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SYNTHESIS OF THE PLANETARY EXPLORATION - HORIZON 2061 - FORESIGHT EXERCISE

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Abstract

The "Planetary Exploration, Horizon 2061" long-term community foresight exercise has been proposed by the Air and Space Academy and led by scientists, engineers and technology experts heavily involved in planetary sciences and in the exploration of the Solar System. This foresight exercise has been elaborated over 3 workshops held in 2016 in Bern, in 2018 in Lausanne and in 2019 in Toulouse. It has been opened to all scientists, engineers, technicians, journalists, industry and space agencies, students and people interested in the future of planetary exploration and the space adventure. The ultimate objective of this sequence of workshops was to develop a long-term picture of the four pillars of planetary exploration:

1. the major scientific questions;
2. the different types of relevant space missions;
3. the key required technologies;
4. the needs in terms of supporting infrastructures and services.

The year 2061 corresponds to the return of Halley's comet into the inner Solar System, the centennial of the first human space flight, and President Kennedy's Moon initiative. It symbolizes the intention to encompass both robotic and human exploration in the same perspective. In the early workshops, planetary scientists were invited to formulate the most important scientific questions that need to be addressed and solved to make progress in our understanding of Planetary Systems, a new class of astrophysical objects which are ubiquitous in our Galactic neighbourhood but can be explored in-situ only in our Solar System! These science questions have been formulated independently of the a priori technical possibilities to address them. Subsequently, engineers and technology experts have been invited to contribute to the exercise to seek for innovative technical solutions that will make it possible to fly the challenging space missions needed.

We will give an overview of Horizon 2061 results. The talk will give a particular focus on pillar 2, elaborating the major future planetary exploration missions that would provide the measurements needed to answer a set of 6 fundamental questions about planetary systems, and about the solar system as the only one we can explore in situ with space probes. We will also address the new technologies required to achieve those missions.

Keywords: (Planetary science, solar system exploration, technology)

1. Introduction

"Planetary Exploration, Horizon 2061" (Blanc et al. 2021a) [1] is a long-term foresight exercise initially proposed by the Air and Space Academy and led by scientists, engineers and technology experts who are heavily involved in the planetary sciences and Solar System exploration. The ultimate objective of this exercise is to draw a long-term picture of four pillars supporting planetary exploration:

- Pillar 1: the major scientific questions concerning planetary systems;
- Pillar 2: the different types of space missions that aim to address these questions;
- Pillar 3: the key technologies needed to make these missions possible;
- Pillar 4: the ground- and space-based infrastructures and services needed to support these missions.

The logics and method of this foresight exercise are detailed in the introductory chapter of [1] by Blanc et al. (2021b) [29].

The year 2061 corresponds to the return of Halley's comet into the inner Solar System, to the centennial of the first human space flight and to the centennial of President Kennedy's Moon initiative. It is a symbolic representation of our intention to encompass both robotic and human exploration in the same perspective. This unusually distant horizon is located well beyond the limits of the typical planning exercises of space agencies to avoid any possible confusion with them. Most importantly, the Horizon 2061 exercise is intended to "free the imagination": free the imaginations of planetary scientists who were invited to share their visions of the most relevant and important scientific questions, independent of the existence of technical solutions to address them; free the imaginations of engineers and technology experts who were invited to look for innovative technical solutions to enable the challenging space missions that will address these questions.

For Horizon 2061, the overarching science goal is to:

explore and understand the evolution of planetary systems, from their formations to the possible emergence of habitable worlds and life.

This goal is then broken down into six key science questions:

- Question 1: How well do we understand the diversity of planetary system objects?
- Question 2: How well do we understand the diversity of planetary system architectures?
- Question 3: What are the origins and formation scenarios for planetary systems?
- Question 4: How do planetary systems work?
- Question 5: Do planetary systems host potential habitats?
- Question 6: Where and how to search for life?

After taking the broad view of science synergies between Solar System and exoplanet studies, we will in the next section narrow in on the Solar System by describing the classes of objects it contains and then identify a set of measurement needs for each of those to address the science questions. Section 3 builds up Pillar 2 by identifying a representative group of future space missions that will make these measurements possible. An analysis of the technical requirements associated with these missions will then be provided.

Another complementary paper on "Planetary Exploration, Horizon 2061" will be presented in the D3 symposium at IAC 2021 by Perino et al[2], and will focus on the major role that international collaboration plays to materialize these ambitious exploration perspectives.

2. Scientific objectives versus mission destinations

The scientific questions stated in introduction are first addressed in the "Planetary Exploration, Horizon 2061" by Rauer et al in the broader context of the exploration of all planetary systems [3]. This analysis shows how synergies between exoplanet and Solar System research will play a key role in the elaboration of answers to these six questions, by placing Solar System exploration in the broader context of the study of extrasolar systems and of their objects.

However, while extrasolar planetary systems are observed by a broad variety of astronomical techniques, the Solar System will keep its unique place in the future study of planetary systems for four main reasons:

- It will remain by far the system that can be observed with the highest spatial resolution: in situ, close-up investigations of its objects by space probes will combine with the enhanced resolving power of Earth-based telescopes to scrutinize even its most distant objects (giant planet systems, Trans-Neptunian objects…); it is also the only planetary system we can ever hope to sample in situ via descent probes and landers.
- Because the Solar System can be observed with this unique combination of orbiting spacecraft, in situ landers and probes, and giant ground- and space-based telescopes, it enables scrutiny of the broadest diversity of objects that a planetary system may be expected to host.
- The Solar System is, for the time being, the only planetary system where we can observe secondary systems within it, formed of an equally diverse collection of objects: numerous systems of satellites that vary in complexity, rings and plasma tori formed around its giant planets, and our Earth-Moon system where life is known to have evolved. Thus, studied together with the Solar System as a whole, these secondary systems provide us with unique insight into the diversity of planetary system architectures.

- Finally, the combination of space missions and telescope observations makes it possible to study in detail its interface with the local interstellar medium surrounding it, the heliopause, and offers the perspective to take soon the first steps outside of our own home planetary system to explore its surroundings.

At this stage, Dehant et al [4] determined for each of the six key science questions some more specific scientific objectives that should be assigned to missions flying to the different provinces of the Solar System. These specific scientific objectives are listed in the matrix of Figure 1 for each of the six key science questions and each solar system destination. An additional column to the right shows which additional objectives are guided by comparisons between the solar system and extra-solar planetary systems, which have been analysed by Rauer et al [3] (2021).

Horizon 2061 science question	Earth-Moon System	Terrestrial Planets			Gas Giants		Ice Giants		Small Bodies and Dwarf planets				Heliopause and beyond	Extrasolar Planetary Systems
		Mars	Venus	Mercury	Planet	Moons	Moons	Planet	Asteroids & Comets	Trojans Irregular moons	TNOs	Dwarf planets		
Q1- Diversity of objects	In-depth characterisation of the Moon as the closest model of a terrestrial planet: Internal structure, surface geology, inventory of mineral resources and volatiles, regolith and exosphere	Detailed comparative characterisation of Earth, Moon and Mars: internal structure and dynamics, crust, atmosphere, magnetic field and magnetospheres.		In-depth characterisation of Mercury: Internal structure, surface geology, inventory of minerals and volatiles, exosphere, magnetosphere	Detailed characterisation of gas giants: structure and dynamics of interiors and atmosphere, magnetic field and magnetosphere	Comparative study of the regular and irregular moons of giant planets: bulk composition, shape and dynamics, internal layering including oceans, geology and surface properties, space environment		Detailed characterisation of ice giants: structure and dynamics of interiors and atmosphere, magnetic field and magnetosphere	Characterise representative samples of the different populations and taxonomic types of small bodies, with emphasis on the most poorly know ones (Trojans, centaurs, TNO's): mass, density, shapes, cratering, chemical composition, degree of internal layering, refractory, organic and volatile contents			Characterise a few dwarf planets: bulk composition, surface properties, degree of internal layering	Explore the population of trans-Neptunian objects, possibly including very distant planets and Oort cloud. Characterise the components of the Very Local Interstellar Medium (VLISM): gas, plasma, B field, GCRs)	Characterize in situ all classes of solar system objects to use them as templates of the diversity of objects in other planetary systems. Characterize ice giants with a degree of precision comparable to other planets
Q2- Diversity of architectures	Understand the Earth-Moon system as the closest example of a secondary system	Study Phobos and Deimos as a second example of a system of moons around a terrestrial planet			Detailed characterisation and comparative study of the four giant planets systems: central planet, ring-moon systems, regular and irregular moon systems, populations of Trojan objects, magnetospheres and their interactions with embedded objects and plasma populations.				Explore the distribution of small body populations in the solar system, particularly on in its outskirts (the Trans-Neptunian Solar System), compare to debris disks around other stars Explore binary systems and secondary systems in the TNO population Revisit the Pluto-Charon system with an orbiter				Characterise and understand the heliosphere as the Solar System's astrosphere Characterise the nature and 3-D shape of heliopause boundaries	Understand the specific architectures of the solar system and giant planet systems in the light of the diversity of other planetary systems architectures
Q3- Origin of Solar System	Discriminate between the different scenarios of Moon formation	Discriminate between the different scenarios of moons formation		Understand how a planet forms in the hottest region of the Solar Nebula	Understand the formation scenarios of gas giants and their role in the formation of the solar system	Understand the formation scenarios of giant planets moons and where they applied, and their connection to solar system formation		Understand the formation scenarios of ice giants and their role in the formation of the solar system	Read the messages of the Solar Nebula and of the formation of the solar system in the elementary and isotopic compositions of the different classes of small bodies. Understand their connection to IDPs and meteorites Remote sensing, then in situ exploration and characterisation, then sample return up to giant planets Trojans and irregular moons					Use the direct observations of protoplanetary disks around other stars to better understand the formation scenario of the solar system
Q4- How does the Solar System work?	Past and present dynamics and activity of the Moon, surface-regolith-exosphere-solar wind interactions Dynamics of the Earth-Moon system	Understand the dynamics of the different layers of a terrestrial planet and their interactions. Understand the processes driving their chemical evolution, loss of atmospheric species and climate evolution		Understand the dynamics of the different layers and their interactions. Understand surface-exosphere-solar wind interactions	Understand how interiors and atmospheres including magnetic field work Understand the "systems within the systems": - Dynamics of rings and coupling with moons - Dynamics of magnetospheres, plasma populations and energetic particles, coupling to host planet and solar wind	Understand how regular moons work including their couplings to their host planet		Understand how interiors and atmospheres including magnetic field work	Understand and monitor the dynamics of Earth-crossing objects, learn to predict and possibly mitigate their hazards				Understand the transfer processes acting across the different boundaries of the heliosphere and their effect on the transfer of matter, momentum, energy, radiations and particles across the heliopause	Use the solar system as an in-situ laboratory where to study how planetary systems work. Understand the heliosphere as the Sun's astrosphere, and its complex interaction with the Galaxy.
Q5- Search for potential habitats	Assessment of the role of Earth-Moon interactions in the maintenance of the habitability of the Earth How to make the Moon habitable for humans?	Compare the delivery of water and organic material to the environments of Earth, Mars and Venus. Understand the impact of their environments and atmospheric evolution on their habitability through time				Characterise the habitability of Europa and other ocean moons	Characterise the habitability of Triton, explore Uranian moons		Explore the water reservoirs of small bodies, assess their respective contributions to the initial water reservoirs of terrestrial planets including Earth			Characterise the habitability of the most promising candidates, e.g. Ceres	Understand the role played by the heliosphere in the habitability of the solar system and learn about the role of astrospheres in the habitability of extra-solar planetary systems	Study habitability in the solar system to better define the habitability conditions to be applied to other planetary systems and exoplanets
Q6- Search for Life	N/A	Active search for extinct and extant life				Search for life at Enceladus, possibly Europa, Titan								Use the search for life in the solar system to improve our search for biosignatures at exoplanets

Figure 1. A summary of the specific scientific objectives of the exploration of the different provinces of the solar system which address each of the six key science questions of the Horizon 2061 foresight.

To properly address these detailed scientific objectives at the different destinations, a large diversity of Earth-based observatories and Solar System exploration missions is needed. They can be ordered along an ascending "scale of complexity" of planetary missions:

(1) Observations from Earth's surface;
(2) Cruise and flyby observations;
(3) Orbital surveys of a small body, planets, moon and/or secondary system;
(4) In situ probes to atmospheres and surfaces;
(5) Sample return from these objects to Earth;
(6) Human missions.

Even given the projected progress in technology development, the last two types of missions are likely to remain limited to the closest destinations even by the 2061 horizon: up to the asteroid belt for Human exploration, up to Jupiter's Trojans and perhaps some moons of Jupiter and Saturn for sample return missions.

Astronomical facilities have for generations aided in our quest to understanding the formation, evolution and workings of objects within our own Solar System. With the emergence of more and more challenging space missions which will likely focus only on a small subset of these objects, the expected contributions of Earth-based telescopes or space based observatories to Solar System exploration will remain extremely important: only they will be able to provide broad and deep spectroscopic surveys of the largest and most distant populations of objects such as comets and trans-neptunian objects, and to capture both the short-term and multi-decennial variability of planets and moons. Earth-based observations will also continue to be the dominant sources of discovery of new objects, and their observations will be instrumental in the preparation of future space missions on which we are going to focus in the rest of this article.

The next chapter explores the diversity of missions to the different destinations of the solar system that will have to be flown to address the six key science questions of the Horizon 2061 foresight exercise.

3. In situ missions to the different provinces of the Solar System

Addressing the six science questions of the Horizon 2061 exercise, we will divide the different destinations of Solar System exploration into eight provinces or destinations, from the nearest to the farthest:

- The Earth-Moon system,
- Venus,
- Mars,
- Mercury,
- Gas Giant planets and their systems,
- Ice Giant planets and their systems,
- Small bodies: asteroids, comets, Trojans, Trans-Neptunian Objects,
- The “frontier regions” of the Solar System, extending from the Trans-Neptunian Solar System to the interstellar medium

For each of these provinces, Lasue et al [5] have first summarized the expected contributions of their exploration to an improved understanding of the Solar System. They have then successively described the missions that will fly in the 2021-2040 time scale, most of which are already defined and in preparation. Considering the synthetic nature of this article, this section will concentrate on the new set of notional missions that should fly in the 2041-2061 period to address the six science questions of the Horizon 2061 exercise. The associated technological challenges will also be addressed.

3.1 Representative missions to the Moon for 2035-2061: A gateway for deep space exploration

The envisioned missions for this long-term timeframe will benefit from the progressive development of robotic and human infrastructures associated to the operations and services. All these developments will contribute to the establishment of a permanent sustainable Moon Village (Foing 1996[6]; Casini et al. 2020[7]).

A number of instruments concepts already proposed, after having been studied and prototyped on Earth, will find ideal locations and support for their deployment in this particularly favourable context. The instruments and laboratories that are envisioned include:

- Geoscience observatories network on the Moon with a goal to probe the interior using seismometers (Yamada et al. 2011[8]);
- Astronomical observatories on the Moon: these may include liquid mirror giant telescopes; optical and infrared interferometers and hyper-telescopes; radio-telescope networks on the far side of the Moon, including a Lunar Crater Radio Telescope (Clery 2019[9]);
- Moon-based Earth observatories for studying global-scale phenomena on Earth (Guo et al. 2016[10]);
- Science and exploration enabled by permanent human research bases at poles, lava tubes and non-polar regions (Heinicke and Foing 2021[11]);
- In-situ manufacturing facilities for research and economical exploitation;
- Curation facilities for extra-terrestrial sample analysis;
- Astrobiology and life science laboratories;
- Research infrastructures benefitting from habitation, business, tourism, entertainment, and citizen science exploration.

3.2 Venus: towards sample return

The key measurements to be performed to address issues encompassing the Venus geodynamics, atmospheric processes and biological potential are available in Earth’s laboratories: microscopic observations and chemical analyses of rock samples; chromatography, mass spectrometry, isotopic measurement, NMR for gas/aerosols. For rock samples, the comparison of analytic data from low lands to high lands will also better constrain the possible elemental transfer at large scale through the atmosphere (radar anomalies).

Most of the required techniques have been space-qualified for in-situ measurements, mainly on Mars. However, for Venus surface or deep atmosphere, analyses by remote sensing are strongly limited by the composition and density of the atmosphere (clouds, IR absorber, etc.) and the extreme conditions of the Venus surface constitute a serious limitation for any in-situ analysis (soil or deep atmosphere). Running a complex scientific rover like Discovery on Mars, for example, is not possible at 470°C. A sample return mission for both surface rocks and atmosphere should be the goal in the 2061 perspective.

Return sample missions are always very challenging. The major obstacle in the case of a terrestrial planet is the energy required for a rocket ascent vehicle and the return flight. Overcoming it will require advanced and breakthrough technologies. It is clear that a Venus sample return mission will benefit from the on-going Mars program. But in the case of Venus, the higher gravity, thick atmosphere and surface temperature imply that still more several critical technical issues have to be overcome such as the electronic accommodation to in-situ high temperatures or the Earth return vehicle and trajectory. Figure 2 summarizes five architecture options. The simplest one, Architecture 1, is the atmospheric skimmer, using a flyby spacecraft. Architecture 2 uses a low-altitude probe that collects samples at low velocities. Architecture 3 and 4 use a lander to collect surface samples, with a balloon that brings the VAV (in 3) or just the sample (in 4) to the VAV launch height. Once in orbit, it executes a rendezvous with an orbiting tug. Architecture 5 has a high-altitude spacecraft burn at the flyby periapsis while collecting samples (Shibata et al. 2017[12]).

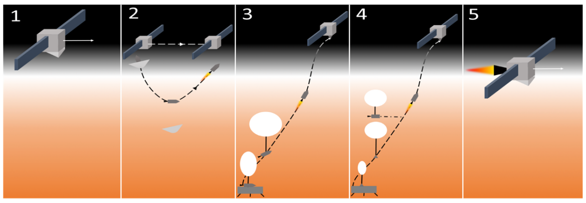

Figure 2: Five possible architectures of Venus sample return missions that have been analysed.

With regards to feasibility, technological advances allow us to be optimistic. We may cite in particular the recent progress in high temperature electronics (Neudeck et al. 2016[13]), the concept of aero-platforms (Cutts 2018[14]) to be pursued and the development project of gateways in the next future allowing the launch of vehicles at low gravity, as well as the development of propelled spacecraft (using pulsed or thermal nuclear propulsion).

3.3 Human exploration of Mars in support to science

As a prerequisite, is Mars Sample Return required prior to sending humans to Mars? The answer is clearly yes. These samples will enhance our understanding of the Martian environment: properties of Martian materials relevant for ISRU, toxicity of Martian materials with respect to human health and performance, or information related to engineering surface hazard. The sample return is obviously a 'proof of concept' for a potential round-trip human mission to the planet, and a potential model for international cooperation.

The current main objective of Mars science, the quest for extra-terrestrial life, is not compatible with humans. Since astronauts carry life with them, this theme must be addressed before their arrival, otherwise the problems of Planetary Protection will make it impossible. The chance to discover life on Mars at present, if it exists, lies within the MSR Campaign. If MSR finds life, Mars will become an outstanding research field for astrobiology, searching for the mechanisms and the successive steps of a "second genesis of life" on Mars. In that case, human presence may very well become severely limited until this question is fully explored (like in an archeology field, everything will have to be done to protect it and not alter the traces of the past). If, on the other hand, MSR conclusively finds there is no life, or very little chance of finding it, Mars' importance for planetary science will likely decrease, but its exploration by humans will not be restricted.

How much are humans an advantage for Mars exploration? Garvin (2004)[15] has tried to evaluate the relative advantages of humans vs. robots for Mars exploration, with regards to various skills: strength, endurance, precision, cognition, perception, speed, reliability, agility, dexterity, fragility, etc. In most cases humans have a clear advantage. But with the endurance of recent rovers, Spirit, Opportunity, Curiosity, their increasing sophistication, robots are regaining ground.
Sending humans to Mars is anyway driven by other forces than scientific knowledge: inspiration, innovation, National prestige and possibly National morale, diplomacy, etc. There is no opposition between robotic and human exploration. Robots lead the way, and they will always be needed when humans are in orbit, or even at their side on the surface. When will that be? Reasonable projections are not earlier than the 2040s. Possibly in 2061!

The main objectives of Mars science in the 2061 perspective will be driven by the results of MSR on the potential presence of life. This outcome will influence the human exploration of Mars by increasing (or not) Planetary Protection precautions. In any case, having field scientists operating on Mars, such as geologists, specialists of ecosystems and astrobiologists, would be an invaluable asset and all efforts should be made to secure their presence within the frame of future expeditions to Mars.

3.4 To the surface of Mercury, and back?

Beyond BepiColombo, NASA's Planetary Mission Concept Studies (PMCS) program recently awarded a study to a multidisciplinary team led by APL, to assess the feasibility of a surface mission to Mercury in the next decade. The resulting mission concept (Ernst et al, 2020)[16] achieves one full Mercury year (~88 Earth days) of surface operations, based on launch in 2035 with landing on Mercury's surface in 2045. All technical requirements are described in the report and are now being discussed in conferences (Kubota et al. 2021)[17].

Finally, sending a lander and planning sample return from Mercury - the final dream of many planetary scientists (Vander Kaaden et al. 2019)[18], which could be foreseen in the future with the development of more powerful launchers and more efficient energy suppliers - would require to face the unique configuration of a planet that rotates so slowly that its surface temperature varies by more than 600° C over the course of a solar day. Also, a given region remains in the night side or in the day side for a very long time with respect to the typical orbital period of an orbiter around Mercury (about 10 hours), which brings tedious but challenging questions of telemetry, energy and heat control.

3.5 Giant Planets, habitability and search for life

Table 1 summarizes the timeline of missions to giant planet systems already flown, in preparation, under study and notional missions addressing the six key science objectives.

Time	Gas giant systems				Ice giant systems	
	Planet	Moons	Rings	Magnetosphere	System	Moons
2021-2040	Workings: JUICE Origins: Atmospheric Probes	Workings: Titan – DragonFly Io Habitability: Europa - EC Ganymede - JUICE Origins: Callisto Irregular moons	Origins & workings: Saturn Ring skimmer Saturn Ring Observer		Diversity + Origins Initiation of orbiter + probe missions to Uranus & Neptune	Habitability: Triton Active moons of Uranus
2041-2061		Workings: Io Search for life: Europa, Enceladus, Titan… Moon orbiter + lander		Workings + Role in habitability Multi-point investigation of Jovian m'sphere	Implementation	Search for life: Design of a mission to the best candidate habitable moon

Table 1: A summary of the missions already decided and of future notional missions to giant planets and their systems to be flown during the two periods considered in this study: 2021-2040 and 2040-2061.

Key generic technology developments will be required to enhance or enable future outer planet missions. In addition, several of the mission types just described require specific technology developments.

Future missions to the Ice Giants (Uranus and Neptune) will be particularly demanding on:

- Power, and development of higher efficiency radioisotope power systems (RPSs). The long flight times and long durations of these missions require light-weight, efficient power sources to provide higher specific power for a given RPS mass. Assuming solar power is not feasible at Uranus or Neptune, the use of nuclear power solutions (Radioisotope Power Sources) seems mandatory.
- Telemetry: how to return back to Earth the significant data volumes required by magnetospheric science and spectro-imaging?
- Orbital choices/longevity of spacecraft and instruments: magnetospheric studies require very large orbits, with periapsides close to the planet and apoapsides as far as possible, for solar wind monitoring in the dayside, and magnetotail investigations in the night side, and as many orbits as possible for a longer temporal coverage.

Multi-point missions to Jupiter or Saturn for magnetosphere studies will require the operation of several platforms, and possibly the development of Cube/Nanosat(s) that can be resilient in the Jovian magnetosphere environment, to be dropped off by a main orbiter. If these missions include an « upstream monitor » capable of providing solar wind parameters upstream of the planet, a special release and orbital scenario will have to be designed to inject it, for instance, in orbit about the L1 Lagrangian point of the giant or icy giant planets. This « upstream » spacecraft could be used by the Heliospheric community in order to monitor the propagation of the solar wind in the outer Solar System (trans-disciplinary science).

The advent of small, miniaturized spacecraft, often called CubeSats, can provide the unique opportunity to directly sample ring particles by sending a small daughter spacecraft to rendezvous with a ring particle, collect a sample and return it to the primary spacecraft such as the Saturn Ring Observer mission (SRO) for detailed imaging of its surface and for compositional analysis. Other CubeSats could attach themselves to ring particles, and radio back data about collisions and the behavior of the ring particles over the several-day lifetime of the CubeSat. CubeSats would enable a new set of on-site ring observations.

Additional technology development is also needed to implement an SRO mission. Higher efficiency RPSs are needed along with more efficient electric propulsion systems to support the hover spacecraft's mass. The efficiencies of the current REP systems are not sufficient to support a capable spacecraft in hover orbit. Another SRO technology development would include remote operations to sense and manoeuver to avoid collisions with any hazardous ring particles that have been deflected above the ring plane. One-way communication from Saturn to Earth is over one hour so the spacecraft would need to detect and react to any hazards in a much shorter time.

Lander missions to the regular moons of giant planets will require EDL (Entry, Descent, Landing) systems capable of landing in full autonomy on sometimes chaotic terrain, or even EDLA (Entry, Descent, Landing, Ascent) systems in the case of sample return missions. Once on the moon surface, the landers will have to perform their assigned science operations in extreme conditions of low temperature, and also of very harsh radiation environment in the case of Europa. Astrobiology-oriented missions will have to operate specific suites of science investigations based on sophisticated strategies to search for bio-signatures at the surfaces and sub-surfaces of ocean moons: see for instance Hand et al. (2017)[19]; Blanc et al. (2020, 2021)[20] [21]and Prieto-Ballesteros et al. (2019)[22].

Finally, magnetospheric studies and interaction with the solar wind require specific instrumentation. All future missions aiming to explore Giant Planets magnetospheres require in-situ measurements of:

i. The distribution functions of all constituents of the plasma
ii. The DC/AC magnetic and electric fields
iii. The distribution functions of energetic particles

All quantities must be measured with high spatial, temporal and directional information.
Future missions need to provide instrumentation enabling higher performance with smaller size, lower power and lower cost: miniaturisation of the list of instruments given above is a key aspect of future exploration. Radiation tolerance is also non-negligible, particularly so for the exploration of the inner Jovian magnetosphere, where the Io torus, its main plasma source, stands in the region of harshest radiation environment.

3.6 Sample return of primitive matter from the outer Solar System

The last thirty years of cosmochemistry and planetary science have shown that one major Solar System reservoir is vastly under-sampled in the available suite of extra-terrestrial materials, namely small bodies that formed in the outer Solar System (>10 au). Because various dynamical evolutionary processes have modified their initial orbits (e.g., giant planet migration, resonances), these objects can be found today across the entire Solar System as P/D near-Earth and main-belt asteroids, Jupiter and Neptune Trojans, comets, Centaurs, and small (diameter <200km) trans-Neptunian objects. This reservoir is of tremendous interest, as it is recognized as the least processed since the dawn of the Solar System and thus the closest to the starting materials from which the Solar System formed. This is underlined by the extremely interesting results obtained by in-situ studies of isotopic compositions of matter from comet 67P/Churyumov-Gerasimenko by ESA's Rosetta mission (see Hoppe et al. 2018 for a review[23]), and from laboratory studies of anhydrous chondritic porous interplanetary dust particles, ultra-carbonaceous Antarctic micrometeorites, and matter from comet 81P/Wild 2 returned to Earth in 2006 by NASA's Stardust mission (Brownlee et al. 2006)[24].

The next major breakthroughs in planetary science will come from studying outer Solar System samples in the laboratory, but this can only be achieved by a large class mission that directly collects and returns to Earth materials from this reservoir. The proposed strategy consists in 1) a direct trajectory to the rendezvous target, 2) a reconnaissance of the terrain with an orbiter payload including at least an optical camera, a near-infrared spectrometer and a thermal infrared camera, 3) collection of surface/subsurface samples (at least two locations) that are volatile and dust rich and 4) return of the samples to Earth. The re-entry capsule must be able to preserve the samples at cryogenic temperature. The selected target should be as primitive as possible, which might exclude near-Earth objects from the candidate list. Comets and P/D main belt asteroids including main belt comets would then appear as the most accessible and scientifically valuable targets, with comets being the preferred targets because of their activity that can be used to characterize the volatiles and also because their surface should be more "primitive".

3.7 From the Trans-Neptunian Solar System to the interstellar medium

The main objectives of the exploration of Trans-Neptunian objects is first to explore their diversity, and to characterize representative objects in each of the groups that can be identified. In the 2041-2061 timeframe, building on a better characterization of some representative objects, and of the family as a whole, we should fly missions with large Delta V capacities, likely based on new non-chemical propulsion technologies, that could orbit one of the most interesting systems (the Pluto-Charon system is likely one of the best choices) and/or collect samples during its fly-by.

The next wave of missions beyond the heliopause and into the VLISM should be used to explore the extreme variations of characteristics of the heliopause and of the adjacent interstellar clouds with the direction of flight. The shape of the heliopause itself is currently unknown, and can be only inferred from theoretical models. To address this, the period 2041-2061 should be used to send interstellar probes in a diversity of directions to unravel the complex geometry of heliosphere-VLISM interface regions and, beyond it, the diversity of interstellar clouds surrounding the Solar System.

4. From future missions to infrastructure and technology requirements

The future generation of missions presented in section 3 will generate a broad spectrum of technology requirement, that we will identify starting from the most distant destinations.

Missions to the Trans-Neptunian Solar System and to the interstellar medium will mostly remain long-duration cruise missions. For them, far away from the sun and Earth, power, propulsion, data downlink capacities will remain the main bottleneck. Their requirements will push forward the corresponding technologies towards non-solar energy sources (necessarily nuclear), long-duration and high specific impulse propulsion systems (likely electric) and a very high degree of on-board data processing and compression before downlink. Progress made on these generic technologies will also become available for closer destinations, even considering that new generations of solar cells will likely push outwards the boundaries of solar power over the same time frame.

Among the objects populating the still poorly explored Trans-Neptunian Solar System, visiting those transiting for the first time closer in, like pristine comets and interstellar objects, will require "on alert" mission scenarios such as Comet Interceptor, to be launched by ESA in 2028 (Snodgrass and Jones 2019)[25].

Giant planets and their moons, particularly icy ones, and Venus will offer great challenges of a different kind because of their extreme environments. Their exploration will require innovative multi-platform mission architectures in which interplanetary carriers and orbiters will progressively be specialized to the function of delivering science platforms and sometimes transferring back samples to Earth. The diversity of science platforms will be tailored to the specific environments in which they will have to operate: atmospheric entry probes, landers operating in extreme temperature, pressure and sometimes radiation conditions, mobile elements moving not only at the surface of their target, but also flying in their atmospheres or jumping from one exploration site to another (following the example of NASA's Dragonfly mission to Titan, Lorenz et al. 2018)[26], networks or clusters of platforms providing multi-point measurements wherever the scientific objectives will require. Just like evolution and selection pushed living beings on Earth to adapt to an increasing diversity of niches, the science platforms of the future will have to adapt to the even larger diversity of planetary environments. Given their long communication time with Earth and the necessity of optimizing the scientific return of their missions, they will require an ever-increasing degree of on-board autonomy and the use of advanced Artificial Intelligence tools to perform their missions.

The scientific instruments carried and operated on these platforms will reflect the increasing diversity of scientific disciplines and measurement techniques required by planetary sciences. In this moving context, sample return caches, geosciences investigations (geophysics and geochemistry) and astrobiology experiments dedicated to the detection and characterization of biosignatures will occupy a larger and larger fraction of payloads.

The continuity of operations between carriers-orbiters and in situ science platforms will have to rely on advanced EDLA (Entry, Descent, Landing and Ascent) systems well adapted to the environments where they will deliver science platforms and from where they will have to carry back samples to orbit.

For the Moon and later Mars, where human outposts could progressively be established, opening expanded possibilities for their scientific investigation, a full new panoply of technologies enabling a sustainable human presence will have to emerge and be proven before being used for routine operations: in situ resource utilization (ISRU), advanced environment control and life support systems (ECLS), in-space and on-site assembly and manufacturing processes.

Finally, for all destinations, optimization of mass, power and telecom budgets will push towards an increased miniaturization of existing technologies, enabling additional in situ measurements with compact mission architectures.

As a synthesis, table 2 lists horizontally the specific technology requirements associated with the different types of mission listed vertically. M. Grande et al [27] elaborate a projection of future technology developments in response to these requirements. Foing et al [28] build up the corresponding projection for future necessary infrastructures, some of which are also listed in Table 2.

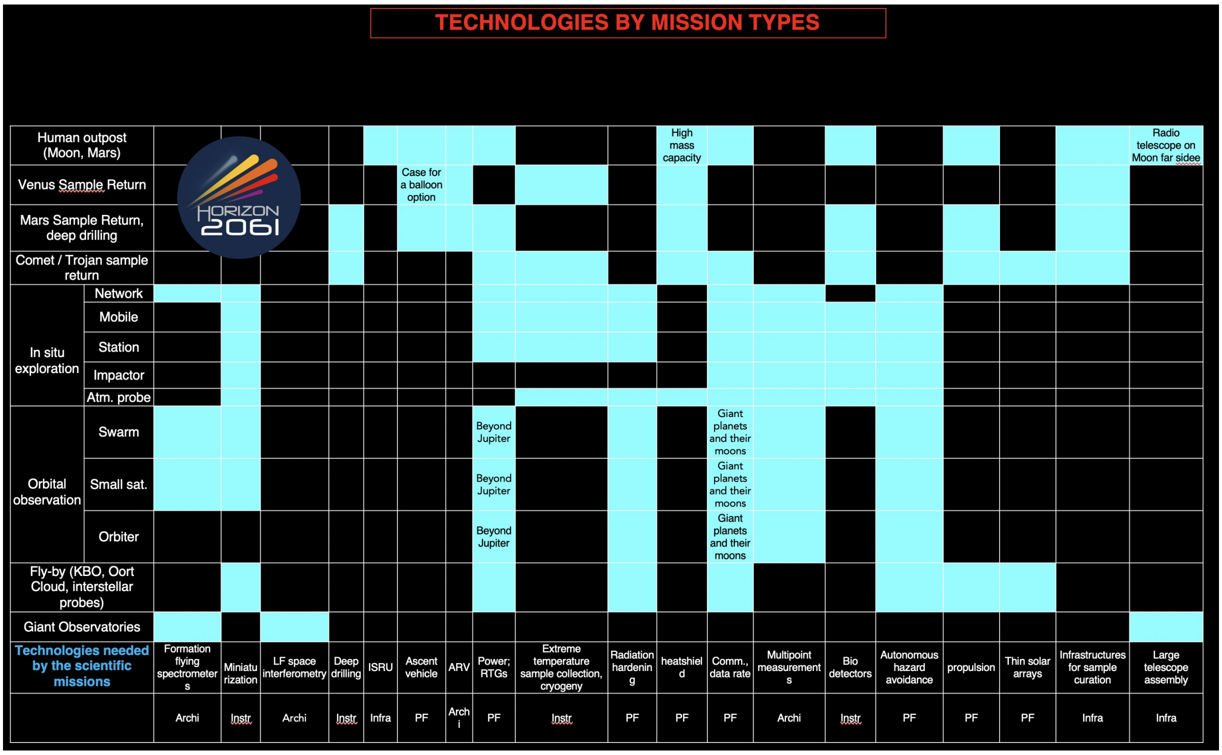

Table 2: Summary of the critical technologies that will be required to fly future missions in the 2061 timeframe

5. Conclusion

The notional missions that should fly to the various provinces of the Solar System in the 2041-2061 period to address the six science questions of the Horizon 2061 exercise have been elaborated. For the closest accessible destinations (the Moon and Mars) planetary exploration should reach the highest level of complexity by 2061, with the establishment of human outposts at both places whose sustainability will rely on a broad spectrum of In Situ Resource Utilisation (ISRU) technologies.

One step further in the Solar System, one finds a clear dominance of sample return missions that will reach increasingly challenging destinations, or will concern an increasing diversity of sampling sites: this will be the major goal of Mars exploration for the coming decades. Samples should also be returned from comets and Jupiter trojans, as well as from Venus despite the exceptional technical difficulties of achieving it. Among all giant planet moons, one can foresee that samples can be returned, in priority from Enceladus on the basis of our current knowledge, a body of major astrobiological interest, at least via fly-by through its plumes. But the next wave of missions to the ocean worlds of Jupiter (JUICE and Europa Clipper) may similarly open the way to sample return from the Galilean moons, particularly Europa.

Farther away, in situ exploration and multi-platform orbital surveys should progressively prevail over orbital exploration at gas giants and their systems: atmospheric probes, moon landers, multi-point studies of their magnetospheres, ring hoppers and skimmers will serve more focused studies or their origins, workings or habitability. The next steps in the exploration of ice giants should be accomplished by pluri-disciplinary orbiter missions at each of the two systems. Combined with the delivery of atmospheric probes to their atmospheres, these missions will provide insight into the formation scenarios and workings of the most abundant class of planets in our galactic neighbourhood and pave the way to more focused missions to characterize the habitability of the most promising of their moons, starting very likely with a Triton orbiter.

Exploration of the Trans-Neptunian Solar System will likely remain dominated by probes combining fly-bys of individual TNOs with long-range travel across the heliospheric boundaries and into the very local interstellar medium. By sending probes in different directions, it will be possible to explore at the same time the diversity of TNO's, the three-dimensional geometry of the heliosphere and of its boundaries, and the heterogeneity of the VLISM around it. Our idea of the diversity of secondary systems in the Solar System would remain incomplete, however, without an orbiter mission to one of the multi-object TNO systems, such as Pluto-Charon.

The requirements on the technologies needed for this future set of innovative missions have been presented here in a synthetic way: technologies, together with the corresponding projection for future necessary infrastructures, are elaborated much further in [1]. This integrated book, "Planetary Exploration, Horizon 2061" is currently getting to the end of its peer review, and will be published at the end of this year. It gives an elaborated vision of the four pillars of planetary exploration (science, space missions, technologies, infrastructures) in the Horizon. 2061 perspective

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http://horizon2061.cnrs.fr/wp-content/uploads/2020/02/H2061participantsList19-02-2020.xlsx

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