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Planetary Exploration HORIZON 2061

A Long-Term Perspective for Planetary Exploration

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Dedication

This book is dedicated to the memory of Dr. Maria Teresa Capria, a wonderful colleague and outstanding planetary scientist whose constant support and encouragements have been a precious source of motivation and inspiration throughout its writing.

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Foreword to *Planetary Exploration, Horizon 2061*

We are living in a dynamic era of planetary exploration. Exploring planets, moons, and small bodies in our solar system allows us to get a glimpse into our origins and investigate the history and diversity of both our own and other planetary systems. An increasing participation of commercial space actors and emerging space countries will soon enable exciting planetary missions to new destinations as well as large-scale space endeavors in low Earth and cis-lunar orbits. Therefore, deep space exploration is expected to showcase significant growth in the coming decades. Robotic and human planetary exploration requires innovative technologies and multinational cooperation. The rapid development of innovative technologies such as robotics and artificial intelligence represents a game changer for planetary exploration. Mastering the challenges of robotic and human deep space exploration broadens our scientific knowledge and strengthens international cooperation. The community foresight exercise, *Planetary Exploration, Horizon 2061*, is pivotal and provides a vision to lead the way forward and assess future opportunities of planetary exploration. The chapters of this book successfully combine the planning of space missions and their enabling technologies as well as supporting infrastructure and services to establish a long-term plan of planetary exploration. The year 2061 was chosen for this exercise to pay tribute to the return of Halley's comet into our inner solar system, the 100th anniversary of Yuri Gagarin's first human space flight and the centennial of President Kennedy's Moon initiative.

In the last few decades there have been many exciting space missions from low Earth orbit (LEO) to the edges of our solar system that have inspired human explorers. The International Space Station (ISS) is the largest international space project ever undertaken and has just celebrated 20 years of continuous human habitation. Over 3000 scientific investigations from more than 100 countries have been conducted in the ISS over the last two decades. Among them are many space medicine experiments that collected crucial data on astronaut health and radiation biology to help us grasp the limits for long-term human exploration missions. Activities in LEO are currently in a transitional phase. New endeavors such as the China Space Station Tiangong, currently under construction, and smaller commercial space stations enabling research and technology development as well as commercial activities will facilitate routes to deep space and a cis-lunar economy.

Many orbiters, landers, and rovers have provided fantastic data on geological evolution, climate, the search for water, and habitability of multiple solar system objects in the past. In December 2020, China has conducted a successful lunar sample return mission Chang'e 5, and JAXA's Hayabusa-2 mission has returned samples from near-Earth asteroid Ryugu. More asteroid samples will arrive from NASA's OSIRIS-Rex mission in 2023. In 2021 we witnessed a fleet of robotic missions arriving at Mars, sent by the United Arab Emirates, China, and NASA. The United Arab Emirates "Mars orbiter HOPE" measures the Martian atmosphere and climate and China's Tianwen-1 mission successfully landed the rover Zhurong at first attempt.

NASA's Perseverance rover started its journey to explore Mars and to collect samples for a future international Mars sample return mission. In 2022, we expect the first uncrewed test flight Artemis-1 of NASA's Artemis program. With the Artemis program, NASA plans to land astronauts on the Moon by 2025 in cooperation with international partners. Russia and China have announced the creation of an International Lunar Research Station and India is advancing its Gaganyaan human space exploration program.

The giant planets and their moons in our outer solar system are major targets for planetary exploration in the future, given that many of them are still unexplored. New missions will continue to investigate unique comets and asteroids as well as extrasolar planetary systems. Nearly 5000 exoplanets have been identified so far, of which more than 800 are multiple planetary systems. Exploring exoplanets will continue to change our view on the habitability of our universe.

We have to master many technological challenges to enable future space missions targeting planets, moons, and small bodies that will advance our knowledge on the origin, history, properties, and environments of our solar and other planetary systems. *Planetary Exploration, Horizon 2061* addresses critical technologies including landers, drills, advanced resource utilization, and ground- and space-based infrastructures, all key to enable and support exciting robotic and human planetary exploration missions. Human exploration requires major research and technology development, in particular when we envisage humans landing on Mars. Astronauts have to be protected from radiation, temperature, and dust storms. Advancements in space medicine investigating stress factors for astronauts in deep space will be required as well as new materials to build outposts and habitats on the Martian surface. The use of artificial intelligence (AI) and robotics for space exploration has many applications from data analysis, planetary navigation, and communication to optimized mission operations and emergency response.

Why is a book on the future perspectives of planetary exploration so compelling at this time? To begin, we are explorers. Planetary exploration can provide answers to key questions of our existence: how our solar system formed, whether life exists beyond Earth, and what our future prospects may be. Furthermore, planetary exploration is a driver for innovation and contributes to technologies that provide economic benefits for our society on Earth. Finally, planetary exploration fosters international cooperation, which allows cost sharing and leverages worldwide expertise, providing sustainability to large-scale and long-term space endeavors.

This book will give you amazing insights into the emerging new planetary exploration context. It outlines the different types of space missions, key technologies, and supporting infrastructure necessary to uncover the properties of planetary systems. With this book, Michel Blanc and his coauthors have provided a crucial foresight exercise of planetary exploration. They are to be commended for the breadth and depth of the content of this excellent book. It is crucial to prepare the future of planetary exploration with proper investment in science, technology, education, entrepreneurship, and supporting societal engagement. This book will help scientists and interested citizens to understand the importance of planetary exploration, and will provide a compelling vision for how we can explore our solar system and other planetary systems in the years to come.

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Preface

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1. Origin and motivations

The *Planetary Exploration, Horizon 2061* exercise originated from an initiative of the Air and Space Academy (https://academieairespace.com/en/), a pool of knowledge unique in Europe aimed to promote the development of scientific, technical, cultural, and human activities in the fields of air and space. Its members are experts in the different activity sectors of aerospace: science, technologies, History, industry, services, laws, and societal dimensions of aeronautics and space activities. In 2015, members of its Section I "Scientific knowledge and applications of air and space" and of its Section II "Applied sciences and technology of air and space" jointly identified the needs for a long-term foresight on the future of planetary exploration. This foresight should be designed to inform technology experts about the "big" science questions of planetary sciences that future scientific missions should contribute to address. In return, technology experts would have the task to identify the future technologies, infrastructures, and services that would be needed to fly these missions of a distant, multidecadal future. The "Groupe de Travail 2061," GT 2061 for short, formed jointly by sections I and II of the Academy, undertook a preliminary design of this foresight. A series of internal meetings in 2015 and 2016 made it possible to identify four complementary and highly intricated dimensions, later called the "pillars" of planetary exploration, that the foresight exercise would have to address:

(1) the major scientific questions on planetary systems for the decades to come;
(2) the different types of planetary missions needed to address these questions;
(3) the key technologies required to make these missions feasible;
(4) the ground-based and space-based infrastructures needed to support them.

The ultimate objective assigned to the foresight exercise by the GT 2061 was to draw up to the 2061 horizon a long-term picture of these four pillars via an international dialogue among experts of these pillars (scientists, engineers, managers) heavily involved in Solar System exploration. The GT 2061 also proposed the main scientific object of the exercise, its temporal horizon, its key players, and finally a method to carry the foresight exercise up to its conclusions.

2. Planetary systems: the main scientific object for a long-term foresight

For planetary scientists contributing to the exercise, it was natural and important to use the emerging unifying paradigm of their interdisciplinary research field, i.e., the concept of "planetary systems" as the main object of the foresight. Planetary systems are a class of astrophysical objects which cover both the solar system, giant planet systems, and extrasolar planetary systems, as Chapters 1–3 of this book illustrate. The fast emergence of this concept, following the discovery of the first exoplanet by the Swiss astronomers and Nobel prizes Michel Mayor and Didier Queloz in 1995 and the discovery of thousands of exoplanet that followed since then, is for planetary sciences the equivalent of a "second Copernican revolution": just as Copernic removed Earth from the center of the world to place it in the family of planets orbiting the Sun, the discovery of several hundreds of extrasolar planetary systems since 25 years places our Solar System as just one planetary system in the vast family of planetary systems populating our Galactic neighborhood. This major change in perspective opens new avenues for a more integrative research, allowing planetary scientists to study all planetary systems as a single class of objects, from their formation in circumstellar disks to the potential emergence of habitable worlds and of life among their planets and moons. As a projection into the decades to come, the Horizon 2061 exercise had to use this unifying paradigm as its main scientific object. Consequently, the high-level scientific questions introduced in Chapter 1 which represent the starting point of our foresight are a short list of key questions about planetary systems: How are they formed? How do they work and evolve? Where, how, and under which conditions may some of their objects become habitable? Do some of these objects harbor life?

3. Year 2061: the long-term horizon of the foresight

To address this large-scale perspective about planetary systems, the foresight had to encompass the whole solar system, from Earth to its farthest regions, its boundaries with the interstellar medium and its scientific connections with stars and exoplanets. Hence the need to give enough time to the space programs to cover such a broad scale, and the need to choose a multidecadal horizon for the exercise.

The choice of the year 2061 carries three symbols connecting us to the early history of planetary exploration. First, 2061 is the date of the next return of Halley's comet into the inner Solar System, reminding us of the international fleet that encountered Halley's comet during its previous visit in 1986. This memorable date reminds European space scientists of the outstanding success of the Giotto mission of ESA, which returned the first pictures ever taken of a cometary nucleus. 2061 will also be the centennial of the first human space flight, the orbital flight of Yuri Gagarin on April 12, 1961, and of President Kennedy's 1961 "Moon address" to his nation and Congress, which launched the United States to the conquest of the Moon. Placing the horizon of our foresight exercise on the centennial of these three major events ideally conveys our intention to encompass both robotic and human exploration in the same perspective. In addition, the choice of this distant horizon, well beyond the usual time frames of the planning exercises of space agencies, avoids possible confusion with them and points out to international collaboration as one of the original specificities of our exercise.

4. Horizon 2061: key players and main motivations

The choice of this long-term perspective allowed to free the imagination of the participants: planetary scientists were invited to identify the most important scientific questions challenging our understanding of planetary systems independently of the technical feasibility of future space missions that could address them; engineers and technology experts were invited to explore innovative technical solutions to fly these future missions by 2061. It also stimulated a free dialogue among them. Five main objectives were assigned to this dialogue:

1. Identify the "big" science questions that will drive planetary sciences in the coming decades;
2. Provide a variety of notional space mission concepts that will address these "big questions";
3. Identify the technologies and infrastructures that will be needed to fly these missions;
4. Inspire coordination and collaborations between the different players of planetary exploration;
5. Share with public/private leaders and the public the major scientific and technological challenges that will drive planetary exploration in the decades to come.

5. Development scheme of the exercise

In the design of planetary missions, the scientists who define scientific objectives for a new mission and the space agency specialists who design the mission use to communicate via a very efficient tool called the "science traceability matrix". For short, this matrix describes the logical links connecting the science objectives of the mission to its more detailed observation requirements and to the technical requirements that the scientific payload, the space platforms to be used and the mission architecture will have to fulfill.

Based on a similar dialogue among scientists, engineers, and managers, it is no surprise that the Horizon 2061 foresight used this same tool to design the four "pillars" of the exercise. As Chapter 1 shows, we started from the high-level science objectives to define the observations to be performed, then the missions to be flown and finally the technologies, infrastructures, and services needed to fly these missions. This logical development, whose complexity comes from its coverage of the whole solar system, was accomplished in three steps, from 2016 to 2019, using three successive international meetings.

The first step was accomplished by a joint ISSI-Europlanet forum hosted by the International Space Science Institute in

Bern, Switzerland, from September 13–15, 2016. Two days of scientific presentations and discussions involving about 50 scientists and engineers led to the formulation of the six major scientific questions (pillar 1) and of the observations needed to address these questions. During the third day, scientists and engineers discussed the technologies needed to fly the planetary missions (pillar 2) that would perform these observations.

The second step was the community workshop "Technologies and Infrastructures for Planetary Exploration" hosted by the Ecole Polytechnique Fédérale de Lausanne (EPFL) from April 23–25, 2018. This second workshop discussed the technologies (pillar 3) and infrastructures (pillar 4) needed for the future missions identified in step 1.

The third step was a colloquium hosted by the Institut de Recherche en Astrophysique et Planétologie (IRAP) and Observatoire Midi-Pyrénées (OMP) in Toulouse, France, with the sponsorship of COSPAR, from September 11–13, 2019. It reviewed each pillar using lessons learnt from the previous steps and additional contributions and defined a method to draw the final conclusions of the exercise and to report to the scientific community.

A fourth meeting, the ISSI-Europlanet forum on "Solar System/exoplanet science synergies," hosted by ISSI in Bern on February 19 and 20, 2019, explored how these synergies help understand planetary systems. The conclusions of this forum, which provided the important exoplanet context to the Horizon 2061 exercise, are presented in Chapter 2 of this book.

Preliminary conclusions of this exercise were presented at the joint meeting of the European Planetary Science Congress (EPSC) and of the Division of Planetary Sciences of the American Astronomical Society (DPS-AAS) in Geneva on September 20, 2019. Near-final conclusions were presented at the Sydney virtual COSPAR Scientific Assembly from February 1–3, 2021, and reports on these final conclusions were given at the International Astronautical Congress in Dubai during the week of October 25–29, 2021.

Programs of all these meetings and most of their presentations can be found on the dedicated Horizon 2061 webpage: https://horizon2061.cnrs.fr.

6. What's next?

Continuation of the Horizon foresight exercise in the coming years will be needed to integrate new scientific discoveries and take into account the new capacities offered by emerging technologies. To this end, a "Horizon 2061" association setup by the editors of this book will continue their work by means of regular updates of the long-term foresight, for instance, every 5 years, and of focused meetings on specific subjects only superficially touched on in this book. We hope that the younger generation will join in and take the lead in the implementation of these new activities.

7. Our dreams for 2061

Among the many perspectives this book offers for the future of planetary exploration, we would like in conclusion to emphasize a few that are representative of our dreams for 2061.

By 2061, characterization of all classes of solar system objects and secondary systems, combined with progress in the detection and characterization of exoplanets and their moons, rings, and magnetospheres, will have integrated the science of planetary systems and helped us understand more deeply the similarities and differences between our solar system, giant planet systems, and extrasolar planetary systems.

By 2061, spectacular progress in robotics, artificial intelligence, miniaturization, and other key platform technologies will make it possible to adapt science platforms to complex operations in the diversity of extreme environments of solar system objects, from the surfaces and subsurfaces of terrestrial planets to the icy crusts and subsurface oceans of giant planet moons.

By 2061, comprehensive exploration of the different families of solar system objects will have uniquely informed our understanding of the formation scenarios of the solar system, its giant planet systems, and extrasolar planetary systems.

By 2061, the main candidate habitable worlds in the solar system will have been characterized by dedicated planetary missions, from Mars to the different ocean worlds, possibly leading to the discovery of a second genesis of life somewhere in the Solar System.

By 2061, interplanetary telecommunications, navigation, space weather, sample curation, etc., will have evolved into distributed networks extensively using assets on the Moon, other bodies, and in interplanetary space to provide Solar System—wide services to deep space exploration missions.

By 2061, the different information systems archiving and disseminating the huge volumes of scientific data produced by telescopes, deep space missions, and laboratory experiments will have evolved into an integrated and distributed virtual observatory offering limitless navigation in the Solar System to scientific users and the public.

Sometime before 2061, residents of a permanent lunar base will follow via the interplanetary internet the first landing of humans on Mars.

Will these perspectives, and many more offered in this book, come true? Rather, will some of them fade away and new ones emerge as decades will follow one another? Most certainly yes! In the end, the main purpose of this book is not so much to make accurate predictions on evolutions and trends that will materialize decades from now, as it is to stimulate continued exchanges of ideas between all players of planetary exploration, for the sake of building a brilliant and exciting future for this unique endeavor in which every human being and every talent can take part. We firmly believe that the stimulating dialogue among scientists, engineers, and managers that has driven the writing of this book will continue to push farther the frontiers of our scientific understanding of the Solar System, as well as of our technical capacities to unravel the secrets of its most extreme environments.

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