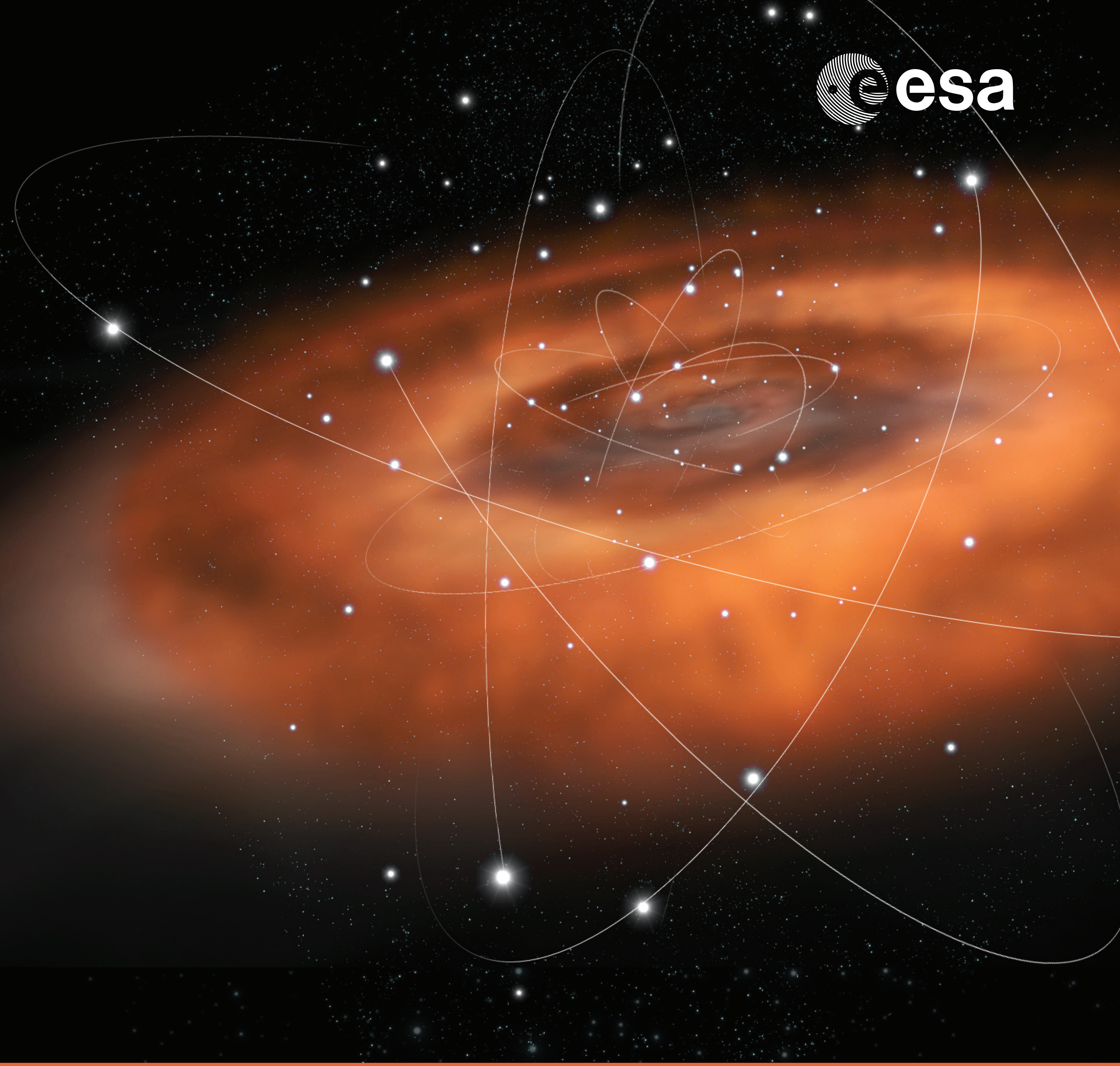

→ REPORT OF THE SENIOR SURVEY COMMITTEE ON THE SELECTION OF THE SCIENCE THEMES FOR THE L2 AND L3 LAUNCH OPPORTUNITIES IN THE COSMIC VISION PROGRAMME

October 2013

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European Space Agency

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Cover image: An artist's impression of the environment at the centre of our Galaxy, the Milky Way
Credit: ESA – C. Carreau
Layout: Sapienza Consulting, United Kingdom

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Foreword

From its inception, ESA's Science Programme has relied on long-term planning cycles, to allow its larger missions, known as the programme's Cornerstone missions (and now dubbed "Large" missions), to be defined well in advance of their launch date. These missions, that have put ESA's Science Programme on the map and in some sense defined it, were decided upon long in advance, typically 20 years or more.

Twenty years is not a short amount of time, but large space science missions such as XMM-Newton, Rosetta, Herschel or Gaia, require significant technology developments – and as such need enough time to allow the technology to be developed and the mission to be built. By selecting missions with a global programmatic view rather than in isolation, the programme can maintain long-term coherence and balance, while at the same time giving a clear perspective to the scientific community in Europe.

Knowing in advance which science fields will be covered by a Large mission allows the scientific community to properly plan career structures, for example, deciding in which areas to recruit postdocs; to invest in technology areas that will have a clear outcome; and also to decide which science fields are best to propose for the programme's other flight opportunities - its "Medium" missions - that provide its flexible element.

The Science Programme has been able to implement, from the outset, three cornerstone-class missions every two decades, and this also appears to be a sustainable rate for the future. As a consequence, the long-term planning exercises that lead to the definition of the programme's Large missions are rare occurrences. I have had the privilege of initiating one such exercise, leading to the definition of the science themes for the L2 and L3 missions in the Cosmic Vision plan (the current cycle of the Science Programme), planned for launch in 2028 and 2034.

In keeping with the bottom-up approach to the definition of the programme's content, this exercise started with a broad community consultation (a "Call for White Papers"), followed by a public presentation by the proposers at an open workshop. The proposed science themes were then evaluated by a Senior Survey Committee, which I asked Catherine Cesarsky to chair. This Committee has advised me that the best science themes for L2 and L3 would respectively be "The hot and energetic Universe" and "The gravitational Universe". Following my proposal in this sense, the Science Programme Committee selected them, and we will now start the process leading to their implementation.

This report represents the synthesis of the Senior Survey Committee's work, and illustrates their recommendations. While of course concentrating on the two science themes recommended for L2 and L3, the report also discusses a number of further, worthwhile proposed themes. I would like to thank the Senior Survey Committee for their support in taking such a long-range decision, the Advisory Structure (Working Groups and Space Science Advisory Committee) for the advice they have given to the Senior Survey Committee, and the whole scientific community for their unfailing enthusiasm and support to the Programme. As usual in any such selection exercise we had to disappoint many of the proponents, given that the number of worthwhile ideas far outstrips the number of flight opportunities in the programme. At the same time, this decision gives European scientists a clear leadership in the two selected areas, and will largely define the landscape in space science for the upcoming two decades.

I plan to be well into retirement by the time the two missions selected here will be implemented! But, I wish the younger scientists in Europe, who will be the ones to reap the fruits of today's decision, to match and surpass the achievements of the previous Cornerstones and Large missions in the programme!

Alvaro Giménez
Director of Science and Robotic Exploration

Contents

1. Introduction

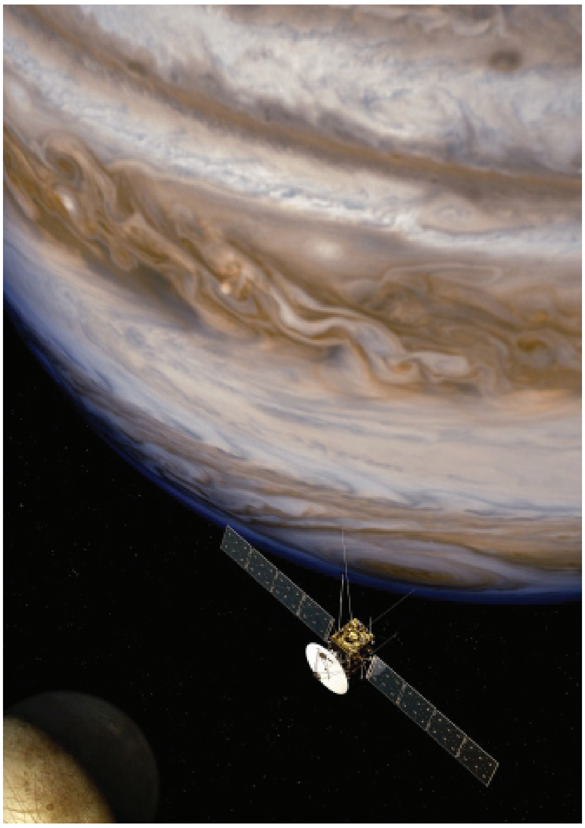
ESA's Scientific Programme today plays a leading role on the world scene, as demonstrated by the success of its missions, current and past. These successes have been made possible in a large part thanks to the Programme's long-term planning and preparation effort. The planning approach implemented has resulted in a proper balance between large and smaller projects, between purely European and cooperative projects, between the various research fields, and between pre-defined missions (providing long-term stability) and missions defined as a result of a regular sequence of Calls for Missions (providing flexibility).

The Programme's pillars (its Large missions) are a fundamental element of its long-term planning, and to ensure the Programme's coherence, their definition cannot rely on the results of individual, uncoordinated calls for missions. A long-term planning mechanism for the definition of the Large missions is needed to ensure the long-term perspective that will guarantee that the hundreds of scientists in Europe who rely on space investigations will feel confident that a flight opportunity will be provided in a definite time. This in turn increases their willingness to fully engage in the mission, secure funding for long-term technology preparation and plan their work accordingly. A long-term planning horizon can support with appropriate funding profiles and schedules the preparation of the costly and technologically complex missions that have been the cornerstones of the Science Programme.

A regular sequence of Medium and Large missions (with an average cost to ESA of respectively one and two yearly Programme budgets) constitutes the backbone of the Programme, and has done so for a long time. Long-term planning has been implemented in the Science Programme starting with the very successful "Horizon 2000" (H2000) plan established in the mid 80s and covering missions until the early 2000s, followed by its extension "Horizon 2000+", which brought the planning effort to cover missions to be launched until 2015. A potential new component (Small missions) is currently being "tested out" through the implementation of the S1 mission (CHEOPS) selected by the SPC in 2012. Missions of Opportunity form an additional, non-regular (by its intrinsic nature) component of the Programme.

The current long-term scientific plan, "Cosmic Vision" (CV) establishes a number of scientific priorities, but is not "prescriptive" in terms of actual missions to be flown (even though a number of missions concepts are described in the plan as possible candidates). While the Medium missions for the CV plan are being selected as a result of regular Calls (with Solar Orbiter and Euclid selected for the M1 and M2 slots respectively, and the M3 selection due in February 2014), the Large missions should be selected with a longer-term view in mind. Following the selection of JUICE as the L1 mission in 2011 (for launch in 2022), the Director of Science and Robotic Exploration, in agreement with the SPC, decided to implement a separate process to define the L2 and L3 missions, currently in the planning for a launch in 2028 and 2034 respectively.

Artist's impression of JUICE
ESA/AOES medialab



The process that led to the selection of the H2000 cornerstones relied on the advice of an ad hoc Senior Survey Committee, entrusted with the advice on the selection of the science areas to be covered by each cornerstone. For the definition of the L2 and L3 missions a similar Senior Survey Committee (SSC) has been appointed, under the chairmanship of Dr. Catherine Cesarsky. This SSC has been called to advise the Director of Science and Robotic Exploration concerning the science themes to be addressed by the L2 and L3 missions. The process that has been initiated with the "Call for Science Themes" released in March 2013, and that will eventually culminate with the launch of the L2 and L3 missions, is described in the next Section. The SSC's recommendations are presented in Sect. 5.

2. Large missions in ESA's Science Programme

L missions are the pillars of the Science Programme, and follow the spirit of the "cornerstones" of the Horizons 2000 planning. These missions provide stability and long-term planning for the scientific community and Member States, supplying "anchoring points" to the rest of the Programme.

Cornerstones in the Science Programme have been identified long in advance. In H2000, a far IR mission (later called FIRST, and then Herschel) was studied in 1983 and selected in the plan in 1985 but only flown in 2009, 24 years later. For the fastest cornerstone mission implemented to date, namely Gaia, 20 years will have elapsed between its first proposal to the Agency in 1993 and its launch planned in late 2013, and 13 from its adoption in 2000 to launch. Large missions represent the "flagships" of European science and must therefore be European-led. In the present plan, Large missions should see Europe responsible for a fraction of the mission's elements of at least approximately 80%, with limited, non-enabling international participation possible. The "rule of thumb" of cornerstones costing on average 2 years of the Level of Resources of the Science Programme implies a cost to ESA for L missions of approximately 1 B€ (2013 e.c.), and this results in a plan which foresees 3 L missions every 2 decades (together with 6 M missions). This is very similar to the actual past sequence of missions implemented by the Science Programme. Based on the already scheduled JUICE (L1 launch) in 2022, the next flight opportunities for large missions (L2 and L3) would be in 2028 and 2034.

The objectives underlying the definition of the scientific content of the Programme's pillars form the rationale of the Programme's long-term planning, i.e.,

- provide long-term perspectives to the scientific community,
- attract new generations into space science,
- give stability to scientific institutions,
- provide stable reference points to national efforts and investments,
- focus the development of advanced technologies,
- provide a long-term reference to European industry and international partners,
- mitigate the level of frustration in the community after decades of investment, and
- avoid nugatory spending in ESA and Member States.

Defining in the near future the science questions to be addressed by both L2 and L3 will have the advantage of providing a long-term perspective to the whole space science community, eliminating much nugatory effort and spending on missions that ultimately will not fly. The communities interested in the selected science areas will work with the knowledge of a guaranteed flight opportunity (even if not in the near future), while communities interested in science fields not selected for either the L2 or L3 opportunity will be able to plan their roadmaps based on the use of M missions and on partnerships with other Agencies.

One additional benefit of defining the science areas for L2 and L3 well in advance of their launch date is to establish European leadership in these fields, effectively staking out in a proactive way the areas Europe will lead in the next 2 decades. This will affect the planning of other space agencies, and by acting early – and proactively – Europe will be in a position to choose and lead.

3. Process adopted to select science areas for L2 and L3

A two-step approach has been adopted to define the L2 and L3 missions. The first step (of which the present report is the outcome) has seen a Senior Survey Committee recommending the two science areas that should be addressed by the L2 and L3 missions. The selection of the actual mission to be flown for each of the flight opportunities will be performed through dedicated Calls for Missions, issued at a later time, which will be restricted to the science areas previously defined by the Senior Survey Committee. To maintain the foreseen 2028 launch date, the Call for the L2 mission will be issued in 2014, while the Call for the L3 mission needs not be issued until later in the present decade.

The Senior Survey Committee was composed of 8 members, i.e.

- Dr. Catherine Cesarsky (CEA, Chair)
- Prof. Willy Benz (Bern University)
- Dr. Sergio Bertolucci (CERN)
- Prof. Giovanni Bignami (INAF)
- Dr. Thérèse Encrenaz (Meudon Observatory)
- Prof. Reinhard Genzel (MPE)
- Dr. Jason Spyromilio (ESO)
- Prof. John Zarnecki (Open University)

The first step in the definition of the science themes has been an open call to the scientific community, soliciting White Papers proposing science themes for the L2 and L3 missions. The White Papers, limited in length to 15 pages, were requested to focus on the proposed science questions that should be addressed by the two flight opportunities, while also including one (or more) strawman mission concept (or possible approaches to obtain the necessary measurements) that could provide the answers to the science questions proposed. Explicit allowance was made for White Papers that proposed astronomical observatories or survey missions.

A total of 32 bona fide White Papers were received by the deadline on 24 May 2013. A list is provided in the Appendix. The White Papers have been published, and are available at the URL http://sci.esa.int/L2L3.

Following reception of the White Papers, the SSC began its work.

4. Preparatory work of the SSC

An open workshop was held in Paris on September 3 and 4, at which the SSC invited the spokespersons of the received White Papers to present their case. All the scientific topics proposed were presented, although for some White Papers which showed very significant overlap in science a single spokesperson was selected to represent the science area in question.

The open workshop, together with the written White Papers, represented one of the several inputs received by the SSC in advance of their deliberations. In parallel, the SSC requested a technical assessment of the feasibility of the presented strawman concepts, and solicited the views of the Advisory Structure to the Science Programme. In this context, the Working Groups (AWG, SSEWG and PSWG) met around the time of the open workshop, and put forward their views to the Space Science Advisory Committee (SSAC), with which the SSC held a joint meeting on September 26. Also, following the workshop the SSC decided to interview a number of spokespersons to request further clarification about the proposed science themes.

The SSC considered with great attention all White Papers and all presentations made at the open workshop, and in addition, input from ESA's Future Missions Office. In their deliberations of the merits of the different proposed science themes, the SSC paid particular emphasis to the following criteria,

- the likelihood that the proposed science theme will lead to fundamental and transformational results in its specific field and beyond,
- the breadth of the science theme,
- whether the science could be achieved with ground-based techniques, or with planned smaller space projects within the L2/L3 time frame,
- whether an L-mission in the field would give the ESA's scientific community the possibility to achieve international leadership,
- the likelihood of mastering the necessary technical challenges of the probable concrete mission scenario(s) of the science theme, within the time and budget of the L2 or L3 mission.

Following an initial ordering and categorization of all themes, the SSC proceeded to identify a "short" list of highly competitive themes in the different science areas addressed by the White Papers, fulfilling the criteria above. The SSC then invited two members of each of five final themes for a further oral interaction and discussion of important issues and questions. This was followed by an interaction with the Head of ESA's Future Missions Office for a final round of discussion on technology and feasibility.

5. Recommendations of the SSC

After receiving and considering the views of the SSAC, including the Chairs of the Working Groups, the SSC reached a unanimous decision and recommends to the Director Science and Robotic Exploration to implement:

- an X-ray observatory, addressing the science theme "The Hot and Energetic Universe" for the L2 launch opportunity, and to implement
- a gravitational wave observatory, addressing the science theme "The Gravitational Universe", for the L3 launch

opportunity.

The rationale behind the SSC recommendations is given below.

5.1. Recommended science themes for L2 and L3

5.1.1. The L2 Science Theme: *The Hot and Energetic Universe*

Over the past five decades, compelling evidence has emerged that black holes are common in the Universe, with masses ranging from stellar remnants (~10 M_{Sun}) to supermassive systems (~10^{10} M_{Sun}). Almost every massive galaxy plausibly contains a massive black hole at its centre, estimated to hold between about 0.015 to 0.06% of the entire mass of its spheroidal stellar component. These supermassive black holes appear to have formed ~10–13 Gyr ago, at about the same time as their host galaxies. The evolution of the hosts and their embedded supermassive lack holes seems to have been closely connected, probably through energy exchange and mergers of galaxies and black holes. This co-evolution of supermassive black holes and galaxies is a remarkable and unexpected discovery, which clearly requires further exploration.

Jets and outflows driven by a black hole at the centre of a galaxy. ESA/AOES medialab

In parallel, investigations on the filamentary structure of matter in the Universe have steadily progressed. In the next few years, we expect to obtain spectacular advances in the understanding of the formation of structures of dark matter in the Universe. LSST and Euclid will use gravitational lensing effects to trace these structures, and numerical simulations of the relevant processes will be ever more accurate and predictive. Meanwhile, ALMA, JWST, E-ELT and eventually SKA will observe galaxies with exquisite detail and will scrutinize the cold baryons in them. The mm-wave surveys, especially from Antarctica, will establish a census of galaxy clusters up to z ~2 on a large area of the sky. But all this will not suffice to answer fundamental questions such as how/why does ordinary matter assemble into the large-scale structures that we see today and how do black holes grow and influence the Universe?

A supermassive black hole (SMBH), through its accretion, releases 30× the binding energy of a galaxy; X-rays from SMBH account for 15% of the energy output in the Universe. To unravel the history of star formation in galaxies, we need to understand gas accretion, galactic winds, and feedback processes that drive out gas, gauging off the efficiency of galaxy formation.

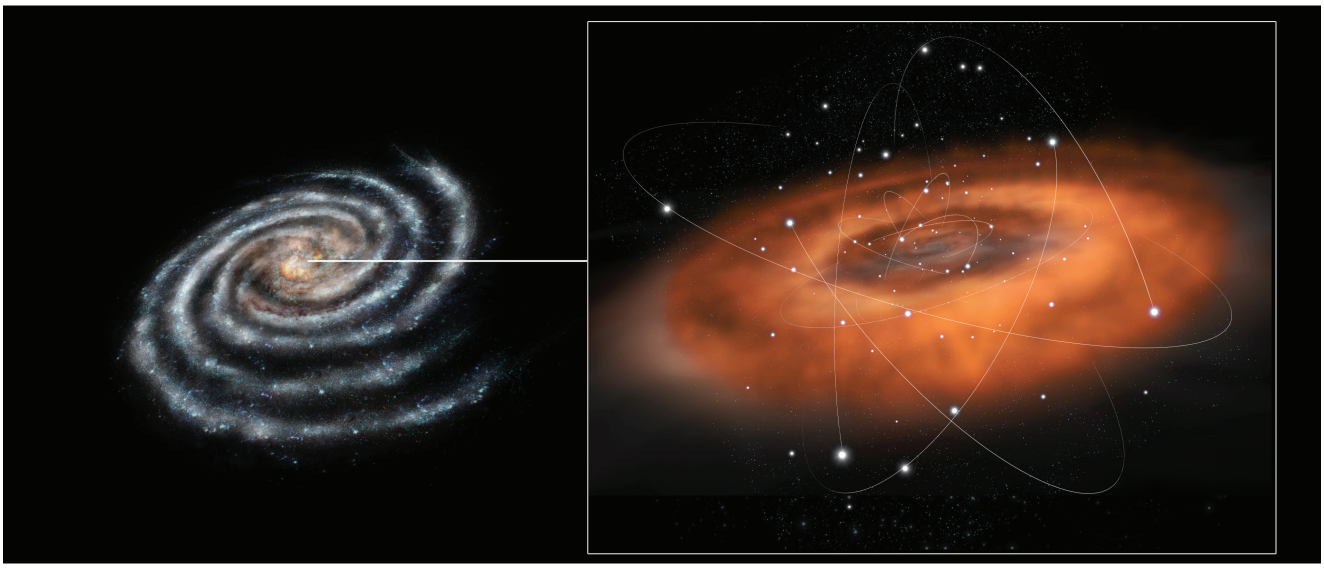
To answer the two fundamental questions above, a bridge connecting astrophysics and cosmology is needed. While the dark components of the Universe set its cosmological framework, the growth of structures of ordinary matter is also driven by hydrodynamic and radiative processes that can only be properly monitored in X-rays.

A third and equally important question connecting high-energy astrophysics and cosmology concerns distant transient phenomena, and in particular the study of gamma-ray bursts (GRBs). Ever since their discovery, and since their even more recent identification as cosmological sources, GRBs have become the most distant known energetic phenomena in our Universe. So far, the powerful diagnostics brought by high-throughput X-ray spectroscopy could not be systematically brought to bear on GRB counterparts. A powerful mission addressing the hot and energetic Universe in the next decade should have the capacity to do science on GRBs, either having onboard the necessary burst alert system or by relying on external trigger inputs. In either case, the delay for pointing to the GRB source should be kept as short as possible.

Addressing the hot Universe with X-ray astronomy will yield transformational science for tomorrow's astrophysics, provided that a mission powerful enough to study the deep Universe, up to z=10 for some areas, can be implemented. Such a mission can study the growth and evolution of SMBHs in galaxies up to the very early Universe, detecting hundreds of active galactic nuclei (AGNs) at z>6, and scrutinizing the interplay between the black hole and the surrounding medium. By addressing these goals, a next-generation X-ray observatory can thus play a crucial role in explaining the joint evolution of galaxy and black holes. It can also assess whether primordial black holes were the seeds of the SMBHs that populate galaxy centres today, or if a population of significantly more massive black holes is needed. The science theme proposed under “the hot and energetic Universe” encompasses quests such as: finding when and how the first structures of hot baryons assembled on large-scales which subsequently evolved into clusters of galaxies, determining when the largest baryon reservoirs in galaxy clusters were chemically enriched, discovering which stellar sources contributed to this enrichment, and finding the missing 40% of ordinary matter in the local Universe. It comprises also investigations on how AGNs, obscured or not, affect the evolution of galaxies, on the amount of AGN energy deposited on very large (cluster) scales, and on how that energy affects the evolution of the large-scale structure.

Furthermore, an ambitious X-ray mission has the potential to explore the vicinity of the black holes, map the circumnuclear matter, and appraise the energy transfer to winds and jets. It can measure the black hole spin and may even peer into the inner region, at a few

Illustration of the environment at the centre of our Milky Way.
ESA – C. Carreau



gravitational radii from the black hole, using reverberation signals.

An X-ray astronomy observatory designed to combine high-throughput imaging (with photometry and timing) with high-resolution spectroscopy is the proposed tool for investigating the high-redshift hot Universe. We foresee, for example, a factor of >100× improvement in high spectral resolution throughput (e.g. compared to the ASTRO-H microcalorimeter and to XMM-Newton gratings), a factor of >100× in survey speed compared to Chandra and 30× compared to XMM-Newton, a factor of 10× in bare throughput (i.e. on axis collecting area) compared to XMM-Newton.

The large throughput, coupled with a reaction time for targets of opportunity of 2-4 hrs, opens also a new window on the transient Universe. Typically, an observation of a GRB afterglow should collect millions of photons, with a spectral resolution of few eV. These observations of GRB afterglows offer the best opportunities to detect the Warm-Hot Intergalactic Medium.

In addition to the "core programme" associated with the fundamental questions mentioned above, the capabilities of the recommended X-ray mission for the L2 opportunity should enable new "observatory science" to be performed for a wide range of sources, and in particular in Galactic science, such as the study of supernova remnants. More generally, such a mission will deliver a rich return of results for basically all classes of astrophysical sources as well as a wealth of serendipitous discoveries, enabled by the orders-of-magnitude improvement in key parameters, in particular throughput, energy resolution and field of view.

A mission to address such challenging scientific themes will require high-throughput optics (of the order of 2m^2 collecting area) with good angular resolution (5 arcsec), coupled with high spectral resolution (e.g. 2.5 eV) and wide field of view in the focal plane. The technologies for the mission should be based on much previous heritage and at the same time benefit from major new technology developments.

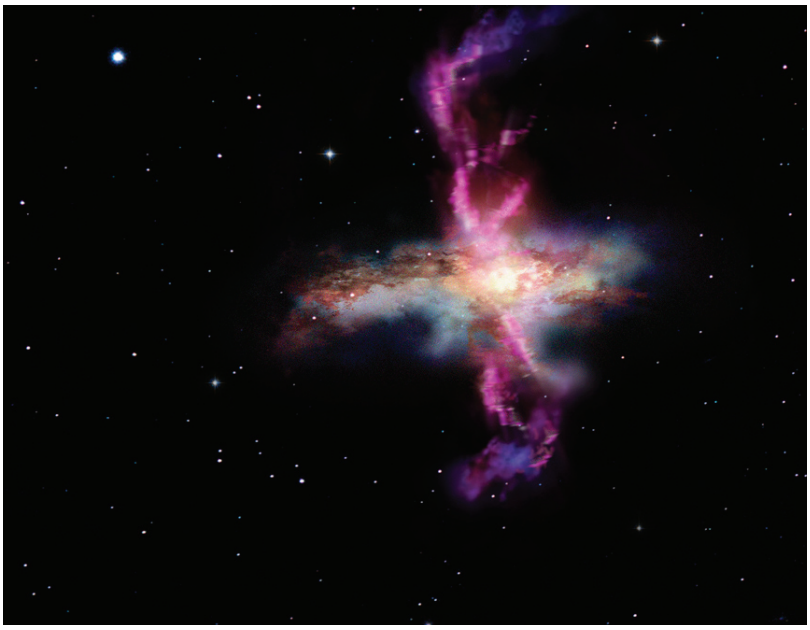
The science theme '*hot and energetic Universe*' fulfills all five key criteria mentioned above. In conclusion, given the present context of search and discovery in astrophysics and the wide and fundamental potentialities, the SSC recommends the science theme *the hot and energetic Universe* for the L2 slot of the implementation of the ESA Cosmic Vision plan.

5.1.2. The L3 Science Theme: The Gravitational Universe

In our quest for understanding the Universe, gravitational waves are the most attractive of the observing windows that have not been exploited yet. The exploration of the Universe with gravitational waves is of the greatest importance to astrophysics and physics alike. A space observatory can operate at low frequencies, in the range 0.1 to 100 mHz, where sources are plentiful, and since gravitational waves do not suffer from obscuration, they give access at once to the whole Universe. Unlike electromagnetic waves, gravitational waves can probe the early stages of the Universe, before decoupling of light and matter and emission of the microwave background. The scientific results from a gravitational wave observatory promise to yield deep insights into some of the most fundamental mysteries of physics.

Einstein's General Theory of Relativity (GR) has so far passed all experimental verifications with flying colours. However, there has not yet been an opportunity to test GR in strong-curvature space times, especially in the highly relativistic regime near the event horizon of the Schwarzschild-Kerr metric. At the same time, recent theoretical work has suggested that quantum corrections to classical GR, as well as alternatives to GR, might well be observable on that scale, thereby giving potential

Illustration of an Ultra-Luminous Infra-Red Galaxy - a result of the merging of gas-rich spiral galaxies hosting supermassive black holes in their centres. ESA/AOES medialab



access to physics on the scale of 10^{12} TeV. Ever more precise numerical simulations carried out in the last decade show that the waveforms of gravitational waves emitted from merging massive black holes and from in-spirals of stellar mass objects into massive black holes are sensitive to the space-time properties in the strong curvature regime. The direct detection and subsequent quantitative analysis of gravitational waves from such systems will thus open a unique and transformational window to the fundamental physics of gravity.

The emerging evidence that every galaxy with a spheroidal stellar system appears to host a massive black hole has been discussed in the previous Section, together with the evidence that the mergers of such black holes in galaxy collisions, and the interaction between actively accreting massive black holes and their hosts are likely to be an important driving element of early galaxy evolution. Gravitational waves are a unique tool to study the otherwise unobservable last phases of the mergers and in-spiral events. As such observations are possible at very large redshifts, beyond z=15 or 20, thus the initial mass of seed black holes may be determined.

Gravitational waves can also help solving long time conundrums of Galactic astrophysics, such as: the explosion mechanism of Type 1a Supernovae, or the endpoints of stellar evolution, by measuring the merger rate of white dwarfs, neutron stars and stellar black holes.

Given the exceedingly stringent requirements on instrumental measurement precision (pm-scale) and the wavelengths and time scales of the gravitational waves in this regime, such measurements cannot be performed from the ground and require instrumentation in space. Detailed studies over the past two decades have made a compelling case that a million-kilometre baseline, laser interferometer system may be the best way of realizing such a gravitational wave detector, with sufficient sensitivity to detect and measure with good signal to noise ratio the mergers of two supermassive black holes throughout the 13 Gyr co-moving “Hubble” volume, as well as the in-spiral of stellar remnants toward a supermassive black hole within the last 6 Gyr.

The experimental realization of the precision "gravitometer" required to observe gravitational waves in a large volume of the observable Universe is extremely challenging and is pushing the boundary of current technology, in terms of length measurements and ranging, stability requirements, optical design, laser technology and electronics. For this reason, ESA and the gravitational wave community have invested in a path finder experiment (LPF) to prepare and verify several of the key technologies. The SSC considers it of utmost importance that LPF be launched on the anticipated 2015 time frame, so that the experience and lessons learned from LPF can serve as an important input for the final selection of the gravitational wave L-mission.

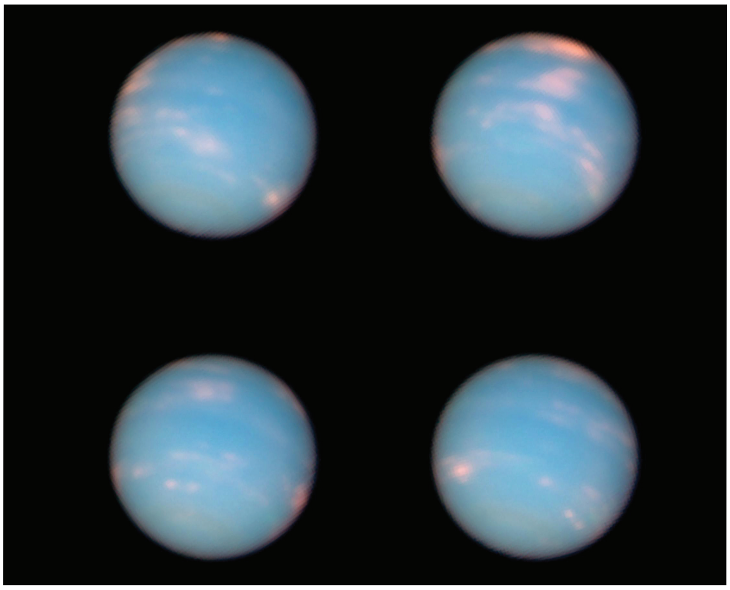
The science theme "the gravitational Universe" fulfills all five key criteria mentioned above. In conclusion, given its importance and the wide and fundamental potentialities, and the required technological advances, the SSC recommends the science theme *the gravitational Universe* for the L3 slot of the implementation of the ESA Cosmic Vision plan.

5.2. Comments on other submitted science themes

In addition to the two science themes recommended for the L2 and L3 opportunities, the SSC wishes to comment on the following other themes submitted in response to the Call for White Papers.

5.2.1. The icy giant planets

The icy giant planets, Uranus and Neptune, are intrinsically different from the gaseous giants. While Jupiter and Saturn are mostly composed of protosolar gas, Uranus and Neptune have accreted little gas around their initial cores that account for most of their mass. In spite of having similar sizes and densities, Uranus and Neptune show striking differences in their geometries (e.g. the rotation axis



Images of Neptune taken with the Hubble Space Telescope Wide Field Camera 3, 25-26 June 2011.
NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

of Uranus is close to the ecliptic plane, while the one of Neptune has a "normal" orientation), in their internal structures (e.g. Uranus has no internal source of energy, while Neptune shows a very high heat flux from its interior) and in their atmospheric dynamics (with Neptune being much more active most likely due to the effects of the interior heat source). All of these differences remain to be understood and explained.

The icy giant planets have been poorly explored so far, as their in situ observations were limited to the Voyager 2 flybys in 1986 and 1989 respectively. These observations have revealed, in particular, the exceptional configuration of their magnetic fields associated with their tilted dipole axes. Their satellites have also shown unexpected properties, in particular Neptune's satellite Triton, which is probably a captured, former trans-neptunian object. Later, Uranus and Neptune have benefited from subsequent observations by astronomical observatories (HST, ISO, Herschel) that have shown evidence, in particular, for strong seasonal atmospheric effects in the case of Uranus. But basically, the icy giant planets remain terra incognita, and are by far the least explored of the solar system planets. Still, we now know that Neptune-mass planets, most likely very different from one another, are numerous in most exoplanetary systems and a natural first step in their exploration requires a far better understanding of our own proxies.

In situ exploration of the icy giant planets would bring major advances in our understanding of these worlds in several respects. First, the study of their internal structure (through radio science, accelerometery and, ideally, a measurement of elemental abundances through mass spectrometry aboard a probe), as well as a study of their satellite properties, could provide key diagnostics concerning the history of these systems. Second, an in-depth study of their atmospheres, ionospheres and magnetospheres, as well as their rings and satellites, will help us understand the physico-chemical processes at work in these two systems. Ideally, comparative planetology could be achieved from similar observations performed on both planets and their environments.

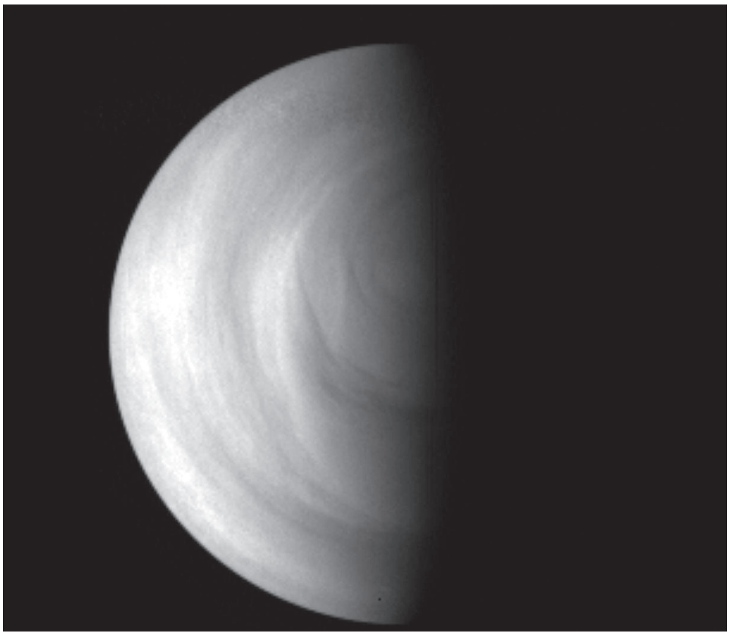
After the success of the Cassini mission, and after the selection of an exploration mission toward the Jovian system, the exploration of the icy giants appears to be a timely milestone, fully appropriate for an L class mission. The whole planetology community would be involved in the various aspects of this mission, including physics of the interior, atmospheric and surface sciences, plasmas physics and dynamics. Several mission concepts could be considered, including orbiters and probes, and would need to be investigated in the next stage.

The SSC considered the study of the icy giants to be a theme of very high science quality and perfectly fitting the criteria for an L-class mission. However, in view of the competition with a range of other high quality science themes, and despite its undoubted quality, on balance and taking account of the wide array of themes, the SSC does not recommend this theme for L2 or L3. In view of its importance, however, the SSC recommends that every effort is made to pursue this theme through other means, such as cooperation on missions led by partner agencies.

5.2.2. Venus science

The physical and orbital properties of Venus make this planet a close twin of the Earth. Its primordial atmosphere must have been comparable to the early one on Earth. However its high surface temperature and pressure at present illustrate the devastating effects of a huge runaway greenhouse effect. Understanding how the Earth and Venus evolved toward such different fates is a key problem of today’s planetology.

The European Venus Express mission has performed an in-depth



Venus' southern hemisphere and the terminator.
ESA/MPS, Katlenburg-Lindau, Germany

investigation of the planet's atmospheric circulation and aeronomy. Still, Venus Express has not been able to answer the question about possible present volcanism. Following the heritage established by Venus Express, the exploration of Venus should be pursued, with special emphasis on its surface and interior. In particular, a high-resolution radar on an orbiter should allow us to make significant progress in the search for active volcanism. International collaboration should be used for the development of future missions, in particular within the M class framework of the Cosmic Vision programme.

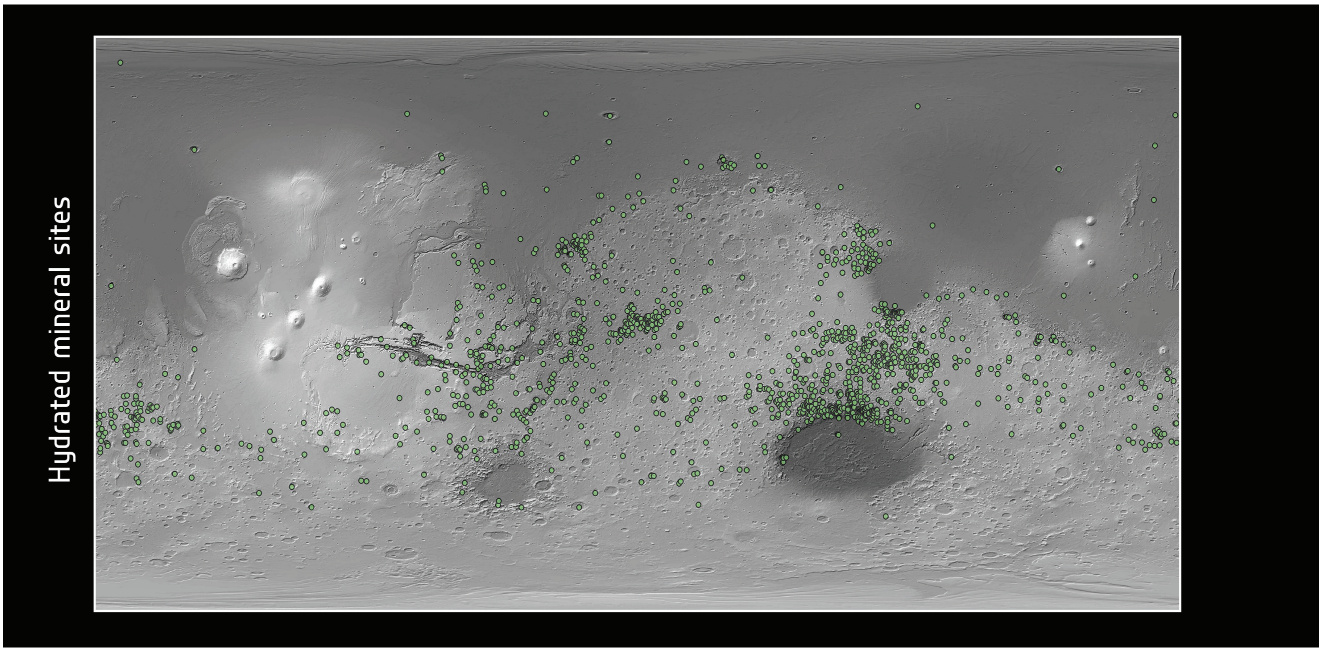
5.2.3. Asteroid science

The small bodies of the solar system are vestiges of the accretion processes that led to planetary formation. They bear key information about the primordial chemical composition of the material from which planets once accreted, as well as on migration processes, prior to the accretion process at later stages. The observed diversity of asteroid families is a consequence of planetary migrations, and their study provides key diagnostics of such migrations, during which they have indeed played a key role, as e.g. illustrated by the late heavy bombardment which is well explained by current planetary migration models (e.g. the so-called Nice model). The study of small bodies can also help us in understanding the origin of water on Earth. The SSC feels that the exploration of asteroids should be pursued using complementary means such as dynamical simulations, ground-based spectroscopic surveys, flybys and sample returns, probably within the M class framework of the Cosmic Vision programme.

5.2.4. Mars sample return

Over four decades, Mars has been a special target for planetary exploration. Flybys, orbiters, landers and rovers have been used to analyse the atmosphere and surface composition and to retrace as best as possible the past history of the planet, with the ultimate goal of searching for past traces of life. One of the key remaining problems of tracing an evolutionary history for Mars is a lack of absolute ages for different lithological units. Laboratory analysis of samples returned from Mars will be the only way to obtain an absolute chronology, as the available Martian meteorites are only igneous and contain no sedimentary samples. A Mars sample return mission remains a first priority objective for the international planetology community. However, such a mission is clearly beyond the scope of an ESA L mission and the significant preparatory activities that have been and continue to be performed have shown that such a mission is likely to be feasible only within the framework of a large-scale international partnership. The SSC feels that this possibility should continue to be actively pursued.

Regions where hydrated minerals have been detected by Mars Express ESA/CNES/CNRS/IAS/Université Paris-Sud, Orsay; NASA/JPL/JHUAPL; Background image: NASA MOLA



5.2.5. Exoplanets

The study of extrasolar planets is arguably one of the fastest growing fields of astrophysics and planetary science. The currently discovered exoplanet population and its amazing diversity have demonstrated the importance of studying planetary systems beyond our own solar system. As the field is now moving from an era of discovery to an era of characterisation, high-resolution spectroscopic observations of a set of exoplanets spanning a wide range of masses and orbital distances to stars of various types are needed to truly open the realm of comparative planetology.

Unfortunately, the technology necessary for reaching temperate exoplanets in the super-earth mass regime as proposed in the White Paper is still beyond what is reasonably foreseeable within the timeframe and budget afforded by either the L2 or the L3 launch opportunities. The focus towards habitability as emphasized in the White Paper may be the most exciting topic sociologically, although not necessarily the most promising one from a purely planetary science perspective. Given the very fast-paced current development of the field and the many projects on the horizon either dedicated to, or with a significant impact on exoplanetary science, major progress will be achieved in this field within the next two decades. It is therefore more than likely that these advances might transform our current understanding and motivate revisiting some of the currently understood priorities and proposed approaches. The SSC thus strongly encourages the exoplanet science community to take advantage of any possible ground-based and space opportunity in the near and mid-term future, in the Cosmic Vision frame with M missions and/or within international partnership.

5.2.6. Astrometry

The SSC considers sub-µas astrometry to be one of the most exciting techniques to probe both astrophysics and fundamental physics. However, the SSC felt that the implementation of an L mission in the context of the L2 and L3 opportunities would not be mature. Along similar lines, the SSC felt that the implementation of a Gaia twin some 20 years down the line, providing a longer temporal baseline and thus increasing accuracy, while providing exciting astrophysics would not be compelling enough to warrant its selection as the next flagship of ESA's Science Programme.

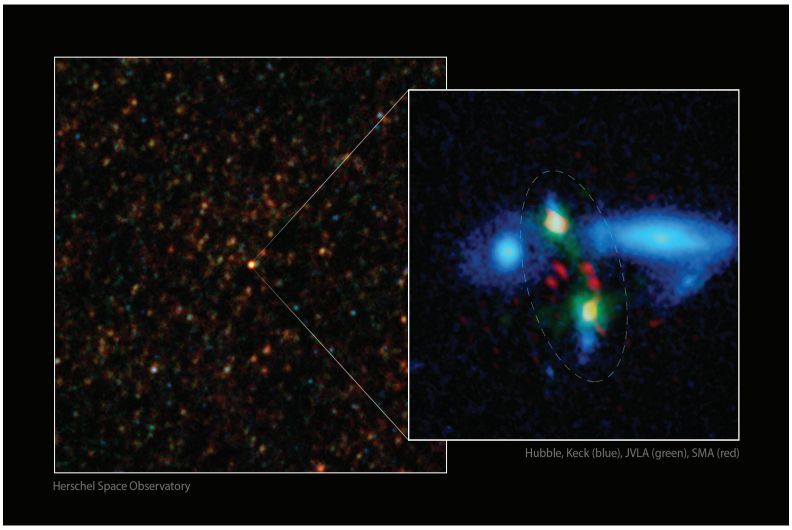
The SSC recommends initiating a careful revision of the science case for future space-borne astrometry missions in order to better define the astrometric requirements (relative vs. absolute astrometry; all-sky vs. limited-angle/pencil beam surveys). The SSC also recommends that the proper modeling tools (most notably the availability of a General Relativity framework able to model photon trajectories to the accuracy required) should be given the proper attention to prove feasibility. Also, it was made clear by the White Papers that a much improved knowledge of the Solar System properties is likely to be required.

5.2.7. Far-Infrared Missions

The far-infrared and submillimetre waveband is a unique probe of the cool and obscured Universe. The extraordinary success and legacy of the NASA/ESA missions IRAS, ISO, Spitzer and Herschel have demonstrated the power of detailed spectrophotometry and spectroscopy in the 30-1000 μm range for studying the physics of cool interstellar media, star forming regions near and far, protostars and protostellar disks, exoplanets and evolving distant galaxies. It is clear that access to this important waveband will continue to be highly desirable, and in some cases crucial in the decades to come.

High resolution imaging in the far-infrared waveband is of substantial interest, but facilities capable of delivering the sub-arcsec resolution

Discovered with the Herschel Space Observatory HXMM01 comprises a pair of massive and gas-rich galaxies in the process of merging. ESA/NASA/JPL-Caltech/UC Irvine/STScI/Keck/NRAO/SAO



required for the numerous interesting science cases are very expensive to deploy, probably beyond the L financial envelope. The SSC considers that, to some extent, they can be replaced by information gathered in adjacent wavebands, such as by ground-based submillimetre interferometry, or by ground- and space-based mid-infrared measurements.

At the same time the SSC felt that very sensitive, broad-band spectroscopy for studies of star, disk and planet formation on the one hand, and distant galaxies in the Early Universe on the other, will likely yield fundamental insights that cannot be obtained in any other way. In view of the general importance of the field and the demonstrated high quality and competitiveness of the European infrared community, the SSC urges the community and ESA to explore possible alternative paths forward to a deep spectroscopy mission, in the framework of international collaborations coupled with a suitable M-mission concept.

5.2.8. Gamma-ray bursts

The ongoing pursuit of science from gamma-ray bursts (GRBs) requires space instrumentation; the SSC is acutely aware of the enormous advances in this field as the discovery of new GRBs and their follow-up have become routine. The SSC was less convinced that the two orders of magnitude increase in discoveries that the White Paper on GRB science indicated could be realistically managed. The SSC strongly endorses the need to continue pursuing in the future the discovery of GRBs, while however, not feeling that this by itself justifies a dedicated L mission.

5.2.9. Probing cosmic structures and radiation with the ultimate polarimetric spectro-imaging of the microwave and far-infrared sky

The White Paper on “Probing cosmic structures and radiation with the ultimate polarimetric spectro-imaging of the microwave and far-infrared sky” addresses a wide range of science topics that would be pursued through millimetre to far-IR polarization-sensitive imaging and absolute spectrophotometry, centred on a fifth/sixth generation cosmic microwave background (CMB) core science programme. The mission proposed in the White Paper (dubbed PRISM) is a cooled 3.5 m mirror, with a precision-calibrated spectrophotometer and very large detector arrays. Such a mission is the 'ultimate' CMB experiment addressing inflation through B-mode polarization, and recombination science through precision spectroscopy. The SSC considered these CMB science goals as extremely important and fundamental, and it is clear that, after what is being achieved with Planck, a space mission is needed to successfully address them. In comparison, while the science cases addressing clusters, high-z galaxy formation and the Galactic ISM are important and of substantial interest, especially the studies of the galactic magnetic field, by themselves they do not justify an L mission 20 years from now, also in view of a number of them being capable of being addressed through other means. Yet, it is the non-CMB science that is the technology and cost driver for the proposed mission, especially in terms of the size and temperature of the telescope. The core CMB science can in principle be carried out with a smaller space mission (which could thus be implemented on a different, faster implementation path). Given the very active ongoing activities in CMB studies by the worldwide scientific community, it's not impossible for the CMB science goals of a PRISM-like mission implemented in either L2 or L3 (thus 15 or more years in the future) to be undercut by a smaller (M mission scale) mission focused on CMB science only. In summary, the SSC was fully convinced of the great importance of the core CMB science and encourages the CMB community to consider proposing this science for a future M-class mission. The SSC did not see that an L mission is needed for the CMB science, nor justified in itself by the other science goals presented.

Annex: List of received White Papers

The following table lists the 32 White Papers received by the deadline for the Call. The complete White Papers are accessible at http://sci.esa.int/L2L3

Lunar Science as a Window into the Early History of the Solar System
Spokesperson: I.A. Crawford, Department of Earth and Planetary Sciences, Birkbeck College London, United Kingdom

Exploring Planetary Origins and Environments in the Infrared: A Planetary Science Infrared Observatory
Spokesperson: Leigh N. Fletcher, Atmospheric, Oceanic and Planetary Physics, Clarendon Laboratory, University of Oxford, United Kingdom

In Situ Exploration of the Giant Planets and an Entry Probe Concept for Saturn
Spokesperson: Olivier Mousis, Institut UTINAM, Université de Franche-Comté, France

Neptune and Triton: Essential Pieces of the Solar System Puzzle
Spokesperson: Adam Masters, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Japan

Venus: Key to understanding the evolution of terrestrial planets
Spokesperson: Colin Wilson, Atmospheric, Oceanic and Planetary Physics, Clarendon Laboratory, University of Oxford, United Kingdom

INSIDER: Interior of Primordial Asteroids and the Origin of Earth's Water
Spokesperson: Pierre Vernazza, Laboratoire d'Astrophysique de Marseille, France

In situ Investigations of the Local Interstellar Medium
Spokesperson: Robert F. Wimmer-Schweingruber, Institute of Experimental and Applied Physics, University of Kiel, Germany

The Exploration of Titan with an Orbiter and a Lake-Probe

Spokesperson: Giuseppe Mitri, Istituto Nazionale di Astrofisica e Planetologia Spaziali, Istituto Nazionale di Astrofisica, Rome, Italy

Astrometry for Dynamics

Spokesperson: Erik Høg, Niels Bohr Institute, Copenhagen, Denmark

Europe returns to Venus

Spokesperson: Emmanuel Marcq, Université de Versailles Saint-Quentin / LATMOS, Versailles, France

Fundamental Processes in Solar Eruptive Events

Spokesperson: S.A. Matthews, Mullard Space Science Laboratory, University College London, United Kingdom

European Ultraviolet-Visible Observatory: Building galaxies, stars, planets and the ingredients for life among the stars

Spokesperson: Ana Inés Gomez de Castro, AEGORA-Facultad de CC Matemáticas, Universidad Complutense de Madrid, Spain

The science goals and mission concept for a future exploration of Titan and Enceladus

Spokesperson: Gabriel Tobie, Laboratoire de Planétologie et Geodynamique de Nantes, CNRS/University of Nantes, France

The Gravitational Universe

Spokesperson: Karsten Danzmann, Albert Einstein Institute Hannover, Max Planck Institute for Gravitational Physics and Leibniz Universität Hannover, Germany

SOLARIS: SOLAR sail Investigation of the Sun

Spokesperson: Thierry Appourchaux, Institut d’Astrophysique Spatiale, Orsay, France

Science from the Farside of the Moon

Spokesperson: Mark Wieczorek, Institut de Physique du Globe de Paris, Université Paris Diderot, France

Light from the Cosmic Frontier: Gamma-Ray Bursts

Spokesperson: Nial R. Tanvir, Department of Physics and Astronomy, University of Leicester, United Kingdom

Stellar Imager

Spokesperson: Thierry Appourchaux, Institut d'Astrophysique Spatiale, Orsay, France

Chronos: A NIR Spectroscopic Galaxy Formation Survey

Spokesperson: Ignacio Ferreras, Mullard Space Science Laboratory, University College London, United Kingdom

Exploring Habitable Worlds beyond our Solar System

Spokesperson: Andreas Quirrenbach, Landessternwarte, Zentrum für Astronomie der Universität Heidelberg, Germany

Venus: A Natural Planetary Laboratory

Spokesperson: Sanjay S. Limaye, University of Wisconsin, Madison, Wisconsin, USA

Space-Time Structure Explorer: Sub-microarcsecond astrometry for the 2030s

Spokesperson: Anthony Brown, Leiden Observatory, Leiden University, The Netherlands

DEX - Dark Ages eXplorer

Spokesperson: Marc Klein Wolt, Department of Astrophysics, Research Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen, The Netherlands

Solar System Debris Disk - S2D2

Spokesperson: Ralf Srama, Universität Stuttgart, Institut für Raumfahrtsysteme, Raumfahrtzentrum Baden Württemberg, Germany

PRISM: Polarized Radiation Imaging and Spectroscopy Mission

Spokesperson: Paolo de Bernardis, Dipartimento di Fisica, Università di Roma "La Sapienza", Italy

Sub-arcsecond far-infrared space observatory: a science imperative

Spokesperson: Marc Sauvage, CEA/DSM/Irfu/SAp, CE Saclay, France

The Case for an ESA L-Class Mission to Volatile-Rich Asteroids

Spokesperson: Geraint H. Jones, Mullard Space Science Laboratory, University College London, United Kingdom

The Science Case for an Orbital Mission to Uranus: Exploring the Origins and Evolution of Ice Giant Planets

Spokesperson: Christopher S. Arridge, Mullard Space Science Laboratory, University College London, United Kingdom

Master: A Mission to Return a Sample from Mars to Earth

Spokesperson: Monica M. Grady, The Open University, Milton Keynes, United Kingdom

Hypertelescope Optical Observatory

Spokesperson: Antoine Labeyrie, Collège de France and Observatoire de la Côte d'Azur, France

The ODINUS Mission Concept – The Scientific Case for a Mission to the Ice Giant Planets with Twin spacecraft to Unveil the History of our Solar System

Spokesperson: Diego Turrini, Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy

The Hot and Energetic Universe

Spokesperson: Kirpal Nandra, Max Planck Institute for Extraterrestrial Physics, Garching, Germany

Acronyms and abbreviations

AGN	Active Galactic Nuclei
ALMA	Atacama Large Millimeter/submillimeter Array
AWG	Astronomy Working Group
CMB	Cosmic Microwave Background
E-ELT	European Extremely Large Telescope
GR	Theory of General Relativity
GRB	Gamma-Ray Burst
HST	Hubble Space Telescope
IRAS	Infrared Astronomical Satellite
ISM	Interstellar Medium
ISO	Infrared Space Observatory
JWST	James Webb Space Telescope
LPF	LISA Pathfinder
LSST	Large Synoptic Survey Telescope
PSWG	Physical Sciences Working Group
SKA	Square Kilometre Array
SMBH	Supermassive Black Hole
SPC	Science Programme Committee
SSAC	Space Science Advisory Committee
SSC	Senior Survey Committee
SSEWG	Solar System Exploration Working Group

List of illustrations

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