Mem. S.A.It. Vol. 92, 128
© SAIt 2021 **Memorie** della

The exploration of the Solar System: recent achievements and future developments

F. Capaccioni[1] and F. Esposito[2]

[1] Istituto Nazionale di Astrofisica – Istituto di Astrofisica e Planetologia Spaziali, Area della Ricerca CNR, Via del Fosso del Cavaliere 100, 00133 Roma, Italy e-mail: fabrizio.capaccioni@inaf.it

[2] Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Capodimonte, Salita Moiariello, 16, 80131 Napoli, Italy e-mail: francesca.esposito@inaf.it

Abstract. Astrobiology poses a number of essential questions, such as how does life begin and evolve? Or, does life exists elsewhere in the Universe? Or, what is life's future on Earth and beyond? To answer these questions the investigation of the most diverse bodies of our Solar System is an essential step. From the giant planets to the small cometary nuclei the Solar System offers a wide reservoir of different environments which can be considered natural laboratories to be exploited to determine what makes a planet habitable, to determine how to recognize the signature of life on other worlds and finally to determine whether there is (or once was) life elsewhere in our Solar System.

Key words. Solar System: Planetary Exploration – Solar System: Search for Life

1. Introduction

The Solar System Exploration in the next decade will not be a purely scientific endeavour but will be influenced by the needs of Resources exploitation and of human exploration.

The long-term goal is to widely expand the human presence in the space in a sustainable way. In this perspective, the 2020s will be a decade of rapid change in many technological areas, and the space exploration sector will have to adapt to new paradigms, such as commercial crew, payload transportation and search and exploitation of local resources. Although the objectives of human exploration precursor measurements focus mainly on issues regarding health and safety and engineering aspects, rather than science, there are a number of examples where common specific interests between Human Exploration and Scientific Exploration can be identified as, for instance, survival of organisms in harsh environments or the search for water. Water is an essential resource for Humans in space, but is also at the basis of the biological activity and the discovery of extant and/or extinct life in the habitable worlds in the Solar System is one of the leading scientific themes, complemented by the search for habitable worlds around other stars. Thus, the programs devoted to the Human exploration of the Solar System (e.g. Artemis) share several aspects common to Scientific programs for planetary sciences devoted to determine the content, origin, and evolution of the Solar System and the potential for life elsewhere. One of the major con-

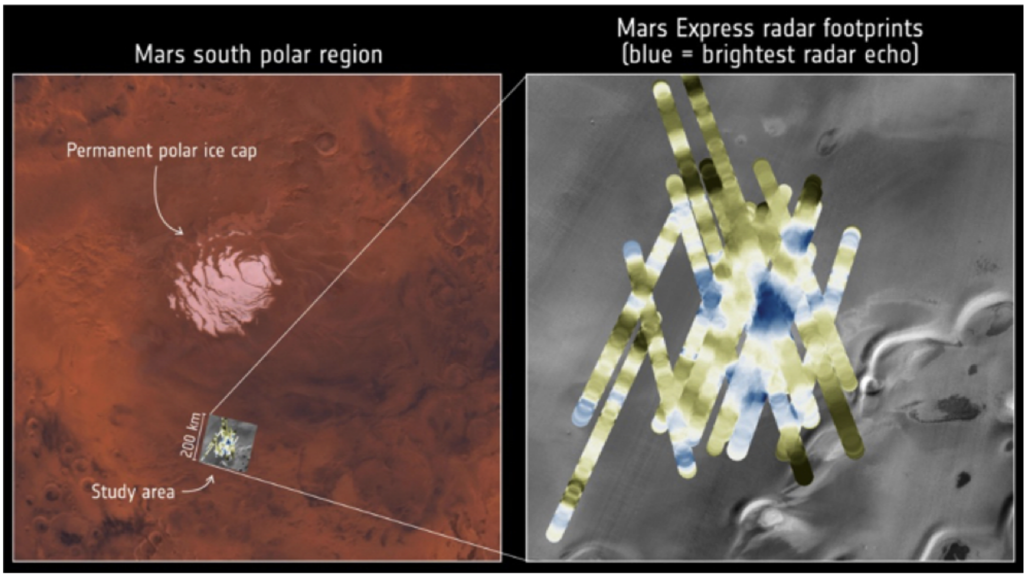

Fig. 1. Detection of a subterranean lake in the interior of Mars by the MARSIS radar sounder oboard Mars Express (ESA). In the study area, reported on the right picture, the strongest radar echoes, indicative of the presence of water, are shown in bluish. The radargram point out a region of 20sqkm at 1.5km depth where water is in the liquid state.

tributions that the Solar System Exploration missions will provide in the framework of an Astrobiology Roadmap is the discovery and characterisation of the environments potentially capable of hosting biological activity in the Solar System. In particular, the objective will be to determine what makes a planet habitable and how common such worlds are. And, even more importantly, determine how to recognize the signature of life on other worlds. This will generate an inventory of those processes and conditions (Presence of water, carbon chemistry, availability of energy sources, etc.) that all together form the Organic Environments of the Solar System. To expand our view of the search for life also on other planetary systems, which is another cornerstone topic of an Astrobiology Roadmap, the characterisation of the organic environments will led to the understanding of the processes which have acted and contributed to their formation and evolution. Thus, the study of the Origin of the Solar System becomes a central theme, and represents one of the trait d'union among astrobiologists, planetary scientists and the exoplanetary community.

The other fundamental contribution from the community of planetary scientists to an Astrobiology Roadmap is represented by the collection and transport to Earth of samples from extra-terrestrial locations. The capability to land and move on the surface of other bodies of the Solar System, coupled with the capability of performing detailed investigations thanks to the presence of sophisticated surface laboratories and in-situ instrumentation is an essential aspect complementing the discoveries made by the remote sensing orbiters. But still some of the most important measurements related to Astrobiology have to be conducted on laboratories on Earth. From this point of view the capability to return to Earth samples from potential organic environments is of huge interest albeit still of great difficulty due to the need not only of collecting samples but also of preserving them without alterations. Thus, the major collaboration with the Astrobiology community is in the definition of which samples, where to collect them and how to preserve them in pristine conditions.

The space missions carried out so far have pointed out the presence of habitable niches in the Solar System in satellites like Enceladus, Europa, Titan, the so-called Ocean Worlds, or in small bodies like Ceres or cometary nuclei (67P/Churyumov-Gerasimenko) with their large amount of organic matter. Moreover, they have allowed a better understanding of the processes acting in the early phases of formation and development of the Solar System leading to environmental conditions, in planets, satellites and small bodies of the Solar System, potentially favourable to the development of life. Space missions like Cassini, Dawn, Juno, Rosetta, Mars Express and the many Martian rovers and surface laboratories have provided essential information, which have reshaped our comprehension of some of the bodies of the Solar System.

2. An inventory of Organic Environments in the Solar System

The last decade has been one of the most important and scientifically productive periods ever in the history of planetary science. From the inner Solar System to the giant planets the inventory of the Organic Environments has grown continuously. And Italy has contributed notably to these achievements being involved with various level of responsibility in the P/L of many of the scientific missions built in the last 20 years.

The Martian exploration has seen, with Mars Express, the Italian community leading the field with two important discoveries: Methane in the atmosphere detected by the PFS interferometer (Formisano et al. (2004)), and the discovery of a subterranean body of liquid water (Orosei et al. (2018)) by means of the MARSIS radar sounder (Fig.1). Since the Methane discovery, there has been a long debate lasting until now, on the biogenic or abiogenic potential sources for the observed Methane abundance. The importance and need to shed light on the presence of methane on Mars, led ESA to design a dedicated mission, the ExoMars TGO, to investigate and monitor the presence of trace gases, with special emphasis on the methane, in the Martian atmosphere. The recent MARSIS discovery did show a body of salty water at depth of about 1.5km. At this depth, temperature is well below the zero degrees, thus salts are required to maintain water in its liquid state. Water, salts, rocks and protection from cosmic radiation are necessary ingredients to create a biological niche.

Small bodies have received a great deal of attention in recent times mainly in view of the significative results and discoveries of two major missions, namely the ESA's cornerstone Rosetta and the NASA discovery mission Dawn. Since the first observations of the nucleus of 67P/Churyumov-Gerasimenko VIRTIS pointed out the ubiquitous presence of Organic materials (Capaccioni et al. (2015)). More recently, the same instrument has been able to identify the major source as aliphatic compounds mixed to ammoniated salts (Raponi et al. (2020)). VIRTIS identified the presence of organic molecules containing Hydrogen and Carbon chains present in the interstellar medium but so far never observed in solid phase on a cometary nucleus (Fig.2). Thus, at least a fraction of the organic compounds in the solar system must be molecules pre-existing the solar system.

Coming to Ceres, the largest of the asteroids in the main belt, was observed in great details by the NASA Dawn probe, which was able to determine that Ceres had a complex history of differentiation and resurfacing making it more similar to a planet than to an asteroid. Spectra of bright deposits in Occator, a crater a 90km geologically young crater ($\leq$100 Ma) (Fig.3) , are consistent with a large amount of sodium carbonate (45-80%), mixed with a dark component and small amounts of phyllosilicates, as well as ammonium carbonate or ammonium chloride (De Sanctis et al. (2016)). The compounds are endogenous and they are the solid residue of crystallization of brines and entrained altered solids that reached the surface from below. Ceres has experienced aqueous processes (hydrothermal) in the recent geological past (Scully et al. (2020)). The combined presence on Ceres of ammonia-bearing

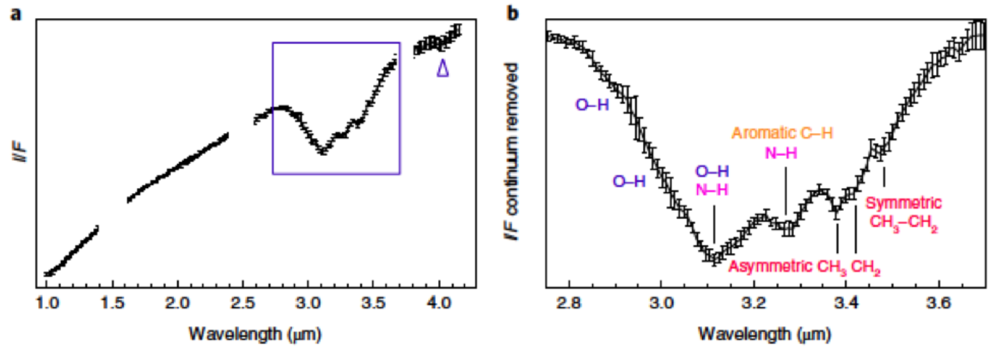

Fig. 2. Infrared spectrum of the surface materials of 67P/CG taken by the VIRTIS instrument onboard Rosetta (ESA). In (a) the Calibrated average I/F spectrum of 67P after removal of thermal emission (see Methods). The blue triangle indicates a tentative absorption. Missing parts of the spectrum correspond to the junctions of the instrument's order sorting filters. In (b) Continuum-removed average spectrum of 67P across the broad absorption at 2.8–3.6μm, corresponding to the blue box in (a). Attributions of the main spectral features are indicated (Raponi et al. (2020)).

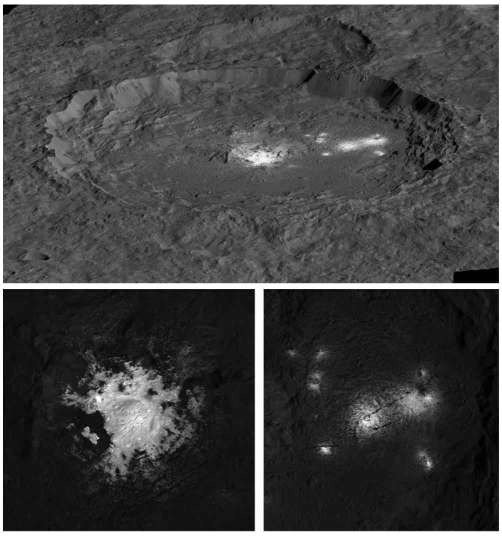

Fig. 3. Top: Perspective view of Occator crater from the south and the bright deposits from Dawn Framing Camera data. The Cerealia Facula is saturated in this brightness stretch. Bottom left: Zoom-in view of the Cerealia Facula at the center of Occator crater shows the details of the bright deposit. Bottom right: Zoom-in view of the Vinalia Faculae (Nathues et al. (2020)).

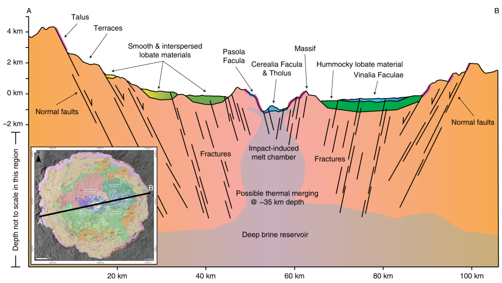

Fig. 4. The varied sources of faculae-forming brines in Ceres' Occator crater emplaced via hydrothermal brine effusion (Scully et al. (2020)).

hydrated minerals, water ice, carbonates, salts, and organic material indicates a very complex chemical environment, suggesting favourable environments for prebiotic chemistry (Fig.4). Ceres, as revealed by Dawn, is now arguably the solar system's best-characterized icy world, and its composition, ongoing geologic activity, and accessibility render it a viable and attractive target for astrobiological exploration.

Ocean worlds, bodies with current liquid subsurface oceans, have been discovered among the icy satellites of Jupiter and Saturn. Enceladus and Europa give evidence for communication between the interior liquid and the surface and with a strong potential for interactions between the ocean and its rocky seafloor. In particular for Enceladus the gravity measurements suggested an ocean 15km thick overlying a rocky core and covered by about

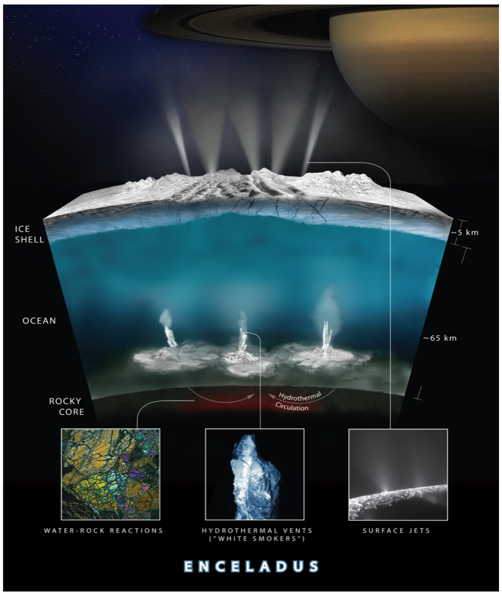

Fig. 5. Cartoon showing a model of Enceladus' interior ocean and the interaction of water with the rocks at the bottom of the ocean (Credits: NASA/JPL-Caltech/Southwest Research Institute)

30km of ice. Models suggests that conditions in the ocean might support the production of aminoacids (see Fig.5).

Other bodies like Titan, Ganymede, and Callisto have relatively thick ice shells, making exchange processes with the surface more difficult, and with no obvious surface evidence of the oceans, but their surface, in particular Titan's, is rich in a wide range of organic species and surface liquids, which are readily accessible and could harbour more exotic forms of life. Further, Titan may have transient surface liquid water such as impact melt pools and fresh cryovolcanic flows in contact with both solid and liquid surface organics. These environments present unique and important locations for investigating prebiotic chemistry and, potentially, the first steps toward life.

3. Solar System exploration: A glimpse of the future

The international programs in Solar system Exploration for the next decade will build on the important results already achieved in previous years and the connection with astrobiology themes is already now of paramount importance.

There is a common understanding that Mars represent a key target for Astrobiology for many reasons. The conditions in its early history may have allowed the formation of prebiotic compounds and have led to the origin of life on the planet. Contrarily to the Earth, where we have completely lost records of the period in which life arose due to the surface rejuvenation caused by plate tectonics, on Mars we expect an excellent preservation of geologic record of early Mars. From this point of view, Mars is a well suited laboratory to understand if life ever arose on another planet and to study the potential relationship between biological and geological evolution, taking into account that Mars experienced important changes in climate and surface evolution that have produced a wide range of environments. We have seen in the previous chapter that there are a number of indications that Mars once was, and perhaps still is, a habitable planet:

- Evidence of great abundance of **liquid water** flowing over the surface on early Mars
- Liquid water in the present Mars: subglacial lakes, recurring slopes, lineae, groundwater
- Presence of six **basic elements** to construct macromolecules (C, H, N, O, P, S)
- Availability of **major and trace elements required by life** evidenced by the presence on Mars of widespread ultramafic and mafic rocks and their alteration products
- **Energy**: a diversity of potential energy sources for life was and are available on Mars

On the other hand many limiting factors to the presence of life exists on present day Mars:

- **UV Radiation** – lack of significant amount of ozone or other gases in the atmosphere to absorb UV above 200 nm. Although this is not relevant already at depth larger 1 mm in the subsurface due to the limited penetration capability of UV radiation.

- **pH range** on the surface has been measured to be 7.7-7.9 (slightly alkaline) and this is a benign environment for organisms; on the other hand, the presence of sulfates indicates possible periods of acidic conditions which could have caused a restriction of the range of organisms capable of active growth
- **Salts**: Solutions containing high concentrations of ions (brines) can constrain the boundaries of active life (reduce water activity and influence other parameters); at the same time the observations show that freshwater could have existed, or can still exist, on Mars and that not all solutions on Mars are necessarily briny.
- **The Oxidants** play an important role in scavenging the organic materials but their effects is not relevant at depth larger than 1m.
- **Ionising radiation** easily reach the surface due to the absence of a global magnetic field but its effect is limited to depths not larger than 1.5meters.

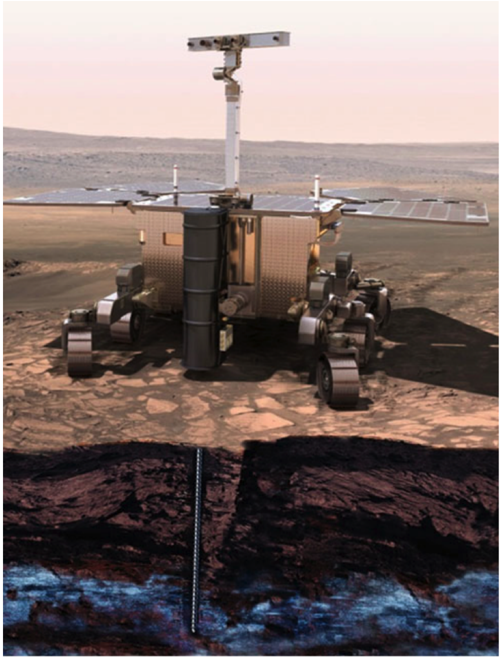

Fig. 6. ExoMars 2024 Lander and Rover

ExoMars is the most important ESA's program (in collaboration with Russia) for the study of Mars. The first orbiter reached the planet in 2016, the next ExoMars launch will bring a lander (the Surface Platform) and the Rosalind Franklin rover on the surface schematically shown in Fig.6. The major goals of the program are:

- Search for signs of past and present life on Mars **(Rover)**;
- Characterize the water/geochemical environment as a function of depth in the shallow subsurface **(Rover)**;
- Investigate Martian atmospheric trace gases and their sources (including methane) that could be evidence for possible biological or geological activity **(TGO)**;
- Context imaging, long-term climate monitoring and atmospheric investigations, subsurface water distribution, atmosphere/surface volatile exchange, radiation environment, geophysics of Mars internal structure **(Surface Platform)**;

The contribution from the Italian community is relevant with instruments on both missions. TGO includes two Co-PIships on NOMAD and CASSIS, while the 2022 ExoMars will include a PIship (MaMiss) on the rover and a Co-PIship / scientific coordination (Dust Complex/ MicroMED) on the surface platform, plus scientific participation on MOMA, WISDOM and CLUPI.

Investigations of habitable conditions on Ocean Worlds, that are the moons of external planets, will be another leading scientific theme. Ocean Worlds are of special astrobiological interest: they are bodies that are large enough ($\approx$ 200km) to retain the original volatiles.

Even if they do not host life, they have the potential to reveal important information about the processing of carbon in the Solar System and the production of molecules of prebiotic significance. From this point of view they carry Information about the limits and distribution of habitable conditions in the Universe.

Titan has a substantial atmosphere and a surface that hosts dunes, craters, and also rivers, lakes and seas that are mainly composed of ethane and methane. On Titan, methane occupies the role played by water on Earth as well as water ice behaves the same as silicate rocks on Earth. Cassini's measurements of a small but significant asynchronicity in Titan's rotation indicate that an ocean of liquid might lie below a thick crust of water ice and beneath a layer of high-pressure ice. Future investigations are needed to understand if this particular environment could host a type of life which uses liquid methane instead of water or if the organic surface material could feed a biosphere in a deep subsurface ocean. Even if Titan is too cold for life, its rich hydrocarbon chemistry might well provide important clues to the formation of prebiotic molecules. NASA New frontiers Dragonfly mission will be launched in 2026 and arrive in 2034. It is a rotorcraft that will fly to dozens of promising locations on Titan looking for prebiotic chemical processes common on both Titan and Earth.

The ocean Worlds in the Jupiter system have become an intense focus for astrobiology, largely on account of the presence of an ocean under their ice crust, as suggested by very sensitive gravity and magnetic measurements of Europa, Ganymede and Callisto, consistent with the surface geological data. Both NASA and ESA have missions in their plan to reach Jupiter and conduct detailed survey of Jupiter's moons. NASA is planning to reach Europa to determine whether the icy moon could harbor conditions suitable for life with the Europa Clipper mission, and is studying a mission to explore Io, IVO (Io Volcanic Observer), a Discovery Mission still in competition, to learn how tidal forces shape planetary bodies, and the Europa lander, a concept for a potential future mission that would look for signs of life in the icy surface material of Europa.

ESA's major goal for the outer Solar System exploration will be the launch of the JUICE mission in 2024, which will conduct Investigation of Jovian system through detailed observations of Jupiter, Europa, Callisto and Ganymende. Particular emphasis will be on Ganymede as a planetary body and potential habitat. The Italian contribution is very relevant with Pi-ship or Co-PIship in 4 instruments (out of a total of 10): the JANUS camera, the MAJIS Spectrometer, radar RIME and the radio science instrument 3GM.

As for the Minor Bodies, two sample return missions have collected material on the surface of asteroids and have either already returned their load on Earth, as the Japan Hayabusa 2 which landed on 6th December 2020 with samples from the primitive asteroid Ryugu, or are in the process of returning it, as the samples from the asteroid Bennu sampled by the NASA Osiris-REX mission. Any aqueous environment hosted by an extraterrestrial body may provide insights into how liquid water can persist in its interior or on its surface in the absence of direct solar heating. This information yields boundary conditions on the production of liquid water in the Universe, improving our understanding of the potential location and origins of habitable worlds. After the success of Rosetta, ESA has identified a new class of missions (Fast) whose first selected candidate is "Comet Interceptor". This is a 3 spacecraft mission designed to visit a truly pristine nucleus comet that is entering for the first time the inner Solar System.

And finally, the Moon has regained much attention in particular to understand the origin of water on the Moon, as the answer to this topic is a key to understand the water distribution in the Solar System. The Comet and asteroids bombardment, but also the interaction of the regolith with the solar wind, could lead to the formation of OH/H2O bearing materials in the outermost layer via chemical reactions between oxygen in the regolith's minerals and implanted protons from the solar wind. ESA payload PROSPECT for the Russian Luna 27 mission will drill beneath the surface in the South Pole region of the Moon and extract samples, expected to contain water ice and other chemicals that can become trapped at the extremely low temperatures expected. Captured samples will then be passed to a chemical laboratory (ProSPA) where they will be heated to extract the cold-trapped volatiles. In figure 7 a most complete

Mission name	Launch date	Description
Chang'e 5	November 2020	Lunar sample return mission
DART	22 July 2021	Asteroid 65803 Didymos impactor
Luna 25	1 October 2021	First mission of the Luna-Glob Moon exploration programme, lunar south pole lander
Lucy	16 October 2021	Flyby of six Jupiter trojan asteroids
James Webb Space Telescope	31 October 2021	Orbital space telescope
Artemis 1	November 2021	Uncrewed lunar orbital test of Orion spacecraft and Space Launch System
Aditya-L1	January 2022	Solar observation spacecraft
JUICE	June 2022	Ganymede, Callisto, and Europa flyby; Ganymede orbiter
Korea Pathfinder Lunar Orbiter	July 2022	Lunar orbiter
Psyche	August 2022	Metallic asteroid 16 Psyche orbiter
ExoMars	2022	Mars lander and rover
DESTINY+	2022	Asteroid 3200 Phaethon flyby
Tera-hertz Explorer	2022	Mars lander
VIPER	November 2023	Lunar rover
Europa Clipper	2024	Europa orbiter
Luna 26	13 November 2024	Lunar orbiter
MMX	September 2024	Martian moon sample return mission
Hera	2024	Asteroid 65803 Didymos rendezvous
Luna 27	August 2025	Lunar south pole lander and rover
Dragonfly	April 2026	Titan rotorcraft lander
Comet Interceptor	2028	Flyby of an Oort Cloud comet

Fig. 7. Planetary Missions planned by the international Space Agencies in the time frame 2021-2028

view of the planned space missions of potentially astrobiological interest is shown.

4. Conclusions

Human Exploration and Scientific Exploration are the major highways shaping the space programs of the leading international space agencies for the next decade and more. The efforts are concentrated in NASA and ESA but many more actors, such as China, Russia, India, etc., have started their endeavours for the explorations of Moon and Mars and for the Solar System at large.

Astrobiology owes much of its foundations to space missions. Synergy among astrobiologists, engineers, physicists, geologists and other experts in fields involved in planning and executing space missions are fundamental to reach the final goals as outlined at the beginning of the paper.

References

Formisano, V., et al. 2004, Science, 306, 1758

Orosei, R., et al. 2018, Science, 361, 490

Capaccioni, F., et al. 2015, Science, 347, 6220

Raponi, A., et al. 2020, Nature Astronomy, 4, 500.

De Sanctis, M.C. et al. 2016, Nature, 536, 7614.

Nathues, A., et al. 2020, Nature Astronomy, 4, 794

Scully, J.E.C. et al. 2020, Nature Communication, 11, 3680.