Chapter

Evolution of the Scientific Instrumentation for *In Situ* Mars Exploration

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Abstract

Mars has always been a magnet for the human curiosity. The more we know about the red planet and its past, the more complex are the unanswered questions. In order to answer them, an ambitious long-term plan for the robotic and manned exploration of Mars has been established by the scientific community worldwide. To ensure success in answering the issues to be investigated on each step of the plan, the selection of "on board" payloads at mission level is specifically designed for achieving the best possible results. This selection also has modified the mission operation modes from a set of individual experiments to a cooperative science paradigm where all the instruments in the mission payload contribute jointly to achieve unprecedented scientific results. Collaboration not only between experiments but also between agencies for achieving major goals has been demonstrated as the optimum way forward for Mars exploration. This chapter presents a historical review, with a look into the future, of the human efforts aimed at understanding the red planet, focusing on the technological advances and scientific discoveries achieved that help answer some of the most thrilling and transcendental questions ever raised by humanity: Are we alone in the Universe?

Keywords: Mars, rover, lander, *in situ* instrumentation, collaborative science

1. Introduction

The study of ancient Mars, as well as its evolution to the planet we can observe today, has become one of the major scientific and technical challenges in the field of planetary exploration. Knowing that Mars was once covered with liquid water, that it had quite an intense geological and volcanic activity, together with the presence of a much denser and rich atmosphere suggest the existence of conditions compatible with the appearance of life, also quite similar to primitive Earth. Considering the vast knowledge we already have about Mars (though probably still a tiny fraction of what is there to learn!), and its accessibility and proximity as our neighbor in the solar system, the study of the red planet is still today the best candidate to look for existing or extant life, or at least to find traces that life might have emerged or existed in those long gone ancient favorable conditions.

It is true that recent studies and discoveries related to the icy moons of the gas giants of the Solar System might present most favorable conditions for past, but also present, existence of life. The evidence of the presence of water liquid oceans below the icy crust of Europa, or the powerful magnetic field that protects the surface of Ganymede, or Io's intense volcanic activity encourages the idea of considering these Jovian moons as potential life reservoirs. This is also true for the moons of Saturn Titan, with a dense methane atmosphere and a great deal of complex organic molecules; and Enceladus, whose surface is also covered by a thick ice layer. Nevertheless, the technical complexities to reach these planetary bodies, together with very long mission duration make these objectives unreachable today. We will have to wait for the technology and political will to evolve during the following years to ensure the viability of *in situ* missions to these moons in the decades to come.

With these considerations, it is quite clear how the exploration of the Martian surface and shallow subsurface has emerged as the best chance at answering some of the most fundamental questions of humankind: Are we an exceptional fortuity in the Universe, in the galaxy, in the Solar System? Does the appearance of life in our planet answers to a natural process in the evolution of the Universe? In this case, if life or traces of life were to be found in Mars, where there were no plate tectonics and which we know had similar characteristics to primitive Earth, we would be able to study the primal forms of life, forever lost in the ever-recycling Earth mantle.

In this context, this chapter will guide the reader through the evolution of the different payloads used for the exploration of Mars since the kickoff of the space career in the 1960s, providing insights to the technological advances and scientific discoveries achieved, bringing the reader into a time travel into the future of the *in situ* exploration of Mars.

2. The pioneering missions

The timeline of the missions to Mars reflects the evolution of the technical capabilities throughout the history of planetary exploration. This technical evolution, together with the understanding of the planet by previous missions, has helped shaping the increasing complexity of the scientific questions investigated: observation from Earth, fly-bys, orbiters, landers, rovers, etc., which will be followed by helicopters (Mars 2020) and subsurface exploration (ExoMars 2022), missions aimed for the return of Martian samples and finally human exploration and, who knows? maybe the establishment of permanent bases on Mars. Every reached milestone, as will happen with those still to come, allowed to contrast and validate scientific hypothesis formulated about Mars formation and evolution; and also open the door to those questions to be answered by missions to come, especially concerning current habitability hazards.

The pioneering missions acquired great momentum with the Moon space race of the 1960s between the US and the USSR, becoming a renewed Mars competition. As a result, every launch window to reach the red planet became exploited as an attempt to flyby first and then to reach its orbit. Every piece of information or picture about its surface or atmosphere and ambient conditions was considered fundamental for planting the flag first. The race between the Mariner and Mapc projects had started.

2.1 First contact with Mars: Mariner 4 to 7

Though the USSR launched Mapc 1 in 1963, the first probe ever sent to flyby another planet, it lost the communication when it was at more than 100 million kilometers away from the Earth. This failure cleared the path for the first ever mission ever to fly above Mars to photograph it, the Mariner 4 (1965). This probe, equipped with a TV camera threw down all the theories regarding the presence of liquid water on the Martian surface (the astronomers' observations of canals on the late nineteenth and early twentieth centuries were still quite present in the collective memory), confirming the terrestrial observations: a desertic and rocky surface with craters, no oceans, and a very thin atmosphere [1, 2]. However, the images also showed more geologically interesting features than expected. Also surprisingly, the magnetometer onboard the ship did not detect any magnetic field [3]. This, together with the lack of a radiation belt around Mars as confirmed by the trapped radiation detector (TRP) instrument [4], showed that the Marian surface was exposed to the solar radiation without any protection.

These results were surprising at the time, and were of course relevant from an astrobiological perspective, as the preservation of organics and/or life tracers on the Martian surface is surely impaired by the intense and unfiltered radiation. These data were complemented by Mariner 6 and 7, identical probes launched during the 1969 launch window. The aim of these ships was the study of the Martian surface and atmosphere (without any measurements during the cruise phase). To fulfill these objectives, a new instrumentation package was developed, also paving the way for future missions. The Mariner 6 and 7 payloads were included in addition to the TV camera, spectrometers in the IR and UV ranges, and an IR radiometer.

The results of these missions showed a topographically complex surface, where not only the craters reported by Mariner 4 were present but also distinctive topographic forms were observed: chaotic and featureless terrains [5]. These kinds of structures need active modification processes to occur, contrary to a Moon-like crater-only landscape which would imply inactivity since the very old ages. In addition, it was observed how in extreme latitudes ice layers formed in the rim of craters, evidencing water activity on the planet.

With Mariner, infrared spectroscopy showed powerful capabilities as it was used to analyze a wide range of parameters on Mars: polar caps, surface and atmospheric composition, or surface temperature and topography. The results showed that the Martian atmosphere was composed by CO_2 with traces of water vapor [6]. On the surface, IR spectrometry detected goethite, an oxidized chemical compound associated with weathering processes in the presence of water. This confirmed for the first time the possibility of a wet ancient Mars. Also, the surface temperature was measured by the IR radiometer, showing values around 140 K [7].

2.2 Visiting the planet: first orbits and soft landing

Traveling a stable orbit around Mars was a milestone reached virtually at the same time by Mapc 2 and 3, and Mariner 9, all of them launched in 1971. Even if Mapc 2 and 3 departed some days before Mariner 9, a faster cruise phase of the latter allowed it to be the first space probe to orbit another planet by a margin of two weeks. However, the main scientific objectives of Mariner 9 were to continue with the studies of the Martian atmosphere started by Mariner 6 and 7, while mapping the Martian surface. Profiting from the relatively low distance orbit (1600 km, the closest at the time), together with a Visual Imaging System consisting of up to nine cameras with notably better resolution than previous missions (98 vs. 790 m per pixel), Mariner 9 was intended to map 70% of the Martian surface during its mission.

At their arrival to Mars, the probes were greeted by a great sandstorm which lasted for several months. This was of course unforeseeable and had a severe impact in the missions. The soviet orbiters were the most affected, as they were mostly able to photograph the sand clouds above the surface, but the worse was still to come since these missions also included two landers that were liberated for landing as programmed, suffering the consequences of the storm: Mapc 2 crushed against the Martian surface, while Mapc 3 could certify the first soft landing on the surface of Mars. However, this was a bitter success, as it could only operate during 20 s before (probably) the storm made it lose communications. Mapc 3 was an extremely ambitious mission (probably too much at the time), as it included a small rover, Prop-M, connected with an umbilical cord to the lander platform. The early failure of the mission made impossible to know if the Passability Estimating Vehicle for Mars was successfully deployed on Mars. It took 25 years for a rover to be successfully deployed on the Martian surface.

Instead of that, the US Mariner 9 mission was just an orbiter, but had however one critical advantage compared to their competitors: an onboard patchable software during the mission. This became a mission-saver for Mariner 9, and a space-race win for the US, as the mission ground control modified the plan to save resources during the storm duration and observe the Martian moons in the meanwhile. Once it settled down, Mariner 9 started mapping the Martian surface, sending back to Earth more than 7000 images covering practically 100% of the planet surface. These images showed river basins, huge ancient volcanos, very long canyons, etc., together with evidences of erosion phenomena caused by water and wind [8]. This mapping, together with the confirmation and more precise study of the Martian atmosphere density and pressure, or the surface temperatures with the infrared radiometer (IRR) instrument, allowed the compilation of all the necessary information to prepare, with the maximum possible confidence, the future landing of the Viking missions.

3. Start of the surface missions: Viking program

As the United States started showing a position of dominance in the space race, the urge for committing to launches at every opportunity relaxed (also due to a reduced economic impulse). This way, the 1973 launch window was not used, and the first Viking launch occurred during the summer of 1975. This program was born with three objectives: acquire high-resolution images from the Martian surfaces; continue with the surface and atmosphere chemical analysis; and to look for evidences of life on the Martian surface. Viking was also conceived as a twin mission (similar to Mapc 2 and 3), each of them with an orbiter plus a lander.

3.1 The Viking orbiters

The main objective of the Viking orbiters was to help on the selection of the landing sites for the landers, as well as serve as communication relays. This was central to the mission, considering the lessons learned from the Soviet Mapc 2 and 3 failures, which could not select the landing site, and needed direct contact with Earth for operation. During more than 1 month, the information gathered by the landers was used to localize and certify the best possible locations to perform the soft landing.

However, the orbiters were also equipped with their own payload, which was reduced compared to their Mariner predecessors, as the lander was onboard. This payload included the IR Mars atmospheric water detector (MAWD), to study the presence of atmospheric water vapor and its latitude and seasonal potential variations [9, 10]. The infrared thermal mapper (IRTM) instrument measured the surface temperature, confirming the night/day cycle temperature variations, as well as characterizing its variability associated with latitude, seasons and atmosphere [11]. Finally, the visual imaging subsystem (VIS) included two high-resolution television cameras with a 17 m/pixel resolution. The geologic analysis of these samples supported the theory that vast ancient liquid water surfaces were present on the surface of Mars. Not only hydro fluvial systems but also geological features compatible with lakes or other water reservoirs were related to weathering process throughout the planet [12].

3.2 The Viking landers

The landers started their mission the moment they were released from the orbiters. During their descent, information regarding the composition, structure, and temperature of the planet ionosphere was obtained. Furthermore, the UAMS mass spectrometer analyzed the higher layers of the atmosphere, while the lander monitored the atmosphere pressure and temperature along the descent. But of course, the leap forward by the Viking landers was the success of sending the first-ever images of the Martian surface after a soft landing, setting a new milestone in the technological development for planetary exploration. This way, on July 20, 1976, Viking 1 landed on the western area of Chryse Planitia (22.27 deg N latitude and 312.05 deg E longitude); and her twin landed on September 3, 1975, 200 km west from the Mie crater in Utopia Planitia (47.6673 deg N latitude, 134.2809 deg E longitude).

The 600 kg Viking landers were equipped with a very complete suite of experiments to try to reach the ambitious objectives planned for the mission: the analysis of the surface and ambient properties derived from the erosion and eolian sedimentations; morphology, organic, and inorganic chemical composition and magnetic properties, based on the mineralogical analysis of the landing site; seismology; meteorology; and to look for potential Martian organisms with a biological experiment attached to a gas chromatographer/mass spectrometer (GC/MS) instrument.

The panoramic cameras on the landers covered a region of 360° of the Martian horizon, but also allowed photographing the lander and its sample-extraction arm, as well as the sun or the Martian moons, Phobos and Deimos. These cameras were the first to be operated, starting to transmit the first data to ground only after 25 s. The 3000 images of Viking 1 plus the 6500 of Viking 2 showed a desertic, powdery, and inhospitable landscape. Also, the images greatly helped in the interpretation of the instrumental data.

The temperature and magnetism of the rock samples in the reach of the landers were analyzed by sensors placed in the arm tip, showing a great abundance of magnetic minerals in the Martian surface [13]. The X-ray fluorescence spectroscopy (XRFS) were used to obtain the chemical nature of the surface regolith, showing a great abundance of Si and Fe, with significative concentrations of Mg, Al, S, Ca, and Ti. When compared with the abundances of these elements on Earth, it was observed that the presence of S was up to two orders of magnitude higher in Mars, while K abundance was 5 times lower than the average found in the Earth crust [14].

The Viking meteorological station was deployed in a mast after landing and included temperature and wind sensors. It also included a pressure sensor under the belly of the lander. All these instruments gathered data as configured from ground, varying the data logging along the mission as required. The results showed and allowed the characterization of the day/night cycles, as well as throughout the seasons during the years the missions lasted [15].

One of the Martian unknowns was related to the seismic activity of the red planet. The Viking landers seismometers were included for this reason. Even the Viking 2 instrument failed (probably due to the landing impact); the seismometer on Viking 1 worked for 2000 h without registering any important events, with the exception of one, which could have been caused by a micro-meteorite impact or even a wind gust [16].

Finally, the key to the mission was the Viking experiment aimed at answering the question of whether Mars might have harbored life in the past or even if there was life present in the soil. In order to do so, Viking included the "biological experiment" consisting of three different instruments: a pyrolitic release (PR), labeled release (LR), and gas exchange (GEX). All these instruments incubated samples extracted from the Martian surface, applying different ambient conditions during several days. In general, the search for organic traces were negative in five out of the six experiments. The remaining one, however, performed by the LR instrument on Viking 2, obtained a positive result [17]. Revolutionary at the beginning, this result was always surrounded by controversy regarding the goodness of the experiment, resulting in serious doubts on the existence of this positive biological response. This controversy is still in force, though the general scientific position nowadays lean the scales toward a false positive result. Even if with controversial or unsatisfactory results, the Viking missions were a great success for the study of Mars, also leaving very important lessons learnt for the generations to come, especially when coming down to looking for alien life or life-tracers. On the one hand, habitable is not the same as inhabited; on the other hand, positively certifying the existence of life requires either repetitive results, and/or a very good assurance that the organic/biological detection is coming from the extraterrestrial source, in order to avoid potential controversies on the results. This might be one reason why, since 1976, no Mars mission has been intended to look for life on Mars, but to look for conditions of habitability.

4. Mobile surface missions: from Pathfinder to Curiosity

Twenty years had to pass before the world looked again toward Mars after the successful Viking missions. The emotional slump caused by the difficulties in finding life on Mars, together with the slowing down of the space race due to the clear leadership of the US after the Viking program, was among the causes of this lack of interest. However, after this time, NASA recovered the impulse considering the new geopolitical scenario in which the study of the Solar System was not anymore a race between countries, but a joint effort among all of them. This way, Europe, Japan, and even Russia were considered as potential allies in this new era of exploration. It is in this framework that the NASA Mars Exploration Program (MEP) [18] kicks-off in 1993. This program laid an ambitious strategy for 1993–2020, with the idea of using all the available launch windows with subsequent missions to study Mars, its climate and geology, available resources for *in situ* exploitation, and the search for life. The original path planned a (now we now) quite optimistically sample-return missions for the decade of 2000, continuing with manned missions to the red planet before 2020.

Understanding the evolution of our neighbor Mars, with which Earth shares a common geological origin, and a similar habitability in their origins 4000 million years ago, is the main objective of the MEP program, the greatest effort for the exploration of the Solar System since the Apollo missions. One of the MEP key characteristics has been the focus on the development of technologies that provide security and reliability on the Martian missions. This has resulted in a high success rate, which has pumped an increasingly great and continuous scientific understanding of Mars. A timeline showing the roadmap for the exploration of Mars can be found in **Figure 1**.

Such an ambitious program requires interdisciplinary collaboration with the Planetary and Martian scientific community, which is done through the Mars Exploration Program Analysis Group (MEPAG)—a scientific group formed by international experts from the main national space agencies around the world; but also MEP interacts closely with the NASA Human Exploration Operation Mission

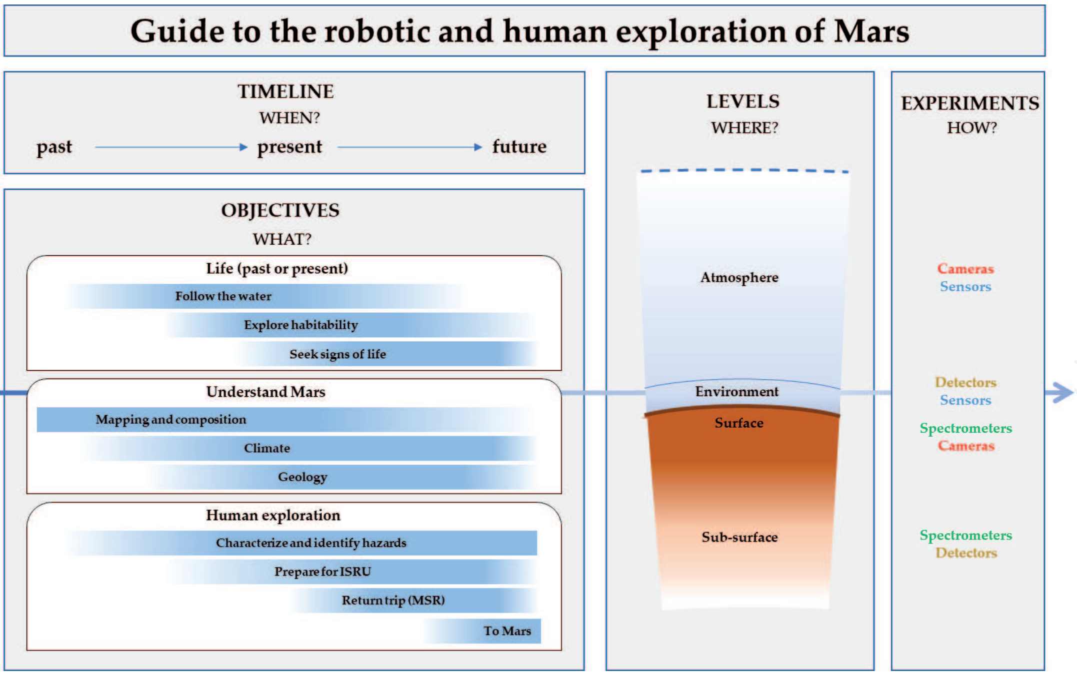

Figure 1.
Key elements and timeline of the robotic and human exploration of Mars.

Directorate (HEMD) and the Space Technology Mission Directorate (STDM), as covered by NASA's 2014 Strategic Plan [19].

As part of this plan, the MEP objectives are updated as necessary with the new scientific discoveries, while considering the following priority aspects: (1) a continued effort for the development of reliable technologies to improve the analytical capabilities with new and more ambitious scientific instruments; (2) a technological evolution to allow for better and safer technologies for entry, descent, and landing (EDL) in order to be able to land more equipment smoother, and with higher confidence and accuracy; and (3) to keep a reliable and continued network of communication relays, by maintaining a sufficient network of orbiters as the best way to facilitate a sustained flow of scientific discoveries around Mars. This approach allows for better instruments, placed with higher accuracy and safety, while ensuring a data flow between Earth and the Martian robots [20].

In order to meet these objectives, MEP has successfully combined orbital and surface missions as needed. On the one hand, orbital missions have provided climate and atmosphere compositional studies, combined with mapping and surface characterization activities to facilitate future landing sites. But they also have served to analyze the planetary characteristics such as magnetic field and solar particle interaction, while fulfilling the communications link with Earth for the surface missions. Successful orbiter missions to date have been the Mars Global Surveyor (MGS) in 1996; Mars Odyssey (ODY) in 2001; Mars Express (MEX), a European mission lead by ESA in 2003; Mars Reconnaissance Orbiter (MRO) in 2005; Maven (MVN) in 2013; and the ExoMars Trace Gas Orbiter (TGO), also from ESA, in 2016.

On the other hand, lander surface missions were proposed to answer maybe more concrete scientific objectives: the Mars Pathfinder (MPF) in 1997, basically a technological demonstrator also equipped with a small rover; Phoenix (PHX) in 2007, which looked for the presence of ice in high latitudes; and Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) in 2018, mainly dedicated to the study of the planet seismology.

But the true heroes, those missions that have harvested the greatest scientific and public relations success are the exploration rovers. Sojourner is the Mars Pathfinder mission rover in 1997; Spirit and Opportunity are the Mars Exploration

Rovers (MER) from 2003, which surprised the world with amazing science for 15 years (while they were designed to last for a nominal mission of 90 sols); and finally, the Curiosity rover, or Mars Science Laboratory (MSL) in 2012, deploys the most complete analytical laboratory ever on another planetary body beyond Earth.

4.1 First orbiters and Pathfinder; 1996: technological readiness

The first steps of the MEP were not easy. Early years of the program were marked by a number of sounding failures: Mars Observer, in 1992, an orbiter, was NASA's first mission for Martian exploration after the Viking project, and lost communications before entering into orbit; and the Mars Climate Orbiter, in 1998, crashed against the planet surface. But not only NASA had problems, other countries either: The Soviet Union lost Phobos 1 and had a limited success with Phobos 2 in 1988. The Mapc 96 in 1996 was also lost. Japan never arrived to Mars with the Naomi mission in 1999.

Not only the technological issues were a concern during the decade of the 1990s but also the geo-economic situation made it difficult to justify missions with the cost and size of previous decades. This way, the Mars Environmental Survey (MESUR) Pathfinder mission was conceived inside the low-cost planetary Discovery Missions program. This was a new mission concept by NASA grounded in the "faster, better, and cheaper" paradigm. However, an unexpected ally appeared with this mission to gain the popularity and acceptance of the US and world public opinion: Internet. On July 4, 1997, the Pathfinder landing was forecasted through Internet, reaching unprecedented records of visits to the Webpages offering information about the mission. NASA called it "the day Internet stood still." From that experience, NASA understood that in order to win the public opinion favor in order to get acceptance on this new era of planetary exploration, public relations activities advertising all aspects of the missions were key to feed a public avid of this kind of information. And Internet was the perfect means of transmission, allowing almost real-time updates on the missions.

This framework helped restart the exploration of Mars, paving the way for a new generation of planetary exploration missions by the US. The low-cost discovery missions such as Pathfinder had the clear objective of demonstrating the technological readiness to land and explore on Mars, investing only three years and with a low cost: safe landing systems, new communications, the use of modern sensors and image devices, etc., but above all, to demonstrate the capability of maneuvering in the Martian surface with a rover.

The Mars Pathfinder landed softly on Ares Vallis (19.33 N, 33.55 W), on Chryse Planitia (already visited by Viking 1). The lander was named Carl Sagan Memoria Station (after the famous astronomer Carl Sagan); and the rover was called Sojourner (in honor to the American civil rights activist Sojourner Truth). Sojourner was the first rover ever to be successfully deployed outside the Earth-Moon system (after the failure of Mapc 3 in 1971, the Soviet Union sent two rovers to the moon surface later in the decade of the 1970s as part of the Lunokhod program). The surface bi-dimensional planetary exploration era was started.

Even though the mission was basically considered as a technological demonstrator, it included several instruments as part of the platform and rover payloads. The lander's main objective was not only to help on the rover operations but also to work as a meteorological station and to investigate the magnetic properties of the Martian powder. The meteorological observations were done by the Atmospheric Structure Instrument/Meteorology Package (ASI/MET). Deployed on the platform mast, it included several temperature, wind, and pressure sensors. The observations performed during the 80 operative sols of the Pathfinder showed daily pressure variations of 0.2–0.3 mbar, with two complete cycles, correlated with the temperature variations observed during the Martian day. The temperature observed during the equatorial summer ranged from 263 to 197 K in the day/night cycles. The winds also followed daily patterns, being able to detect some dust-devil episodes as well. All the results were in agreement with those measured 21 years before by the Viking 1 [21].

The magnetic analysis of the Martian powder by the Magnetic Properties Investigation (MPI) experiment showed that the detected iron oxides (Fe_2O_3, in its phase gamma-maghemite) could be used to infer their water-related formation. However, a higher-than-expected (compared to Earth environment) abundance of goethite (alpha-FeOOH) and hematite (alpha-Fe_2O_3) was detected by this instrument [22], raising new scientific questions about their formation.

The images acquired by the Pathfinder lander Imager for Mars Pathfinder (IMP) instrument were used to contextualize the images by the Sojourner rover, and these also showed a complex surface with rims and canals clearly weathered by fluvial, eolian, and impact processes. Also, some atmospheric processes such as the formation of clouds were observed [23].

The Sojourner rover was equipped with an Alpha Proton X-Ray Spectrometer (APXS) devoted to analyze the composition and atmospheric and water-related weathering of the surface materials from a geochemical perspective. The results showed rock compositions similar to the ones present in the Earth crust (as well as in the SNC meteorites). Thanks to this, it was inferred that volcanic processes were present in the planet geological history, as mafic components and volcanic gasses are needed for the formation of this kind of rocks [24, 25].

4.2 MER, 2003+2003: follow the water

After the success of the Pathfinder mission in 1996, NASA's Mars Odyssey was successfully set in orbit around Mars in 2001. The next launch window in 2003 placed ESA's Mars Express (MEX) in orbit, but saw the failure of the Beagle 2 lander after being unable to completely deploy its solar panels. This window was also selected by NASA to launch the most ambitious scientific mission to date: the Mars Exploration Rover (MER). This mission was intended to land two twin rovers, Spirit and Opportunity, on opposite points of the planet, in order to answer a set of scientific questions following the motto *follow the water*. The experience and results gained by NASA and the scientific community with the Pathfinder mission marked the path for the exploration of Mars: water was the key.

4.2.1 The mission objectives

The questions that the MER missions were to address could be summarized as follows:

1. **Was life ever present on Mars?** Assuming life as what we know, the presence of stable liquid water is needed for long periods of time on the planet surface. The presence of water, then, increases the probabilities (though it is not necessarily essential) of harboring life. In this sense, and even that the rovers were not equipped to directly detect life even if present, they were capable of performing mineralogical analysis that would help deduce the formation and evolution conditions of the analyzed materials. So, the search for minerals formed or evolved in water-related processes (precipitation, sedimentation, evaporation, hydrothermal processes, etc.) was priority for the MER rovers.

2. **What are the current weather conditions on Mars? What were they like in the past and why did they change?** Again, the mineralogical analysis of the

composition of the Martian rocks and soil can be used to infer the ambient conditions under which they are formed, including potential water-related alteration processes. In addition, the rovers were also designed to study the lower layers of the atmosphere to help understand the current Martian weather.

3. **What are the geological characteristics of Mars? What role the wind, water, plaque tectonics, or volcanism have played in the Martian geological history?** Iron compounds, carbonates, clays, salts, and other minerals in which water plays an important role were candidates to answer this kind of questions. Analysis performed on these samples would also help confirm the measurements performed by orbiter missions such as MGS, Mars Odyssey, Mars Express, or the Mars Reconnaissance Orbiter that improved their detection capabilities with the help of the MER rovers.

4. **Learn how a human exploration mission could be setup.** To study the Martian environment to identify potential risks for humans; and to understand and gather information regarding the chemical nature of the minerals and local resources, to be potentially used for exploitation and use during a manned mission, including course water in any of its forms, as it is the only way to ensure long-term manned missions on the Martian surface.

4.2.2 The robotic geologists

The Spirit and Opportunity rovers were designed with these questions on mind, considering the rovers as geologists *roving* on the Martian surface, and equipped with a portable laboratory to perform *in situ* analysis of the samples. A 360° panoramic camera (Pancam) and an IR thermal emission spectrometer (Mini-TES) were placed on the rover mast at 1.5 m above the ground. These allowed the optical characterization of the terrain (the geologist eyes) plus a first IR analysis on the potentially interesting targets. In addition, the rovers were equipped with an articulated robotic arm with several tools: a Microscopic Imager (MI) to take closeup images of the samples (the geologist magnifier); the Rock Abrasion Tool (RAT) to allow access to the interior of the rocks (the geologist hammer); and a series of instruments constituting the geologist portable laboratory—the Alpha Particle X-Ray Spectrometer (APXS), the Mossbauer Spectrometer (MS), and a Magnet array for direct analysis of the samples (another Magnet array was placed on the rover chassis to passively analyze the powder depositing on them). The rovers were also equipped with navigation (NavCams) and Hazard Avoidance (HazCams) cameras to facilitate a safe roving capability of these robotic geologists.

4.2.3 A journey through the Martian geology

The MER rovers landed on Mars at the beginning of 2004, during the last days of the southern summer. The soft landings were achieved by means of airbags, with which the rovers bounced very long distances along the Martian surface for a period of time much longer than expected. Spirit landed on January 4, 2004 in the Gusev crater (14.572° S, 175.478° E). Three weeks later, on January 25, Opportunity landed inside a 20-m diameter crater in Terra Meridiani (1.946° S and 354.473° E) in the opposite side of the planet.

MER rovers' journey on the Martian surface is one of the greatest successes among all the planetary exploration missions. From an engineering perspective, the results are impressive: rovers were designed for a 90-sol nominal mission and to rove up to 600 m. However, both rovers operated successfully for years (Spirit lasted for 6 years and 2 months, or 1892 sols; and Opportunity worked for 14 years and 42 days, or 5111 sols). During this time, they managed to travel 7.73 km in the case of Spirit, and a stounding distance of 45.16 km in the case of Opportunity. This longevity and traveling capacity allowed the generation of tens of GB of data that were downloaded to Earth. This enormous data volume allowed an unprecedented identification and consolidation of scientific advances to date, contributing greatly to the knowledge of Mars and its geological history.

4.2.3.1 A dense atmosphere and fresh water

First Opportunity success was its initial lucky-shot, landing inside the Eagle crater, where it performed analysis for 2 months. It detected hematite, which was a clear indicator of a past presence of water in the area, as it is formed in water environments. However, it was also deduced that the water presence was salty and with low pH (so not optimal for life thriving due to the water acidity), with this area probably being a coast region with tidal waters [26]. Later in December 2011, Opportunity also detected other evidences of liquid water in the Martian past. In the Endeavor crater, the instruments detected veins of gypsum (calcium sulfate) inside some rocks. This hydrated mineral was probably formed by water flowing through cracks in the rocks, where the calcium was left behind [27]. Before that, in October 2005, while analyzing the Comanche outcrop by MS, APXS and Mini-TES, the Spirit rover identified rocks formed by key chemical elements such as magnesium and iron carbonates, in proportions up to 10 times higher than the previous analysis on Mars [28]. This discovery was evidence that the Martian past had warmer and wetter areas, with a thick atmosphere and with neutral pH values that are required for the formation of these carbonates. These conditions would potentially favor the existence of some kinds of microscopic life compared to any of the previous analysis performed on the Martian surface.

4.2.3.2 Thermal waters

One of the Spirit wheels was damaged long after the nominal mission had passed, which was in itself a stroke of luck. In March 2007, the stuck wheel uncovered a whitish area below the soil regolith, which, after analysis, revealed as an area composed by silica with 90% concentration. This kind of crystals, with this purity, can only be found (on Earth) in areas bathed by thermal waters, or water vapor currents where the water or vapor get in contact with volcanic rocks. These places in Earth are thriving with bacteria and microorganisms due to the optimal conditions set by the hot and wet ambient [29].

4.2.3.3 An active water cycle

The Spirit mission looked terribly bad when it was trapped in sand without any possibility of moving from that position. However, during the maneuvers to try to be released, the wheels uncovered sulfates (among other things) under the regolith in the Troy location. These sulfates seemed to have been in contact with water only 1 million years ago (a very short time by geological standards), suggesting the possibility of the existence of an active water cycle on the planet.

4.2.3.4 Stable water bodies and volcanic activity

In May 2007, Spirit observed the ancient remains of a volcanic eruption in Home Plate. The remains suggested that the explosion might have been caused by a water-lava interaction [30], as suggested by the "bomb sag" structures found in the lower layers of the plateau. These structures are formed on Earth by the rocks falling on soft surfaces, which would confirm the presence of stable water bodies heated up by volcanic activity, which could also be favorable for microscopic life.

4.2.3.5 Ambient and atmospheric conditions

In addition to water-related discoveries, both Spirit and Opportunity helped performing many other discoveries and studies to further the knowledge of the red planet. Opportunity became an expert on the geology of Martian craters [31] after visiting more than 100 impact craters, which allowed understanding their formation and erosion on the Martian atmosphere. The Martian environment was monitored as well, studying the cloud formation and the suspended powder and opacity, and how it affected the solar panels of the rovers (curiously, the next rover sent to Mars would be equipped with a nuclear battery instead of being solar-powered). The dust-devils on the surface (firstly detected by the Pathfinder) were photographed by Spirit, and were key for the mission extension, as they helped recovering power for the rovers by cleaning the powder accumulating on the solar panels [32]. A complete temperature profile of the Martian atmosphere was performed by Opportunity, combining Mini-TES data [33] with the Mars Global Surveyor orbiter TES instrument data. Also, Opportunity found the first extra-Martian meteorite on Mars called Heat Sink Rock [34].

Spirit and Opportunity rovers were decidedly successful missions that provided prolifically scientific evidences of the past presence of water on the Martian surface among other things. Whichever of those discoveries would have absolutely justified the missions by themselves; but considering MER missions' success all together is simply overwhelming.

In order to prepare for the missions to come, NASA launched the Mars Reconnaissance Orbiter (MRO) in 2005, with the objective of mapping and facilitating communications. And the *follow the water* motto would be closed after the limited results obtained by the Phoenix lander in 2008, which landed in the polar regions of Mars (68° N latitude), but did not keep up with the very high expectations of this unexplored area. So, once the existence of an ancient wet Mars had been proved, the next milestone in the Martian exploration was to understand if the water presence could facilitate conditions favorable for the appearance of life: *explore habitability.*

4.3 Curiosity (MSL) 2011: explore habitability—seek for signs of life

The foundations laid by the Mars Exploration Program, with communications guaranteed by several orbiters on Mars (ODY, MEX, and MRO were operative in 2012; with two other on their way: MVN and TGO), and the experience gathered during the MER missions in many aspects, including the power source for the rovers, facilitated a science-centered design for the next rover to be operated on Mars. The Mars Science Laboratory (MSL), or Curiosity rover, landed in 2012 with only a small mass dedicated for communications (an UHF antenna) with orbiter relays. It also incorporated a light radioisotope thermoelectric generator (RTG) as a power source, which would also guarantee a stable power source for the rover (contrary to the solar-based power system on the MER). Furthermore, MSL introduced a new landing method based on the famous *sky crane*, which greatly reduced the mass of the entry, descent, and landing (EDL) system, being this mass allocated for the rover itself. This way, on August 5, 2012, the heaviest scientific mobile platform was deployed on Mars, with almost 900 kg of mass devoted to the exploration of the Martian surface.

4.3.1 Mission objectives

The Curiosity rover, equipped with the most powerful set of scientific instruments ever on another planetary body, was bound to determine if Mars could have harbored life at any time in its past, as well as continue understanding the role played by the water to this end; of course, it was also prepared to study the Martian climate and geology. So, the new exploration paradigm migrated from *follow the water* to *explore habitability*, by studying the chemical and structural properties of the soil and rocks, especially those presenting water-related formation scenarios.

Contrary to MER, Curiosity included instrumentation capable of performing analysis which can be related to biological studies or processes in order to address the following objectives: the search of organic carbon compounds or biosignatures; geological and geochemical analysis based on the analyzed rocks; analysis of the Martian climate and its evolution; and also to prepare potential future manned missions by being able to characterize the planet radiation on the surface.

4.3.2 The rover instrument suite

Lacking from a landing platform, the Curiosity rover incorporated some instruments to help during the EDL stage, such as the Mars Descent Imager (MARDI), or the atmospheric sensor MEDLI (MSL EDL Instrument). Also, the NavCams and HazCams on the rover ensure a safe navigation system for the rover. In addition to these, the rover contains a very complete suite of scientific instruments.

4.3.2.1 Cameras

MASTCAM is a color panoramic camera that is used for macroscopic analysis. It is used to establish the geological context of the analyzed samples by analyzing the weathering, erosion, and morphologic analysis of the Martian landscape. MAHLI is a camera suite for the analysis of closeup images of the samples to establish the mineral, textural, and structural contexts.

4.3.2.2 Spectrometers

Several analytical instruments are included in the payload of the rover for the determination and quantification of the chemical composition of the analyzed rocks and regolith: the Alpha-Particle X-Ray Spectrometer (APXS); the Chemistry and Camera (ChemCam), a LIBS spectrometer; Chemical and Mineralogy (CheMin), an X-Ray Diffraction/Fluorescence (XRD/XRF) instrument; or Sample Analysis at Mars (SAM), a suite of three instruments including gas chromatography, mass spectroscopy, and laser spectroscopy, aimed at the detection of elements associated with the potential existence of life.

4.3.2.3 Radiation detectors

Several instruments are onboard the rover dedicated to the following: the characterization of high-energy particles on the surface with the Radiation Assessment Detector (RAD), critical to determine the risks for a potential manned mission; and the detection of subsurface water molecules by the Dynamic Albedo of Neutrons (DAN) instrument, which has astrobiological implications, but also serves to study the potential use of *in situ* water by future missions.

4.3.2.4 Environmental sensors

The meteorological station onboard the MSL is called Rover Environmental Monitoring Station (REMS) monitors temperature, pressure, winds, UV radiation, humidity, etc. The data gathered by REMS are used to characterize and model the Martian climate along the seasons and years, which are key not only to understand the Martian weather, but also for the planning of future manned missions.

4.3.3 Where has curiosity led Curiosity? The science discoveries

The Curiosity rover has been working nonstop since its arrival to Mars in 2012, and it will continue to do so for the time being, as it is still in good shape. Probably the Mars 2020 rover, Perseverance, will arrive to Mars in 2021, while Curiosity is still fully operative. Given the scientific feedback already provided by this rover, it can be considered as a new great success by NASA, but it will for sure still bring interesting new discoveries during the remainder of the mission. Some of the MSL findings have confirmed or supported the knowledge gained by MER, but others have pushed the Martian understanding some steps further.

4.3.3.1 The water: sustained water currents, and fresh water and thick atmosphere

The Curiosity rover identified boulders that likely were rounded by the effect of water currents in Mount Sharp, in what was probably a river/lake system where water flowed for around one million years [35]. Also, the SAM instrument isotopic analysis on the Martian atmosphere elements indicates that the planet has come to be deprived of its early thicker atmosphere and water masses by, among other things, the effects of the solar winds in a planet without a magnetosphere [36–38].

4.3.3.2 A habitable environment

The analysis of the Martian chemistry of mudstones in the Yellowknife Bay confirmed the presence of key elements needed for life, such as oxygen, phosphorus, sulfur, and nitrogen. Also, the presence of fresh water can be inferred from the lack of many salts and the presence of clay minerals [39].

4.3.3.3 Organic carbon

One of the most important discoveries performed by the SAM instrument is based on the analyses from drilled samples (at some centimeters depth) in Mount Sharp. These analyses confirmed the presence of organic molecules. This is a very important discovery considering that any form of life would be formed from organic compounds. Also, it shows that preservation (and detection) of these molecules is possible, even at a few centimeters below the surface (where the UV-radiation degrades and breaks the long molecular chains of the organics) [40].

4.3.3.4 The methane cycle on Mars

The presence of methane on Mars is puzzling the scientific community, as it varies in concentration with time, meaning that there is an existing methane cycle on the planet. The formation of methane can occur from chemical reactions, but also by living organisms. Curiosity has monitored the Martian methane with SAM's Tunable Laser Spectrometer, observing variations up to one order of magnitude in a period of only 2 months. Its source, however, is still to be identified [41].

4.3.3.5 Radiation

The RAD instrument has performed analysis during the whole duration of the mission, including cruise. The results show that the radiation dose during a Mars mission would pose a risk for the human crew. The Galactic Cosmic Rays and the Solar Energetic Particles are the main radiation sources that will affect potential future astronauts on the surface of Mars. The radiation characterization performed by Curiosity during the mission will help defining safe mission concepts for the manned exploration of Mars [42–43].

The Martian missions after MSL have been orbiters centered in the study of the Martian atmosphere. Mars Atmosphere and Volatile Evolution (MAVEN) and the Indian Mars Orbiter Mission (Mangalyaan) were launched in 2013 and have been studying the evolution of the higher layers of the atmosphere in order to understand its loss. MAVEN has confirmed how the solar wind, in absence of a protective magnetic field, facilitates the escape of the charged particles on the Martian atmosphere [44]. Later in 2016, the first part of the ExoMars mission deployed the Trace Gas Orbiter (TGO) in the Martian orbit, incorporating a suite of instruments (ACS and NOMAD) to analyze the concentration of methane and other gases with detection limits as low as 10 parts per thousand, with the ultimate objective of helping understand the methane cycle in Mars.

Finally, 2018 saw the launch of another NASA lander, using the same platform concept as for the Phoenix mission some years before. This mission was named Interior Exploration using Seismic Investigation, Geodesy and Heat Transport (InSight) and was devoted to the analysis of the planet interior, performing seismologic and in-depth thermal analysis. The data gathered by this mission will help understand the formation process of the planet compared to others in the Solar System.

5. What's next? The future of Martian exploration

The decade of the 2020s opens a *golden age* of the *in situ* Martian exploration. During the summer of 2020, two missions of great impact will be launched to Mars. On the one hand, the improved (1 Ton heavy) version of MSL, the Perseverance rover, will be deployed by NASA on the Jezero crater in Mars. On the other hand, China will launch the ambitious Tianwen-1, which will try to place, in only one mission, an orbiter, a lander and a mid-size rover (240 kg). In the following launch window in 2022, Europe (ESA) and Russia (Roscosmos) will join the exploration of Mars with the second phase of the ExoMars mission, which will deploy the Rosalind Franklin rover (named in honor of the British scientific) on Oxia Planum by the beginning of 2023.

5.1 Flying high: the perseverance breakthroughs

The upcoming NASA mission to Mars with the Perseverance rover breaks frontiers in many scientific and technological aspects, also giving clear steps as defined by the Mars Exploration Program. Perseverance is in many aspects similar to Curiosity, but it implements several improvements and novel analytical techniques. On the one hand, Raman spectroscopy, a powerful analytical technique for molecular identification of samples, unprecedented in planetary exploration missions, appears in the payload of the rover not one, but twice. The SuperCam multi-analytical instrument suite includes a remote Raman spectrometer that will analyze rocks and soils at distances of up to 12 m. Also, the SHERLOC instrument placed in the arm of the rover will use an UV laser source to perform Raman spectroscopy optimized for the detection of organics.

Paving the way for future human missions, Perseverance is equipped with the Mars Oxygen ISRU Experiment (MOXIE), a technological demonstrator bound to evaluate the feasibility of extracting pure oxygen out of the CO_2 present in the Martian atmosphere. If working, this technology could be escalated to obtain propellent for vehicles leaving Mars for return to Earth in sample return missions (or to be used during manned stays in the planet in the long term).

Another technological demonstrator is related to the 3-D exploration of Mars, as the Perseverance rover will deploy a helicopter capable of flying in the thin Martian atmosphere. This will demonstrate the feasibility of future drone-based exploration missions on Mars.

Last but not least, a very critical payload in the Martian exploration roadmap is the Sample Caching System. This is one of the most complex robotic systems ever built on a rover and will be used to cache samples deemed interesting by the analytical instruments of the rover, sealing them in tubes that will be left on the Martian surface to be picked up by a rover on a future mission to be returned to Earth. With all these novelties, Perseverance will be setting new milestones in the Mars Exploration Program pathway.

5.2 Drilling down: the collaborative robotic biologist

The ExoMars 2022 mission is the result of a collaborative effort from several points of view. On the one hand, the European Rosalind Franklin rover will be landed by the Russian Kazachok lander, constituting a joint effort and tight collaboration between ESA (and the different European participant countries) and Roscosmos. On the other hand, the rover itself is equipped with a sample preparation and distribution system that has been designed in order to allow a very tight collaboration of all the payload instruments, with a clear objective in mind: to look for traces of life.

The most important novel technology used by the ExoMars rover is a drill that will be used to obtain samples from down to 2 m depth. This element is critical for the mission: this robotic biologist will be able to analyze samples obtained from a depth at which the organic molecules will be much better preserved from the radiation on the surface.

Other interesting features of this rover are the automatic navigation system that will allow an unattended daily navigation of ~100 m, including a novel *walking wheel* design that will be used to avoid getting stuck in sandy terrains.

The rover payload includes a Panoramic Camera (PanCam) and the Infrared Spectrometer for ExoMars (ISEM) placed on the rover mast. These instruments will help mapping the terrain and the sample selection for other instruments. This selection will also be narrowed with the help of the Water Ice and Subsurface Deposit Observation on Mars (WISDOM), a subsurface radar to study the soil stratigraphy under the rover; also the Autonomous Detector of Radiation of Neutrons Onboard Rover at Mars (ADRON-RM) will look for water or hydrated minerals under the Martian surface. Considering the information obtained from all these instruments, a decision will be taken on the drilling site to optimize the chances of detecting biosignatures. There will be several opportunities for analysis as the rover is designed to support several drilling cycles.

The sample analysis will be performed by several instruments in a choreographed sequence starting during the drilling with the Mars Multispectral Imager for Subsurface Studies (Ma_Miss), an IR spectrometer placed on the drill tip. The results from this instrument will be key to understand the rock formation and sedimentation processes without considering the atmospheric influence or weathering, while also helping contextualize the sample texture and structure. The sample will then be extracted and color-imaged by the Close-Up Imager (CLUPI) for morphologic, structural, and textural analysis. Finally, the sample is introduced in the rover body for analysis by the Analytical Laboratory Drawer (ALD), inside an Ultra Clean Zone (UCZ), an area with the highest cleanliness and sterilization requirements to avoid controversies regarding the results obtained by the very sensitive instrumentation of the ALD.

The Rosalind Franklin rover includes a sophisticated sample preparation and distribution system that will crush, dose, and flatten the sample on a carrousel that will move in sequence to allow the analysis of the sample by the three ALD instruments: MicrOmega is an IR spectrometer that will identify the potential regions of interest for analysis by the other instruments. The Raman Laser Spectrometer (RLS), the first ever Raman spectrometer qualified for a space mission, will perform a molecular identification of the materials on the same spots indicated by MicrOmega as regions of interest, and others randomly on the sample surface. And finally, the Mars Organic Molecule Analyzer (MOMA), a gas chromatography/mass spectrometry (GC/MS) instrument that can also work in Laser Desorption/Mass Spectrometer (LDMS) mode, will analyze the sample. With MOMA-LDMS, it will be possible to analyze the very same spots analyzed by RLS and MicrOmega. If the sample is considered interesting, then MOMA-GC/MS can be commanded on the sample (by dosing sample on one-use pyrolysis ovens) to characterize, with very low limits of detection, the organic compounds present on the sample.

This is how the ExoMars rover will perform a sequential collaborative analysis in which all the elements need to work as expected to ensure a successful measurement. This risky but an ambitious approach is necessary to maximize the chances of obtaining a major breakthrough in the exploration of Mars: the possibility of detecting preserved complex organic molecules or biomarkers on the red planet.

When considering all the rover missions to Mars, it can be observed how payloads and mission designs have evolved to give answers to the scientific questions that arise after every new discovery; of course, to the extent that technological advances have allowed. **Figure 2** includes a summary of the payloads included in the Martian rovers.

ROVERS' PAYLOADS DEFINITION

SCIENCE LAYER \ ROVER	Sojourner	Spirit & Opportunity	Curiosity	Perseverance	Rosalind Franklin
Atmosphere	IPM (*)	PanCam	MARDI (**) MEDLI (**) MASTCAM	SUPERCAM Mastcam-Z	PanCam
Environment	ASI/MET (*) MPI (*)	Magnet Array	REMS RAD	MEDA	
Surface	IPM (*) RIC APXS	APXS MI Mini-TES MS	CHEMCAM CHEMIN MAHLI APXS SAM MASTCAM	PIXL SUPERCAM SHERLOC WATSON	ISEM PanCam CLUPI
Sub-surface			DAN	RIMFAX	WISDOM Ma_MISS MicrOmega ADRON RLS CLUPI MOMA
Engineering	WAE Wheel abrasion MAE (dust on solar panels) RIC Wheels Camara	RAT	NavCam HazCam	NavCam HazCam MOXIE	

Cameras Sensors Spectrometers Detectors

(*) on Pathfinder Lander
(**) during descent

Figure 2.
Martian rovers' payloads and analysis objectives on Mars.

5.3 Bring it home: the Mars sample return

Converting the planetary exploration paradigm into a world effort instead of national initiatives will be necessary for the mid-term plans of Mars exploration and will require a tight collaboration between agencies in order to make substantial advances in the coming decades. As soon as technology readiness allows it, returning samples to Earth for analysis with the best available instrumentation is the next reachable step in the exploration effort. In this framework, the Mars Sample Return (MSR) program is designed as a joint effort between NASA and ESA, defining a complex sequence of missions beginning with the Perseverance rover, selecting and caching the first samples. Later, an ESA rover will be sent sometime during the decade (2026?) to retrieve and store the samples to be placed in a Mars Ascent Vehicle (MAV) that will place the samples in orbit, where they will wait until a return-trip ship captures them to bring them to Earth for analysis.

These complex mission designs, launches, and operations' sequence will constitute a major milestone in the Martian exploration, where the next step will be the design of *in situ* manned missions to Mars.

6. Conclusions

The robotic exploration of Mars is a consequence of humanity's awe toward our red neighbor and has become a reality when technology has reached the needed maturity, also influenced by other socio-economical aspects. The space race of the 1960s and the 1970s was the starting point of the Martian exploration and is a good example of how technological development was pushed beyond unimaginable limits thanks to the social, political, and economic support. In the late 1970s, however, the race had already been won over by the United States, and economies were suffering the petrol crisis. This resulted in a loss of momentum in the exploration missions to Mars, and the missions to Mars stopped until the implementation of the Martian Exploration Program in the 1990s.

The MEP is an ambitious program for the exploration of Mars, which was conceived as an exploration effort based on an international collaboration, aimed at joining efforts among the different space agencies worldwide. This set a new era in the exploration of Mars, where not only collaboration between Agencies is needed for mission's preparation, but also cooperation is required among different instruments once on Mars to give proper answers to scientific challenges. This has resulted into complex rover designs and missions where a suite of experiments works altogether for a common goal.

The decade of the 2020s will set new milestones in the Martian exploration paradigm, not only for pushing the technological limits and conquering new dimensions of explorations (helicopters, subsurface drilling), but also achieving the final step in the Mars studies evolution observations (with telescopes from Earth, from orbit, *in situ* from surface, etc.), bringing home (Earth) Martian samples for its study, paving the way for the human exploration of the red planet.

In this new era, the collaboration between instruments, rovers, missions, and, finally, agencies and political actors will be key to obtain the best results to, ultimately, unravel the mysteries of our red neighbor and, who knows, maybe answer one of the most transcendental questions of humankind: Are we alone?

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Conflict of interest

The authors declare that they have no conflicts of interest with respect to research, authorship and/or publication of this book chapter.

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