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Review

Future of Space Astronomy: A global Road Map for the next decades

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Abstract

The use of space techniques continues to play a key role in the advance of astrophysics by providing access to the entire electromagnetic spectrum from radio to high energy γ rays. The increasing size, complexity and cost of large space observatories places a growing emphasis on international collaboration. Furthermore, combining existing and future datasets from space and "ground based" observatories is an emerging mode of powerful and relatively inexpensive research to address problems that can only be tackled by the application of large multi-wavelength observations. While the present set of astronomical facilities is impressive and covers the entire electromagnetic spectrum, with complementary space and "ground based" telescopes, the situation in the next 10–20 years is of critical concern. The James Webb Space Telescope (JWST), to be launched not earlier than 2018, is the only approved future major space astronomy mission. Other major highly recommended space astronomy missions, such as the Wide-field Infrared Survey Telescope (WFIRST), the International X-ray Observatory (IXO), Large Interferometer Space Antenna (LISA) and the Space Infrared Telescope for Cosmology and Astrophysics (SPICA), have yet to be approved for development.

A "Working Group on the Future of Space Astronomy" was established at the 38th COSPAR Assembly held in Bremen, Germany in July 2010. The purpose of this Working Group was to establish a Road Map for future major space missions to complement future large "ground based" telescopes. This paper presents the results of this study, including a number of recommendations and a Road Map for the next decades of space astronomy research.

Keywords: Future of Space Astronomy; COSPAR Working Group

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Executive summary

Astronomers today have access to an impressive set of space missions and "ground based" observatories that gives them nearly continuous coverage of the electromagnetic spectrum from the γ-ray to the radio regions. But there is serious concern about the situation in the next 10–15 years, when current space astronomy missions will have ended and new missions will be much less numerous.

Astronomy is a difficult observational science requiring continuous and simultaneous access to the full electromagnetic spectrum to explore our complex Universe and to pursue answers to fundamental scientific questions. The history of space astronomy, especially the past three decades, has demonstrated clearly the importance and benefits of access to the γ-ray, X-ray, UV-optical, near IR and far-IR spectrum from space. To build on this success, continuing technical and scientific advances and commitment to space science on the part of the world's space agencies are going to be needed. It will be essential to complement the powerful "ground based" facilities that will soon be available, and to ensure that the next generation of astronomers has access to the whole spectrum.

To this end, COSPAR appointed the "Future of Space Astronomy" Working Group (hereafter, WG) under the aegis of Commission E[1] with the aim to analyze the difficult situation of space astronomy over the next two decades and recommend ways to improve the prospects.

Having assessed the scientific needs and the current plans of a number of space agencies worldwide, the Working Group identified some major concerns about the lack of a secured future plan. This study was conducted during the period April 2010 – April 2011. During this time and in the months following there were significant changes in the plans of multiple space agencies as they adjusted to programmatic realities in their countries. This paper reports the conclusions of the Working Group as of the end of the period of our discussions. We hope that our findings will remain of value as a vision statement in spite of the rapidly changing short-term circumstances.

Recommendations concerning international planning and implementation of large space astronomy missions

1. It is important to maintain the rate of fundamental scientific discoveries in space science that has been achieved in recent decades. This success will continue to derive from the ability to use space to access the full electromagnetic spectrum.
2. Large and powerful space astronomy missions have an outstanding track record of technical success, new discoveries, and long-lasting legacy science. In the future, such missions will continue to be essential to address key questions in astrophysics including the properties of dark matter and dark energy, gravitational wave astrophysics, the formation of the first stars, the evolution of galaxies like the Milky Way, the development of planetary systems, and the characteristics of exoplanets.
3. The astronomy community has developed methodologies to implement ambitious and powerful "ground based" observatories as multinational projects. It is necessary to bring about an equivalent paradigm for large space missions based on international cooperation and coordination. Without this, space agencies will imple-

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[1] COSPAR scientific organisation: http://www.cospar2010.org/files/Finalprogramme-2010.pdf, http://cosparhq.cnes.fr/Scistr/Scistr.htm.

ment only smaller scale and more fragmented projects. Whilst these will continue to be important and productive, without a balancing large-mission programme the overall outcome will be less effective, less competitive, and less successful scientifically.

4. Recent indications that major space agencies may adopt a go-it-alone policy with respect to large mission implementation are a concern. Such missions will not be as powerful as they could be if carried out as international projects, and may result in unnecessary duplication or not occur at all.
5. The international astronomical community, matured in the developed countries, is now spreading worldwide and is fertilising the scientific environment and the intellectual life of newly developed countries. Participation in major international space missions is a great opportunity for developing nations, both to help make such endeavours possible, and to share in the technical and scientific benefits.
6. COSPAR and the IAU can play an influential role in promoting the involvement of developing countries in major missions, and should establish and pursue an active joint programme to foster increased international cooperation in the area of space astronomy.
7. Space agencies worldwide should develop a process for strategic planning that takes into account and exploits opportunities for international cooperation. Technical and programmatic challenges are inevitable, but must be overcome.
8. The scientific community at large must find ways to provide the necessary encouragement and support to space agencies, and to help create the conditions in which international cooperation can bring about a better scientific outcome for all.

We note that many of the ideas and conclusions of this report are reflected by Bonnet and Bleeker (2011). Having reviewed the current situation and prospects, these authors propose a global equivalent of the Horizon 2000 programme which ESA successfully implemented over a 25-year period from the mid 1980s. This would involve inter-agency agreement on a long-term programme with defined large missions to be built within fixed budgets, and scope for additional smaller missions to be proposed and selected in a flexible manner. As a starting point, such a programme would require the establishment of an inter-agency coordination group to formulate a long-term programme for observatory-class missions. The Working Group regards this suggestion as one option that is quite consistent with the key conclusions of this report.

Road Map principles

The Working Group considers it essential to develop a space astronomy Road Map in the context of some important underlying principles:

- *Science driven*: pursue top priority science topics stemming from state-of-the art observations and theory, and set in a worldwide context.
- *Observatory class missions*: provide open access to the scientific community at large, preferably with data available with no more than a short turn-around time (6–12 months) after observations.
- *Innovative enabling technology and cutting-edge scientific instrumentation*: focus research and development support on innovative technologies and instrument concepts driven by science requirements for future observatory-class missions.
- *Technology development*: national agencies and scientific councils support research and development programmes to advance the Technical Readiness Level of mission-critical elements to flight-ready status early in mission preparation.

Recommended space astronomy Road Map

A select group of future space astronomy missions has been identified in major studies by national scientific committees to be of the highest priority. Critical technologies and instrumentation for these missions have been brought to a high level of technical readiness. Though these missions do not provide complete coverage of the electromagnetic spectrum, the WG considers these missions to be the most feasible core of the near-term major space astronomy missions, and recommends this list as a Road Map for the next few decades.

- *JWST*. JWST[2] is a collaborative mission of NASA, ESA and the Canadian Space Agency (CSA). It is the only future large space astronomy mission already approved for development, with a planned launch in 2018. It was the highest priority programme recommended in the US National Academy of Sciences decadal survey in 2000 (Astronomy and Astrophysics for the New Millenium), and its central importance to astronomy was reiterated in the 2010 survey (New Worlds, New Horizons, NRC, 2010a). With a combination of near- and mid-infrared imagers and spectrometers, JWST will provide unprecedented capability to study systems from the first galaxies that formed in the early Universe, to newly forming stars and planetary systems, and to bodies in our solar system. The WG recommends completion and launch of this major observatory as soon as possible. JWST is recognised to be the only new large space astronomy Observatory to be possibly operational in the next 10–20 years. It is an essential asset for space science investigations complementing “ground based” facilities planned.

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[2] The James Webb Space Telescope, NASA, http://www.jwst.nasa.gov/.

- *Euclid/WFIRST*,[3,4] (Laureijs et al., 2011), (SIR, 2010). Both ESA and NASA are currently evaluating missions to study dark energy: Euclid (ESA; dark energy and dark matter) (Bignami et al., 2005) and Wide-Field Infrared Survey Telescope (WFIRST) (NASA; dark energy, exoplanets and near-infrared sky survey (SIR, 2010). The scientific goals of these missions have been recommended as being of the highest importance by the worldwide astronomical community. Euclid has been selected as an ESA M-class mission; NASA is conducting a definition study for WFIRST. Possible collaboration has been discussed by the national agencies, but the situation is unclear at the time of this study. The WG believes it would best serve the interests of science and the community to have a single optimised mission or programme, combining the resources and technical capabilities of NASA and ESA. Canada, India, China, Russia and others could be added as partners.
- *International X-ray Observatory (IXO)* (Barcons et al., 2011). IXO has been extensively studied and reviewed as a collaborative NASA/ESA/Japan mission, now re-scoped by ESA as an L-Class candidate for the 2020–2025 time-frame, Athena, without NASA collaboration.[5] The proposed IXO satellite, or a similar large high energy observatory, would be able to exploit a broad scientific scenario, possibly including investigation of the ‘first stars’ via a high-z γ-ray burst detection capability. The WG recommends development of a large X-ray space observatory, operative in the next decade.
- *Large Interferometer Space Antenna (LISA)* (Brillet et al., 2011). LISA is a pioneering gravitational wave mission, designed to open a new window on the cosmos. LISA has been extensively studied as a collaborative NASA/ESA mission, but, though highly ranked in the 2010 US Decadal Survey, programmatic constraints are preventing NASA from proceeding. The LISA Pathfinder mission[6] is in development in Europe. ESA has re-scoped LISA as NGO, an L-Class mission candidate. The WG recommends that the agencies involved support, exploit and finalise the R& D programmes necessary to have in operation a gravitational wave mission at the latest in the time-frame 2025–2030. Even though the previous collaborative mission concepts for IXO and LISA are not feasible in the current ESA or NASA plans, the Working Group recommends that some multinational aspect of the missions be preserved to prevent significant loss of scientific capability.
- *Space Infrared Observatory for Cosmology and Astrophysics (SPICA)* (Ferlet et al., 2009). SPICA is a large aperture, cryogenically cooled far-infrared observatory studied as a collaborative JAXA/ESA/Canada mission. Contribution of an additional instrument was recommended by the US 2010 Decadal Survey, but may not be possible due to US programmatic constraints. The WG believes that a large aperture, cryogenically cooled far-infrared observatory is essential to bring about the major advance in sensitivity needed to continue investigation of the cold and dust obscured Universe.
- In the longer term, it is to be expected that detailed characterisation of Earth-like exoplanets, a major scientific priority, will require the stability and sensitivity afforded by a large space mission. Numerous UV/optical and infrared mission concepts have been proposed and studied. The WG recommends further technical development to bring the most promising approaches to readiness. The WG also recommends that space-faring nations pursue robust cooperative programmes devoted to solving specific burning scientific questions via the implementation of multilateral medium and small size dedicated missions.

In addition to the specific high priority near-term missions listed above, the WG compiled a list of additional missions of interest around the globe, some of which might be accomplished by 2030. Such missions are listed, by approximate size class, in Section 3 of this paper.

Conclusions

The Working Group members and all who have worked on or participated in the year long activity that resulted in this report have been aware of the extraordinary “golden age” which astronomers have experienced in the last decade, with unique and great opportunities for science. The use of space-borne observatories continues to play a key role in the advance of astronomy and astrophysics by providing access to the entire electromagnetic spectrum from radio to high energy γ rays. The existence of an impressive fleet of space observatories complemented by “ground based” facilities has given the worldwide scientific community an incredible opportunity to make spectacular advances in our knowledge of the Universe. The open availability of existing and future datasets from space and “ground based” observatories facilitates powerful and relatively inexpensive collaboration to address problems that can only be tackled by the application of extensive, multi-wavelength observations. Unfortunately, the future panorama, with only a few main space missions planned, requires remedial global action to correct this negative trend, to ensure positive prospects for future research, and to avoid a “dark age” for space astronomy.

We conclude that the size, complexity and costs of large space observatories must place a growing emphasis on international collaboration and multilateral cooperation. Although this poses technical and programmatic challenges,

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[3] http://sci.esa.int/euclid/.

[4] http://wfirst.gsfc.nasa.gov/.

[5] http://sci.esa.intscience-ewwwobjectindex.cfm?fobjectid=48727.

[6] http://www.rssd.esa.int/index.php?project=LISAPATHFINDER.

these challenges are not insurmountable, and the great scientific benefits will be a rich reward for everyone.[7]

1. The COSPAR Working Group on the Future of Space Astronomy

1.1. Establishment of the Working Group

The use of observations from space continues to play a key role in the advance of astrophysics by providing access to the entire electromagnetic spectrum from the radio region to high energy γ rays. The increasing size, complexity and cost of large space-based observatory missions leads to a growing emphasis on international collaboration, marked by the increasing range of joint missions involving the large space agencies in the US (NASA), Europe (ESA), Japan (JAXA), and Russia (RKA). Major future contributions are foreseen from the Indian, Chinese and Korean space agencies, and countries in South America. It is important that the world's space agencies coordinate their mission plans for both large and small scale enterprises, both to make major missions affordable and to provide maximum scientific value for money. The coordination of existing and future datasets from space-based and "ground based" observatories is an emerging mode of powerful and relatively inexpensive collaboration to address problems that can only be tackled by the application of large multi-wavelength datasets. In April 2010, the President of COSPAR, Roger-Maurice Bonnet, created the "Future of Space Astronomy Working Group", to be chaired by Pietro Ubertini and co-chaired by Neil Gehrels, under the aegis of Commission E, with the task of analyzing the difficult situation of space astronomy over the next two decades and recommending ways to improve the prospects. During his opening message to the 38th COSPAR Assembly, held in Bremen, Germany on 18–25 July, 2010, Prof. Bonnet announced the establishment of the Working Group.

1.2. Terms of Reference and Membership of the Working Group

During the Bremen meeting, the newly elected President, Giovanni Fabrizio Bignami, fully endorsed the initial Working Group Terms of Reference, specified to be as follows:

"If the present set of space and "ground based" astronomy facilities is today impressive and fairly complete, with space and "ground based" astronomy telescopes complementing nicely, the situation becomes much more concerning and critical in the next 10 or 15 years when new main space missions will be much less numerous, probably restricted to JWST and possibly WFIRST and SPICA, since no other main facilities are already recommended. The planning of "ground based" astronomy facilities is in the hands of dedicated institutions (ESO, NOAO, NRAO, etc.) which deal with their respective spectral bands, while the planning of space missions is in the hands of space agencies which deal with the whole space accessible spectrum, from high energy through infrared and sub-millimetre ranges to the radio ranges. Space missions are becoming so big that no space agency is able to cover alone the whole range of wavelengths and clearly international cooperation is needed. That situation gives a strong advantage to "ground based" astronomy, where plans are already being made for the next decade or so with such telescopes or facilities as ALMA, etc.

Following a discussion in Rio de Janeiro in August 2010, the IAU decided also to review the situation and has resurrected a Working Group on big facilities to look at the issue concerning all of astronomy including both space and "ground based" astronomy. The IAU plans to prepare a report for its next General Assembly in 2012.

At a meeting with the IAU General Secretary Jan Corbett on Monday 12 April, 2010, it was agreed that COSPAR would establish its own Working Group aiming at developing a Road Map for the planning of future main space missions which would complement the future big "ground based" telescopes.

It was further agreed that the report from the COSPAR Working Group would be an input to the IAU study, and that both Working Groups (COSPAR and IAU) would incorporate representatives of the other organisation in their respective membership".

The membership of the COSPAR Working Group, chosen to provide wide international participation and broad astrophysical competence, is as follows: Paolo De Bernardis, Italy; Ian Corbett, UK, and IAU General Secretary (IAU liaison); Neil Gehrels, USA (Co-Chair); Matt Griffin, UK; Michael Hauser, USA; Nobuyuki Kawai, Japan; Marcos Machado, Argentina; Ravinder K. Manchanda, India; Mikhail Pavlinsky, Russia; Pietro Ubertini, Italy (Chair); Shuang-Nan Zhang, China.

The basic mandate of the Working Group was to establish a Road Map for the planning of future main space missions with a particular focus on their capability to complement the future large scale "ground based" telescopes and observatories. An important role will surely be played by "small" and "explorer" type satellites and/or attached payloads on the International Space Station (ISS), with focused though effective scientific objectives. Small/medium size experiments, affordable by single space agencies or bi-lateral/multilateral collaborations, will continue to be important for solving specific open astrophysical questions as they have in the past.

The Working Group started with a comprehensive review of the "cornerstone" studies that will influence planning of space and "ground based" astronomy in the next two decades. Of particular relevance are the following:

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[7] Note: The information, recommendations and data contained in the "Executive summary" are reported in the following sections of the paper in a more expanded and elaborated way.

1. The Astronet Report (AST, 2007)
2. The ESA Cosmic Vision (Bignami et al., 2005)
3. The US National Academy of Sciences Astro2010 Decadal Survey (NRC, 2010a)
4. National Agency's Road Maps

The remit of the COSPAR WG is more limited than that of the above studies, and of course the WG does not have any power of decision or direct influence on the different space agencies. With this boundary condition in mind, the WG has adopted a very pragmatic approach to formulate a conceptual international space astronomy Road Map for the coming decades.

The WG has identified a limited number of major space missions and observatories that are considered vital to solving key astrophysical questions identified in the above reports. These missions can be guaranteed to provide major advances in our knowledge of the Universe. This Road Map was the final result of almost 1 year of study, achieved after a detailed analysis of the currently operating fleet of space satellites for astronomical studies (Section 4.3), a review of the future missions already approved by the main national space agencies and multilateral inter-Agency agreements (Section 4.4), and potential additional missions proposed or under study (Section 5). It is important to recognise that lack of success in launching a minimum number of identified missions in the next two decades would have harmful consequences beyond the serious reduction in science investigation capability on the part of the existing astronomical community. It would also represent a decline in leadership on the part of the Space Agencies of the main developed countries, and give rise to a damaging loss of technological know-how, hampering the cutting-edge research and development advances historically enabled by space science programmes.

2. The Role of Developing Space-Faring Nations, a New Concept in International Cooperation

The last two decades have seen a growing number of developing countries acquiring the technical expertise to develop and build their own spacecraft. Besides China and India, which have become major players in space research activities, Argentina, Brazil, Chile, Korea, Malaysia, Mexico, Pakistan, Thailand and various other countries have demonstrated the capabilities to build their own satellites or space qualified instruments that can be flown on board third party spacecraft. In times of globalisation, developing countries do not wish to and cannot afford to be passive spectators of the newly emerging opportunities related to Earth observations, materials science, biotechnology research, geophysical and environment studies and, even though it may be considered by some as a "luxury", the use of space as a laboratory and vantage point for fundamental research in astronomy and physics, and for the exploration of the solar system. A recent Euroconsult report (EUR, 2010) shows that over the next decade, 280 Earth observation and meteorology satellites are expected to be launched from 41 countries, a significant increase over the 135 launches during the previous 10 years. Space programmes of developing countries will play a significant role, launching an estimated 75 satellites, quadrupling their launches from the last decade. The results of the Euroconsult report (EUR, 2010) confirm the fact that, thus far, emerging space-faring nations have concentrated their efforts in developing "practical" missions related to areas perceived by the politicians, the media and the public as having a strong social impact and/or economic benefits. Such is the case in Argentina and Brazil, where basic science projects have either been abandoned or considerably delayed, and the situation is similar itself in other countries. Furthermore, the costs associated with the advanced technologies used in state of the art astronomical instrumentation, make it rather unlikely that these countries will independently develop any major astrophysics missions within the coming decade. Nevertheless, there will be a growing desire on the part of developing countries to contribute significantly to world-class space astronomy missions in order to develop internal technical capabilities and to participate in high profile scientific investigations which are of great cultural importance to the global community. In this respect, a good deal can be learned from recent experiences associated with world class "ground based" observatories. LOFAR,[8] ALMA,[9] SKA,[10] ELT,[11] Gemini,[12] LSST,[13] TMT,[14] CTA,[15] HAWC,[16] Pierre Auger,[17] to name some of the better known, have significant contributions from a wide range of countries including developing nations.

These concepts were developed over decades by large international consortia. In some cases one of their major contributions is the provision of the site, but this is by no means a general rule or condition for a country's participation; in fact, in most cases the opportunity to participate in a major scientific endeavour is what is most attractive to the countries' academic communities, government agencies, and high-tech enterprises.

We thus envision the possibility that a similar scheme can be adopted in space science missions. Examples already exist in areas outside astronomy and astrophysics, like the China–Brazil (Sausen, 2001) series of remote sensing satellites, or the recently launched Argentina–USA SAC-D/Aquarius mission devoted to the study of ocean salinity. Since future large observatories in space will require a

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[8] LOFAR: Low Frequency Array, http://www.lofar.org/.

[9] ALMA, http://www.almaobservatory.org/.

[10] Square Kilometre Array: http://www.skatelescope.org/.

[11] European Extremely Large Telescope, http://www.eso.org/sci/facilities/eelt/.

[12] Gemini Telescope project: http://www.gemini.edu/.

[13] Large Synoptic Survey Telescope: http://www.lsst.org/.

[14] Thirty Meter Telescope: http://www.tmt.org/.

[15] Cerenkov Telescope Array: http://www.cta-observatory.org/.

[16] High Altitude Water Cerenkov Experiment: http://hawc.umd.edu/.

[17] Pierre Auger Cosmic ray observatory South: http://www.auger.org/.

partnership of several or even many national agencies, it will be important to develop a new model of partnership. Even though in practice leadership by major agencies such as NASA or ESA may need to remain, given their available resources and infrastructure, the decision-making process will need to be improved if smaller agencies are to be involved in major international missions. Often the leadership role by larger agencies gets misinterpreted as a commanding role, rather than a true partnership where all parties are sensitive and respectful to all involved. Once again, the experience of large "ground based" projects shows how science-driven facilities can be developed and implemented through large multi-agency collaborations.

It may therefore be helpful to adopt a new paradigm for International space astronomy collaboration, perhaps analogous to that used at CERN for large experiments like the LHC with several levels of associate-ship, ranging from simple observer to non-member to full member. National participation as an observer would allow the member to attend the meetings without any participation. Associate members could participate in the science and technical discussions and influence the decision making without having an actual vote, and nations providing funding for the project would have the right to take part in the decision making process. Such a model would serve two key purposes. First, a national presence, even as an observer, will give the relevant country the respectability of its association with large international missions, motivate the national space research programmes and also help deal with capacity building in space sciences. Second, it may motivate the politicians of the participating nations to aspire to become full members in order to contribute effectively in the decision making process.

A practical issue which is already known as a real impediment to wider collaboration is the application of the US International Traffic in Arms Regulations (ITAR), which has proved to be a serious problem in several instances already.

3. The Working Group Vision

An international Road Map is needed that will take into account the importance of key space missions enabling the scientific integration of the space observational windows with large "ground based" facilities. This Working Group has promoted open discussions involving the IAU, IAF, IAA and all the national agencies willing to contribute,

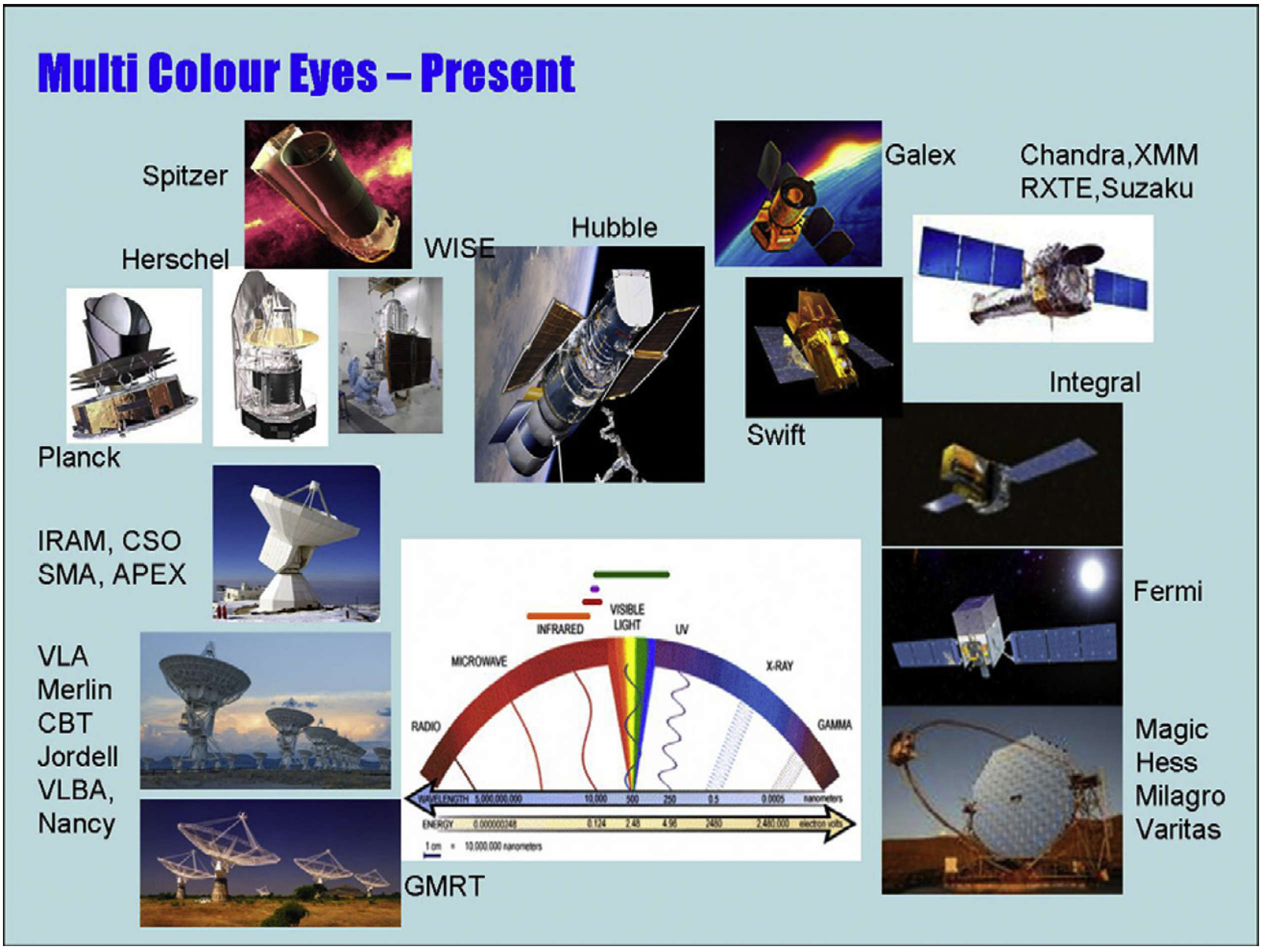

Fig. 1. Present panorama for ground and space large facilities.

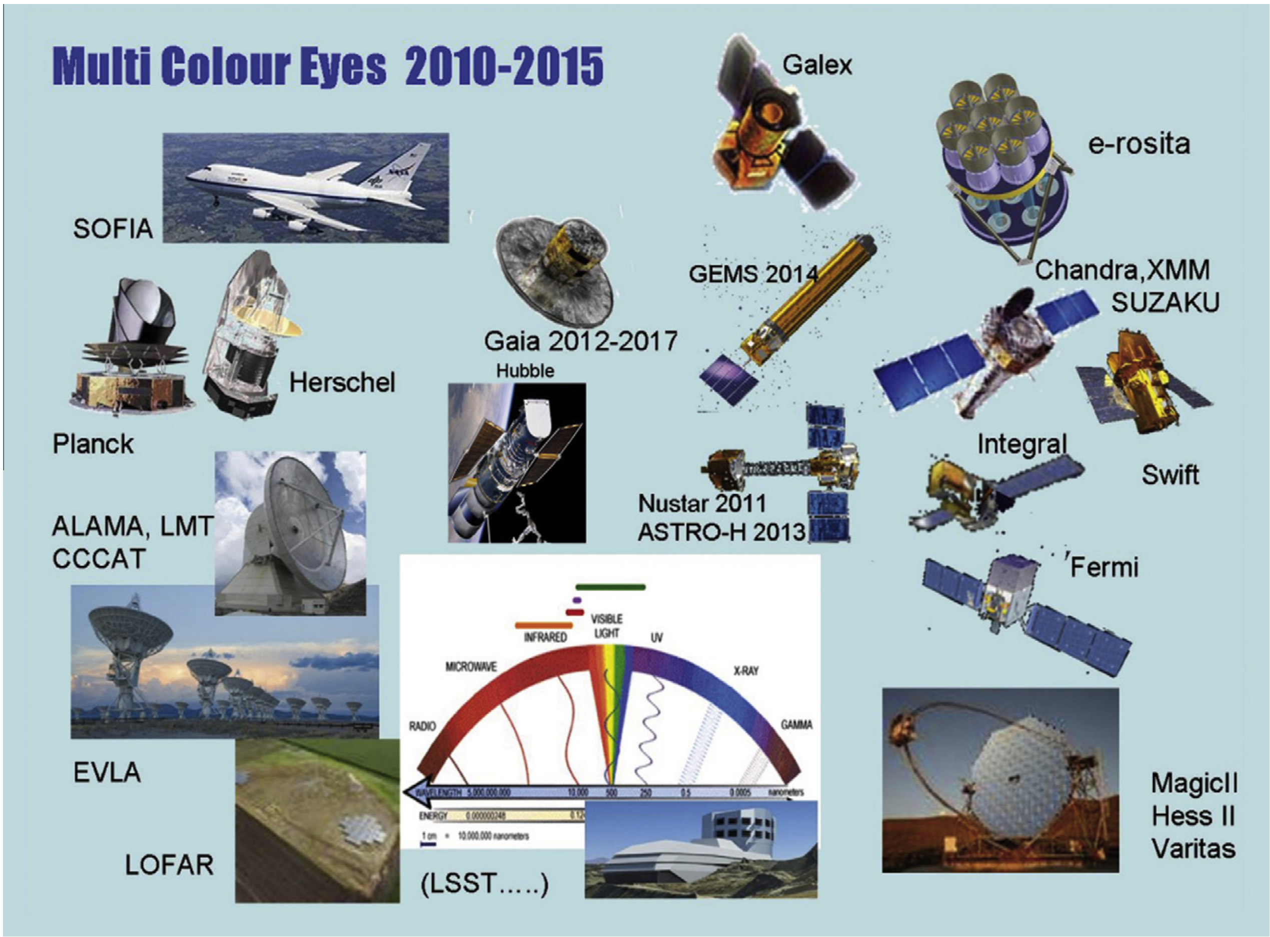

Fig. 2. The best scenario. A few small/medium size missions are expected to be completed and placed in orbit. Current operative missions, like Chandra, XMM, INTEGRAL, SWIFT, etc. will hopefully be supported and in good hardware status in the future years. Few new entries are expected: ASTROSAT, Nustar, Astro-H, GEMS, e-Rosita etc.

in order to analyse the best approach to the establishment of a viable and solid global Road Map.

The most likely candidates for new major space astronomy missions in the next few decades may be found in the plans of ESA and NASA. ESA has a long term plan articulated in the document *ESA Cosmic Vision: Space Science for Europe 2015–2025* (Bignami et al., 2005). The selection process is still under way. The next L-class mission is to be selected by 2012. The future vision for the US ground and space astronomy programmes, with current key scientific questions and discovery areas as well as programmatic recommendations, is included in the US National Academy of Sciences Astro2010 Decadal Survey Report *New Worlds, New Horizons in Astronomy and Astrophysics* (NRC, 2010a), with much more detail in each subject area in the reports from the Astro2010 Science Frontiers Panels and Program Prioritization Panels (NRC, 2010b).

3.1. The Present Scenario

In order to develop specific Road Map recommendations, the WG began by reviewing the present context. We provide here a summary of our findings. Much more detail is presented in Section 3 of this paper.

The present panorama for ground and space large facilities, summarised in an incomplete picture, is shown in Fig. 1. In the next 5 years only a few small/medium size missions are expected to be completed and placed in orbit. Currently operating large Observatories will continue to operate with aging hardware and weakened scientific grasp. The best scenario we can hope for through 2015 could be as shown in Fig. 2.

The robust state of space astrophysics missions over the past three decades and the diminished prospect in the future is perhaps more clearly illustrated in Fig. 3. Without strong corrective action, the space astrophysics community will lose the main space observatories without comprehensive future replacement for decades.

3.2. Issues

A credible Road Map must take into account the basic problems made evident in these figures, and seek to devise a way of resolving these issues:

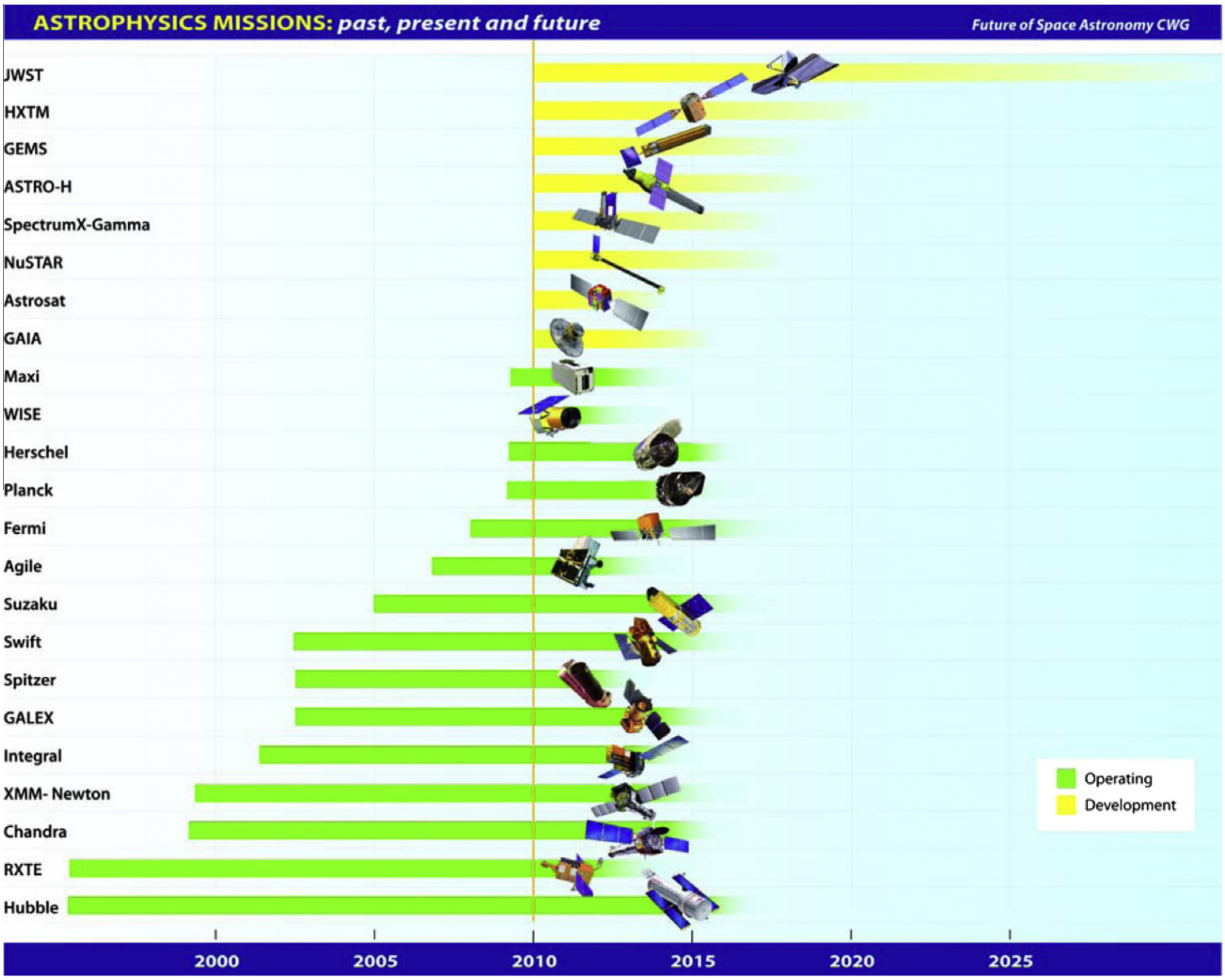

Fig. 3. Missions in operation with projected lifetime (Green), and Missions under development (Yellow) with scheduled launch date indicated by the S/C position.

1. The impressive fleet of currently operating space observatories is aging: HST,[18] Chandra (Weisskopf et al., 2002), XMM-Newton (Jansen et al., 2001) and RXTE[19] are more than 10 years old, and INTEGRAL (Winkler et al., 2011), SWIFT (Gehrels et al., 2004), Spitzer,[20] Suzaku,[21] and GALEX (Bianchi et al., 1999) have all been operating for between 5 and 8 years. Most of them are in the extended phase operation and can be expected to suffer hardware degradation. The successful Herschel[22] and Planck[23] missions have lifetimes limited by their cryogenic design, and will both come to an end by 2014.
2. Following JWST,[24] there are no large astrophysics space missions currently approved. Consequently, a major gap in the coverage of the electromagnetic spectrum will arise after 2015. This raises the prospect of a new ‘dark age’, with lack of large facilities, in particular for high energy astrophysics.
3. In contrast, there are solid and internationally agreed plans for the implementation of major “ground based” observatories, from the long-wavelength radio region to ultra high energy γ-rays. Space missions with comparable scientific power will be needed to give complementary access to spectral regions not accessible from the ground.
4. The development and implementation of large space observatories, with increasing cost, large consortia, heavy payloads and space facilities, requires multilateral effort and solid decadal or multi-decadal agreements that are not easy to attain in view of short-middle term budget planning by different countries (USA, Europe

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[18] The Hubble Space Telescope, http://hubble.nasa.gov/.

[19] Rossi X-ray Timing Explorer (RXTE), http://heasarc.nasa.gov/docs/xte/.

[20] Spitzer Space Telescope, http://www.spitzer.caltech.edu/.

[21] The X-ray Observatory Suzaku (ASTRO-E2): http://www.astro.isas.ac.jp/suzaku/.

[22] The Herschel satellite: http://sci.esa.int/science-e/www/area/index.cfm?fareaid=16.

[23] The Planck satellite: http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=13244.

[24] The James Webb Space Telescope, NASA, http://www.jwst.nasa.gov/.

etc.). An example of how this is now damaging the prospects for space astronomy is the mismatch between the timescales for mission selection in the NASA programme and ESA Cosmic Vision.

5. A different type of collaboration programme, system and instrument level, requiring multilateral cooperation among agencies, but an easier programmatic interface has been adopted by ESA and NASA for the Mars Missions. In this scenario the national agencies collaborate at the PROGRAMME level, where one or two nations develops one mission of mutual interest and another nation (or two) develops another. Scientists from all countries in the PROGRAMME are supported by their countries to participate in the scientific planning and research with data from all missions. This may simplify management and cost control, and circumvent technology transfer constraints and issues preventing exchange of funds. The potential value of such arrangements for astrophysics missions is worth considering.

3.3. Road Map principles

The Working Group adopted a few basic principles to guide development of a space astronomy Road Map that would be widely accepted:

- Science driven: pursue top priority science topics stemming from state-of-the art observations and theory, and set in a worldwide context.
- Observatory class missions: provide open access to the scientific community at large, preferably with data available with no more than a short turn-around time (6–12 months) after observations.
- Innovative enabling technology and cutting-edge scientific instrumentation: focus research and development support on innovative technologies and instrument concepts driven by science requirements for future observatory-class missions.
- Technology development: national agencies and scientific councils support research and development programmes to advance the Technical Readiness Level of mission-critical elements to flight-ready status early in mission preparation.

3.4. A Road Map for the 2010–2020 Decade

With the above issues and principles in mind, the WG recommends that the following new missions be pursued vigorously in the present decade. We assume that JWST will be launched in this decade as planned.

3.4.1. IXO: International X-ray Observatory

In May 2008 ESA and NASA established a coordination group involving ESA, NASA and JAXA, to study a joint mission merging their independent XEUS and Constellation-X concepts. The International X-ray Observatory (IXO) was announced to the astronomical community in July 2008 as a joint X-ray observatory with participation from ESA, NASA and JAXA. Top level science goals and derived key science measurement requirements were established. Peering through dust and obscuring clouds of gas, IXO would discover and map super-massive black holes at very early times when the Universe was still assembling galaxies. The unprecedented sensitivity of the IXO images and spectra would uncover the history and evolution of matter and energy, visible and dark, as well as their interplay during the formation of the largest structures. Observations of neutron stars would show how matter rearranges itself under crushing pressures well beyond what can be studied in any laboratory, while studies of spinning black holes would reveal how these objects form and grow. IXO planned to explore both when and how elements were created, how they dispersed into the intergalactic medium, and much more.

The study team had the target to provide the input to the US decadal process and to the ESA selection for the Cosmic Vision Plan. The starting configuration for the IXO study was a mission featuring a single large X-ray mirror and an extensible optical bench with a 20–25 m focal length, with an interchangeable focal plane. To achieve its science goals, IXO featured a single large X-ray mirror with a 3 square metre collecting area and 5 arc sec angular resolution, and a suite of instrumentation, including a wide field imaging detector, a hard X-ray imaging detector, a high-spectral-resolution imaging spectrometer (calorimeter), a grating spectrometer, a high time-resolution spectrometer, and a polarimeter. IXO would provide up to 100-fold increase in effective area for high resolution spectroscopy from 0.3 to 10 keV, deep spectral imaging from 0.3 to 40 keV over a wide field of view, and microsecond spectroscopic timing with high count rate capability.[25]

Working group assessment and recommendations: The increasing cost and schedule delay of JWST has made the US timescale inconsistent with that of ESA. As a consequence the re-scoped ESA L-class mission down-selection[26] had been planned for the second half of 2012.[27] Consequently, ESA has announced the re-scoping of the mission compatible with an ESA-led project within a more limited budget envelope. The new ESA policy is triggering the development of new mission scenarios with new possible participating partners, and it is possible that a world-class mission could emerge. Nevertheless, there are serious concerns that the scientific capabilities originally envisaged may be significantly compromised.

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[25] http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=47796.

[26] *Note*: The statement 'down-selection' is used by ESA to indicate 'no further consideration' during the mission selection process.

[27] *Note*: the JWST cost increase prevents NASA from funding a large scale observatory with a launch date compatible with the ESA Cosmic Vision Plan, i.e., L1 launch 2020–2022 timeframe.

3.4.2. LISA: Laser Interferometer Space Antenna

The Laser Interferometer Space Antenna (LISA) was planned as a cooperative mission between NASA and ESA, designed to measure 'ripples' in space–time, detecting and characterising gravitational waves that are emitted during the most powerful events in the universe. LISA will detect gravitational radiation from astronomical sources, observing galaxies far back in time, and testing the fundamental theories of gravitation. Predicted by Einstein's general theory of relativity, these ripples, called gravitational waves, are generated during events in which very massive objects undergo strong acceleration. Examples of such events are massive black holes swallowing neutron stars or the collision of two massive black holes. LISA was due to be the first mission to detect gravitational waves from space, making possible observations at low frequencies that would be difficult from the ground. LISA's three spacecraft were planned to form an equilateral triangle with arms of about 5 million km in length. Each spacecraft was designed to house two free-floating test masses made of a gold-platinum alloy, shielded from adverse effects of being in interplanetary space, with the distance between the test masses in different spacecraft being monitored using highly accurate laser-based techniques. In this manner, it is possible to detect minute changes caused by passing gravitational waves. Gravitational waves are an integral part of Einstein's theory of general relativity. When a massive body is strongly accelerated, it radiates gravitational waves. The difficulty is that, even for very massive bodies, such as black holes or neutron stars, gravitational waves are very weak and their effects are small. To detect gravitational waves, increasing the size of the detectors and going to a very quiet place is key. This is why scientists need LISA – a space-based detector, 5 million km in size.

Working group assessment and recommendations: The future of the LISA concept and mission depends on the outcome of the LISA Pathfinder mission, which is designed to demonstrate some of the key technologies for LISA. The construction and testing of the Pathfinder spacecraft is currently nearing completion, but subject to schedule delay due to some remaining technical difficulties. As with IXO, the increasing cost and schedule delay of JWST are making the US timescale inconsistent with ESA's plans, and ESA has announced a re-scoping of the mission within a more limited budget and ESA-led scheme. Scientific and technical studies are currently being carried out to assess what could be achieved within the confines of such a reduced budget. It remains to be seen what options will emerge from this exercise, but, as with IXO, there are strong worries that the compelling scientific promise of LISA may be greatly degraded unless it can be redefined as an ambitious mission involving major international partnership.

3.4.3. EJSM: Europa Jupiter System Mission

The fundamental theme for the Jupiter System Mission is focused on science goals relating to habitability (especially on Europa and Ganymede) and processes at work within the Jupiter System and the system's origin. Europa is believed to have a saltwater ocean beneath a relatively thin and geodynamically active icy crust. Ganymede is believed to have a liquid ocean sandwiched between a thick ice shell above and high-density ice polymorphs below, more typical of volatile-rich icy satellites. The discovery of hydrothermal fields on Earth's sea floor suggests that such areas are potential habitats, powered by energy and nutrients that result from reactions between the sea water, and silicates. Consequently, Europa and Ganymede are interesting candidates in the search for habitable zones and life in the solar system. In addition, Ganymede is the only satellite known to have an intrinsic magnetic field, which makes the Ganymede-Jupiter magnetospheric interaction unique in the Solar System. The Jupiter system includes a broad diversity of objects, including Jupiter itself, 55 currently known outer irregular satellites, the Jovian ring system, four small inner satellites, and the four large Galilean Satellites: Io, Europa, Ganymede, and Callisto. The Jupiter System Mission has the goal of determining whether the Jupiter system harbours habitable worlds, while detailing the geophysical, compositional, geological, and external processes that affect these icy and active planet-sized worlds. The mission will study Jupiter's atmosphere while focusing on complementary scientific questions through measurements of the troposphere, stratosphere, thermosphere, and ionosphere for comparisons with Jupiter's interior and magnetosphere. In mid-April 2011, ESA appointed the Science Study Team (SST) for the Jupiter System Mission concept to re-formulate the science case, re-structure the mission, and study which of the original science goals of the EJSM mission concept can be achieved by a European led mission. The SST process is scheduled to be terminated in February 2012.

3.4.4. Dark Energy and Exoplanet Science: WFIRST (NASA Decadal Survey) and Euclid (ESA M-class mission)

3.4.4.1. WFIRST (NASA).

The Wide-Field Infrared Survey Telescope (WFIRST) is a recommended NASA observatory based on a 1.5-metre-class telescope with a wide field-of-view to carry out near-infrared imaging and low-resolution spectroscopy. WFIRST will address two of the most fundamental questions in astrophysics: why is the expansion rate of the universe accelerating? and are there other solar systems like ours, with worlds like Earth? In addition, WFIRST will allow astronomers to tackle issues of central importance to our understanding of how galaxies, stars, and black holes form and evolve. To settle fundamental questions about the nature of dark energy, the postulated cause of the accelerating expansion of the universe, WFIRST will employ three distinct techniques – measurements of weak gravitational lensing, baryon acoustic oscillations, and supernova distances. To search for exoplanets, it will monitor a large sample of stars in the central bulge of the Milky Way for small deviations in brightness due to microlensing by intervening stars and their associated planetary systems. Finally, WFIRST will offer a robust guest investigator programme supporting key and archival studies of broad astrophysical topics.

3.4.4.2. Euclid (ESA – M Class Mission). The mission has a 1.2-metre-class telescope and instruments in the visible and near-infrared. Its primary observation is a large (∼15,000 square degree) imaging and spectroscopic (slitless) sky survey. Euclid is designed to address key questions relevant to fundamental physics and cosmology, namely the nature of the mysterious dark energy and dark matter. Astronomers are now convinced that these substances dominate ordinary matter. Euclid would map the distribution of galaxies to reveal the underlying 'dark' architecture of the Universe.

Working group assessment and recommendations: Euclid has now been selected by ESA. Join together the Dark Energy missions in Europe and the US. Add-in possible other partners from Canada, China, India and possibly Russia.

3.4.5. The ESA change of L Class mission collaborative scheme

On March 15 2011, F. Favata, Head of the Science Planning and Community Coordination Office informed the community of a relevant change of collaborative scheme with NASA on the three L Class mission candidates with an e-mail to the Members of the Space Science Advisory Committee, Astronomy Working Group, and Solar System and Exploration Working Group, to be distributed to interested people. The main message was that "the US budgetary prospective has now also become known in February 2011, and, given the decadal prioritisation, our initial discussions with US counterparts indicate that it has become quite unlikely for any of the three L mission candidates to be implemented as a joint Europe-US mission in the planned early 2020s timeframe. The ESA advisory bodies and the Science Programme Committee have decided to revise the structure of each L-class mission study and of the corresponding team in the context of a European framework. Each revised team will be asked to examine if they can restructure their mission concept and its science case to meet a scenario where, in the least optimistic case, a Europe-alone mission could be envisaged".

3.4.5.1. The impact of the "ESA alone" programmatic decision on NASA-JAXA common programme. The Astrophysics and Planetary decadal prioritisation and NASA's projected resources for the 2012 budget were clearly in contrast with the ESA Cosmic Vision priorities and programmatic scenario. This situation has forced ESA to face the fact that none of the three mission concepts, IXO, LISA and EJSM, could have been feasible in an ESA–NASA common scenario. As an immediate consequence, ESA has ended plans to implement the three L-Class Missions as partnerships at the level proposed in the *New Worlds*, *New Horizons* Decadal Survey and *Visions and Voyages for Planetary Science*. At the same time ESA has started a rapid rescoping/definition phase with nomination of new Science Teams (ST) for each Mission. The main objectives of those teams, to be completed by the end of 2011, are the re-definition and identification of the key science goals and consequent redefinition of the high level scientific requirements, and identification of re-scoped mission concepts that could be implemented as ESA led missions. It is intended that the selected mission be implemented on a schedule compatible with the original Cosmic Vision timeframe, with a launch in the 2022–2023 timeframe. The total ESA cost envelope (not including national participation in the science payload) is to be <1BEuro, with possible additional contributions from other agencies. A future minor role for NASA in the new ESA-led X-ray mission, in particular, contributions at the instrument level, has not been ruled out, while participation of scientists from the US and Japan is planned. The final down selection is planned in May 2012.

Working group assessment and recommendations: LISA and IXO are large scale observatories, both of which are vital to ensure a breakthrough in knowledge of the Universe. It is important that if a similar mission is selected by ESA for implementation in Cosmic Vision, it should have scientific objectives that are compatible with the ambitions of the scientific community. If not selected, the international community should pursue a new route to implementation. An international X-ray mission should be planned, focused on First Stars, black hole physics and cosmic chemical evolution of the Universe. Likewise, a low-frequency gravitational wave observatory such as LISA will be essential to realise the promise of this new area of science.

The WG expresses a strong concern about the feasibility of developing large space observatories by a single Agency/country.

3.5. The 2020–2030 Decade Road Map

In the post-2020 era, without corrective actions, the best case scenario may become as shown in Fig. 4, with JWST the only new mission launched in the present decade and many current missions ceasing operation before 2020. As this Figure illustrates, there would be little synergy between ground and space observatories, and the international community will have lost parts of the electromagnetic spectrum. In the area of high energy astrophysics, the only foreseen Observatory class mission is IXO/Athena. This ESA led-NASA-JAXA mission is now in competition with LISA and EJSM for the ESA 2012 L-Class down selection process. The final selection to fly is expected by middle 2012.

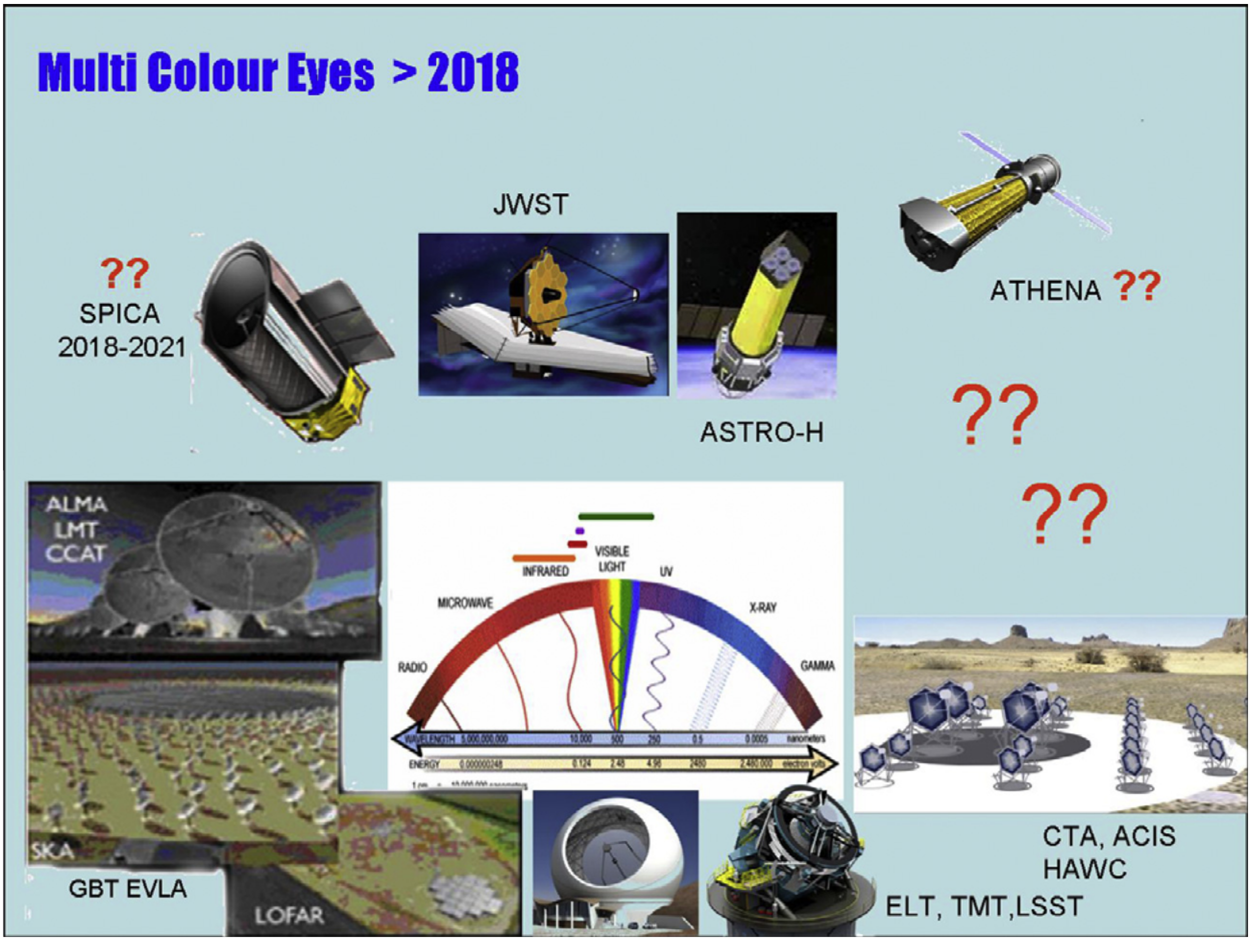

Fig. 4. In the post 2020 scenario only JWST is actually planned and approved. In the high energy astrophysics domain the only foreseen Observatory Class Mission is IXO/Athena. This ESA lead-NASA-JAXA mission is now under final selection process.

3.5.1. *Proposed longer term large missions (to fly within ~two decades)*

In addition to the major mission candidates discussed above, numerous additional ideas have been advanced in countries around the world. We list here examples to illustrate the rich potential of space astronomy in the future.

- Next generation γ ray Observatory.
- Large specialised exoplanet characterisation mission (e.g., a version of TPF, Terrestrial Planet Finder).
- Next generation UV-Optical-IR-optical telescope, such as ATLAST (Advanced Technology Large Aperture Space Telescope, studied in the US).
- Large-aperture far-infrared (FIR) telescope (recommended by US Decadal Survey in 2000) and a future priority of the FIR/submillimetre community).
- Far Infrared Interferometer (high angular resolution imaging and spectroscopy) studied in US and Europe, and a future priority of the FIR community.
- Space Submillimetre array.
- Post-Planck CMB polarisation mission (exploration of the physics of inflation).

3.5.2. *Medium sized missions proposed to NASA, ESA, JAXA, Roscosmos and other Agencies*

- GRB First Stars Finder: rapid response, 1-m IR telescope, wide-field X-ray instrument to detect high z γ-ray bursts (GRB).
- Hard X-ray/soft γ-ray focusing or modulation telescope.
- HXMT – Hard X-ray Modulation Telescope (approved by CNSA and CAS for launch in 2014–2015): China, Italy, others.
- LOFT – X-ray timing large area (ESA M3 candidate; possible selection by end 2012).
- SVOM – GRB detection and study (launch 2014–2015): China–France collaboration.
- Timing and X-ray Timing and Polarisation – India, China, Russia.
- Cosmic-ray and dark matter origin: China, Japan, etc.; possible joint mission.
- PLATO (ESA M2 candidate).
- EChO (ESA M3 candidate) – exoplanet.
- MARCO POLO (ESA M3 candidate) – exoplanet.
- STE-QUEST (ESA M3 candidate) – equivalence principle.

- Post-Planck CMB polarisation mission (exploration of the physics of inflation); concepts under development in USA, Europe, Japan.
- SPICA: far infrared observatory (Japan, ESA, Canada, USA) – to be considered medium-large; launch 2018.
- Millimetron – VLBI and submillimetre single dish observatory; Russia, Italy, etc.
- Radioastron – VLBI; Russia with international participation.

In addition to the aforementioned missions, there are a number of small missions planned at national and multinational levels.

3.6. The COSPAR Working Group on Future of Space Astronomy Basic Recommendations

- Launch JWST as early as possible in the present decade. JWST is recognised to be the only approved large space observatory to be possibly operational in the next 10–20 years. It is an essential asset for space science investigations complementing "ground based" facilities planned (e.g. LOFAR,[28] ALMA,[29] SKA,[30] ELT,[31] Gemini,[32] LSST,[33] TMT,[34] CTA,[35] HAWC,[36] Pierre Auger,[37] etc.).
- Vigorously pursue a large X-ray space observatory, operative in the next decade. The proposed IXO satellite, or a similar large high energy observatory, should be able to exploit a broad scientific scenario, possibly including investigation of the 'first stars' via a high-z γ-ray burst detection capability.
- At the same time we recommend that the agencies involved support, exploit and finalise the R&D programmes necessary to have in operation the gravitational wave mission LISA at the latest in the time-frame 2025–2030.
- Develop and launch a dark energy/exoplanet mission such as Euclid/WFIRST, preferably involving multinational participation.
- Pursue a robust co-operative programme devoted to solving specific burning scientific questions via the implementation of multilateral medium size/small size dedicated missions.

3.7. WG conclusions

The scenario recommended above is the minimum necessary programme to successfully:

- Maintain the rate of fundamental discoveries in science, with particular emphasis in astrophysics. The capability to achieve outstanding breakthroughs in scientific knowledge has been a key characteristic of the field.
- Observe formation of the 'first stars' and, in turn, advance our knowledge of evolution of the universe at $z \geqslant 10$, filling the gap between the Big Bang and the re-ionisation era. Preserve and advance the knowledge and skills of the large scientific and technical space astrophysics community that was borne and has matured in the first 50 years of the Space Age.
- Maintain observational access to the Universe across the electromagnetic spectrum and open up the new window of gravitational wave astronomy. This is a fundamental scientific requirement to complement large "ground based" telescopes and facilities in the observational windows hampered from the ground by atmospheric absorption and emission. This will also preserve the invaluable Space-Ground synergy achieved so far.
- Preserve and expand the knowledge and skills of the scientific and technical space community that has contributed so much to the technical and cultural life in the developed world during recent decades. This community has now spread worldwide and is fertilising the scientific environment and the intellectual life of newly developed countries.

4. The Present Scenario

4.1. The ASTRONET report: A Science Vision for (European) Astronomy

This paragraph is a summary of the Astronet report published in 2007 (AST, 2007), which presents a vision shared by the WG. The excerpt below in italics is simply reported here as a reminder of the "basic facts" that the WG endorses. The short following paragraph is also a good summary of the WG vision for "ground based" observatory status and future plans. Astronomy is the study of everything beyond Earth. It is a science driven by observations, with links to mathematics, physics, chemistry, computer science, geophysics, material science and biology. Astronomy is important for society and culture, and helps attract young people to the physical sciences. The field benefits from and also drives advances in technology. As a result, it is now possible to study objects which are so far away that they are seen at a time when the Universe was only 5% of its present age, and – perhaps even more astoundingly – to detect and characterise planets orbiting other stars, and to search for evidence of life. European astronomers have access to a range of observational facilities on the ground and in space. Plans

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[28] LOFAR: Low Frequency Array, http://www.lofar.org/.

[29] ALMA, http://www.almaobservatory.org/.

[30] Square Kilometre Array: http://www.skatelescope.org/.

[31] European Extremely Large Telescope, http://www.eso.org/sci/facilities/eelt/.

[32] Gemini Telescope project: http://www.gemini.edu/.

[33] Large Synoptic Survey Telescope: http://www.lsst.org/.

[34] Thirty Meter Telescope: http://www.tmt.org/.

[35] Cerenkov Telescope Array: http://www.cta-observatory.org/.

[36] High Altitude Water Cerenkov Experiment: http://hawc.umd.edu/.

[37] Pierre Auger Cosmic ray observatory South: http://www.auger.org/.

are being made for a next generation of facilities, which would continue to exploit the rapid advances in, e.g., adaptive optics, detector sensitivity, computing capabilities, and in the ability to construct large precision structures, sending probes to Solar System objects, and even bring back samples from some of them. Realizing all the plans and dreams would require substantial investments by national and international funding agencies, with significant long-term commitments for operations. The Astronet Science Vision Working Group identified four key questions where significant advances and breakthroughs can be expected in the coming two decades:

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

These are amongst the most fundamental questions in science and generate considerable interest in the general public.

In addition to the Astronet Report, the COSPAR Working Group has analyzed the information already existing in national strategic plans, ESA's Cosmic Vision, the US National Academay of Science Decadal Survey, ESA–ESO studies, etc. …*the Astronet work led to specific scientific recommendations, which were incorporated in a draft version of the Science Vision, made available to the entire astronomical community in late 2006. The draft was discussed in-depth during a Symposium in Poitiers, Paris, January 23–25, 2007. Many of the 228 participants from 31 countries provided constructive input, and additional comments were received via a dedicated website. This led to further sharpening of the scientific requirements, an improved balance across the four main areas, and improvements in the text… Care was taken to describe these in a fairly generic way, focusing on the scientific requirements, and not to identify too closely with specific proposed implementations of missions or facilities, as this is the purview of the infrastructure roadmapping activity that will follow. … summarises the main recommendations by thematic area, and distinguishes essential facilities or experiments, without which a certain scientific goal simply cannot be achieved, and complementary ones, which would go a long way towards answering the question, but may have their main scientific driver elsewhere… Activities needed across the four thematic areas are identified as well. In all cases, the focus is on the most promising avenues for scientific progress, without detailed consideration of cost or technological readiness, which are the subject of the infrastructure roadmapping. Some of the more ambitious facilities may take a significant time to develop, and in some case may only start to produce a scientific harvest towards the end of the 20 year horizon. Progress relies on a healthy mix of approaches including imaging, spectroscopy and time-series analysis across the entire electromagnetic spectrum, in situ measurements in the Solar System, and use of particles and gravitational waves as additional messengers from celestial objects.*

Most of the above concepts were shared by the COSPAR WG members and a similar approach was taken as a starting point to elaborate the WG vision.

4.2. Spectral Coverage of Currently Operating Space Astrophysics Missions

To clarify the full electromagnetic spectral coverage of the currently operating space astronomy and astrophysics missions and the more limited coverage of those approved and under development (Fig. 3), we begin with a short description organised by spectral range. In the following section we provide more detail about each of the missions and the scientific contributions of the operating missions.

4.2.1. X-rays and γ-rays

The NASA Rossi-XTE mission, providing high resolution timing studies of X-ray sources over the 1–200 keV range, continues to operate successfully producing key findings on variable, pulsed and quasi-periodic sources. The world-wide γ-ray burst and transient monitoring capability is in excellent shape with the continued operation of the Swift mission. Bursts have been detected from the early universe at redshifts in the range of the most distant objects known. NASA's Chandra observatory and ESA's X-ray Multi-mirror Mission (XMM-Newton) have been operating successfully in space since 1999. With their complementary emphases on high angular resolution (Chandra) and high throughput spectroscopy (XMM-Newton), these observatory missions continue to generate major advances in astrophysics. The two missions have been particularly effective in studying distant galaxies, including the massive black holes at their centres, galactic mergers, and the billion-degree gas that permeates the intergalactic medium in clusters of galaxies. Japan's Suzaku X-ray mission was launched in 2005. It has X-ray and hard X-ray telescopes that are producing high-quality broad-band observations of accreting and jetting sources. Japan's MAXI experiment was installed on the International Space Station (ISS) in 2009 and is successfully performing full-sky monitoring of the X-ray sky. At the relatively low γ-ray energies associated with nuclear spectral lines, ESA's International γ Ray Astrophysics Laboratory observatory (INTEGRAL), launched in 2002, is now supplying the world γ-ray astronomy community with an important imaging, spectroscopic and polarimetric capability, complemented by X-ray and optical monitoring. INTEGRAL has provided the most accurate images of the Universe at high energy. It will also provide a legacy of almost 10 years of continuous observation of the Galactic Center, and the discovery of the new class of high energy Super giant Fast X-ray Transients (SFXT). to observe higher energies that facilitate investigation of the highest energy processes in the universe, Italy's AGILE (Astro-rivelatore γ a Immagini Leggero) was launched in 2007 and the major Fermi γ-ray Space Telescope developed by NASA & the Department of Energy in the US plus universities and agencies in France, Germany, Italy, Japan and Sweden was launched in 2008. These missions are producing discoveries every month. The future outlook includes the launch in 2012 of the Nuclear Spectroscopic Telescope Array (NuSTAR) that is a NASA Small Explorer mission (SMEX), a high energy mission with two small focusing hard X-ray telescopes. The Indian ASTROSAT mission, an X-ray and multiwavelength satellite is also scheduled for launch in 2012. ASTRO-H is a joint JAXA/NASA mission to perform high-resolution spectroscopy of X-ray sources that is in development for launch in 2014. During 2010, the Gravity and Extreme Magnetism SMEX (GEMS) was selected in the NASA Explorer programme for X-ray polarisation measurements and is in development for launch in 2014. Spectrum RG is an RKA X-ray observatory with Russian and German X-ray instruments for launch in 2014.

4.2.2. UV/Extreme UV and Visible

The Hubble Space Telescope (HST) continues to operate successfully producing spectacular images and spectra. In 2009, the fourth servicing mission replaced key spacecraft sub-systems. In addition, two new instruments were installed, Wide-Field Camera 3 (WFC3) and the Cosmic Origins Spectrograph (COS), and two instruments were repaired, the Space Telescope Imaging Spectrograph (STIS) and the Advanced Camera for Surveys (ACS). NASA's GALEX (Galaxy Evolution Explorer), has conducted the first deep all-sky survey in the ultraviolet, and has detected more than one million hot stars and galactic cores since launch in 2003.

4.2.3. Infrared and Submillimetre

NASA's Spitzer Space Telescope, launched in 2003, has detected tens of millions of infrared point sources and probed the dust and gas in star-forming regions in the Milky Way and in other galaxies extending to the early Universe. Its extensive legacy programmes are devoted to specific large-scale surveys. With the exhaustion of its stored cryogen in 2009, it is continuing exciting studies including exoplanets and the high-redshift universe with the two shortest-wavelength channels of its Infrared Array Camera. ESA's Herschel is a major mission launched (with Planck) in 2009. It is a far-infrared to submillimetre telescope. Herschel is providing astronomers with an unprecedentedly high spatial and spectral resolution view of the cold Universe, observing tiny stars, molecular clouds and galaxies enshrouded in dust. In 2009, NASA launched the WISE SMEX mission. In its operational lifetime it performed an all-sky IR survey in the 3–25 micron range. The James Webb Space Telescope (JWST) is a large, infrared-optimised space telescope, scheduled for launch not early than 2018. It is a joint project of NASA, ESA, and the Canadian Space Agency (CSA).

4.2.4. Submillimetre

NASA's Wilkinson Microwave Anisotropy Probe (WMAP) Explorer mission, launched in 2001, has reported the spectacular results of its all-sky survey of the cosmic microwave background radiation. While pinning down the age of the universe to approximately 1% accuracy, these results also offer powerful confirmation of all the measurable predictions of the 'hot big bang with inflation' history of the early universe. An added surprise of these first

Table 1
Fig. 3 details.

Mission	Details: in operation
HST 1990	(NASA/ESA) Observatory mission: 2.4 m telescope, imaging/spectroscopy of galactic and extragalactic sources
Rossi XTE 1995	(NASA) Timing and broadband spectroscopy of compact X-ray sources (2–250 keV)
CHANDRA 1999	(NASA) X-ray Observatory mission. High resolution imaging and spectroscopy in the soft X-ray range
XMM-Newton 1999	(ESA) Observatory mission. High throughput spectroscopy and imaging in the soft X-ray range
INTEGRAL 2002	(ESA) high resolution Imaging and spectroscopy in the soft γ-ray range from 20 keV to 10 MeV
GALEX 2003	(NASA) Galactic Evolution Explorer. UV all-sky survey mission
Spitzer 2003	(NASA) Observatory Infrared Telescope Facility. IR telescope of 0.85 m aperture
Swift 2004	(NASA/UK/Italy) Medium Explorer. Γ-ray burst detection with X-ray and optical telescopes for rapid follow-up
Suzaku 2005	(Japan/NASA) X-ray and hard X-ray telescopes
AGILE 2007	(ASI) high energy γ-ray mission
Fermi 2008	(NASA/DOE/France/Germany/Italy/Japan/Sweden) High energy Γ ray telescope
Planck 2009	(ESA) M-mission to study the spectrum and anisotropy of the diffuse MW cosmic background radiation
Herschel 2009	(ESA) Observatory, 3 m Cassegrain telescope, high throughput heterodyne and far IR spectroscopy and imaging
MAXI 2009	(JAXA) experiment on ISS for X-ray sky monitoring and survey
To be launched	
Gaia 2013	(ESA) 3-D mapping of the stars of the Galaxy
ASTROSAT 2012–2013	(ISRO-INDIA) multi-wavelength astronomy mission from visible (320–530 nm) to hard X-ray (3–80 keV and 10–150 keV)
NuSTAR 2012	(NASA) SMEX mission for hard X-rays with a focusing telescope
SRG 2013	(Roscosmos) The Specturm X-*Gamma* – eRosita experiment
Astro-H 2014	(JAXA-NASA) X-ray mission for high resolution spectroscopy and hard X-rays
GEMS 2014	(NASA) SMEX X-ray polarisation mission
HXMT 2015	(China Space Agency) Hard X-ray Modulation Telescope (1–250 keV)
JWST 2018	(NASA/ESA) Observatory, IR 6.5 m mirror telescope sensitive from 0.6 to 27 μm

WMAP results is the apparent evidence for the appearance of the first stars earlier than was expected from the standard model of galaxy formation. The operations of WMAP were concluded in 2010. The ESA Planck mission is a precision cosmology satellite launched (with Herschel) in 2009 and is providing new insights clusters of galaxies and on the cold objects in the Universe, from within our Galaxy to the distant reaches of the cosmos. It follows on WMAP to make comprehensive observations of the cosmic microwave background radiation.

4.3. Missions in Operation: short description and basic scientific characteristics

This section provides an expanded account of the missions actually in operation and highlights of their scientific contributions to date. Fig. 3 and Table 1 show and list respectively the satellites and observatory class missions which are operating in space and have continuing data analysis efforts.

Fig. 3 includes all:

- Missions in operation with projected lifetime.
- Missions under development.

Table 1 includes:

- The main responsible agency or nation.
- Actual launch dates for already in flight satellites.
- Actual or scheduled launch dates for mission under development.
- A brief description of the main characteristics of the mission.

4.3.1. Hubble Space Telescope

On 24 April 1990, the Space Shuttle Discovery lifted off from Earth with the Hubble Space Telescope nestled securely in its bay. The following day, Hubble was released into space, ready to peer into the vast unknown of space, offering mankind a glimpse upon distant, exotic cosmic shores yet to be described. In Fig. 5 HST is shown as viewed from the Space Shuttle Discovery during the Servicing Mission STS-82. NASA suggested that the lifetime of the Hubble telescope be 15 years, which implied that the instruments needed the ability to be replaced on the ground or even serviced in orbit, an ability not afforded to any satellite before or since. Scientists also had to balance the size and quantity of scientific instruments versus their cost. The European Space Agency joined the project in 1975 and provided 15% of the funding of the HST via contribution of the Faint Object Camera and the solar arrays. In return, NASA guaranteed at least 15% of telescope time to European astronomers. In 1977, Congress approved funding to build HTS, one of the most sophisticated satellites ever constructed. Over the course of Hubble's 20-year mission, new and improved instruments have been periodically installed in order to bring the most advanced instrument technologies to the observatory.[38]

Fig. 5. The Hubble Space Telescope in space.

HST currently has the most powerful suite of instruments in its history.

4.3.1.1. Mission achievement summary. The Hubble Space Telescope has arguably had a greater impact on astronomy and, as importantly, on worldwide appreciation of and support for astronomy, than any observatory since Galileos telescope. HST has produced many remarkable discoveries, some anticipated and some totally surprising, ranging from our solar system to galaxies as they appeared within a billion years after the Big Bang. As a few examples, Hubble images of solar system bodies from Venus to Kuiper-belt objects, including comets crashing into the atmosphere of Jupiter, star and planetary systems forming in our Galaxy, galaxies in collision and the host galaxies of gamma-ray burst sources grace text-books and class-room walls around the globe and advance our understanding of how we got here. Hubble spectral data showed us the atmospheric constituents of planets orbiting other stars, and showed us that there are supermassive black holes in the centers of most galaxies. Most surprisingly, HST played a key role in perhaps the most transformative scientific discovery since Edwin Hubble discovered the expansion of the Universe. In 1998, two teams of astronomers (Perlmutter et al., 1999; Riess et al., 1998) using data from "ground based" telescopes and HST presented evidence that the expansion of the Universe is currently accelerating, rather than decelerating under the influence of gravity as expected. Unless Einsteins general theory of relativity needs to be modified, the acceleration appears to be propelled by the repulsive force of a mysterious dark energy. The nature of the dark energy is arguably the most profound puzzle facing physics today. The observers used

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[38] The Hubble Space Telescope, http://hubble.nasa.gov/.

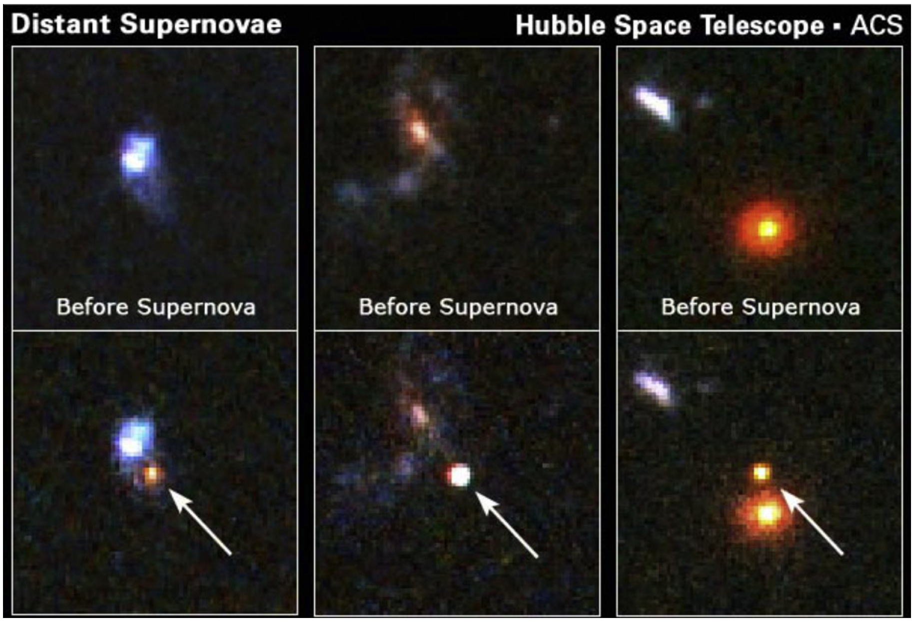

Fig. 6. HST discovery of distant Supernovae.

Type Ia supernovae as bright, standard candles to trace the expansion history of the Universe. The high angular resolution of HST was essential to separating the light of the most distant supernovae from that of the host galaxy, and thereby obtaining an accurate distance. Fig. 6) shows HST data for three such events, both before and after the supernova explosions. The HST observations demonstrated three critical points confirming the reality of the acceleration: prior to about 5 billion years ago, the expansion was decelerating, indicating that gravity was then dominating over dark energy; dark energy was already present as early as 9 billion years ago, though not yet dominant; dark energy behaves in a manner consistent with what quantum mechanics predicts for vacuum energy. Improving observational determinations of the character of dark energy is a major motivator for future astronomical studies.

Fig. 7. Rossi X-Ray Timing Explorer (RXTE) during ground test.

4.3.2. Rossi X-ray Timing Explorer (RXTE)

The Rossi X-ray Timing Explorer (RXTE) was launched on 30 December 1995 from NASA's Kennedy Space Center (see Fig. 7) and decommissioned the 5 January 2012. The mission is managed and controlled by NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. RXTE features unprecedented time resolution in combination with moderate spectral resolution to explore the variability of X-ray sources. Time scales from microseconds to months are covered in an instantaneous spectral range from 2 to 250 keV. Originally designed for a required lifetime of 2 years with a goal of five, RXTE has been performing well completing 16 years of operation in December 2011. The mission carries two pointed instruments, the Proportional Counter Array (PCA) developed by GSFC to cover the lower part of the energy range, and the High Energy X-ray Timing Experiment (HEXTE) developed by the University of California San Diego covering the upper energy range. These instruments are equipped with collimators yielding a FWHM of one degree. In addition, RXTE carries an All-Sky Monitor (ASM) from the Massachusetts Institute of Technology (MIT) that scans about 80% of the sky every orbit, allowing monitoring at time scales of 90 min or longer. Data from PCA and ASM are processed on board by the Experiment Data System (EDS), also built by MIT.[39]

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[39] Rossi X-ray Timing Explorer (RXTE), http://heasarc.nasa.gov/docs/xte/.

4.3.2.1. Mission achievement summary. The RXTE has proved to be a successful mission for exploration and new discoveries. In particular, the large collecting area of the PCA is a key tool for study of the rapid X-ray variability phenomena of galactic sources. This capability has allowed investigations to address fundamental questions concerning the properties of dense matter and strong gravitational fields around astrophysical objects. In the past 15 years, the RXTE mission has achieved several new breakthrough results from neutron stars and black holes. Discovery of the accretion-powered millisecond X-ray pulsars, with spin frequencies ranging from 185 to 435 Hz and discovery of twin kilohertz QPOs detected in weak-field neutron stars having frequencies from $\sim$100 to $\sim$1300 Hz has clearly demonstrated the complexity of these strong gravity phenomena and thermonuclear bursts. The separation of the twin peaks remains nearly constant while the QPO frequency shifts by a factor of $\sim$2–3. Other key results of RXTE include a strong correlation between the X-ray spectra and X-ray variability of accreting stellar mass black holes and the launch of jets correlated with changes in the inner part of the accretion disk (disk-jet connection). RXTE has also clearly established that soft γ-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are isolated neutron stars with similar properties, having extremely large magnetic fields (Magnetars). In the case of extragalactic X-ray sources, some important examples are observations of correlated X-ray and TeV flares in Blazars and the variability of broad iron Kα lines in active galactic nuclei. Seyfert galaxies and quasars which have low fluxes of a few tenths of a milliCrab can be measured in the range 30–100 keV in a few days of observation with RXTE.

4.3.3. Chandra X-ray Observatory

NASA's Advanced X-ray Astrophysics Facility, (AXAF), renamed the Chandra X-ray Observatory in honour of Subrahmanyan Chandrasekhar, was launched and deployed by the Space Shuttle Columbia on the 23 of July 1999 (see Fig. 8). The combination of high angular resolution, large collecting area, and sensitivity to high energy X-rays make it possible for Chandra to study extremely faint sources, sometimes strongly absorbed, in crowded fields. Chandra was boosted into an elliptical high-earth orbit that allows long-duration uninterrupted exposures of celestial objects (Weisskopf et al., 2002). The Smithsonian Astrophysical Observatory (SAO) in Cambridge, Massachussets, is responsible for the conduct of the day-to-day fight operations and science activities from the Operations Control Center and Chandra X-ray Center (CXC) facilities.

Mission characteristics:

1. Lifetime: 23 July, 1999 – (nominal 5 year mission; extended by NASA and still operating).
2. Energy range: 0.1–10 keV.
3. Spatial resolution better than 1 arc sec.
4. Orbit: 64 h period, highly-eccentric Earth orbit.
5. Payload: A single Wolter Type 1 grazing incidence iridium-coated imaging telescope with a ghost-free field of view of about 30 arc min diameter and an effective area of 800 and 400 cm^2 @ 0.25 and 5 keV, respectively.
6. Four detectors can be inserted, one at a time, into the focal plane. Two of these are designed to be used primarily with the gratings:
   - AXAF Charged Coupled Imaging Spectrometer (ACIS): energy range 0.2–10 keV: one 4-chip imaging array (ACIS-I), Field of View 16 X 16, one 6-chip spectroscopic array (ACIS-S), Field of View 8 × 48.
   - High Resolution Camera (HRC): energy range 0.1–10 keV.
   - High Energy Transmission Grating + ACIS-S (HETG): energy range 0.5–10 keV.

Fig. 8. Chandra X-Ray Observatory artist's concept.

- Low Energy Transmission Grating + HRC-S (LETG) energy range 0.08–6.0 keV.

4.3.3.1. Mission achievement summary. The main features of the Chandra X-ray Observatory are the sub-arcsecond angular resolution and capability to provide spatially resolved spectra on the same scale. These characteristics are not provided by any other mission and may not be provided by any other mission for several decades. Chandra is one of NASAs Great Observatories and its main strengths are unprecedented spatial resolution, sensitivity that extends from soft X-rays up to 10 keV, and the ability to obtain high spectral resolution observations over most of this range with the use of the gratings. Chandra has provided outstanding scientific results in a broad range of extragalactic studies from cosmology, to clusters of galaxies, to AGN, and to resolution of the sources of the cosmic X-ray background radiation. Chandra has also enabled Galactic studies of star formation, white dwarfs, neutron stars and black holes. Chandra studies have advanced our understanding of the dark energy, dark matter, and baryonic matter that comprise the Universe; of the physical processes that govern the formation and evolution of stars, galaxies, and galaxy clusters; of the formation and dispersal of heavy elements needed for planets and life; and of the nature of the laws of physics under extreme conditions. Chandra and XMM-Newton (see next paragraph) have been two most powerful X-ray Observatories in orbit for more than a decade and are complementary to each other: Chandra providing the best angular resolution ever achieved and XMM-Newton providing the highest throughput. A comprehensive review of the main results achieved in the first 10 years of scientific observations of these two Observatory-class satellites is reported in (Santos-Lleo et al., 2009). Table 2 summarises the main achievements of the two observatories. Examples of the scientific investigation power of these observatories are illustrated

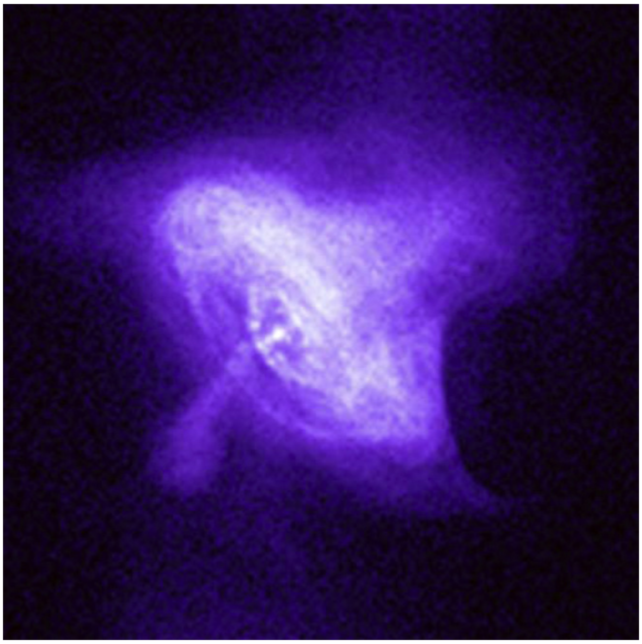

Fig. 9. A sharp X-ray image of the Crab Nebula and Pulsar obtained with the CHANDRA Observatory (Credit: NASA/CXC/SAO).

Table 2
Chandra and XMM-Newton first decade results summary (Santos-Lleo et al., 2009).

Scientific area	Main achievement
Planetary science	
Comets	Established charge-exchange as mechanism for X-ray emission
Galactic astrophysics	
Stars	Measured densities, temperatures and composition of hot plasmas, testing models for stellar evolution, X-ray emission from stellar coronae, and stellar winds
Star formation and	Discovered X-ray emission from gas-accreting star-forming regions onto stellar surfaces and influenced by magnetic fields detected giant flares from young stars, with implications for planet formation.
Supernovae	Established that Keplers supernova was a thermonuclear event
Supernova remnants (SNRs)	Discovered a central compact object in the CasA SNR11 and traced the distribution of elements indicating turbulent mixing along with an aspherical explosion. Imaged forward and reverse shock waves in several SNR, with implications for the acceleration of cosmic rays
Pulsar wind nebulae	Resolved jets and rings of relativistic particles produced by young neutron stars
Black hole accretion processes	Measured the flaring of central black hole and resolved the galactic ridge emission into individual sources
Galactic centre	Measured the flaring of central black hole and resolved the galactic ridge emission into individual sources
Extragalactic astrophysics	
Starburst galaxies	Discovered evidence for enrichment of the interstellar medium and the intergalactic medium by starbursts
Active galactic nuclei feedback	Discovered evidence for heating of hot gas in galaxies and clusters of in galaxies and clusters by outbursts produced galaxies by supermassive black holes,supporting the concept that supermassive black holes can regulate the growth of galaxies
Cosmology	
Dark matter	Determined the amount of dark matter in galaxy clusters and, by extension, the Universe; observed the separation of dark matter from normal matter in the Bullet Cluster, demonstrating that alternative theories of gravity are very unlikely to explain the evidence for dark matter
Dark energy	Observed galaxy clusters to generate two independent measurements of the accelerated expansion of the Universe

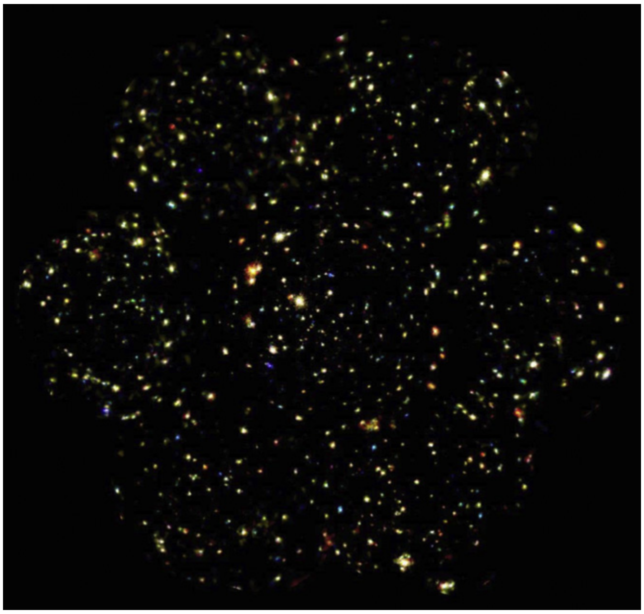

Fig. 10. A deep XMM-Newton extragalactic X-Ray image (Credit: Image courtesy of Ian Stewart and Mike Watson (Leicester University, XMM-Newton Survey Science Centre) and ESA).

in Figs. 9 and 10, which show respectively the best X-ray image of the Crab Nebula and Pulsar ever achieved and the image of a deep XMM-Newton extragalactic field.

XMM-Newton preparation

Image courtesy of D. Parker

European Space Agency

Fig. 11. XMM during ground testing.

4.3.4. The XMM-Newton Observatory

XMM-Newton observatory is ESA's second 'Cornerstone' mission and was launched on 10 December, 1999 from Kourou on the first commercial Ariane-5 into a highly elliptical 48 h orbit (see Fig. 11). The mission provides high-quality X-ray and optical/UV data from the European Photon Imaging Camera (EPIC), the Reflection Grating Spectrometer (RGS) and the Optical Monitor (OM) (Jansen et al., 2001). XMM-Newton is a 3-axis-stabilised spacecraft with a mass of about 4 t. The satellite is dominated by a large carbon-fibre telescope tube attached to the Service Module (SVM) at one end and to the Focal Plane Assembly (FPA) at the other. The mission routinely responds to Targets of Opportunity (ToO) requests with a response time as short as 5 h. This has been put to good use a number of times when XMM-Newton has performed rapid follow-up of γ-ray bursts.

4.3.4.1. Mission achievement summary. XMM-Newton is a facility-class X-ray observatory that is a cornerstone of ESAs Horizon 2000 programme. The instruments on XMM-Newton are the European Photon Imaging Camera, which contains three imaging devices (EPIC, 0.2–12 keV, 30' FOV, 6" FWHM), two Reflection Grating Spectrometers (RGS, 0.33–2.5 keV, 3–38 A, spectral resolution of 0.06 A), and the Optical Monitor (OM) with a 16' FOV operating from 1800 to 6500 A. With this impressive set of co-aligned telescopes in its operative energy band XMM-Newton provides to the scientific observer the largest collecting area for imaging and spectroscopic studies from a fraction of a keV up to 15 keV, over a field of view that is larger than Chandra and Suzaku. A summary of Chandra and XMM-Newton first decade scientific results, adapted from (Santos-Lleo et al., 2009), is given in Table 2.

4.3.5. INTEGRAL: International Gamma-Ray Astrophysics Laboratory

The ESA INTEGRAL mission was approved as the 2nd medium size ESA project of the Horizon 2000 scientific programme in April 1993 (see Fig. 12), (Winkler et al., 2003). The programme is led by ESA, with the instrument complement and the Scientific Data Centre (based in Geneva) provided by five different European consortia. Contributions were also provided by Russia, for the Proton launcher, and by the USA which made available the NASA Deep Space Network ground station at Goldstone.[40] The payload was calibrated at the beginning of 2002 at the European Space Research and Technology Centre (ESTEC) in Noordwijk, the Netherlands. INTEGRAL was successfully launched from Baikonur (Kazakhstan) on 17 October, 2002 for a planned operational lifetime of 2 years with possible extension. The Observatory is devoted to the observation of the γ-ray Universe in the energy range

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[40] Goldstone Deep Space Communications Complex: http://deep-space.jpl.nasa.gov/dsn.

Fig. 12. INTEGRAL during ground testing at ESTEC, ESA.

from 15 keV to 10 MeV with substantial monitoring capability in the X-ray range, from 3 to 30 keV, and in the optical V band at 550 nm. The two γ-ray instruments are the spectrometer, SPI, and the imager, IBIS. SPI is a high resolution, cooled, germanium-based coded mask spectrometer with unprecedented sensitivity to diffuse emission over a very wide field of view ($\sim$25° FWHM) (Vedrenne et al., 2003). It is optimised for high resolution γ-ray line spectroscopy in the energy range 20 keV–8 MeV. IBIS is a large area coded aperture mask telescope based on two layers of 16,384 Cadmium Telluride (CdTe) detectors and 4,096 Caesium Iodide (CsI) detectors (Ubertini et al., 2003). It provides fine angular resolution (<12 arc min), wide spectral response (15 keV–10 MeV), high resolution timing (60 μs) and spectroscopy (6% at 100 keV) . In view of the impossibility of focusing high energy X-rays and soft γ-rays, the three high energy instruments are operated with a coded mask to provide good imaging capability over a wide field of view. Of course, the coded mask technology and "pixel" size are different for the X-ray monitor and for the two γ-ray instruments.

This technique is a key feature of INTEGRAL to provide simultaneous images of the whole field observed and detection and location of all the sources. It also provides the best "on-source" and "background" measurements in a time-independent manner. INTEGRAL provides almost an order of magnitude improved performance in spectroscopy and imaging compared to earlier high energy observatories, such as BeppoSAX, RXTE, GRANAT and the Compton Gamma-Ray Observatory (CGRO). On 15 January, 2010, ESA's advisory bodies approved the extension of INTEGRAL operations until 2014.

4.3.5.1. Mission achievement summary. With its broad energy range, INTEGRAL provides an astronomical bridge between the soft X-ray missions, such as XMM-Newton, Chandra, Suzaku, Swift, and NuSTAR, the space-based high-energy γ-ray facilities in the GeV regime, such as Fermi and AGILE, and "ground based" γ-ray telescopes for higher ($\sim$TeV) energies, such as the The High Energy Stereoscopic System (H.E.S.S), the Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes (MAGIC) and the Very Energetic Radiation Imaging Telescope Array System (VERITAS). The primary astronomical usage of the observatory is for high-resolution spectroscopy with imaging and arc min positioning of celestial sources of hard X-ray/γ-ray emission. High-resolution spectroscopy over the entire energy range permits spectral features to be uniquely identified and line profiles to be measured for studies of physical conditions in the source region. The high-resolution imaging capability of INTEGRAL within a large field of view permits accurate location of the high energy emitting sources and hence identification with counterparts at other wavelengths

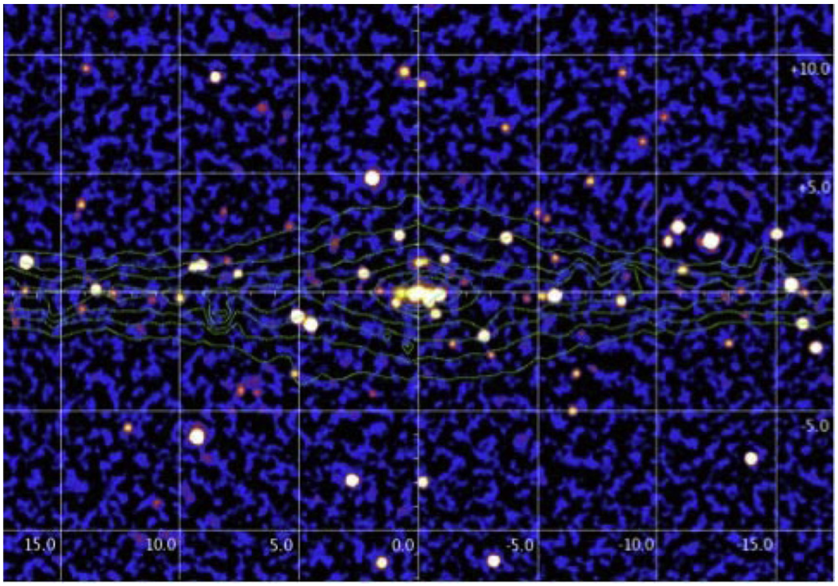

Fig. 13. The central part of the Milky Way Galaxy seen by INTEGRAL/IBIS (17–60 keV). Green curves are iso-contours of surface brightness in the infrared from COBE/DIRBE, tracing the surface density of stars in the Galaxy. The maximum sensitivity of the map is within 5–10 of the Galactic Centre. Credit: Krivonos et al., A& A 519, A107, 2010.

(Bazzano et al., 2006). It also enables extended regions to be distinguished from point sources and provides considerable serendipitous science, which is very important for an observatory-class mission (see Fig. 13). INTEGRAL remains unique world-wide as an observatory providing these capabilities. Key science areas of INTEGRAL include:

1. Studies of nucleosynthesis through γ-ray lines from elements formed in supernovae.
2. Studies of positron production and annihilation.
3. Studies of the physics of emission mechanisms of white dwarfs, neutron stars, and black holes and associated transient phenomena.
4. Deep surveys for supermassive black holes in Active Galactic Nuclei, and
5. γ-ray burst studies.

The main results obtained so far include the first sky map in the light of the 511 keV annihilation emission, the discovery of a new class of high mass X-ray binaries and detection of polarisation in cosmic high energy radiation. For the foreseeable future, INTEGRAL will remain the only observatory enabling the study of nucleosynthesis in our Galaxy, including the next, long overdue, nearby supernova, through high-resolution γ-ray line spectroscopy (Winkler et al., 2011). INTEGRAL observations have uncovered a new class of highly absorbed, slowly spinning pulsars, have shown pulsar wind nebulae to be the γ-ray counterpart of the new TeV sources, and detected the most distant γ-ray quasars, a break-trough in relativistic astrophysics. The 30% unidentified new INTEGRAL sources are a remaining mystery. Recently, the new class of Fast Supergiant X-Ray Transients has been discovered by INTEGRAL, posing a challenge to stellar evolution modeling (Sguera et al., 2005; Ubertini et al., 2006; Sidoli et al., 2007).

4.3.6. GALEX, Galaxy Evolution Explorer

The Galaxy Evolution Explorer (GALEX) is a small mission with an ultraviolet space telescope for imaging

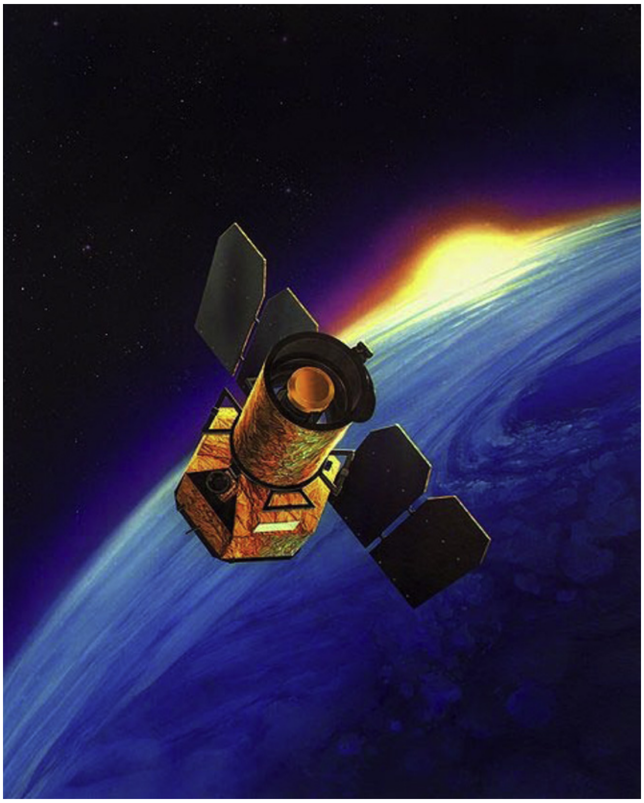

Fig. 14. GALEX artist's concept.

the sky with a 1.2 degree field of view and a resolution of ~5 arc sec. A Pegasus rocket launched GALEX into orbit on April 28th, 2003 (see Fig. 14). The mission is now in an extended phase, but the formal Guest Investigator Program has been discontinued. The observatory continues to collect near-ultraviolet (227 nm) images for a Legacy Survey. Led by the California Institute of Technology, GALEX is conducting several first-of-a-kind sky surveys, including an extra-galactic (beyond our galaxy) ultraviolet all-sky survey. During its mission, GALEX produced the first comprehensive map of a Universe of galaxies under construction, bringing us closer to understanding how galaxies like our own Milky Way were formed. GALEX is also identifying celestial objects for further study by ongoing and future missions. GALEX data now populate a large archive available to the entire astronomical community and to the general public. Scientists would like to understand when the stars that we see today and the chemical elements that make up our Milky Way galaxy were formed. With its ultraviolet observations, GALEX is filling in one of the key pieces of this puzzle (Bianchi et al., 1999).

4.3.6.1. Mission achievement summary. A 5-year survey of 200,000 galaxies, stretching back seven billion years in cosmic time, has led to one of the best independent confirmations that dark energy is driving our universe apart at accelerating speeds. The survey used data from NASA's space-based Galaxy Evolution Explorer and the Anglo-Australian Telescope on Siding Spring Mountain in Australia. The findings offer new support for the favored theory of how dark energy works – as a constant force, uniformly affecting the universe and propelling its runaway expansion. They contradict an alternate theory, where gravity, not dark energy, is the force pushing space apart. According to this alternate theory, with which the new survey results are not consistent, Einstein's concept of gravity is wrong, and gravity becomes repulsive instead of attractive when acting at great distances.

4.3.7. Spitzer Space Telescope

The Spitzer Space Telescope (see Fig. 15) was launched on 25 August, 2003. It consists of a 0.85-m diameter telescope and three cryogenically cooled science instruments which perform imaging and spectroscopy in the 3–180 micron wavelength range. Since infrared radiation is primarily heat radiation, detectors are most sensitive to infrared light when they are kept extremely cold. Using the latest in large-format detector arrays, Spitzer was able to make observations that are more sensitive than any previous mission. The telescope is surrounded by an outer shell that radiates heat to cold space in the anti-Sun direction, and is shielded from the Sun by the solar panel assembly. Intermediate shields intercept heat from the solar panel and the spacecraft bus. Spitzer operated at cryogenic temperature until May 2009 when the cryogen was exhausted, greatly exceeding its lifetime requirement of 2.5 years. The only instrument able to operate after cryogen expiration, the Infrared Array Camera, continues to enable outstanding science investigations with its two shortest wavelength channels at 3.5 and 4.6 microns.[41]

Fig. 15. The Spitzer satellite during ground testing.

4.3.7.1. Mission achievement summary. Spitzers wavelength coverage and sensitivity have made it a highly productive observatory demonstrating the importance of the infrared spectral region for galactic, extragalactic, and solar system astrophysics; a few of its scientific discoveries are mentioned here as examples. Among Spitzers many extragalactic science highlights are the identification of the individual galaxies responsible for most of the Cosmic Infrared Background (CIB), tracing the history of star formation out to redshift 3, showing that the CIB contains roughly the same amount of energy as the optical background and that galaxy formation and evolution processes have produced radiation equivalent to 5% of the cosmic microwave background (CMB). Star formation by galaxies that are not very luminous in the infrared has been found to dominate the energy production in the Universe at low redshift (z less than ~0.5), but the contribution of luminous

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[41] Spitzer Space Telescope, http://www.spitzer.caltech.edu/ and http://science.nasa.gov/missions/spitzer

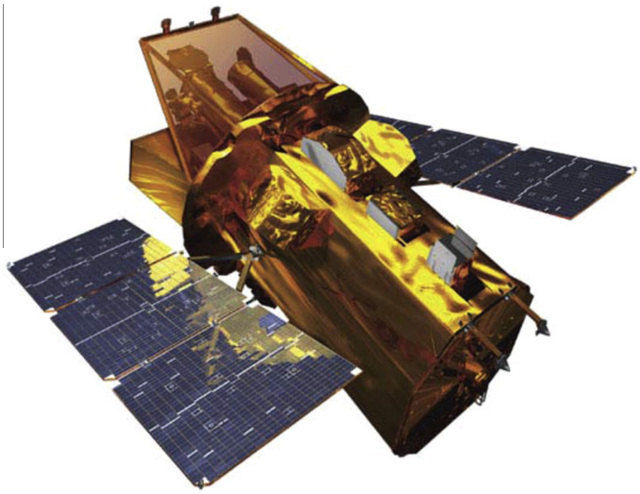

Fig. 16. Swift artist's concept.

and ultraluminous infrared galaxies increases steadily out to redshifts of 2–3. Emission by polycyclic aromatic hydrocarbon particles (essentially very large molecules) has been shown to be a characteristic signature and probe of star formation throughout the Universe. A population of dust-obscured active galactic nuclei has been identified through their IR spectral energy distributions. In the study of nearby galaxies, the wavelength coverage and imaging capabilities of Spitzer probe various components, including stellar atmospheres and dust in quiescent and star forming clouds. Spitzer has provided detailed images of nearby galaxies giving new insights into the distribution and properties of stars and the interstellar medium. Spitzer has also enabled major advances in the study of planetary system formation and evolution. For example, debris disks comprising cold material, identified via their 70 μm excess, have been shown to be common features of main sequence stars, with no correlation of the excess with metallicity or spectral type, but a weak dependence on stellar age, with younger stars more likely to have excess emission. Systems with warmer debris (of the kind discovered by the IRAS satellite around the star Vega) created by collisions in forming planetary disks, and heated by the central star, have also been studied. Their emission is found to be strongly dependent on recent collision history, suggesting that interplanetary dust around main sequence stars varies stochastically as a result of major collision events. Spectroscopic study with Spitzer of the atmospheres of brown dwarf stars reveal non-equilibrium chemistry and show that brown dwarfs are just as likely as more massive stars to harbour circumstellar disks. This implies that brown dwarfs as low in mass as ~10 Jupiters appear to form by the same process as solar-mass stars.

Spitzer has made the first detections of secondary eclipse signatures from 'hot Jupiter' exoplanets, providing information on the temperature and atmospheric properties of the planets. Within the solar system, spectral observations by Spitzer of the debris created by the collision of the Deep Impact probe with Comet Tempel1, revealed the silicate composition of the interior.

4.3.8. The Swift Gamma-Ray Burst Mission

Swift (see Fig. 16), a mission designed to study γ-ray bursts, is part of NASA's medium explorer (MIDEX) programme and was launched into a low-Earth orbit on a Delta 7320 rocket on 20 November, 2004 (Gehrels et al., 2004). Gamma-ray bursts (GRBs) are the most powerful explosions the Universe has seen since the Big Bang. They occur approximately once per day and are brief, but intense, flashes of γ radiation. They come from all different directions of the sky and last from a few milliseconds to a few 100 s. So far scientists do not know what causes them. Do they signal the birth of a black hole in a massive stellar explosion? Are they the product of the collision of two neutron stars? Or is it some other exotic phenomenon that causes these bursts? With Swift, a NASA mission with international participation, scientists have a tool dedicated to answering these questions and solving the γ-ray burst mystery. Its three instruments give scientists the ability to scrutinise γ-ray bursts as never before. Within seconds of detecting a burst, Swift relays its location to ground stations, allowing both "ground based" and space-based telescopes around the world the opportunity to observe the burst's afterglow. GRB 100413B is Number 500 (see Fig. 17) detected by Swift/BAT since the mission was launched (Gehrels et al., 2004).

4.3.9. Suzaku X-ray and hard X-ray telescopes

Suzaku (previously called Astro-E2) was successfully launched on 10 July, 2005 by the Japan Aerospace Exploration Agency (JAXA) in collaboration with US (NASA/GSFC and MIT) and Japanese institutes (see Fig. 18). Suzaku covers the energy range 0.3–600 keV and is currently performing astronomical observations using imaging CCD cameras (XIS) and a hard X-ray detector (HXD). Suzaku provides new capabilities to observe all classes of astronomical objects including active galactic nuclei, clusters of galaxies, stars, supernova remnants, X-ray binaries and solar system objects. After a 9 months performance verification phase, Suzaku began operating as an observatory, open to the world-wide astronomical community.[42] Since the start of open time observations, JAXA has kindly offered to allocate 8% of the open observing time to proposals from scientists from institutes located in ESA Member States. The European proposals are peer-reviewed by an ESA-appointed Time Allocation Committee and the recommended proposals forwarded to JAXA for merging with those resulting from the parallel Japanese and US calls. The Suzaku Announcement of Opportunity-6 yelded a total of 28 valid proposals, corresponding to an over-subscription in time of 3.2.

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[42] The X-ray Observatory Suzaku (ASTRO-E2): http://www.astro.isas.ac.jp/suzaku/

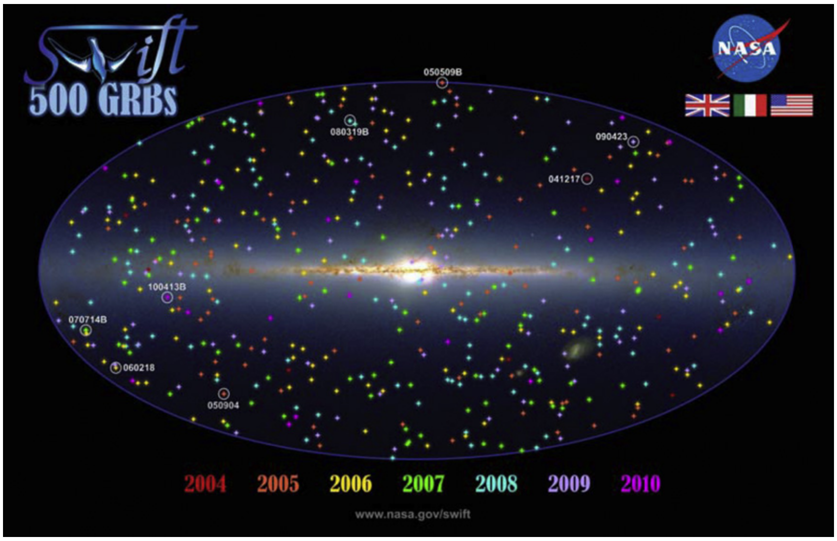

Fig. 17. Sky distribution of 500 γ-ray bursts detected by Swift.

Fig. 18. Suzaku artist's concept.

4.3.10. *AGILE high energy gamma-ray mission*

AGILE ("Astrorivelatore Gamma a Immagini Leggero") is the Italian Space Agency (ASI) Mission dedicated to the observation of the gamma-ray Universe (Tavani et al., 2009). The AGILE instrument consists of a gamma-ray imager (30 MeV–50 GeV), a hard X-ray imager (18–60 keV), a calorimeter (350 keV–100 MeV), and an anti-coincidence system (see Fig. 19). AGILE was launched on 23 April, 2007 from the Indian base of Sriharikota and inserted in an equatorial orbit. AGILE surveyed the γ-ray sky in pointing mode until 2009 and now is operating in spinning mode. Hundreds of Galactic and extragalactic sources are detected with emphasis on the energy range near 100 MeV.

4.3.10.1. Mission achievement summary. The main discoveries and achievements include: The surprising discovery of very rapid and variable γ-ray emission from the Crab Nebula, a source believed to be the constant reference source in high-energy astrophysics. The AGILE discovery of a strong γ-ray flaring episode from the Crab Nebula in September 2010 (later confirmed by the Fermi, LAT) shattered this belief; the discovery of the first unambiguous neutral pion signature of accelerated protons/hadrons in the γ-ray emission of the Supernova Remnant W44. Fig. 20 shows a detailed map of the W44 region in the energy range from 400 MeV to 3 GeV. Contours of the 324 MHz radio continuum flux density detected by the VLA (Giuliani et al., 2011) are overlaid in green; the detection of several tens of bright γ-ray Blazars, including the γ-ray flare from the super-massive black hole 3C 454.3 in November 2010, the brightest ever detected from any cosmic source; the discovery of γ-ray emission from the micro-quasar Cygnus X-3; the discovery of γ-ray emission up to 100 MeV from Terrestrial Gamma-Ray Flashes (TGFs), a detection that shows how the atmosphere can

Fig. 19. AGILE artist's concept.

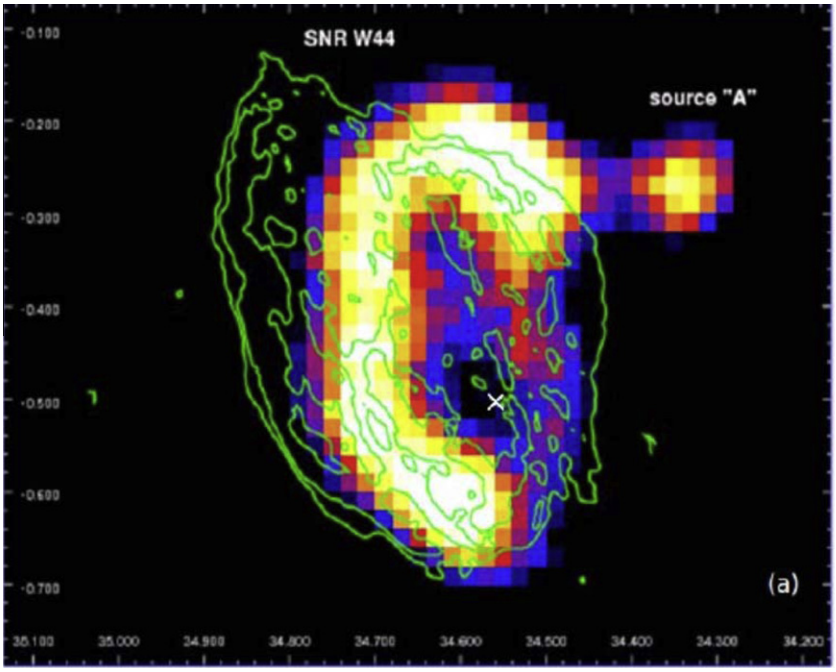

Fig. 20. AGILE γ-ray intensity map of the Supernova Remnant W44 in the energy range 400 MeV–3 GeV. Green contours show the 324 MHz radio continuum flux density.

very efficiently accelerate particles during lightning associated with powerful thunderstorms.

4.3.11. Fermi High Energy Gamma ray Telescope

The Fermi Gamma-Ray Space Telescope (Fermi) (see Fig. 21) was launched on 11 June, 2008 into a nearly circular orbit of ~565 km altitude at an inclination of 25.6 degrees. The mission has a design lifetime of 5 years, with a goal of 10 years. Science operations began on 4 August, 2008, and the spacecraft and instrument packages have operated in a nearly flawless manner up to the present time. The mission is managed by the NASA Goddard Space Flight Center. Fermi is a multiagency and international observatory-class facility designed to study the cosmos in the <10 keV to >300 GeV energy range. Its primary instrument, the Large Area Telescope (LAT), is a pair-conversion telescope. Gamma rays pair-produce in tungsten foils, silicon strip detectors track the resulting pairs, and the resulting particle shower deposits energy in a CsI calorimeter. An anticoincidence detector provides discrimination against the large flux of charged particles incident on the LAT. The anticoincidence detector is segmented to eliminate the self-vetoing problems of previous instruments. The LAT has a peak effective area (>8000 cm^2), angular resolution (<3.5 degree at 100 MeV, <0.15 degree above 10 GeV), field-of-view (>2 sr), and deadtime (<100 μs per event) that provides a factor of 30 or more advance in sensitivity compared to previous missions. Fermi also carries a secondary experiment, the Gamma-ray Burst Monitor (GBM) that facilitates the study of transient phenomena. The GBM has a field-of-view larger than the LAT and a spectral range that extends from the LATs lower limit down to less than 10 keV.

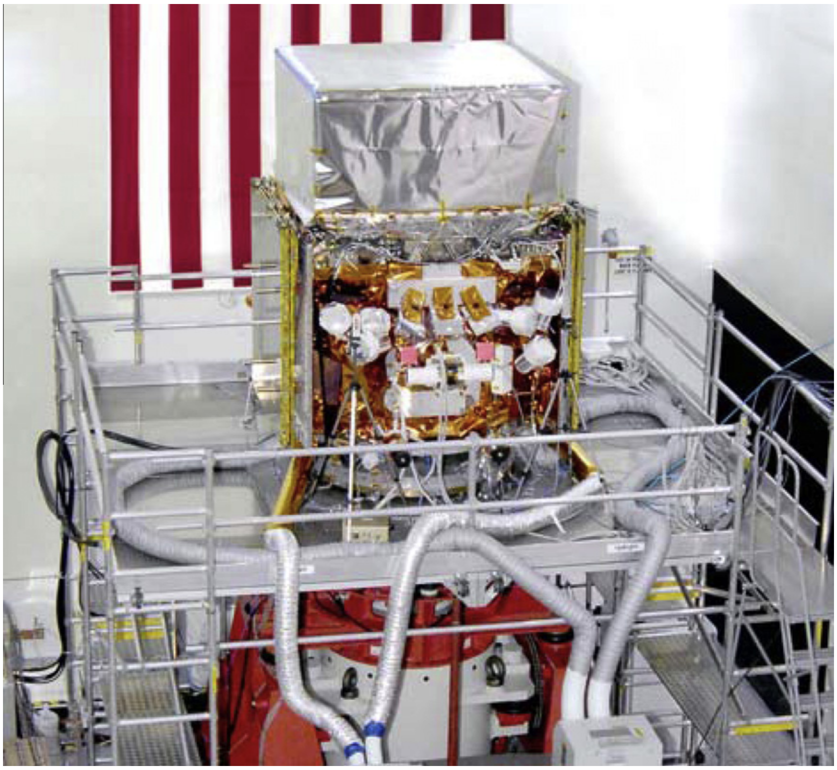

Fig. 21. The Fermi Gamma-Ray Space Telescope being prepared for launch in the clean room at the Kennedy Space Center in February 2008.

4.3.11.1. Mission achievement summary. Although pointed observations are possible, Fermi primarily scans the sky continuously because of the LATs large field-of-view. In this sky survey mode Fermi provides nearly uniform sky exposure every ~3 h. During its first 2 years, the Fermi LAT's has detected and catalogued over 1800 cosmic γ-ray sources. Collectively, the study of these sources has led to new insights into basic astrophysical issues such as the structure of pulsar magnetospheres, the galactic millisecond pulsar population, jet production and propagation in active galaxies and the sources and composition of galactic cosmic-rays. The mission is an astrophysics and particle physics partnership, developed by NASA in collaboration with the US Department of Energy, along with important contributions from academic institutions (Ritz, 2007)[43] Fig. 22 shows the Fermi γ-ray sky as observed during the first 2 years of observations.

4.3.12. The Planck mission

Planck is a mm/sub-millimetre-wave sky-survey satellite, including a wide-field cold telescope (1.5 m aperture) with two focal plane instruments, covering the frequency range from 30 to 857 GHz. It was launched by ESA on 14 May, 2009, (see Fig. 23) and is currently operating from an orbit around in L2 with excellent performance (Ade et al., 2011a; Ade et al., 2011b; Mennella et al., 2011). As planned after 50 days, as foreseen, Planck entered its final orbit around the second Lagrange point of the Sun–Earth system (L2), at a distance of 1.5 million km from Earth. Since the end of the commissioning and performance verification phases in mid-August 2009, Planck has been performing its scientific mission. On 15 January, 2010, ESA's advisory bodies approved an extension of Planck operations by 12 months. Planck is now scheduled to continuously acquire high-quality science data until the end of 2011. The Planck collects and characterises radiation from the Cosmic Microwave Background (CMB) using sensitive radio receivers operating at extremely low temperatures, and is capable of distinguishing temperature variations of about 1 micro-deg Kelvin. These measurements are used to produce maps of anisotropies in the CMB radiation field. The Planck spacecraft is 4.2 m high with a launch mass of around 1.9 t, consisting of a service module with the warm parts of the scientific instruments, and a payload module. The payload module contains the telescope, the optical bench, with the parts of the instruments that need to be cooled – the sensitive detector units – and the cooling systems. The Planck telescope is an off-axis tilted Gregorian design with a primary mirror measuring 1.9 × 1.5 m, and with a projected aperture of 1.5 m diameter. The 1.1 × 1.0 m secondary mirror focuses the collected light onto the two scientific instruments: Low Frequency Instrument (LFI), an array of radio receivers using high electron mobility transistor mixers; and High Frequency Instrument (HFI), an array of microwave detectors using spider bolometers equipped with neutron transmutation doped germanium thermistors.

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[43] Fermi Gamma ray Space Telescope: http://fermi.gsfc.nasa.gov/

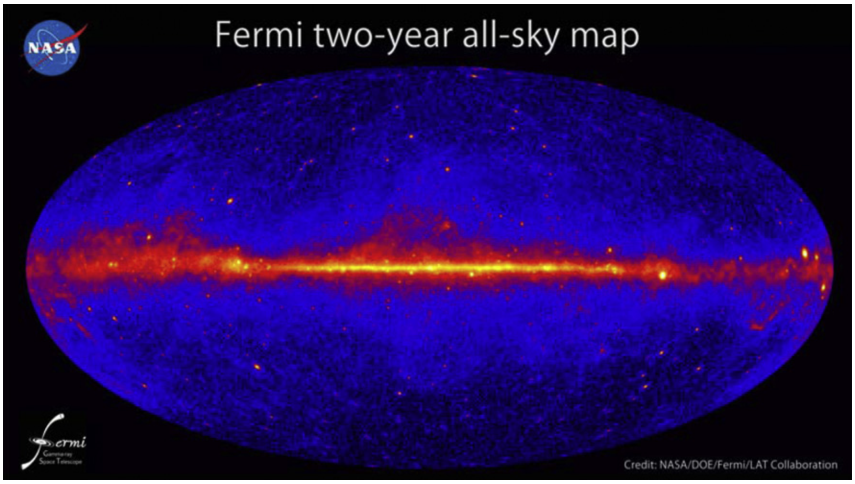

Fig. 22. The Fermi γ-ray sky, integrating the data obtained during the first 2 years of observations. Credit: NASA/DOE/Fermi/LAT Collaboration.

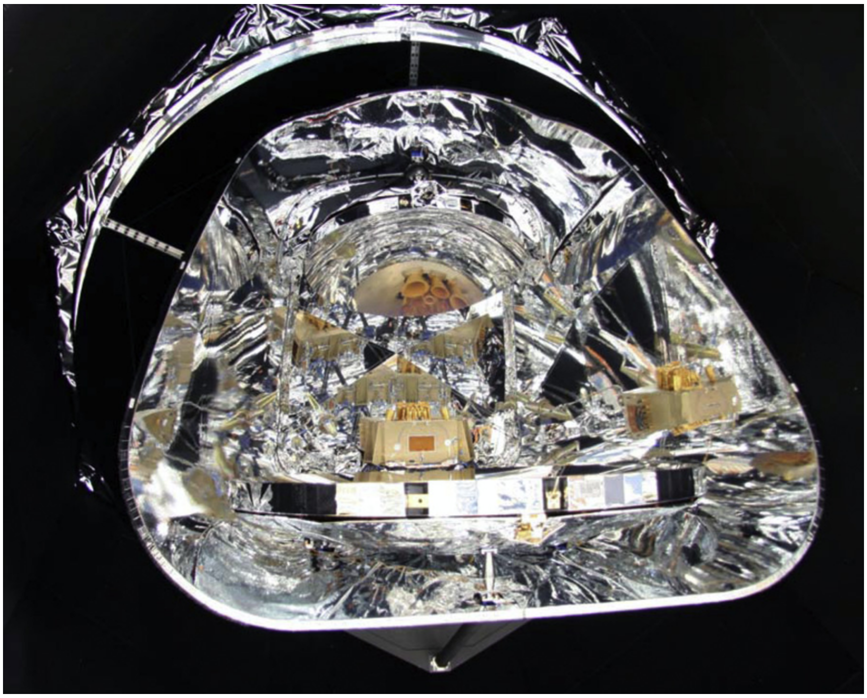

Fig. 23. The Planck satellite during integration tests.

4.3.12.1. Mission achievement summary. Planck has been designed to measure the temperature and polarisation anisotropies of the Cosmic Microwave Background with unprecedented accuracy. With respect to WMAP, Planck provides broader frequency coverage, higher angular resolution (down to a few arc min in the high frequency channels), and increased sensitivity of the survey (roughly by a factor of 10). The first CBM data release is scheduled for January 2013. A set of early results was published in January 2011. The main product released so far, the Early Release Compact Source Catalog (ERCSC), is a list of high reliability (>90%) sources, both Galactic and extragalactic, derived from the data acquired by Planck between 13 August, 2009 and 6 June, 2010. The 10σ photometric flux density limit of the catalogue at $|b| > 30$ degree is a fraction of a Jy in all bands, resulting in a total of more than 15000 unique sources (Ade et al., 2011c). The ERCSC consists of nine lists of sources, extracted independently from each of Planck's nine frequency channels, plus two lists extracted using multi-channel criteria. These are the Early Cold Cores catalogue (Ade et al., 2011d) (ECC, including 915 Galactic dense and cold cores, selected mainly on the basis of their temperature) and the Early Sunyaev–Zeldovich catalogue (Ade et al., 2011e) (ESZ, including 190 galaxy clusters selected by the spectral signature of the Sunyaev–Zeldovich effect). This is the first all-sky shallow survey

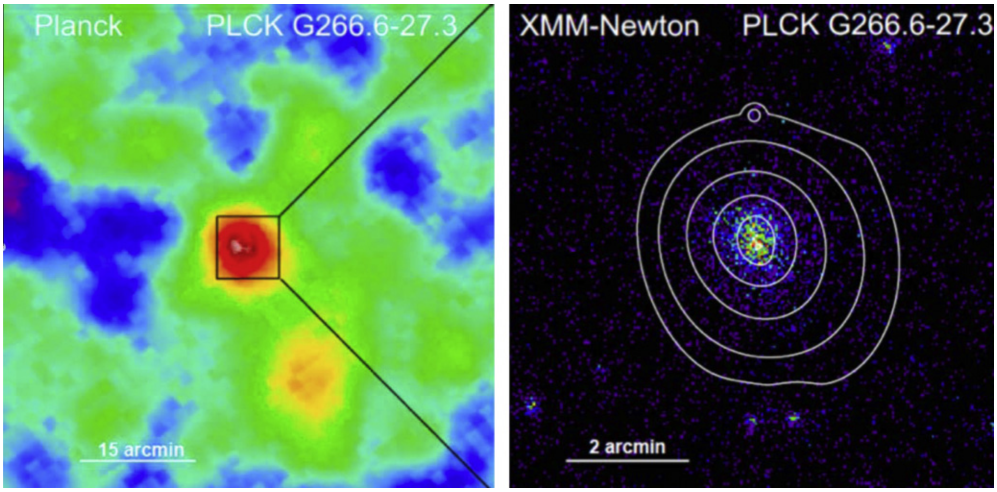

Fig. 24. Left: Image of the SZ effect in the cluster PLCKG266.6-27.3, discovered by Planck. Right: follow-up observation of the same cluster from XMM-Newton in the 0.3–2.0 keV band (Aghanim et al., 2011).

for SZ clusters, and is especially sensitive to the high-mass tail of the cluster mass distribution. In the early results, Planck has been able to discover 21 new clusters, and most of them have already been confirmed by follow-up observations of XMM and “ground based” mm-wave telescopes. A typical example of these discoveries is PLCKG266.6–27.3 (Aghanim et al., 2011), see Fig. 24), a high redshift ($z = 0.94$), relaxed, high mass (8×10^{14} M_{sun} cluster, extremely luminous in X-rays (1.4×10^{45} erg/s). Planck is perfectly suited to carry-out a systematic survey of these objects, opening the way to statistical studies of population evolution. Planck[44] is providing a map of the CMB field at all angular resolutions greater than 10 arc min and with a temperature resolution of the order of one part in 10^6.

4.3.13. The Herschel mission

The Herschel Space Observatory is the largest infrared space observatory launched to date (Pilbratt, 2001) (see Fig. 25). Equipped with a 3.5 m diameter reflecting telescope and instruments cooled to close to absolute zero, Herschel is observing at far-infrared and submillimetre wavelengths that have never previously been explored with such high sensitivity and spatial and spectral resolution. Herschel will spend a nominal mission lifetime of >2 years in orbit around the second Lagrange point of the Sun-Earth system (L2). Infrared astronomy is a young and exciting science. In recent decades infrared astronomers have unveiled tens of thousands of new galaxies, and have made surprising discoveries such as the huge amount of water vapour throughout our Galaxy. The spacecraft is approximately 7.5 m high with a launch mass of around 3.4 t. The spacecraft consists of a service module containing the warm parts of the scientific instruments, and a payload module. The payload module contains of the telescope, the optical bench, with the parts of the instruments that need to be cooled, i.e., the sensitive detector units and cooling systems. The payload module is fitted with a sunshield, which protects the telescope and cryostat from solar visible and infrared radiation and spectrometer; Photodetector Array Camera and Spectrometer (PACS),

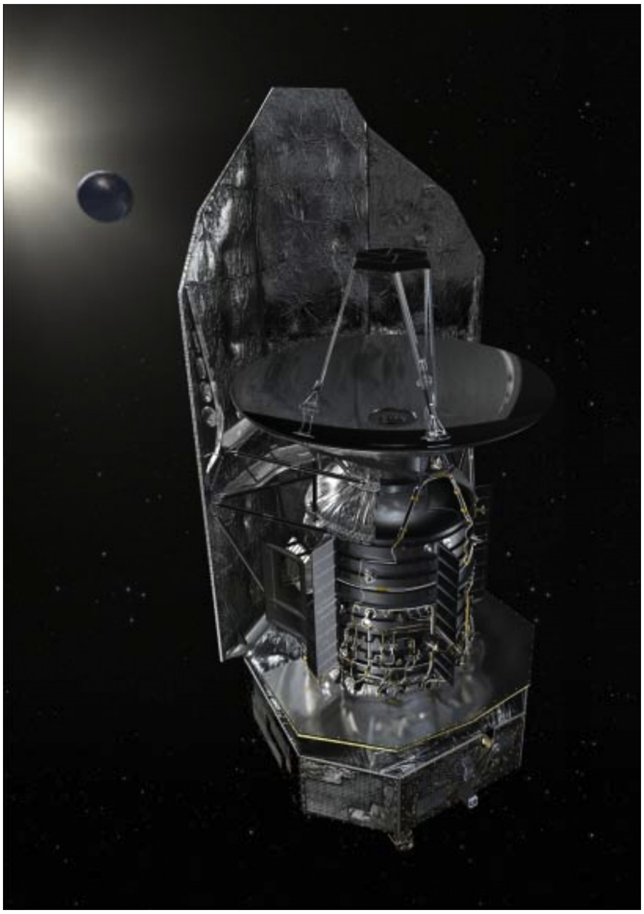

Fig. 25. Herschel artist’s concept.

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[44] The Planck satellite: http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=13244

an imaging photometer and medium resolution grating spectrometer; and SPIRE (Spectral and Photometric Imaging Receiver), an imaging photometer and an imaging Fourier transform spectrometer. The instruments have been designed to take maximum advantage of the characteristics of the Herschel mission. In order to make measurements at infrared and submillimetre wavelengths, parts of the instruments have to be cooled to near absolute zero. The optical bench, the common mounting structure of all three instruments, is contained within a cryostat, and over 2000 l of liquid helium will be used during the mission for primary cooling. Individual instrument detectors are equipped with additional, specialised cooling systems to achieve the very lowest temperatures, down to 0.3 K for PACS and SPIRE.

4.3.13.1. Mission achievement summary. Herschel has followed on from Spitzer, extending wavelength coverage beyond 200 μm, and achieving better angular resolution due to its larger telescope. The main science drivers for Herschel have included: (i) wide-area photometric surveys of the extragalactic and Galactic sky to measure dust-enshrouded star-formation activity throughout cosmic time and in our own and nearby galaxies today; (ii) detailed studies of the physics and chemistry of the interstellar medium, in our own and local galaxies; (iii) observational astrochemistry as a tool for understanding the stellar/interstellar lifecycle and investigating the physical and chemical processes involved in star formation and early stellar evolution; (iv) spectroscopic and photometric study of comets, asteroids and outer planet atmospheres and their satellites. At the time of writing, the Herschel spacecraft and instruments are performing as planned, with scientific capabilities and data quality matching or exceeding pre-launch expectations. Two thirds of Herschel observing time is available to the worldwide astronomical community, with the remainder allocated to the teams which have worked on the observatory and the instruments. The first half of the mission has been mainly used for Key Projects, substantial programmes addressing core science goals in a comprehensive manner and producing large coherent data sets. Extragalactic science highlights to date include accurate measurements of FIR/submillimetre number counts and the implications for the origin of the Cosmic Infrared Background (CIB); characterisation of galaxy luminosity function evolution with redshift; galaxy clustering analysis suggesting that multiple dusty star-forming galaxies occupy the same dark matter halos; and evidence for strong AGN-driven molecular outflows that regulate star formation and may be responsible for the correlation between central black hole mass and host galaxy mass. Herschel's angular resolution, wavelength coverage, and instrumentation are well suited to study of the ecology of the Milky Way galaxy in unprecedented detail. Significant results so far include the observation of complex and highly structured networks of filaments which appear to be ubiquitous in the galactic interstellar medium, suggesting a scenario for star formation in which protostellar condensations form inside and at the junctions of filaments; multi-band photometry yielding accurate masses, luminosities, temperatures, and lifetimes of protostellar objects, and characterising the origin of the stellar initial mass function down to the brown dwarf regime; a high resolution survey of the nearby star-forming region in Orion revealing tens of thousands of spectral lines; and imaging of debris disks around nearby young stars. Solar system observations with Herschel are allowing comparison of the isotopic composition of cometary water with that of the Earths oceans, improving global models of the atmospheres of the giant planets, and giving accurate estimation of the sizes and thermophysical properties of asteroids and Kuiper Belt objects. The observatory will continue to operate until its tank of liquid helium is exhausted, which is expected to happen in the spring of 2013. All Herschel data will be stored long-term in the Herschel Science Archive. The spatial and spectral survey data especially are expected to be of considerable archival value well beyond the lifetime of the mission. A text book example of the synergy and powerful capability of space observatories is shown in Figs. 26–28. The Herschel image contains basic information about a region of the Galaxy with strong star formation processes; the optical image shows 'normal stars' during their thermonuclear evolution

Fig. 26. Optical image of the Andromeda Galaxy. Credit: NASA/ESA/R. Gendler, T. Lauer (NOAO/AURA/NSF), and A. Field (STScl).

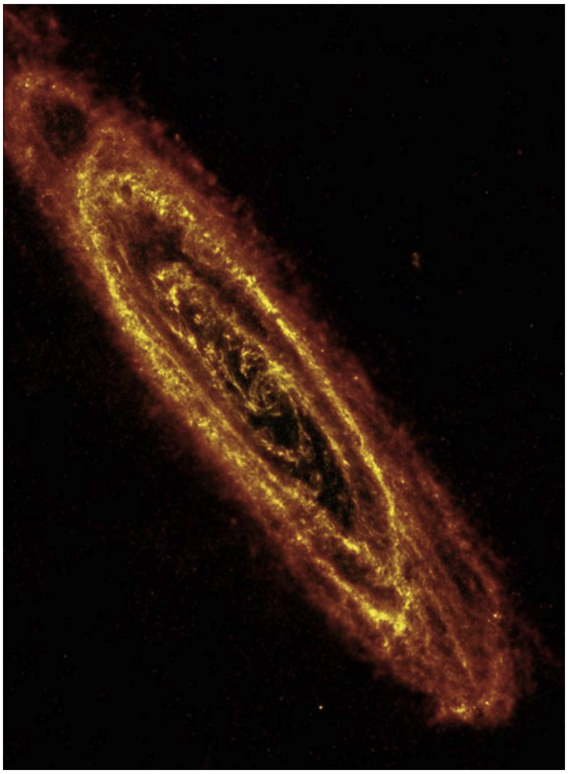

Fig. 27. IR-Herschel image of the Andromeda Galaxy. Credit: ESA/Herschel – PACS/SPIRE/J. Fritz, U. Gent.

period, lasting from millions to billions of years; and the X-ray image shows the ’end-of-life- activity, with high energy photons emitted mainly by white dwarfs, neutron stars or black holes accreting matter from companion stars. Fig. 29, (Fritz et al., 2011) shows the image obtained by overlapping the two images of Figs. 27 and 28. This image clearly shows where the star forming regions, emitting in the IR, and the collapsed stars, emitting high energy X-rays, are located.

4.3.14. MAXI Monitor of All-sky X-ray Image

Monitor of All-sky X-ray Image (MAXI) is a highly sensitive X-ray slit camera for the monitoring of more than 1000 X-ray sources in space over an energy band range of 0.5–30 keV (see Fig. 30). It is an attached payload to the International Space Station (ISS), externally mounted on the Japanese Experiment Module (JEM), Kibo, Exposed Facility. MAXI is continuously observing to monitor flux variability once every 96 min for more than 1000 X-ray sources covering the entire sky on time scales from a day to a few months. As an all-sky monitor, MAXI employs slit cameras. They determine one coordinate of the X-ray sources within the narrow field of view of the slit, which is orthogonally oriented to a one-dimensional position-sensitive X-ray detector. As an X-ray source moves according to the motion of the International Space Station, another coordinate of the X-ray source is determined when the sources are captured by the collimated field-of-view of the camera. The International Space Station orbits around the Earth every 96 min. During this time, MAXI’s two semicircular (arc-shaped) fields-of-view will scan the whole

Fig. 28. XMM-Newton image of the Andromeda Galaxy. Credit: ESA/XMM Newton/EPIC/W. Pietsch, MPE.

Fig. 29. Composite X-Ray – Infrared image of the Andromeda Galaxy: from the birth to the death of the stars.

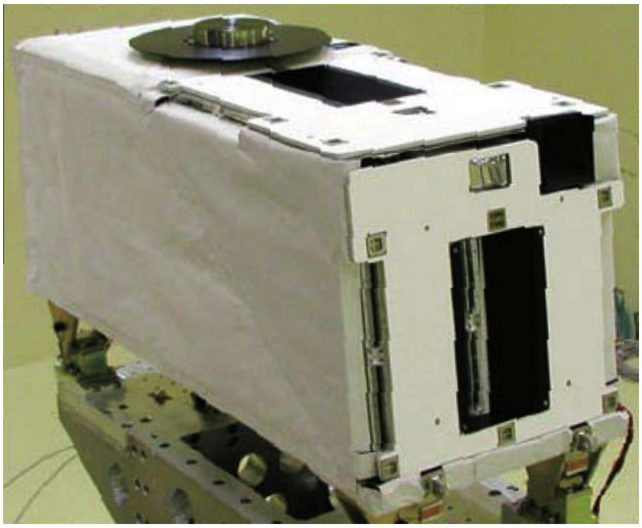

Fig. 30. Photo of the MAXI payload before launch.

sky once. MAXI has two types of X-ray slit cameras with wide FOVs and two kinds of X-ray detectors: gas proportional counters covering the energy range of 2–30 keV; and X-ray CCDs, covering the energy range of 0.5–12 keV. MAXI is equipped with 12 counters with a total effective area of 5000 cm^2. The main MAXI scientific objectives include:

1. to alert the community to X-ray novae and transient X-ray sources,
2. to monitor long-term variability of X-ray sources,
3. to stimulate multi-wavelength observations of variable objects,
4. to create unbiased X-ray source catalogues, and
5. to observe diffuse cosmic X-ray emissions, especially with better energy resolution for soft X-rays down to 0.5 keV (Matsuoka et al., 2009).

Fig. 31 shows the all-sky image obtained by MAXI/GSC (energy range 4–10 keV) in the period from September 2009 to March 2011 (Hiroi et al., 2011).

Table 3
Fig. 32 details.

Mission	Details
Gaia	(ESA) 3-D mapping of the stars of the Galaxy
ASTROSAT	(TIFR-INDIA) multi-wavelength astronomy mission from visible (320–530 nm) to hard X-ray (3–80 keV and 10–150 keV)
NuSTAR	(NASA) SMEX mission for hard X-rays with a focusing telescope
SRG	The Spectrum X-Gamma-eRosita experiment
Astro-H	(JAXA-NASA) X-ray mission for high resolution spectroscopy and hard X-rays
GEMS	((NASA) SMEX X-ray polarisation mission
HXMT	Hard X-ray Modulation Telescope (1–250 keV)
JWST	(NASA/ESA/CSA) Observatory, IR 6.5 m mirror telescope sensitive from 0.6 to 27 μm
SOFIA	Stratospheric Observatory for Infrared Astronomy (NASA-DLR) NASA EXPLORER outcome (selection in progress): several astrophysical Missions relevant for this WG
ESA CV	
M1	Solar Orbiter
M2	Euclid
ESA CV-M3	Outcome: selection in progress: see chapter 4 for details
WFIRST NASA	US 2010 Decadal Survey recommendation
ESA CV-NASA	LISA (NGO) or IXO (Athena) to be selected

4.4. Approved Missions in Development and Future Concepts

A summary of future missions approved and under development worldwide, of which the Working Group has learned, is presented in this section and summarised in Table 3. We include missions under construction or being tested. The WG looks forward to successful execution of all of these missions. We also mention candidate future missions now under study by ESA, NASA and other national space agencies for possible approval for flight. Missions in this latter category and others are discussed in more detail in Section 5 of this Report in the context of the space programmes of individual nations. Fig. 32 is

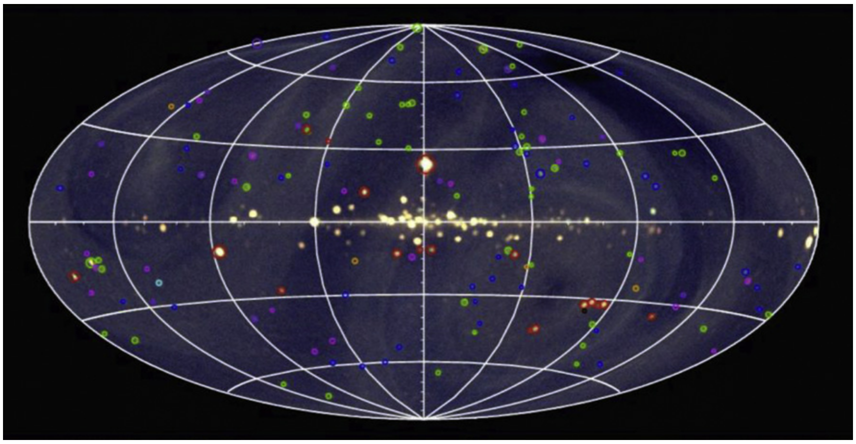

Fig. 31. MAXI all-sky image in the energy range 4–10 keV. The data were obtained in the period September 2009 to March 2011.

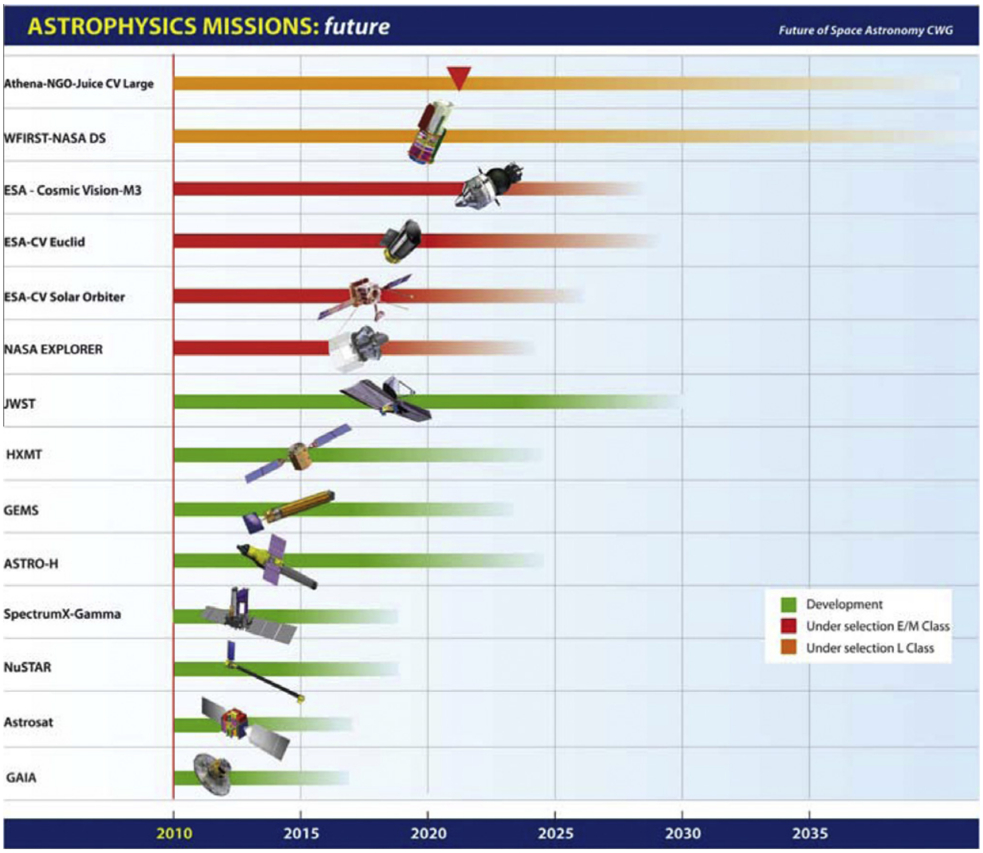

Fig. 32. Missions under development (Green), Explorer/Medium class missions under selection processes from ESA and NASA (Red) and the Observatory class mission proposed by the NASA Decadal Survey (DS) and the ESA L-Class mission scheduled for a launch in 2021 (Orange). See Section 4.2.2 for the recent ESA M1/M2 undergoing selection development). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a graphical summary of the following categories of space astronomy missions:

- Missions under development with projected launch date and lifetime.
- ESA Missions to be selected by the Cosmic Vision process as M1, M2 and Class-L Observatories.
- ESA Missions to be selected by the ongoing process Cosmic Vision M3.
- NASA Missions proposed as Small Explorers.
- NASA Missions recommended by the US National Academy of Sciences 2010 Decadal Survey committee.

A short description and basic characteristics of these missions and planned launch dates are presented in this section.

4.4.1. Gaia 3-D mapping of the stars of the Galaxy (ESA)-Launch 2013

Gaia is an ambitious mission to chart a three-dimensional map of our Galaxy, the Milky Way, in the process revealing the composition, and evolution of the Galaxy (see Fig. 33).[45] Gaia will provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars in our Galaxy and throughout the Local Group. This amounts to about 1% of the Galactic stellar population (Mignard, 2005). Combined with astrophysical information for each star, provided by on-board multi-colour photometry, these data will have the precision necessary to quantify the early formation, and subsequent dynamical, chemical and star formation evolution of the Milky Way Galaxy. Additional scientific products include detection and orbital classification of tens of thousands of extra-solar planetary systems, a comprehensive survey of objects ranging from huge numbers of minor bodies in our Solar System, through galaxies in the nearby Universe, to some 500,000 distant quasars. It will also provide a number of stringent new tests of general relativity and cosmology.

4.4.2. ASTROSAT: Launch 2012–2013

Multi-wavelength astronomy mission from visible (320-530 nm) to hard X-rays (3–80 keV and 10–150 keV). ASTROSAT[46] is the first dedicated Indian Astronomy satellite mission, which will enable multi-wavelength

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[45] http://sci.esa.int/science-e/www/area/index.cfm?fareaid=26.

[46] http://meghnad.iucaa.ernet.in/astrosat/

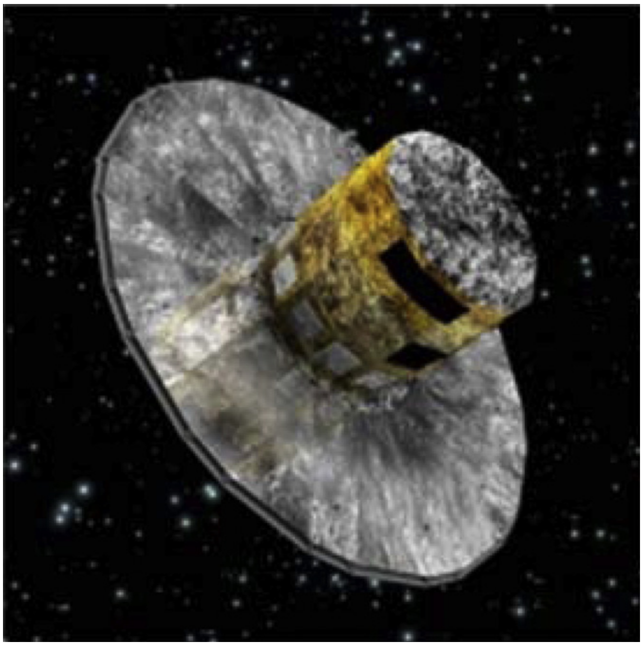

Fig. 33. Gaia artist’s concept.

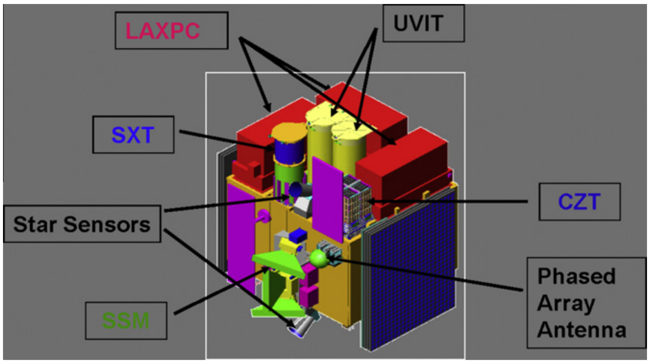

Fig. 34. ASTROSAT artist’s concept.

observations of celestial bodies and cosmic sources in X-ray and UV spectral bands simultaneously (see Fig. 34). The scientific payload covers the visible (3500–6000 A), UV (1300–3000 A), and soft and hard X-ray regimes (0.5–8 keV; 3–80 keV). The uniqueness of ASTROSAT lies in this wide spectral coverage. There are four co-aligned instruments and an all-sky monitor. The all-sky monitor is very similar to the RXTE-ASM. The co-aligned instruments are:

- Soft X-ray Telescope (SXT): X-ray Mirror + CCD, similar to one ASCA-SIS.
- Large Area Xenon Proportional Counter (LAXPC): Three large area proportional counters, geometric area same as the original RXTE-PCA, but with a larger detection efficiency for hard X-rays and 40% efficiency at 80 keV
- CZT Imager (CZTI): A pixelated CZT detector with a CAM. Total area 1000 cm^2, field of view of 8 degree.
- UV Imaging Telescope (UVIT): A pair of telescopes with three bands available simultaneously, near-UV, far-UV and optical.

The LAXPC and UVIT are the main instruments of ASTROSAT. The scientific outcome of ASTROSAT will mainly be in the following areas:

1. X-ray timing, especially hard X-ray timing (high frequency QPOs from BHC, etc.).
2. Broad band spectroscopy with emphasis on hard X-rays (Cyclotron line, reflection component in BHCs/AGNs etc.).
3. Simultaneous multi-wavelength studies.
4. Diffuse UV studies (the UVIT has a sensitivity similar to GALEX but with higher angular resolution).

ASTROSAT is scheduled for a launch in the window from the end of 2012 to the beginning of 2013 (Manchanda, 2011).

4.4.3. NuSTAR Nuclear Spectroscopic Telescope Array (NuSTAR) : launch 2012

The Nuclear Spectroscopic Telescope Array is a NASA Explorer mission that will allow astronomers to study the universe in high energy X-rays (see Fig. 35).

Launching in 2012, NuSTAR will be the first focusing hard X-ray telescope to orbit Earth and is expected to greatly exceed the performance of the largest “ground based” observatories that have observed the high energy sky. NuSTAR will also complement astrophysics missions that explore the cosmos in other regions of the spectrum. X-ray telescopes such as Chandra and XMM-Newton have observed the X-ray universe at low X-ray energy levels. By focusing higher energy X-rays, NuSTAR will start to answer several fundamental questions about the Universe including:

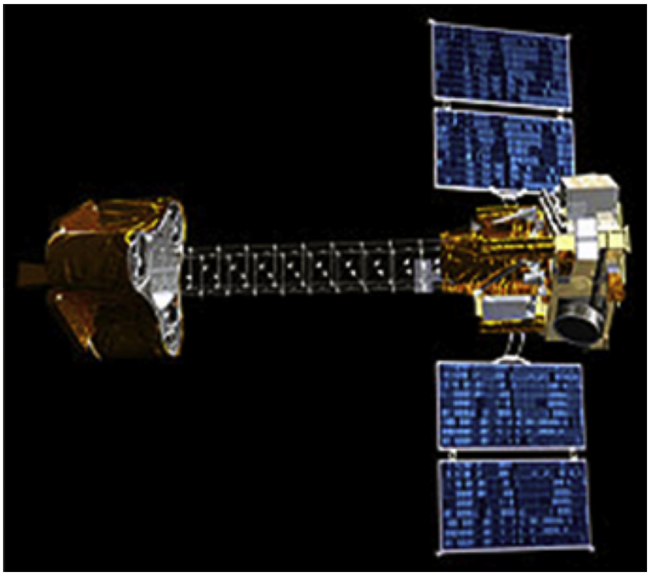

Fig. 35. NuSTAR artist’s concept.

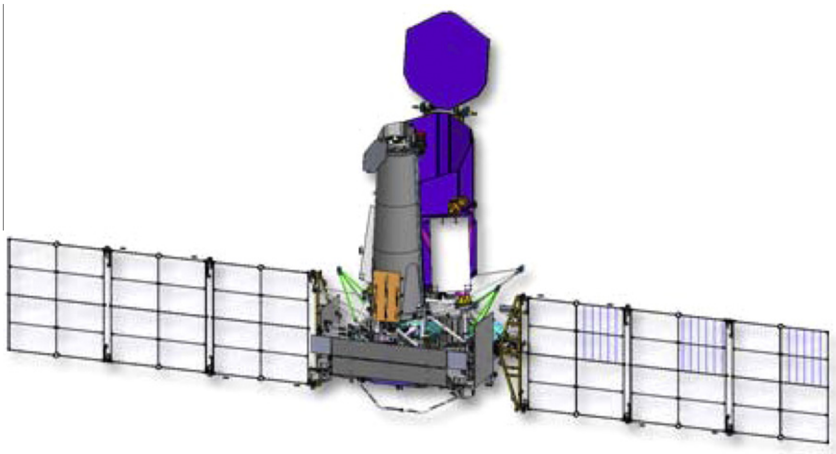

Fig. 36. Spectrum RG artist's concept.

- How are black holes distributed through the cosmos?
- How were heavy elements forged in the explosions of massive stars?
- What powers the most extreme active galaxies?

NuSTAR's primary science objectives include:

- Conducting a census for black holes on all scales using wide-field surveys of extragalactic fields and the Galactic center.
- Mapping radioactive material in young supernova remnants.
- Studying the birth of the elements and to understand how stars explode.
- Observing relativistic jets found in the most extreme active galaxies and to understand what powers giant cosmic accelerators.

NuSTAR will also study the origin of cosmic rays and the extreme physics around collapsed stars while responding to targets of opportunity including supernovae and γ-ray bursts. NuSTAR will perform follow-up observations to discoveries made by Chandra and Spitzer, and will team with Fermi, making simultaneous observations which will greatly enhance Fermi's science return (Harrison et al., 2010).

4.4.4. The Spectrum Roentgen-Gamma (SRG) – eRosita experiment: Launch 2012

Spectrum-RG is a Russian – Germany X-ray astrophysical observatory. Germany is responsible for the development of the key mission instrument – the X-ray grazing-incident mirror telescope, eROSITA, mounted on the optical bench of the SRG satellite, shown in Fig. 36. The second experiment is ART-XC, an X-ray mirror telescope with a harder response than eROSITA, which is being developed by Russia (IKI, Moscow and VNIIEF, Sarov). The scientific payload is housed on the Navigator bus, developed by Lavochkin Association (Russia). Spectrum-RG will be delivered to the L2 point with use of the Soyuz-2 rocket and Fregat booster. The total mass of the SRG is about 2200 kg. The SRG mission will be launched in 2012 from Baikonur and the observational programme will last 7 years. The first 4 years will be devoted to an all-sky survey, and the rest of the mission lifetime will be spent on follow-on pointed observations of a selection of the most interesting galaxy clusters and AGNs (Cappelluti et al., 2011). The mission will conduct an all-sky survey in the 0.5–11 keV band with the imaging telescopes eROSITA and ART-XC. It will permit the discovery of all obscured accreting black holes in nearby galaxies, many (millions) of new distant AGNs, and the detection of all massive clusters of galaxies in the Universe. In addition to the all-sky survey, dedicated sky regions will be observed with higher sensitivity, and thereafter follow-on pointed observations of selected sources at energies up to 30 keV will take place in order to investigate the nature of dark matter, dark energy and the physics of accretion.

4.4.5. Astro-H: Launch: 2014

Astro-H is a powerful observatory being developed by the Japan Aerospace Exploration Agency (JAXA) for studying extremely energetic processes in the universe (see Fig. 37). NASA and the JAXA/Institute of Space and Astronautical Science have teamed up to develop a high resolution "Soft X-Ray Spectrometer" (SXS) for Astro-H. SXS, with its unprecedented sensitivity for high-resolution X-ray spectroscopy, will perform a wide variety of breakthrough science investigations directly aligned with NASA goals. SXS will test theories of structure formation by measuring the velocity field of X-ray-emitting gas in clusters of galaxies and the energy output from the jets and winds of active galaxies. SXS will accurately measure metal abundances in the oldest galaxies, providing unique information about the origin of the elements. SXS will observe matter in extreme gravitational fields, obtaining time-resolved spectra from material approaching the event horizon of a black hole. SXS will determine the chemical

Fig. 37. Astro H artist's concept.

abundances and velocity structure in Galactic Type Ia supernova remnants to provide insight into the explosion mechanism. To accomplish these investigations, the SXS uses a state-of-the-art X-ray calorimeter spectrometer at the focus of a high-throughput X-ray telescope. The X-ray calorimeter is a low-temperature sensor that measures the energy of each X-ray photon as heat with extraordinary precision, and allows high-resolution spectra to be obtained from extended sources without degradation. The instrument utilises a multi-stage cooling system that will maintain the ultra-low temperature of the calorimeter array for more than 3 years in space. X-rays are focused onto an array of calorimeters by a highly efficient, grazing-incidence X-ray mirror that provides large collecting area. The result is a high-resolution spectrum at each pixel of the image. The NASA contribution to Astro-H is being built at the NASA/Goddard Spaceflight Center in collaboration with the University of Wisconsin. Astro-H will be launched into low-Earth orbit from the Tanegashima Space Center, Japan, by a JAXA H-IIA rocket (Takahashi et al., 2010).

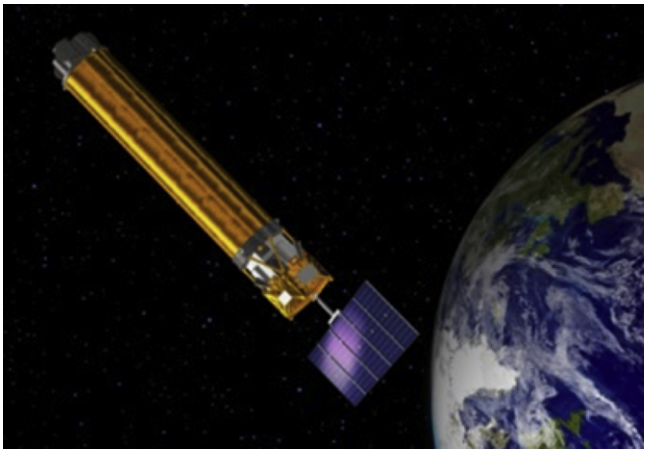

Fig. 38. GEMS artist's concept.

4.4.6. Gravity and Extreme Magnetism Small Explorer (GEMS): Launch 2014

GEMS is a NASA SMEX mission designed to measure X-ray polarisation. It will use three grazing incidence X-ray optics to explore the shape of space that has been distorted by a spinning black hole's gravity, and probe the structure and effects of the magnetic field around neutron stars (see Fig. 38). Current missions cannot do this because the required angular resolution is far beyond what is technically feasible and, in the case of magnetic field imaging, can't do this because magnetic fields are invisible. GEMS will use a new technique to accomplish what has been impossible until now. It will build up a picture indirectly by measuring the polarisation of X-rays. This will open new discovery space because GEMS is orders of magnitude more sensitive than previous X-ray polarisation experiments (Jahoda, 2010). X-rays are just a powerful kind of light. When light travels freely through space, its electric field can vibrate in any direction; however, under certain conditions, it becomes polarised. This means it is forced to vibrate primarily in only one direction. This happens when light scatters off of a surface, for example, or when it traverses a strong magnetic field.

4.4.7. Hard X-ray Modulation Telescope (HXMT): Launch 2015

The "Hard X-ray Modulation Telescope" (HXMT) was proposed in 1994 (Fangjun, 2009). In 2000, the feasibility and technical demonstration study of HXMT was selected as a project under the Major State Basic Research Development Program in China. The project entered its full design phase in October 2005. In March 2007, the Chinese National Space Administration (CNSA) released the 5-year plan for space science development in the period 2006–2010, in which HXMT was scheduled for launch in around 2010. The technical feasibility review was concluded successfully in September 2007. However, a full funding decision was not made until March 2011, when CNSA finally confirmed its funding approval request with a new launch date in 2014–2015. HXMT (see Fig. 39) will be launched into a low Earth orbit with an altitude of 550 km and an inclination angle of 43 degree. HXMT carries three slat-collimated instruments, the High Energy X-ray instrument (HE: NaI/CsI phoswitch scintillators, 20–250 keV, 5000 cm^2), the Medium Energy X-ray instrument (ME: SiPIN, 5–30 keV, 952 cm^2), and the Low Energy X-ray instrument (LE: Si-SCD, 1–15 keV, 384 cm^2). Each instrument contains a number of individual modules, and the typical field of view of a module is 5.7 degree × 1.1 degree (Full Width Half Maximum). The total payload and satellite weights are about 1200 and 2700 kg, respectively. The designed mission lifetime is 4 years. HXMT will perform sky surveys and pointed observations in the energy range 1–250 keV, with the following main scientific objectives:

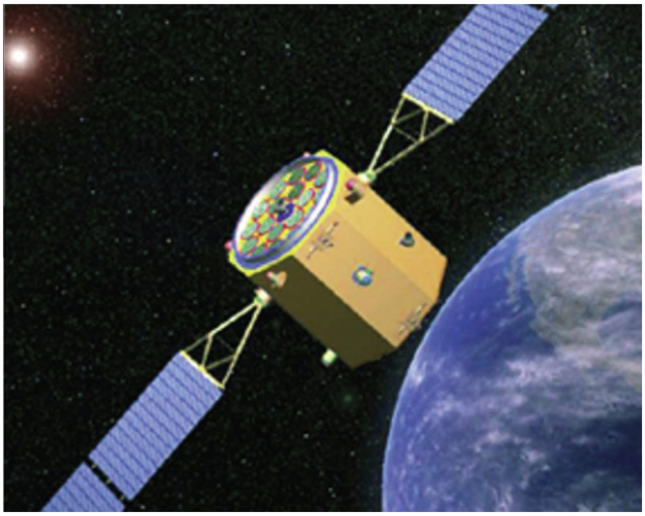

Fig. 39. HXMT artist's concept.

- Perform repeated scanning surveys of the Galactic plane, in order to monitor Galactic variable sources and to detect new Galactic transient sources.
- Make large-area sky observations, in order to study the cosmic variance of the cosmic X-ray background.
- Obtain broad band X-ray spectra of bright AGNs, in order to constrain the geometry of the various components in the AGNs unified model.
- Observe X-ray binaries with broad band spectral and timing capabilities, in order to understand the physics under the extreme physical conditions near compact objects.

4.4.8. The James Webb Space Telescope: Launch 2018

The James Webb Space Telescope (JWST) is a collaborative mission involving NASA, ESA and the Canadian Space Agency. The observatory consists ofa large, infrared-optimised space telescope with a segmented 6.5 m primary mirror four instruments sensitive from 0.6 to 27 μm. JWST is scheduled for launch on an Ariane rocket not earlier than 2018. It will be launched to a location about 1.5 million km from the Earth, orbiting the Earth-Sun Lagrange point L2.[47] JWST will find the first galaxies that formed in the early Universe, connecting the Big Bang to our own Milky Way Galaxy. It will peer through dusty clouds to see stars and planetary systems forming, connecting the Milky Way to our own solar system. The JWST instruments will be designed to work primarily in the infrared range of the electromagnetic spectrum, with some capability in the visible range (see Fig. 40). In order to achieve high sensitivity in the infrared, JWST will have a multilayer sunshield the size of a tennis court to shield the telescope and instruments from direct radiation from the Sun and Earth. Both the telescope and sunshade are too large to fit into the rocket shroud fully open, so both will fold up and be deployed once Webb is in outer space. The James Webb Space Telescope was named after the early NASA Administrator who assured that science would be an important element of the NASA programme.

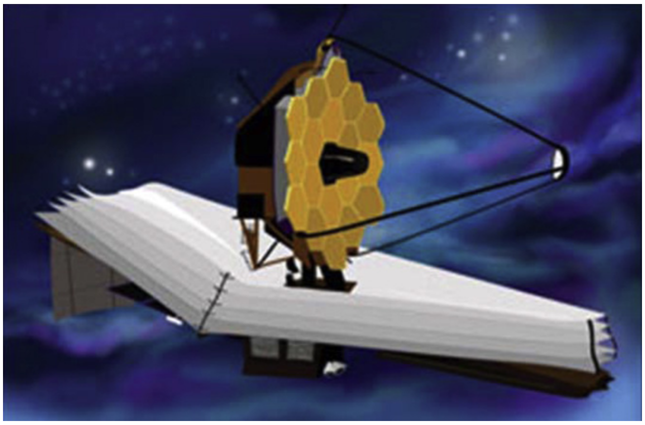

Fig. 40. James Webb Space Telescope artist's concept.

4.4.9. Stratospheric Observatory for Infrared Astronomy (SOFIA): Fully operational 2014

SOFIA (Krabbe, 2000) is a world-class airborne infrared observatory (see Fig. 41) that will complement the Hubble, Spitzer, Herschel and Webb space telescopes and major Earth-based telescopes. SOFIA is a joint program by NASA and DLR, Deutsches Zentrum fur Luft und Raumfahrt (German Aerospace Center). Major modifications of a Boeing 747-SP aircraft and installation of the 2.5 m telescope built in Germany were carried out at the L-3 Communications Integrated Systems facility at Waco, Texas. Completion of systems installation, integration and flight test operations were conducted at NASA's Dryden Flight Research Center at Edwards Air Force Base, California, from 2007 to 2010. SOFIA's science operations are being planned jointly by the Universities Space Research Association (USRA) and the Deutsches SOFIA Institut (DSI) under leadership of the SOFIA Science

Fig. 41. Photo of SOFIA, the Stratospheric Observatory for Infrared Astronomy, during 'open-door' flight tests.

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[47] The James Webb Space Telescope, NASA, http://www.jwst.nasa.gov/.

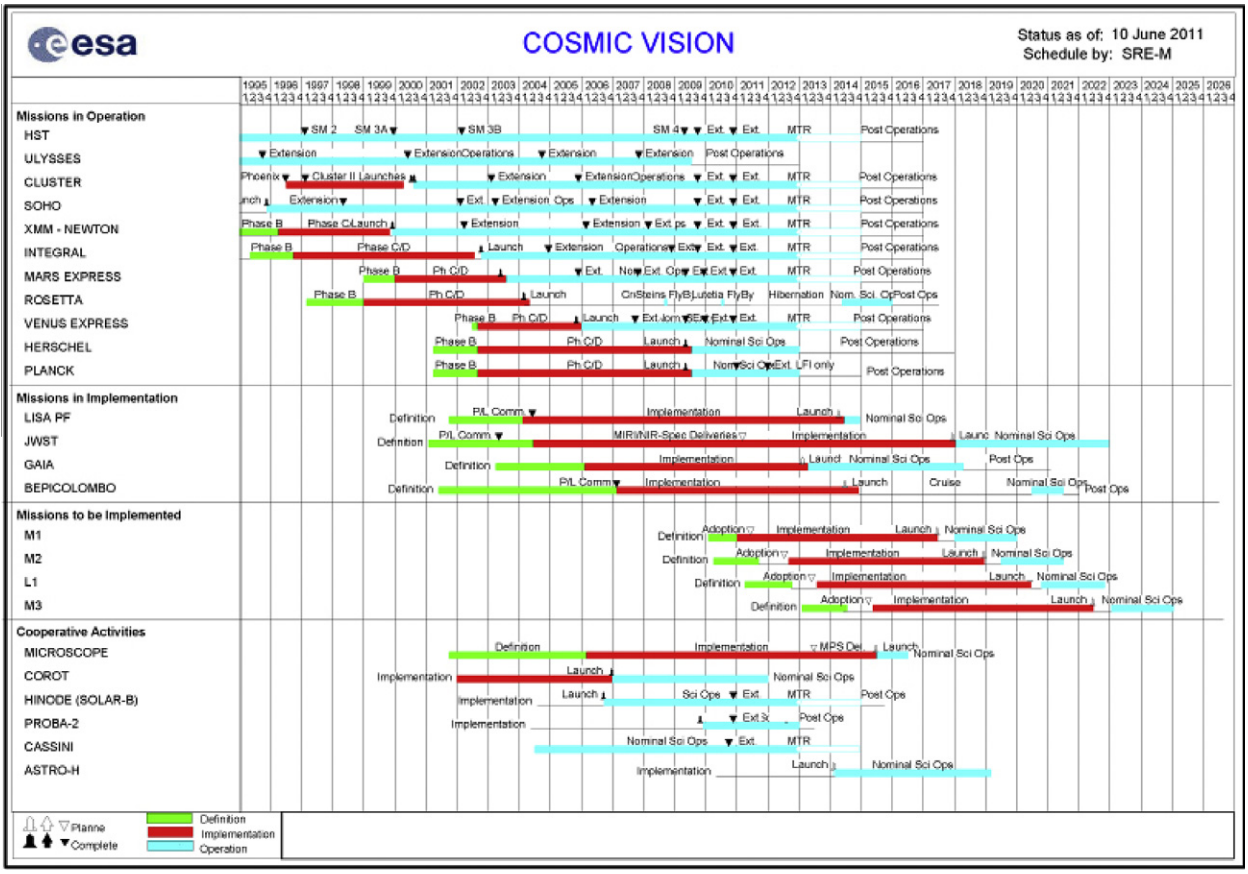

Fig. 42. ESA Cosmic Vision long term plan and time schedule for M- and L-Class planned missions.

project at NASA's Ames Research Center at Moffett Field near San Jose, California.

SOFIA early science operations began in 2010, with full operational capability planned for 2014. SOFIA'S instruments will provide astronomers with access to the visible, infrared and submillimetre spectrum, with optimised performance in the mid-infrared to submillimetre range. During its 20-year expected lifetime it will be capable of "Great Observatory" – class astronomical science, and permit installation of up-graded instruments as technology advances. By recording infrared measurements not possible from the ground, SOFIA will be able to observe occultation of stars by solar system objects to help determine the objects' sizes, compositions and atmospheric structures. It will help answer many fundamental questions about the creation and evolution of the universe, including how stars and planets are formed, how organic materials necessary for life form and evolve, and the nature of the black hole at the center of our Milky Way galaxy.

5. The Future Programmes of the National Space Agencies

In this section we review the main mission opportunities already under study for selection or firmly planned in the context of space agencies around the world.

5.1. The NASA future programs and Vision

The US National Academy of Sciences Astro2010 Decadal Survey scientific and programmatic priority recommendations were made by the Committee for a Decadal Survey of Astronomy and Astrophysics (NRC, 2010a). More detailed discussions of the science questions and programmatic options on which the recommendations were based are presented in a separate publication containing the reports of the Science Frontiers Panels and Program Prioritization Panels (NRC, 2010b). The recommended programme is organised by three science objectives that represent its scope:

- Cosmic Dawn.
- New Worlds.
- Physics of the Universe.

The highest priority recommendations for space missions and programs are as follows:

Large programmes (in rank order)

- *Wide-Field Infrared Survey Telescope (WFIRST)*.W-FIRST is an observatory designed to address essential questions in both exoplanets and dark energy research, and to conduct near infrared sky surveys of unprece-

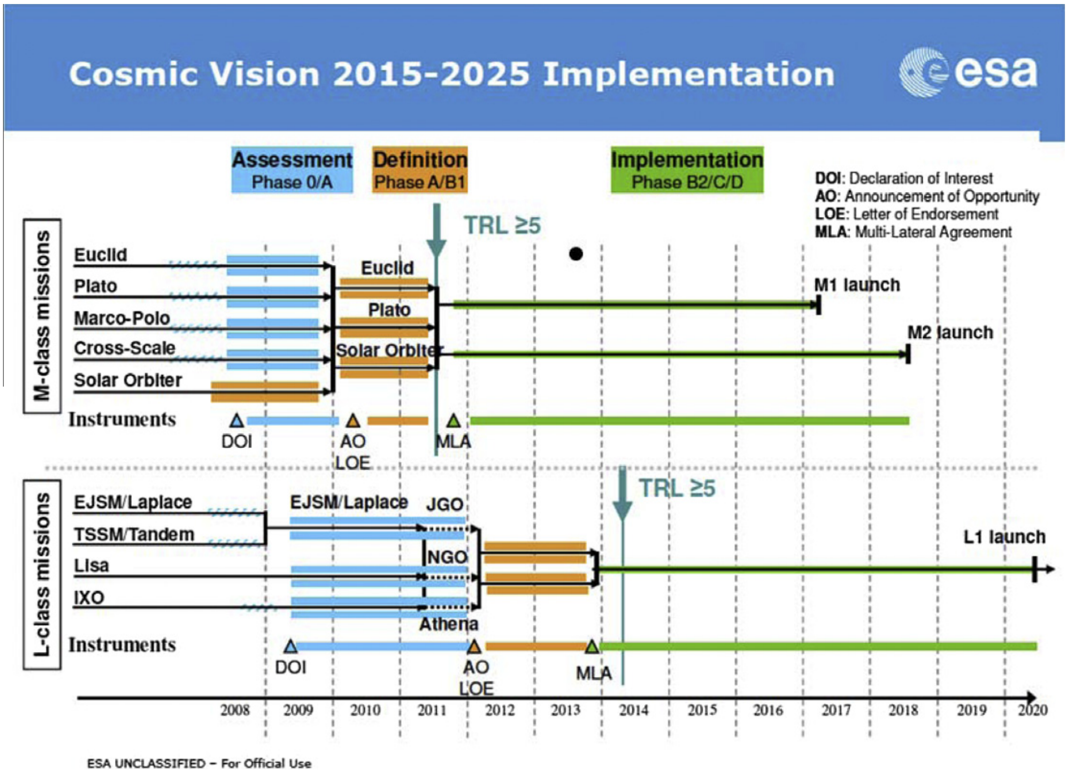

Fig. 43. Cosmic Vision 2015–2025. Implementation plan and selection milestone for Medium and Large Class planned missions (Clavel, 2010).

dented sky coverage, sensitivity and angular resolution. Such surveys will advance research on topics ranging from galaxy evolution to the study of objects within our own Galaxy. The primary operations will consist of surveys defined by selected science teams (SIR, 2010). It is the top-ranked overall programme in the New Worlds, New Horizons Decadal Survey of Astronomy and Astrophysics.

- *An Augmented Astrophysics Explorer Program.*This is a recommendation to increase the rate of launching PI-led missions. Such missions deliver a high level of scientific return on relatively moderate investment and provide the capability to respond rapidly to new scientific and technical breakthroughs.
- *Laser Interferometer Space Antenna (LISA).*LISA is a low-frequency gravitational wave observatory that will open an entirely new window on the cosmos by measuring ripples in space-time caused by many new sources, including nearby white dwarf stars, and will probe the nature of black holes. This recommendation assumed partnership with ESA.
- *International X-ray Observatory (IXO).*IXO is a powerful X-ray telescope that will transform our understanding of hot gas associated with stars and galaxies in all evolutionary stages. This recommendation assumed partnership with ESA and JAXA.

Medium scale Programmes (in rank order)

- *New Worlds Technology Development Program*. This is a competed programme to lay the technical and scientific foundation for a future mission to study nearby Earth-like planets.
- *Inflation Probe Technology Development Program*. This is a competed programme designed to prepare for a potential next-decade cosmic microwave-background mission to study the epoch of inflation.

Small programmes (mentioned here because there is a relatively small NASA contribution to a large international programme)

- *Background-limited Submillimetre Spectrometer on SPICA* A spectrometer of unprecedented sensitivity for Galactic and extragalactic studies provided by NASA to the Japanese Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission.[48] [*Note*: the Astro2010 Survey Report indicated that if sufficient funding were not available to do the full recommended programme, this should be the first activity removed from the recommended list. Since the release of the Astro2010 Survey Report, NASA has indicated that it cannot participate on the current SPICA schedule.]

5.2. The ESA future programmes and Cosmic Vision

The European Space Agency started the definition of a new long term plan in 2004 with the call for new Space

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[48] SPICA: To Discover the Origins of Galaxies, Stars and Planets; http://sci.esa.int/spica.

Science missions to be conducted in the next decade. The community responded with more than 150 ideas that were reviewed by the Agency advisory groups. The results are summarised in: *Cosmic Vision Space Science for Europe 2015–2025* (Bignami et al., 2005).

An updated Cosmic Vision Long Term Plan is shown in Fig. 42.

The ESA Science Vision Working Group identified four key questions where significant advances and breakthroughs can be expected in the coming two decades:

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

These are amongst the most fundamental questions in astrophysical science and generate considerable interest in the general public. The Cosmic Vision basic implementation schedule Clavel (2010) is shown in Fig. 43

Following is a short description of all the emissions under selection.

5.2.1. The Cosmic Vision L-Class priority (under selection)

In February 2009 a down-selection took place between the two L-class missions Laplace (Jupiter) and TandEM (Saturn). Both missions had been proposed as collaborations with NASA, and a joint decision was taken to retain the mission to the Jupiter system as candidate for the L1 launch slot in 2020. The remaining candidate L missions for the L1 launch slot are EJSM/Laplace, IXO and LISA.

5.2.1.1. L1: Europa Jupiter System Mission (EJSM): Mission Summary (see Table 4). The ESA-NASA Europa Jupiter System Mission (Clark et al., 2010) consists of two primary flight elements operating in the Jovian system: the NASA-led Jupiter Europa Orbiter (JEO),[49] and the ESA-led Jupiter Ganymede Orbiter (JGO).[50] JEO and JGO will execute a choreographed exploration of the Jupiter System before settling into orbit around Europa and Ganymede, respectively. JEO and JGO carry 11 and 10 complementary instruments, respectively, to monitor dynamic phenomena (such as Io's volcanoes and Jupiter's atmosphere), map the Jovian magnetosphere and its interactions with the Galilean satellites, and characterise water oceans beneath the ice shells of Europa and Ganymede. By understanding the Jupiter system and unraveling its history from origin to the possible emergence of habitable worlds, a better understanding will be gained as to how gas giant planets and their satellites form and evolve. Most important, new light will be shed on the potential for the emergence of life in the galactic neighbourhood and beyond. Thus, the overarching theme for EJSM has been formulated as: The emergence of habitable worlds around gas giants. To understand the Galilean satellites as a system, Europa and Ganymede are singled out for detailed investigation. This pair of objects provides a natural laboratory for comparative analysis of the nature, evolution, and potential habitability of icy worlds. The primary focus is on an in-depth comparative analysis of their internal oceans, current and past environments, surface and near-surface compositions, and their geologic histories. Moreover, objectives for studying the other two Galilean satellites, Io and Callisto, are also defined. To understand how gas giant planets and their satellites evolve, broader studies of Jupiter's atmosphere and magnetosphere will round out the Jupiter system investigation.

Table 4
Europa Jupiter System Mission: EJSM/Laplace.

Theme	How does the Solar System work?
Goal	What have been the conditions for the formation of the Jupiter system? How does Jupiter work? Is Europa habitable?
Ganymede Orbiter (ESA-led)	JEO: Jupiter Europa Orbiter (NASA-led)
Lifetime	5–7 year cruise & 2-years in orbit
Partners	ESA–NASA
Type	L-class mission

5.2.1.2. L1: LISA Mission Summary (see Table 5). Unlike electromagnetic radiation (radio to optical to γ-rays), gravitational waves penetrate through all matter, thereby allowing us to see back to the beginning of the Universe without obscuration by dust or other matter. LISA (Brillet et al., 2011), the first instrument to directly measure gravitational radiation from space, will peer back to the epoch of initial star formation. It will test Einstein's theory of general relativity in the strong-field regime, and will witness the merger of supermassive black holes throughout the Universe, along with other astrophysical phenomena. LISA is a gravity wave telescope similar to a Michelson interferometer. Three identical spacecraft are flown in deep space in an Earth-trailing orbit, forming the vertices of an equilateral triangle with arm spacing of 5 million kilometers. Laser beams between these spacecraft enable interferometric measurement of relative displacements between these spacecraft, with the incredible accuracy of several picometers. With this accuracy, one is able to measure the tiny distortions of spacetime caused by a passing gravitational wave. These waves, produced by such cataclysmic events as the merger of supermassive black holes, propagate unattenuated throughout the Universe, and thus allow us to see back to the time of star formation and beyond. LISA detects gravitational radiation with periods of several seconds to a few hours, such as that produced by two coalescing massive black holes in a distant galaxy. LISA will also provide an unprecedented test

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[49] Jupiter Europa Orbiter (JEO), http://opfm.jpl.nasa.gov/europajupitersystemmissionejsm/jupitereuropaorbiterconcept/.

[50] Jupiter Ganymede Orbiter (JGO), http://opfm.jpl.nasa.gov/europajupitersystemmissionejsm/jupiterganymedeorbiterjgoconcept/.

Table 5
LISA: Laser Interferometer Space Antenna.

Theme	What are the fundamental physical laws of the Universe? How did the Universe originate and what is it made of?
Goal	Detect and observe gravitational waves from astronomical sources in a frequency range of 10^{-4} to 10^{-1} Hz
Spacecraft	Three identical spacecraft, each carrying two telescopes with associated lasers and optical systems that together act as an interferometer
Orbit	The three spacecraft fly in a near-equilateral triangular formation separated from each other by 5 million km Together they trail behind the Earth at a distance of 50 million km in the planet's orbit around the Sun
Partners	NASA–ESA
Type	L-class mission

of strong field general relativity theory. As the first dedicated space-based gravitational wave observatory, LISA will detect waves generated by binaries within our Galaxy, the Milky Way, and by massive black holes in distant galaxies. LISA will make its observations in a low-frequency band that "ground based" detectors can't achieve. The difference in frequency bands between LISA and gravitational wave ground detectors such as the Laser Interferometer Gravitational Wave Observatory (LIGO) (Abbott et al., 2004), which operate above 1 Hz, make these detectors complementary rather than competitive.

5.2.1.3. L1: IXO Mission Summary (see Table 6). IXO (Barcons et al., 2011) is the result of the merging of NASAs Constellation-X and ESA/JAXAs XEUS mission concepts. Following discussions involving ESA, NASA and JAXA the XEUS mission concept was merged with the Constellation-X concept (NASA) into the International X-ray Observatory (IXO). After this merger a study was performed for IXO which ran from October 2008 to November 2008. In the first half of 2009 the Invitation to Tender was issued to industry, resulting in parallel industrial assessment studies that lasted 18 months. These studies were completed by the end of 2010 and a new X-ray observatory class mission was designed: the International X-ray Observatory (IXO) – a joint effort of NASA, ESA, and JAXA- that combined a large X-ray mirror with powerful new instrumentation designed to explore the high energy Universe. The launch was planned for 2021 (a detailed description of IXO characteristics are reported in Section 3.4.1).

5.2.1.4. Why do IXO?. High-energy phenomena in the X-ray band characterise the evolution of cosmic structures on both large and small scales. On the smallest scales, X-rays provide the only electromagnetic spectral signatures from the regions of strong gravity near black holes through absorption and emission features, such as the Fe K emission line at 6.4 keV and its profile, and can penetrate the surrounding gas and dust allowing us to uncover the earliest massive black holes and measure their distances. In neutron stars, X-ray spectra and light curves carry the observable imprints of exotic processes occurring in these objects. Detailed simulations of spectra of various sources have shown the IXO ability to:

1. Determine redshift autonomously in the X-ray band.
2. Determine temperatures and abundances, even for low luminosity groups to $z < 1$.
3. Make spin measurements of AGN to a similar redshift.
4. Uncover the most heavily obscured, Compton-thick AGN.

On the largest scales, X-rays are essential for detecting the "missing" half of baryons in the local Universe, as a probe of both dark energy and dark matter and to measure the energy deposited in the surrounding medium by AGN's jets and winds. Building on a rich technological heritage, IXO will have improved instrumental capabilities in X-ray imaging, timing, and spectroscopy far beyond the current generation of X-ray missions (e.g. Chandra, XMM, RXTE, and Suzaku). Moreover, IXO will carry an X-ray polarimeter, which will open a new window on the study of high-energy phenomena. These will enable observations that will address the above science issues-among others-with unprecedented detail and precision.

5.2.2. The Cosmic Vision M-Class priority

ESA has initially chosen three scientific missions for further M Class study. Dark energy, habitable planets around

Table 6
IXO: International X-ray Observatory.

Themes	What are the fundamental physical laws of the Universe? How did the Universe originate and what is it made of?
Goal	Black holes and matter under extreme conditions. Formation and evolution of galaxies, clusters and large scale structure Life cycles of matter and energy
Targets (keV)	High redshift AGN Clusters of galaxies Neutron stars and black holes
Telescope	3.3 m diameter mirror with 20 m focal length
Orbit	Halo orbit at L2
Lifetime	5 years
Partners	ESA–NASA–JAXA
Type	L-class Mission

Table 7
Euclid: Mapping the geometry of the dark Universe.

Theme	How did the Universe originate and what is it made of?
Primary goal	To map the geometry of the dark Universe
Targets	Galaxies and clusters of galaxies out to $z \sim 2$, in a wide extragalactic survey covering 20000 $\deg^2$, plus a deep survey covering an area of 40 $\deg^2$
Wavelength	Visible and near-infrared
Telescope	1.2 m Korsch
Orbit	Second Sun–Earth Lagrange point, L2
Lifetime	5 years
Partners	To be confirmed
Type	M-class mission

Table 8
PLATO: PLAnetary Transits and Oscillations of stars.

Theme	What are the conditions for planet formation and the emergence of life?
Primary goal	Discover and characterise a large number of close-by exoplanetary systems,with a precision in the determination of mass and radius of 1%
Targets	Detect Earth sized planets around solar-type stars detect super-earths around solar-type stars Measure solar oscillations in the host stars of exoplanets measure oscillations of classical pulsators
Wavelength	Optical
Telescope	A number of small,optically fast,wide-field telescopes
Orbit	Large amplitude libration orbit around Sun–Earth Lagrangian point, L2
Lifetime	Minimum 6 years
Partners	To be confirmed
Type	M-class mission

other stars, and the mysterious nature of our own Sun, have been chosen by ESA as candidates for two medium-class missions to be launched no earlier than 2017. On February 2010, ESA's Science Programme Committee (SPC) approved three missions to enter the so-called definition phase. This is the next step required before the final decision is taken as to which missions are implemented. The three proposals chosen to proceed are Euclid (Laureijs et al., 2011), PLAnetary Transits and Oscillations of stars (PLATO) (Catala et al., 2011), and Solar Orbiter.[51]

5.2.2.1. M1/2: Euclid Mission Summary (see Table 7). Euclid would address key questions relevant to fundamental physics and cosmology, namely the nature of the mysterious dark energy and dark matter (Laureijs et al., 2011). Astronomers are now convinced that these form of mass-energy dominate ordinary matter. Euclid would map the distribution of galaxies to reveal the underlying 'dark' architecture of the Universe.

5.2.2.2. M1/2: PLATO Mission summary (see Table 8). The PLATO mission (Catala et al., 2011) would address one of the most timely and long-standing questions in science, namely the frequency of planets around other stars. This would include terrestrial planets in a star's habitable zone, so-called Earth-analogues. In addition, PLATO would probe stellar interiors by detecting the gaseous waves rippling their surfaces.

5.2.2.3. M1/2: Solar Orbiter Mission Summary (see Table 9). Solar Orbiter would take the closest look at our Sun yet possible, approaching to just 62 solar radii.[52] It would deliver images and data that include views of the Sun's polar regions and the solar far side when it is not visible from Earth. These three missions are the finalists from 52 proposals that were either made or carried forward in 2007. They were whittled down to just six mission proposals in 2008 and sent for industrial assessment. The reports from those studies were completed and the missions pared down again. "It was a very difficult selection process. All the missions contained very strong science cases," says Lennart Nordh, Swedish National Space Board and chair of the SPC. The tough decisions were not yet over. Only two missions out of three of them: EUCLID, PLATO and Solar Orbiter, were competing for selection for the M-class launch slots. All three missions presented challenges that were resolved at the definition phase. A specific challenge, of which the SPC was conscious, was the ability of these missions to fit within the available budget. The final decision about which missions to implement has been finally taken in September 2011 (see next paragraph for details).

5.2.2.4. M1/2: SPICA Mission Summary (see Table 10). SPICA[53] would be an infrared space telescope led by the Japanese Space Agency JAXA. It would provide

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[51] http://sci.esa.int/solarorbiter.

[52] http://sci.esa.int/solarorbiter.

[53] SPICA: To Discover the Origins of Galaxies, Stars and Planets; http://sci.esa.int/spica.

Table 9
Solar orbiter: exploring our nearest star.

Theme	How does the solar system work?
Primary goal	To produce images of the Sun at an unprecedented resolution and perform closest ever in-situ measurements
Targets	The Sun
Wavelength	Visible, extreme ultra violet, X-rays
Orbit	Elliptical orbit around the Sun with perihelion as low as 0.28 AU and with increasing inclination up to more than 30° with respect to the solar equator
Lifetime	6 years (nominal)
Partners	To be confirmed
Type	M-class mission

Table 10
SPICA: to discover the origins of galaxies, stars and planets.

Theme	What are the conditions for planet formation and the emergence of life? How does the solar system work? How did the universe originate and what is it made of?
Primary goal	Understanding how galaxies, stars and planets form and evolve as well as the interaction between the astrophysical processes that have led to the formation of our own solar system
Targets	Young gas giant planets, Protoplanetary disks, Galactic and extragalactic star forming regions Luminous IR galaxies, AGNs and starburst galaxies at high redshift. Deep cosmological surveys
Wavelength	Medium to Far Infra-red (~5–210 μm)
Telescope	3.5 m Ritchey–Chrtien
Orbit	L2
Lifetime	Minimum 5 years
Partners	JAXA–ESA
Type	M-class mission

’missing-link’ infrared coverage in the region of the spectrum between that seen by the ESA-NASA James Webb Space Telescope and the “ground based” ALMA telescope. SPICA would focus on the conditions for planet formation and distant young galaxies. The Japanese Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission is envisaged to be launched around 2018 and will carry a 3.2-m diameter telescope cooled to around 6 K and a set of instruments covering 5–210 microns. SPICA will be launched warm and cooled down in orbit by a combination of radiative cooling and on-board mechanical coolers. Unlike previous cryogenically cooled missions, its lifetime will therefore not be determined by a limited cryogen supply but by fuel for the attitude control system or component reliability. A lifetime of at least 5 years is envisaged. A European contribution to SPICA is being developed in the form of the telescope (to be provided by ESA under an industrial procurement) and an FIR camera/spectrometer, SAFARI, to be provided by a Dutch-led consortium of European nationally-funded institutes with collaboration from Canada and Japan. SAFARI will have an imaging Fourier Transform Spectrometer, based on the Herschel-SPIRE design, with transition-edge superconducting (TES) detector arrays. In addition, SPICA will also carry a NIR camera and spectrometer, a Mid-IR Camera, and spectrograph, and possibly a US-provided submillimetre spectrometer. In September 2008, SPICA successfully passed its System Requirements Review in Japan, and is still on track for a confirmation of mission implementation. More recently SPICA received a strong endorsement in the 2010 US Decadal review, strengthening the probability of a NASA-provided instrument being included in the payload. Cooled single aperture missions have also been studied in the USA, e.g., SAFIR and CALISTO. In the event that SPICA proceeds through implementation, it is unlikely that these missions will be further developed.

5.2.2.5. The M1 and M2 selection. The M1/M2 selection has been completed in September 2011with the approval to completion of the Solar Orbiter and EUCLID satellites. The launch date are scheduled for the time frame 2017 and 2018, respectively (see Fig. 43 for details).

5.2.2.6. ESA Cosmic Vision selection for the M3 mission. 25 February 2011: Four candidates selected for the next medium-class mission in ESA’s Cosmic Vision Looking ahead to the next decade of scientific exploration, ESA has selected four candidates for a medium-class mission that will launch in the period 2020–2022. The candidates cover very different areas of scientific research, ranging from investigations of black holes and general relativity to near-Earth asteroid sample return and studies of planets orbiting distant stars.

ESA issued a call to the scientific community on 29 July, 2010, soliciting proposals for a third medium-class mission (M3) within the long-term science plan known as Cosmic Vision 2015–2025. A total of 47 proposals was submitted and then peer reviewed by the Advisory Structure to the Science Programme. As a result of this review process, recommendations based on the scientific excellence of the missions were forwarded by the Space Science Advisory Committee to David Southwood, ESA's Director of Science and Robotic Exploration. ESA has now selected four missions to undergo an initial Assessment Phase. Once this is completed, a further down-selection will be performed, leading to a decision on which mission will be finally implemented.

The four proposals chosen to proceed for assessment are EChO, LOFT, MarcoPolo-R and STE-QUEST.[54]

5.2.2.7. M3: Exoplanet Characterisation Observatory (EChO). The Exoplanet Characterisation Observatory (EChO) would be the first dedicated mission to investigate exoplanetary atmospheres, addressing the suitability of those planets for life and placing our Solar System in context.

Orbiting around the L2 Lagrange point, 1.5 million km from Earth in the anti-sunward direction, EChO would provide high resolution, multi-wavelength spectroscopic observations. It would measure the atmospheric composition, temperature and albedo of a representative sample of known exoplanets, constrain models of their internal structure and improve our understanding of how planets form and evolve.

5.2.2.8. M3: Large Observatory For X-ray Timing (LOFT). The Large Observatory For X-ray Timing (LOFT) is intended to answer fundamental questions about the motion of matter orbiting close to the event horizon of a black hole, and the state of matter in neutron stars, by detecting their very rapid X-ray flux and spectral variability.

LOFT would carry two instruments: a Large Area Detector with an effective area far larger than current spaceborne X-ray detectors, and a Wide Field Monitor that would monitor a large fraction of the sky. With its high spectral resolution, LOFT would revolutionise studies of collapsed objects in our Galaxy and of the brightest supermassive black holes in active galactic nuclei.

5.2.2.9. M3: MarcoPolo-R. MarcoPolo-R is a mission to return a sample of material from a primitive near-Earth asteroid (NEA) for detailed analysis in "ground based" laboratories. The scientific data would help to answer key questions about the processes that occurred during planet formation and the evolution of the rocks which were the building blocks of terrestrial planets.

The mission would also reveal whether NEAs contain pre-solar material not yet found in meteorite samples, determine the nature and origin of the organic compounds they contain, and possibly shed light on the origin of molecules necessary for life.

5.2.2.10. M3: Space-Time Explorer and Quantum Equivalence Principle Space Test (STE-QUEST). The Space-Time Explorer and Quantum Equivalence Principle Space Test (STE-QUEST) is devoted to precise measurement of the effects of gravity on time and matter. Its main objective would be to test the Principle of Equivalence, a fundamental assumption of Einstein's Theory of General Relativity. STE-QUEST would measure space-time curvature by comparing the tick rate of an atomic clock on the spacecraft with other clocks on the ground.[55]

A second primary goal is a quantum test of the Universality of Free Fall – the theory that gravitational acceleration is universal, independent of the type of body.

5.2.2.11. A Cosmic Vision update. The missions flown as part of ESA's Cosmic Vision 2015–2025 plan will tackle some of the major outstanding scientific questions about the Universe and our place in it:

- What are the conditions for planet formation and the emergence of life?
- How does the Solar System work?
- What are the fundamental physical laws of the Universe?
- How did the Universe originate and what is it made of?

There are currently three missions – Euclid, PLATO and Solar Orbiter – which are undergoing competitive assessment for selection as the first and second medium class missions under Cosmic Vision. The final selection for M1 and M2 will be made soon, with launches expected in 2017–2018.

6. The role and plan of the National Agencies

In this section we briefly report the future role and plan, when available, of some national agencies.

6.1. The Japan Space Astronomy Plan: JAXA Long Term Vision

In 2005, JAXA published a Long Term Vision that included orbiting observatories at every wavelength band for the coming decade. Three basic themes were included as follows:

1. Structure and history of the Universe
    - First galaxies, first black holes, co-evolution of galaxies and black holes.
    - Formation of large scale structure, clusters of galaxies.
2. Physics in extreme conditions
    - Physics of black holes and in their vicinity, verification of general relativity.

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[54] http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=48467.

[55] http://sci.esa.int/science-e/www/object/.../object/index.cfm?fobjectid=49350.

- Cosmic ray acceleration, equation of state of neutron stars.

3. Composition of the Universe
   - Dark matter, dark energy (through galaxy clusters).
   - History of matter and its chemical composition, planets, and life.

JAXA's currently approved astronomy projects include:

- ASTRO-H (2014, X-ray astronomy).
- ASTRO-G (space VLBI).
- SPICA (in pre-project phase, undergoing feasibility study).

No further missions have been approved by the Steering Committee for Space Science of ISAS. In 2008–2009 the astronomy and astrophysics division of the Japanese Science Council conducted a survey for large and/or medium astrophysics projects. In 2010, this group recommended three projects, two "ground based" observatories and 1 space observatory, to be promoted on the national scale. These were LCGT (Underground Gravity Wave Telescope), ELT, and SPICA. These do not have strong obligations on the government and JAXA. Funding for LCGT was approved in 2010.

6.2. Future Space Astronomy Programmes in China

6.2.1. Road Maps and Plans

Over the last several years a number of reports, road maps and plans including future space astronomy programmes have been proposed in China by various working groups, committees and panels, including "Space Science & Technology in China: A Road Map to 2050", "Medium and Long Term Development Plan for Space Science Missions" (study funded by Chinese Academy of Sciences), "Report of Strategic Study on Mid- and Long-Term Development of Astronomy in China" (study jointly funded by Chinese Academy of Sciences and National Natural Science Foundation of China), "Report on the Development of Astronomy in China" (study funded by the Association of Science and technology in China) and the "2011–2016 Space Science Plan of China's National Space Agency". This section summarises the future space astronomy programmes listed in these documents and provides a description of missions funded, approved, selected or under-study.

6.2.2. Summary of China's Space Astronomy Programmes

Black Hole Probe Programme (BHP): The objective of this programme is to study high-energy processes of cosmic objects and black hole physics through observations of compact objects such as all kinds of black holes and γ-ray bursts. The programme will explore the extreme physical processes and laws in the universe using extreme objects such as black holes as examples of how stars and galaxies evolve. The main missions will include the Hard X-ray Modulation Telescope (HXMT) satellite, the Space Variable Objects Monitor (SVOM) satellite, and the Gamma-ray Burst Polarisation (POLAR) experiment on board China's Spacelab.

Diagnostics of Astro-Oscillations (DAO) Programme: The objective of this programme is to make high precision photometric and timing measurements of electromagnetic radiation in various wavebands and non-electromagnetic radiation, in order to understand the internal structures of various astrophysical objects and the processes of various violent activities. The main missions will include the X-ray Timing and Polarisation (XTP) satellite, and possible participation in relevant international missions.

Portraits of Astrophysical Objects Programme (PAO): The objective of this programme is to obtain direct photographs (portraits) of astrophysical objects beyond the solar system such as solar-like stars, exoplanets, white dwarfs, neutron stars, and black holes which are essential for understanding scientific questions such as the construction of the universe. The main mission will include the proposed submillimetre Space Very Long Baseline Interferometer (VLBI) telescope array.

Dark Matter Detection Programme (DMD): This programme is based on space platforms to detect the products of dark matter annihilation predicted in various theoretical models. The main mission will include the dark matter particle detection satellite and dark matter particle detection experiment aboard China's manned space station to be operational around 2012.

6.2.3. Missions from 2011 to 2015

Selected and funded missions:

Gamma-ray Burst Polarisation (POLAR) experiment on board China's Spacelab: 2012–2013 launch.

This experiment consists of a stack of plastic scintillators for measuring the linear polarisation of prompt γ-rays from bright γ-ray bursts (GRB), between 50 and 300 keV. This experiment is being conducted in collaboration with a Switzerland-led (Geneva and ISDC) European team.

Space Variable Objects Monitor (SVOM) satellite: 2014–2015 launch. This monitor consists of four instruments: Coded-mask ECLAIRs as a GRB imager and trigger between 5 and 150 keV, GRM for GRB spectral measurement and trigger between 30 keV and 1 MeV, a 21 cm aperture X-ray telescope and a 45 cm aperture optical telescope for GRB localisation and afterglow observations. This monitor is being developed in collaboration with France. It has been selected and is a fully funded mission.

6.2.4. Selected and fully funded missions

Hard X-ray Modulation Telescope (HXMT) satellite: 2014–2015 launch. This telescope consists of three sets of collimated (about 1 degree by 6 degree FOV) instruments, high energy instruments between 20 and 250 keV of about 5000 cm^2 (NaI/CsI phoswitch), medium energy instruments between 5 and 300 keV of about 1000 cm^2 (Si-PIN), and low energy instruments between 1 and 15 keV of about 400 cm^2 (SCD). The main scientific goals include a broadband wide-area survey and pointed observations of compact galactic objects.

Dark matter and cosmic ray detection satellite: 2014–2015 launch.

This satellite consists of a stack of charged particle detector and calorimeter of 1.2 ton payload mass, aiming for the detection of the annihilation and decay products (electrons, positrons and γ-rays) of suspected dark matter particles, as well as the determination of a precision cosmic ray spectrum, between 5 GeV and 1 TeV.

6.2.5. Mid-Long Term Missions Funded for Development and Study

Moderate funding is provided for key technology development and conceptual studies which may lead to future missions. Several conceptual studies are fundedannually, and at the conclusion of these studies some missions may be funded for key technology development. At the present time, the following are funded for key technology development:

- X-ray Timing and Polarisation (XTP) satellite: launch around 2020 with instruments including large arrays of soft X-ray and hard X-ray telescopes to achieve several meter squared sensitive area, and X-ray polarimeter telescopes, for high throughput X-ray observations.
- Dark matter and cosmic ray observatory on board China's Space Station with a projected 2020–2022 launch.

The following are funded for conceptual studies:

- Infrared sky survey small satellite mission.
- Fast photometry observation mission from optical to X-ray bands.
- Submillimetre space VLBI mission.

6.3. The Indian Space science programme

6.3.1. Space Astronomy in India: the 2010–2020 vision

The availability of opportunities in space astronomy in India have been generally linked to the indigenous rocket development programme, and the rocket load-carrying capacities and the 5-year plan funding of ISRO, the nodal agency for the space activities in India. The PSLV rocket, which is the work horse of the Indian remote sensing satellites, has the capability to put 1500 kg in orbit and is the key vehicle for science experiments today. There is no formal Road Map for the space astronomy missions in ISRO; the missions are approved on an ad-hoc case-bycase basis. In recent years, ISRO launched the Moon mission Chandrayaan-1, and ASTROSAT, a multi-wavelength astronomy satellite carrying a suite of instruments is due for launch next year. Several small missions in astronomy have been funded for development. These include an IR astronomy satellite, the Coronagraph mission Aditya and a solar spectrograph mission. Chandrayaan-2 is also in preparation, as are future planetary probes. Both Chandrayaan and ASTROSAT were conceived as multi-instrument satellites carrying a suite of instruments for a variety of observations; other payloads are planned as small co-passenger missions. In the 2004, a committee appointed by the Indian Academy of Sciences in Bangalore, submitted the Decadal Vision Document for Astronomy and Astrophysics, which was the first such exercise undertaken in India. The committee noted that, given the relatively small size of the Indian astronomical community and the large range of research activities,there are no discernible thrust areas and many of the existing experimental efforts in space astronomy are sub-optimal. After surveying the ongoing research, critically assessing the contributions made in the past in various areas and evaluating their impact and the future directions in different areas worldwide, some key developments were recommended:

1. Multi-wavelength astronomy as a niche area.
2. Some modest new initiatives in "ground based" and space astronomy and technology initiatives.
3. Participation in large international projects.

The prioritised list of recommended space-based initiatives include a small solar coronagraph and a Near Infrared Spectro-photometer, while the prioritised list of technology initiatives suggested were detector development for γ-rays, hard X-rays and infrared; hard X-ray mirrors: X-ray polarimeter; and space platforms for fundamental physics experiments. While recommending the participation in international projects, the committee noted that multinational collaboration is the new paradigm in big science. This is going to be true in all branches of astronomy. Therefore, the Indian scientists have no option but to participate in future international ventures. While it was noted that they must pursue their own projects, they felt they must exploit every opportunity to collaborate in major international projects. The necessary expertise which will empower them to do so must be developed. Since the Academy's recommendations are used as the guiding principals by ISRO when deciding on the future missions, therefore, the Indian Space astronomy programme will only be targeted to small missions in different areas of astronomy. ISRO has, however, always encouraged participation with the international groups even in such missions. For example, Chanrayaan-1, ASTROSAT and the IR satellite have foreign participation. For large missions, ISRO will work together with other agencies if supported by the Indian Astronomy community.

There are future considered astronomical satellites considered for two medium class missions of ISRO.[56] Aditya-1

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[56] Indian Space research Organisation: http://www.isro.org/.

is proposed to be a space-based Solar Coronagraph to study the solar corona in visible and near-IR bands. The launch of the Aditya mission is planned during the next high solar activity period in 2014. The main objective is to study the Coronal Mass Ejections (CME) and consequently the crucial physical parameters for space weather such as the coronal magnetic field structures, evolution of the coronal magnetic field, etc. This will provide completely new information on the velocity fields and their variability in the inner corona which have an important knowledge to address the unsolved question of how the corona is heated.

A Thomson X-ray polarimeter has been developed for a small satellite mission. The instrument works in the 5–30 keV band and will be suitable for X-ray polarisation measurements in many hard X-ray sources. The accretion-powered X-ray pulsars, black hole X-ray binaries, rotation-powered pulsars and non-thermal supernova remnants will be the prime targets for this mission. In spite of its moderate sensitivity, this experiment will give an unique opportunity to expand the field of X-ray astronomy into a hitherto unexplored dimension.

6.4. The Russian Space Science programme

At the present time, Russian scientific space missions are being developed based on the 10-year Federal space programme for the 2006–2015 period. The Russian Federal Space Agency, Roscosmos, is responsible for the implementation of this programme. It is planned that during 2011 the space programme will be corrected for the period 2013–2015 and new tasks will be formulated for the 5-year period 2016–2020, or even possibly for the 10 year period 2016–2025. In the current programme, the manned space flight programme associated with the International Space Station support has the highest priority. Half of the available financial resources are being allocated to the human space flight programme. The other half goes to telecommunications, remote sensing and scientific research satellites.

The Global Navigation System (GLONAS) has its own separate programme.

The scientific space programme is being realised as a rule according to the interest of the Russian Academy of Sciences and covers the following directions:

1. Planetary research – projects: Phobos-Soil (2011), Luna-Resource (2013), Luna-Glob (2013).
2. Extraterrestrial astronomy: Spectrum-Radioastron (2011), Spectrum-Ultraviolet (2014), Spectrum-Roentgen-Gamma (2013), Gamma-400 (after 2015), Millimetron (after 2015).
3. Sun – Interhelioprobe (after 2015).
4. Cosmic rays – Resurs-DK/Pamela (it is operating on the orbit from 2006), “Lomonosov”.
5. Plasma physics – Resonance (2013).
6. Cosmic rays – Resurs-Dk/Pamela (operational since 2006), Lomonosov (Moscow State University, 2012 TBD).

The projects are being developed in wide international cooperation with the participation of ESA, NASA and other national space agencies: DLR, CNES, ASI, etc. Development of separate small experiments for the foreign space planetary missions is also supported. These missions include: Mars missions (Mars Odyssey Spacecraft, NASA, and Mars Express, ESA), Venus missions (Venus Express, ESA), Moon (LRO, NASA) and Mercury (BepiColombo, ESA) missions. In the branch of extraterrestrial astronomy, the nearest perspective of the Federal Space Programme is associated with the three missions of the “Spectrum” series: “Spectrum-Radioastron”, “Spectrum-UV” and “Spectrum-Roentgen-Gamma”.

Spectrum-Radioastron (Astro Space Center of the P.N. Lebedev Physical Institute of the Russian Academy of Science). The spacecraft is scheduled for launch in the middle of 2011. Radioastron is an international collaborative mission to launch a free-flying satellite carrying a 10-m space radio telescope (SRT) into an elliptical orbit around the Earth. The aim of the mission is to use the space telescope for radio astronomical observations using VLBI (Very Long Baseline Interferometry) techniques in conjunction with “ground based” VLBI networks located in Australia, Chile, China, Europe, India, Japan, Korea, Mexico, Russia, South Africa, Ukraine, and USA. The expected orbit of the Radioastron satellite is evolving with time and has an apogee between 310,000 and 390,000 km, a perigee between 10,000 and 70,000 km, a period of 8–9 days, and an initial inclination of 51 degrees. Radioastron will operate at the standard radio astronomical wavelengths of 1.19–1.63, 6.2, 18, and 92 cm. Space-ground VLBI observations using Radioastron will provide morphological information on galactic and extragalactic radio sources. The spacecraft’s guaranteed operational lifetime is 5 years.

Spectrum-UV (Institute of Astronomy of the Russian Academy of Science). Spectrum UV is an international space observatory designed for observations in the ultraviolet domain. The observatory includes a single 170 cm aperture telescope capable of high-resolution spectroscopy, long slit low-resolution spectroscopy, and deep UV and optical imaging. The telescope optical configuration is Ritchey-Chetien, with primary mirror diameter – 170 cm, focal length – 1700 cm, field of view – 30 arc min. The spectrograph unit comprises three different single spectrographs: two high-resolution spectrographs – UVEC and VUVES (Germany), and a long-slit spectrograph LSS (see Table 11).

A Field Camera Unit (FCU) is being developed to carry out UV and optical diffraction limited imaging of astronomical objects. The FCU incorporates two UV cameras, FUV and NUV, and an optical camera (OC) (see Table 12).

The telescope is planned to be launched by a Zenit-2SB medium-class launcher equipped with a Fregat-SB accelerating module from Baikonur in 2014. The observatory is expected to operate for about 10 years. A geosynchronous

Table 11
Spectrograph-range (nm)-resolution.

Spectrograph	Range (nm)	Resolution
UVEC	174–310	50000
VUVES	102–172	55000
LSS	102–310	2500

Table 12
Camera range (nm) scale (arc sec/px) field of view (arc min^2).

Camera	Range (nm)	Scale (arc sec/px)	Field of view (arc min^2)
FUV	115–190	0.2	6.6×6.6
NUV	150–280	0.03	1.0×1.0
OC	250–700	0.07	4.6×4.6

orbit with an inclination of 51.8 degrees has been chosen. For this orbit the effects of the radiation belts will be negligible and the observing efficiency will be high.

Spectrum-Roentgen Gamma (Space Research Institute of the Russian Academy of Science). This mission is a Russian – German X-ray astrophysical observatory. Germany is responsible for the development of the key mission instrument – an X-ray grazing-incidence mirror telescope, eROSITA. The second experiment is ART-XC – an X-ray mirror telescope with a harder response than eROSITA, which is being developed by Russia (IKI, Moscow and VNIIEF, Sarov). The scientific payload is housed on the Navigator bus, developed by Lavochkin Association (Russia). Spectrum-RG will be delivered to the Sun-Earth L2 point with the use of a Zenit-2SB rocket and Fregat buster. The total mass of the SRG is 2385 kg. The SRG mission will be launched in 2013 from Baikonur and the observational programme will last 7 years. The first 4 years will be devoted to an all-sky survey, and the rest of the mission lifetime will be spent on follow-on pointed observations of a selection of the most interesting galaxy clusters and AGNs.

The mission will conduct an all-sky survey in the 0.5–11 keV band with the imaging telescopes eROSITA and ART-XC. It will permit the discovery of all obscured accreting Black Holes in nearby galaxies, many ($\sim$ millions) of new distant AGN, and the detection of all massive clusters of galaxies in the Universe. In addition to the all-sky survey, dedicated sky regions will be observed with higher sensitivity. Thereafter, follow-on pointed observations of selected sources at energies up to 30 keV will take place in order to investigate the nature of dark matter, dark energy and the physics of accretion.

The following projects are being considered for a more distant perspective: “Gamma-400”, “Millimetron” and “Interhelioprobe”. These projects are currently at the stage of experimental development; they are likely to be transferred to the 2016–2020 programme.

Gamma-400 (P.N. Lebedev Physical Institute of the Russian Academy of Science). This is the γ-ray observatory satellite. The scientific objectives of this project are comparable to those of the NASA Fermi mission. The main parameters for the Gamma-400 satellite are given in Table 13.

Millimetron (Astro Space Center of the P.N. Lebedev Physical Institute of the Russian Academy of Science). The goal of this project is to construct a space observatory operating in millimetre, sub-millimetre and infrared wavelength ranges (10 μm–2 cm) using a 12-m cryogenic telescope in a single-dish mode and as an interferometer with space-ground and space-space baselines (the latter after the launch of the second identical space telescope). The observatory will provide the possibility to conduct astronomical observations with super-high sensitivity (down to the nanoJansky level) in a single dish mode, and observations with super-high angular resolution in an interferometric mode. The current status of the project is draft design of payload.

Interhelioprobe (Institute of Earth magnetism, ionosphere and radiowaves propagation named after Nikolay Pushkov of the Russian Academy of Science). This satellite is targeted towards the close distance study of the Sun, its internal heliosphere, solution of the problems of the solar corona heating, acceleration of the solar wind, origins of the most powerful phenomena of the solar activity – solar flares and outbursts. After launch and numerous gravitational maneuvers near Venus, the spacecraft will approach the Sun, thus saving fuel and shortening the time of insertion into operational orbit. Gravitational maneuvers near Venus will also tilt the spacecraft orbit with respect to the Ecliptic and enable studying of the solar pole areas. When at perigee at distances of the order of 40 Solar radii, the spacecraft will be co-rotating with the Sun for about 7 days. During this period, the spacecraft will be observing the same part of the Sun which enable it to perform specific observations and measurements.

6.5. Decadal Plan for Australian Space Science

In the last few decades, the astronomy, astrophysics and space science activities in Australia have been confined to only a few areas using “ground based” observations. In

Table 13
Main parameters of the Gamma-400 Satellite.

Orbit	500–3,00,000 km
Gamma-ray energy range	100 MeV–3000 GeV
Sensitivie area	0.64 m^2
Coordinate detectors	Si strips with 0.1-mm pitch
Field of view	±45°
Angular resolution ($E\gamma > 100$ GeV)	$\sim$0.01°
Calorimeter-thickness, r.l.	BGO + Si strips, 30
Energy resolution ($E\gamma > 20$ GeV)	$\sim$1%
Proton rejection	10^6
Point source sensitivity, ph/cm^2/s ($E\gamma > 100$ MeV)	5×10^{-9}
Power consumption	2000 W
PL, total mass	2500 kg
Life time	5 years

the area of astronomy and astrophysics, the activities in the past flourished only in the lower end of the electromagnetic spectrum, i.e., optical and radio bands due to the distinct advantage of being in the southern hemisphere. This advantage has eroded to some extent over the past 10 years with the arrival of the ESO observatory in Chile. Major facilities like the Australia telescope for radio astronomy and the Anglo-Australian telescope for optical studies have been operating in Narabrai and Siding Springs and have given several remarkable results in recent years (?).

Australian presence in space-based research has been absent even though the indigenously built small satellite named Wresat was launched in 1967 and Fedsat followed in 2002. Balloon-borne experiments in X-ray/γ-ray astronomy were carried out in the last decades. Several proposed starts like the Mirabooka mission for X-ray astronomy and the Lyman ultraviolet space telescope were made in the past decades but they were not approved or not funded.

A major initiative has been recently proposed in the Australian Decadal plan for Space Science activities and the technology scenario for the 2011–2019 period as desired by the space science community. The proposed theme areas of P2P i.e. plasma-to-planets and RS, i.e. remote sensing, of the other members of the solar system will give new insight to our understanding of ‘Sun as a star’ as well as the solar system as a whole.

6.6. Programmes of Other Space Agencies

Most developing nations concentrate their space activities in Earth observation and meteorological studies, either through the use of third party satellites or, in cases where a sufficiently developed technological and industrial basis exists, through the construction and launch of indigenous spacecraft. As examples of the latter we can mention Argentina and Brazil, that show a proven record of capability to design and build reliable satellites and space-borne instrumentation. The Argentine Space Plan calls for the development and launch of two main series of Earth observing satellites, carrying either optical cameras and microwave sensors, or synthetic aperture radars. In the case of Brazil, the two “flagship” science missions, Equars and Mirex, have had considerable delays and priority is now given to remote sensing satellites like Amazonia-1 and Mapsar, among others. Similar cases can be noted in other regions of the world, like e.g., Taiwan, where the first Rocsat scientific satellite was followed by a second one devoted to remote sensing of the Earth. At a time when even the most developed space-faring nations tend to concentrate their efforts in “politically correct” endeavours to satisfy politicians and the general public, the road taken by less developed countries is easy to understand. What is important, however, in the possible framework of international cooperation described earlier, is that several of these countries have developed a substantial expertise in carrying out fairly complex space missions in cooperation with international partners. Argentina’s experience in a long-standing collaboration with US/NASA, as well as Denmark, France and Italy, and Brazil’s partnership with China on the CBERS (Sausen, 2001) series of Earth observing spacecraft, as well as with France, are primary examples of this type of relationship. Both Argentina and Brazil have also developed an incipient industrial basis able to provide instruments, spacecraft subsystems and even complete satellites.

7. Conclusions

The Working Group members and all who have worked on or participated in the year-long activity that resulted in this report have been aware of the extraordinary “golden age” which astronomers have experienced in the last decade, with unique and great opportunities for science.

The use of space-borne observatories continues to play a key role in the advance of astronomy and astrophysics by providing access to the entire electromagnetic spectrum from radio to high energy γ-rays.

The existence of an impressive fleet of space observatories complemented by “ground based” facilities has given the worldwide scientific community an incredible opportunity to make spectacular advances in our knowledge of the Universe. The open availability of existing and future datasets from space and “ground based” observatories is a clear path to enabling powerful and relatively inexpensive collaboration to address problems that can only be tackled by the application of extensive multi-wavelength observations.

Unfortunately, the panorama in the next decades, with only a few new major space missions planned, promises a much less productive future. At this stage remedial global action is required to correct this negative trend, to ensure positive prospects for future research, and to avoid a “dark age” for space astronomy.

We conclude that the size, complexity and costs of large space observatories must place a growing emphasis on international collaboration and multilateral cooperation. Although this poses technical and programmatic challenges, these challenges are not insurmountable, and the great scientific benefits will be a rich reward for everyone.

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Appendix A. The Astronet Report

A.1. Preface

Astronomy is the study of everything beyond Earth. It is a science driven by observations, with links to mathematics, physics, chemistry, computer science, geophysics, material science and biology. Astronomy is important for society and culture, and helps attract young people to the physical sciences. The field benefits from and also drives advances in technology. As a result, it is now possible to study objects which are so far away that they are seen at a time when the Universe was only 5% of its present age, and – perhaps even more astoundingly – to detect and characterise planets orbiting other stars, and to search for evidence of life. European astronomers have access to a range of observational facilities on the ground and in space. Plans are being made for a next generation of facilities, which would continue to exploit the rapid advances in, e.g., adaptive optics, detector sensitivity, computing capabilities, and in the ability to construct large precision structures, sending probes to Solar System objects, and even bring back samples from some of them. Realizing all the plans and dreams would require substantial investments by national and international funding agencies, with significant long-term commitments for operations. For this reason, funding agencies from a number of European countries established ASTRONET, an ERA-net with financial support from the European Union, to develop a comprehensive strategic plan for European astronomy covering the ambitions of all of astronomy, ground and space, including links with neighbouring fields, to establish the most effective approach towards answering the highest priority scientific questions. The first step is the development of an integrated Science Vision with strong community involvement, which identifies the key astronomical questions which may be answered in the next 20 years by a combination of observations, simulations, laboratory experiments, interpretation and theory. The next step is to construct a Road Map which defines the required infrastructures and technological developments, leading to an implementation plan. To this end, the ASTRONET Board appointed a Science Vision Working Group and an Infrastructure Road Map Working Group, both of them with supporting thematic panels. The Science Vision Working Group identified four key questions where significant advances and breakthroughs can be expected in the coming two decades:

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

These are amongst the most fundamental questions in science and generate considerable interest in the general public. The Science Vision Working Group and four supporting panels brought together about 50 scientists with a good distribution of expertise, gender and nationalities. Each of the panels concentrated on one of the key questions, and established the approach, experiment or new facility needed to make progress. Much information already existed in national strategic plans, ESA’s Cosmic Vision, and the three ESA-ESO studies. This work led to specific scientific recommendations, which were incorporated in a draft version of the Science Vision, made available to the entire astronomical community in late 2006. The draft was discussed in-depth during a Symposium in Poitiers, January 23–25, 2007. Many of the 228 participants from 31 countries provided constructive input, and additional comments were received via a dedicated website. This led to further sharpening of the scientific requirements, an improved balance across the four main areas, and improvements in the text... Care was taken to describe these in a fairly generic way, focusing on the scientific requirements, and not to identify too closely with specific proposed implementations of missions or facilities, as this is the purview of the infrastructure Road Mapping activity that will follow. ...summarises the main recommendations by thematic area, and distinguishes essential facilities or experiments, without which a certain scientific goal simply cannot be achieved, and complementary ones, which would go a long way towards answering the question, but may have their main scientific driver elsewhere... Activities needed across the four thematic areas are identified as well. In all cases, the focus is on the most promising avenues for scientific progress, without detailed consideration of cost or technological readiness, which are the subject of the infrastructure roadmapping. Some of the more ambitious facilities may take a significant time to develop, and in some case may only start to produce a scientific harvest towards the end of the 20 year horizon. Exploration remains an integral component of the entire field, as many problems require investigation of large numbers of objects, all different. This leads naturally to searches and surveys with modest-sised telescopes, and follow-up by larger facilities, together with a strong programme of theory, numerical simulations and laboratory experiments. Progress relies on a healthy mix of approaches including imaging, spectroscopy and time-series analysis across the entire electromagnetic spectrum, in situ measurements in the Solar System, and use of particles and gravitational waves as additional messengers from celestial objects. Europe has the opportunity to lead the expected scientific harvest, if the Infrastructure Road Map leads to an effective and timely implementation of the plans outlined in the Science Vision. This is a very exciting prospect…

Appendix B. Acronyms

AGILE	Astrorivelatore Gamma a Immagini LEggero
AGN	Active Galactic Nucleus (or Nuclei)
ALMA	Atacama Large Millimeter/submillimetre Array
Aquarius/SAC-D	Aquarius/Satlite de Aplicaciones Cientficas D (USA/Argentina)
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
ASTROSAT	Indian multi-wavelength astronomy mission on an IRS-class satellite
ATLAST	Advanced Technology Large Aperture Space Telescope (US study)
AO	Announcement of Opportunity
AXAF	Advanced X-ray Astrophysics Facility (Chandra X-ray Observatory)
CBERS	China. Brazil Earth Resources Satellite
CIFS	Consorzio Interuniversitario per la Fisica Spaziale, Italy
CMB	Cosmic Microwave Background
CNSA	Chinese National Space Administration
COBE/DIRBE	Cosmic Background Explorer/Diffuse Infrared Background Experiment
COSPAR	Committee on Space Research
CSA	Canadian Space Agency
CTA	Cherenkov Telescope Array
DLR	German Aerospace Center
DMD	Dark Matter Detection Programme (China)
EChO	Exoplanet Characterisation Observatory
ESF	European Science Foundation
EJSM/Laplace	Europa Jupiter System Mission / Laplace
ELT	Extremely Large Telescope
EQUARS	Equatorial Atmosphere Research Satellite (Brazil)
e-Rosita	German X-ray survey instrument on-board the Russian “Spectrum-Roentgen-Gamma” (SRG) spacecraft
ESA L Class Mission	ESA Large size Mission.
ESA M Class Mission	ESA Medium size Mission.
ESTEC	European Space Research and Technology Centre
ESSC	European Space Science Committee (of the European Science Foundation)
Fermi	γ Ray Space Telescope, formerly named Gamma Ray Large Area Space Telescope (GLAST)
FIR	far-infrared
Gaia	Global Astrometric Interferometer for Astrophysics
GALEX	Galaxy Evolution Explorer
GEMS	Gravity and Extreme Magnetism Small Explorer
GLAST	Gamma-ray Large Area Space Telescope, now named Fermi γ Ray Space Telescope
GLONAS	Global Navigation System (Russia)
GRB	γ Ray Burst
GSFC	Goddard Space Flight Center (NASA)
IAA	International Academy of Astronautics
IAF	International Astronautical Federation
IAU	International Astronomical Union
INTEGRAL	INTErnational Gamma-Ray Astrophysics Laboratory
INAF	Istituto Nazionale di Astrofisica (National Institute for Astrophysics, Italy)
INFN	Istituto nazionale di Fisica Nucleare (National Institure for Nuclear Physics, Italy)
ISRO	Indian Space Research Organisation
ISS	International Space Station
ISSI	International Space Science Institute (Bern)
ITAR	International Traffic in Arms Regulations (US)
IXO	International X-ray Observatory

JAXA	Japan Aerospace Exploration Agency
JWST	James Webb Space Telescope
LISA	Laser Interferometer Space Antenna
LOFAR	Low Frequency Array
LOFT	Large Observatory For X-ray Timing
LSST	Large Synoptic Survey Telescope
MAGIC	Major Atmospheric Gamma-ray Imaging Cherenkov telescope
MAXI	Monitor of All-sky X-ray Image
MIREX	Monitor e Imageador de Raios X (Brazil)
NuSTAR	Nuclear Spectroscopic Telescope Array
PACS	Photodetector Array Camera and Spectrometer, on board Planck
PAO	Portraits of Astrophysical Objects Programme (China)
PLATO	PLAanetary Transits and Oscillations of stars
PSLV	Payload Solar Launching Vehicle
POLAR	Gamma-ray Burst Polarisation instrument (on Chinas Spacelab)
RKA	Rossiskoye Kosmicheskoye Agentsvo (Russia)
RXTE	Rossi X-ray Timing Explorer
SAO	Smithsonian Astrophysical Observatory
SFXT	Supergiant Fast X-ray Transients
SKA	Square Kilometer Array
SMEX	Small Explorer, a US PI-led low-cost mission
Roscosmos	Russian Federal Space Agency
RXTE	Rossi X-ray Timing Explorer
SFXT	Supergiant Fast X-ray Transients project
SKA	Square Kilometer Array
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPC	Space Programme Committee
SPICA	Space Infrared Telescope for Cosmology and Astrophysics (Japan)
SPIRE	Spectral and Photometric Imaging Receiver, on board Planck
Spitzer ST	Spitzer Space Telescope
SRG	SpectrumX-Gamma Satellite (Russia)
STE-QUEST	Space-Time Explorer and Quantum Equivalence Principle Space Test
Suzaku (previously called Astro E2)	Japanese X-ray astronomy mission
Fermi Gamma Ray Space Telescope	Formerly named GLAST
SVOM	Space multi-band Variable Object Monitor
SWIFT	Swift Gamma-Ray Burst Mission
TMT	Thirty Meter Telescope
TPF	Terrestrial Planet Finder
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VLBI	Very Long Baseline Interferometry
WFIRST	Wide-Field Infrared Survey Telescope
WG	the COSPAR Working Group on the Future of Space Astronomy
WMAP	Wilkinson Microwave Anisotropy Probe
XMM-Newton	X-ray Multi-mirror Mission / Newton
XTP	X-ray Timing and Polarisation satellite

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