

Elsevier Editorial System(tm) for Advances in Space Research
Manuscript Draft

Manuscript Number: ASR-D-11-00388R1

Title: Future of Space Astronomy: a Global Road Map for the Next Decades

Article Type: IR - Invited Review Paper

Keywords: Future of Space Astronomy; COSPAR Working Group

Corresponding Author: Dr. pietro ubertini,

Corresponding Author's Institution:

First Author: Pietro Ubertini

Order of Authors: Pietro Ubertini; Neil Gehrels; Ian Corbett; Paolo De Bernardis; Marcos Machado; Matt Griffin; Michael Hauser; Ravinder K Manchanda; Nobuyuki Kawai; Shuang-Nan Zhang; Mikhail Pavlinsky

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 the radio observations to the high energy gamma 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. If the present set of space and ground-based astronomy facilities today is impressive and complete, with space and ground based astronomy telescopes nicely complementing each other, the situation becomes concerning and critical in the next 10-20 years. In fact, only a few main space missions are planned, possibly restricted to JWST and, perhaps, WFIRST and SPICA, since no other main facilities are already recommended.

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 roadmap 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.

Suggested Reviewers:

Response to Reviewers:

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



Email address: pietro.ubertini@iasf-roma.inaf.it (Pietro Ubertini)

Preprint submitted to Elsevier

November 20, 2011

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Future of Space Astronomy: a Global Road Map for the Next Decades

Pietro Ubertini^a, Neil Gehrels^b, Ian Corbett^c, Paolo De Bernardis^d, Marcos Machado^e, Matt Griffin^f, Michael Hauser^g, Ravinder K. Manchanda^h, Nobuyuki Kawaiⁱ, Shuang-Nan Zhang^j, Mikhail Pavlinsky^k

^a*INAF/IASF-Rome, Via del Fosso del Cavaliere, 100 - 00133 Rome, Italy*

^b*Astroparticle Physics Laboratory/NASA-GSFC, belt, MD 20771, U.S.A.*

^c*IAU - UAI Secretariat, F75014 Paris, France*

^d*University "La Sapienza", 00185 Rome, Italy*

^e*Comisión Nacional de Actividades Espaciales, 1063 Buenos Aires, Argentina*

^f*School of Physics and Astronomy, Cardiff University, The Parade, Cardiff, CF24 3AA, UK*

^g*Michael Hauser, Space Telescope Science Institute, Baltimore, MD 21218, U.S.A.*

^h*Tata Institute of Fundamental Research, 400005 Mumbai, India*

ⁱ*Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan*

^j*Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

^k*Russian Academy of Science, 117997 Moscow, Russia*

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 roadmap for future major

Email address: pietro.ubertini@iasf-roma.inaf.it (Pietro Ubertini)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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,

1
2
3
4
5
6
7
8
9 **Table of Contents**

10
11 **Executive Summary**

12 Recommendations concerning international planning and implementation of
13 large space astronomy missions

14 Roadmap Principles

15 Recommended Space Astronomy Roadmap

16 Conclusions
17

18
19 **1. The COSPAR Working Group on the Future of Space Astron-**
20 **omy**

21 1.1 Establishment of the Working Group

22 1.2 Terms of Reference and Membership of the Working Group

23 1.3 Mandate of the Working Group

24 1.4 Schedule of the Working Group
25
26

27 **2. Role of Developing Space-Faring Nations, a New Concept in In-**
28 **ternational Cooperation**

29
30 **3. The Working Group Vision**

31
32 3.1 The Present Scenario

33
34 3.2 Issues

35
36 3.3 Roadmap Principles

37
38 3.4 A Roadmap for the 2010-2020 Decade

39 3.4.1 IXO: International X-Ray Observatory

40 3.4.2 LISA: Laser Interferometer Space Antenna

41 3.4.3 EJSM: Europa Jupiter System Mission

42 3.4.4 Dark Energy and Exoplanet Science: Euclid and WFIRST

43 3.4.5 The ESA change of L-Class mission collaborative scheme
44
45

46 3.5 The 2020-2030 Decade Road Map

47
48 3.6 COSPAR Working Group Basic Recommendations

49
50 3.7 WG Conclusions
51

52 **4. The Present Scenario**

53
54 4.1 The ASTRONET Report: a Science Vision for (European) Astronomy

55
56 4.2 Spectral Coverage of Currently Operating Space Astrophysics Missions
57
58

- 4.2.1 X-Ray and γ -Ray
- 4.2.2 UV/Extreme UV and Visible
- 4.2.3 Infrared and Submillimeter
- 4.2.4 Submillimeter

4.3 Missions in Operation: short description and basic scientific characteristics

- 4.3.1 Hubble Space Telescope (HST)
- 4.3.2 Rossi X-ray Timing Explorer (RXTE)
- 4.3.3 Chandra X-Ray Observatory (CXO)
- 4.3.4 XMM-Newton Observatory
- 4.3.5 International Gamma-Ray Astrophysics Laboratory (INTEGRAL)
- 4.3.6 Galaxy Evolution Explorer (GALEX)
- 4.3.7 Spitzer Space Telescope
- 4.3.8 Swift Gamma-Ray Burst Mission
- 4.3.9 Suzaku X-Ray and hard X-Ray Telescopes
- 4.3.10 AGILE high energy gamma-ray mission
- 4.3.11 Fermi High Energy Gamma-Ray Telescope
- 4.3.12 Planck Mission
- 4.3.13 Herschel Mission
- 4.3.14 Monitor of All-sky X-Ray Image (MAXI)

4.4 Approved Missions in Development and Future Concepts

- 4.4.1 Gaia 3-D mapping of the stars of the Galaxy: launch 2013
- 4.4.2 ASTROSAT: launch 2012-2013
- 4.4.3 NuSTAR: launch 2012
- 4.4.4 Spectrum X- γ - eRosita experiment: launch 2014
- 4.4.5 Astro-H: launch: 2015
- 4.4.6 GEMS, Small Explorer, X-ray polarization mission launch: 2014
- 4.4.7 Hard X-ray Modulation Telescope (HXMT): Launch 2015
- 4.4.8 James Webb Space Telescope (JWST): launch 2018
- 4.4.9 Stratospheric Observatory for Infrared Astronomy (SOFIA): Fully operational 2014

5. The Future Programmes of the National Space Agencies

5.1 NASA future programmes and Vision

5.2 ESA future programmes and Cosmic Vision

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

6.0 The role and plan of the National Agencies

6.1 The Japan Space Astronomy Plan: JAXA Long Term Vision

6.2 Future Space Astronomy Programmes in China

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

6.3 The Indian Space science programme

6.4 The Russian Space Science programme

6.5 Decadal Plan for Australian Space Science

6.6 Programmes of Other Space Agencies

7. Conclusions

8. Acknowledgements

9. References

Appendix A: R. M. Bonnet talk at COSPAR meeting

Appendix B. Roadmap implementation plan

Appendix C: The Astronet Report

Appendix D. Message from F. Favata

Appendix E. Acronyms

1
2
3
4
5
6
7
8
9 **Executive Summary**

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

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

27
28 To this end, COSPAR appointed the "Future of Space Astronomy" Working
29 Group (hereafter, WG) under the aegis of Commission E [1], with the aim to
30 analyze the difficult situation of space astronomy over the next two decades and
31 recommend ways to improve the prospects.

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

41
42
43 **Recommendations concerning international planning and implemen-**
44 **tation of large space astronomy missions**

- 45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
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 implement 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 (see the message from F. Favata, Appendix C).
5. The international astronomical community, matured in the developed countries, is now spreading worldwide and is fertilizing 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 [2]. 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.

Roadmap Principles The Working Group considers it essential to develop

1
2
3
4
5
6
7
8
9 a space astronomy roadmap in the context of some important underlying prin-
10 ciples:

- 11 • Science driven: pursue top priority science topics stemming from state-of-
12 the art observations and theory, and set in a worldwide context;
- 13
- 14 • Observatory class missions: provide open access to the scientific commu-
15 nity at large, preferably with data available with no more than a short
16 turn-around time (6-12 months) after observations;
- 17
- 18 • Innovative enabling technology and cutting-edge scientific instrumenta-
19 tion: focus research and development support on innovative technolo-
20 gies and instrument concepts driven by science requirements for future
21 observatory-class missions;
- 22
- 23 • Technology development: national agencies and scientific councils support
24 research and development programmes to advance the Technical Readiness
25 Level of mission-critical elements to flight-ready status early in mission
26 preparation;
- 27

28 **Recommended Space Astronomy Roadmap**

29 A select group of future space astronomy missions has been identified in major
30 studies by national scientific committees to be of the highest priority. Critical
31 technologies and instrumentation for these missions have been brought to a high
32 level of technical readiness. Though these missions do not provide complete
33 coverage of the electromagnetic spectrum, the WG considers these missions to
34 be the most feasible core of the near-term major space astronomy missions, and
35 recommends this list as a roadmap for the next few decades.
36

- 37 • JWST. JWST [3] is a collaborative mission of NASA, ESA and the Cana-
38 dian Space Agency (CSA). It is the only future large space astronomy
39 mission already approved for development, with a planned launch in 2018.
40 It was the highest priority programme recommended in the US National
41 Academy of Sciences decadal survey in 2000 (Astronomy and Astrophysics
42 for the New Millenium), and its central importance to astronomy was re-
43 iterated in the 2010 survey (New Worlds, New Horizons). With a combi-
44 nation of near- and mid-infrared imagers and spectrometers, JWST will
45 provide unprecedented capability to study systems from the first galaxies
46 that formed in the early Universe, to newly forming stars and planetary
47 systems, and to bodies in our solar system. **The WG recommends**
48 **completion and launch of this major observatory as soon as pos-**
49 **sible. JWST is recognised to be the only new large space as-**
50 **tronomy Observatory to be possibly operational in the next 10-**
51 **20 years. It is an essential asset for space science investigations**
52 **complementing ground-based facilities planned.**
- 53 • Euclid/WFIRST [4], [5]. Both ESA and NASA are currently evaluat-
54 ing missions to study dark energy: Euclid (ESA; dark energy and dark
55
56
57
58

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

matter [6]) and Wide-Field Infrared Survey Telescope (WFIRST)(NASA; dark energy, exoplanets and near-infrared sky survey [7]). 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) [8]. 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 [9]. 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) [10]. LISA is a pioneering gravity-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 [11] 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 gravity-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) [12]. SPICA is 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, these challenges are not insurmountable, and the great scientific benefits will be a rich reward for everyone.¹

¹Note: 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.
The COSPAR Working Group Road Map implementation plan is outlined in Appendix B.

1
2
3
4
5
6
7
8
9 **1. The COSPAR Working Group on the Future of Space Astronomy**

10
11 *1.1. Establishment of the Working Group*

12 The use of observations from space continues to play a key role in the ad-
13 vance of astrophysics by providing access to the entire electromagnetic spectrum
14 from the radio region to high energy γ rays. The increasing size, complexity
15 and cost of large space-based observatory missions leads to a growing emphasis
16 on international collaboration, marked by the increasing range of joint missions
17 involving the large space agencies in the US (NASA), Europe (ESA), Japan
18 (JAXA), and Russia (RKA). Major future contributions are foreseen from the
19 Indian, Chinese and Korean space agencies, and countries in South America.
20 It is important that the world's space agencies coordinate their mission plans
21 for both large and small scale enterprises, both to make powerful missions af-
22 fordable and to provide maximum scientific value for money. The coordination
23 of existing and future datasets from space-based and ground-based observato-
24 ries is an emerging mode of powerful and relatively inexpensive collaboration
25 to address problems that can only be tackled by the application of large multi-
26 wavelength datasets. In April 2010, the President of COSPAR, Roger-Maurice
27 Bonnet, created the "Future of Space Astronomy Working Group", to be chaired
28 by P. Ubertini and co-chaired by N. Gehrels, under the aegis of Commission E,
29 with the task of analyzing the difficult situation of space astronomy over the
30 next two decades and recommending ways to improve the prospects. During his
31 opening message to the 38th COSPAR Assembly, held in Bremen, Germany on
32 18-25 July 2010 and attended by 3,500 scientists from 58 nations, Prof. Bonnet
33 announced the establishment of the Working Group. The relevant part of his
34 opening statement regarding the WG activity, is presented in Appendix A.

35 The newly elected COSPAR President, Giovanni Fabrizio Bignami, has fully
36 endorsed the objectives and activity of the Working Group.
37
38
39

40
41 *1.2. Terms of Reference and Memberships of the Working Group*

42 During the Bremen meeting, the new President fully endorsed the initial
43 Working Group Terms of Reference, specified to be as follows:

44 "If the present set of space and ground-based astronomy facilities is to-
45 day impressive and fairly complete, with space and ground based astronomy
46 telescopes complementing nicely, the situation becomes much more concerning
47 and critical in the next 10 or 15 years when new main space missions will be
48 much less numerous, probably restricted to JWST and possibly WFIRST and
49 SPICA, since no other main facilities are already recommended. The planning
50 of ground based astronomy facilities is in the hands of dedicated institutions
51 (ESO, NOAO, NRAO, etc...) which deal with their respective spectral bands,
52 while the planning of space missions is in the hands of space agencies which deal
53 with the whole space accessible spectrum, from high energy through infrared
54 and sub-millimeter ranges to the radio ranges. Space missions are becoming so
55 big that no space agency is able to cover alone the whole range of wavelengths
56 and clearly international cooperation is needed. That situation gives a strong
57
58

1
2
3
4
5
6
7
8
9 advantage to ground-based astronomy, where plans are already being made for
10 the next decade or so with such telescopes or facilities as ALMA, etc.

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

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

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

24 The membership of the COSPAR Working Group was finalised a few weeks
25 later with wide international participation and broad astrophysical competence.
26 The work commenced immediately after the end of the 2010 COSPAR Assem-
27 bly - a perfect starting point to focus on the state-of-the-art of worldwide space
28 astronomy research. The Working Group membership is as follows: Paolo
29 De Bernardis, Italy; Ian Corbett, UK, and IAU General Secretary (IAU liai-
30 son); Neil Gehrels, USA (Co-Chair); Matt Griffin, UK; Michael Hauser, USA;
31 Nobuyuki Kawai, Japan; Marcos Machado, Argentina; Ravinder K. Manchanda,
32 India; Mikhail Pavlinsky, Russia; Pietro Ubertini, Italy (Chair); Shuang-Nan
33 Zhang, China. Figure 1 is a photograph of the members that were able to at-
34 tend the meeting held in Bern, Switzerland in March 2011 and Figure 2 provides
35 photographs of the other members.
36
37

38 *1.3. Mandate of the Working Group*

39 The basic mandate of the Working Group was to establish a roadmap for the
40 planning of future main space missions with a particular focus on their capability
41 to complement the future large scale ground-based telescopes and observatories.
42 An important role will surely be played by ”small” and ”explorer” type satellites
43 and/or attached payloads on the International Space Station (ISS), with focused
44 though effective scientific objectives. These small/medium size experiments,
45 affordable by single space agencies or bi-lateral/multilateral collaborations, will
46 continue to be important for solving specific open astrophysical questions. The
47 BeppoSAX Italian-Dutch satellite [13] is a prototypical example of a moderate
48 cost satellite that was able, at the end of the '90s, to solve the three-decade old
49 mystery of the galactic or extragalactic nature of γ Ray Bursts [14], [15], [16].

50 The initial step to fulfill this task was to review the large amount of infor-
51 mation and material that already exists in agency-level strategic plans such as
52 ESA’s Cosmic Vision, the US National Academy of Science Decadal Survey, the
53 three ESA-ESO studies, etc.
54
55
56
57
58

1
2
3
4
5
6
7
8
9 The Working Group started with a comprehensive analysis of the outcomes
10 of the "cornerstone" studies that will influence in the next two decades the
11 future of space and ground-based astronomy [17]. Of particular relevance are:

- 12 1. The Astronet Report, [18]
- 13 2. The ESA Cosmic Vision, [6]
- 14 3. The US National Academy of Science Astro2010 Decadal Survey, [7]
- 15 4. National Agency's Roadmaps

16
17
18 The remit of the COSPAR WG is more limited than that of the above studies
19 and of course the WG does not have any power of decision or direct influence on
20 the different Space Agencies. With this boundary condition in mind, the WG
21 has adopted a very pragmatic approach to formulate a possible Road map for
22 the coming decades. The Astronet Report [18], which was released in 2006 in a
23 draft version, was subsequently discussed in depth during a Symposium held in
24 Poitiers (France) in January 2007, and is still considered a reference document
25 for the astrophysical community, states:

26 *" the main chapter describes the background of one of the four fundamental*
27 *questions (see the following paragraph), identifies the key goals, and then sum-*
28 *marises the experiments or observations needed to make significant progress.*
29 *Care was taken to describe these in a fairly generic way, focusing on the scien-*
30 *tific requirements, and not to identify too closely with specific proposed imple-*
31 *mentations of missions or facilities, as this is the purview of the infrastructure*
32 *roadmapping activity that will follow"*

33
34 The WG has identified a limited number of space missions and observato-
35 ries that are considered vital to solving key astrophysical questions and can be
36 guaranteed to provide major advances in our knowledge of the Universe. This
37 process was the final result of almost one year of study, achieved after a detailed
38 analysis of the currently operating fleet of space satellites for astronomical stud-
39 ies (Section 4.3), a review of the future missions already approved by the main
40 national space agencies and multilateral inter-Agency agreements (Section 4.4),
41 and potential additional missions proposed or under study by space agencies,
42 scientific institutions, consortia, single PIs etc. (Section 5). It is important
43 to recognise that lack of success in launching a minimum number of identified
44 missions in the next two decades would have harmful consequences beyond the
45 serious reduction in science investigation capability on the part of the existing
46 astronomical community. It would also represent a decline in leadership on the
47 part of NASA, ESA and the Space Agencies of the main developed countries,
48 and give rise to a damaging loss of technological know-how, hampering the
49 cutting-edge R&D advances historically enabled by space science programmes.

50 51 52 *1.4. Schedule of the Working Group*

53 The WG's activity plan was to conduct a comprehensive analysis of the
54 present situation and currently foreseen scenario for space science, and to ex-
55 amine future perspectives with the aim of defining a number of high level rec-
56 ommendations and a 'road map'.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

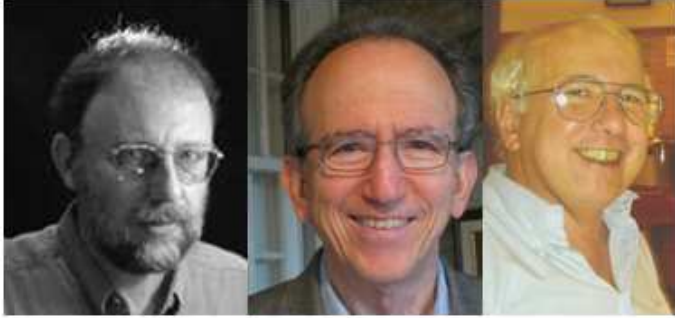


Figure 2: Paolo De Bernardis, Michael Hauser, Marcos Machado

their own satellites or space qualified instruments that can be flown on board third party spacecraft. In times of globalization, 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 [19] 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 ten 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 [19] 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, ALMA, SKA, , ELT, Gemini, LSST, TMT CTA, HAWC, Pierre Auger, [20] [21] [22] [23] [24] [25] [26] [27] [28] [29], to name some of the better known, have significant contributions from a wide range of countries including developing nations.

1
2
3
4
5
6
7
8
9 These concepts were developed over decades by large international consortia.
10 In some cases one of their major contributions is the provision of the site, but
11 this is by no means a general rule or condition for a country's participation; in
12 fact, in most cases the opportunity to participate in a major scientific endeavor
13 is what is most attractive to the countries' academic communities, government
14 agencies, and high-tech enterprises.
15

16 We thus envision the possibility that a similar scheme can be adopted in space
17 science missions. Examples already exist in areas outside astronomy and astro-
18 physics, like the China-Brazil [30] series of remote sensing satellites, or the re-
19 cently launched Argentina-USA SAC-D/Aquarius mission devoted to the study
20 of ocean salinity. Since future large observatories in space will require a partner-
21 ship of several or even many national agencies, it will be important to develop a
22 new model of partnership. Even though in practice leadership by major agencies
23 such as NASA or ESA may need to remain, given their available resources and
24 infrastructure, the decision-making process will need to be improved if smaller
25 agencies are to be involved in major international missions. Often the leadership
26 role by larger agencies gets misinterpreted as a commanding role, rather than
27 a true partnership where all parties are sensitive and respectful to all involved.
28 Once again, the experience of large ground-based projects shows how science-
29 driven facilities can be developed and implemented through large multi-agency
30 collaborations.
31
32

33 It may therefore be helpful to adopt a new paradigm for International space
34 astronomy collaboration, perhaps analogous to that used at CERN for large ex-
35 periments like the LHC with several levels of associate-ship, ranging from simple
36 observer to non-member to full member. National participation as an observer
37 would allow the member to attend the meetings without any participation. As-
38 sociate members could participate in the science and technical discussions and
39 influence the decision making without having an actual vote, and nations pro-
40 viding funding for the project would have the right to take part in the decision
41 making process. Such a model would serve two key purposes. First, a national
42 presence, even as an observer, will give the relevant country the respectability
43 of its association with large international missions, motivate the national space
44 research programmes and also help deal with capacity building in space sciences.
45 Second, it may motivate the politicians of the participating nations to aspire to
46 become full members in order to contribute effectively in the decision making
47 process.
48

49 A practical issue which is already known as a real impediment to wider
50 collaboration is the application of the U.S. International Traffic in Arms Regu-
51 lations (ITAR), which has proved to be a serious problem in several instances
52 already.
53
54
55
56
57
58

1
2
3
4
5
6
7
8
9 **3. The Working Group Vision**

10
11 An international Roadmap is needed that will take into account the im-
12 portance of key space missions enabling the scientific integration of the space
13 observational windows with large ground-based facilities. This Working Group
14 has promoted open discussions involving the IAU, IAF, IAA and all the na-
15 tional agencies willing to contribute, in order to analyse the best approach to
16 the establishment of a viable and solid global Roadmap.

17
18 The most likely candidates for new major space astronomy missions in the
19 next few decades may be found in the plans of ESA and NASA. ESA has a
20 long term plan articulated in the document *ESA Cosmic Vision: Space Science*
21 *for Europe 2015-2025* [6]. The selection process is still under way. The next
22 L-class mission is to be selected by 2012. The future vision for the US ground
23 and space astronomy programmes, with current key scientific questions and
24 discovery areas as well as programmatic recommendations, is included in the US
25 National Academy of Sciences Astro2010 Decadal Survey Report *New Worlds,*
26 *New Horizons in Astronomy and Astrophysics*[7], with much more detail in
27 each subject area in the reports from the Astro2010 Science Frontiers Panels
28 and Program Prioritization Panels *Panel Reports - New Worlds, New Horizons*
29 *in Astronomy and Astrophysics* [31].

30
31 *3.1. The Present Scenario*

32 In order to develop specific roadmap recommendations, the WG began by
33 reviewing the present context. We provide here a summary of our findings.
34 Much more detail is presented in section 4 of this paper.

35 The present panorama for ground and space large facilities, summarised in an
36 incomplete picture, is shown in Figure 3. In the next five years only a few
37 small/medium size missions are expected to be completed and placed in orbit.
38 Currently operating large Observatories will continue to operate with aging
39 hardware and weakened scientific grasp. The best scenario we can hope for
40 through 2015 could be as shown in Figure 4.

41 The robust state of space astrophysics missions over the past three decades
42 and the diminished prospect in the future is perhaps more clearly illustrated in
43 Figure 5. Without strong corrective action, the space astrophysics community
44 will lose the main space observatories without comprehensive future replacement
45 for decades.
46
47
48
49
50
51
52
53
54
55
56
57
58

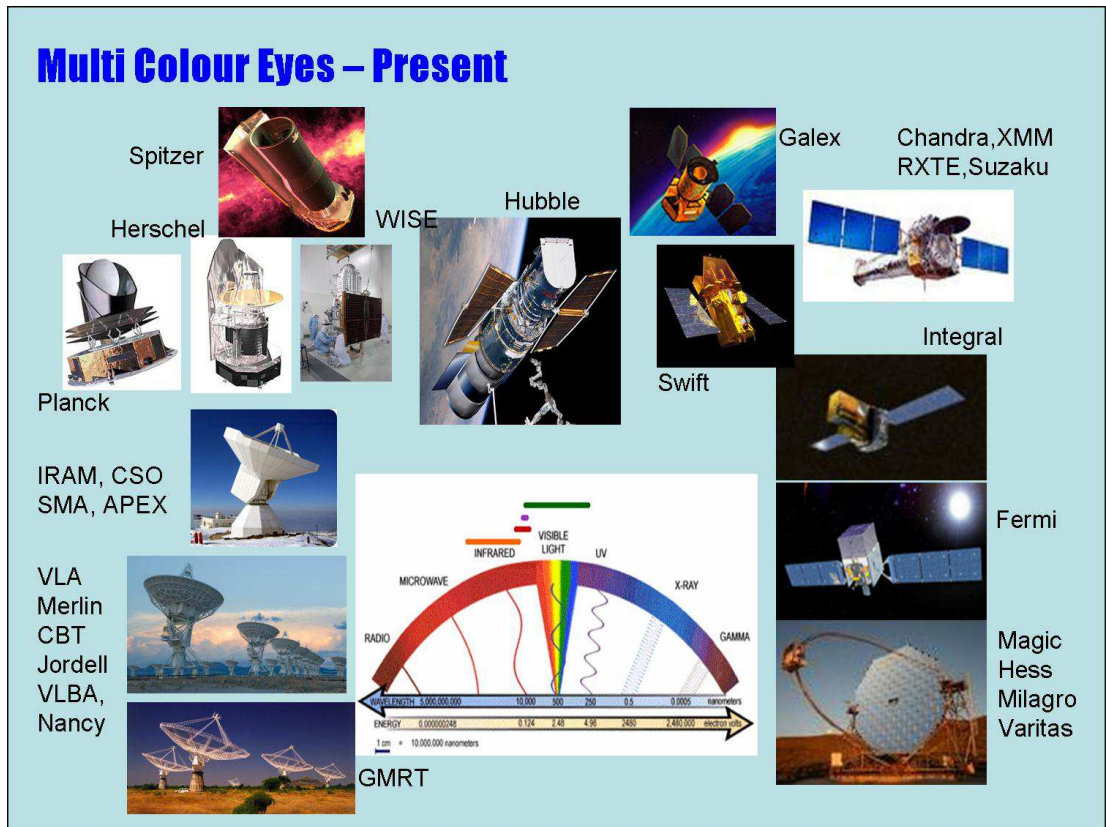


Figure 3: Present panorama for ground and space large facilities.

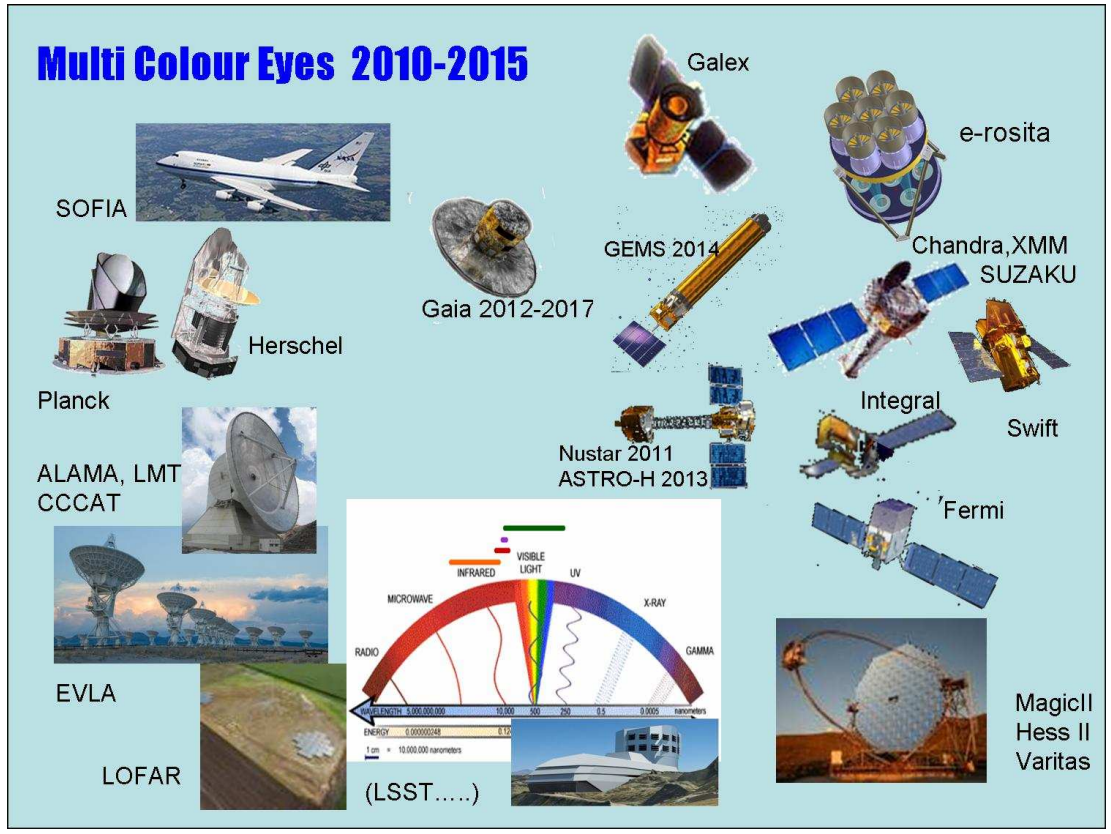


Figure 4: The best scenario. A few small/medium size missions are expected to be completed and placed in orbit. Current operative missions, like Chandra, XMM, INTEGRAL, SWIFT, etc. will hopefully be supported and in good hardware status in the future years. Few new entries are expected: ASTROSAT, Nustar, Astro-H, GEMS, e-Rosita etc.

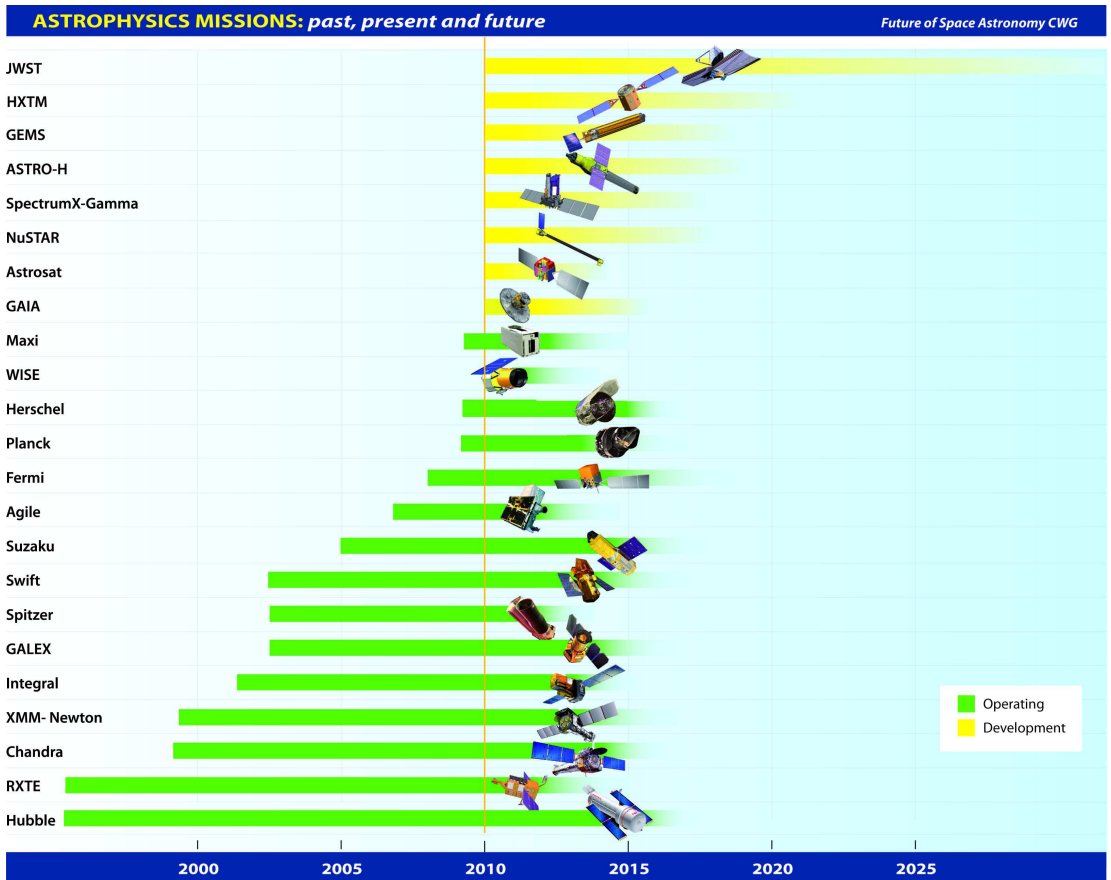


Figure 5: Missions in operation with projected lifetime (Green), and Missions under development (Yellow) with scheduled launch date indicated by the S/C position

1
2
3
4
5
6
7
8
9
3.2. *Issues*

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

- 12 1. The impressive fleet of currently operating space observatories is aging:
13 HST [32], Chandra [33], XMM-Newton [34], and RXTE [35] are more
14 than 10 years old, and INTEGRAL [36], SWIFT [37], Spitzer [38], Suzaku
15 [39], and GALEX [40] have all been operating for between 5 and 8 years.
16 Most of them are in the extended phase operation and can be expected to
17 suffer hardware degradation. The successful Herschel [41] and Planck [42]
18 missions have lifetimes limited by their cryogenic design, and will both
19 come to an end by 2014.
- 20 2. Following JWST [3], there are NO large astrophysics space missions cur-
21 rently approved. Consequently, a major gap in the coverage of the elec-
22 tromagnetic spectrum will arise after 2015. This raises the prospect of a
23 new 'dark age', with lack of large facilities, in particular for high energy
24 astrophysics.
- 25 3. In contrast, there are solid and internationally agreed plans for the imple-
26 mentation of major ground-based observatories, from the long-wavelength
27 radio region to ultra high energy γ -rays. Space missions with comparable
28 scientific power will be needed to give complementary access to spectral
29 regions not accessible from the ground.
- 30 4. The development and implementation of large space observatories, with
31 increasing cost, large consortia, heavy payloads and space facilities, re-
32 quires multilateral effort and solid decadal or multi-decadal agreements
33 that are not easy to attain in view of short-middle term budget planning
34 by different countries (USA, Europe etc). An example of how this is now
35 damaging the prospects for space astronomy is the mismatch between the
36 timescales for mission selection in the NASA programme and ESA Cosmic
37 Vision.
- 38 5. A different type of collaboration programme, system and instrument level,
39 requiring multilateral cooperation among agencies, but an easier program-
40 matic interface has been adopted by ESA and NASA for the Mars Mis-
41 sions. In this scenario the national agencies collaborate at the PRO-
42 GRAMME level, where one or two nations develops one mission of mutual
43 interest and another nation (or two) develops another. Scientists from all
44 countries in the PROGRAMME are supported by their countries to partici-
45 pate in the scientific planning and research with data from all missions.
46 This may simplify management and cost control, and circumvent technol-
47 ogy transfer constraints and issues preventing exchange of funds. The
48 potential value of such arrangements for astrophysics missions is worth
49 considering.
- 50
51
52
53

54 3.3. *Roadmap Principles*

55 The Working Group adopted a few basic principles to guide development of
56 a space astronomy roadmap that would be widely accepted:
57
58

- 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 Roadmap 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 meter collecting area and 5 arcsec angular resolution, and a suite of instrumentation, including a wide field imaging detector, a hard X-ray

1
2
3
4
5
6
7
8
9 imaging detector, a high-spectral-resolution imaging spectrometer (calorimeter),
10 a grating spectrometer, a high time-resolution spectrometer, and a polarimeter.
11 IXO would provide up to 100-fold increase in effective area for high resolution
12 spectroscopy from 0.3-10 keV, deep spectral imaging from 0.3-40 keV over a
13 wide field of view, and microsecond spectroscopic timing with high count rate
14 capability [43].

15 **Working group assessment and recommendations:**

16 **The increasing cost and schedule delay of JWST has made the US**
17 **timescale inconsistent with that of ESA. As a consequence the re-**
18 **scheduled ESA L-class mission down-selection² had been planned for**
19 **the second half of 2012³ Consequently, ESA has announced the re-**
20 **scheduling of the mission compatible with an ESA-led project within a**
21 **more limited budget envelope. The new ESA policy is triggering the**
22 **development of new mission scenarios with new possible participating**
23 **partners, and it is possible that a world-class mission could emerge.**
24 **Nevertheless, there are serious concerns that the scientific capabilities**
25 **originally envisaged may be significantly compromised.**
26

27
28 *3.4.2. LISA:Laser Interferometer Space Antenna*

29 The Laser Interferometer Space Antenna (LISA) was planned as a cooper-
30 ative mission between NASA and ESA, designed to measure 'ripples' in space-
31 time, detecting and characterising gravitational waves that are emitted during
32 the most powerful events in the universe. LISA will detect gravitational radia-
33 tion from astronomical sources, observing galaxies far back in time, and testing
34 the fundamental theories of gravitation. Predicted by Einstein's general the-
35 ory of relativity, these ripples, called gravitational waves, are generated during
36 events in which very massive objects undergo strong acceleration. Examples of
37 such events are massive black holes swallowing neutron stars or the collision of
38 two massive black holes. LISA was due to be the first mission to detect gravi-
39 tational waves from space, making possible observations at low frequencies that
40 would be difficult from the ground. LISA's three spacecraft were planned to
41 form an equilateral triangle with arms of about 5 million km in length. Each
42 spacecraft was designed to house two free-floating test masses made of a gold-
43 platinum alloy, shielded from adverse effects of being in interplanetary space,
44 with the distance between the test masses in different spacecraft being moni-
45 tored using highly accurate laser-based techniques. In this manner, it is possible
46 to detect minute changes caused by passing gravitational waves. Gravitational
47 waves are an integral part of Einstein's theory of general relativity. When a
48 massive body is strongly accelerated, it radiates gravitational waves. The diffi-
49 culty is that, even for very massive bodies, such as black holes or neutron stars,
50
51
52

53 ²Note: The statement 'down-selection' is used by ESA to indicate 'no further consideration'
54 during the mission selection process

55 ³Note: the JWST cost increase prevents NASA from funding a large scale observatory
56 with a launch date compatible with the ESA Cosmic Vision Plan, i.e., L1 launch 2020-2022
57 timeframe.
58

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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 harbors 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-

1
2
3
4
5
6
7
8
9 formulate the science case, re-structure the mission, and study which of the
10 original science goals of the EJSM mission concept can be achieved by a Euro-
11 pean led mission. The SST process is scheduled to be terminated in February
12 2012.

13
14 *3.4.4. Dark Energy and Exoplanet Science: WFIRST (NASA Decadal Survey)*
15 *and Euclid (ESA M-Class Mission)*

16 **WFIRST (NASA)**

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

33
34 **Euclid (ESA - M Class Mission)**

35 The mission has a 1.2-meter-class telescope and instruments in the visible
36 and near-infrared. Its primary observation is a large (~15,000 square degrees)
37 imaging and spectroscopic (slitless) sky survey. Euclid is designed to address
38 key questions relevant to fundamental physics and cosmology, namely the nature
39 of the mysterious dark energy and dark matter. Astronomers are now
40 convinced that these substances dominate ordinary matter. Euclid would map
41 the distribution of galaxies to reveal the underlying 'dark' architecture of the
42 Universe.

43
44 **Working group assessment and recommendations:**

45 **Euclid has now been selected by ESA. Join together the Dark Energy**
46 **missions in Europe and the US. Add-in possible other partners from**
47 **Canada, China, India and possibly Russia.**

48
49
50 *3.4.5. The ESA change of L Class mission collaborative scheme*

51 On March 15 2011, F. Favata, Head of the Science Planning and Community
52 Coordination Office informed the community of a relevant change of collabora-
53 tive scheme with NASA on the three L Class mission candidates with an e-mail
54 to the Members of the Space Science Advisory Committee, Astronomy Working
55 Group, and Solar System and Exploration Working Group, to be distributed to
56 interested people. The main message was that "the US budgetary prospective
57
58

1
2
3
4
5
6
7
8
9 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 2020's 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".⁴

19 *The impact of the "ESA alone" programmatic decision on NASA-JAXA common programme*

22 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 2022-23 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 first down selection from three to two missions is planned for the beginning of 2012.

47 **Working group assessment and recommendations:**

48 **LISA and IXO are large scale observatories, both of which are vital**
49 **to ensure a breakthrough in knowledge of the Universe. It is impor-**
50 **tant that if a similar mission is selected by ESA for implementation in**
51 **Cosmic Vision, it should have scientific objectives that are compatible**
52 **with the ambitions of the scientific community. If not selected, the**
53 **international community should pursue a new route to implementa-**

56 ⁴The whole text is reported in Appendix D

1
2
3
4
5
6
7
8
9 **tion. An international X-Ray mission should be planned, focused on**
10 **First Stars, black hole physics and cosmic chemical evolution of the**
11 **Universe. Likewise, a low-frequency gravitational wave observatory**
12 **such as LISA will be essential to realise the promise of this new area**
13 **of science.**
14

15 **The WG expresses a strong concern about the feasibility of develop-**
16 **ing large space observatories by a single Agency/country.**
17

18
19 *3.5. The 2020-2030 Decade Roadmap*

20 In the post-2020 era, without corrective actions, the best case scenario may
21 become as shown in Figure 6, with JWST the only new mission launched in
22 the present decade and many current missions ceasing operation before 2020.
23 As this Figure illustrates, there would be little synergy between ground and
24 space observatories, and the international community will have lost parts of the
25 electromagnetic spectrum. In the area of high energy astrophysics, the only
26 foreseen Observatory class mission is IXO/Athena. This ESA led-NASA-JAXA
27 mission is now in competition with LISA and EJSM for the ESA 2012 L-Class
28 down selection process, with two out of the three studies to go ahead to the
29 next stage of study. The final selection to fly is expected by 2014.
30

31
32 *Proposed longer term large missions (to fly within \sim two decades)*
33

34 In addition to the major mission candidates discussed above, numerous ad-
35 ditional ideas have been advanced in countries around the world. We list here
36 examples to illustrate the rich potential of space astronomy in the future.
37

- 38 • Next generation γ Ray Observatory
- 39 • Large specialised exoplanet characterization mission (e.g., a version of
40 TPF, Terrestrial Planet Finder)
- 41 • Next generation UV-Optical-IR -optical telescope, such as ATLAST (Ad-
42 vanced Technology Large Aperture Space Telescope, studied in the US)
- 43 • Large-aperture far-infrared (FIR) telescope (recommended by US Decadal
44 Survey in 2000) and a future priority of the FIR/submillimeter commu-
45 nity)
- 46 • Far Infrared Interferometer (high angular resolution imaging and spec-
47 troscopy) studied in US and Europe, and a future priority of the FIR
48 community)
- 49 • Space Submillimeter array
- 50 • Post-Planck CMB polarization mission (exploration of the physics of in-
51 flation)
- 52
- 53
- 54
- 55
- 56
- 57
- 58

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



Figure 6: 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 (down selection between IXO, LISA and EJSM by 2012 and final selection to fly by 2014)

1
2
3
4
5
6
7
8
9 *Medium sized missions proposed to NASA, ESA, JAXA, Roscosmos and*
10 *other Agencies*

- 11 • GRB First Stars Finder: rapid response, 1-m IR telescope, wide-field X-
12 ray instrument to detect high z γ -ray bursts (GRB)
- 13
- 14 • Hard X-ray/soft γ -ray focusing or modulation telescope
- 15
- 16 • HXMT - Hard X-ray Modulation Telescope (approved by CNSA and CAS
17 for launch in 2014-2015): China, Italy, others
- 18
- 19 • LOFT- X-Ray timing large area (ESA M3 candidate; possible selection by
20 end 2012)
- 21
- 22 • SVOM - GRB detection and study (launch 2014-2015): China-France col-
23 laboration
- 24
- 25 • Timing and X-ray Timing and Polarization- India, China, Russia
- 26
- 27 • Cosmic-ray and dark matter origin: China, Japan, etc.; possible joint
28 mission
- 29
- 30 • PLATO (ESA M2 candidate)
- 31
- 32 • EChO (ESA M3 candidate) - exoplanet
- 33
- 34 • MARCO POLO (ESA M3 candidate) - exoplanet
- 35
- 36 • STE-QUEST (ESA M3 candidate) - equivalence principle
- 37
- 38 • Post-Planck CMB polarization mission (exploration of the physics of in-
39 flation); concepts under development in USA, Europe, Japan
- 40
- 41 • SPICA: far infrared observatory (Japan, ESA, Canada, USA) - to be con-
42 sidered medium-large; launch 2018
- 43
- 44 • Millimetron - VLBI and submillimeter single dish observatory; Russia,
45 Italy, etc
- 46
- 47 • Radioastron - VLBI; Russia with international participation

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

50 *3.6. The COSPAR Working Group on Future of Space Astronomy Basic Rec-*
51 *ommendations*

- 52 • Launch JWST as early as possible in the present decade. JWST is recog-
53 nised to be the only approved large space observatory to be possibly op-
54 erational in the next 10-20 years. It is an essential asset for space science
55 investigations complementing ground-based facilities planned (e.g., LO-
56 FAR, ALMA, SKA, , ELT, Gemini, LSST, TMT CTA, HAWC, Pierre
57 Auger, [20] [21] [22] [23] [24] [25] [26] [27] [28] [29], 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 gravity-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 $z \geq 10$, 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.

1
2
3
4
5
6
7
8
9 **4. The Present Scenario**

10 *4.1. The ASTRONET Report: a Science Vision for (European) Astronomy*

11 This paragraph is a summary of the Astronet report published in 2007, [18]
12 which presents a vision shared by the WG. The excerpt below in italics is simply
13 reported here as a reminder of the "basic facts" that the WG endorses. The
14 short following paragraph is also a good summary of the WG vision for ground-
15 based observatory status and future plans⁵.
16

17 *Astronomy is the study of everything beyond Earth. It is a science driven by*
18 *observations, with links to mathematics, physics, chemistry, computer science,*
19 *geophysics, material science and biology. Astronomy is important for society*
20 *and culture, and helps attract young people to the physical sciences. The field*
21 *benefits from and also drives advances in technology. As a result, it is now*
22 *possible to study objects which are so far away that they are seen at a time*
23 *when the Universe was only five per cent of its present age, and - perhaps even*
24 *more astoundingly - to detect and characterise planets orbiting other stars, and*
25 *to search for evidence of life. European astronomers have access to a range of*
26 *observational facilities on the ground and in space. Plans are being made for a*
27 *next generation of facilities, which would continue to exploit the rapid advances*
28 *in, e.g., adaptive optics, detector sensitivity, computing capabilities, and in the*
29 *ability to construct large precision structures, sending probes to Solar System*
30 *objects, and even bring back samples from some of them. Realizing all the plans*
31 *and dreams would require substantial investments by national and international*
32 *funding agencies, with significant long-term commitments for operations. The*
33 *Astronet Science Vision Working Group identified four key questions where sig-*
34 *nificant advances and breakthroughs can be expected in the coming two decades:*
35

- 36
- 37 • *Do we understand the extremes of the Universe?*
 - 38
 - 39 • *How do galaxies form and evolve?*
 - 40
 - 41 • *What is the origin and evolution of stars and planets?*
 - 42
 - 43 • *How do we (and the Solar System) fit in?*

44 *These are amongst the most fundamental questions in science and generate con-*
45 *siderable interest in the general public.*

46 In addition to the Astronet Report, the COSPAR Working Group has analyzed
47 the information already existing in national strategic plans, ESA's Cosmic Vi-
48 sion, the US National Academy of Science Decadal Survey, ESA-ESO studies,
49 etc. ...the Astronet work led to specific scientific recommendations, which were
50 incorporated in a draft version of the Science Vision, made available to the entire
51 astronomical community in late 2006. The draft was discussed in-depth during
52 a Symposium in Poitiers, Paris, Jan 23-25, 2007. Many of the 228 participants
53 from 31 countries provided constructive input, and additional comments were
54

55

56 ⁵Note: Appendix C provides more of the Astronet report relevant for this paper
57

1
2
3
4
5
6
7
8
9 received via a dedicated website. This led to further sharpening of the scientific
10 requirements, an improved balance across the four main areas, and improve-
11 ments in the text... Care was taken to describe these in a fairly generic way,
12 focusing on the scientific requirements, and not to identify too closely with spe-
13 cific proposed implementations of missions or facilities, as this is the purview of
14 the infrastructure roadmapping activity that will follow. ...summarises the main
15 recommendations by thematic area, and distinguishes essential facilities or ex-
16 periments, without which a certain scientific goal simply cannot be achieved,
17 and complementary ones, which would go a long way towards answering the
18 question, but may have their main scientific driver elsewhere...Activities needed
19 across the four thematic areas are identified as well. In all cases, the focus is on
20 the most promising avenues for scientific progress, without detailed considera-
21 tion of cost or technological readiness, which are the subject of the infrastructure
22 roadmapping. Some of the more ambitious facilities may take a significant time
23 to develop, and in some case may only start to produce a scientific harvest
24 towards the end of the 20 year horizon. Progress relies on a healthy mix of
25 approaches including imaging, spectroscopy and time-series analysis across the
26 entire electromagnetic spectrum, in situ measurements in the Solar System, and
27 use of particles and gravitational waves as additional messengers from celestial
28 objects.
29

30 Most of the above concepts were shared by the COSPAR WG members and a
31 similar approach was taken as a starting point to elaborate the WG vision.
32

33 4.2. Spectral Coverage of Currently Operating Space Astrophysics Missions 34

35 To clarify the full electromagnetic spectral coverage of the currently operat-
36 ing space astronomy and astrophysics missions and the more limited coverage
37 of those approved and under development (Figure 5, we begin with a short de-
38 scription organised by spectral range. In the following section we provide more
39 detail about each of the missions and the scientific contributions of the operating
40 missions.
41

42 4.2.1. X-rays and γ -rays

43 The NASA Rossi-XTE mission, providing high resolution timing studies
44 of X-ray sources over the 1-200 keV range, continues to operate successfully
45 producing key findings on variable, pulsed and quasi-periodic sources. The
46 world-wide γ -ray burst and transient monitoring capability is in excellent shape
47 with the continued operation of the Swift mission. Bursts have been detected
48 from the early universe at redshifts in the range of the most distant objects
49 known. NASA's Chandra observatory and ESA's X-ray Multi-mirror Mission
50 (XMM-Newton) have been operating successfully in space since 1999. With
51 their complementary emphases on high angular resolution (Chandra) and high
52 throughput spectroscopy (XMM-Newton), these observatory missions continue
53 to generate major advances in astrophysics. The two missions have been partic-
54 ularly effective in studying distant galaxies, including the massive black holes
55 at their centres, galactic mergers, and the billion-degree gas that permeates the
56
57
58

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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 polarization 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 Submillimeter*

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 sur-

veys. 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 submillimeter 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 to 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. Submillimeter

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 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. Figure 5 and Table 1 show and list respectively the satellites and observatory class missions which are operating in space and have continuing data analysis efforts.

Figure 5 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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table 1: Figure 5 details

MISSION	Details: in Operation
HST 1990	(NASA/ESA) Observatory mission: 2.4m telescope, imaging/spectroscopy of galactic and extragalactic sources
Rossi XTE 1995	(NASA) Timing and broadband spectroscopy of compact X-ray sources (1-200 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, 3m 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	The Specturm X- γ eRosita experiment
Astro-H 2014	(JAXA-NASA) X-ray mission for high resolution spectroscopy and hard X-rays
GEMS 2014	(NASA) SMEX X-ray polarization mission
HXMT 2015	Hard X-ray Modulation Telescope (1-250 keV)
JWST 2018	(NASA/ESA) Observatory, IR 6.5m mirror telescope sensitive from 0.6 to 27 micrometers



Figure 7: The Hubble Space Telescope in space

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 Figure 7 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 fifteen 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 fifteen percent of the funding of the HST via contribution of the Faint Object Camera and the solar arrays. In return, NASA guaranteed at least fifteen percent of telescope time to European astronomers. In 1977, Congress approved funding to build HST, 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 [32].

1
2
3
4
5
6
7
8
9 HST currently has the most powerful suite of instruments in its history.

10 ACS - Advanced Camera for Surveys - The Advanced Camera for Surveys
11 (ACS) is a third-generation UV-optical imaging camera installed in 2002. It
12 contains a Wide-Field Camera (WFC), a High-Resolution Camera (HRC), and
13 a Solar Blind Camera (SBC). The WFC and HRC failed in 2006. In Servicing
14 Mission 4 (SM4, May 2009), the Wide Field Camera was repaired; but the High
15 Resolution camera did not recover. The ACS conducts surveys of the universe
16 and studies the nature and distribution of galaxies. It studies ultraviolet emis-
17 sions from stars, takes pictures of other planets in our solar system, and is used
18 to search neighboring stars for planets.

19
20 NICMOS - Near Infrared Camera/Multi-Object Spectrometer - The Near-
21 Infrared Camera/Multi-Object Spectrometer (NICMOS) is a 2nd generation
22 instrument installed in 1997. It is Hubble's first infrared instrument, with life-
23 time extended by installation of a mechanical NICMOS Cooling System (NCS)
24 in 2002. Its sensitivity to infrared light makes it useful for observing objects
25 obscured by interstellar gas and dust, such as stellar birthsites and planetary
26 atmospheres, and for peering into deepest space.

27 STIS - Space Telescope Imaging Spectrograph- The Space Telescope Imaging
28 Spectrograph (STIS) is a second-generation imager/spectrograph installed in
29 1997. It had an electronics failure in 2004, but was repaired in SM4. STIS
30 is a versatile instrument used to obtain high resolution spectra or spectrally-
31 resolved images of objects such as nebulae, galaxies and the atmospheres of
32 planets around other stars, among other things.

33 WFC 3 - Wide Field Camera 3 - Wide Field Camera 3 (WFC3) is a 4th-
34 generation camera installed in SM4 that contains both a powerful ultraviolet-
35 optical channel and a highly sensitive, wide-field infrared channel. WFC 3
36 is used to study the way galaxies evolve over time, the history of individual
37 galaxies, the mystery of dark energy and the nature of objects in our solar
38 system.

39 COS - Cosmic Origins Spectrograph - The Cosmic Origins Spectrograph
40 (COS) is a 4th -generation spectrometer installed in SM4. COS is an ultra-
41 violet spectrograph optimised for observing faint point sources with moderate
42 spectral resolution. It is used to examine galaxy evolution, the formation of
43 planets and the rise of the elements needed for life, and the "cosmic web" of gas
44 between galaxies.

45
46 *Mission achievement summary*

47 The Hubble Space Telescope has arguably had a greater impact on astronomy
48 and, as importantly, on worldwide appreciation of and support for astronomy,
49 than any observatory since Galileo's telescope. HST has produced many remark-
50 able discoveries, some anticipated and some totally surprising, ranging from our
51 solar system to galaxies as they appeared within a billion years after the Big
52 Bang. As a few examples, Hubble images of solar system bodies from Venus to
53 Kuiper-belt objects, including comets crashing into the atmosphere of Jupiter,
54 star and planetary systems forming in our Galaxy, galaxies in collision and the
55 host galaxies of gamma-ray burst sources grace text-books and class-room walls
56 around the globe and advance our understanding of how we got here. Hubble
57
58

1
2
3
4
5
6
7
8
9 spectral data showed us the atmospheric constituents of planets orbiting other
10 stars, and showed us that there are supermassive black holes in the centers of
11 most galaxies. Most surprisingly, HST played a key role in perhaps the most
12 transformative scientific discovery since Edwin Hubble discovered the expansion
13 of the Universe. In 1998, two teams of astronomers [44] [45] using data from
14 ground-based telescopes and HST presented evidence that the expansion of the
15 Universe is currently accelerating, rather than decelerating under the influence
16 of gravity as expected. Unless Einsteins general theory of relativity needs to
17 be modified, the acceleration appears to be propelled by the repulsive force of
18 a mysterious dark energy. The nature of the dark energy is arguably the most
19 profound puzzle facing physics today. The observers used Type Ia supernovae
20 as bright, standard candles to trace the expansion history of the Universe. The
21 high angular resolution of HST was essential to separating the light of the most
22 distant supernovae from that of the host galaxy, and thereby obtaining an ac-
23 curate distance. Figure 8) shows HST data for three such events, both before
24 and after the supernova explosions. The HST observations demonstrated three
25 critical points confirming the reality of the acceleration: prior to about 5 billion
26 years ago, the expansion was decelerating, indicating that gravity was then dom-
27 inating over dark energy; dark energy was already present as early as 9 billion
28 years ago, though not yet dominant; dark energy behaves in a manner consistent
29 with what quantum mechanics predicts for vacuum energy. Improving observa-
30 tional determinations of the character of dark energy is a major motivator for
31 future astronomical studies
32
33

34 *4.3.2. Rossi X-Ray Timing Explorer (RXTE)*

35 The Rossi X-ray Timing Explorer (RXTE) was launched on 30 December
36 1995 from NASA's Kennedy Space Center (see Figure 9). The mission is man-
37 aged and controlled by NASA's Goddard Space Flight Center (GSFC) in Green-
38 belt, Maryland. RXTE features unprecedented time resolution in combination
39 with moderate spectral resolution to explore the variability of X-ray sources.
40 Time scales from microseconds to months are covered in an instantaneous spec-
41 tral range from 2 to 250 keV. Originally designed for a required lifetime of two
42 years with a goal of five, RXTE is still performing well and will complete 16
43 years of operation in December 2011. The mission carries two pointed instru-
44 ments, the Proportional Counter Array (PCA) developed by GSFC to cover the
45 lower part of the energy range, and the High Energy X-ray Timing Experiment
46 (HEXTE) developed by the University of California San Diego covering the
47 upper energy range. These instruments are equipped with collimators yielding
48 a FWHM of one degree. In addition, RXTE carries an All-Sky Monitor (ASM)
49 from the Massachusetts Institute of Technology (MIT) that scans about 80% of
50 the sky every orbit, allowing monitoring at time scales of 90 minutes or longer.
51 Data from PCA and ASM are processed on board by the Experiment Data Sys-
52 tem (EDS), also built by MIT [35].

53 *Mission achievement summary*

54 The RXTE has proved to be a successful mission for exploration and new discov-
55 eries. In particular, the large collecting area of the PCA is a key tool for study
56
57
58

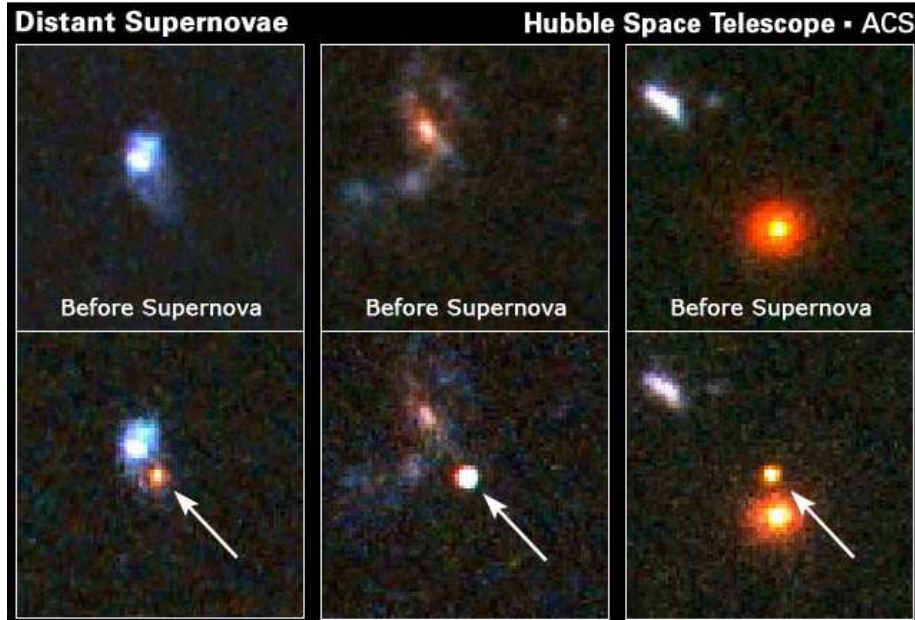


Figure 8: HST discovery of distant Supernovae

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 Hz to 435 Hz and discovery of twin kilohertz QPOs detected in weak-field neutron stars having frequencies from ~ 100 Hz to ~ 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 $K\alpha$ 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.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



Figure 9: Rossi X-Ray Timing Explorer (RXTE) during ground test



Figure 10: Chandra X-Ray Observatory artist's concept

4.3.3. Chandra X-ray Observatory

NASA's Advanced X-ray Astrophysics Facility, (AXAF), renamed the Chandra X-ray Observatory in honor of Subrahmanyan Chandrasekhar, was launched and deployed by the Space Shuttle Columbia on the 23 of July 1999 (see Figure 10). 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 [33]. The Smithsonian Astrophysical Observatory (SAO) in Cambridge, Massachusetts, is responsible for the conduct of the day-to-day flight 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-second
4. Orbit: 64 hour 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-minutes diameter and an effective area of 800 and 400 cm^2 @ 0.25 and 5 keV, respectively.

- 1
2
3
4
5
6
7
8
9 6. Four detectors can be inserted, one at a time, into the focal plane. Two
10 of these are designed to be used primarily with the gratings:
- 11 • AXAF Charged Coupled Imaging Spectrometer (ACIS): energy range
12 0.2-10 keV:
13 one 4-chip imaging array (ACIS-I), Field of View 16 X 16,
14 one 6-chip spectroscopic array (ACIS-S), Field of View 8 X 48
 - 15 • High Resolution Camera (HRC): energy range 0.1-10 keV,
 - 16 • High Energy Transmission Grating + ACIS-S (HETG): energy range
17 0.5-10 keV
 - 18 • Low Energy Transmission Grating + HRC-S (LETG) energy range
19 0.08-6.0 keV

20
21
22
23 *Mission achievement summary*

24 The main features of the Chandra X-Ray Observatory are the sub-arcsecond an-
25 gular resolution and capability to provide spatially resolved spectra on the same
26 scale. These characteristics are not provided by any other mission and may not
27 be provided by any other mission for several decades. Chandra is one of NASAs
28 Great Observatories and its main strengths are unprecedented spatial resolution,
29 sensitivity that extends from soft X-rays up to 10 keV, and the ability to obtain
30 high spectral resolution observations over most of this range with the use of the
31 gratings. Chandra has provided outstanding scientific results in a broad range
32 of extragalactic studies from cosmology, to clusters of galaxies, to AGN, and to
33 resolution of the sources of the cosmic X-Ray background radiation. Chandra
34 has also enabled Galactic studies of star formation, white dwarfs, neutron stars
35 and black holes. Chandra studies have advanced our understanding of the dark
36 energy, dark matter, and baryonic matter that comprise the Universe; of the
37 physical processes that govern the formation and evolution of stars, galaxies,
38 and galaxy clusters; of the formation and dispersal of heavy elements needed
39 for planets and life; and of the nature of the laws of physics under extreme
40 conditions. Chandra and XMM-Newton (see next paragraph) providing have been
41 two most powerful X-Ray Observatories in orbit for more than a decade and are
42 complementary to each other: Chandra providing the best angular resolution
43 ever achieved and XMM-Newton providing the highest throughput. A compre-
44 hensive review of the main results achieved in the first 10 years of scientific
45 observations of these two Observatory-class satellites is reported in [46]. Table
46 2 summarises the main achievements of the two observatories. Examples of the
47 scientific investigation power of these observatories are illustrated in Figures 11
48 and 12, which show respectively the best X-Ray image of the Crab Nebula and
49 Pulsar ever achieved and the image of a deep XMM-Newton extragalactic field.

50
51
52 *4.3.4. The XMM-Newton Observatory*

53 XMM-Newton observatory is ESA's second 'Cornerstone' mission and was
54 launched on 10 December 1999 from Kourou on the first commercial Ariane-5
55 into a highly elliptical 48 h orbit (see Figure 13). The mission provides high-
56 quality X-ray and optical/UV data from the European Photon Imaging Camera
57
58

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

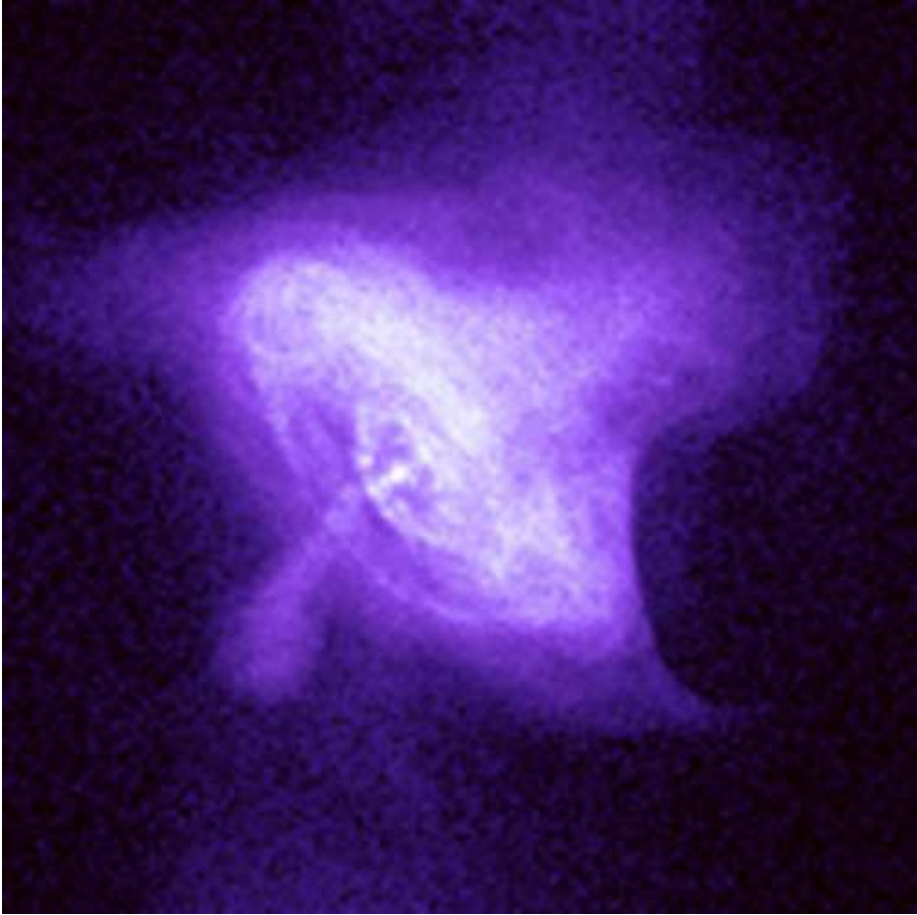


Figure 11: A sharp X-ray image of the Crab Nebula and Pulsar obtained with the CHANDRA Observatory (Credit: NASA/CXC/SAO).

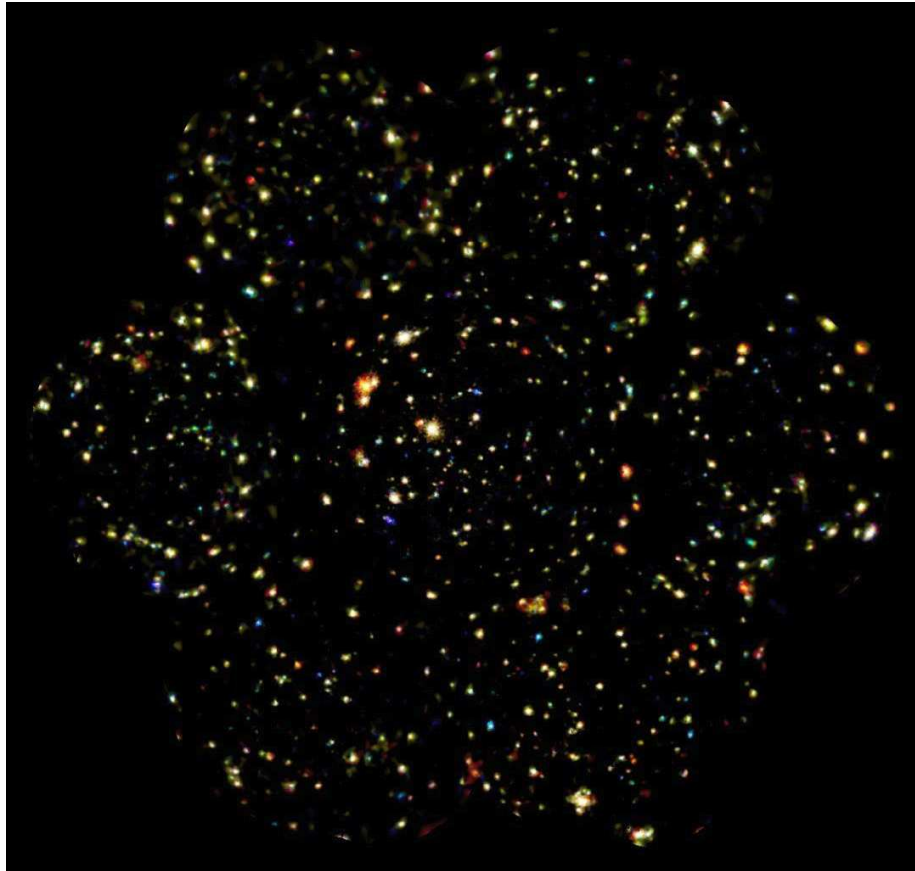


Figure 12: A deep XMM-Newton extragalactic X-Ray image (Credit: Image courtesy of Ian Stewart and Mike Watson (Leicester University, XMM-Newton Survey Science Centre) and ESA).



Image courtesy of D. Faber

XMM-Newton preparation

European Space Agency

Figure 13: XMM during ground testing

1
2
3
4
5
6
7
8
9 (EPIC), the Reflection Grating Spectrometer (RGS) and the Optical Monitor
10 (OM) [34]. XMM-Newton is a 3-axis-stabilised spacecraft with a mass of about
11 4 t. The satellite is dominated by a large carbon-fibre telescope tube attached
12 to the Service Module (SVM) at one end and to the Focal Plane Assembly
13 (FPA) at the other. The SVM is a platform that carries all the equipment for
14 the power, data handling, and attitude and orbit control subsystems, including
15 the structure to support the solar arrays and antennas. The attitude control
16 loop uses a star tracker and momentum wheels, which allow for a slew rate of
17 90 per hour and a pointing reconstruction accuracy of a few arcsec. Gyros are
18 used only in cases of eclipses or anomalies. The operations efficiency allows for
19 a maximum of 132 ksec of science observations per revolution; the remaining 40
20 ksec are spent inside the Earth's radiation belts. The mission routinely responds
21 to Targets of Opportunity (ToO) requests with a response time as short as 5
22 h. This has been put to good use a number of times when XMM-Newton has
23 performed rapid follow-up of γ -ray bursts.

24
25 *Mission achievement summary*

26 XMM-Newton is a facility-class X-ray observatory that is a cornerstone of ESA's
27 Horizon 2000 programme. The instruments on XMM-Newton are the European
28 Photon Imaging Camera, which contains three imaging devices (EPIC, 0.2-12
29 keV, 30' FOV, 6" FWHM), two Reflection Grating Spectrometers (RGS, 0.33-
30 2.5 keV, 3-38A, spectral resolution of 0.06A), and the Optical Monitor (OM)
31 with a 16' FOV operating from 1800-6500 Å. With this impressive set of co-
32 aligned telescopes in its operative energy band XMM-Newton provides to the
33 scientific observer the largest collecting area for imaging and spectroscopic stud-
34 ies from a fraction of a keV up to 15 keV, over a field of view that is larger than
35 Chandra and Suzaku. A summary of Chandra and XMM-Newton first decade
36 scientific results, adapted from [46], is given in Table 2.
37
38

39
40 *4.3.5. INTEGRAL: International Gamma-Ray Astrophysics Laboratory*

41 The ESA INTEGRAL mission was approved as the 2nd medium size ESA
42 project of the Horizon 2000 scientific programme in April 1993 (see Figure 14),
43 [36]. The programme is led by ESA, with the instrument complement and the
44 Scientific Data Centre (based in Geneva) provided by five different European
45 consortia. Contributions were also provided by Russia, for the Proton launcher,
46 and by the USA which made available the NASA Deep Space Network ground
47 station at Goldstone [47]. The payload was calibrated at the beginning of 2002
48 at the European Space Research and Technology Centre (ESTEC) in Noord-
49 wijk, the Netherlands. INTEGRAL was successfully launched from Baikonur
50 (Kazakhstan) on 17 October 2002 for a planned operational lifetime of 2 years
51 with possible extension. The Observatory is devoted to the observation of the
52 γ -ray Universe in the energy range from 15 keV to 10 MeV with substantial
53 monitoring capability in the X-ray range, from 3 to 30 keV, and in the optical
54 V band at 550 nm. The two γ -ray instruments are the spectrometer, SPI, and
55 the imager, IBIS. SPI is a high resolution, cooled, germanium-based coded mask
56 spectrometer with unprecedented sensitivity to diffuse emission over a very wide
57
58

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table 2: Chandra and XMM-Newton First Decade Results Summary [46]

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 star-forming regions	Discovered X-ray emission from gas-accreting 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 in galaxies and clusters of galaxies	Discovered evidence for heating of hot gas in galaxies and clusters by outbursts produced 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.

1
2
3
4
5
6
7
8
9 field of view ($\sim 25^\circ$ FWHM) [48]. 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 [49]. It provides fine angular resolution (<12 arcmin), wide spectral response (15 keV-10 MeV), high resolution timing (60 sec) 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.

10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28 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.

29 *Mission achievement summary*

30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49 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 arcmin 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 [50]. 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 Figure 15). INTEGRAL remains unique world-wide as an observatory providing these capabilities. Key science areas of INTEGRAL include:

- 50 1. Studies of nucleosynthesis through γ -ray lines from elements formed in supernovae,
 - 51 2. Studies of positron production and annihilation,
 - 52 3. Studies of the physics of emission mechanisms of white dwarfs, neutron stars, and black holes and associated transient phenomena
 - 53 4. Deep surveys for supermassive black holes in Active Galactic Nuclei, and
 - 54 5. γ -ray burst studies.
- 55
56
57
58

1
2
3
4
5
6
7
8
9 The main results obtained so far include the first sky map in the light of the
10 511 keV annihilation emission, the discovery of a new class of high mass X-ray
11 binaries and detection of polarization in cosmic high energy radiation. For the
12 foreseeable future, INTEGRAL will remain the only observatory enabling the
13 study of nucleosynthesis in our Galaxy, including the next, long overdue, nearby
14 supernova, through high-resolution γ -ray line spectroscopy [51]. INTEGRAL
15 observations have uncovered a new class of highly absorbed, slowly spinning
16 pulsars, have shown pulsar wind nebulae to be the γ -ray counterpart of the new
17 TeV sources, and detected the most distant γ -ray quasars, a break-trough in
18 relativistic astrophysics. The 30% unidentified new INTEGRAL sources are a
19 remaining mystery. Recently, the new class of Fast Supergiant X-Ray Transients
20 has been discovered by INTEGRAL, posing a challenge to stellar evolution
21 modeling [52], [53], [54].
22

23 4.3.6. GALEX, Galaxy Evolution Explorer

24 The Galaxy Evolution Explorer (GALEX) is a small mission with an ultra-
25 violet space telescope for imaging the sky with a 1.2 degree field of view and
26 a resolution of ~ 5 arcsec. A Pegasus rocket launched GALEX into orbit on
27 April 28th, 2003 (see Figure 16). The mission is now in an extended phase, but
28 the formal Guest Investigator Program has been discontinued. The observatory
29 continues to collect near-ultraviolet (227 nm) images for a Legacy Survey. Led
30 by the California Institute of Technology, GALEX is conducting several first-of-
31 a-kind sky surveys, including an extra-galactic (beyond our galaxy) ultraviolet
32 all-sky survey. During its mission, GALEX produced the first comprehensive
33 map of a Universe of galaxies under construction, bringing us closer to under-
34 standing how galaxies like our own Milky Way were formed. GALEX is also
35 identifying celestial objects for further study by ongoing and future missions.
36 GALEX data now populate a large archive available to the entire astronomical
37 community and to the general public. Scientists would like to understand when
38 the stars that we see today and the chemical elements that make up our Milky
39 Way galaxy were formed. With its ultraviolet observations, GALEX is filling in
40 one of the key pieces of this puzzle [40].
41

42 *Mission achievement summary*

43 A five-year survey of 200,000 galaxies, stretching back seven billion years in cos-
44 mic time, has led to one of the best independent confirmations that dark energy
45 is driving our universe apart at accelerating speeds. The survey used data from
46 NASA's space-based Galaxy Evolution Explorer and the Anglo-Australian Tele-
47 scope on Siding Spring Mountain in Australia. The findings offer new support
48 for the favored theory of how dark energy works – as a constant force, uniformly
49 affecting the universe and propelling its runaway expansion. They contradict
50 an alternate theory, where gravity, not dark energy, is the force pushing space
51 apart. According to this alternate theory, with which the new survey results
52 are not consistent, Einstein's concept of gravity is wrong, and gravity becomes
53 repulsive instead of attractive when acting at great distances.
54
55
56
57
58



Figure 14: INTEGRAL during ground testing at ESTEC, ESA

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

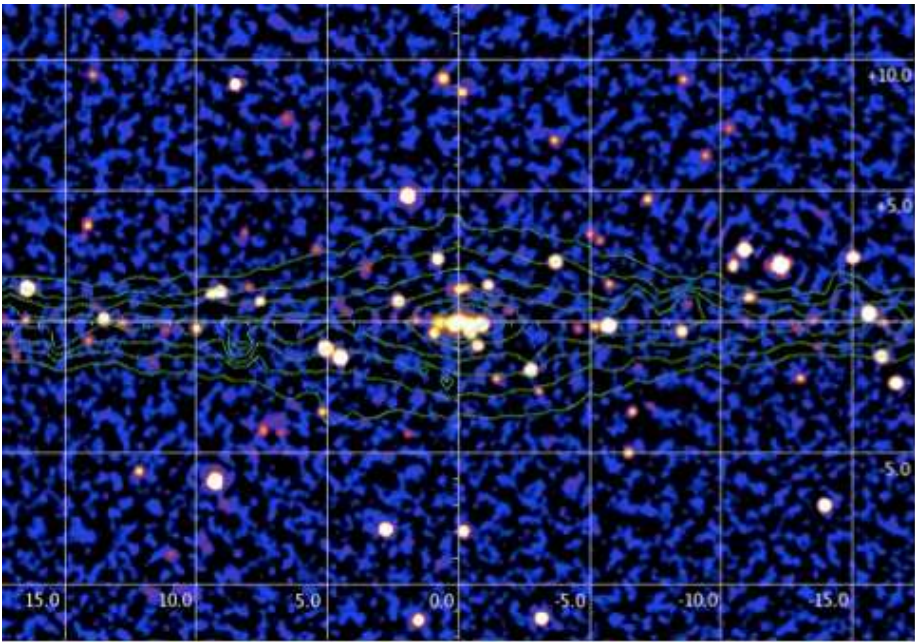


Figure 15: The central part of the Milky Way Galaxy seen by INTEGRAL/IBIS (17-60 keV). Green curves are iso-contours of surface brightness in the infrared from COBE/DIRBE, tracing the surface density of stars in the Galaxy. The maximum sensitivity of the map is within 5 to 10 of the Galactic Centre. Credit: Krivonos et al., A&A 519, A107, 2010, reproduced with permission ESO.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

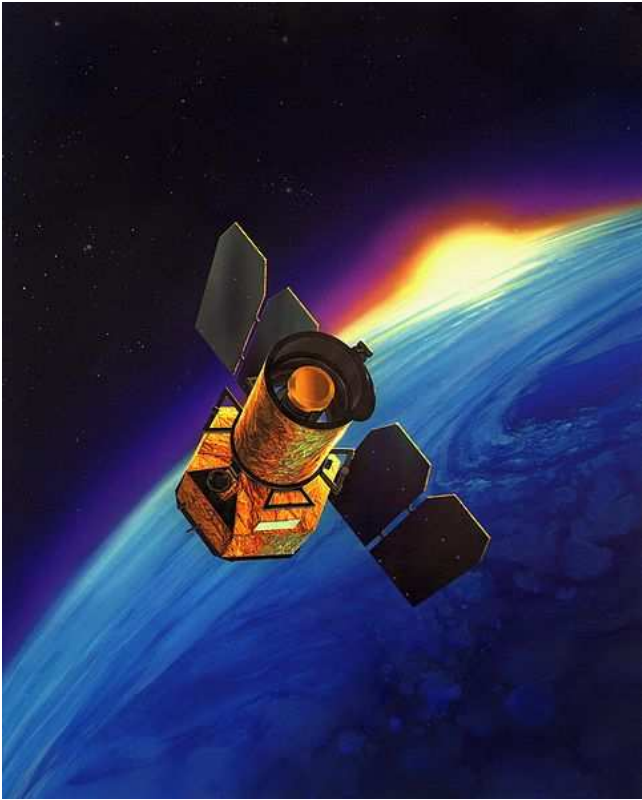


Figure 16: GALEX artist's concept

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

4.3.7. Spitzer Space Telescope

The Spitzer Space Telescope, launched on 25 August 2003 into an Earth trailing solar (see Figure 17), consists of a 0.85-meter 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.

The outer shell and inner, middle, and outer shields are vapor cooled, i.e., the cold helium exhaust vapor from the liquid helium tank is used to carry away the heat from these structures. The telescope is attached to the top to the vapor-cooled cryostat shell. The telescope and cryostat shell were launched warm, and cooled down radiatively once in orbit. The multiple instrument chamber (MIC) containing the science instruments is mounted in the cryostat, and warm electronics are mounted on 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 [38].

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 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

1
2
3
4
5
6
7
8
9 and the interstellar medium. Spitzer has also enabled major advances in the
10 study of planetary system formation and evolution. For example, debris disks
11 comprising cold material, identified via their $70\mu\text{m}$ excess, have been shown to
12 be common features of main sequence stars, with no correlation of the excess
13 with metallicity or spectral type, but a weak dependence on stellar age, with
14 younger stars more likely to have excess emission. Systems with warmer debris
15 (of the kind discovered by the IRAS satellite around the star Vega) created by
16 collisions in forming planetary disks, and heated by the central star, have also
17 been studied. Their emission is found to be strongly dependent on recent col-
18 lision history, suggesting that interplanetary dust around main sequence stars
19 varies stochastically as a result of major collision events. Spectroscopic study
20 with Spitzer of the atmospheres of brown dwarf stars reveal non-equilibrium
21 chemistry and show that brown dwarfs are just as likely as more massive stars
22 to harbor circumstellar disks. This implies that brown dwarfs as low in mass as
23 ~ 10 Jupiters appear to form by the same process as solar-mass stars.

24
25 Spitzer has made the first detections of secondary eclipse signatures from 'hot
26 Jupiter' exoplanets, providing information on the temperature and atmospheric
27 properties of the planets. Within the solar system, spectral observations by
28 Spitzer of the debris created by the collision of the Deep Impact probe with
29 Comet Tempell, revealed the silicate composition of the interior.

30 31 *4.3.8. The Swift Gamma-Ray Burst Mission*

32 Swift (see Figure 18), a mission designed to study γ -ray bursts, is part of
33 NASA's medium explorer (MIDEX) programme and was launched into a low-
34 Earth orbit on a Delta 7320 rocket on 20 November 2004 [37]. Gamma-ray
35 bursts (GRBs) are the most powerful explosions the Universe has seen since the
36 Big Bang. They occur approximately once per day and are brief, but intense,
37 flashes of γ radiation. They come from all different directions of the sky and
38 last from a few milliseconds to a few hundred seconds. So far scientists do not
39 know what causes them. Do they signal the birth of a black hole in a massive
40 stellar explosion? Are they the product of the collision of two neutron stars?
41 Or is it some other exotic phenomenon that causes these bursts? With Swift, a
42 NASA mission with international participation, scientists have a tool dedicated
43 to answering these questions and solving the γ -ray burst mystery. Its three
44 instruments give scientists the ability to scrutinise γ -ray bursts as never before.
45 Within seconds of detecting a burst, Swift relays its location to ground stations,
46 allowing both ground-based and space-based telescopes around the world the
47 opportunity to observe the burst's afterglow. GRB 100413B is Number 500 (see
48 Figure 19) detected by Swift/BAT since the mission was launched [55].

49 50 51 *4.3.9. Suzaku X-ray and hard X-ray telescopes*

52 Suzaku (previously called Astro-E2) was successfully launched on 10 July
53 2005 by the Japan Aerospace Exploration Agency (JAXA) in collaboration with
54 US (NASA/GSFC and MIT) and Japanese institutes (see Figure 20). Suzaku
55 covers the energy range 0.3-600 keV and is currently performing astronomi-
56 cal observations using imaging CCD cameras (XIS) and a hard X-ray detector
57
58

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



Figure 17: The Spitzer satellite during ground testing

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

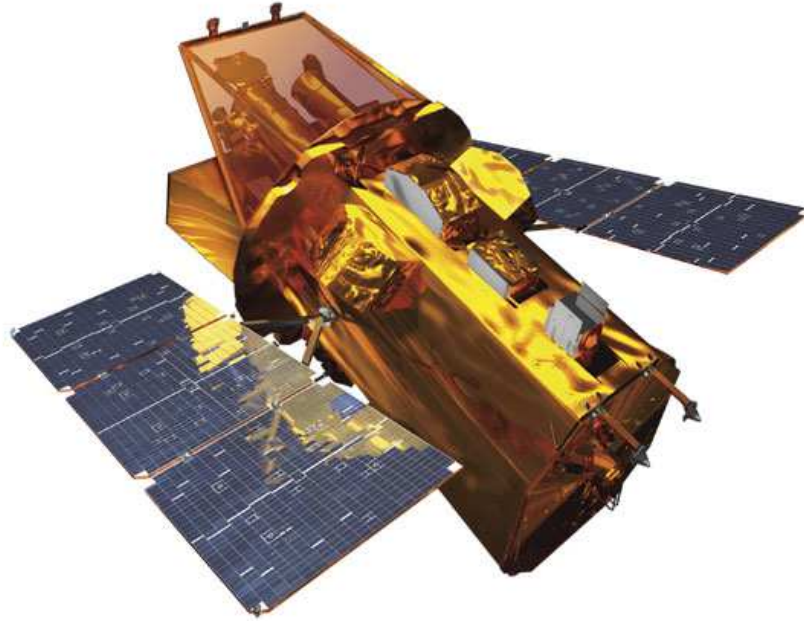


Figure 18: Swift artist's concept

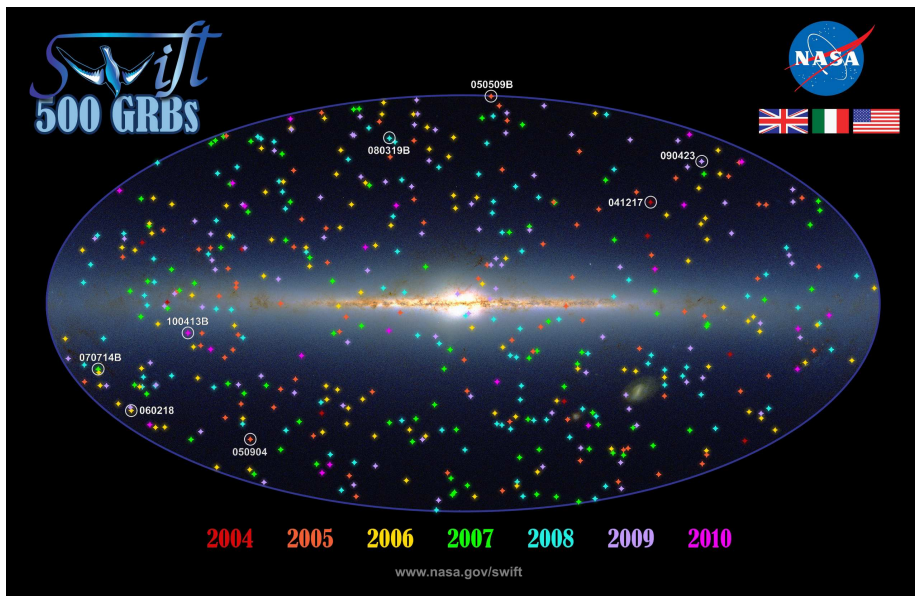


Figure 19: Sky distribution of 500 γ -ray bursts detected by Swift



Figure 20: Suzaku artist's concept

(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 nine month performance verification phase, Suzaku began operating as an observatory, open to the world-wide astronomical community [39]. 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 yielded a total of 28 valid proposals, corresponding to an over-subscription in time of 3.2.

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 [56]. 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 Figure 21). 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.



Figure 21: AGILE artist's concept

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. Figure 22 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 [57] 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 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) 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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

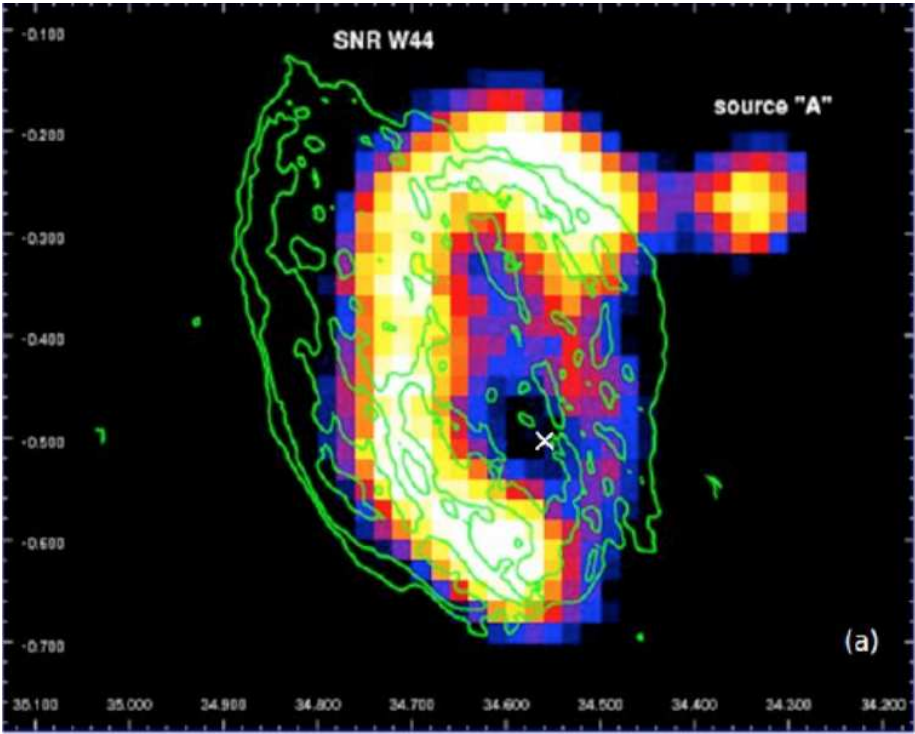


Figure 22: AGILE γ -ray intensity map of the Supernova Remnant W44 in the energy range 400 MeV - 3 GeV. Green contours show the 324 MHz radio continuum flux density.

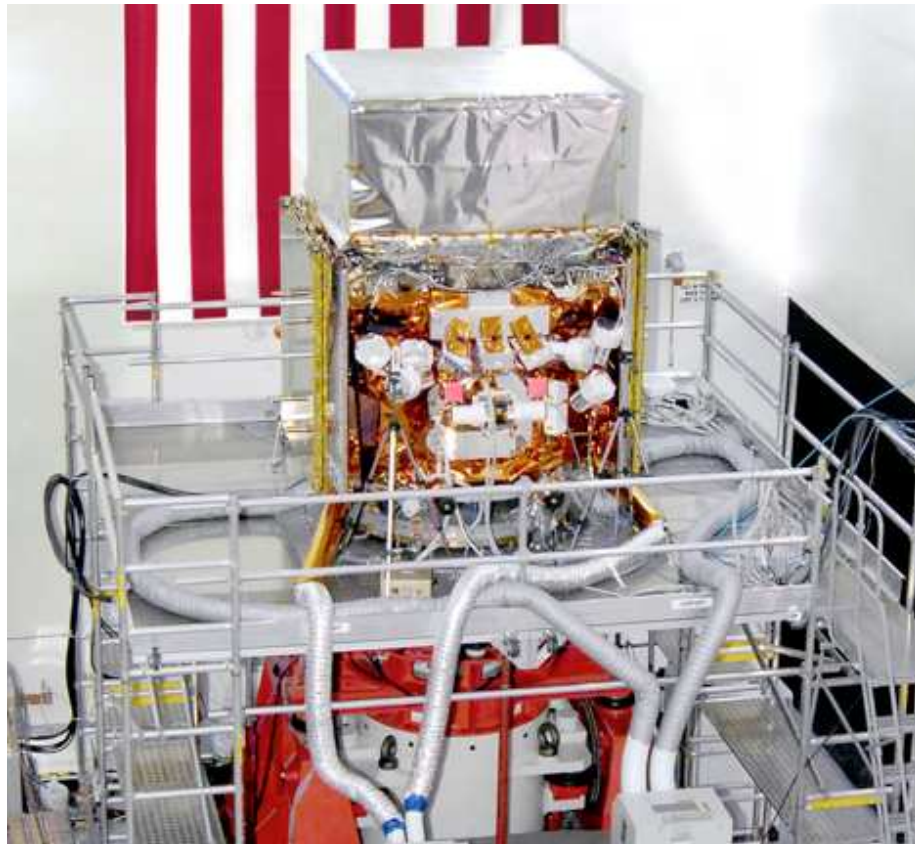


Figure 23: The Fermi Gamma-Ray Space Telescope being prepared for launch in the clean room at the Kennedy Space Center in February 2008.

1
2
3
4
5
6
7
8
9 packages have operated in a nearly flawless manner up to the present time. The
10 mission is managed by the NASA Goddard Space Flight Center. Fermi is a
11 multiagency and international observatory-class facility designed to study the
12 cosmos in the <10 keV to >300 GeV energy range. Its primary instrument,
13 the Large Area Telescope (LAT), is a pair-conversion telescope. Gamma rays
14 pair-produce in tungsten foils, silicon strip detectors track the resulting pairs,
15 and the resulting particle shower deposits energy in a CsI calorimeter. An anti-
16 coincidence detector provides discrimination against the large flux of charged
17 particles incident on the LAT. The anticoincidence detector is segmented to
18 eliminate the self-vetoing problems of previous instruments. The LAT has a
19 peak effective area (>8000 cm^2), angular resolution (<3.5 degree at 100 MeV,
20 <0.15 degree above 10 GeV), field-of-view (>2 sr), and deadtime (<100 μs per
21 event) that provides a factor of 30 or more advance in sensitivity compared to
22 previous missions. Fermi also carries a secondary experiment, the Gamma-ray
23 Burst Monitor (GBM) that facilitates the study of transient phenomena. The
24 GBM has a field-of-view larger than the LAT and a spectral range that extends
25 from the LATs lower limit down to less than 10 keV.
26

27 *Mission achievement summary*

28 Although pointed observations are possible, Fermi primarily scans the sky con-
29 tinuously because of the LATs large field-of-view. In this sky survey mode
30 Fermi provides nearly uniform sky exposure every ~ 3 hours. During its first
31 two years, the Fermi LAT's has detected and cataloged over 1800 cosmic γ -ray
32 sources. Collectively, the study of these sources has led to new insights into
33 basic astrophysical issues such as the structure of pulsar magnetospheres, the
34 galactic millisecond pulsar population, jet production and propagation in active
35 galaxies and the sources and composition of galactic cosmic-rays. The mis-
36 sion is an astrophysics and particle physics partnership, developed by NASA in
37 collaboration with the U.S. Department of Energy, along with important con-
38 tributions from academic institutions [58]. Figure 24 shows the Fermi γ -ray sky
39 as observed during the first 2 years of observations.
40

41 *4.3.12. The Planck mission*

42 Planck is a mm/sub-millimeter-wave sky-survey satellite, including a wide-
43 field cold telescope (1.5 m aperture) with two focal plane instruments, covering
44 the frequency range from 30 to 857 GHz. It was launched by ESA on 14 May
45 2009, (see Figure 25) and is currently operating from an orbit around in L2 with
46 excellent performance [59] [60] [61] [62]. As planned after 50 days, as foreseen,
47 Planck entered its final orbit around the second Lagrange point of the Sun-Earth
48 system (L2), at a distance of 1.5 million km from Earth. Since the end of the
49 commissioning and performance verification phases in mid-August 2009, Planck
50 has been performing its scientific mission. On 15 January 2010, ESA's advi-
51 sory bodies approved an extension of Planck operations by 12 months. Planck
52 is now scheduled to continuously acquire high-quality science data until the
53 end of 2011. The Planck collects and characterises radiation from the Cos-
54 mic Microwave Background (CMB) using sensitive radio receivers operating at
55 extremely low temperatures, and is capable of distinguishing temperature vari-
56
57
58

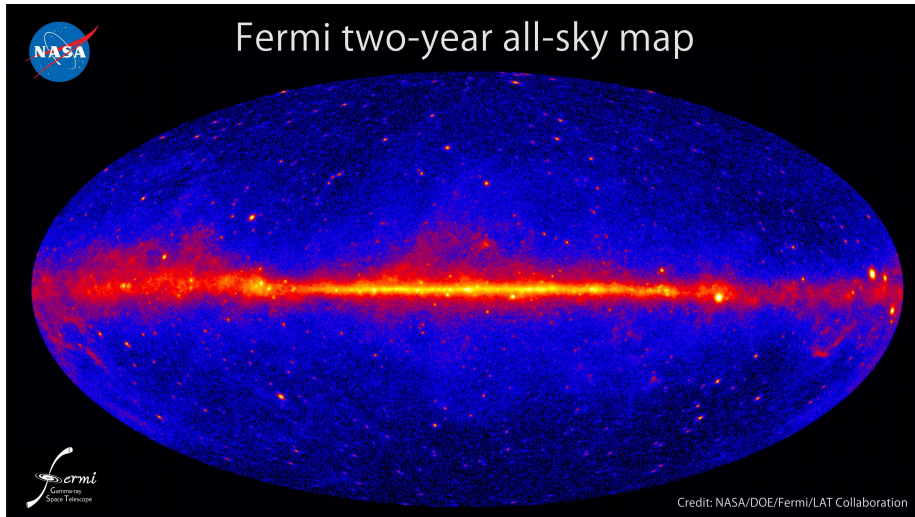
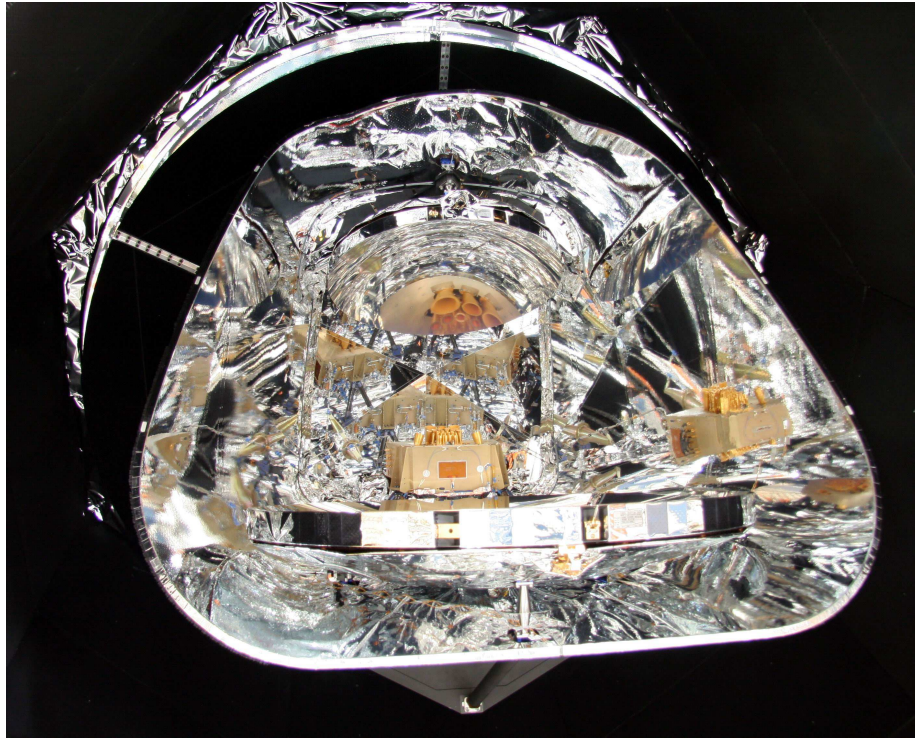


Figure 24: The Fermi γ -ray sky, integrating the data obtained during the first 2 years of observations. Credit: NASA/DOE/Fermi/LAT Collaboration

ations 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 1.9x1.5 m, and with a projected aperture of 1.5 m diameter. The 1.1x1.0 m secondary mirror focuses the collected light onto the two scientific instruments: LFI (Low Frequency Instrument), an array of radio receivers using high electron mobility transistor mixers; and HFI (High Frequency Instrument), an array of microwave detectors using spider bolometers equipped with neutron transmutation doped germanium thermistors.

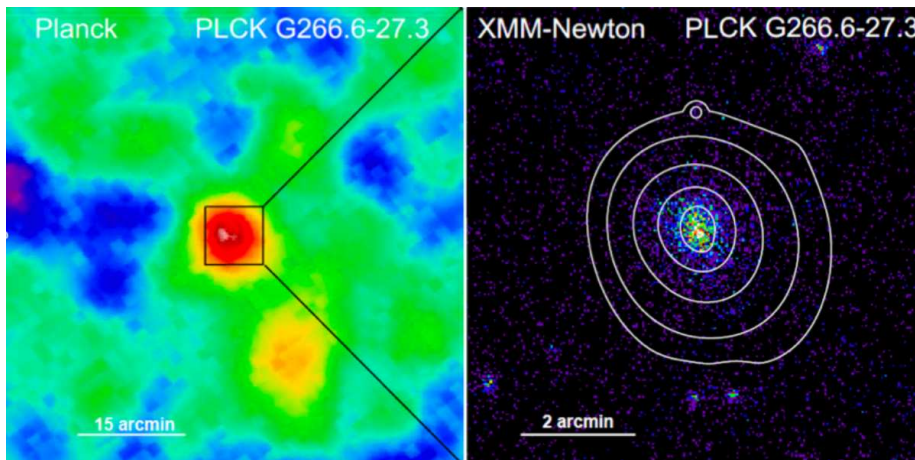
Mission achievement summary

Planck has been designed to measure the temperature and polarization 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 arcmin 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 13 2009 and 6 June 2010. The 10σ photometric flux density limit of the catalogue



34
35
36
37

Figure 25: The Planck satellite during integration tests



53
54
55
56
57
58
59
60
61
62
63
64
65

Figure 26: 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 [0.32,0] keV band [66]

1
2
3
4
5
6
7
8
9 at $|b| > 30$ deg is a fraction of a Jy in all bands, resulting in a total of more
10 than 15000 unique sources [63]. The ERCSC consists of nine lists of sources,
11 extracted independently from each of Planck's nine frequency channels, plus two
12 lists extracted using multi-channel criteria. These are the Early Cold Cores cat-
13 alogue [64] (ECC, including 915 Galactic dense and cold cores, selected mainly
14 on the basis of their temperature) and the Early Sunyaev-Zeldovich catalogue
15 [65] (ESZ, including 190 galaxy clusters selected by the spectral signature of
16 the Sunyaev-Zeldovich effect). This is the first all-sky shallow survey for SZ
17 clusters, and is especially sensitive to the high-mass tail of the cluster mass
18 distribution. In the early results, Planck has been able to discover 21 new clus-
19 ters, and most of them have already been confirmed by follow-up observations
20 of XMM and ground-based mm-wave telescopes. A typical example of these
21 discoveries is PLCKG266.6-27.3 ([66], see Figure 26), a high redshift ($z=0.94$),
22 relaxed, high mass ($8 \times 10^{14} M_{sun}$ cluster, extremely luminous in X-rays (1.4
23 $\times 10^{45}$ erg/s). Planck is perfectly suited to carry-out a systematic survey of
24 these objects, opening the way to statistical studies of population evolution.
25 Planck is providing a map of the CMB field at all angular resolutions greater
26 than 10 arc-minutes and with a temperature resolution of the order of one part
27 in 10^6 [42].
28
29

30 4.3.13. The Herschel mission

31 The Herschel Space Observatory is the largest infrared space observatory
32 launched to date [67] (see Figure 27). Equipped with a 3.5 m diameter reflecting
33 telescope and instruments cooled to close to absolute zero, Herschel is observing
34 at far-infrared and submillimetre wavelengths that have never previously been
35 explored with such high sensitivity and spatial and spectral resolution. Her-
36 schel will spend a nominal mission lifetime of three years in orbit around the
37 second Lagrange point of the Sun-Earth system (L2). Infrared astronomy is a
38 young and exciting science. In recent decades infrared astronomers have un-
39 veiled tens of thousands of new galaxies, and have made surprising discoveries
40 such as the huge amount of water vapor throughout our Galaxy. The spacecraft
41 is approximately 7.5 m high with a launch mass of around 3.4 t. The spacecraft
42 consists of a service module containing the warm parts of the scientific instru-
43 ments, and a payload module. The payload module contains of the telescope,
44 the optical bench, with the parts of the instruments that need to be cooled,
45 i.e., the sensitive detector units and cooling systems. The payload module is
46 fitted with a sunshield, which protects the telescope and cryostat from solar
47 visible and infrared radiation and also prevents Earth straylight from entering
48 the telescope. The sunshield also carries solar cells for electric power generation.
49 The Herschel telescope is a Cassegrain design with a primary mirror diameter
50 of 3.5 m. There are three scientific instruments: HIFI (Heterodyne Instrument
51 for the Far Infrared), a very high resolution heterodyne spectrometer; PACS
52 (Photodetector Array Camera and Spectrometer), an imaging photometer and
53 medium resolution grating spectrometer; and SPIRE (Spectral and Photometric
54 Imaging Receiver), an imaging photometer and an imaging Fourier transform
55 spectrometer. The instruments have been designed to take maximum advantage
56
57
58
59
60
61
62
63
64
65

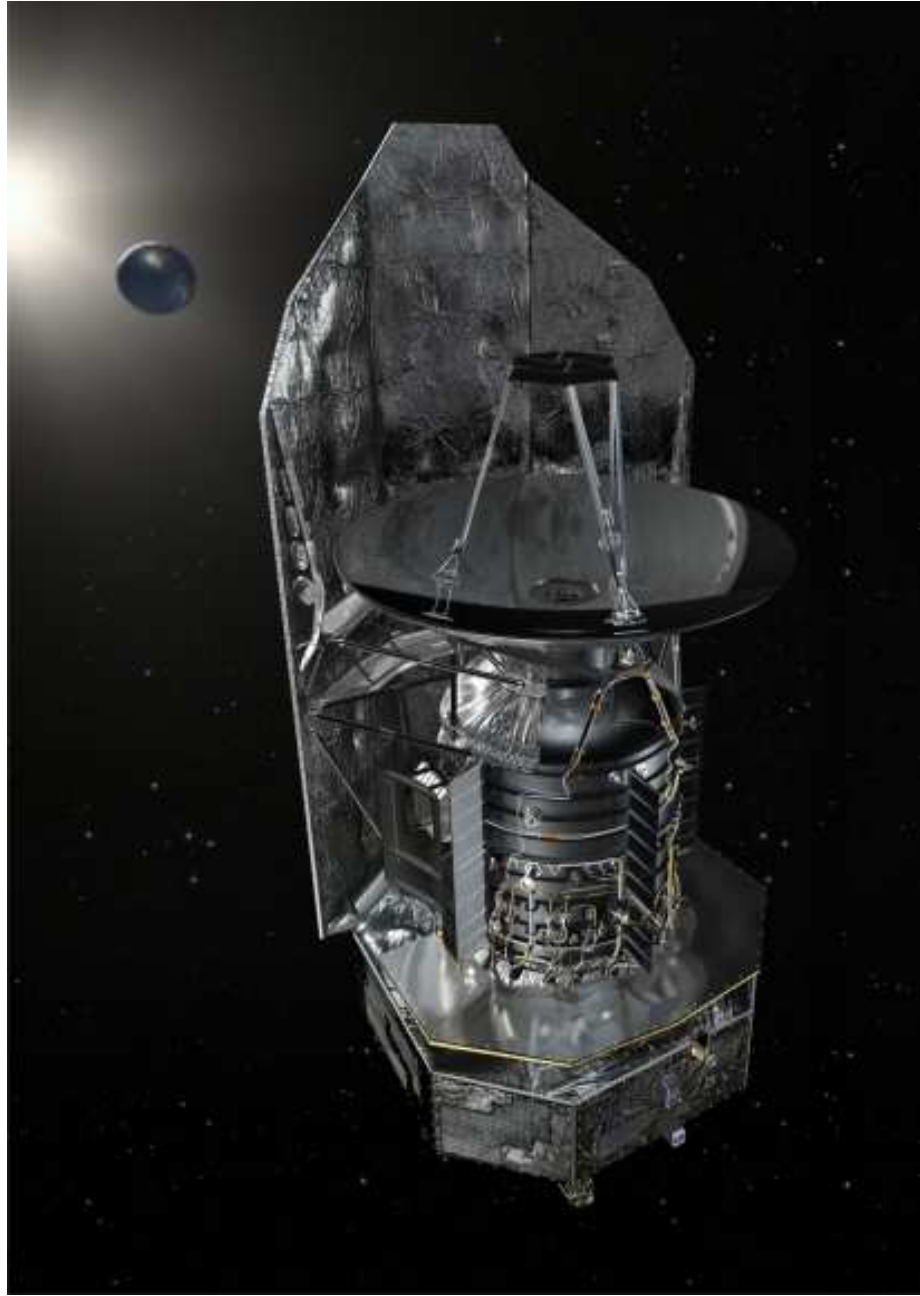


Figure 27: Herschel artist's concept

1
2
3
4
5
6
7
8
9 of the characteristics of the Herschel mission. In order to make measurements
10 at infrared and submillimetre wavelengths, parts of the instruments have to be
11 cooled to near absolute zero. The optical bench, the common mounting struc-
12 ture of all three instruments, is contained within a cryostat, and over 2000 l of
13 liquid helium will be used during the mission for primary cooling. Individual
14 instrument detectors are equipped with additional, specialised cooling systems
15 to achieve the very lowest temperatures, down to 0.3 K for PACS and SPIRE.

16 *Mission achievement summary*

17 Herschel has followed on from Spitzer, extending wavelength coverage beyond
18 200 μm , and achieving better angular resolution due to its larger telescope.
19 The main science drivers for Herschel have included: (i) wide-area photometric
20 surveys of the extragalactic and Galactic sky to measure dust-enshrouded star-
21 formation activity throughout cosmic time and in our own and nearby galax-
22 ies today; (ii) detailed studies of the physics and chemistry of the interstellar
23 medium, in our own and local galaxies; (iii) observational astrochemistry as
24 a tool for understanding the stellar/interstellar lifecycle and investigating the
25 physical and chemical processes involved in star formation and early stellar evo-
26 lution; (iv) spectroscopic and photometric study of comets, asteroids and outer
27 planet atmospheres and their satellites. At the time of writing, the Herschel
28 spacecraft and instruments are performing as planned, with scientific capabilities
29 and data quality matching or exceeding pre-launch expectations. Two thirds of
30 Herschel observing time is available to the worldwide astronomical community,
31 with the remainder allocated to the teams which have worked on the observatory
32 and the instruments. The first half of the mission has been mainly used for Key
33 Projects, substantial programmes addressing core science goals in a compre-
34 hensive manner and producing large coherent data sets. Extragalactic science
35 highlights to date include accurate measurements of FIR/submillimetre number
36 counts and the implications for the origin of the Cosmic Infrared Background
37 (CIB); characterisation of galaxy luminosity function evolution with redshift;
38 galaxy clustering analysis suggesting that multiple dusty star-forming galax-
39 ies occupy the same dark matter halos; and evidence for strong AGN-driven
40 molecular outflows that regulate star formation and may be responsible for the
41 correlation between central black hole mass and host galaxy mass. Herschel's
42 angular resolution, wavelength coverage, and instrumentation are well suited to
43 study of the ecology of the Milky Way galaxy in unprecedented detail. Signif-
44 icant results so far include the observation of complex and highly structured
45 networks of filaments which appear to be ubiquitous in the galactic interstellar
46 medium, suggesting a scenario for star formation in which protostellar conden-
47 sations form inside and at the junctions of filaments; multi-band photometry
48 yielding accurate masses, luminosities, temperatures, and lifetimes of protostel-
49 lar objects, and characterising the origin of the stellar initial mass function down
50 to the brown dwarf regime; a high resolution survey of the nearby star-forming
51 region in Orion revealing tens of thousands of spectral lines; and imaging of de-
52 bris disks around nearby young stars. Solar system observations with Herschel
53 are allowing comparison of the isotopic composition of cometary water with that
54 of the Earth's oceans, improving global models of the atmospheres of the giant
55
56
57
58

1
2
3
4
5
6
7
8
9 planets, and giving accurate estimation of the sizes and thermophysical prop-
10 erties of asteroids and Kuiper Belt objects. The observatory will continue to
11 operate until its tank of liquid helium is exhausted, which is expected to happen
12 in the spring of 2013. All Herschel data will be stored long-term in the Herschel
13 Science Archive. The spatial and spectral survey data especially are expected to
14 be of considerable archival value well beyond the lifetime of the mission. A text
15 book example of the synergy and powerful capability of space observatories is
16 shown in Figure 28, Figure 29 and Figure 30. The Herschel image contains basic
17 information about a region of the Galaxy with strong star formation processes;
18 the optical image shows 'normal stars' during their thermonuclear evolution pe-
19 riod, lasting from millions to billions of years; and the X-ray image shows the
20 'end-of-life- activity, with high energy photons emitted mainly by white dwarfs,
21 neutron stars or black holes accreting matter from companion stars. Figure 31,
22 [68] shows the image obtained by overlapping the two images of Figure 29 and
23 Figure 30. This image clearly shows where the star forming regions, emitting
24 in the IR, and the collapsed stars, emitting high energy X-rays, are located.
25
26

27 4.3.14. *MAXI Monitor of All-sky X-ray Image*

28 Monitor of All-sky X-ray Image (MAXI) is a highly sensitive X-ray slit cam-
29 era for the monitoring of more than 1000 X-ray sources in space over an energy
30 band range of 0.5 to 30 keV (see Figure 32). It is an attached payload to the
31 International Space Station (ISS), externally mounted on the Japanese Exper-
32 iment Module (JEM), Kibo, Exposed Facility. MAXI is continuously observing
33 to monitor flux variability once every 96 minutes for more than 1,000 X-ray
34 sources covering the entire sky on time scales from a day to a few months. As
35 an all-sky monitor, MAXI employs slit cameras. They determine one coordinate
36 of the X-ray sources within the narrow field of view of the slit, which is orthog-
37 onally oriented to a one-dimensional position-sensitive X-ray detector. As an
38 X-ray source moves according to the motion of the International Space Station,
39 another coordinate of the X-ray source is determined when the sources are cap-
40 tured by the collimated field-of-view of the camera. The International Space
41 Station orbits around the Earth every 96 minutes. During this time, MAXI's
42 two semicircular (arc-shaped) fields-of-view will scan the whole sky once. MAXI
43 has two types of X-ray slit cameras with wide FOVs and two kinds of X-ray de-
44 tectors: gas proportional counters covering the energy range of 2 to 30 keV; and
45 X-ray CCDs, covering the energy range of 0.5 to 12 keV. MAXI is equipped with
46 12 counters with a total effective area of 5000 cm^2 . The main MAXI scientific
47 objectives include:
48

- 49 1. to alert the community to X-ray novae and transient X-ray sources,
- 50 2. to monitor long-term variability of X-ray sources,
- 51 3. to stimulate multi-wavelength observations of variable objects,
- 52 4. to create unbiased X-ray source catalogues, and
- 53 5. to observe diffuse cosmic X-ray emissions, especially with better energy
54 resolution for soft X-rays down to 0.5 keV [69]
55
56
57
58



Figure 28: Optical image of the Andromeda Galaxy. Credit: NASA/ESA/R. Gendler, T. Lauer (NOAO/AURA/NSF), and A. Field (STScI)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

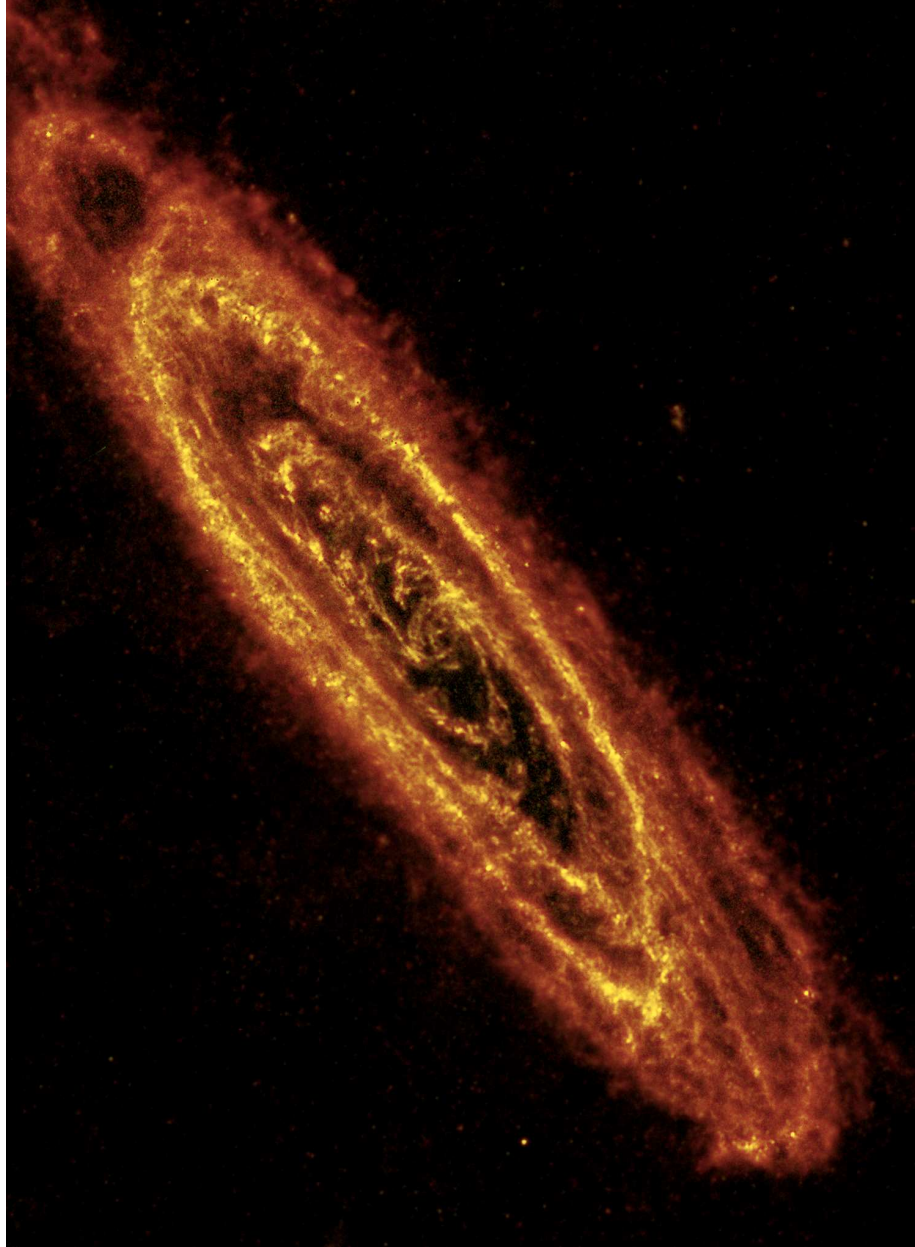


Figure 29: IR-Herschel image of the Andromeda Galaxy. Credit: ESA/Herschel - PACS/SPIRE/J. Fritz, U. Gent

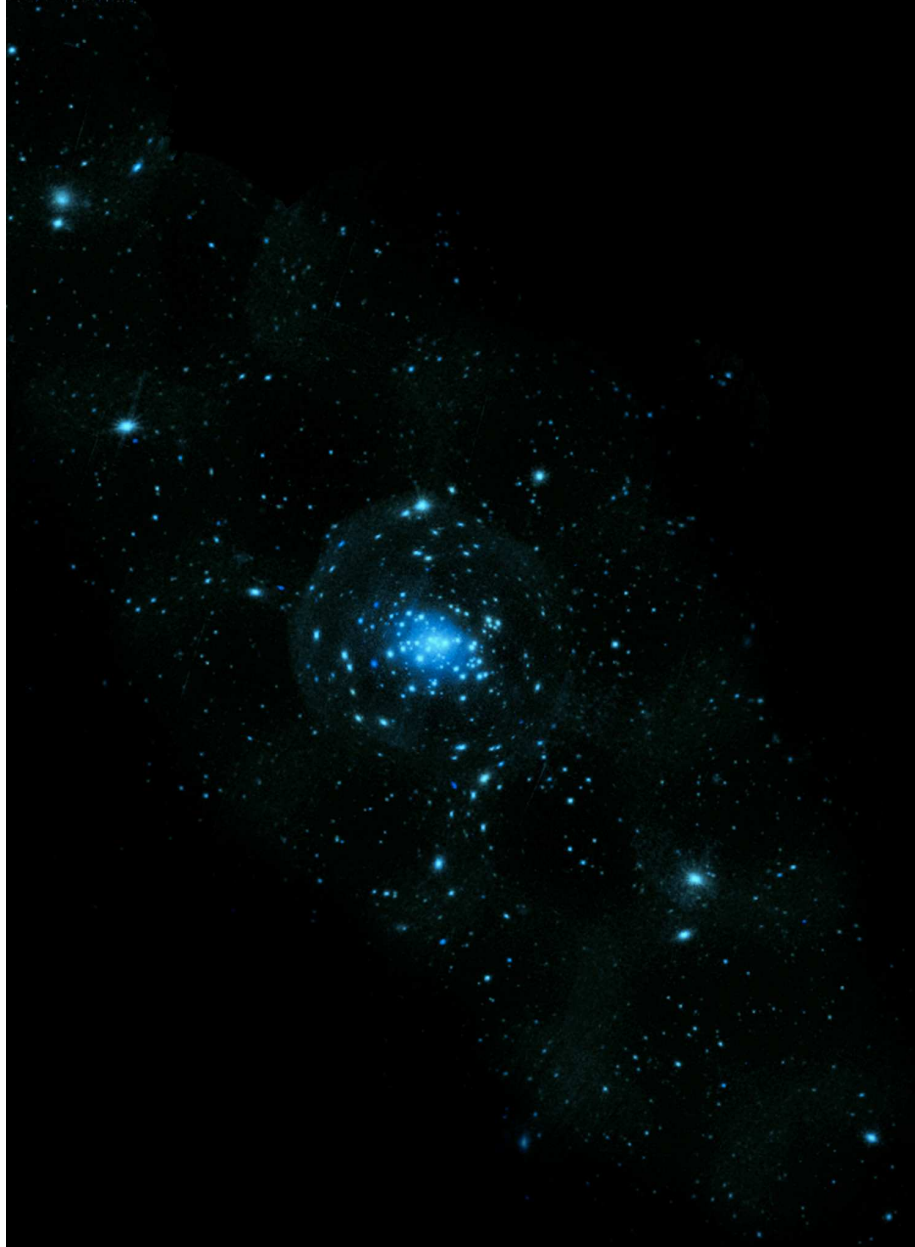


Figure 30: XMM-Newton image of the Andromeda Galaxy. Credit: ESA/XMM Newton/EPIC/W. Pietsch, MPE



Figure 31: Composite X-Ray - Infrared image of the Andromeda Galaxy: from the birth to the death of the stars

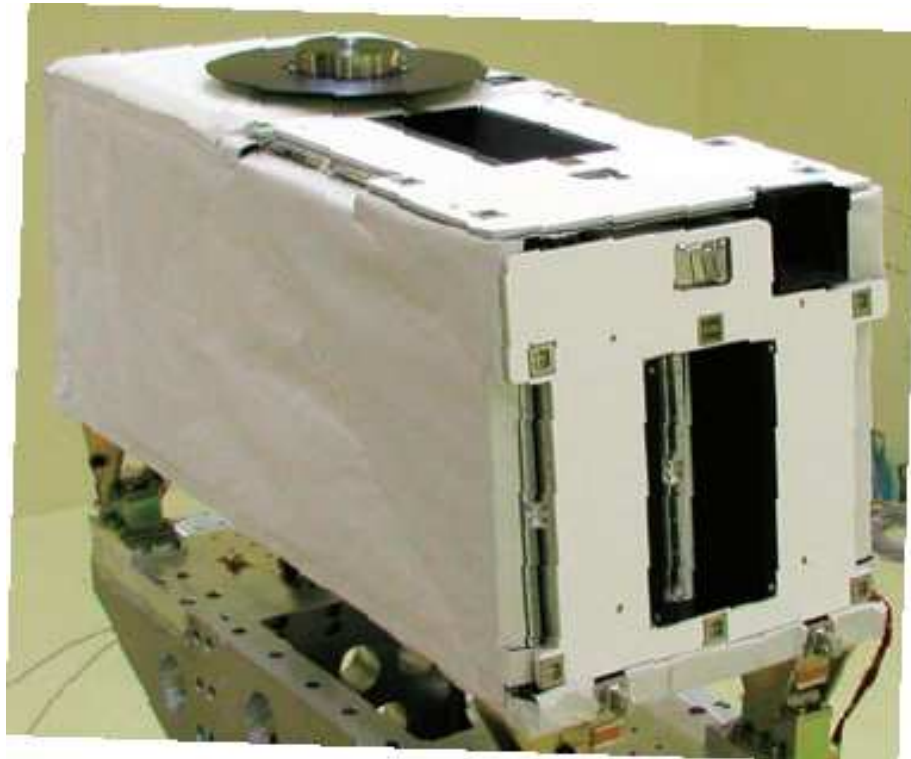


Figure 32: Photo of the MAXI payload before launch

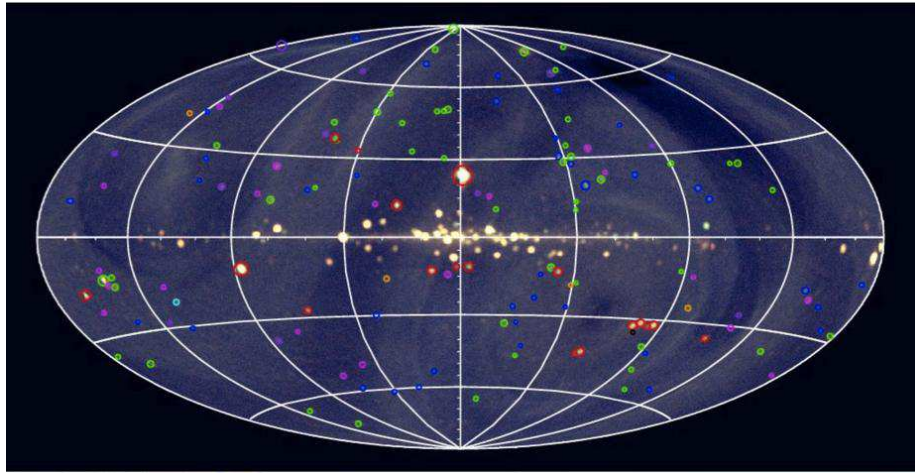


Figure 33: MAXI all-sky image in the energy range 4-10 keV. The data were obtained in the period September 2009 to March 2011

Figure 33 shows the all-sky image obtained by MAXI/GSC (energy range 4-10 keV) in the period from September 2009 to March 2011 [70].

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. 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. Figure 43 is 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 Science 2010 Decadal Survey committee.

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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table 3: Figure 43 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 2013
Astro-H	(JAXA-NASA) X-ray mission for high resolution spectroscopy and hard X-rays
GEMS	((NASA) SMEX X-ray polarization mission
HXMT	Hard X-ray Modulation Telescope (1-250 keV)
JWST	(NASA/ESA/CSA) Observatory, IR 6.5m mirror telescope sensitive from 0.6 to 27 micrometers
SOFIA	Stratospheric Observatory for Infrared Astronomy (NASA-DLR)
NASA EXPLORER	outcome (selection in progress): several astrophysical Missions relevant for this WG
ESA CV M1 M2	Solar Orbiter 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

4.4.1. 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, formation and evolution of the Galaxy (see Figure 34). 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 per cent of the Galactic stellar population [71]. 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.

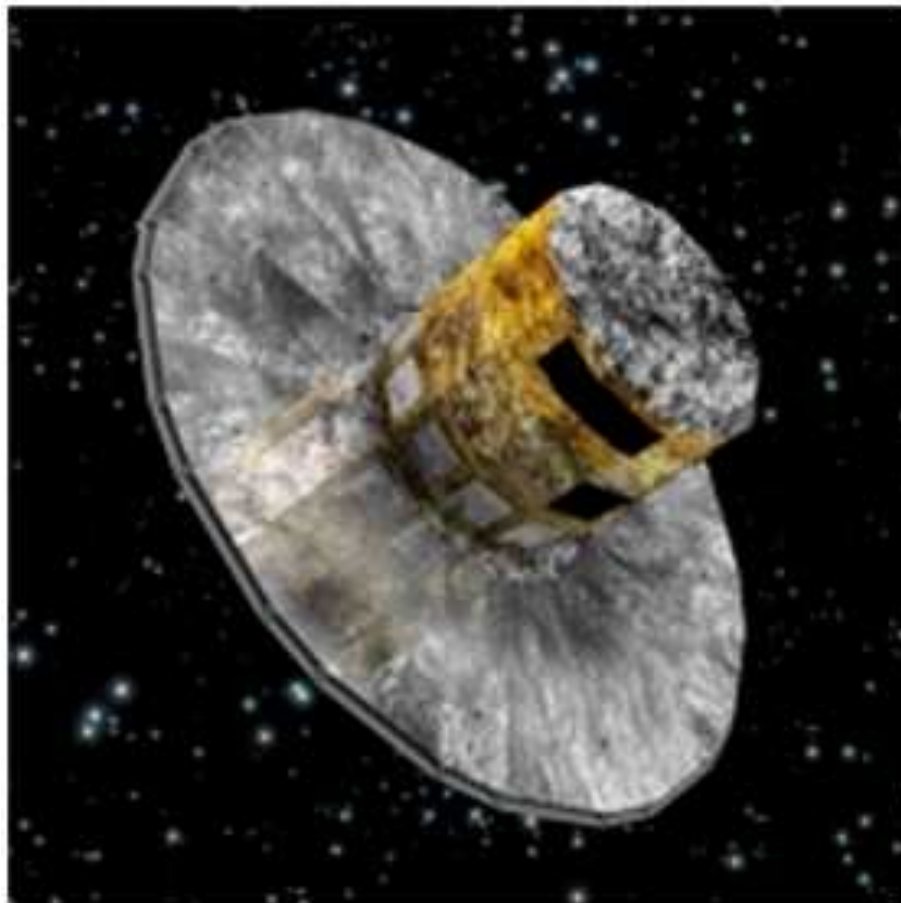


Figure 34: Gaia artist's concept

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

4.4.2. ASTROSAT: Launch 2012-13

Multi-wavelength astronomy mission from visible (320-530 nm) to hard X-rays (3-80 keV and 10-150 keV). ASTROSAT is the first dedicated Indian Astronomy satellite mission, which will enable multi-wavelength observations of celestial bodies and cosmic sources in X-ray and UV spectral bands simultaneously (see Figure 35). The scientific payload covers the visible (3500-6000 Å), UV (1300-3000 Å), 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 deg.
- 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 [72].

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 Figure 36).

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 this region of the electromagnetic spectrum. NuSTAR will also complement astrophysics missions that explore the cosmos in other regions of the spectrum. X-ray telescopes such as Chandra and

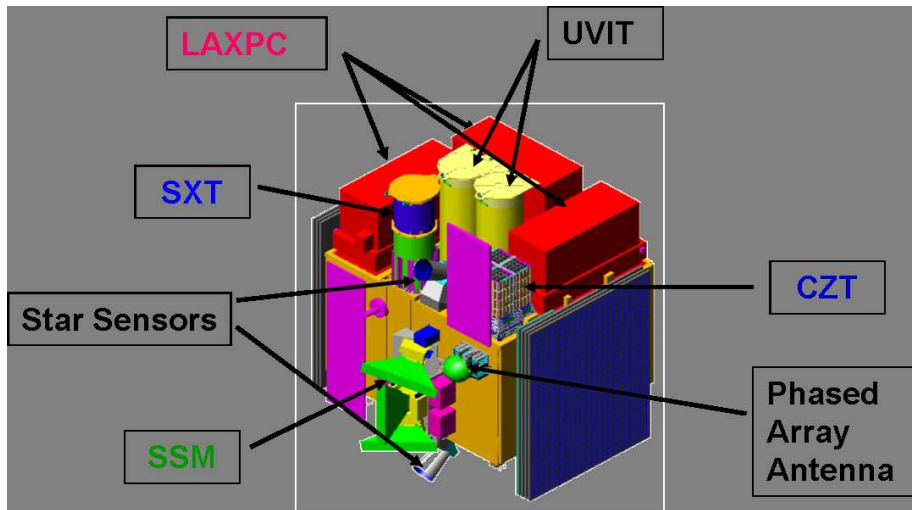


Figure 35: ASTROSAT artist's concept

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:

- 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, [73].



Figure 36: NuSTAR artist's concept

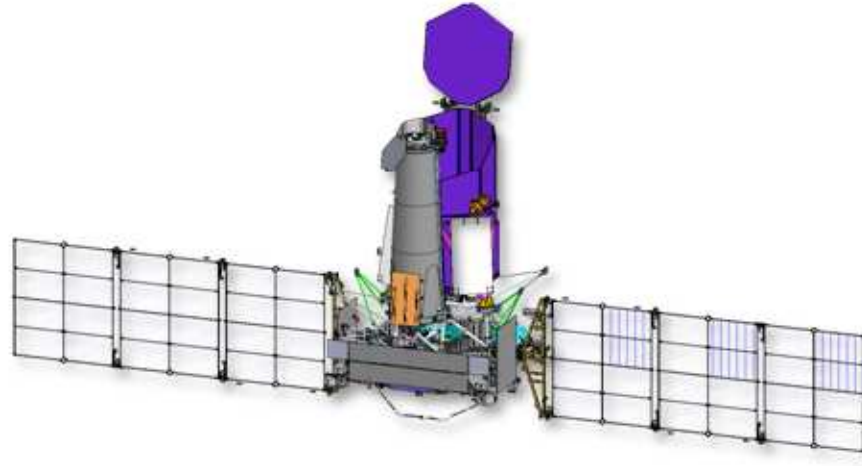


Figure 37: Spectrum RG artist's concept

4.4.4. The Spectrum Roentgen-Gamma (SRG) - eRosita experiment: Launch 2013

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 Figure 37. 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 [74]. 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.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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 Figure 38). 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 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 [75].

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

GEMS is a NASA SMEX mission designed to measure X-ray polarization. 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 Figure 39). 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 polarization of X-rays. This will open new discovery space because GEMS is orders of magnitude more sensitive than previous X-ray polarization experiments [76]. 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.



Figure 38: Astro H artist's concept

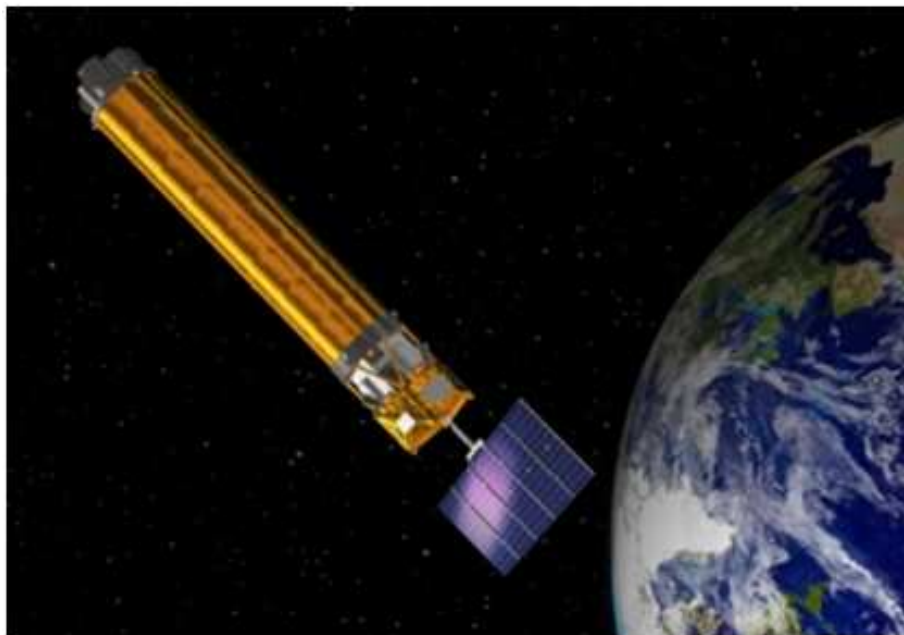


Figure 39: GEMS artist's concept

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

The "Hard X-ray Modulation Telescope" (HXMT) was proposed in 1994 [77]. 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 five-year plan for space science development in the period 2006-10, 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 Figure 40) will be launched into a low Earth orbit with an altitude of 550 km and an inclination angle of 43 deg. HXMT carries three slat-collimated instruments, the High Energy X-ray instrument (HE: NaI/CsI phoswich 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 $5.7\text{ deg} \times 1.1\text{ deg}$ (Full Width Half Maximum). The total payload and satellite weights are about 1200 kg and 2700 kg, respectively. The designed mission lifetime is four years 40. HXMT will perform sky surveys and pointed observations in the energy range 1-250 keV, with the following main

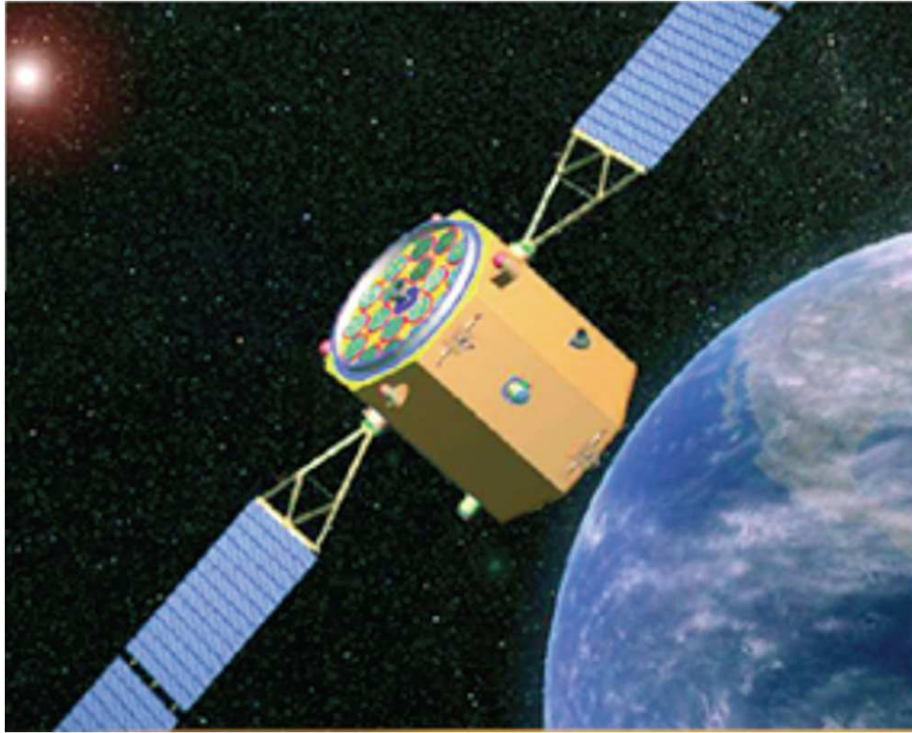


Figure 40: HXMT artist's concept

scientific objectives:

- 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 of a large, infrared-optimised space telescope with a segmented 6.5 m primary mirror and four instruments sensitive from 0.6 to 27 micrometers. JWST is scheduled

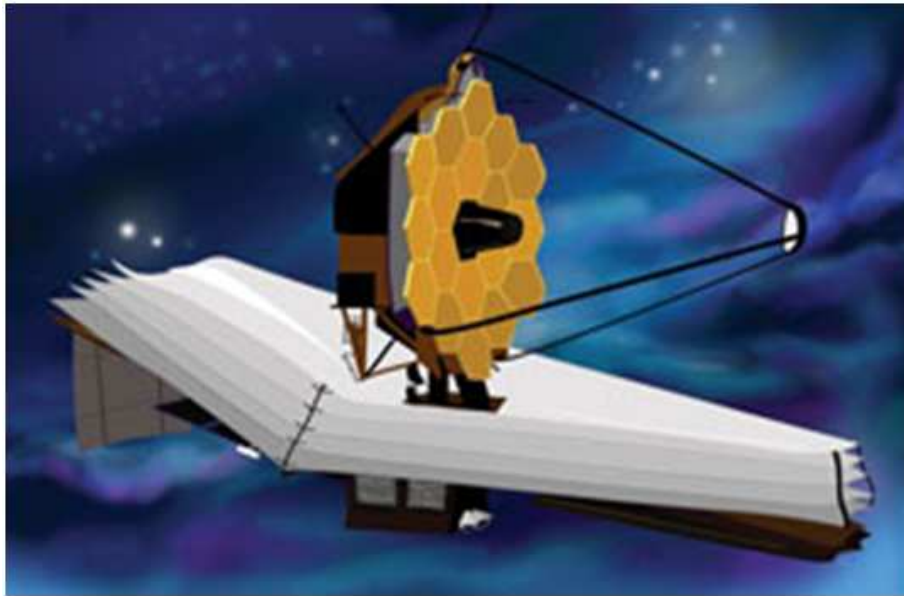


Figure 41: James Webb Space Telescope artist's concept

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 [3]. 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 Figure 41). In order to achieve high sensitivity in the infrared, JWST will have a multi-layer 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.

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

SOFIA [78] is a world-class airborne infrared observatory (see Figure 42) 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 für Luft und Raumfahrt (German Aerospace Center). Major modifications of a Boeing 747-SP aircraft and installation of the 2.5



Figure 42: Photo of SOFIA, the Stratospheric Observatory for Infrared Astronomy, during 'open-door' flight tests

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, Calif., from 2007 through 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 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.

1
2
3
4
5
6
7
8
9 **5. The Future Programmes of the National Space Agencies**

10 In this section we review the main mission opportunities already under study
11 for selection or firmly planned in the context of space agencies around the world.
12

13 *5.1. The NASA future programs and Vision*

14 The US National Academy of Sciences Astro2010 Decadal Survey scientific
15 and programmatic priority recommendations were made by the Committee for
16 a Decadal Survey of Astronomy and Astrophysics [7]. More detailed discussions
17 of the science questions and programmatic options on which the recommenda-
18 tions were based are presented in a separate publication containing the reports
19 of the Science Frontiers Panels and Program Prioritization Panels [31]. The rec-
20 ommended programme is organised by three science objectives that represent
21 its scope:
22

- 23 • Cosmic Dawn.
- 24 • New Worlds.
- 25 • Physics of the Universe.

26
27
28 The highest priority recommendations for space missions and programs are as
29 follows:
30

31 Large programmes (in rank order)

- 32 • *Wide-Field Infrared Survey Telescope (WFIRST)*.
33 WFIRST is an observatory designed to address essential questions in both
34 exoplanets and dark energy research, and to conduct near infrared sky
35 surveys of unprecedented sky coverage, sensitivity and angular resolution.
36 Such surveys will advance research on topics ranging from galaxy evolution
37 to the study of objects within our own Galaxy. The primary operations
38 will consist of surveys defined by selected science teams [5]. It is the
39 top-ranked overall programme in the New Worlds, New Horizons Decadal
40 Survey of Astronomy and Astrophysics.
41
- 42 • *An Augmented Astrophysics Explorer Program*.
43 This is a recommendation to increase the rate of launching PI-led missions.
44 Such missions deliver a high level of scientific return on relatively moderate
45 investment and provide the capability to respond rapidly to new scientific
46 and technical breakthroughs.
47
- 48 • *Laser Interferometer Space Antenna (LISA)*.
49 LISA is a low- frequency gravitational-wave observatory that will open
50 an entirely new window on the cosmos by measuring ripples in space-
51 time caused by many new sources, including nearby white dwarf stars,
52 and will probe the nature of black holes. This recommendation assumed
53 partnership with ESA.
54
55
56
57
58

- 1
2
3
4
5
6
7
8
9
- *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.

10
11
12
13
14

Medium scale Programmes (in rank order)

- 15
16
17
18
19
20
21
22
- *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.

23
24
25

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

- 26
27
28
29
30
31
32
33
34
35
- *Background-limited Submillimeter 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 [79]. [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.]

36
37

5.2. The ESA future programmes and Cosmic Vision

38
39
40
41
42

The European Space Agency started the definition of a new long term plan in 2004 with the call for new Space 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* [80].

43

An updated Cosmic Vision Long Term Plan is shown in Figure 44.

44
45
46

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

- 47
48
49
50
51
52
- 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?

53
54
55
56

These are amongst the most fundamental questions in astrophysical science and generate considerable interest in the general public. The Cosmic Vision basic implementation schedule [81] is shown in Figure 45

57
58

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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

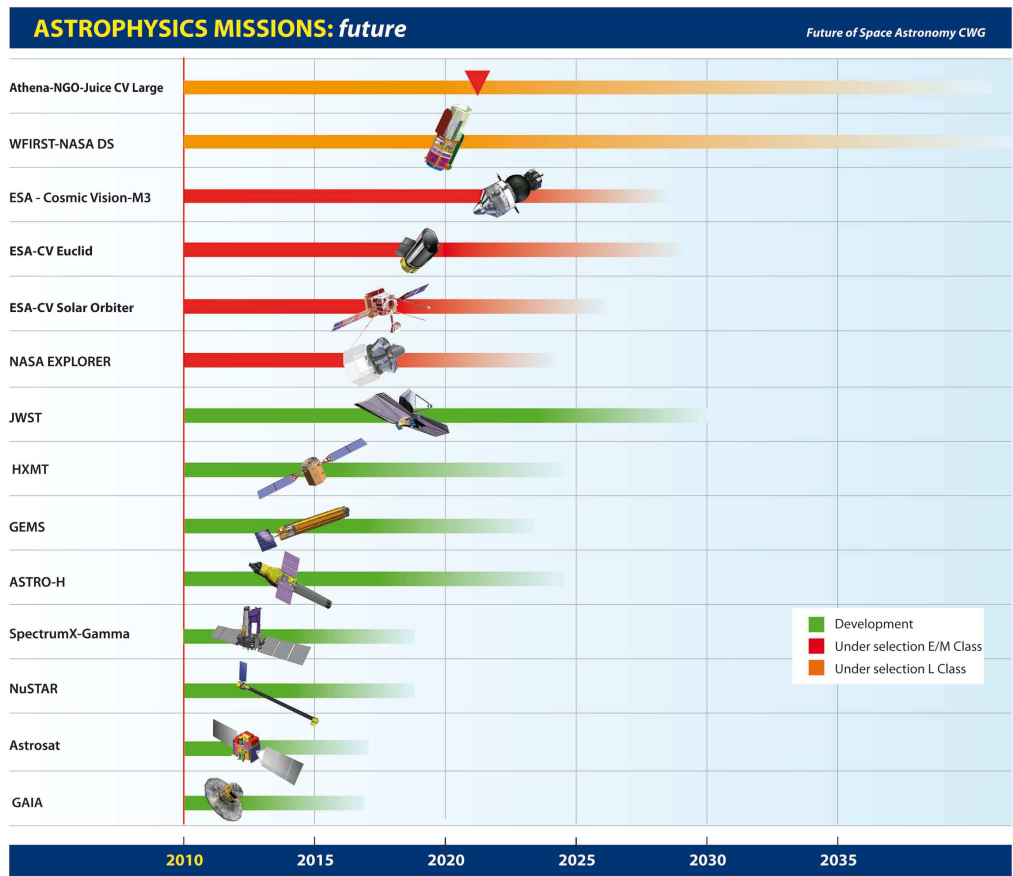


Figure 43: Missions under development (Green), Explorer/Medium class missions under selection processes from ESA and NASA (Red) and the Observatory class mission proposed by the NASA Decadal Survey (DS) and the ESA L-Class mission scheduled for a launch in 2021 (Orange). See section 5.2.2 for the recent ESA M1/M2 undergoing selection development)

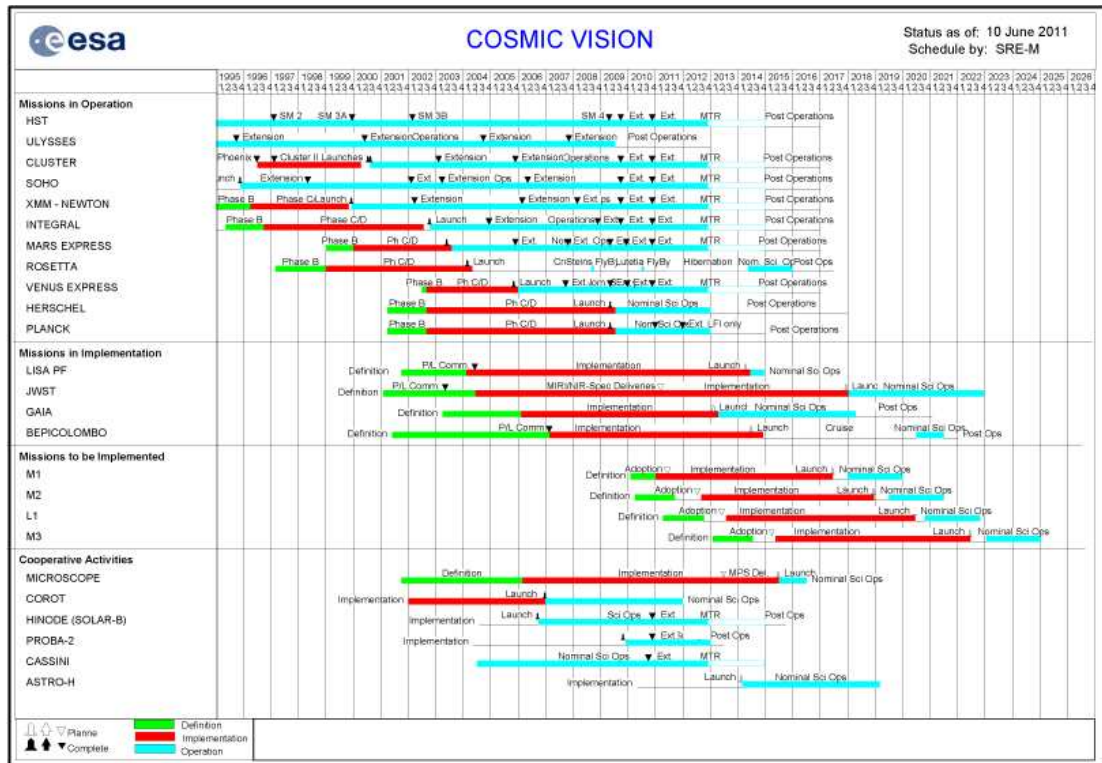


Figure 44: ESA Cosmic Vision long term plan and time schedule for M- and L-Class planned missions

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

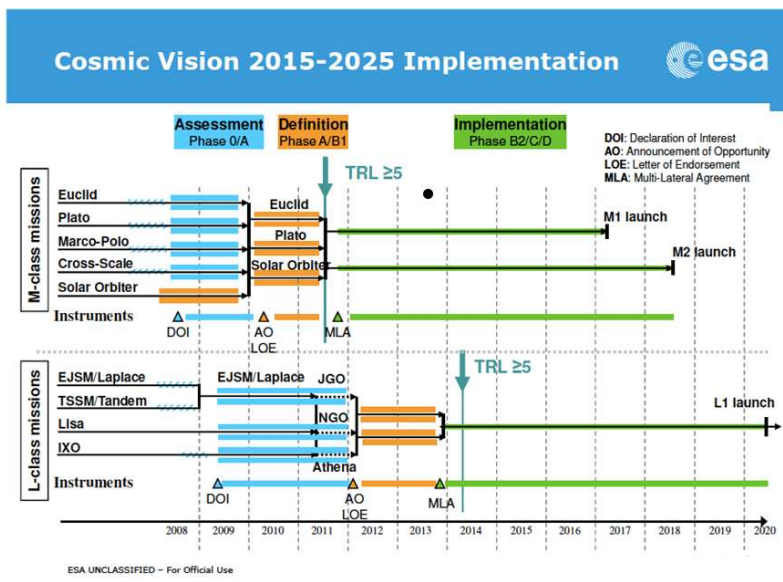


Figure 45: Cosmic Vision 2015-2025. Implementation plan and selection milestone for Medium and Large Class planned missions [81]

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.

L1: Europa Jupiter System Mission (EJSM): Mission Summary (see Table 4)
 The ESA-NASA Europa Jupiter System Mission [82] consists of two primary flight elements operating in the Jovian system: the NASA-led Jupiter Europa Orbiter (JEO) [83], and the ESA-led Jupiter Ganymede Orbiter (JGO) [84]. 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 neighborhood 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

L1: LISA Mission Summary (see Table 5)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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 kilometres. 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

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 [10], 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 five 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 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 gravity-wave ground detectors such as the

Laser Interferometer Gravitational Wave Observatory (LIGO) [85], which operate above 1 Hz, make these detectors complementary rather than competitive.

L1: IXO Mission Summary (see Table 6)

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	High redshift AGN Clusters of galaxies Neutron stars & black holes
keV)	
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

IXO [8] 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 paragraph 3.1.1).

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

1
2
3
4
5
6
7
8
9 the observable imprints of exotic processes occurring in these objects. Detailed
10 simulations of spectra of various sources have shown the IXO ability to:

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

16
17 On the largest scales, X-rays are essential for detecting the "missing" half
18 of baryons in the local Universe, as a probe of both dark energy and dark
19 matter and to measure the energy deposited in the surrounding medium by
20 AGN's jets and winds. Building on a rich technological heritage, IXO will have
21 improved instrumental capabilities in X-ray imaging, timing, and spectroscopy
22 far beyond the current generation of X-ray missions (e.g. Chandra, XMM,
23 RXTE, and Suzaku). Moreover, IXO will carry an X-ray polarimeter, which
24 will open a new window on the study of high-energy phenomena. These will
25 enable observations that will address the above science issues-among others-with
26 unprecedented detail and precision.
27

28 *5.2.2. The Cosmic Vision M-Class priority*

29 ESA has initially chosen three scientific missions for further M Class study.
30 Dark energy, habitable planets around other stars, and the mysterious nature
31 of our own Sun, have been chosen by ESA as candidates for two medium-class
32 missions to be launched no earlier than 2017. On February 2010, ESA's Science
33 Programme Committee (SPC) approved three missions to enter the so-called
34 definition phase. This is the next step required before the final decision is taken
35 as to which missions are implemented. The three proposals chosen to proceed
36 are Euclid [4], PLANetary Transits and Oscillations of stars (PLATO) [86], and
37 Solar Orbiter [87].
38
39

40 *M1/2: Euclid Mission Summary* (see Table 7)

41 Euclid would address key questions relevant to fundamental physics and cos-
42 mology, namely the nature of the mysterious dark energy and dark matter [4].
43 Astronomers are now convinced that these form of mass-energy dominate ordi-
44 nary matter. Euclid would map the distribution of galaxies to reveal the
45 underlying 'dark' architecture of the Universe.
46

47 *M1/2: PLATO Mission summary* (see Table 8).

48
49 The PLATO mission [86] would address one of the most timely and long-
50 standing questions in science, namely the frequency of planets around other
51 stars. This would include terrestrial planets in a star's habitable zone, so-called
52 Earth-analogues. In addition, PLATO would probe stellar interiors by detecting
53 the gaseous waves rippling their surfaces.
54

55 *M1/2: Solar Orbiter Mission Summary* (see Table 9).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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

Solar Orbiter would take the closest look at our Sun yet possible, approaching to just 62 solar radii [87]. 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).

M1/2: SPICA Mission Summary (see Table 10).

SPICA [79] would be an infrared space telescope led by the Japanese Space Agency JAXA. It would provide ‘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,

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	min. 6 years
Partners	To be confirmed
Type	M-class mission

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

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 five 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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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 ($\sim 5\text{-}210\mu\text{m}$)
Telescope	3.5 m Ritchey-Chretien
Orbit	L2
Lifetime	min. 5 years
Partners	JAXA-ESA
Type	M-class Mission

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.

The M1 and M2 selection.

The M1/M2 selection has been completed in September 2011 with 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 Figure 45 for details).

ESA Cosmic Vision selection for the M3 mission

25 Feb 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 2020-22. 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

1
2
3
4
5
6
7
8
9 known as Cosmic Vision 2015-2025. A total of 47 proposals was submitted and
10 then peer reviewed by the Advisory Structure to the Science Programme. As a
11 result of this review process, recommendations based on the scientific excellence
12 of the missions were forwarded by the Space Science Advisory Committee to
13 David Southwood, ESA's Director of Science and Robotic Exploration. ESA
14 has now selected four missions to undergo an initial Assessment Phase. Once
15 this is completed, a further down-selection will be performed, leading to a deci-
16 sion on which mission will be finally implemented.

17 The four proposals chosen to proceed for assessment are EChO, LOFT, MarcoPolo-
18 R and STE-QUEST [88].
19

20
21 *M3: Exoplanet Characterisation Observatory (EChO)*

22 The Exoplanet Characterisation Observatory (EChO) would be the first dedi-
23 cated mission to investigate exoplanetary atmospheres, addressing the suitabil-
24 ity of those planets for life and placing our Solar System in context.

25 Orbiting around the L2 Lagrange point, 1.5 million km from Earth in the anti-
26 sunward direction, EChO would provide high resolution, multi-wavelength spec-
27 troscopic observations. It would measure the atmospheric composition, temper-
28 ature and albedo of a representative sample of known exoplanets, constrain
29 models of their internal structure and improve our understanding of how plan-
30 ets form and evolve.
31

32
33 *M3: Large Observatory For X-ray Timing (LOFT)*

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

38 LOFT would carry two instruments: a Large Area Detector with an effective
39 area far larger than current spaceborne X-ray detectors, and a Wide Field Mon-
40 itor that would monitor a large fraction of the sky. With its high spectral
41 resolution, LOFT would revolutionise studies of collapsed objects in our Galaxy
42 and of the brightest supermassive black holes in active galactic nuclei.
43

44
45 *M3: MarcoPolo-R*

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

51 The mission would also reveal whether NEAs contain pre-solar material not
52 yet found in meteorite samples, determine the nature and origin of the organic
53 compounds they contain, and possibly shed light on the origin of molecules nec-
54 essary for life.
55

56
57 *M3: Space-Time Explorer and Quantum Equivalence Principle Space Test (STE-
58 QUEST)*
59

1
2
3
4
5
6
7
8
9 The Space-Time Explorer and Quantum Equivalence Principle Space Test (STE-
10 QUEST) is devoted to precise measurement of the effects of gravity on time and
11 matter. Its main objective would be to test the Principle of Equivalence, a fun-
12 damental assumption of Einstein's Theory of General Relativity. STE-QUEST
13 would measure space-time curvature by comparing the tick rate of an atomic
14 clock on the spacecraft with other clocks on the ground [89].

15 A second primary goal is a quantum test of the Universality of Free Fall - the the-
16 ory that gravitational acceleration is universal, independent of the type of body.
17

18 A Cosmic Vision update:

19 The missions flown as part of ESA's Cosmic Vision 2015-2025 plan will tackle
20 some of the major outstanding scientific questions about the Universe and our
21 place in it:
22

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

27
28
29
30 There are currently three missions - Euclid, PLATO and Solar Orbiter - which
31 are undergoing competitive assessment for selection as the first and second
32 medium class missions under Cosmic Vision. The final selection for M1 and
33 M2 will be made later this year, with launches expected in 2017-18.
34
35

36 6. The role and plan of the National Agencies

37
38 In this section we briefly report the future role and plan, when available, of
39 some national agencies.
40

41 6.1. *The Japan Space Astronomy Plan: JAXA Long Term Vision*

42 In 2005, JAXA published a Long Term Vision that included orbiting obser-
43 vatories at every wavelength band for the coming decade. Three basic themes
44 were included as follows:
45
46

- 47 1. Structure and history of the Universe
 - 48 • First galaxies, first black holes, co-evolution of galaxies and black
 - 49 holes
 - 50 • Formation of large scale structure, clusters of galaxies
- 51 2. Physics in extreme conditions
 - 52 • Physics of black holes and in their vicinity, verification of general
 - 53 relativity
 - 54 • Cosmic ray acceleration, equation of state of neutron stars
 - 55
 - 56
 - 57
 - 58

1
2
3
4
5
6
7
8
9 3. Composition of the Universe

- Dark matter, dark energy (through galaxy clusters)
- History of matter and its chemical composition, planets, and life

10 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)

14
15
16
17
18
19
20 No further missions have been approved by the Steering Committee for Space
21 Science of ISAS. In 2008-2009 the astronomy and astrophysics division of the
22 Japanese Science Council conducted a survey for large and/or medium astro-
23 physics projects. In 2010, this group recommended three projects, two ground-
24 based observatories and 1 space observatory, to be promoted on the national
25 scale. These were LCGT (Underground Gravity Wave Telescope), ELT, and
26 SPICA. These do not have strong obligations on the government and JAXA.
27 Funding for LCGT was approved in 2010.
28

29
30
31 *6.2. Future Space Astronomy Programmes in China*

32 Road Maps and Plans.

33 Over the last several years a number of reports, road maps and plans including
34 future space astronomy programmes have been proposed in China by various
35 working groups, committees and panels, including "Space Science & Technology
36 in China: A Roadmap to 2050", "Medium and Long Term Development Plan
37 for Space Science Missions" (study funded by Chinese Academy of Sciences),
38 "Report of Strategic Study on Mid- and Long-Term Development of Astronomy
39 in China" (study jointly funded by Chinese Academy of Sciences and National
40 Natural Science Foundation of China), "Report on the Development of Astron-
41 omy in China" (study funded by the Association of Science and technology
42 in China) and the "2011-2016 Space Science Plan of China's National Space
43 Agency". This section summarises the future space astronomy programmes
44 listed in these documents and provides a description of missions funded, ap-
45 proved, selected or under-study.
46

47
48 Summary of China's Space Astronomy Programmes:

49 Black Hole Probe Programme (BHP): The objective of this programme is to
50 study high-energy processes of cosmic objects and black hole physics through
51 observations of compact objects such as all kinds of black holes and γ -ray bursts.
52 The programme will explore the extreme physical processes and laws in the uni-
53 verse using extreme objects such as black holes as examples of how stars and
54 galaxies evolve. The main missions will include the Hard X-ray Modulation Tele-
55 scope (HXMT) satellite, the Space Variable Objects Monitor (SVOM) satellite,
56 and the Gamma-ray Burst Polarization (POLAR) experiment on board China's
57

1
2
3
4
5
6
7
8
9 Spacelab.

10
11 Diagnostics of Astro-Oscillations (DAO) Programme: The objective of this pro-
12 gramme is to make high precision photometric and timing measurements of
13 electromagnetic radiation in various wavebands and non-electromagnetic radi-
14 ation, in order to understand the internal structures of various astrophysical
15 objects and the processes of various violent activities. The main missions will
16 include the X-ray Timing and Polarization (XTP) satellite, and possible partic-
17 ipation in relevant international missions.
18

19 Portraits of Astrophysical Objects Programme (PAO): The objective of this
20 programme is to obtain direct photographs (portraits) of astrophysical objects
21 beyond the solar system such as solar-like stars, exoplanets, white dwarfs, neu-
22 tron stars, and black holes which are essential for understanding scientific ques-
23 tions such as the construction of the universe. The main mission will include
24 the proposed submillimeter Space VLBI (Very Long Baseline Interferometer)
25 telescope array.
26

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

32 *Missions from 2011 to 2015.*

33 Selected and funded missions:

34 Gamma-ray Burst Polarization (POLAR) experiment on board China's Space-
35 lab: 2012-2013 launch.

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

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

47 *Selected and fully funded missions:*

48 Hard X-ray Modulation Telescope (HXMT) satellite: 2014-2015 launch. This
49 telescope consists of three sets of collimated (about 1degree by 6 degree FOV)
50 instruments, high energy instruments between 20-250 keV of about 5000 cm^2
51 (NaI/CsI phoswich), medium energy instruments between 5-300 keV of about
52 1000 cm^2 (Si-PIN), and low energy instruments between 1-15 keV of about 400
53 cm^2 (SCD). The main scientific goals include a broadband wide-area survey and
54 pointed observations of compact galactic objects.
55
56
57
58

1
2
3
4
5
6
7
8
9 Dark matter and cosmic ray detection satellite: 2014-2015 launch.

10 This satellite consists of a stack of charged particle detector and calorimeter of
11 1.2 ton payload mass, aiming for the detection of the annihilation and decay
12 products (electrons, positrons and γ -rays) of suspected dark matter particles,
13 as well as the determination of a precision cosmic ray spectrum, between 5 GeV
14 and 1 TeV.

15
16 *Mid-Long Term Missions Funded for Development and Study*

17 Moderate funding is provided for key technology development and conceptual
18 studies which may lead to future missions. Several conceptual studies are
19 funded annually, and at the conclusion of these studies some missions may be
20 funded for key technology development. At the present time, the following are
21 funded for key technology development:
22

- 23 • X-ray Timing and Polarization (XTP) satellite: launch around 2020 with
24 instruments including large arrays of soft X-ray and hard X-ray telescopes
25 to achieve several meter squared sensitive area, and X-ray polarimeter
26 telescopes, for high throughput X-ray observations.
- 27
- 28 • Dark matter and cosmic ray observatory on board China's Space Station
29 with a projected 2020-2022 launch.
- 30

31 The following are funded for conceptual studies:

- 32 • Infrared sky survey small satellite mission
- 33
- 34 • Fast photometry observation mission from optical to X-ray bands
- 35
- 36 • Submillimeter space VLBI mission
- 37

38
39 *6.3. The Indian Space science programme*

40 Space Astronomy in India: the 2010-2020 vision.

41 The availability of opportunities in space astronomy in India have been gen-
42 erally linked to the indigenous rocket development programme, and the rocket
43 load-carrying capacities and the 5-year plan funding of ISRO, the nodal agency
44 for the space activities in India. The PSLV rocket, which is the work horse of the
45 Indian remote sensing satellites, has the capability to put 1500 kg in orbit and
46 is the key vehicle for science experiments today. There is no formal roadmap
47 for the space astronomy missions in ISRO; the missions are approved on an
48 ad-hoc case-by-case basis. In recent years, ISRO launched the Moon mission
49 Chandrayaan-1, and ASTROSAT, a multi-wavelength astronomy satellite carry-
50 ing a suite of instruments is due for launch next year. Several small missions in
51 astronomy have been funded for development. These include an IR astronomy
52 satellite and a solar spectrograph mission. Chandrayaan-2 is also in prepara-
53 tion, as are future planetary probes. Both Chandrayaan and ASTROSAT were
54 conceived as multi-instrument satellites carrying a suite of instruments for a va-
55 riety of observations; other payloads are planned as small co-passenger missions.
56
57
58

1
2
3
4
5
6
7
8
9 In 2008, a committee appointed by the Indian Academy of Sciences in Banga-
10 lore, submitted the Decadal Vision Document for Astronomy and Astrophysics,
11 which was the first such exercise undertaken in India. The committee noted
12 that, given the relatively small size of the Indian astronomical community and
13 the large range of research activities, there are no discernible thrust areas and
14 many of the existing experimental efforts in space astronomy are sub-optimal.
15 After surveying the ongoing research, critically assessing the contributions made
16 in the past in various areas and evaluating their impact and the future directions
17 in different areas worldwide, some key developments were recommended:
18

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

23
24 The prioritised list of recommended space-based initiatives include a small solar
25 coronagraph and a Near Infrared Spectro-photometer, while the prioritised list
26 of technology initiatives suggested were detector development for γ -rays, hard
27 x-rays and infrared; hard x-ray mirrors; X-ray polarimeter; and space platforms
28 for fundamental physics experiments. While recommending the participation in
29 international projects, the committee noted that multinational collaboration is
30 the new paradigm in big science. This is going to be true in all branches of
31 astronomy. Therefore, the Indian scientists have no option but to participate
32 in future international ventures. While it was noted that they must pursue
33 their own projects, they felt they must exploit every opportunity to collaborate
34 in major international projects. The necessary expertise which will empower
35 them to do so must be developed. Since the Academy's recommendations are
36 used as the guiding principals by ISRO when deciding on the future missions,
37 therefore, the Indian Space astronomy programme will only be targeted to small
38 missions in different areas of astronomy. ISRO has, however, always encouraged
39 participation with the international groups even in such missions. For example,
40 Chanrayaan-1, ASTROSAT and the IR satellite have foreign participation. For
41 large missions, ISRO will work together with other agencies if supported by the
42 Indian Astronomy community.
43

44 There are future considered astronomical satellites considered for two medium
45 class missions of ISRO [90]. Aditya-1 is proposed to be a space-based Solar
46 Coronagraph to study the solar corona in visible and near-IR bands. The launch
47 of the Aditya mission is planned during the next high solar activity period
48 in 2014. The main objective is to study the Coronal Mass Ejections (CME)
49 and consequently the crucial physical parameters for space weather such as the
50 coronal magnetic field structures, evolution of the coronal magnetic field, etc.
51 This will provide completely new information on the velocity fields and their
52 variability in the inner corona which have an important knowledge to address
53 the unsolved question of how the corona is heated.

54 A Thomson X-ray polarimeter has been developed for a small satellite mission.
55 The instrument works in the 5-30 keV band and will be suitable for X-ray
56 polarisation measurements in many hard X-ray sources. The accretion-powered
57
58

1
2
3
4
5
6
7
8
9 X-ray pulsars, black hole X-ray binaries, rotation-powered pulsars and non-
10 thermal supernova remnants will be the prime targets for this mission. In spite
11 of its moderate sensitivity, this experiment will give an unique opportunity to
12 expand the field of X-ray astronomy into a hitherto unexplored dimension.
13

14 *6.4. The Russian Space Science programme*

15 At the present time, Russian scientific space missions are being developed
16 based on the 10-year Federal space programme for the 2006-2015 period. The
17 Russian Federal Space Agency, Roscosmos, is responsible for the implementation
18 of this programme. It is planned that during 2011 the space programme will
19 be corrected for the period 2013-2015 and new tasks will be formulated for
20 the 5-year period 2016-2020, or even possibly for the ten year period 2016-
21 2025. In the current programme, the manned space flight programme associated
22 with the International Space Station support has the highest priority. Half of
23 the available financial resources are being allocated to the human space flight
24 programme. The other half goes to telecommunications, remote sensing and
25 scientific research satellites.
26

27 The Global Navigation System (GLONAS) has its own separate programme.
28 The scientific space programme is being realised as a rule according to the
29 interest of the Russian Academy of Sciences and covers the following directions:
30

- 31 1. Planetary research - projects: Phobos-Soil (2011), Luna-Resource (2013),
32 Luna-Glob (2013)
- 33 2. Extraterrestrial astronomy: Spectrum-Radioastron (2011), Spectrum-Ultraviolet
34 (2014), Spectrum-Roentgen-Gamma (2013), Gamma-400 (after 2015), Mil-
35 limetron (after 2015);
- 36 3. Sun - Interhelioprobe (after 2015);
- 37 4. Cosmic rays - Resurs-DK/Pamela (it is operating on the orbit from 2006),
38 "Lomonosov"
- 39 5. Plasma physics - Resonance (2013);
- 40 6. Cosmic rays - Resurs-Dk/Pamela (operational since 2006) , Lomonosov
41 (Moscow State University, 2012 TBD).
42

43 The projects are being developed in wide international cooperation with the
44 participation of ESA, NASA and other national space agencies: DLR, CNES,
45 ASI, etc. Development of separate small experiments for the foreign space
46 planetary missions is also supported. These missions include: Mars missions
47 (Mars Odyssey Spacecraft, NASA, and Mars Express, ESA), Venus missions
48 (Venus Express, ESA), Moon (LRO, NASA) and Mercury (BepiColombo, ESA)
49 missions. In the branch of extraterrestrial astronomy, the nearest perspective
50 of the Federal Space Programme is associated with the three missions of the
51 "Spectrum" series: "Spectrum-Radioastron", "Spectrum-UV" and "Spectrum-
52 Roentgen-Gamma".
53

54
55 Spectrum-Radioastron (Astro Space Center of the P.N. Lebedev Physical Insti-
56 tute of the Russian Academy of Science). The spacecraft is scheduled for launch
57
58

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 to 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 five 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-Chretien, with primary mirror diameter - 170 cm, focal length - 1700 cm, field of view - 30 arcmin. 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

Table 11: Spectrograph-Range (nm)-Resolution

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

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

Table 12: Camera Range (nm) Scale (arcsec/px) Field of view (arcmin²)

Camera	Range (nm)	Scale (arcsec/px)	Field of view (arcmin 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

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 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 *gamma*-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 millimeter, sub-millimeter and infrared wavelength ranges ($10\mu\text{m}$ - 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 prop-

Table 13: Main parameters of the Gamma-400 Satellite

Orbit	500 - 300000 km
Gamma-ray energy range	100 MeV - 3000 GeV
Sensitive area	0.64 m ²
Coordinate detectors	Si strips with 0.1-mm pitch
Field of view	±45°
Angular resolution ($E_\gamma > 100$ GeV)	~0.01°
Calorimeter-thickness, r.l.	BGO + Si strips, 30
Energy resolution ($E_\gamma > 20$ GeV)	~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

agation 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 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 [91].

Australian presence in space-based research has been absent even though the indigenously built small satellite named Wresat was launched in 1967 and Fed-sat followed in 2002. Balloon-borne experiments in X-ray/ γ -ray astronomy were carried out 30 years ago, but there have been no major satellite-based initiatives to study the high energy universe using UV, X-ray and low energy γ -ray windows, either individually or in international collaboration. Several proposed

1
2
3
4
5
6
7
8
9 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

10
11
12 The other space science studies have also mainly been confined to heliophysics using ground-based observation facilities without any emphasis on developing a systems approach to the space-based research programmes along with the ground data.

13
14
15
16 The strategic vision of the Australian astronomical community outlined in the Decadal Plan 2006-2015, articulated a continued engagement and enhancing the ongoing areas of ground-based observational facilities and participation in the larger international projects like the Square Kilometer Array (SKA) and the Extremely Large Telescope (ELT). No new horizon in space-based astronomy was proposed or recommended in the report and there is a lack of policy to put resources into space based research in Australia, the Astronomy community in Australia is quite small and has remained so for the past 30 years.

17
18
19 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 (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.

20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000

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

1
2
3
4
5
6
7
8
9 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" endeavors 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 [30] 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.

35 7. Conclusions

37 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.

38 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.

39 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.

40 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.

1
2
3
4
5
6
7
8
9 We conclude that the size, complexity and costs of large space observatories
10 must place a growing emphasis on international collaboration and multilateral
11 cooperation. Although this poses technical and programmatic challenges, these
12 challenges are not insurmountable, and the great scientific benefits will be a rich
13 reward for everyone.
14

15 **8. Acknowledgements**

16
17 We acknowledge the former COSPAR President, Roger Bonnet, for the ap-
18 pointment of the committee, his successor, Giovanni Fabrizio Bignami, for his
19 full endorsement of the Working Group activity and his unconditional support
20 during more than a year of work, and and Robert Williams, IAU President, for
21 supporting the Working Group activity and a companion IAU Study.
22

23 Most of the work has been carried out within the COSPAR framework and we
24 are grateful for the support of the COSPAR-CSAC chair, Lennard Fisk, the
25 Executive Director, Jean-Louis Fellous, and to Johan Bleeker, Aaron Janofsky,
26 Jean-Pierre Swings and all the other members for their positive attitude toward
27 the WG activity.

28 We acknowledge the support of ISSI for several meetings held in Berne, which
29 were very well organised by Silvia Wenger and Jennifer Zaugg.

30 During the preparation of this report we have consulted with many colleagues
31 and people from the astronomy and astrophysics community involved in space
32 science, and we acknowledge all of them. Several have made important contribu-
33 tions to the preparation of the report and we wish to mention the following peo-
34 ple explicitly: Angela Bazzano, Johan Bleeker, Joao Braga, Iver Cairns, Parizia
35 Caraveo, Jean Clavel, Martin Elvis, Josh Grindlay, Wim Hermsen, Chryssa
36 Kouveliotou, Miguel Mass, Luigi Piro, Jean Pierre Roques, Ravi K. Sood, Mike
37 Watson, Jean-Claude Worms, Sergio Volonte', Peter von Ballmoos and Martin
38 Weisskopf.

39 PU is grateful to Alvaro Gimenez and Jon Morse for very useful discussions and
40 advice. Finally, a special thanks to Mrs. Catia Spalletta for her professional
41 and timely production of the manuscript.
42
43

44 **9. References**

45 **References**

- 46
47
48 [1] COSPAR scientific organization: [http://www.cospar2010.org/files/Finalprogramme-](http://www.cospar2010.org/files/Finalprogramme-2010.pdf)
49 [2010.pdf](http://cosparhq.cnes.fr/Scistr/Scistr.htm), <http://cosparhq.cnes.fr/Scistr/Scistr.htm>
50
51 [2] Bonnet, R. M., Bleeker, J. A. M., *Science*, 333, 161, 2011
52
53 [3] The James Webb Space Telescope, NASA (<http://www.jwst.nasa.gov/>),
54 <http://www.jwst.nasa.gov/>
55
56 [4] Euclid Definition Study Report ; R. Laureijs, J. Amiaux, S. Arduini et al.,
57 ESA/SRE(2011)/12, <http://sci.esa.int/euclid>
58

- 1
2
3
4
5
6
7
8
9 [5] The Wide-Field Infrared Survey Telescope (WFIRST) : Green J., P.
10 Schechter and C. Baltay et al.; in Science definition Interim report,
11 <http://wfirst.gsfc.nasa.gov/>
12
13 [6] ESA cosmic vision 2015-2025: 2005, G. Bignami, P. Cargill, B. Schutz and
14 C. Turon : ISBN: 92-9092-489-6, ESABR247,2005, <http://sci.esa.int/science->
15 [e/www/object/index.cfm?fobjectid=38542](http://www/object/index.cfm?fobjectid=38542)
16
17 [7] New Worlds, New Horizons in Astronomy and Astrophysics, Report of
18 the Committee for a Decadal Survey of Astronomy and Astrophysics; Na-
19 tional Research Council 2010, National Academy Press., [htt://www.nap.edu](http://www.nap.edu),
20 <http://science.nasa.gov/earth-science/decadal-surveys/>
21
22 [8] International X-ray Observatory (IXO) Assessment Study Report for the
23 ESA Cosmic Vision 2015-2025: X. Barcons, D. Barret, M. Bautz et. al.;
24 ESA/SRE(2011)/2<http://sci.esa.int/ixo>
25
26 [9] Athena: The Advanced Telescope for High Energy Astrophysics: D.
27 Lumb , K. Nandra, X. Barcons et. al. (<http://www.mpe.mpg.de/athena>),
28 <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=48727>
29
30 [10] LISA assessment study report (Yellow Book): A. Brillet, I. Ciufolini, M.
31 Cruise et. al. ESA/SRE(2011)/3, <http://sci.esa.int/lisa>
32
33 [11] Lisa pathfinder. ESA Research and Scientific support,
34 <http://www.rssd.esa.int/index.php?project=LISAPATHFINDER>
35
36 [12] SPICA Yellow book, M. Ferlet, N. Geis, Javier et. al.; ESA/SRE (2009/6)
37 http://www.ir.isas.jaxa.jp/SPICA/SPICA_HP/index_English.html
38
39 [13] Boella, G. et al., A&A Supplement series, 122, 299, 1997
40
41 [14] van Paradijs, J., et al., Nature, 386, 6626, 686, 1997
42
43 [15] Costa, E. et al., Nature, 387, 6635, 783, 1997
44
45 [16] Piro, L.; et al., 2002, ApJ, 577,680
46
47 [17] Ubertini, P. et al. Future of Space Astronomy: A Global Road Map for
48 the Next Decades , Report V2.4, COSPAR-Working Group on the Future of
49 Space Astronomy
50
51 [18] A Science Vision for European Astronomy, Astronet Report, 2007 Editors:
52 P.T. de Zeeuw & F.J. Molster ISBN 978-3-923524-62-4
53
54 [19] Satellites to be built launched by 2020 [http://euroconsult-ec.com/research-](http://euroconsult-ec.com/research-reports/soaceindustry-reports/satellite-to-be-built-launched-by-2020-29-50.html)
55 [reports/soaceindustry-reports/satellite-to-be-built-launched-by-2020-29-](http://euroconsult-ec.com/research-reports/soaceindustry-reports/satellite-to-be-built-launched-by-2020-29-50.html)
56 [50.html](http://euroconsult-ec.com/research-reports/soaceindustry-reports/satellite-to-be-built-launched-by-2020-29-50.html)
57
58 [20] LOFAR: Low Frequency Array, <http://www.lofar.org/>
59
60
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9 [21] Atacama Large Millimeter/submillimeter Array (ALMA),
10 <http://www.almaobservatory.org/>
11
12 [22] Science with Square Kilometre Array: 2004 Ed. C. Carilli, S. Rawlings New
13 Astronomy Reviews, <http://www.skatelescope.org/>
14
15 [23] European Southern Observatory - The European Extremely Large Tele-
16 scope project E-ELT, <http://www.eso.org/sci/facilities/eelt/>
17
18 [24] Gemini Telescope project: F. Gillett, M. Mountain, R. Curz et al.: 1996.
19 RPT-PS- G0064, <http://www.gemini.edu/>
20
21 [25] Large Synoptic Survey Telescope - Design and Development document,
22 2003, corporation, <http://www.lsst.org/>
23
24 [26] Thirty Meter Telescope: 2007 TMT Document Number:
25 TMT.PMO.MGT.07.009 Eds: S. Dawson and S. Roberts,
26 <http://www.tmt.org/>, [http://www.tmt.org/employment/tmt-observatory-](http://www.tmt.org/employment/tmt-observatory-corporation)
27 [corporation](http://www.tmt.org/employment/tmt-observatory-corporation)
28
29 [27] Cerenkov Telescope Array, <http://www.cta-observatory.org/> and The Sta-
30 tus and future of ground-based TeV gamma-ray astronomy: A White Paper
31 prepared for the Division of Astrophysics of the American Physical Society, J.
32 Buckley, K. Byrum, B. Dingus et al. 2008, arXiv:0810.0444, [http://www.cta-](http://www.cta-observatory.org/)
33 [observatory.org/](http://www.cta-observatory.org/)
34
35 [28] High Altitude Water Cerenkov Experiment: a High Energy gamma-Ray
36 Observatory: 2007, <http://hawc.umd.edu/>
37
38 [29] Pierre Auger Cosmic ray observatory South: 1995, <http://www.auger.org/>
39
40 [30] T.M. Sausen, ISPRS Society Vol. 6, N. 2, 27-28, 2001
41
42 [31] Panel Reports New Worlds, New Horizons in Astronomy and Astrophysics
43 (National Research Council, National Academies Press, Washington, DC,
44 2010)
45
46 [32] The Hubble Space Telescope, <http://hubble.nasa.gov/>
47
48 [33] Chandra X-ray Observatory, Weisskopf, M. C. et al. An overview of the
49 performance and scientific results from the Chandra X-Ray observatory.
50 Publ. Astron. Soc. Pacif. 114, 124 (2002), [http://www.nasa.gov/mission-](http://www.nasa.gov/mission-pages/chandra/)
51 [pages/chandra/](http://www.nasa.gov/mission-pages/chandra/)
52
53 [34] X-ray Multi-Mirror Mission XMM-Newton, Jansen, F. et al. XMM-Newton
54 observatory, Astron. Astrophys. 365, L1L6 (2001)., [http://sci.esa.int/science-](http://sci.esa.int/science-e/www/area/index.cfm?fareaid=23)
55 [e/www/area/index.cfm?fareaid=23](http://sci.esa.int/science-e/www/area/index.cfm?fareaid=23)
56
57 [35] Rossi X-ray Timing Explorer (RXTE), <http://heasarc.nasa.gov/docs/xte/>
58
59
60
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9 [36] C. Winkler, T. J.-L. Courvoisier, G. Di Cocco, N. Gehrels, A. Gimenez,
10 S. Grebenev, W. Hermsen, J. M. Mas-Hesse, F. Lebrun, N. Lund, G. G. C.
11 Palumbo, J. Paul, J.-P. Roques, H. Schnopper, V. Schonfelder, R. Sunyaev,
12 B. Teegarden, P. Ubertini, G. Vedrenne, and A. J. Dean, 2003, A&A, 411,
13 349
14
15 [37] Swift Gamma ray burst mission: S. D. Barthelmy et. al.; P. W. A. Roming
16 et al. and D. N. Burrows et al. 2005, Space Science Reviews, 120, 95-195,
17 <http://swift.gsfc.nasa.gov/>
18
19 [38] Spitzer Space Telescope, <http://www.spitzer.caltech.edu/> and
20 <http://science.nasa.gov/missions/spitzer/>
21
22 [39] The X-ray Observatory Suzaku (ASTRO-E2) : 2007 Publ. Astron. Soc.
23 Japan 59, S1-S7 and <http://www.astro.isas.ac.jp/suzaku/>
24
25 [40] GALEX - Galaxy Evolution Explorer : L. Bianchi et al. 1999, MmSAI. 70,
26 365-374, <http://www.galex.caltech.edu/>
27
28 [41] The Herschel satellit: <http://sci.esa.int/science->
29 [e/www/area/index.cfm?fareaid=16](http://www/area/index.cfm?fareaid=16)
30
31 [42] The Planck satellite: <http://sci.esa.int/science->
32 [e/www/object/index.cfm?fobjectid=13244](http://www/object/index.cfm?fobjectid=13244)
33
34 [43] Barcons, X., et al., eprint arXiv:1102.2845
35
36 [44] A. G. Riess, A. V. Filippenko, P. Challis et al., 1998, AJ, 116, 1009-1038
37
38 [45] S. Perlmutter, G. Aldering, G. Goldhaber, et al., 1999, ApJ, 517, 565-586
39
40 [46] The first decade of science with Chandra and XMM-Newton: Maria Santos-
41 Lleo, Norbert Schartel, Harvey Tananbaum, Wallace Tucker and Martin C.
42 Weisskopf, Nature, 462, 24-31, 2009
43
44 [47] Goldstone Deep Space Communications Complex, JPL, NASA, California,
45 (<http://deepspace.jpl.nasa.gov/dsn>)
46
47 [48] Vedrenne, G., et al.: SPI: The spectrometer aboard INTEGRAL. A&A
48 411, L63-L70 (2003)
49
50 [49] Ubertini, P., et al.: IBIS: The Imager on-board INTEGRAL. A&A, 411,
51 L131-L139 (2003)
52
53 [50] Bazzano, A., et al.: INTEGRAL IBIS Census of the Sky Beyond 100 keV.
54 ApJ 649, L9-L12 (2006)
55
56 [51] C. Winkler, R. Diehl, P. Ubertini, and J. Wilms, Space Science Reviews,
57 2011, in press, ArXiv:111.6279
58
59 [52] Ubertini, P., et al.: The INTEGRAL gamma-ray sky after 1000 days in
60 orbit. Proc IAU Symp. 230, August 2005,
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9 [53] Sguera, V., Barlow E.J., Bird, A.J., et al.: INTEGRAL observations of
10 recurrent fast X-ray transient sources, *A&A* 444, 221-231 (2005)
11
12 [54] Sidoli, L., Paizis and Mereghetti, S.: INTEGRAL observations of
13 IGRJ11215-5952: the first Supergiant Fast X-ray Transient displaying pe-
14 riodic outbursts, *AIP Conf. Proc.* 924:508-512, (2007)
15
16 [55] The Swift Gamma-Ray Burst Mission: Gehrels, N., Chincarini, G.,
17 Giommi, P., et al., *ApJ*, 611, 1005, 200; [http://www.nasa.gov/mission-
19 pages/swift/bursts/500th.html/](http://www.nasa.gov/mission-
18 pages/swift/bursts/500th.html/)
20
21 [56] Tavani, M., Barbiellini, :, Argan, A., et al, 2009, *A&A* 502, 99;
22 <http://agile.asdc.asi.it/news.html/>
23
24 [57] Giuliani A., et al., 2011, *Astrophys. Journal Letters*, in press
25
26 [58] Fermi Gamma ray Space Telescope: Mission Overview and Opportunities ,
27 S. Ritz in *Proc. First GLAST Symposium 4-8, February 2007, Stanford Univ.*
28 *California, AIP Conference Proceedings* 921, <http://fermi.gsfc.nasa.gov/>
29
30 [59] Planck Collaboration, 2011, Planck early results. I. The Planck mission,
31 *Astronomy and Astrophysics*, in press, astro-ph/1101.2022
32
33 [60] Planck Collaboration, 2011, Planck early results. II. The thermal perfor-
34 mance of Planck, *Astronomy and Astrophysics*, in press, astro-ph/1101.2023
35
36 [61] Mennella, A., et al., 2011, Planck early results. III. First assessment of
37 the Low Frequency Instrument in-flight performance, *Astronomy and Astro-*
38 *physics*, in press, astro-ph/1101.2038
39
40 [62] Planck HFI Core-team, 2011, Planck early results. IV. First assessment of
41 the High Frequency Instrument in-flight performance, *Astronomy and Astro-*
42 *physics*, in press, astro-ph/1101.2039
43
44 [63] Planck Collaboration, 2011, Planck Early Results. VII. The Early Re-
45 lease Compact Source Catalog, *Astronomy and Astrophysics*, in press, astro-
46 ph/1101.2041
47
48 [64] Planck Collaboration, 2011, Planck early results. XXIII. The Galactic cold
49 core population revealed by the first all-sky survey, *Astronomy and Astro-*
50 *physics*, in press, astro-ph/1101.2035
51
52 [65] Planck Collaboration, 2011, Planck early results. VIII. The all-sky early
53 Sunyaev-Zeldovich cluster sample, *Astronomy and Astrophysics*, in press,
54 astro-ph/1101.2024
55
56 [66] Planck Collaboration, 2011, Planck Early Results XXVI: Detection with
57 Planck and confirmation by XMM-Newton of PLCK G266.6-27.3, an excep-
58 tionally X-ray luminous and massive galaxy cluster at $z = 1$, *Astronomy and*
59 *Astrophysics*, in press, astro-ph/1106.1376
60
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9 [67] Herschel Space Observatory: G. L. Pilbratt in Proc. Symposium The Promise of the Herschel Space Observatory 1215 December 2000, Toledo, Spain, ESA SP-460, eds. G.L. Pilbratt, J. Cernicharo, A.M.Heras, T. Prusti and R. Harris <http://www.herschel.caltech.edu/> and <http://herschel.esac.esa.int/>
- 14
15 [68] B. Altieri, Herschel Science Results: POS, proceedings of "The Extreme and variable sky", Chia Laguna, Sardinia, Italy, 19-23 September 2011, in press
- 18
19 [69] The MAXI Mission on the ISS: Science and Instruments for Monitoring All Sky X-Ray Images; M. Matsuoka, K Kawasaki and S. Ueno et al. : 2009, Publ. Astron. Soc. Japan 61, 999, <http://maxi.riken.jp/>
- 22
23 [70] Kazuo Hiroi, Yoshihiro Ueda, Naoki Isobe, et al., The First MAXI/GSC Catalog in the High Galactic-Latitude Sky, 2011, PASJ, in press, arXiv:1108.5516
- 26
27 [71] Overall Science goals of the Gaia mission:, F. Mignard in Proc. Symposium on the Three-Dimensional Universe with Gaia, 2005, ESA SP-576, eds. C. Turon, K.S. O'Flaherty, M.A.C. Perryman, <http://sci.esa.int/science-e/www/area/index.cfm?fareaid=26>
- 30
31 [72] Astrosat: Science and the Status, R. K. Manchanda, 2011 in Proceedings of the 29th meeting of the Astronomical Society of India, ASI Conf. Series, 4, Eds, Pushpa Khare and C.H. Ishwara-Chandra, <http://meghnad.iucaa.ernet.in/astrosat/>
- 34
35 [73] The Nuclear Spectroscopic Telescope Array (NuSTAR) F. A. Harrison, S. Boggs, F. Christensen et al. arXiv:1008.1362v1 [astro-ph.IM] and 2011 Bulletin of the American Astronomical Society, Vol. 43. AAS 217, <http://science1.nasa.gov/missions/nustar/>
- 38
39 [74] eROSITA on SRG - a X-ray all-sky survey mission ; N. Cappelluti, P. Predehl, H. Boehringer et al. 2011 arXiv:1004.5219v2 [astro-ph.IM] and <http://www.mpe.mpg.de/erospita>
- 42
43 [75] The ASTRO-H Mission : Takahashi, T; Mitsuda, K ; Kelley, R; et al.; 2010 Proc. SPIE 7732 , pp. 77320Z-77320Z-18, <http://astro-h.isas.jaxa.jp/>, <http://heasarc.nasa.gov/docs/astroh/>
- 46
47 [76] The Gravity and Extreme Magnetism Small Explorer (GEMS) : Jahoda, K. et al. 2010, Proc. SPIE 7732, 77320W, <http://heasarc.nasa.gov/docs/gems/>
- 50
51 [77] The Hard X-ray Modulation Telescope (HXMT): Mission and Its Current Status Fangjun Lu et al. AAPPS Bulletin April 2009, Vol. 19, No. 2, <http://www.hxmt.cn/english/>
- 54
55
56
57
58

- 1
2
3
4
5
6
7
8
9 [78] SOFIA: Stratospheric Observatory for Infrared Astronomy: A. Krabbe,:
10 2000 Proceedings of SPIE: Airborne Telescope Systems, Vol. 4014,
11 <http://www.sofia.usra.edu/>
12
13 [79] SPICA: To Discover the Origins of Galaxies, Stars and Planets;
14 <http://sci.esa.int/spica>
15
16 [80] ESA/SPC (2011) 26, 2011, ESA Science Programme Committee: 2011
17 (<http://sci.esa.int/spc>)
18
19 [81] J. Clavel, ESA's Space Science Programme: Cosmic Vision 2015-2025:
20 ESA's long term programme in space sciences, J. Clavel, Mem. S.A. It. Vol.
21 81, 467-474, 2010, and Jenam2001, 5 July 2011, St. Petersburg
22
23 [82] Europa Jupiter System Mission (EJSM): Mission Study final report,
24 K. Clark et al. NASA/ESA Task Order NMO710851, 30 January 2009,
25 <http://opfm.jpl.nasa.gov/europajupitersystemmissionejsm/>
26
27 [83] Jupiter Europa Orbiter (JEO) Concept: Proposed Mission,
28 <http://opfm.jpl.nasa.gov/europajupitersystemmissionejsm/jupitereuropaorbiterconcept/>
29
30 [84] Jupiter Ganymede Orbiter (JGO) project: Proposed Mission,
31 <http://opfm.jpl.nasa.gov/europajupitersystemmissionejsm/jupiterganymedeorbiterjgoconcept/>
32
33 [85] Laser Interferometer Gravitational-Wave Observatory (LIGO): for detector
34 description refer, B. Abbotta, R. Abbottb, R. Adhikaric et al. 2004, Nuc,
35 Instrum. and Methods, 517, pp 154-179, <http://www.ligo.caltech.edu/>
36
37 [86] PLATO definition study report (Red Book) : C. Catalia et al., 2011
38 ESA/SRE/ 13, <http://sci.esa.int/plato>
39
40 [87] Solar Orbiter: Exploring the Sun-heliosphere connection; Definition study
41 report (Red Book): 2011 ESA/SRE/14, <http://sci.esa.int/solarorbiter>
42
43 [88] <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=48467>
44
45 [89] Space-Time Explorer and QUantum Equivalence Principle Space Test
46 (STE-QUEST) : K. Bongs, P. Bouyer, W. Ertmer, et al. SRE-PA/2011-
47 075/TN/PW (<http://sci.esa.int/ste-quest>)
48
49 [90] Indian Space research Organisation: <http://www.isro.org/>
50
51 [91] Australia Telescope National Facility: <http://www.atnf.csiro.au/>
52
53 [92] Australia in Space-Australian Space Program;
54 <http://www.aerospaceguide.net/worldspace/australia-in-space.html/>
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9 **Appendix A. R. M. Bonnet talk at COSPAR meeting**

10 *Message from Roger-Maurice Bonnet at the 38 Working Group constitution*
11 *under the aegis of COSPAR Commission E [1]*

12 "It is my great pleasure to welcome you to Bremen and to the 38th COSPAR
13 Scientific Assembly....

14 This Assembly takes place at a turning point in the development of space re-
15 search. Our domain is increasingly influenced by a growing trend toward greater
16 globalization, now a common theme in many fields but certainly inevitable in
17 ours. Two of the major threads running through our discussions this week
18 will be climate change and exploration, the approaches to which must be as
19 global in nature, or even more so, than for the many other topics likely to be
20 addressed.....Concerning exploration, COSPAR recently embarked on an impor-
21 tant exercise. The new Panel on Exploration (PEX) prepared a comprehensive
22 report at the request of the COSPAR Scientific Advisory Committee (CSAC)
23 on robotic and human exploration of the Moon, Mars and near-Earth asteroids.
24 The report will be revised for transmission by the COSPAR President to space
25 agency heads with the aim of encouraging a coherent approach to international
26 collaborative exploration while protecting scientific assets and promoting scien-
27 tific advancement, a role most appropriate, indeed essential, for our Committee.
28 Although it is perhaps less of a common thread at this Assembly than explora-
29 tion and climatology, let me mention another concern that has preoccupied
30 COSPAR recently, i.e., the dearth of forthcoming space astronomy missions and
31 the consequent lack of space astronomy data that is looming on the horizon. In
32 January 2010 COSPAR organised at UNESCO in the context of the closing of
33 the International Year of Astronomy (IYA) a symposium on the Contribution
34 of Space Research to Astronomy. This event was extremely well received by the
35 speakers as well as the general public who were the primary audience for the
36 symposium. Feedback was so positive that COSPAR envisages creating a series
37 of symposia open to the public, perhaps a bit on the 38th COSPAR Scientific
38 Assembly model of the capacity building workshops in the sense that a topic
39 and team of lecturers can be employed several times to reach audiences in a
40 number of different countries wishing to host such events. Be that as it may,
41 one of the obvious conclusions of the IYA symposium at UNESCO, as well as
42 other recent meetings, is the need to address the problems soon to be faced by
43 space astronomers. To this end, COSPAR plans to constitute at this Assembly
44 a dedicated working group to be chaired by Professor Pietro Ubertini, under
45 the aegis of Commission E, whose aim will be to analyze the situation of space
46 astronomy missions over the next two decades, also taking into account the im-
47 pressive activity and plans - some of them already in implementation phase -
48 for major ground based astronomy facilities over a broad range of wavelengths
49 accessible from the surface of the Earth. This working group will participate in
50 a similar IAU-led reflection on the future of astronomy which has already been
51 initiated.

52 ...With best wishes to all participants for a most successful Assembly result-
53 ing in numerous international collaborative projects. Figure A.46; the former
54
55
56
57
58



Figure A.46: left: Prof. R. M. Bonnet, former COSPAR President; right: Prof. G. F. Bignami, COSPAR President

President, Prof. R.M. Bonnet, and current President of COSPAR, Prof. G. F. Bignami

Appendix B. Roadmap implementation plan

The present paper has been produced by the Future of Space Astronomy Working Group under the auspices of COSPAR: the international COMMITTEE ON SPACE RESEARCH. In general, COSPAR's objectives are to promote on an international level scientific research in space, with emphasis on the exchange of results, information and opinions, and to provide a forum, open to all scientists, for the discussion of problems that may affect scientific space research. These objectives are achieved through the organization of Scientific Assemblies, publications and other means. COSPAR, as an interdisciplinary scientific organization, focuses its objectives on the progress of all kinds of research carried out with the use of space.

The first step toward the finalisation of the report was its presentation at the 6th Meeting of the CSAC (COSPAR Scientific Advisory Committee) held in Paris on 23 March 2011 [17]. The Report was endorsed by the CSAC and recommended for publication in *Advances in Space Research (ASR)*.

It was also suggested that the Working Group findings be presented at the European Science Foundation, on the occasion of the 41st ESSC PLENARY MEETING, 5-6 MAY 2011, Liege, Belgium.

Future steps for dissemination of the Report to a wide audience include the following invited presentations:

- JENAM 2011 European Week of Astronomy and Space Science, European Astronomical Society, 4-8 July 2011, in Saint-Petersburg, Russia

- American Astronomical Society, High Energy Astrophysics Division, 12th Divisional Meeting 2011, Newport, Rhode Island, USA, 7-10 September 2011
- 62nd International Astronautical Congress of the International Astronautical Federation, 3-7 October 2011, in Cape Town, South Africa
- 39th COSPAR Scientific Assembly to be held 14-22 July, 2012 at Infosys Training Center, Mysore, India
- IAU General Assembly, to be held 20-31 August 2012, in Beijing, China
- any other main international symposia, forums and roundtable events focused to provide a roadmap scenario for the Future of Space Astronomy.

Finally, by publishing this paper in ASR, we hope that it will be read worldwide by the main Space Agencies, (NASA, ESA, JAXA, Roscosmos, CNES, ASI, etc), scientific institutes active in space research, and the space industries and stakeholders in the field.

Appendix C. The Astronet Report

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 five per cent 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

1
2
3
4
5
6
7
8
9 key astronomical questions which may be answered in the next twenty years by a
10 combination of observations, simulations, laboratory experiments, interpretation
11 and theory. The next step is to construct a roadmap which defines the required
12 infrastructures and technological developments, leading to an implementation
13 plan. To this end, the ASTRONET Board appointed a Science Vision Working
14 Group and an Infrastructure Roadmap Working Group, both of them with sup-
15 porting thematic panels. The Science Vision Working Group identified four key
16 questions where significant advances and breakthroughs can be expected in the
17 coming two decades:
18

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

23
24
25
26 These are amongst the most fundamental questions in science and generate con-
27 siderable interest in the general public. The Science Vision Working Group and
28 four supporting panels brought together about 50 scientists with a good distri-
29 bution of expertise, gender and nationalities. Each of the panels concentrated
30 on one of the key questions, and established the approach, experiment or new
31 facility needed to make progress. Much information already existed in national
32 strategic plans, ESA's Cosmic Vision, and the three ESA-ESO studies. This
33 work led to specific scientific recommendations, which were incorporated in a
34 draft version of the Science Vision, made available to the entire astronomical
35 community in late 2006. The draft was discussed in-depth during a Symposium
36 in Poitiers, Jan 23-25, 2007. Many of the 228 participants from 31 countries
37 provided constructive input, and additional comments were received via a dedi-
38 cated website. This led to further sharpening of the scientific requirements, an
39 improved balance across the four main areas, and improvements in the text...
40 Care was taken to describe these in a fairly generic way, focusing on the scien-
41 tific requirements, and not to identify too closely with specific proposed imple-
42 mentations of missions or facilities, as this is the purview of the infrastructure
43 roadmapping activity that will follow. ...summarises the main recommendations
44 by thematic area, and distinguishes essential facilities or experiments, without
45 which a certain scientific goal simply cannot be achieved, and complementary
46 ones, which would go a long way towards answering the question, but may have
47 their main scientific driver elsewhere...Activities needed across the four thematic
48 areas are identified as well. In all cases, the focus is on the most promising
49 avenues for scientific progress, without detailed consideration of cost or techno-
50 logical readiness, which are the subject of the infrastructure roadmapping. Some
51 of the more ambitious facilities may take a significant time to develop, and in
52 some case may only start to produce a scientific harvest towards the end of the
53 20 year horizon. Exploration remains an integral component of the entire field,
54 as many problems require investigation of large numbers of objects, all different.
55 This leads naturally to searches and surveys with modest-sized telescopes, and
56
57
58

1
2
3
4
5
6
7
8
9 *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 Roadmap leads to an effective and timely implementation of the plans outlined in the Science Vision. This is a very exciting prospect...*

20 **Appendix D. Message from F. Favata**

21 *"Dear Colleagues, To: Members of Space Science Advisory Committee, Astronomy Working Group, Solar System and Exploration Working Group*
22 *Dear Colleagues,*

23 *As you are well aware, 3 Large ("L") mission were selected from the Call for Missions issued in 2007 for the first L mission opportunity in ESA Cosmic Vision 2015-2025 plan, for a launch in the early 2020. These 3 missions, i.e. EJSM-Laplace, IXO and LISA, are currently nearing the end of the relative Assessment Phases.*

24 *All 3 L mission candidates have been proposed to ESA, and have been studied to date, as cooperative enterprises with international partners, with NASA in a key role in all three. As discussed repeatedly with all the Science Programme's stakeholders, a decision on the future of these missions cannot as a consequence be taken in isolation from the prospective partners.*

25 *Recently the US National Research Council has released "decadal" surveys for both astronomy and planetary science. While both surveys recommended continued cooperation with ESA, and ranked highly all three of the L mission concepts under study, none of these was however ranked at first priority.*

26 *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 2020's timeframe.*

27 *We have therefore consulted with both the chairman of Science Programme Committee and the chairman of the Space Science Advisory Committee, and agreed on a way forward for the L missions, which takes these developments into consideration.*

28 *Following the completion of the Assessment Phase activities at the end of 2010, and the public presentations of their science cases in February of this year, the plan of activities for the L missions foresaw a decision by the Science Programme Committee on a possible down-selection of the L missions in June 2011. In the light of the new situation, we no longer see the possibility for a programmatically meaningful decision on down-selection of these missions to be taken in the middle of 2011. Therefore we have decided not to propose a down-selection of the L1 missions in June 2011, and have set a new target, in February 2012 for*

1
2
3
4
5
6
7
8
9 *a decision by the Science Programme Committee on the way forward with the L*
10 *missions.*

11 *All three study teams have hitherto been international with equal US and Eu-*
12 *ropean (and Japanese in the case of IXO) representation, consistent with the*
13 *proposed cooperative mission framework. We have decided to revise the struc-*
14 *ture of each L mission study and of the corresponding team in the context of a*
15 *European framework. Each revised team will be asked to examine if they can*
16 *restructure their mission concept and its science case to meet a scenario where,*
17 *in the least optimistic case, a Europe-alone mission could be envisaged. The goal*
18 *of this activity will be to examine to what extent it will be possible to preserve*
19 *essential parts of the science goals of each original mission within the framework*
20 *of an European-led mission with an affordable budget for Europe. The revised*
21 *missions and their science cases will, in due time, be subject to a new assess-*
22 *ment by the ESA Advisory Structure.*

23 *We have informed our international partners of this action. We should em-*
24 *phasise that this is not to imply that US or Japanese involvement would not be*
25 *possible but that it should be understood that the study activities outlined above*
26 *will be conducted under the assumption of a European-led L1 mission. We shall*
27 *remain in close contact with JAXA and NASA to ensure the possibility of co-*
28 *operation if feasible.*

29 *Please feel free to circulate this information among all interested colleagues, and*
30 *feel free to contact us should you wish any additional information on this.*

31 *Regards*

32 *Fabio Favata*

33 *European Space Agency Head of the Science Planning and Community Coordi-*
34 *nation Office*

35 36 37 38 **Appendix E. Acronyms**

39 AGILE: Astrorivelatore Gamma a Immagini LEggero

40
41 AGN: Active Galactic Nucleus (or Nuclei)

42
43 ALMA: Atacama Large Millimeter/submillimeter Array

44
45 Aquarius/SAC-D: Aquarius/Satellite de Aplicaciones Cientificas D (USA/Argentina)

46
47 ASI: Agenzia Spaziale Italiana (Italian Space Agency)

48
49 ASTROSAT: Indian multi-wavelength astronomy mission on an IRS-class satel-
50
51 lite

52
53 ATLAST: Advanced Technology Large Aperture Space Telescope (US study)

54
55 AO: Announcement of Opportunity

1
2
3
4
5
6
7
8
9 AXAF: Advanced X-ray Astrophysics Facility (Chandra X-ray Observatory)
10
11 CBERS: China. Brazil Earth Resources Satellite
12
13 CIFS: Consorzio Interuniversitario per la Fisica Spaziale, Italy
14
15 CMB: Cosmic Microwave Background
16
17 CNSA: Chinese National Space Administration
18
19 COBE/DIRBE: Cosmic Background Explorer/Diffuse Infrared Background Ex-
20 periment
21
22 COSPAR: Committee on Space Research
23
24 CSA: Canadian Space Agency
25
26 CTA: Cherenkov Telescope Array
27
28 DLR: German Aerospace Center
29
30 DMD: Dark Matter Detection Programme (China)
31
32 EChO: Exoplanet Characterization Observatory
33
34 ESF: European Science Foundation
35
36 EJSM/Laplace: Europa Jupiter System Mission / Laplace
37
38 ELT: Extremely Large Telescope
39
40 EQUARS: Equatorial Atmosphere Research Satellite (Brazil)
41
42 e-Rosita: German X-ray survey instrument on-board the Russian "Spectrum-
43 Roentgen-Gamma" (SRG) spacecraft
44
45 ESTEC: European Space Research and Technology Centre
46
47 ESSC: European Space Science Committee (of the European Science Founda-
48 tion)
49
50 Fermi: γ Ray Space Telescope, formerly named Gamma Ray Large Area Space
51 Telescope (GLAST)
52
53 FIR: far-infrared
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9 Gaia: Global Astrometric Interferometer for Astrophysics
10
11 GALEX: Galaxy Evolution Explorer
12
13 GEMS: Gravity and Extreme Magnetism Small Explorer
14
15 GLAST: Gamma-ray Large Area Space Telescope, now named Fermi γ Ray
16 Space Telescope
17
18 GLONAS: Global Navigation System (Russia)
19
20 GRB: γ Ray Burst
21
22 GSFC: Goddard Space Flight Center (NASA)
23
24 IAA: International Academy of Astronautics
25
26 IAF: International Astronautical Federation
27
28 IAU: International Astronomical Union
29
30 INTEGRAL: INTERnational Gamma-Ray Astrophysics Laboratory
31
32 INAF: Istituto Nazionale di Astrofisica (National Institute for Astrophysics,
33 Italy)
34
35 INFN: Istituto nazionale di Fisica Nucleare (National Institute for Nuclear
36 Physics, Italy)
37
38 ISRO: Indian Space Research Organisation
39
40 ISS: International Space Station
41
42 ISSI: International Space Science Institute (Bern)
43
44 ITAR: International Traffic in Arms Regulations (US)
45
46 IXO: International X-Ray Observatory
47
48 JAXA: Japan Aerospace Exploration Agency
49
50 JWST: James Webb Space Telescope
51
52 LISA: Laser Interferometer Space Antenna
53
54 LOFAR: Low Frequency Array
55
56
57
58

1
2
3
4
5
6
7
8
9
10 LOFT: Large Observatory For x-ray Timing
11
12 LSST: Large Synoptic Survey Telescope
13
14 MAGIC: Major Atmospheric Gamma-ray Imaging Cherenkov telescope
15
16 MAXI: Monitor of All-sky X-ray Image
17
18 MIREX: Monitor e Imageador de Raios X (Brazil)
19
20 NuSTAR: Nuclear Spectroscopic Telescope Array
21
22 PACS: Photodetector Array Camera and Spectrometer, on board Planck
23
24 PAO: Portraits of Astrophysical Objects Programme (China)
25
26 PLATO: PLAnetary Transits and Oscillations of stars
27
28 PSLV: Payload Solar Launching Vehicle
29
30 POLAR: Gamma-ray Burst Polarization instrument (on Chinas Spacelab)
31
32 RKA: Rossiskoye Kosmicheskoye Agentsvo (Russia)
33
34 RXTE: Rossi X-ray Timing Explorer
35
36 SAO: Smithsonian Astrophysical Observatory
37
38 SFXT: Supergiant Fast X-ray Transients
39
40 SKA: Square Kilometer Array
41
42 SMEX: Small Explorer, a US PI-led low-cost mission
43
44 Roscosmos: Russian Federal Space Agency
45
46 RXTE: Rossi X-ray Timing Explorer
47
48 SFXT: Supergiant Fast X-ray Transients project
49
50 SKA: Square Kilometer Array
51
52 SOFIA: Stratospheric Observatory for Infrared Astronomy
53
54 SPC: Space Programme Committee
55
56
57
58

1
2
3
4
5
6
7
8
9
10 SPICA: Space Infrared Telescope for Cosmology and Astrophysics (Japan)
11
12 Spitzer ST: Spitzer Space Telescope (US infrared observatory)
13
14 SPIRE: Spectral and Photometric Imaging Receiver, on board Planck
15
16 Spitzer ST: Spitzer Space Telescope
17
18 SRG: SpectrumX-Gamma Satellite (Russia)
19
20 STE-QUEST: Space-Time Explorer and Quantum Equivalence Principle Space
21 Test
22
23 Suzaku (previously called Astro E2): Japanese X-ray astronomy mission
24
25 Fermi Gamma Ray Space Telescope: Formerly named GLAST
26
27 SVOM: Space multi-band Variable Object Monitor
28
29 SWIFT: Swift Gamma-Ray Burst Mission
30
31
32 TMT: Thirty Meter Telescope
33
34 TPF: Terrestrial Planet Finder
35
36 VERITAS: Very Energetic Radiation Imaging Telescope Array System
37
38 VLBI: Very Long Baseline Interferometry
39
40 WFIRST: Wide-Field Infrared Survey Telescope
41
42 WG: the COSPAR Working Group on the Future of Space Astronomy
43
44 WMAP: Wilkinson Microwave Anisotropy Probe
45
46 XMM-Newton: X-ray Multi-mirror Mission / Newton
47
48 XTP: X-ray Timing and Polarization satellite
49
50
51
52
53
54
55
56
57
58

Dear Editor,

We have read and analysed in detail the two reviewers reports.

Both reviewers have given to us very useful comments and suggestions to improve the text and figures for the paper publication on ASR.

Rev. 1 has made basic comments and criticisms we have coped with. In particular we have reduced redundant parts of the text, shrank substantially the Executive Summary, moved four parts in the appendix etc.

A main substantial change has been the addition of several sections with the main scientific results obtained by operational satellites/observatories in the space astrophysics domain. This addition was suggested by both reviewers. The scientific results have been added in the sections from 4.3.1 to 4.3.14, complemented with the most relevant figures.

Rev. 2 has made a substantial work to improve our manuscript providing to us a red marked copy with several new parts to be finalized and other to be deleted. We have started our revision from this version, accepting all her/his suggestions and requests. Then we have substantially improved the manuscript, added the proper references, acronyms table, reviewed the language, typos etc. We have also removed 3 figures, not essential for the paper.

The new uploaded manuscript is the result of this long work. We have spent particular attention to the language revision of the text (done by a US and a UK native co-authors), style uniformity, elimination of the typos, reference included, instead of web sites citation whenever possible, and provided better figures. We have also moved four parts in the appendix, including the Roadmap Implementation Plan, as requested by the Rev. 1.

Finally, as already said, we have appreciated very much the reviewers work and we are willing to mention their names explicitly in the acknowledgements if they are willing to reveal their names.

Follow the detailed answer to the reviewers points.

We plan to have all the figures in color in the electronics version and select a sub-set for the printed version.

Reviewers' comments:

Please note that editors and/or reviewers have uploaded files related to this submission. To access these file(s) while you are not logged into the system, please click on the link below. (Note: this link will expire after 5 clicks or 30 days.) Alternatively, you may log in to the system and click the 'View Review Attachments' link in the Action column (file is attached to the mail).

Reviewer #1: Major comments:

The present version reads as a report and not a paper for publication in a journal. Significant rewriting is necessary. There is need for a major reduction in number of pages. Many things are repeated.

-OK, point taken and manuscript changed accordingly (see later)

A major weakpoint of the report appears to be that it is ESA/Europe centric. It extensively quotes from the ESANET report but there is little reference to the Decadal Survey Report of the US National Research Council.

-This is not intentional, rather the result of the WG view. There is a substantial agreement among the members, several from US side. We have now moved the long referenced part about the Astronet report document in Appendix and given more room to the Decadal Survey part.

If it is to be presented as a paper, Section 1.4 should be removed.

-This part has been changed following the suggestion of Rev. 2, renamed as 'road map implementation plan' and moved in Appendix.
We believe this version can be acceptable by both reviewers.

Section 2.

Much of the first part is repeated from Section 1.

The second part that describes setting up of the committee etc. can be written briefly.

-We have changed the Executive Summary for top level readers and added the Conclusion, as suggested by rev. 2. We think this could be acceptable for both reviewers.

Section 2.1

The first part is repeated exactly from the abstract.

-probably the rev 1 meant the beginning of section 2 was identical to the abstract. We have now modified both parts, though maintaining the basic information in the abstract.

Section 3.1.3:

EJSM: Why is there no recommendation by the WG on EJSM ?

-This due to the fact that our mandate is limited to 'electromagnetic astrophysics'. We are not expected to recommend anything about planetary missions. Anyway, EJSM was included in the analysis because in direct competition with IXO and LISA in Cosmic Vision selection process.

page 23-24:

Communication from F. Favata:

In stead of quoting from original, a brief and clear summary can be given.

-Done, the text is now moved in Appendix.

section 3.2: 2020-2030 road-map

page 29:

proposed longer term large missions to be launched within two decades.

The list includes 'next generation gamma-ray observatory' 'space sub-millimeter array' etc. which are not at all mentioned before. There is no background given for some of these recommendations.

-All the mentioned missions are part of the proposed mission to the ESA call for L or M missions in the past years. It is true that none of the listed missions have been selected for further studies, as far as we know. However, we have (just) mentioned them here for completeness and because proposed at least as response to call from ESA, NASA or other national agencies.

page 33, section 4.1, last few lines

'Europe has the opportunity to lead the expected scientific harvest...'
It may very well be, and that is fine in a report. But it is inappropriate to highlight the regional perspectives in this international forum..

-Removed; point taken. As said before we have moved most of this Astronet incipit to appendix C, for information. The section 4.1 is now a short summary of the initially quoted report. This was also asked from the Rev. 2

page 36:

The concepts of Constellation-X and Xeus must be mentioned in the past tense.

-Done

page 36: The earliest launch of JWST, if at all is 2018 and not 2014-15 ?

Somewhere else 2018 is written as the year of launch.

Why mention the details like the size of the sunshade of JWST and the fact that it won't fit in the rocket if fully open ?

-Done, launch date updated to 'not early than 2018'.

-We have removed the part about the sunshade etc, from line 47 to 54.

Section 4.1 : It is not clear why so much of detail is given about the current space observatories like HST, RXTE, Chandra, XMM etc. Instead, another column can be added to Table 1, giving the main lifespan and till what period are these expected to operate. I suggest all the sections from 4.2.1 (page 40) to 4.2.14 (page 54) be removed.

-As specified above we have added the main scientific results obtained by the mentioned space missions in the section 4.2. This was also a request from Rev. 2, and we have followed his/her request.

Table 2:

Astrosat: There is a misrepresentation. Though TIFR has a major role, it is only one of the participating institutes. If at all an organisation has to be mentioned, it should be ISRO.

-Point taken. We have specified the ISRO role instead of TIFR.

Table 2 shows three sections. What is the difference between different

sections? If the top section represents the selected missions, should not JWST be there ?

-It was a mistake. The table shows all missions planned to fly or under selection. Fixed.
-We have also added SOFIA, that was just missing.

Wherever possible, references should be given to articles in journals rather than web pages. This is most important for section 4.3

-Done, now we have added a full reference list, whenever possible.

Information in Section 4.3 should be more up-to-date:
Astrosat launch is delayed to 2012, GAIA to 2013 etc.

-Done, all the launch dates have been updated.

For a vision document, too much details are given for the individual missions. Section 4.3 should be shortened significantly.

-This point is in conflict with the rev. 2 request, i.e. to extend those sections including the main scientific request. We hope the new version is acceptable by Rev. 1 (see also later points)

The sections on different observatories (4.3) are written in very different styles, probably by different individuals. Some uniformity in style is essential.

-Done, all the text has been reviewed for style.

If some description of SOFIA is to be included in this report, then why also not some of the major balloon borne programmes?

-The point arose is basically correct. We have been asked to include only satellites. The addition of SOFIA was due to completeness. We consider the balloon programmes to be very valuable, but they are beyond the scope of the WG study.

Section 5.1,

The last part, on NASA small contributions to otherwise large programmes need not be mentioned at all. These programmes will be listed in their own right elsewhere.

-This paragraph is taken from the Decadal Survey report and was included for completeness.

Section 5.2.1: Regarding L1:IXO

There is reference to a figure showing the simulated spectra, but the figure is missing. Figure number is not given in the text.

-Apologize, this was a typo. Sentence removed.

The sections on different national agencies (6.1 onwards) are written in very different styles, probably by different individuals. Some uniformity in style is essential. No references are given for the documents regarding the

reports from the national agencies. How authentic are the things mentioned in this section? This section should also be shortened.

-Actually, these are the original contributions from people responsible to provide national plans and information. The material is taken from original documents (i.e. China, Australia etc), in some way re-adapted to be shortened. We have difficulties to make them uniform in style, even if some attempt is done for the current version. We have also added references whenever available or possible.

Section 6.3:

The decadal vision document (2008) that is mentioned here was actually brought out in 2004 and is meant for the decade 2010-2020. The first part of this section is written in first person, why? Why is the name of the PI mentioned here for the X-ray polarimeter?

-Point taken. We have specified the 2010-2020 period, corrected the first person part and eliminated the reference to the PI (was a typo).

Minor:

Contents:

3.1

..media sized missions

-->

..medium sized missions

-Done

4.3.7: HXMT China

--> What about SVOM ?

-Done, now SVOM is included in the document.

p5, 141

is today impressive

-->

today is impressive

-Done

p10, 144

Judy --> July

-Done

p15, para 2

some links to sections are missing

-Fixed, has been re-written

section 2.3, para 2:

All references about decision to publish it in the ASR etc. should be removed.

-The para 2.3 has been updated as suggested by rev. 2 The decision about the ASR was maintained as a recommendation of the COSPAR CSAC, as actually was.

section 3.1.2, 132

Is the main advantage of LISA over LIGO/Virgo a large baseline or reduced seismic background?

-Actually, they operate at different frequencies. For consistency we have removed the reference to the reduced seismic background.

p21, 142:

When a massive body is accelerated in the proper manner..

-->

.in the proper manner... Can the authors give a scientific description ?

-Done, re-phrased.

p24, 130

will soon lose of parts of

-->

will soon loose parts of

-Done

Figure 1, Figure 2, Figure 3 : Not necessary for the paper

-Done, figure 1 and 2 moved in appendix 1.

Figure 7: labels are too small

-Done, now the figure is enlarged.

Figure 10: The caption says 'Current Instruments' but no instruments can be seen in this figure and nothing is marked.

-OK, reference to the instruments was deleted.

Section 4.2.1

The history of Hubble launch etc. is irrelevant for this paper and the writing style is also inappropriate for a journal.

Description of WFC 3: '4th generation camera' unless the authors wish to explain what are 1-3 generations of camera, they need not describe this as a 4th generation camera. It makes little sense to the reader. Same about '4th generation spectrograph' mentioned in the next paragraph.

-Done. This section has been re-written substantially

4.2.2: The RXTE energy range is mentioned to be 2-250 keV. I think 2-150 is a more appropriate description.

-The figure is the one provided by NASA and we feel we have to stay with this. We know the RXTE has a limited capability above 150 keV.

4.2.4:

Chandra observatory is 12 years old and here it is said '...will make it possible for Chandra to study extremely faint sources...'

-Done, re-phrased.

section 4.2, para 2, line 8
have operating successful

-->

have been operating successfully

Done.

5.2.2

On Thursday 18 February

Is the date and day important here?

Not really, deleted the reference to the day.

Figure 34: Why have this figure ?

-Done, removed

Figure 35: Fonts are too small to read anything in this figure.

-OK, enlarged and provided a better quality picture.

Table 3: Why have this table?

Point taken: deleted.

Reviewer #2: Review of the Manuscript

Future of Space Astronomy: a Global Road Map for the Next Decades

by Pietro Ubertini and 10 co-authors

To begin with, this reviewer was informed that this manuscript was originally a report prepared for COSPAR. I was also informed that this manuscript would probably be published as a special issue of ASR, would be reviewed by two referees in accordance with journal policy, and that the journal formatting requirements should be maintained. I should also mention that I am not an astrophysicist; my own field is in the solar-terrestrial domain. Therefore I have reviewed this manuscript from the viewpoint of an "interested" scientist not completely familiar with astrophysics and many of the technical terms used by members of that community. Since ASR is an international journal covering all aspects of space science, this paper (as well as other papers)

should be understandable by space scientists who read the journal

-OK, point taken. Thanks for the appreciation of the work -Done.

With that said, I was disappointed in this manuscript and wonder if this is simply a copy of the report that was submitted to COSPAR. As written, this paper is not yet up to international standards of a journal article. The manuscript needs considerable revision. There are places within the manuscript itself where entire sentences are repeated (excluding the executive summary). There are several incomplete sentences. There are other places where sections have been run together instead of being separated. Many figures and tables are not referenced within the text. At the end I found that I was lost in the many details (some being repeated) such that the overall impact (which should be there) was lost.

-Upgrade -Done, see each points addressed below.

While I can appreciate that English is not the native language of most of the authors, I am somewhat surprised that the English language authors did not correct several of the items that should have been corrected. For example, in the description of the Hubble Telescope, there are many "will be -Done" type of sentences where these have already been -Done. Apparently the text was "lifted" from a NASA pre-launch document.

-We apologise for that. We have now revised the manuscript for typos, verb mistaken etc USA and UK scientists have reviewed the language.

Finally, I tried to think of myself as a manager in a funding agency being requested to allocate funds to some of these interesting experiments. My first reaction would be to ask "What has been accomplished so far in this area of space science?" The paper does not mention many of the wonderful accomplishments of previous missions - something that should be addressed in the revision. Sections 4.2.1-4.2.14 are sections where scientific results could be highlighted. Key references in the refereed literature would be most desirable.

--Done, this has been the main upgrade of the text. We have included scientific results, as asked, in the above mentioned sections. References have been fully reviewed and new of them added accordingly.

I feel that this roadmap and suggested missions plus the details contained in this manuscript should be published and a special article in ASR would be most appropriate. The authors have worked hard to assemble the material into one document and this hard work is appreciated by this reviewer. This information should be available to the scientific community in one easily found document instead of being scattered all over the literature or web sites. I learned a lot from reviewing this article, and I think other readers not completely familiar with the astrophysical community research efforts would be interested in this paper.

-Point taken, thanks again

Therefore, I strongly urge the authors to carefully consider my remarks in the spirit in which they are given. I do feel this is a valuable internal report for the COSPAR community - and with some effort can be revised into an excellent journal article.

--Done

I will first list some major items that I noted. I will then list several places where I think changes should be made. At the same time I have tried to put the pdf document into a MSWord document and have made some (not all) suggested changes on that document, hoping these will be useful. My suggested revisions are in red - some notes are in blue. The authors should note that the "translator between pdf and MSWord documents" does not always do a "one-to-one" translation, and I will probably not find all those translator problems. In two or three places there were question marks ? in the manuscript itself which I could not understand and suspect that something was lost between the original manuscript, the submission, and final conversion to pdf by Elsevier's system. These need to be carefully checked for any revision.

-This has been a major help from the reviewer we appreciate very much. We have started the revised version using the red marked/improved copy. Most of the new parts are in italics, not the typo or minor correction and errors corrected.

Major items:

1. A table of acronyms and abbreviations is essential. While most of the acronyms have been identified when first used, I found myself lost in the "alphabet soup" at times. Most of the abbreviations are well known to the astrophysical community; they are not as well known to others in the space science community. There are several places in my detailed comments where I have questioned the abbreviation or acronym.

-Done: a table with acronyms has been added

2. I was disturbed by the lack of references to journal articles or equivalent, especially those articles giving major scientific accomplishments of past successes. Most of the references are web sites which may or may not be periodically changed as time progresses. ASR does not have a standard policy for web site citations. The reference citation within the text of the article is the Harvard style; references are not numbered as they are in this submission. Therefore I strongly suggest that all those web citations be moved to footnotes on the appropriate pages since including the web sites in the actual text would be distracting.

-Done

3. All Tables and Figures should be referenced within the text itself. While the figures of some of the spacecraft are visually nice to include, I think most of them are artist's drawings and these should be so identified vs. an actual spacecraft picture. (It may be that Figure 10 is an actual photograph taken from the space station although I am not certain.) I am also concerned about the large number of color figures. Color figures are "free" on the Elsevier web site; however, Elsevier charges heavily for color in the print version. It may be that the authors can provide both black and white figures and color versions for many of the figures that do not require color. In these cases the captions should not use colors to identify specific items in the figures unless the authors provide two sets of captions for each of the figures where you have one caption for color figures and one caption for black and white (or shaded) figures. There is a way this can be arranged.

--Done

4. The use of the term "courtesy of NASA, etc." on paragraphs and figures is a distraction and annoyance. I suggest you acknowledge all the organizations (by name) for the use of material in the acknowledgement section and omit these individual citations.

-Done: all the Courtesies removed

5. There should be a consistent use of fonts throughout. I found italics used for several different items. Bold face fonts were used for some spacecraft and some satellite programs but not for all of them. The report needs to be checked for consistency. I suggest that the major points in the Executive Summary (and in the body of the text) be placed in bold face. However, too many items in bold print are distracting. You need to emphasize the most important items in your executive summary so that an organizational administrator can "get the point" in a few minutes of review.

-Done: the font has been changed accordingly. We have used the bold for the WG recommendations and the italics for the citations from other documents.

Detailed items - page by page or section by section. Note that line numbers may not always line up correctly. I have used the line numbers as inserted by Elsevier on the pdf version of the manuscript when listing line numbers. You will have to refer to that pdf version to see the actual lines being identified.

-ok, thanks

1. I have slightly revised the abstract as shown on the annotated document. I do have a question: Is the work of this committee completed with the finalization of this report? In re-writing the abstract, I have included the sentence "The purpose of this Working Group was to establish a roadmap for future major space missions to complement future large ground-based telescopes" and I need to know if the work is completed (in which case the correct verb would be "was" or if there are other purposes in which case the sentence should read something like "The major purpose of this Working Group is to establish..")

--Done: All changes suggested has been included in the reviewed version

2. I like the idea of a "Contents" section; however, the page numbers would not coincide with those of the journal which are numbered consecutively throughout a volume. I suggest just removing the page numbers. Care should be taken if sections are re-numbered in the revision or sections moved or changed.

--Done. Note: the page numbers of the contents should be not included

3. Page 6, line 46. With respect to reference 2, the actual reference citation (at the end of the article in the list of references) should include the title of the article and inclusive page numbers. You might want to reword this sentence as "We note that many of the ideas and conclusions of this report are reflected by Bonnet and Bleeker (2011).

--Done, sentence included

4. Page 7, line 54. I am confused. Is IXO renamed Athena? If so, this should be updated as necessary with some type of indication that Athena was originally IXO. On this same page, on line 19, you mention IXO without reference to Athena which is what has confused me. A footnote would be fine. Appropriate changes should be made throughout the manuscript. If the current name is Athena, it would be better to use the new name and refer to the previous name of IXO. This might be able to be -Done using a global change in the manuscript.

--Done, the change from IXO and LISA to Athena and NGO is addressed later on in the paper. Now the new missions are ESA alone and has been de-scoped.

5. Page 8, line 51. Why isn't EChO a separate bullet?

--Done

6. Page 9, line 12. In some cases Radioastron is spelled as RadioAstron. This should be consistent throughout.

--Done

7. Page 9. I have made some suggested revisions in the MSWord document. I note that the findings of the Working Group were to be conveyed to the new ESA Director for Science but doesn't the last paragraph of this section imply that all space agencies will be presented with these findings. Why just the new director of ESA? I don't think anyone one person (or director of a specific organization) should be singled out in a scientific journal publication. Hopefully directors of many space organizations will receive a copy of the COSPAR report.

--Done

8. Page 10. Line 10. You mention "Roscos" in some places and "Roscosmos" in other places. This should be consistent.

--Done

9. Pages 10-12. While ASR does not typically have "Inserts" (similar to Tables) or "Sidebars" as they are often called, I think the words of Professor Bonnet should be separate from the text. It calls attention to those words instead of having them "lost" in the rest of the text. I have indicated this on the marked up copy. I really feel this (as well as the "quoted documents" on pages 22-23 and 32-33 should be given as three Appendices. Perhaps more of Prof. Bonnet's talk could be included - at least the relevant sections. I have also mentioned that the "Dear Colleague." letter on pages 22 and 23 be handled in the same manner as well as a section of the text on pages 32-33. All of these lengthy items, placed where they currently are placed, detract from the main features of the report - which is really what you want to emphasize. See items number 26 and 37 where I suggest these other sections should be in Appendices.

--Done: the Bonnet letter (and picture) may be moved in Appendix. The three mentioned parts are moved in the Appendices.

10. Page 12, last two paragraphs. I revised them somewhat; see the marked up copy.

--Done

11. Page 13. Can specific references be cited for items 1-4? The US Academy Report should have some type of publication number. Is the Astronet Report still only a draft as mentioned as having been released in 2006? Has this been updated?

--Done

12. Page 13, line 52. Give the country for Poitiers.

--Done

13. Page 14, top paragraph. Fill in the question marks shown in two places.

--Done (Section 4.2, 4.3, 5)

14. Page 14, lines 38-42 See marked up copy for suggested revision. A lot of these activities have been concluded and are not necessary for this publication.

--Done

15. I would put the membership of the Working Group at the end of Section 2.2 and refer to your Figure 2. Figures 1 and 3 are not appropriate for a journal article (although fine for a COSPAR report). The caption for your Figure 2 should mention the members not present, and that Professor Bonnet was the host of the meeting since he is not a member of the working group. I have tried to revise the text in this way - see the markup.

--Done. We have moved figure 1 in the Appendix with the text. And update the text as suggested. We fill unfair to drop the picture with the three WG members not present at the meeting. If required by reviewers we can drop it.

16. I would have your section 2.4 as a completely new and independent section; it is not really related to the heading of section 2.

--Done

17. Page 16, line 42. Can you provide a reference for the recent Euroconsult report?

--Done

18. Page 17, line 23. The sentence starting with "We thus envision." should start a new paragraph.

--Done

19. Page 17, last paragraph. I am delighted you mentioned the ITAR problem; many US scientists are very unhappy with this restriction. You have also eluded to the problem of relying on NASA for cooperative efforts. Unfortunately NASA funding is decided by the USA Congress and the funds are not always granted as requested. As a US scientist I understand the problem, and while US scientists may regret this situation, there is nothing we can do about it. Even programs solely in the USA are frequently budget casualties.

-Thanks to appreciate!

20. Page 18, line 22. The term "down selected" is alien to many. Since it is used frequently in the report (and I know what it means), I suggest you have a footnote explaining it. Perhaps the use of "elimination" could explain this action.

--Done: we have added a footnote to explain its meaning.

21. Page 18, line 36. Please mention expected years instead of "next two years" since this report is expected to be used for some time. Also it will not be printed in ASR until 2012 since all ASR issues for 2011 have been allocated.

--Done

22. Page 19, section 3.1 media should probably be medium. Also for consistency I think the words ESA - L Class Missions should be on the same line, or list each of the missions as L or medium class on the line where each is identified. Some consistency is necessary here. I have tried to indicate on the markup what I mean.

--Done

23. Page 19, last two paragraphs. Much of these two paragraphs are repeated (in some cases word by word) on page 72. One section (perhaps the latter one) should refer to the earlier section for details.

--Done. See also your note 103

24. Page 20. Could you give some indication of why the JWST delay is a problem for ESA. I suspect that the astrophysical community would greatly benefit by having all those spacecraft in orbit at the same time for complementary measurements. A footnote would be appreciated.

--Done, footnote added

Regarding all the recommendations in the main text of the report, I would put them in bold type to accentuate them.

--Done

25. Page 21. How about "is schedule to be terminated" in February 2012. Of course if it is definite, you can use "will". But knowing the action of many committees...

--Done

26. Pages 22-23. The "Dear Colleagues" letter should be in an Appendix and not part of the text since you lose the main thrust of the entire paper.

--Done

27. Page 22, line 31. Shouldn't this be a new section since it does not refer to a specific mission or spacecraft?

--Done

28. Page 24, line 13. I believe the word "and" should be inserted between physics and cosmic .

-Done

29. Pages 25-27. The figures should be enlarged so that the "rainbow" in the center can be read. I cannot read those numbers. Elsevier can reduce the size of figures submitted; they cannot

enlarge them. Therefore I suggest you enlarge all three of these figures. What does Multi Color Eyes mean?

--Done, figures enlarged Multi color eyes is used as 'multi color view'. If the Figures are not improved enough we can change re-do them and drop the Multi color eyes statement.

30. Page 28, lines 42 and 47. SVOM GRB are given twice.

--Done

31. Page 28, line 51. Shouldn't EChO have a separate bullet?

--Done

32. Page 28, bottom section list. What happened to MarcoPolo-R and STE-QUEST? Neither one is listed here but both are included on pages 76 and 77.

Ok, -Done

33. Page 29, line 13. This should not be a bulleted item. I suggest a separate sentence reading something like the following:

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

-Done

34. Page 30. Figure 7. (a) The figure should be enlarged so that the numbers and letters can be read. (b) The purple lines should be explained in the caption. (c) I don't fully understand the insert "Less mission/decade but lasting longer and very productive". I think you mean that from 1990 to 2007 there were less missions per decade but those that were implemented lasted longer and were very productive. This can be mentioned in the caption. (d) Why isn't the Hubble Telescope included in this figure? Maybe it isn't considered high energy.

-Done. We have removed figure 7, not essential/relevant for this paper.

Note: we have also removed figure 6 and 35.

35. Page 30, line 43. Picture 7 should be Figure 7.

-Done

36. Page 31. Figure 8 is not referenced in the text. Also enlarge the figure so that the lettering can be read.

-Done. We have shorten the caption and included the basic information in the text.

37. Page 32. I have two comments here. First on page 13 there is a statement that this report was released in draft form in 2006 with no mention of the final publication in 2007. A reference to the actual 2007 publication should probably be given on page 13 where it is first mentioned.

-Done.

Second, I would put the text of the report in an Appendix but not within the text of this article. While I realize that you quote the report exactly, I have no idea what ERA-net means. Perhaps it is explained in the actual document. I also assume this is a public document and is not a copyrighted publication in which case you need to obtain permission to use it.

I think you could summarize this entire section in a few key sentences and then have this part of the document as an Appendix.

-Done.

38. Pages 33-35. Should each of the italicized sections be numbered?

- 4.2.1 X-rays and Gamma rays
- 4.2.2 UV/Extreme UV and Visible
- 4.2.3 Infrared
- 4.2.4 Sub-Millimetre

-Done

39. Page 34, line 16. Burst should be plural: Bursts

-Done

40. Page 34, line 44. Delete the word "and" at the beginning of the line.

-Done

41. Page 34, bottom 1/3 of the page. You give many launch dates. Please check to see if those dates are still current.

-Done

42. Page 35, lines 43-53. These are essentially repeated on pages 62 and 63.

OK, we have removed the text from line 44 to line 53 of page 35. Also, line from 47 to 54 of page 35, now present later in the document (page 63).

43. Page 36, lines 20-21. What is the intent of the line "Missions in Operation: from launch to planned in orbit operations."

It was a typo: the sentence has been removed

44. Page 36, line 22. I think this should be a new section - maybe 4.3

-Done

45. Page 36, line 27. Delete the leading "The" before Figure 9

-Done

46. Page 36, first two bullets. Mission should be plural: Missions

-Done

47. Page 36, line 32. Delete the leading "The" before Table 1

-Done

48. Page 37, Figure 9 caption. Mission should be plural in both places. This figure is an excellent size.

-Done

49. Page 39, Figure 10. Is this an actual photograph or an artist's conception? It looks like an actual photograph and should be so identified in the caption. I don't see what instruments can be identified in the picture although the caption mentions the instruments.

-It is an actual picture. We have removed in the caption the reference relative to the instruments, actually not visible.

50. Page 39, line 39. What is LST?

-It is a typo: the correct word is HST

51. Page 39, line 55. NICMOS should start a new line just as ACS did.

-Done

52. Page 40, line 14. STIS should start a new line.

-Done

53. Page 40 and continuing. First there is a missing space between 1999 and (Figure 12) on line 57. You might want to say (see Figure 12) but this is not necessary. If you change it, do it for all the figures in this section.

-Done, for all the figure in the text

54. Page 41 and continuing. I think most of the pictures are artist's conception. This is fine but it could be so stated.

-Done

55. Page 42, line 32. Delete the word "will"; the spacecraft is operational

-Done

56. Page 42, lines 39-52. These might be best in a table. There appears to be something missing after FOV in line 43. While I assume FOV is field of view, I do not know what FI and BI mean. If written as a Table, it would be best to identify ACIS, HETG and LETG in the Table after the written words; it took me a while to determine what these were the way this is presently presented.

-Done: we have restated the characteristics in a more clear way. The FOV is explicit (field of view) and FI and BI removed (front illuminated and back illuminated, is a detail not necessary).

57. Page 46, line 40. Change "are" to "were" and "cool" to "cooled"

-Done

58. Page 47, line 56. What is EAO-6?

-Done Is a typo read AO6 (Announcement of Opportunity, in the acronym table)

59. Page 48, top paragraph. You should not start a sentence with a numeric. I suggest the following: "A total of 28 valid proposals." Also this should be updated since the February-March deadline has passed.

-Done.

60. Pages 49-50. This has been written in the future tense and should be changed to the present tense. There are many changes necessary. See the revised two paragraphs on the marked up copy. I have deleted a few words here and there in the text and highlighted only some of the changes. There is something missing at the end - perhaps a repeat of lines 50-52 on page 49 which would not be necessary to repeat.

-Done, Line 44-52 are exactly the repetition of the above sentence. It was a typo: removed.

61. Page 51. You need a space after "10"

-Done

62. Page 52. Please include the launch date for HERSCHEL. You give all other launch dates.

-Done

63. Page 52, line 42. You need a space between SPIRE. and The

-Done

64. Pages 52-53, section on MAXI. It should be mentioned that this is on the ISS. What are the operational dates? Is it continual operation?

-Done, details added

65. Page 53, line 42. cm². the 2 should be a superscript.

-Done

66. Page 53, lines 42-47. You might want to "bullet" these five items or make a list of the 5 items. It would be easier to read.

-Done

67. Page 53, first paragraph of section 4.3. I suggest revising this paragraph as follows: "A summary of the missions approved worldwide, of which the Working Group has noted, is

presented in this section. We have included missions under construction or being tested and future mission opportunities from ESA, NASA and other national Space Agencies".

-Done

68. Page 53, line 57, and Page 54 lines 9-15. Change "mission" to Missions (plural)

-Done

69. Page 54, line 17. Delete the word "The" before Table 2.

-Done

70. Page 54, lines 22-25. I suggest the following: "Figure 24 is a graphical presentation of the missions under development or under the selection process. A short description and basic characteristics of these missions and planned launch dates are presented in this section."

-Done

71. Page 55, Figure 24 caption. Change "Mission" to "Missions"

-Done

72. Page 57, Figure 26. The abbreviations in the figure should be identified.

-Done, now they are identified in the text

73. Page 57. Top written section. There are a lot of abbreviations that need to be identified here. I also suggest these 4 items be listed as 1.,2, 3, and 4 similar to a Table. .

-Done

74. Page 57, Line 40. What does the number 40 mean? Is this reference 40?

-Typo, removed

75. Page 57, line 50. Lunch should be launch.

-Done

76. Page 58, line 45. I believe that the item "Studying the birth of the elements." should be a separate bullet.

Yes, -Done

77. Page 59, line 33. Figure 28 is of Spectrum, not eROSITA.

-Done, now the text is consistent with the figure

78. Page 59, line 38. Buster should probably be booster.

-Yes, corrected

79. Page 59, line 44. "The mission will conduct an all-sky." (Add the word "an")

-Done

80. Page 61, line 27. Figure 31 should be Figure 30.

-Done. Figures have been changed and now the numbers have been checked.

81. Page 61, line 35-37. I suggest the following: "When light travels freely through space, it can vibrate in any direction; however, under certain conditions, it becomes polarized."

-Done

82. Page 61, line 45. Insert the word "conduct" before "sensitive".

-NOTE: the whole paragraph 43.7 (HXMT Chinese satellite, has been replaced. We have carefully checked for consistency and typo.

83. Page 61, section 4.3.7 Refer to Figure 31.

-Done, reference added

84. Page 61, line 55. Insert the word "the" before "Ziyuan II"

-NOTE: the whole paragraph 43.7 (HXMT Chinese satellite, has been replaced. We have carefully checked for consistency and typo.

85. Page 62, line 29. Use "development" instead of "develop"

-NOTE: the whole paragraph 43.7 (HXMT Chinese satellite, has been replaced. We have carefully checked for consistency and typo.

86. Page 62, line 30. Start the paragraph with the word "The.."

-NOTE: the whole paragraph 43.7 (HXMT Chinese satellite, has been replaced. We have carefully checked for consistency and typo.

87. Page 62, line 38. I think the All-sky hard X-ray survey should be a separate bullet item.

-NOTE: the whole paragraph 43.7 (HXMT Chinese satellite, has been replaced. We have carefully checked for consistency and typo.

88. Page 62, lines 49-54. In line 49 you give the launch date as 2018-2019; in line 54, you have 2014 as the launch year (we should be that lucky!)

-Done. We do not hope to be THAT lucky!

89. Page 62, line 52. Insert the word "an" before IR 6.5.

-Done

90. Page 63, top paragraph. This is a repeat from page 35.

-Yes, see your NOTE 42 The redundant text has been removed.

91. Page 63, Section 4.4 title: Use fully operational 2014 instead of full operative

-Done

92. Page 63, section 4.4. Reference should be made to Figure 33.

-Done

93. Pages 64-65, section on the Decadal priorities. The text is not written in a consistent manner. In some cases there are complete sentences; in other cases just a few words. I have revised this entire section on the markup using complete sentences. You can use either this or an updated version of your own. I have also suggested a reference be given for the New Horizon Decadal Survey of Astronomy and Astrophysics.

-Done We have used your text (thanks!)

94. Page 66, line 54. Could you use the word "astrophysics" or "astrophysical science" instead of just the word science?

-Done

95. Page 67. The lettering on Figure 35 is too small to be read. I suggest a full page with the figure printed sideways so it can be read.

-Done. A better figure has been supplied (actually we think the reviewer meant figure 36)

96. Page 68, Figure 36 caption. Change from M/L to "for middle and low class planned missions"

-Done

97. Pages 69-76. Tables 3-10 are never referenced in the text. Also they should contain (as much as possible) the same basic information: Theme, Primary Goal(s), Spacecraft, Orbit, Targets, Wavelength, Telescope, Expected Lifetime, Partners, Type. I realize that Targets, Wavelength and Telescope may not be appropriate for each table; however, the other items should all be included and current.

-Done

98. Page 69, Table 3. Either delete this Table or update it. There is no equivalent table in the Executive Summary. While I realize that many aspects of this paper will be outdated in the future, outdated information should not be part of the initial submission.

-Done: deleted

99. Page 69. You list JAXA as a partner, but there is nothing in the text that reflects their

participation. At least there should be a sentence or two.

-Done: removed JAXA (minor participation, not confirmed)

100. Page 70, Table 5. I think ESA should be listed as a partner.

-Done

101. Page 71, line 54. What is CDF? Also, in line 55, you need a space between sentences (between 2008 and the next sentence starting with the word "In").

-Done: CDF removed.

102. Page 72. Top two lines. This should be updated. Was the study completed? What were the results?

-Done, text updated.

103. Page 72. A lot of the top and second paragraph are the same text as on page 19 - sometimes word-by-word. Either re-write or refer back to page 19.

-OK, we have removed the two mentioned paragraphs and referred to the previous paragraph (3.1.1)

104. Page 72, line 39. FE K? emission line. I don't know what the ? represents. This may be a computer translation problem.

-Is a typo, removed

105. Page 72, line 43-45. What is meant by the sentence that starts with WFI Simulation of in inset. Is there a figure missing? This needs to be clarified.

-We apologize. These were old figures removed from the text. We have updated the text accordingly.

106. Page 73, line 17. Change "have" to "has".

-Done

107. Page 73, line 19. Add the year (2010?) after 18 February

-Done, yes, 2010

108. Page 74, Table 8. The "Type" is missing from this table.

-Done

109. Page 74, line 37. What is SPC?

-Space Program Committee (SPC). Now is specified the first time is mentioned and part of the acronym table

110. Page 74, line 39. Delete the first word "And".

-Done

111. Page 74, line 45. Can you update this?

-Done. The whole paragraph has been updated.

112. Page 75, Table 9. "Partners" are not shown. Probably To be determined. Nevertheless this line should be given.

-Done

113. Page 75, line 27. I suggest a period (full stop) after the word "reliability" and a new sentence with "A lifetime of at least five years is envisaged."

-Done

114. Page 75, line 31. Insert a comma after SAFARI

-Done

115. Page 75, line 39. Can you update?

-Done

116. Page 75, line 47. Add the letter "s" to Mission (Medium Size Missions)
Relevant part removed according with update as per point 115 above.

117. Page 77, line 30. Add "(STE-QUEST) at the end of the line (see markup manuscript)

-Done

118. Page 78, Line 15. Suggested change as follows: "In 2005, JAXA publish their Long Term Vision that included orbiting observatories at every wave band for the coming decade. Three basic themes were included as follows: " (What you presently have are not complete sentences.)

-Done

119. Page 78, line 31. Use a capital letter "H" for consistency.

-Done

120. Page 78, line 38. Insert the word "the" before "Steering "

-Done

121. Page 78, Lines 40 and 43. Start each of these with the word "In" followed by the years. It is not good to start a sentence with a numeric. See the marked up manuscript where I have revised this slightly.

-Done, thanks for the revision

122. Pages 79 and 80. This entire section needs an overhaul. The first paragraph should have proper references to those documents even if they are written in Chinese. (If written in Chinese, this information can be included in the reference citation.) I have made some suggested changes on the marked up manuscript. These should be checked by the Chinese member of the committee.

*-Done

123. Pages 80-81. I have slightly revised this section, separating some of the ideas into individual paragraphs. I have also changed some of the English. See the marked up copy. Note that there is something missing before -rays in line 31 (gamma?) Also this section should be written in the passive sense instead of the active sense in keeping with the rest of the manuscript. My suggested revision should be checked by your Indian committee member.

-Done

124. Page 82, line 27. I suggest inserting the words "the available" between "of" and "financial".

-Done

125. Page 82, lines 34-39. See the marked up copy for suggested formatting.

-Done

126. Page 82, line 39. What does TBC mean? Should it be TBD?

-Yes, changed

127. Page 82, line 14. 51 should have a degree symbol or the word "degrees".

-Done

128. Page 82, line 50. Should this be Spectrum-RadioAstron? The letter "A" is capitalized in some cases and not in others. It should be consistent.

-Done

129. Page 83, line 18. the number 7? should be clarified. This may be a computer difference.

-Done, sentence fixed

130. Page 83, lines 20-26. See marked up manuscript. You need to start a new paragraph on line 20 for Spectrum-UV.

-Done

131. Page 83, Tables 11 and 12 are not referenced in the text.

-Done

132. Page 84, line 26. Start a new paragraph with the words "The following..

-Done

133. Page 84, line 31. Start a new paragraph with Gamma-400.

-Done

134. Page 84, line 33. The main parameters for the Gamma-400 satellite are given in Table 13.

-Done

135. Page 85, line 12. Start a new paragraph with Intergelioprobe. (see the marked up copy for the above changes)

-Done

136. Page 85, line 30. Insert the word "been" between have and confined (have been confined)

-Done

137. Page 85, line 38. Need some references cited for "remarkable results".

-Done

138. Page 85, line 39. Insert the word "the" at the end of the line (even though the.)

-Done

139. Page 85, lines 46 and 47. I assume "without success" means not approved or not funded (vs. a failure).

-Yes, clarified.

140. Page 85, line 56. What is SKA and ELT?

-Done, specified.

141. Page 86, line 9. Insert the word "The" before Astronomy (The Astronomy.)

-Done

142. Page 86, line 12. Change "have" to "has"

-Done

143. Page 86, lines 29-35. The quoted reference should be cited.

-Done

144. Page 87, line 9. Delete the word "it" at the end of the line.

-Done

145. Page 87, line 15. Define CBERS

-Done, see acronym table

146. Page 87. The conclusions are excellent and should be incorporated (as written) into the Executive Summary.

-Done.

147. Pages 88 onward. References require titles of articles, inclusive page numbers (when given) and the names of the first 3 authors for multi-authored papers before using et al. All authors can, of course, be cited.

-Done

Finally this paper needs to be completely reviewed when re-submitted. I strongly urge the submitting author to have all members of the committee review the next version before it is submitted.

-Done, two of the native language have reviewed the manuscript. We have used generally English rather than US (programme vs program, analyse vs analyze etc).