



Introducing the *Voyage 2050* White Papers, contributions from the science community to ESA's long-term plan for the Scientific Programme

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The Scientific Programme is at the foundation of the European Space Agency, being the main “mandatory programme”, to which all Member States contribute by virtue of their being part of ESA. Member States¹ decide on the level of funding for the Scientific Programme by unanimous decision, and so far in ESA's history they have shown their unwavering support to the Programme through a remarkably constant level of funding through the last three decades.

This long-term funding horizon has allowed the Programme's stakeholders to decide and plan their priorities well in advance, providing the scientific community in Europe with a clear vision about which scientific areas deserve investment and development. Thanks also to this, the Programme has, since the 1980s, been planned in cycles² of approximately 20 years durations, commensurate with the amount of time necessary to implement ambitious space missions.

The first planning cycle, called *Horizon 2000*, was established in 1984, and consisted of a decision at the beginning of the cycle about the themes of the larger

¹ The European Space Agency (ESA) has 22 Member States. The national bodies responsible for space in these countries sit on ESA's governing Council: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Spain, Sweden, Switzerland and the United Kingdom.

² Further information about the previous planning cycles can be found here: <https://sci.esa.int/s/WvjPyoW>

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Programme elements (*Cornerstones*, or *Large missions*)³, from which the SOHO, Cluster, Rosetta, XMM-Newton, and Herschel missions emerged. The smaller programme elements would be selected through peer review via open Calls for Missions implemented during the planning cycle.

Horizon 2000 was followed by an update, called *Horizon 2000+* in 1994–1995, with the addition of two Cornerstones, Gaia and BepiColombo, along with a number of smaller missions. A further planning cycle, *Cosmic Vision*, started to take shape in 2005, preparing the way for the implementation of the Large missions JUICE (to be launched in 2022), Athena and LISA (with launch dates in the 2030s), all three now firmly established in the Programme. It is thus high time to decide upon the future beyond Athena and LISA, and for this reason the Director of Science has initiated a new long-term planning cycle⁴, with the name *Voyage 2050*, to decide what should be the scientific priorities of the Scientific Programme following Athena and LISA.

The approach to long-term planning adopted for the Programme has shown its success by providing European scientists with the tools (space missions) to establish their leadership in a number of fields, and has established the Scientific Programme as a reference among space-faring actors worldwide.

1 Programme structure

The Scientific Programme is structured in discrete “building blocks”, or mission types, that can be grouped in *Large missions* (called *Cornerstones* in the past), *Medium missions*, and smaller mission types. With very few exceptions, ESA implements missions in the Scientific Programme in cooperation with its Member States, which provide and fund the scientific instruments aboard these missions. The Programme is usually responsible for implementation of the spacecraft, as well as for its launch and operations. All missions are open to international cooperation, and the Scientific Programme has worked together with most of the space-faring nations in the world, starting with the USA (with NASA being the Programme’s oldest and most established partner), and extending to Russia, China, Japan, India, and others. In fact, most of the missions the Scientific Programme has implemented have elements of international cooperation, with “European-only” missions being in the minority. The Programme is also an active participant to missions led by international partners, providing European scientists an effective vehicle for participating in scientific endeavors led by other space-faring entities. The European partnership with NASA on flagship missions such as the Hubble Space Telescope, the Cassini-Huygens mission to the Saturn system, and, more recently, the James Webb Space Telescope beautifully exemplifies this international cooperation.

³ Horizon 2000 was built around four Cornerstones: a Solar Terrestrial Programme, implemented as the SOHO and Cluster missions; a mission to primordial bodies in the Solar System, which became the Rosetta mission; an X-ray Spectroscopy mission, which led to the XMM-Newton mission, and a Submillimetre Observatory, which was realized as the Herschel mission.

⁴ The Voyage 2050 website provides details of the various steps in the process: <https://www.cosmos.esa.int/web/voyage-2050>

Large missions are the most ambitious scientific missions that Europe can realise, and are planned at a cost to ESA of approximately twice the Programme's yearly income, to which the value of the nationally provided payloads and of the contributions from international partners must be added. Large missions provide the scaffolding of the whole Programme, and deciding their scientific themes long in advance enables the effective synchronisation of research priorities and technology developments across the 22 ESA Member States, as well as providing a clear framework against which the medium and smaller missions can be decided. Large missions are all ESA-led, and define the areas in which Europe stakes a claim to leadership. As such, past and ongoing Large missions have effectively established European "firsts" in a number of areas. Examples include the first exploration of a comet with the Rosetta orbiter⁵ and the Philae lander, the largest monolithic space telescope flown to date with the Herschel telescope, the unique large-scale astrometric survey carried out by Gaia, the BepiColombo mission to Mercury, and the upcoming first probe orbiting the moon of another planet, JUICE. The scientific successes of the Large missions implemented by the Scientific Programme are too numerous to even attempt to illustrate in the present context. It suffices to say that the six Large missions flown to date have launched the European scientific community to become a key player on the world stage in the respective fields. The three Large missions currently in the pipeline will no doubt further cement this European scientific leadership.

Medium missions, with a cost to ESA of approximately half of the cost of the Large missions, are on the contrary not decided long in advance, but are competitively selected among proposals submitted by the scientific community when a Call for Missions is released. Medium missions provide flexibility to the Programme, and have been important in addressing emerging science themes during ongoing planning cycles. Examples include the dark energy surveyor mission Euclid, and the two exoplanetary missions PLATO and Ariel, that together with the smaller mission CHEOPS make a clear statement about Europe's wish to lead in this field.

Smaller missions (that include variously named small and fast missions, as well as small contributions by the Programme to missions led by other agencies, called *missions of opportunity*) are an important element providing additional flexibility and agility to the Programme (in addition to being a key tool in international cooperation). By virtue of their smaller size, they are however less "visible" in the context of the long-term planning, and are decided upon in a more ad hoc basis.

2 The Voyage 2050 planning cycle

The JUICE mission is fast approaching its launch, and Athena and LISA are on a clear course toward their implementation with a launch foreseen for both missions around the mid 2030s. While this date might appear far away, the timescale for the implementation of Large missions has in the past always been upwards of 15 years, and it is therefore high time to define the missions that will follow Athena and LISA.

⁵ Rosetta benefitted from the experience gained with ESA's first deep space mission, Giotto.

For this reason, the Director of Science has tasked a team of thirteen scientists (the “*Voyage 2050 Senior Committee*”)⁶ chaired by Linda Tacconi (MPE, Garching) and Chris Arridge (Lancaster University) to lead the definition of a new long-term plan that will set the European priorities in space science for the couple of decades following the end of the current *Cosmic Vision* planning cycle. Such an ambitious undertaking, which affects European space science for decades, can only be implemented based on an open consultation of the broad scientific community interested in space science, and should involve as many members of the scientific community as possible.

In this spirit, the *Voyage 2050* planning exercise started, back in 2019, with an open “Call for White Papers”, through which the community was invited to submit their ideas for the science themes that the Scientific Programme should address following the launch of Athena and LISA. The response from the Call for White Papers was overwhelming, with an unprecedented number of almost 100 replies received⁷ representing a number of scientific ideas far exceeding what will be possible to implement within the planning cycle. This is a clear sign of the vibrancy of the European scientific community, but also a reflection of the limitations of the Programme’s funding relative to the ambition of the European scientists.

To ensure the broadest possible peer support and involvement, a much larger number of scientists have been given the possibility of contributing in the process, through an open Call. This Call gave the opportunity to any scientist working in Europe, with a strong preference for early career scientists, to participate in five “Topical Teams” who led the analysis of the White Papers, and who provided their recommendations to the Senior Committee. The Topical Teams ensured that the Senior Committee had access to broad and diverse scientific views and opinions, enabling what otherwise would have been an impossible task for the Senior Committee to carry out. It also gave the possibility to a significant cross-section of the European scientific community to contribute to the definition of the future of their disciplines.

The Director of Science requested the Senior Committee make a three-tiered recommendation. The first, and the one with the strongest impact on the Programme, was to provide a clear recommendation about the scientific themes that shall be addressed by the three Large missions following Athena and LISA. This is in line with the long-term planning being by its nature mainly concerned with the Programme’s Large missions. Large missions require significant technology development, which often takes a number of years. While these developments require

⁶ The *Voyage 2050 Senior Committee* was appointed by the Director of Science and comprised: Chris Arridge (Lancaster University), Alessandra Buonanno (MPG, Potsdam), A.M. Cruise (University of Birmingham), Olivier Grasset (University of Nantes), Amina Helmi (University of Groningen), Luciano Iess (Sapienza University, Rome), Eiichiro Komatsu (MPIA, Garching), Jérémy Leconte (CNRS/Bordeaux University), Jorrit Leenaarts (Stockholm University), Jesús Martín-Pintado (Spanish Astrobiology Center, CAB), Rumi Nakamura (Space Research Institute, Austrian Academy of Sciences), Linda Tacconi (MPE, Garching), and Darach Watson (University of Copenhagen).

⁷ A complete list of the White Papers submitted in response to the Call can be found here: <https://www.cosmos.esa.int/web/voyage-2050/white-papers>

significant resources (certainly from ESA, and often also from Member States), they are best carried out well in advance of the actual mission development activities being started. To justify the significant investments required to carry out these technology developments and avoid nugatory spending it is thus necessary to decide well in advance which Large missions the Programme will implement, hence the request to provide a clear and prescriptive recommendation in this sense. Depending on the content of the recommendation, the Director of Science will likely discuss with Member States the early start of technical and scientific studies, as well as potential technology developments necessary to enable the implementation of ambitious missions some fifteen years from now.

The second request was to provide a list of possible themes that could be addressed through Medium missions. This list will be neither exhaustive nor prescriptive, and Medium missions will continue to be selected following open Calls for Missions issued periodically. The purpose of the recommendation is multifarious: it will provide evidence to both the Director of Science and the Science Programme Committee (the body responsible for deciding the content of the Scientific Programme) that Medium missions will continue to be a good investment for the future Programme. It will also provide the Executive with possible areas where modest technology developments might enable future Medium missions.

The third and final request concerned long-term technology developments: a number of ideas presented in the White Papers would be feasible should certain specific technologies become available. In some cases this concerns availability *tout court*, in some other cases it concerns availability in Europe. Either way, an ESA-led technology effort (likely with Member States' involvement) could enable the implementation of such ideas in the future (likely in the planning cycle following *Voyage 2050*). Thus, in parallel with the implementation of the ideas selected for the current cycle, this recommendation will guide the Programme in starting now to create and enable a path to the future beyond *Voyage 2050*.

As an aside, there has been significant discussion with and within the Senior Committee as to whether three is the correct number of Large mission slots to aim for. In fact, previous planning cycles aimed at doing more, with four Large missions selected. However, history shows that more than three Large missions per planning cycle was very difficult, if not impossible, to realise, hence the decision to ask to limit the recommendation to three. Of course, the ambition to do more remains, and nothing would forbid, should the resources available to the Programme increase significantly in the future, to use the recommendations of the Senior Committee as the basis for a more ambitious Programme.

3 The future

The purpose of the present publication, which will be divided across two Special Issues of this journal, is to give the broadest possible visibility to the ideas and ambitions of the European space science community for the decades to come, by publishing the White Papers received in preparation for the *Voyage 2050* planning cycle. The White Papers were always meant to be public, as already announced in

the relevant Call, and in fact, they are already available, in the form in which they were received at the time of the Call, on the ESA website detailing the *Voyage 2050* exercise. The present publication provides a more permanent record of the ideas submitted, in a more uniform and homogeneous form, affording a unique overview of the broad-reaching ambitions and ideas of European scientists for space science programmes.

In the spirit of the original solicitation to the scientific community, no attempt has been made to filter the submissions in terms of their financial affordability. The community has been requested to put forward their scientific priorities, rather than a detailed mission proposal, and this has been essential to provide the Senior Committee with a broad panorama of the ideas and ambitions. The solicitation deliberately did not request scientists to include in their response the details of a mission concept through which the scientific goals presented could be addressed. As a consequence, some White Papers focus mainly on the science, with only an outline description of a possible implementation scheme, while others include very detailed and realistic mission concepts, often based on previous mission concept proposals.

Some of the ideas presented by the scientific community clearly will not fit within the context of the current financial envelope of ESA's Science Programme, and some would rely on technologies yet to be developed. While the recommendations that the Senior Committee will issue to the Director of Science will have unfortunately to be constrained by affordability, the broad collection of White Papers published here provide an overview of long-range aspirations of the European scientific community, and of some of the ideas that could be implemented.

It has been both reassuring and sobering to realise how broad and solid the ambitions and capabilities of the European scientific community are in the fields covered by space science. Reassuring because the outcome of the Call provided confirmation that the scientific community in the Member States of ESA is vibrant and dynamic, with ideas spanning all possible areas of science, from the fields that have traditionally formed the backbone of space science to new and yet to be explored fields. Sobering because the number of ideas that the Programme will be able to implement in the timeframe covered by the *Voyage 2050* planning cycle will only cover a small fraction of the ideas that would be worth implementing.

The Senior Committee has been particularly aware of this limitation, and would easily recommend a significantly larger number of science themes and possible missions had the financial and programmatic constraints not been so stringent. Converging on only three possible Large missions, as affordable by the current financial horizon for the Science Programme, has required unavoidable choices. These choices are even more complex and difficult due to the fact that the low-hanging fruits in many fields have long since been picked. The first planning cycles took place in a scientific landscape in which the simple exploration of a yet-to-be open wavelength range in astrophysics, or a visit to a yet unexplored body of the Solar System with even modest scientific instrumentation, were guaranteed to result in scientific breakthroughs.

The situation today is radically different. Many scientific fields have matured, and require new sophisticated approaches to address some of the formidable and fascinating scientific questions currently on the table. In a number of fields the obvious approach is to build bigger and bigger telescopes, or to send more and more complex robotic probes to Solar System bodies. This “obvious solution” is unfortunately not one that necessarily can be implemented within the fiscal envelope of the Programme.

The Senior Committee will issue its recommendations to the Director of Science in Spring 2021, and based on such recommendations the Director of Science intends to submit in June 2021 a detailed proposal for the long-term planning of the Scientific Programme to the Member States of the Agency, as represented in the Science Programme Committee (SPC).

The decision by the SPC in June 2021 will be the start of a new long-term planning cycle for the Scientific Programme. It will enable the Director of Science to issue, in the near future, the Calls for Missions that will ask the scientific community to flesh out the scientific ideas selected by the Senior Committee and approved by the SPC in the form of actual space missions.

The Senior Committee had thus the unenviable task of addressing the issue of how to progress in the fields of space science and to maintain and extend the leadership of European scientists in a number of fields in an era of (nearly) constant budgets. This is a challenge that will no doubt have to be very present in the minds of the scientific community as they respond to the first round of Calls for mission proposals.

The first Large mission resulting from the work of the *Voyage 2050* Senior Committee won't be flying before the late 2030s. This is a time-frame well beyond the professional horizon of most members of the Senior Committee and Topical Teams, as well as of many White Paper authors. The amount of time and effort that the involved scientific community has invested in this effort, whose results will be harvested by the next generation of scientists, is a tribute to the generosity and ability to look beyond one's own direct interest. The generation that will make the astonishing scientific discoveries that this new crop of missions will enable once they will fly is largely still in school and University and possibly at best marginally aware of the far-reaching planning exercise that is currently ongoing, although some may have participated in the broad public consultation⁸ that accompanied the *Voyage 2050* call.

We hope that the present publication will provide a record of the work that will enable the future generation to achieve their scientific excellence, and that these future brilliant scientists, twenty or thirty years in the future, will realise that their success builds upon an amazing amount of work carried out selflessly by the previous generation. They will be standing not necessarily on the shoulders of giants but rather on the shoulders of dedicated, forward-looking colleagues who did their best to enable a long-term future for space science in Europe.

The recommendations of the Senior Committee, based on the White Papers published here, will be the start of a long and complex process. Very significant

⁸ In 2019, the ESA Director of Science invited the public to share their views on the questions that *Voyage 2050* should address: <https://sci.esa.int/web/discovering-our-universe>

resources, and work by many in Europe (scientists and engineers, in research institutions, in industry and in ESA) will be necessary before the ideas herewith exposed turn into space missions first and into scientific results subsequently. It will be a path often impervious, with the occasional setback. It is a well-trodden path, set by each of the successful missions of the ESA Scientific Programme. It is one that, however at times steep, will lead to exciting and often unexpected discoveries. The Latin saying *per aspera ad astra* is perhaps the most concise and effective description of what awaits us!

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