CHALLENGE 2

FUTURE VOYAGES TO THE SOLAR SYSTEM

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1. INTRODUCTION AND GENERAL DESCRIPTION

From the beginning of time, mankind has looked up at the sky fascinated by the movement of the heavenly bodies and, as a result of that human concern, the astronomy emerged, the oldest natural science. All the most important ancient civilizations have their own interpretations of how our universe works and we have found and studied the legacies of the Egyptians, Greeks, Indians, Chinese or Maya astronomers. At the renaissance period, the "Heliocentric Revolution", also known as the "Copernican Revolution", gave us the first rational interpretation of how the planets of the Solar System moves around the Sun. In addition, at that memorable time of the culture history the telescope was born, developed by Galileo Galilei, and from that moment the instruments have not stopped pointing to the sky to unravel the laws that control its movement and how our universe formed. In the second part of the 20th century, observation became exploration and the mankind started to dream with travelling to other worlds of the Solar System and to achieve it.

Nowadays, the frontiers of the Solar System are moving fast due to the breaking information we are receiving from the space missions to planets, moons and diverse small bodies like comets and asteroids. They are essential to decipher basic science questions such as the origin and the evolution of our planetary system, the physical, chemical and geological properties of the bodies, how is/was the activity of some of them, or the requisites of the emergence of environments that could be habitable. National space agencies are currently renewing their programs, identifying the challenges for the future decades. It will not be a long time, if it is compared with the periods of history we have mentioned, but a lot of questions will be solved and many others will arise in the unceasing advance of scientific knowledge of the Solar System. CSIC researchers, as a part of the scientist community involved in this exploration tasks, have acknowledged challenges at different levels at mid- or long-term in which their contribution will be important: 1) scientific questions coming from the early phases of the solar system and planetary bodies, manly of Venus, Mars and Icy Moons; 2) studies on terrestrial analogs to, and 3) technological demand associated to the future missions.

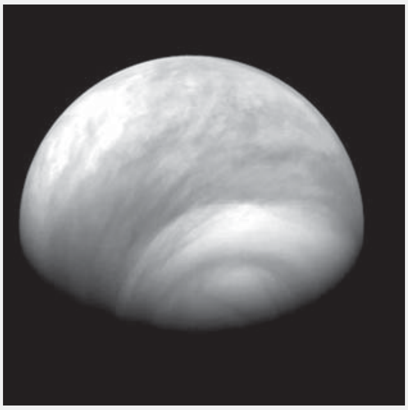
The challenges associated to the brightest light in our sky and centre of our system, the Sun, deserves a full separate chapter (see Challenge 3) and is not taken into account in this Chapter.

A brief description of the challenges to be faced is below.

Deciphering the origin of the Solar System by the early phases

The formulation of a solid theory about the origin of the solar system has been a concern of the scientific community for a long time and to study the life cycle of matter in the Universe gives us key insights into the origin of the Solar System. Sun-like Main Sequence stars with $M < 8M_\odot$ deplete their core hydrogen and start fusion in their upper layers after ~5 Gyr, turning into red giants. This is followed by fusion of core helium in the horizontal branch phase and fusion of H and He in the outer layers in the asymptotic giant branch or AGB phase, when the star loses much of its mass. Silicate and carbonaceous dust grains are ejected by AGB stars into the interstellar medium, where relatively high densities of gas and dust form diffuse and dense clouds. Dust grains contribute to a new cycle of star formation, absorbing the excess energy generated during gravitational collapse of clouds and radiating it away in

FIGURE 1–Clouds covering the south hemisphere of Venus. Image taken by the VMC camera/ Venus Express. Copyright: ESA/ MPS/DLR/IDA



the infrared (IR). Shielding of radiation and low temperatures allow the survival of molecules and ice accretion on dust inside clouds. Conservation of angular momentum leads to the formation of gas and dust disks around proto-stars, which can further evolve forming new planetary systems. Spectroscopic analysis of radiation emitted, absorbed or scattered by stars, interstellar clouds, protoplanetary disks or exoplanetary atmospheres informs about the composition and physical conditions of these gas, dust and ice-containing environments. Interpreting observations requires laboratory experiments and theoretical calculations, which provide key parameters for astrophysical models.

Venus, the unfairly forgotten neighbour?

Venus and the Earth have very similar sizes and masses, but their atmospheres are strikingly different. Venus atmosphere is very thick (~90 at the surface) and composed mainly of CO_2, producing a strong greenhouse effect driving surface temperatures of ~470ºC. Venus is permanently covered by very thick clouds, composed mostly of sulfuric acid, preventing the direct observation of Venus surface except in some narrow spectral windows (see *Fig. 1*). Venus' atmospheric dynamics is also unique, with the atmosphere up to the cloud level rotating much faster than the surface of the planet (super-rotation).

It is thus without surprise that Venus was a preferential objective for space exploration since the beginning of the space era. More than 20 missions visited Venus during the 20^{th} century, and by the end of the Magellan mission in the mid 1990s Venus was the best-known planet after the Earth. However, in the 21st century the focus of space exploration moved to Mars, and today our knowledge of Venus is well behind that of the red planet. More than 10 missions have successfully studied Mars in this century, and 4 more are planned in the next years. In sharp contrast, only two missions, Venus Express (ESA) and Akatsuki (JAXA), have visited Venus after the Magellan mission. In the near future, India is studying the possibility of launching a Venus mission around 2023, though there is not yet official confirmation. The next opportunity to visit Venus may be in the mid 2030s, as one of the candidates for the future ESA M5 mission is EnVision, a Venus orbiter focused on the study of the surface and the search for possible plumes produced by volcanic activity.

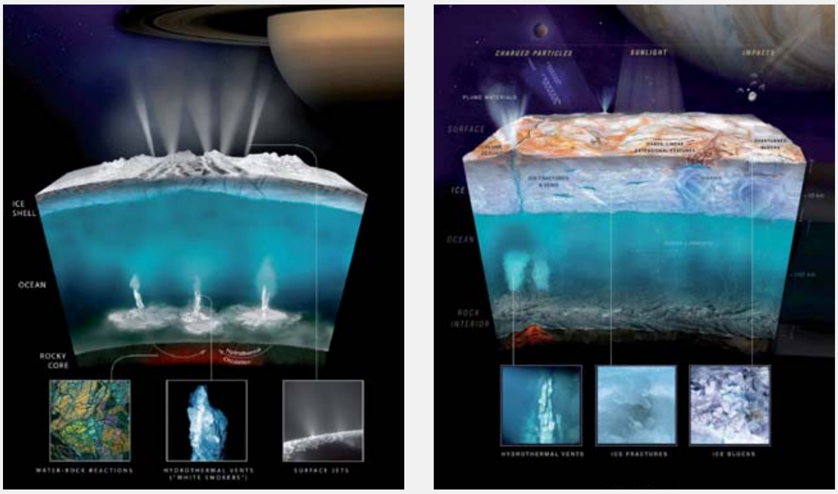
The only two Venus missions in the 21st century have, however, significantly improved our knowledge about this planet. Venus Express has, among many other results, improved the characterization of the temperature structure, the atmospheric dynamics, the atmospheric composition and the ion escape from the atmosphere, and has also found clues of recent volcanic activity. The Akatsuki mission, still operational today, is strongly focused on the characterization of the atmospheric dynamics by tracking the movements of the clouds. A recent review of our current knowledge of the Venus system can be found in Taylor et al. (2018).

Regarding modelling efforts, Venus is also well behind Mars. Aspects such as the details of the mechanisms behind super-rotation, the coupling between the lower atmosphere, the thermosphere/ionosphere and the exosphere and magnetosphere, and the implications of these couplings for atmospheric escape and the long-term atmospheric evolution, still require significant work (Sánchez-Lavega et al., 2017).

Mars environments, the next frontier of human exploration

The understanding of distribution, composition, and physical processes associated with the surface and atmosphere of Mars has vastly improved during the last decade. Continued advances in instrumentation and detector design allowed sophisticated analytical instrumentation to obtain higher spectral resolution measurements, both orbital and ground-based. However, there are still many uncertainties regarding the martian atmosphere, its surface, and its internal structure that would be critical for the future colonization of the planet. All the issues related to the Mars colonization is deeply described in previous chapter and is out of the scope of this chapter.

FIGURE 2–Illustrations of the possible activity in the interior and the surface of Enceladus (right) and Europa (left). Credits: NASA



Icy Moons, where the inaccessible liquid water is stored

The Pioneers, the Voyagers, Galileo, Cassini Huygens, Juno and New Horizons missions have explored the outer solar system so far, showing that geological activity is not exclusive of rocky bodies (Fig. 2). The recent geological activity in some of the moons is revealed as diverse tectonic and cryomagmatic structures as well as features resulting from the atmosphere dynamics if present. The scientific interest on these icy moons has increased in the planetary community since evidences of deep habitable environments were discovered. Indeed, some of the satellites of the giant planets are now called as ocean worlds because liquid water layers characterize their interiors, so they become targets of astrobiology (see Challenge 5). Planetary researchers at CSIC are waiting now for the new information coming from the future missions planned to arrive to ocean worlds such as Europa, Ganymede or Titan.

Understand terrestrial analogues, a step to get the extreme conditions beyond

Terrestrial analogs are defined as environments on Earth that present one or more geological or environmental conditions similar to those found on any extra-terrestrial body, either current or past. They are exceptionally helping to advance knowledge in planetary science since half a century. They are useful in studies of comparative planetary geology of the terrestrial planets and rocky and icy moons (Chapter 6 of Volume 14), in astronaut training and testing of exploration technologies, and in developing hypotheses and exploration strategies in astrobiology (see Challenge 5 of this Volume).

Technology for the future demanding science of the solar system

Up to the present, the economic resources and infrastructures to conceive, develop and launch its own scientific exploration probes of the bodies of the solar system have been only available to a very few teams, so the most relevant contributions of CSIC researchers, like instruments on board of Solar Orbiter, Rosetta, Curiosity or Perseverance, to name a few, have gone hand in hand with the large space agencies, mainly ESA and NASA. The extremely rigorous selection and qualification processes applied to instruments for being approved demonstrate the high competitiveness of the science and technology developed by CSIC. Very likely, this model of involvement is not going to change in the next future and most of the research lines, and the technology to be developed to satisfy their demands, will be necessarily aligned with the ones included in the roadmaps for the next decades of the largest space agencies. In the future, the strategies of the current emerging agencies involved in the exploration of the solar system will be consolidated, and a new horizon of opportunities will open up for this type of collaboration.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Solar system exploration helps to address fundamental questions about our place in the Universe and how it evolves. Through addressing the challenges related to space exploration we expand technology, create new industries and open strong international collaborations.

Humanity will step on the surface of Mars in the not so far future, and to characterize things as the environmental hazards and in-situ resource to be utilized will be vital. Our neighbour holds the key to understand the physical and chemical processes during old ages, but also to predict what could be the future of our planet. Earth undergoes intensive resurfacing causing that rocks older than 3 billion years are nowhere to be found. Mars, however, still hosts surface rocks dating from the earliest times of the Solar System.

Future accepted missions to the icy moons will be exciting, involving rotorcrafts to Titan and landers to Europa to perform studies on bizarre conditions. Apart from the technological defies that these missions involve, local studies will certainly revolutionize the knowledge we have of the solar system in the same manner than the landers on Mars. We will be able to characterize the ice moons as potential habitats and better understand how planetary icy bodies dynamics evolve. The high challenge will be to go from the surface to the liquid environments of the interior and characterize them. In the way down, some other questions have to be solved. CSIC researchers are involved in those that are shown below.

Analog studies are significant for understanding data and selecting targets in future missions. National space agencies like NASA, and Science networks such as Europlanet assist researchers from multidisciplinary fields in accessing remote analogue sites and performing fundamental planetary science research and development. In Spain, researchers are leaders of terrestrial analogue studies and several places along the country are referent for the planetary community, such as Rio Tinto, La Mancha lagoons, or the Canary Island volcanos. Since the access to the planetary environments is costly and risky, terrestrial analogue studies will continue to be an essential component of planetary science and exploration for the years to come.

3. KEY CHALLENGING POINTS

3.1. Origins

What was the gas and ice chemistry of the Solar System protoplanetary disk?

The accretion and desorption processes of gas molecules on cold grains play an important role in the evolution of dense clouds and young stellar envelopes. During star formation, circumstellar ices are heated causing desorption of ice components. This leads to the formation of hot cores and corinos around protostars. In protoplanetary disks, the radial distance at which an ice component is thermally desorbed is termed snowline (an example of a CO snowline is shown in Fig. 3). The location of major snowlines (N_2, CO, CO_2, NH_3, H_2O) determines planet composition and formation mechanisms.

H_2 is the dominant gas species in protoplanetary disks, from which gas giants form, yet its mass is mostly unknown. Using CO as surrogate yields uncertainty factors of 10-1000. The far IR transitions of HD would be much better tracers of H_2, but ground observation is precluded by atmospheric opacity. Only Stratospheric Observatory for Infrared Astronomy (SOFIA) is currently able to observe them from the stratosphere (Kral, et al., 2018). Similarly, IR telescopes with high spectral and spatial resolution are required to investigate the composition and physical properties of cosmic dust clouds.

Interpretation of astronomic spectra is done by comparison to laboratory dust and ice analogs produced under astrophysical relevant pressure, temperature, irradiation, and ion bombardment conditions (Muñoz-Caro, 2018). The main IR absorption bands of ice mantles have been assigned to H_2O, CO, CO_2, CH_3OH, OCN^-, OCS, H_2CO, HCOOH, CH_4, and NH_3 or NH_4^+. Relatively complex gas phase organic molecules formed on irradiated bare or ice-covered dust surfaces are detected toward dense inter- and circumstellar environments (see Challenge 5). Regarding binding energies on ice surfaces, intramolecular modes observed in the IR are perturbed by the local molecular environment in the ice, being thus sensitive to ice composition and structure. Changes in the IR band position, profile and strength, can be used to study intermolecular interactions within the ice. Temperature programmed desorption of ice analogues using a constant heating rate are used to derive the binding energies of species. Molecules are able to diffuse within the ice according to their binding energy, enabling further reaction or desorption. Desorbed molecules are detected in the gas phase using mass spectrometry and IR spectroscopy - improving sensitivity in these experiments is a major short-term goal. Intermolecular binding energies in laboratory experiments and in astronomical observations of Solar System icy bodies can also be traced in the UV. To achieve this scientific objective, along with new space missions, the support of new experiments is required to study binding energies of mixed and segregated multicomponent ices. Measurement of the binding energy between ice and carbonaceous/silicate dust surfaces is key to estimate the onset temperature of grain accretion. Concurrent ice IR spectroscopy and mass spectrometry of desorbed gas species should be reinforced, but implementation of novel techniques is also needed.

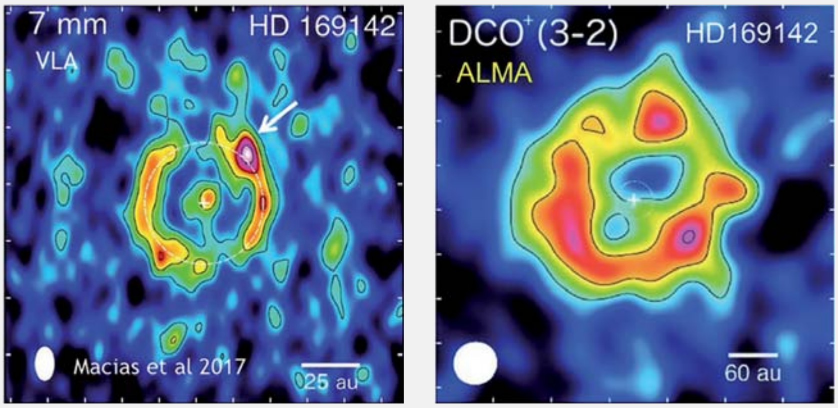
What are the signs of planet formation in the protoplanetary disks?

Increasingly detailed observations of protoplanetary disks using interferometers with high sensitivity and angular resolution such as the Very Large Array (VLA) and the Atacama Large Millimetre/submillimetre Array (ALMA), have revealed substructures such as gaps, rings, spirals, and other asymmetries (DSHARP project). It is thought that in most cases these result from the interaction between nascent protoplanets and the disk (Figure 1). Hydrodynamic models support this interpretation. Furthermore, Hα and IR sources have been detected inside cavities and gaps, which may correspond to planets in formation (e.g. PDS70b, c, Haffert et al., 2019). Currently, one of the biggest challenges is detecting protoplanets in their early formation stages.

Several mechanisms have been proposed to overcome collisional and drift barriers to grain growth. e.g., dust particles may be trapped in local pressure maxima regions of the disk (Andrews, 2020). In these dust traps the grains can grow and reach masses large enough so that friction with the gas does not produce a significant slowdown and they can remain in orbit around the star while they continue to grow. There is observational evidence in (sub) mm images of dust traps in the form of horseshoe-shaped asymmetries. Hydrodynamic models describe their formation from vortices. Alternative mechanisms are magneto-rotational and streaming instabilities and snowlines. It is not clear if a single mechanism dominates or if they act together in regulating growth and migration of dust grains, depending on the evolutionary state and conditions of each disk.

In order to decipher the details of these processes, very high angular resolution observations with state-of-the-art instrumentation are needed. Besides existing (VLA, SMA, ALMA) and upcoming James Web Space Telescope (JWST) and Square Kilometre Array (SKA) thermal imaging facilities, high contrast imaging polarimeters (Spectro-Polarimetric High-Contrast Exoplanet Research (SPHERE) at Very Large Telescope(VLT), GPI Spectrometer at GEMINI) and upcoming scattered light imaging observatories (JWST, Wide Field Infrared Survey Telescope (WFIRST) or Extremely Large Telescope, ELT) will continue to provide data for studying the evolution of disks. A multi-wavelength approach is needed to test models, since the interpretation of features is often degenerate. In order to maximize the information about the composition and structure of dust particles extracted from remote photo-polarimetric observations of circumstellar disks (Muñoz et al., 2017), new laboratory and theoretical developments on electromagnetic scattering by dust particles are required.

FIGURE 3—Left: VLA image of the HD 169142 disk. Right: ALMA image of the DCO+(3–2) emission around HD 169142 (measurement of the CO snowline). Dashed circles: dust ring. Plus signs: position of the star. Macías et al., 2017, with permission of the Institute of Physics (IOP)



Clues about the formation and evolution of planets in rocks and meteorites

Protoplanetary and geological information can be extracted from the interpretation of mineral features in meteorites and rocks. For example, pristine carbonaceous chondrites (CCs) show scarce thermal and aqueous processing and their fine-grained matrix particles are considered as representative of protoplanetary disk dust, containing information such as the size distribution. CCs are chemically unequilibrated, so separating their matrix components is technically possible. The particles can be then sized, and the results can be compared with those obtained by remote sensing.

Geological information is recorded in minerals as exsolution and transformation patterns, in addition to specific chemical compositions in solid solution systems, metallic alloys and aluminosilicates. Feldspars are the most abundant group of minerals in the crusts of the Earth, Moon and Mars, and also occur in Ca and Al-rich inclusions (CAIs) in CCs. Thus, spectroscopic and microscopic analysis of feldspars is particularly relevant for the identification of different planetary processes, including the development of different crustal compositions, like horizontal plate tectonics and vertical magmatic processes.

3.2. Primitive bodies

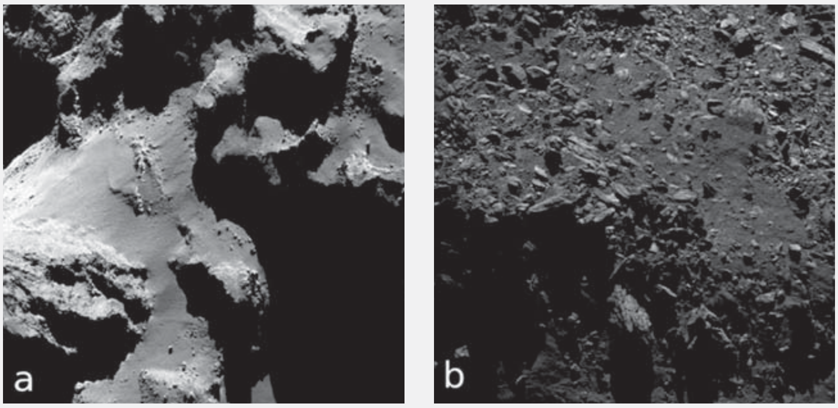
How was the formation and evolution of comets and trans-neptunian objects?

Coagulation of grains leading to cometesimal formation protects the products of ice photochemistry from subsequent irradiation. Thus, comets are reservoirs of the Solar System's most primitive materials. The way in which volatiles are stored within the nucleus is a long-standing problem of cometary physics: directly condensed? as clathrates? trapped in an amorphous matrix? Laboratory ice experiments may provide information on processes relevant to the long-term evolution of cometary nuclei.

To date, the most accepted scenario describing Solar System evolution (Nice model) advocates a trans-neptunian disk with $M \sim 35M_{\oplus}$ leading to a dynamically hot primordial disk. In this model, comets would be similar to asteroids, i.e. second-generation collisional rubble piles. By contrast, Rosetta's observations indicate that comets show neither signs of thermal processing nor aqueous alteration. This suggests that cometary nuclei formed late enough to avoid radiogenic heating, and that they never formed part of a larger body affected by collisions, compaction, differentiation and/or aqueous alteration. In this new scenario, comets would slowly form by pebble hierarchical agglomeration (see Fig. 4), while larger bodies would form by streaming instabilities in a lower mass trans-neptunian disk with $M \sim 15M_{\oplus}$ (Davidsson et al., 2016). Since agglomeration is hampered by barriers, alternative descriptions of comet growth still rely on streaming instabilities, although delayed long enough to allow a significant gas loss, thus avoiding radiogenic heating. In order to advance the knowledge of the formation of comets and trans-neptunian objects, the big challenges are estimating the mass of the primordial disk and the dust-to-gas ratio and how they evolved with time (Andrews, 2020), and what was the size and sticking efficiency of the dust grains.

So far, most of our knowledge on coagulation comes from laboratory experiments on bare refractory grain accretion. However, beyond the snow lines, dust particles have ice mantles. Laboratory research on the role of ice in particle aggregation is scarce (Blum, 2018). Knowledge on the density and internal structure of comets is also needed in order to progress in our understanding on the formation of minor bodies. Comets are very porous and show layered structures, but the nature of these features is elusive. Progress can be made by studying their rotational evolution and fragmentation events. There

FIGURE 4—Surface of 67P observed by NAC/OSIRIS on board Rosetta. Image a) shows the complex landscape constraining a landing mission on a comet with the purpose of perforation and sample return. Image b) illustrates the possible size of parent pebbles and the thermophysical complexity involved in modelling the activity of the nucleus. Credits: @ESA/Rosetta/MPS for OSIRIS Team.



are multiple physical and geometrical complexities involved in modelling state-of-the-art observational data (Fig. 4). Sophisticated and realistic numerical models need to be developed using a multidisciplinary approach to include new concepts such as subsurface sublimation, seasonal mass transfer, volatile segregation, heterogeneity, volatile trapping, re-condensation, surface evolution, surface self-heating and shadows, etc.

Valuable information can be extracted from remote observations and from interplanetary dust and micrometeorites (see Challenge 3). However, the ground truth in cometary nature will only be reached by in situ exploration. In the long term, the most difficult challenge is conducting a sample return mission to bring unaltered samples to the Earth's surface.

3.3. Terrestrial planets

Understand Venus as a dynamic planet

Clearly, many open questions remain to be solved in the years to come. The NASA Venus Exploration Analysis Group (VEXAG), in its latest report has identified the three most important top-level goals for future Venus exploration (2019, https://www.lpi.usra.edu/vexag/reports/VEXAG_Venus_GOI_Current.pdf):

- Early evolution and potential habitability to constrain the evolution of Venus-sized (exo)planets
- Atmospheric composition and dynamics on Venus
- The geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere

The first goal is motivated by whether or not Venus was once habitable. The evidences show that Venus was much wetter in the past, and it may have even hosted a water ocean. The second goal pretends a complete understanding of the Venus atmosphere as an intensely coupled system, contributing to provide context to investigations of the atmospheres of exoplanets of similar size to Earth and Venus. The third goal pursues a thorough characterization of the surface of the planet, understanding the geological processes that shaped the surface of Venus, and how they affected the atmosphere and its evolution.

Three key investigations are needed to better constrain the early Venus climate: i) characterization of the surface mineralogy, trying to identify minerals of hydrous origin that would indicate the sustained presence of liquid water in the past; ii) understanding current atmospheric escape processes to better constrain the primitive atmosphere; and iii) measuring isotopic ratios in the lower atmosphere to infer the characteristics of the early Venus atmosphere.

What is the meaning of the volatile content in the martian atmosphere?

Volatiles are molecules that readily evaporate, converting to their gaseous forms, such as water, carbon dioxide, and methane. Their study provides critical information on the evolution of the Martian geosphere, hydrosphere, and atmosphere. The isotopic rates of volatiles provide information about the oxygen and carbon cycles, critical for understand biological or geological activity.

The formation and destruction pathways of trace gas molecules and the variability of gases are investigated by several missions. Orbiters characterize the variation and localization of trace gas sources for a broad list of atmospheric gases, showing that the deterioration of Mars' atmosphere is still very intense and increases significantly during solar storms. We have observed specific volatiles leaving behind more heavy isotopes. However, the inventory of Martian volatiles as a function of geological time and their interactions with the Martian surface and rocks is unknown. Their chemical reactions and seasonal and diurnal variability, as well as the processes that lead to their ionization and the resulting escape rates, are still unresolved. The present-day concentration of gases in the Martian atmosphere is elusive; for example, the inconsistency between surface and orbit observations of methane. Evidence suggests that there must be an unknown destruction mechanism, keeping the global methane abundance within the surface observed range, but also consistent with the non-detection from orbit (Pla-García et al, 2019).

How the upper atmosphere and geomagnetism of Mars are related?

Mars has experienced significant atmospheric loss up to the present. The upper atmosphere of Mars is the main reservoir for atmospheric escape. Escape rate is related to the state of the atmosphere, and understanding how is affected by external forcing allows us to extrapolate past conditions. During the last years, significant advances have been made in monitor Mars' seasonal variation of temperatures, abundances (including water vapor profile) and hydrogen escape; the study of the importance of the coupling with the lower atmosphere via waves and tides; and the behaviour of the dayside ionosphere as ion outflow (one of the essential atmospheric loss mechanisms). The characterization of the upper atmosphere of Mars is yet very incomplete, and it is a critical mechanism in atmosphere loss.

Magnetic fields measurements indicate the existence in the past of a martian dynamo as on Earth. Crustal magnetic fields interact with the solar wind to generate transient fields and electric currents in Mars's upper atmosphere. In the latest in-situ observations, the magnetometer shows a surficial magnetic field ten times stronger than previously thought. Those fluctuations provide important clues about the upper atmosphere. The interaction of the solar wind with the geomagnetic field will be vital to understand what may have been the density of its thick atmosphere in the past and how it got lost.

What is the effect of dust on the water cycles of Mars?

One of the most natural cycles of the Martian atmosphere is the circulation of mineral micron-sized aerosols, namely dust. Dust particles are lifted into the atmosphere by near-surface wind and by convective vortices (dust devils) and settled down on the surface by the sedimentation mechanism. This cycle shows an inter-annual variability that, in contrast to the situation of Earth, has a reproducible pattern. For example, periodically, dust covers the whole planet during global storms. The dust cycle is monitored by the total column opacity when it is monitored from the surface and can be monitored in the visible range and IR range from satellites. The rate and mechanisms of atmospheric dust settling and lifting are not well characterized, as which aerosols are involved. The dust sinks and sources, the averaged time of flight, and the expected trajectories are unknown. The dust deposition affects the efficiency of solar panels, and dust storms affect the atmosphere dramatically and endanger surface missions.

Dust alters the thermal structure and the dynamics of the planetary boundary layer (PBL). Small-scale turbulences (eddies) in PBL are the primary mechanism by which energy, momentum, gasses, and aerosols are exchanged between the surface and the atmosphere. Eddy fluxes have never been directly measured on a planet other than Earth, and model estimations show variations by factors of two or more.

Rover atmospheric measurements show that, within one day, the temperature on Mars can vary in 75 degrees and pressure in 0.8 mbar. It also shows large thermal gradients between the surface and the atmosphere, as well as significant diurnal variations in the water volume mixing ratio and the relative humidity. Liquid water has not been observed yet on Mars, but polar water ice and water vapor have been extensively mapped. There are potential sites where liquid brines may be present, and subsurface polar-brines have been indirectly observed recently under the ice cap. Orbital instruments are helping to detect water vapor concentrations and subsurface water ice. Water ice clouds presence affects the composition and evolution of the Martian atmosphere as they serve of support for heterogeneous chemical processes. However, their nucleating conditions have still not been well parametrized. Understanding the water cycle is critical to know the history of the planet and water availability for future In-Situ-Resource-Utilization (ISRU).

What is the story of water on Mars?

Water-related landforms and their associated assemblages of hydrated materials are a reliable source to know past environments. Some researchers hypothesize that the Martian climate was warmer and wetter during early Mars. Alternatively, groundwater and subsurface hydrothermal processes can lead to similar results under cold and relatively dry environments. Martian oceans and long-lasting aquifers might have been low in temperature, with only temporary heat coming from volcanic or impact-related activity. Multiple secondary products indicate various alteration, erosion, and aqueous episodes that provided diversity in water chemistry and environments with at least short-lived liquid water. The study of the detailed story of water on Mars and thus its current situation will undoubtedly be subject to study in the next decades.

The extreme cold, dry, and low-pressure conditions on the surface of Mars, today, make water ice stable only in the polar regions. Geomorphologic landforms in middle to high latitudes, however, points to significant and possibly cyclical climate changes during Mars history. Spectral and geomorphic indications of ice in the low latitudes show that ground ice has equilibrated under current conditions, allowing for the build-up of ice deposits that could last for millions of years. Identify the distribution, age and formation mechanism of these reservoirs, and their derived landforms is an upcoming challenge. Permafrost and glaciation have dominated for the last billion years on Mars, and we found today potential sublimation landforms on its surface. However, characterize, model, or predict sublimation-based processes is very limited as it only occurs naturally in a few places on Earth, as the Dry Valleys of Antarctica (Douglas and Mellon, 2019).

What is the information memorize in Mars materials?
The Martian surface is a mixture of highly oxidized secondary minerals and relatively pristine basalts. Correlative trends in S, Cl, and H_2O abundances are indicators of past and present environmental conditions. Often formed under unique environmental conditions, sulphates are considered diagnostic minerals that can be used to assess aqueous processes and chemical weathering that correlates with the duration and magnitude of past and current climatic changes. Oxidized chlorine, as perchlorate and chlorate, has been reported on Mars by numerous missions and even in meteorites. Perchlorate seems to be found more concentrated and with different variability of its species on Mars compared to its analogs on Earth. The study of presence and varied concentration of oxychloride compounds in the geologic record are indicators of changes in the atmosphere and aqueous activity, as its low eutectic temperature could explain liquid water in low-temperature scenarios. Oxychloride is also key to the study of past and present life. The water activity of its brine is below life requirements, and its pyrolysis can destroy or alter the chemical composition of organic compounds.

Carbonates are a common product of the interaction between CO_2, water, and rocks. Carbonate precipitation in aqueous environments is an excellent mechanism for biosignature preservation, and their isotopic composition could serve as a record of atmospheric loss on Mars. Evidence of carbonate minerals has been provided by ground-based, airborne, and spacecraft observations, but definitive mineralogic identifications and detailed spatial mapping of these materials were lacking until the last decade.

Chemical and mineralogical changes that accompany weathering of basaltic rocks and soils on Earth are well known. But on Mars, the alteration of such majoritarian rocks seems to have evolved differently. Elemental measurements from rocks and soils in Mars landing sites indicate low-pH and low water to rock ratio alteration. Surface dust is also a major component in martian soil, hugely affected by volatile elements. Atmospheric deposition of salts may be an essential process in martian soil, but due to the limitation to study fresh rocks on Mars, weathering is poorly constrained.

Are the clues to understand the Mars' evolution underneath the surface?

The surface of Mars is a very extreme environment, subject to numerous hazards. The study of Mars has been restricted to its surface, but different conditions are expected to be found underground. Lava tubes and other types of cave-likes formation, as volcano-tectonic or even karstic and thermokarstic formations, besides the unquestionable interest as a shelter for life and even metastable water-ice deposits, can protect mineral formations. Lava tubes even could enable a better understanding of thermodynamics and hydrodynamics under martian conditions. These advances, combined with better computation and data processing, could support numeric modelling application to dynamic processes modelling on Mars, another hot topic in the years to come.

Seismic measurements on Mars are revealing many small magnitude marsquakes, which, together with the seismic response from dust devils, are now being used to constrain the very shallow and crustal structure of Mars. Seismic wave speeds and attenuation of energy permitted to constrain the seismic structure and to compare it to the moon and Earth. Different structural discontinuities are being revealed and mapped owing to the identification of reflected waves.

The surface and crustal thickness difference between the northern lowlands and the southern highlands on Mars is known as the global dichotomy. Despite being such a notorious martian landform, its structure and formation are yet unknown. The Arabia Terra region, one of the oldest terrains on the planet, is the most gradual transition between both sides of Mars' dichotomy. This region, landing site of the Exomars' Rosalind Franklin rover, may hold the key to understand not only a wide range of the geologic record of Mars, but the origin of the dichotomy itself. Next missions will be able to drill on Mars to obtain fresh samples, providing new simulation and experimental approaches to the alteration of materials in Mars conditions and to correlate the observed mineralogic changes with variations in other physical properties.

3.4. Icy moons

What is the origin and transformations of surface materials on icy moons?

Due to low resolution of the surface imagery collected so far, the determination of the origin, endogenous or exogenous, of materials on the icy satellites results ambiguous. The surface of icy moons without atmospheres such as those of Europa or Enceladus, is exposed to high-energetic solar particles and UV radiation. Organic and inorganic compounds can be altered by dehydration and/or amorphization processes, as well as form radicals that can start chain-reactions. Significant studies have been already done on the radiation effects on icy surfaces, but many questions still remain, mostly focused on non-water ice materials and potential biosignatures. In the cases of moons with atmosphere, Titan and Triton, the reactivity of materials will be dependent on the meteorological activity and photochemistry of the atmosphere molecules. Compositions of the solid materials on Titan's surface are still essentially unknown. How far organic chemistry has progressed is an issue to future missions. Sites where transient liquid water may have interacted with the abundant photo-chemical products that litter the surface are of particular interest. In Triton, the crust is covered by a regolith of mainly frozen N_2 and it reflects a reddish colour whose origin it is postulated to be the formation of tholins after CH_4 ice UV-radiation. The cycle of carbon and nitrogen in these moons is something to determine in the future.

How is the interaction between the surface and the liquid environment in Europa and Enceladus?

The stabilization of internal liquid reservoirs inside the icy crust is astrobiologically relevant, since they will imply potential niches to sustain life (see Challenge 5). Their existence within an icy crust infer that they must be rich in impurities like salts and/or antifreezes (e.g. ammonia, methanol), which contribute to the decrease of their melting temperature, as well as they can act as reactants in organic reactions if the temperature is sufficiently high to overcome the catalytic barriers. Transportation of both, materials and heat can occur by endogenous activity through the crust: tectonics and cryomagmatism. Long fractures cut the surfaces, and sometimes non-water ice materials are associated around. Plumes of materials emerging from these cracks have been detected and analyzed in Enceladus by Cassini and suggested in Europa by Hubble images. Europa Clipper mission will provide more information about this activity. We already do not know how deep is fracturing, or if the open conducts reach the global ocean nor long-term aqueous reservoirs at shallow levels. Furthermore, the analyses of the complex features in Europa suggest that a plate tectonics-like dynamics can exist on Europa, which could bury oxidants formed in the surface to deeper layers.

On the other hand, cryomagmatic processes, like differentiation of salt-volatile-rich aqueous solutions, will cause chemical variety within the icy crusts, altering both the mechanical and thermal properties (Muñoz-Iglesias et al 2014).

What is the impact of the geological activity at sea floor of Europa and Enceladus?

Serpentinization and other processes altering the silicates intervene in the C cycle at planetary scale, and have been suggested as an inorganic source of CH_4 in planetary bodies such as Mars or Enceladus. Some inorganic catalysts (e.g. awaruite and iron oxides) could allow the Fischer-Tropsch reaction in serpentinization of olivine-rich rocks at lower temperatures than usual without the intervention of organisms in deep ocean conditions. The introduction of N-molecules in the system also would form simple precursor monomers of a more complex chemistry. This type of alteration occurs under reduced conditions and high pH, which derive specific properties in the fluid. How all these reactions occur, including the possible removal of the organics from the system by formation of gas clathrates after the inorganic formation of methane from iron-rich olivine and CO2 in a saline solution, are still under study.

Is the crust of icy moons such as Europa or Titan homogeneous?

It is already known that some icy moons are completely differentiated in a core, a rocky mantle, a liquid ocean and an icy crust, such as Europa (or with a high-pressure-ice layer between the mantle and the ocean, as Ganymede and Titan). Others are just partially differentiated like Callisto. But these estimations are still pending of good accuracy, including the possible segregation of layers within the ice crust. High-pressure phases of some ices are under investigation by laboratory experiments to better model the geophysics of the moons, in particular the giants such as Ganymede, Titan or Callisto. Clathrate hydrates, hydrated salts and other compounds could stabilize at deep levels imposing their properties to the crust and mantle, and modifying the dynamics and thermal state (Prieto-Ballesteros et al. 2014, Muñoz-Iglesias et al. 2019). Cryopetrology will help to interpret the data about the composition and dynamics of the ice crust of the future missions.

3.4. Terrestrial analogues in the solar system

Terrestrial analogues to the volcanic processes of rocky planets.

Volcanic activity is a common feature of most of the rocky bodies of our Solar System and has been directly responsible for forming at least three quarters of the surface rocks of Earth and Venus, all of the surface materials of Jupiter's satellite Io, and extensive parts of the surfaces of Mars, Earth's Moon, and Mercury. Morphological features observed on the different rocky bodies are compared to terrestrial ones and related to different styles of volcanic activity (e.g. explosive or effusive) due to, for example, composition and gas content of the magma. Additionally, morphological evidences of magma-ice and magma-water interactions have been found on Mars thanks to our knowledge of volcano-ice/ water interaction occurring on Earth in alpine environments or beneath broad continental-scale glaciers or ice sheets such as tuyas, hyaloclastitic ridges, mudflows, tuff cones and rings, and possibly maars.

The surface of Venus, obscured by dense cloud cover, is similar in many ways to the seafloor of the Earth's oceans dominated primarily by basaltic volcanism. Both environments are characterized by significantly elevated pressure at the surface, resulting respectively, from the burden imposed by the overlying ocean water and the weight of the dense atmosphere.

Terrestrial analogues to Mars Hydrogeology: mechanisms and morphologies

Outburst floods are abrupt releases of water lasting typically between days and weeks and leaving a recognisable signature in the landscape, usually in the form of erosion channels or large sedimentary deposits. Many such scenarios have been identified in Mars, mostly attributed to the first half of the planet's life. For example, the circum-Chryse outflow channel systems are the largest known fluvially eroded planetary landscapes in the Solar System, resulting from catastrophic floods released from groundwater aquifers. Understanding the water discharges responsible is important in reconstructing the hydrological past of Mars. How were these enormous erosion channels initiated? How did the channels erode through time? Were they carved by multiple flood episodes? When were they carved? Addressing these questions is of great significance to reconstructing the evolution of the Martian hydrologic cycle because these channels record the largest movements of surface water on the planet. There is today a wide record of these type of events on Earth that are being studied (Garcia-Castellanos and O'Connor, 2018).

Terrestrial analogues to Mars' shorelines features

More than 200 Martian paleolake basins have reportedly breached their confining topography and then been drained by an outlet canyon. Lake overflow events include some of the largest floods in the Earth's geologic history, and have the ability to do significant amounts of geomorphic work in short periods of time a process that can teach us much about the speed at which topography responds to surface water flow erosion and long-term landscape evolution (Garcia-Castellanos and O'Connor, 2018).

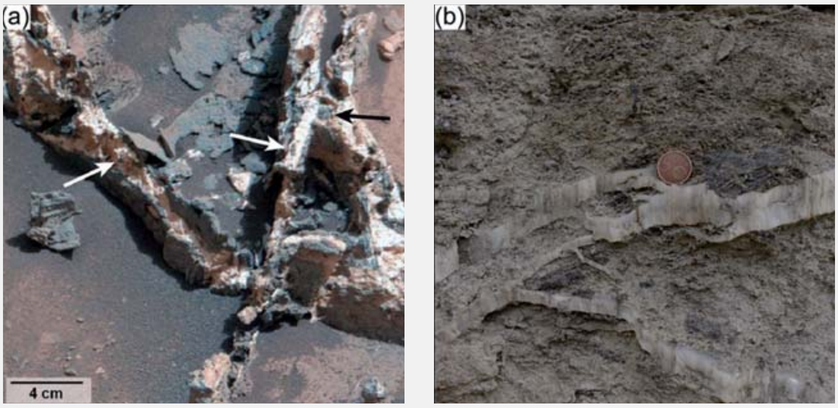
Local features interpretation (e.g. fractures) by analogy

The Mars Curiosity rover has captured a large number of images and geochemical data of evaporite veins in the area of Mount Sharp of Gale's crater. Hydrofacturing is the primary mechanism proposed to form Mars veins, thus implying fluid circulation and high fluid pressure in the subsurface. However, since Mars' gravity is considerably lower than that of the Earth's, hydrofractures in Mars would typically form at much deeper depth than those in the Earth (5-10 km). It is very unlikely that the sedimentary rocks currently exposed at Gale's crater have been at such depth. Otherwise, these veins could had not been buried, like those that are ubiquitous in the Triassic and Tertiary evaporite host rocks of the Ebro Basin and other sedimentary basins worldwide (Fig. 5). In this case, anhydrite/gypsum of such veins grew antitaxially from thin cracks or layer interfaces by the pressure exerted by the very crystal growth in a way that the vein walls were pushed apart while the mineral precipitated.

Terrestrial analogues to the hydrated minerals on Mars

The paleoenvironments on Mars, including those associated with the presence of liquid water, are reconstructed using the surface composition information from spectroscopy and other techniques implemented in space

FIGURE 5–(a) Evaporite veins within a soft host rock at the Pahrump Hills Member of the Murray Formation (Gale Crater, Mars). From Kronyak et al., 2019. (b) Antitaxial gypsum veins embedded in a matrix composed of marls, gypsum and anhydrite at the Odena quarry (Ebro Basin, NE Spain)



missions. Numerous terrestrial analogs are being used to find the origin of the clays or the salts that dominate the geological record of the Noachian and the Hesperic ages respectively. Mineral paragenesis of terrestrial hydrothermal, volcanic, or lake environments help constraint the conditions that could exist on Mars and are critical to plan future exploration missions.

Terrestrial analogues to Ceres resurfacing features

Ceres dwarf planet has a heterogeneous crust, formed by water ice, salt and silicates. The large number of domes on Ceres' surface indicates geological activity, which origin has been attributed to cryovolcanism. Alternatively, some authors have proposed that the formation of these domes is due to water ice flow within a heterogeneous crust, a process directly analogous to the formation of salt domes in the Earth. Diapir and dome formation in the Earth due to salt tectonics is a process where low-viscosity, low-density (LVLD) salts flow relative to higher-viscosity, higher-density (HDHV) sedimentary rocks, when they are affected by differential loading. According to this, the LVLD water-ice rich layers could flow relative to HDHV salt and silicate layers, driven by differential gravitational loading. Different scenarios can be assumed as the cause of the differential loading, such as the lateral thickness variation of the water-ice layer or simply by impact craters.

Terrestrial analogues to the deep seafloor composition and activity within icy moons

Oceanographic and Antarctic investigations on the Earth are helping to understand some chemical and physical aspects of the oceans and potential aisle liquid water reservoirs within the icy moons. Hydrothermal vents are claimed to sustain the geological and biological activity at the seafloor of the icy moons without sunlight from their discovery on the Earth some decades ago. Antarctica subglacial lakes are used as test case for exploring icy moon liquid water reservoirs (ice penetrating radar interpretation, drilling technologies, low temperature extremophile environments). Recently, deep-sea brines are investigated. They are poly-extreme environments on deep oceanic basins at Earth, where sharp brine-seawater interfaces with steep gradients of e.g. salinity, temperature, density, and O_2 are formed. They show associated tectonic activity and some evaporitic layers of the geological record were formed as trapped brines in local topographical depressions. Far from be sterile, new extremophiles has been detected and isolated, so due to their unique nature these deep pools should be prioritized as targets for Astrobiological-based research.

3.5. Technological challenges

From a technology perspective, not all solar system exploration missions face the same challenges. If we start from inner planets, high temperatures are perhaps the main drawback: Venus, one of the most scientifically attractive, reaches temperatures on its surface above 673 K , but the main problem is the large oscillations in the day-night cycle. Similarly, Mercury has daily oscillations from 703-93 K.

For the next decades, it is well known that Mars will be the main focus of interest. The most important space agencies worldwide identify among their main objectives, in the framework of the planetary exploration, the characterization and evolution of the atmospheric environments, as well as its interaction with the near surface. So, either with the scientific purpose of understanding

- the climate;
- the characteristics and dynamics of the atmospheric and/or subsurface environments, and their impact on the geology;
- the role of the atmosphere on the habitability potential of the planet; or
- the implications in whatever activities the mankind is thinking to develop in the red planet, the future exploration missions will inexorably require scientific instrumentation in support of these investigations and goals.

For that, the required in-situ technologies are those that will be involved in:

- quantifying and monitoring surface and subsurface chemical species, solvents capable of supporting complex biochemistry, energy sources;
- characterizing the interactions in the lower-atmosphere – surface – subsurface, including those that may affect resource accessibility;
- understanding the climate and atmosphere processes, including its dynamics, photochemistry, and energy transferring;
- developing and improving models and simulations to extend discrete-site knowledge into a broader mapping (even at a planetary level) – note that, for this purpose, the greater the number of environmental systems simultaneously working, the more accurate the models will be-; or, in other words, including surface sensors[1] such as seismometers, weather sensors (temperature, wind speed and direction, pressure, humidity, solar radiation), devices to characterize the properties and transport conditions of dust and other atmospheric aerosols, electric and magnetic fields, chemical species, particle detectors, geo-physical magnitudes, etc.

On the planet surface, low temperatures are quite demanding for mechanisms and electronics. Power based on solar panels has limitations due to dust accumulations. Mobility or robot movements in abrupt areas are not easy with current designs. Network of surface explorers, e.g. for environmental parameter monitoring or seismic movement recording, have been also proposed having important implications in many technical aspects, such as safe landing, communication, power consumption, miniaturization, etc. Mechanisms for deploying instruments, for manipulators, or for drilling systems are also constrained by the low temperatures. Ball bearings, gaskets, etc. are components that need lubricants to operate, and most of the materials used for space are not qualified for those low temperatures. Also, in many cases, these lose its lubricant properties at those extreme conditions. Therefore, new materials should be considered in the design of those elements. Motors are electromechanical components that need special design to operate at low temperatures.

Also, from orbit, the successful experience of Small/Cubesat missions monitoring terrestrial parameters suggests the extrapolation of this paradigm to Mars, or other bodies in the Solar System, in order to obtain a part of the aforementioned information. With the foreseen improvement of the space

1 Versus those other remote systems used from orbit or even from Earth.

transportation in the next decade, a deploy of a relatively small aircraft constellation (10-100) will allow on-orbit remote sensing and a better communication coverage of on-surface mobile sensing stations. A highly miniaturized and previously successfully tested space instrumentation need to be developed at a very reasonably cost to the maintain as low as possible the product "cost by number of elements", as it is done at any satellite constellation around the Earth. To achieve this ambitious goal, it will be necessary to make progress in the efficiency of antennas, for instance, to establish and maintain reliable crosslink with other aircrafts or with ground stations, in reconfigurable and distributed computing, smaller solar panels and more efficient batteries, high efficiency and high reliability DC/DC power converters, high resolution sensors, etc.

Bodies from the Asteroid Belt, NEO or comets are also another group of interest with specific technology challenges. Just remember the landing issue during the Rosetta mission but also the success of Hayabusa landing in Ryugu. In this group Vesta has a special scientific interest: its temperature oscillations are in the same range of Mars, and its distance to the Sun implies larger solar panels than those used for Mars mission although still in a reasonable size. Nevertheless, the main differences with Mars are the landing process, with a very low gravity, and also the mobility capability of a potential robotic exploration on its surface under those conditions.

Beyond Jupiter, the ice moons are perhaps the main exploration targets. Although the conditions of Europa, Ganymede, Enceladus, Titan or Triton are quite different, there are a number of common technology challenges, like: very low temperatures, reduced sun power availability by its distance to the Sun, low communications capabilities and therefore the need of important autonomy capabilities, unknowledge of its surface details for landing design, among others. For Europa, in addition to those, the radiation levels are extremely dangerous for the current electronic technology. In all cases, the subsurface exploration is a key goal to understand its interior, and even more in the case of Europa or Enceladus, where an interior ocean in contact to the rocky mantle or large water deposits are expected. Instruments to characterize the composition of the surface and subsurface, the internal structure and the search for life need to be adapted to these extreme conditions (see Challenge 5).

The low temperature and high radiation levels are requiring designs with a heavy protection bay where most of the electronics systems and instruments are installed. This has as a drawback that part of the landing mass available is spent in protections. This issue could be overcome if electronics circuits and components could operate at very low temperatures. For that, two strategies could be followed: i) testing the current parts and circuits at those extreme conditions to assess their performances, and determine if there are degradations, or ii) developing new parts and circuits specifically designed for that environment: new materials, different encapsulations, different concepts of thermal control, etc.

As a common point in the next stages of the exploration of the Solar System, the autonomy of spacecrafts and surface explorers is a critical aspect that must be addressed for future missions: the communications delay implies that teleoperation is not an option and so, probes (e.g. rotorcrafts, submarines) must be able to take decisions autonomously based on the information collected by its sensors, not only in the lander or robot operation but also in taking decisions about scientific exploration and the use of the instrumentation payload on board.

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