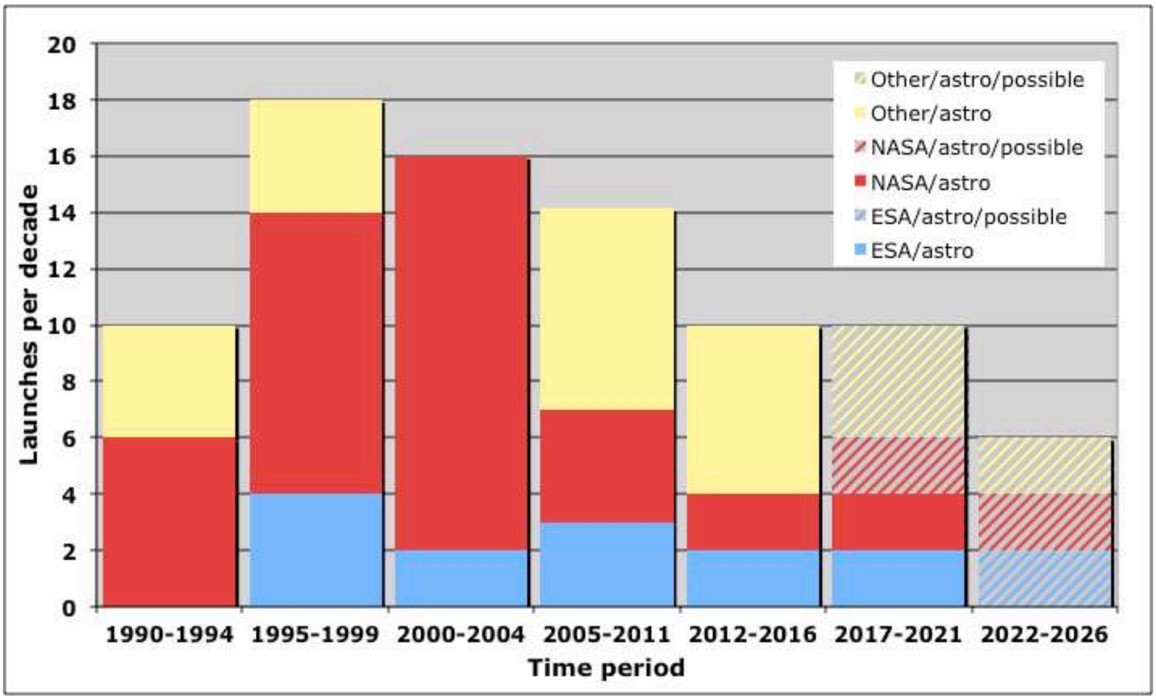

Figure 3: Launch history summary using data in Table 1. Values in the table have been converted to equivalent launch rates per decade.

Table 1: Launch history for space science missions.

Agency/discipline	**1990 - 1994**	**1995 - 1999**	**2000 - 2004**	**2005 - 2011 ‡**	**2012-2016**	**2017-2021**	**2022-2026**
ESA/astro		2	1	2	1 Gaia	1 Euclid	1? M3
ESA/helio		1	2			1 Solar Orbiter	
ESA/planetary			3	1	1 BepiColombo		1+? JUICE
ESA total		**3**	**6**	**3**	**2**	**2**	**2?**
NASA/astro	3	5	7	3	1 NuStar	1+SMEX? JWST	1? WFIRST
NASA/helio	3	5	3	7	3 IRIS, RBSP, MMS		
NASA/planetary	2	9	6	10	2 LADEE, MAVEN	1? ILN	
NASA total	**8**	**19**	**16**	**20**	**6**	**2?***	**1?**
Other/astro	2	2		5	3 Astrosat, SRG, Astro-H	2? SVOM, HMXT	1? SPICA
Other/helio	2	1		1			
Other/planetary			2	3			
Other agency total	**4**	**3**	**2**	**9**	**3**	**2?**	
Total/astro	**5**	**9**	**8**	**10 (7) ‡**	**5**	**5?**	**1?**
Total/all disciplines	**12**	**25**	**24**	**32 (23) ‡**	**11**	**6?**	**3?**

‡ this column is a 7-year interval, chosen to separate past and future projects. The equivalent 5-year totals are shown in brackets in the last two rows of the table.
* excluding the NASA SMEX currently under review.

Notes on specific missions:
ESA L and M3 slots – listed with '?' as choice of missions has not yet been made.
JWST – listed with '?' due to continuing uncertainty about possible cancellation and launch date.
WFIRST – listed with '?' due to uncertainty of mission status and impact of link with JWST completion.
SVOM – listed with '?' due to uncertain launch date
SPICA – listed with '?' as mission (and ESA contribution) is not yet approved
NuSTAR – mission was successfully launched in June 2012

The launch history distribution is more informative as it directly reflects the opportunities for new missions, as opposed to the observing opportunities offered by operating missions.

Our main conclusions from this are as follows:

- In terms of ESA launches, Table 1 and Fig.3 shows that the average past rate is 2-4 space astronomy missions per decade. In the next 5 years, one ESA space astronomy mission is expected to be launched (Gaia), followed by Euclid in the subsequent five-year period. ESA of course also has a significant involvement in JWST (nominal launch 2018), but JWST's status and launch date continue to be very uncertain. The anticipated launch rate in the next decade is thus not that different to that enjoyed over the previous 20 years, albeit launch delays for Euclid and JWST would change that picture. Looking further ahead, there are only two launch opportunities in the 2022-2026 timeframe: the M3 and L1 slots (although an M4 mission could also be launched in this interval). The L1 slot has now been allocated to a planetary mission (JUICE); there are two or possibly three astronomy missions in contention for the M3 opportunity. This presents a very lean perspective for the decade after this.

- In terms of NASA launches the situation is currently more uncertain, at least beyond the next few years. Two launches were planned in the next three years: NuSTAR and GEMS, both of which are Explorer-class missions. NuSTAR has very recently been successfully launched (2012), but sadly NASA has decided to cancel the GEMS mission due to cost overruns. NASA also has significant involvement in the Japanese Astro-H mission. The future for NASA space astronomy after that is very uncertain. JWST suffers from continuing insecurity and the status of WFIRST, ranked top in the Astro2010 Decadal Review, is completely unclear (current statement is that WFIRST development will not start until JWST is launched). In the next decade perhaps the most certain element of the NASA program is one (or more) Explorer-class missions. Selection for the first set of these is currently underway for launch "not later than the end of 2018". Two space astronomy missions are candidates for this "Explorer 2011" opportunity and further solicitations for Explorer missions are anticipated.
- It is also evident that missions led by other agencies are becoming a more significant part of the landscape. Recent launches of space astronomy missions led by other agencies have exceeded the rate of ESA and NASA launches, and this trend seems likely to continue in coming years.

3.5 A historical perspective

In order to provide an alternative perspective on the current state of space astronomy and its outlook, we attempted to find out what the ESA Space Science Program looked like a decade ago, using the 2001 ESA Annual Report published at the end of 2001[5]. In that report, the following missions were in the implementation stage (ie. were approved missions):

Integral (astrophysics)
Mars Express (planetary)
SMART-1 (planetary/technology)
Rosetta (planetary)
Double Star (heliophysics)
Herschel (astrophysics)
Planck (astrophysics)

All of these were successfully launched in the subsequent decade, with launch delays of two years or less with respect to expectations in that report.

The following missions were then in the study/planning stage (the names used then and the then expected launch dates are given in brackets):

Gaia (2009)
BepiColombo (Mercury Orbiter) (2009)
Solar Orbiter (SOLO) (2009)
JWST (NGST) (2007)
IRSI/Darwin (2012)
XEUS (?)

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[5] http://www.esa.int/esapub/annuals/annual01.htm

LISA Pathfinder (SMART-2) (2006)
LISA (2010)

Several other projects (STEP, Eddington, Hyper, Lobster/ISS and EUSO) also figured in the future project list (none has survived).

None of these missions has yet been launched. Gaia, BepiColombo, LISA Pathfinder, JWST and Solar Orbiter are now approved missions with nominal launch dates four, five, eight, eleven and eight years respectively later than envisaged a decade ago. IRSI/Darwin has been dropped from the ESA program (although some of its science goals are reflected by new missions like Plato), whilst XEUS and LISA were until recently L-class mission candidates in their new incarnations as ATHENA and NGO, with implied launch delays of a decade or more. As only one L-class mission was selected for the L1 slot, the unsuccessful projects will have to be reproposed (nominally in 2013) in an open competition for the L2/L3 slots.

Interestingly, two missions eventually launched in the decade starting in 2001 were not mentioned at all in the 2001 report: Venus Express (planetary, launched 2005) and CoRoT (astrophysics in collaboration with CNES etc., launched 2006). Both were first mentioned in the 2002 report, implying a very fast turn-around between mission adoption and implementation.

Of the 2001 missions, two missions (plus LISA Pathfinder) are now approved and in the implementation phase: Gaia (astrophysics) and BepiColombo (planetary), and two further missions have recently been approved: Solar Orbiter (heliophysics) and Euclid (astrophysics).

ESA will soon embark on a new 10 year-horizon planning exercise, aimed at getting the community to reflect on, and to define, the scientific priorities that should be pursued in the decade following the missions defined in the current plan. This exercise will represent the next phase of ESA science planning, continuing on from the Horizon 2000, Horizon 2000+ and Cosmic Vision initiatives. It is not yet known how this new plan will mesh with Cosmic Vision.

Section 4: Conclusions

In this section we summarise the main conclusions reached by the Working Group on the current status and future of space astronomy.

1. Our examination of space astronomy has reaffirmed its continued importance as a key component in the future of astrophysical research. This matches the conclusions of recent international survey activities such as Astronet (2007) and views implicit in ESA's Cosmic Vision Program and the US Astro2010 Decadal Survey of Astronomy and Astrophysics. A comparison between space astronomy and the status of ground-based facilities emphasizes some key differences (see [3.] below).
2. More specifically, a key feature of contemporary astrophysics is the importance of the synergy between space-based and ground-based studies. This synergy is inherent in the ever-increasing importance of a multi-wavelength approach coupled with the unique window offered by space missions for parts of the spectrum not accessible from the ground, or indeed for studies whose precision could not be matched with terrestrial facilities.
3. European space astronomy involves a large and active community. It includes scientific and technical staff who have expertise in diverse areas, ranging from data analysis and interpretation, software skills and advanced detector and optics technology. A strong

space astronomy program plays a vital role in the training of space scientists and engineers. Space astronomy activities have strong links to other areas of physics, particularly with respect to detector technologies, eg. for particle physics. Current coordination of these activities even at the national level is not strong and Europe lacks coordination at the international level. This is also reflected in the funding routes which are predominantly from national agencies, with only limited funding opportunities at the European level through ESA and the EU.

4. Space astronomy has a significant impact on society through stimulating public interest in astronomy and science in general, providing an important route for attracting young people to engage in careers in science and technology. Developing the advanced technology needed for space astronomy forms makes important contributions to the knowledge economy.
5. Our survey of the current status of space astronomy missions and future prospects indicates an effective decrease in the number of mission opportunities over the next two decades, especially when compared with the last twenty years when the discipline had a relatively 'golden' period. Our findings thus echo Roger Bonnet's comment, in a speech to the 2010 COSPAR assembly, of the concern over "the dearth of forthcoming space astronomy missions and the consequent lack of space astronomy data that is looming on the horizon." More specifically this reduction in opportunities arguably derives not from a reduction in the net budget, instead it originates primarily from increased mission costs as new science goals demand ever more complex (and expensive) payloads or place additional requirements on space systems, often coupled with longer lifetimes. Likewise the increased demand for access to space from new subdisciplines (eg. exoplanet studies) serves to further reduce the number of effective opportunities for a specific mission topic.
6. This reduction in prospects is particularly marked in the NASA program which has evolved strongly over the last two years, with budgetary pressures having a major impact the NASA's whole space program and, from a European perspective, particularly on joint NASA-ESA missions. But even within Europe, future opportunities appear to be becoming more limited and certainly subject to increasing uncertainty. The only area seeing stability or even growth relates to space astronomy missions within the programs of agencies outside Europe, in Japan, China and India, although these are often smaller projects.
7. There appears to be no single reason for this decline in mission opportunities. Funding pressures are having an impact, particularly within the NASA program, but even here are strongly coupled to specific issues (such as the increasing cost of JWST), or to policy changes moving money to other space areas. Within ESA, the global financial issues that have emerged over the last 3-4 years have not yet had a strong impact on the space science program. There has however been an impact on European national agency programs which now makes it difficult for some countries to fund their own missions as they have done in the past. The need for national funding to cover the study phase for several ESA missions in competition has, however, led to policy changes, such as the L-class down-selection now being restricted to a single mission.
8. Perhaps the single most important factor has been the increase in mission cost, driven in a large part by the increase in cost of the instrumental payload and in some cases the spacecraft cost, whilst launch costs are stable or decreasing. Instrument payloads are becoming more expensive primarily due to the need to meet ever more ambitious performance goals, an inexorable pressure that cannot be avoided if cutting-edge science is to be attained.

In comparison with ground-based activities, space astronomy faces some special challenges. For ground-based astronomy there are many more possibilities (at different levels of involvement) to contribute to existing and forthcoming facilities. This does not apply to space missions, where there are far fewer missions to which institutes/laboratories can contribute, compounded by the fact that even relatively minor contributions to space projects require significant funding which can only be achieved with national agency support. The largest ground-based facilities face similar funding challenges as those experienced by major space missions, but the ground-based community has arguably benefited from greater freedom in pursuing their goals. Some large projects have developed under the auspices of organisations like ESO (ALMA, E-ELT), others have evolved their own organisation specifically focused on that project, examples include LOFAR, SKA and CTA. For both approaches, the relevant communities have maintained a united external front, avoiding internal competition to a large extent.

The funding structure in which European space astronomers work is fundamentally different, dominated by ESA and NASA. Both agencies have well-established procedures for planning and executing their programs which have, over the last few decades, delivered excellent space astronomy missions. This does not mean, of course, that current practice cannot be improved and in our recommendations below we comment on some areas which might benefit from a modified approach.

Section 5: Recommendations

The Working Group believes there is a strong case for maintaining a solid portfolio of space astronomy missions with European involvement, at a level commensurate with scientific needs. This approach is crucial to maintain the European space technology base, capitalizing on previous investment and ensuring a healthy future for the relevant communities.

In formulating our recommendations we noted the special characteristics of space astronomy:

- that space provides unique environments for observations that can not be made from the ground, or require space platforms to achieve ultimate sensitivity;
- the key role played by synergy between space- and ground-based observations; that the greater demand for access to space from new fields, eg. exoplanet studies, without corresponding increase in funding implies longer intervals between missions in specific sub-disciplines;
- that space research is international endeavour in which Europe can play a leading role but will continue to benefit from collaborations with non-European partners.

Our main recommendations are as follows:

A. Planning

Planning of the space astronomy program within ESA and other agencies should emphasize stability and predictability of future missions to ensure that appropriate investments can be made in in technology development. Equally important is the need to minimise the potential waste of resources inherent in developing missions that are not selected for implementation.

This level of predictability has arguably been absent within the ESA Cosmic Vision program, in contrast with the approach provided previously in Horizon 2000+ which provided clarity of science priorities, setting the overall program framework. This is of particular importance given the long interval between mission concept and realization.

The planning process needs to recognise the links between each cycle of the decision-making process. Within ESA, for example, the finite number of mission opportunities and the need for overall program balance means that the current ESA L-class mission selection will influence the outcome of the M3 selection a year later. Conversely knowledge of the set of candidate missions under consideration for M3 may play a role in the L-class outcome.

There is an argument, therefore, that ESA's program should return to a model closer to the Horizon 2000+ approach adopted by ESA in earlier decades ESA. The Horizon 2000 model is largely a top-down process which certainly seems attractive for the mid-sized and large missions to give the stability and predictability required. The alternative, "bottom-up" approach is epitomised by the recent Cosmic Vision contest for the M-class missions. This approach, which yielded over 50 proposals for the M3 slot, amply demonstrated the vitality of the community. Having such a wide portfolio of missions clearly makes it possible for the strongest ideas to emerge. But by encouraging competition without a detailed framework of priorities, this exercise served to minimise the possibility of a coherent, united approach whilst also representing a significant effective waste of resources.

The current L-class mission selection, finalized in May 2012 with the selection of JUICE for the L1 slot by the ESA SPC, perhaps provides an illustration of the problems that will emerge when even the largest future missions have to compete. (It is of course true that the protracted period required for the current L-class selection has resulted from a unique set of circumstances which could not have been anticipated.) The candidate L-class missions, selected 5 years ago, have been the subject of an extraordinarily intensive period of study and assessment by ESA, by industry and by the instrument teams. To undertake this scope of activity for three missions when only one can be selected for launch within the next decade, not only leads to vast disappointment for their respective communities, it also represents a waste of effort which surely should be avoided in the future, for example by committing to a number of cornerstone missions at the earliest stage possible. It is arguable that a core set of M-class missions should also be defined this way, reserving a small number of M-class mission opportunities for open competition.

Achieving the correct balance is difficult of course. One could envisage a science program that was completely determined in advance by a committee of wise individuals and that had pre-defined slots for the highest priority missions. But such an approach would provide little opportunity for innovation, or to the react to changing scientific perspectives, potentially leading to a program that rapidly became uncompetitive.

Recent news from ESA indicates a willingness to modify the approach for the selection of future missions. It is understood that one option being considered is the definition of new 'pillars' for the future science program, equivalent in some ways to the 'cornerstones' of the Horizon 2000 approach. Although this approach would not mandate the selection of specific missions, the idea is that these pillars would define the key priority areas to set the framework for the selection of subsequent L-class missions at least. Further elaboration of how this approach will work is expected in the coming months. Although these developments are to be welcomed, it is arguable that they do not fully address the current somewhat haphazard approach to mission selection which is undoubtedly compounded by the recent call for S-class missions.

B. International cooperation

The most ambitious space astronomy missions will inevitably only be achieved at a high cost. Such missions will require full cooperation between the one or more of the major space agencies, NASA, ESA, JAXA, and potentially national partners, for their realization. Current international cooperation approaches often fail to deliver the mechanisms required because of the mismatch between decision-making procedures and timescales. Past successes, such as HST, demonstrate that such cooperation is possible, but recent failures have demonstrated how difficult this can be in practice.

Any successful approach to making interagency missions possible needs to tackle the issue of trust between the agencies, the viability of project commitments in an international framework and the possibility of a joint decision-making process for program planning and execution. This is a major undertaking that might require the establishment of a truly international space agency, clearly an ambitious goal which could only be achieved with a real will for it to succeed. Failing that, other less demanding avenues should be explored. Any initiative that encourages cooperation and sharing of capabilities represents a positive step. An early recognition that the most effective approach involves a clearly defined lead agency can also improve the cooperation framework.

Although providing a solution to this problem was beyond its scope, the working group wished to make a strong recommendation that agencies should be encouraged to vigorously pursue workable solutions to this problem.

C. Mission sizes

Space astronomy would benefit significantly from having greater flexibility, for example in having access to focused medium/small class missions. Such missions could be provided through ESA or through national initiatives or a combination of these approaches. They would potentially provide additional opportunities for the community to undertake more focused science projects and to demonstrate the viability of new instrumentation. To be effective with a smaller cost envelope, such missions would require a more flexible approach to some elements, eg. to mission operations and launch and spacecraft procurement. To make room for a small mission program would of course require some adjustment to the overall funding split between missions of different size, unless additional resources were added to the overall budget. Adopting this approach thus requires a careful balancing of the program.

At the time this report was being finalized, ESA announced a new, S-class, small mission initiative[6]*. This novel component of the ESA science program is to be welcomed, particularly the emphasis on flexibility in the call for proposals. It remains to be seen whether the cost constraints imposed in the initial call for this program (50 MEuro cost to ESA, or up to around 150 MEuro total cost for a mission in partnership with European national agencies) will be large enough to encompass scientifically compelling projects. A simple comparison with the total funding envelope for NASA explorer missions indicates that the ESA S-class missions, as currently envisaged, will typically have to fit into a smaller budget unless very large investments form national agencies emerge.*

D. Setting the European agenda

Astronomy from space currently suffers from insufficient coordination at the European level, resulting in a program that can lack coherence and experiences duplication, producing an inefficient program which arguably does not achieve its full European potential. Significant coordination of efforts at the European level occurs primarily in the context of the focused effort to develop instruments for ESA projects. Technology development within Europe receives considerable funding from both ESA and national agencies, but these programs could be more coherent.

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[6] http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=50119

The working group believes that an improved framework for developing a more coherent approach to space astronomy should be developed. This could, for example, be provided by the EU working in close collaboration with ESA. It is, of course, already the case that the EU has a significant role to play in European space policy. Since 2004, ESA and the EU have been working together to achieve common aims in space. This cooperation was strengthened in 2007 with the effective adoption of European Space Policy. In practical terms, EU initiatives in space have focused on the Framework 7 program (FP7), administered by the European Commission, which contains elements specifically directed towards enhancing Europe's space activities. Within FP7, funding levels in those parts of the "FP7 Space" program relevant to space astronomy have amounted to ~10 MEuro/year on R&D with similar amounts available for space data exploitation. This funding extends over the full range of space activities however and the total amount directed specifically to projects relevant to space astronomy are only a fraction of this total. Within the next framework program, now named "Horizon 2020", support for space activities is expected to continue, potentially at an enhanced level.

Within this framework, the working groups notes the following points:

- the importance of space astronomy needs to be fully recognized by the EU and should appear in their strategic roadmap. Space astronomy is currently not differentiated from other space research activities. This is a prerequisite for ensuring that there is a proper framework for adequate national research money to be directed towards developments related to space astronomy.
- The EU could play an important role in setting up trans-national networks for different space astronomy development areas (e.g. high energy astrophysics, sub-mm, data processing and analysis). This could provide the framework for a significantly more effective and targeted approach, strengthening Europe's space astronomy community.

Appendix A: Survey of European Space Science Institutes

Institute	Main Fields	Main technology	Size [FTE]	Technology [FTE]
SRON, the Netherlands	submm, IR, X-ray, gamma-ray, exoplanets	sensors, electronics and cryogenics	200	50
Instituto de Astrofísica de Canarias (IAC), Spain	IR, visual, gamma-ray, cosmic rays, exoplanets, archeoastronomy	optics, sensors, data processing, electronics, mechanics, cryogenics, control software	114	67
CAB, Spain	submm/mm, IR, Optical, UV, exoplanets, astrometry	optics, sensors, cryogenics, thermo-mechanics, data processing	45	20
MPE, Garching, Germany	mm/submm, IR, X-ray, gamma-ray, optical	optics, sensors, DP, cryogenics, electronics	290	86
MPIA, Heidelberg, Germany	near-IR/thermal-IR instrum. for ground/space	opto-mechanics, control/detector electronics, software	180	60†
IAAT, Germany	visual, UV, X-ray, gamma-ray, gravitational, planet formation	sensors, data processing, electronics	55	15
Cardiff University, UK	submm/mm; IR	optics, sensors, data-processing, cryogenics	22	n/a
Astronomy Technology Centre, UK	radio, submillimetre and infrared	submillimetre through optical instrumentation, astronomical, cryogenic opto-mechanical systems, detectors and readouts	82	58
MSSL, UK	IR, optical, EUV, X-ray, planetary, space plasma physics, space science and instrumentation	imagers, adiabatic demagnetization refrigerators, optical systems, plasma analysers, cubesat technologies, instrument subsystems, image processing and data processing software.	160	50
Leicester SRC, UK	X-ray, optical, UV, IR	optics, detectors, cryogenics, readouts	50	50

Institute	**Main Fields**	**Main technology**	**Size [FTE]**	**Technology [FTE]**
IAS, Paris	solar physics, solar system and extrasolar planets, extraterrestrial and interstellar matter, galaxies and cosmology	sensors for space missions, optics, thermal control and mechanical systems, electronics, calibration facility, data and operations centre	140	100?
IRAP, Toulouse, France	X-ray, gamma-ray, astroparticle, cosmology, interstellar medium, stellar evolution	front end analog electronics, ASICs, digital electronics, on-board computers, science ground segment	300	100
CEA/Irfu, Saclay, France	sub-mm, mid-IR, X-Ray, gamma-ray	sensors, electronics, data processing	220	80
CEA-Grenoble, France		space cryogenics	70	18
LAM, France	IR, visual, UV, exoplanets, gamma-ray	optics, data processing, electronics, cryogenics, opto-mechanics, active/adaptive optics	118	70
IEEC, Barcelona	X and gamma-ray astronomy, gravitational waves, astrometry, solar system and exoplanets, stellar astrophysics, extragalactic astrophysics, cosmology	high energy photon & particle detectors, thermal analysis, on board computers, data processing, robotic scheduling	~100	200
ISDC, University of Geneva, Switzerland	X-ray, gamma-ray, optical	data processing	50	20
DTU, Denmark	X-ray, gamma-ray, submm, gravitation waves	optics (X-ray, submm), sensors, data processing, electronics	30	17

Institute	Main Fields	Main technology	Size [FTE]	Technology [FTE]
INAF, Italy INAF includes the following institutes: INAF/Torino, INAF/OAPA, INAF/IASF-Bologna, INAF/OACT, INAF/IRA, INAF/IASF-Milano, INAF/Oss. Arcetri, INAF/OACA, INAF/OATS	IR, visual, microwave, mm, infrared, optical, X-ray, gamma-ray, space physics, Visible and UV radiation, radio, UHECRs, astrobiology, planetology, solar system, exoplanets, solar physics, astrometry, tests of relativity, stellar astrophysics, SNs & SNRs, extragalactic astrophysics, cosmology, galactic astrophysics, GRB, space surveillance; space debris; bistatic radar measurements; space VLBI. planetary exploration, gravitation & gravitational waves.	optics, sensors, data processing, sensor for planetary research, electronics, X-ray optics, X-ray microcalorimeters, mK cryogenic systems, X-ray detector filters, micro-technologies, high-performance parallel computers, cryogenics, mm-wave radiometers, microwave antennas, mm antennas for polarization studies, electrical ground support equipment, ground segment for space mission, radio, IR, optical, UV, X and gamma-ray detectors, high-performance computing, sensors and electronics, opto-mechanics, radar data acquisition system; simulations, software development, software integration, data analysis, database, scientific ground segment, IR detectors, stereo reconstruction	534	206
University of Helsinki, Finland	X-ray, optical submm	X-ray sensors, data processing, electronics, cryogenics	45	12

Appendix B: Space Astronomy Mission Table

Our mission survey was based on on-line resources including:

- http://science.nasa.gov/missions/
- http://sci.esa.int/

cross-checked and expanded through a range of other resources.

Mission	start	end	duration (years)	status	lead agency	partners	wave band	mission focus
IUE	1978	1996	18	4	ESA-NASA-UK		u	
Ginga	1987	1991	4	4	JAXA	UK	x	
COBE	1989	1993	4	4	NASA		s	all-sky survey
Granat	1989	1998	9	4	RUSSIA	F, DK, BU	x	
Hipparcos	1989	1993	4	4	ESA	NASA	o	astrometry
HST	1990		22	3	NASA	ESA	o	
ROSAT	1990	1999	9	4	GERMANY	NASA, UK	x	
CGRO	1991	2000	9	4	NASA	D	g	
EUVE	1992	2001	9	4	NASA		u	
ASCA	1993	2001	8	4	JAXA	NASA, ESA	x	
ISO	1995	1998	3	4	ESA	NASA	i	
RXTE	1995	2012	17	4	NASA		x	
BeppoSAX	1996	2002	6	4	ITALY-NL	ESA	x	
ORFEUS-2	1996	1998	2	4	NASA-D		u	
HALCA	1997	2003	6	4	JAXA	NASA	s	
SWAS	1998	2004	6	4	NASA	D	s	
Chandra	1999		13	3	NASA	NL, D, UK	x	
FUSE	1999	2007	8	4	NASA	F, CA	u	
XMM-Newton	1999		13	3	ESA	NASA	x	
HETE 2	2000	2006	6	4	NASA	F, I, JP, BR, IN	g	
WMAP	2001	2010	9	4	NASA		s	all-sky survey
Integral	2002		10	3	ESA	NASA, RU, CZ, PL	g	
MOST	2003		9	3	CANADA	NASA, AU	o	astroseismology
CHIPS	2003	2007	4	4	NASA		u	
GALEX	2003		9	3	NASA	F, KO	u	
Spitzer	2003		9	3	NASA		i	
GP-B	2004	2005	1	4	NASA		f	
Swift	2004		8	3	NASA	I, UK	x	GRBs
Suzaku	2005		7	3	JAXA	NASA, ESA	x	
Akari	2006	2007	1	4	JAXA	ESA, UK, NL	i	all-sky survey
CoRoT	2006		6	3	FRANCE	ESA, BR, AU, BE, D, ES, I, HU, RO	o	exoplanets

Mission	start	end	duration (years)	status	lead agency	partners	wave band	mission focus
Agile	2007		5	3	ITALY		g	GRBs
Fermi	2008		4	3	NASA	F, I, D, SW, J, AU, IS, ES	g	
Herschel	2009		3	3	ESA	NASA, CA, CN, TW, RU	i	
Kepler	2009		3	3	NASA	DK	o	exoplanets
Planck	2009		3	3	ESA	NASA	s	all-sky survey
WISE	2009	2011	2	4	NASA		i	all-sky survey
Spektr-R (Radiastron)	2011		1	3	RUS	IN, AUS, NL, D, FI, NASA, CA	s	
NuSTAR	2012		~0.1	3	NASA	DK	x	
AstroSat	2012			2	INDIA	UK, CA	x	
Gaia	2013			2	ESA		o	astrometry
Spektrum R-G	2013			2	RUS	D	x	
Astro-H	2014			2	JAXA	NASA, NL, CH	x	
GEMS[1]	2014			2	NASA		x	X-ray poln.
HMXT	2014			2	CHINA	UK	x	
SVOM	2017			2	CHINA	F, UK	g	GRBs
NASA SMEX	2017			0	NASA		z	
JWST	2018			2	NASA	ESA, CA	i	
Euclid	2020			2	ESA		o	
WFIRST	2022			1	NASA		i	
SPICA	2022			1	JAXA	ESA ++	i	
ESA M3	2024			0	ESA		z	
ESA L2	2028			0	ESA		z	

Notes

Our table excludes a number of missions whose status we were unclear about, eg. the Russian WSO-UV project.

status - 4 :past; 3: operational; 2; under development; 1: under study; 0: mission selection TBD

(NB: the differentiation between status codes 1 and 2 is often difficult)

waveband - g: gamma-ray; x: X-ray; u: ultraviolet; o: optical; i: infra-red; s: sub-mm/radio; f: fundamental physics; z: TBD

(NB: there is some ambiguity in assignment between adjacent bands)

1: NASA announced the cancellation of **GEMS** in June 2012.

Appendix C: Approved and planned missions

We provide here a summary of approved and planned space astronomy missions that we are aware of, noting that there are often substantial uncertainties in the status of many missions that are currently in study, assessment and planning stages.

- **Astrosat** is a multi-wavelength astronomy mission foreseen to be launched by India in 2012. It is expected to operate 5 years and will carry several astronomy payloads from the far-UV to hard X-rays. Its main scientific topics will relate to timing and spectroscopic studies of cosmic sources.

- **NuSTAR** is a NASA mission launched in June 2012 planned to operate for at least 2 years. NuSTAR is the first focusing high energy X-ray mission, opening the hard X-ray sky for sensitive study for the first time.

- **Gaia** is an ESA mission to map in 3D our Galaxy to be launched in 2013 and to operate 5 years. Its array of 106 CCDs will provide obtain astrometry, photometry, and spectroscopy in the optical band, yielding precise astrometry of about 1 billion stars.

- **ASTRO-G**, also known as VSOP-2, was foreseen to be launched in 2013 but has been suspended by JAXA.

- **Spektrum R-G** is a Russian-German mission to be launched in 2013 with a foreseen operation lifetime of 7 years. The mission will conduct an all-sky survey in the X-rays in the first 4 years, and will then perform dedicated pointed observations of X-ray cosmic sources.

- **ASTRO-H** is a Japanese satellite to be launched in 2014. During its 3+ years of operation, it will use its soft and hard X-ray imaging and spectroscopic capabilities to observe X-ray sources, and its extended capabilities in the gamma-ray regime. Its soft X-ray calorimeter should provide unprecedented high spectral resolution at high energies.

- **GEMS** is a NASA satellite to be launched in 2014 and with an operational lifetime of at least 9 months. Its primary instrument is an X-ray polarimeter instrument designed to measure the linear polarization of X-ray cosmic sources. **NASA announced the cancellation of GEMS in May 2012.**

- **HMXT** (the Hard X-ray Modulation Telescope) is a Chinese X-ray mission incorporating an array of slat-collimated detectors, collimated to 5.7°×1° overlapping fields of view and covering a broad energy range. Current launch date is somewhat uncertain.

- **SVOM** is a Chinese-French mission dedicated to the study of gamma-ray bursts. Launch is currently foreseen in 2017 with an expected lifetime of 5 years.

- **JWST** is a NASA-led satellite with ESA and CSA participation to be launched no earlier than 2018. Its operations should last at least 5 years. With its large, 6.5-m mirror, JWST will observe in the near and mid-infrared. The main science topics are grouped around the formation and evolution of galaxies and of planets and stars.

- **SPICA** is Japanese satellite with potential ESA involvement to be launched in 2022 with an initial operational lifetime of 3 years. SPICA will carry a large telescope actively cooled down to less than 6 K to suppress the telescope background emission. The infrared satellite will operate in the mid and far-infrared regimes with science goals aimed to reveal the origins of planets and galaxies.

- **WFIRST** is a NASA mission with uncertain launch date. During its 5 years lifetime, it will study dark energy via microlensing in the infrared. It will also perform large sky surveys and exoplanet science.

- **Euclid** is an ESA mission selected to be launched in 2020 with an expected operational lifetime of 6 years. Its objective is to measure the dark matter distribution in the Universe and its time evolution. Its payload is optical and infrared cameras and a near-infrared spectrometer. A modest US contribution to Euclid hardware is currently under consideration.

- **ESA M3:** Four projects were selected to compete for the third launch slot of medium-class ESA missions, among them two astronomy-related projects: EChO (dedicated to exoplanetary atmospheres), LOFT (an X-ray timing mission), and one fundamental physics project: STE-QUEST (precise measurement of the effects of gravity on time and matter). The PLATO project, not selected for the M1 and M2 slots, is also likely to compete for the M3 slot. The selected M3 project should be launched in ~2024.

- **ESA L:** Three projects competed for the first launch of a large mission, among them two astronomy projects: IXO (previously XEUS, an X-ray observatory), LISA (proposed gravitational wave observatory). The projects, initially with NASA collaborations, were requested by ESA to re-examine their concepts with an ESA-led approach and limited international participation. In the current incarnations they are, respectively, Athena and NGO.

  Selection of the planetary mission JUICE for the L1 slot was made by the ESA SPC in May 2012.

- **NASA Explorers:** As part of the Explorers program, several astronomy missions were proposed in response to the 2010 solicitation. A first selection was announced in September 2011, with two astronomy Explorer projects (FINESSE focused on spectroscopy of exoplanets, TESS as an exoplanet transit survey) and two astronomy Explorer Mission of Opportunity projects (NICER that would place an X-ray timing instrument in the ISS, GUSSTO that would launch a THz telescope on a stratospheric balloon to study the Milky Way and nearby galaxies), and one project funded for technology development (EXCEDE that will image directly exoplanetary systems). Down-selection for up to two Explorer and one or more of Mission of Opportunity proposals is foreseen in 2013 with an earliest target launch of 2017.