# VOLUME 12
# OUR FUTURE? SPACE COLONIZATION & EXPLORATION

**Topic Coordinators**
Luisa Mª Lara López & Gildas Léger

CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030

Challenges coordinated by:
Jesús Marco de Lucas & M. Victoria Moreno-Arribas

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## *CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030*

What are the major scientific challenges of the first half of the 21st century? Can we establish the priorities for the future? How should the scientific community tackle them?

This book presents the reflections of the Spanish National Research Council (CSIC) on 14 strategic themes established on the basis of their scientific impact and social importance.

Fundamental questions are addressed, including the origin of life, the exploration of the universe, artificial intelligence, the development of clean, safe and efficient energy or the understanding of brain function. The document identifies complex challenges in areas such as health and social sciences and the selected strategic themes cover both basic issues and potential applications of knowledge. Nearly 1,100 researchers from more than 100 CSIC centres and other institutions (public research organisations, universities, etc.) have participated in this analysis. All agree on the need for a multidisciplinary approach and the promotion of collaborative research to enable the implementation of ambitious projects focused on specific topics.

These 14 "White Papers", designed to serve as a frame of reference for the development of the institution's scientific strategy, will provide an insight into the research currently being accomplished at the CSIC, and at the same time, build a global vision of what will be the key scientific challenges over the next decade.

## VOLUMES THAT MAKE UP THE WORK

1. *New Foundations for a Sustainable Global Society*
2. *Origins, (Co)Evolution, Diversity and Synthesis of Life*
3. *Genome & Epigenetics*
4. *Challenges in Biomedicine and Health*
5. *Brain, Mind & Behaviour*
6. *Sustainable Primary Production*
7. *Global Change Impacts*
8. *Clean, Safe and Efficient Energy*
9. *Understanding the Basic Components of the Universe, its Structure and Evolution*
10. *Digital and Complex Information*
11. *Artificial Intelligence, Robotics and Data Science*
12. *Our Future? Space, Colonization and Exploration*
13. *Ocean Science Challenges for 2030*
14. *Dynamic Earth: Probing the Past, Preparing for the Future*

*CSIC scientific challenges: towards 2030*
**Challenges coordinated by:**
Jesús Marco de Lucas & M. Victoria Moreno-Arribas

**Volume 12**
***Our Future? Space Colonization & Exploration***

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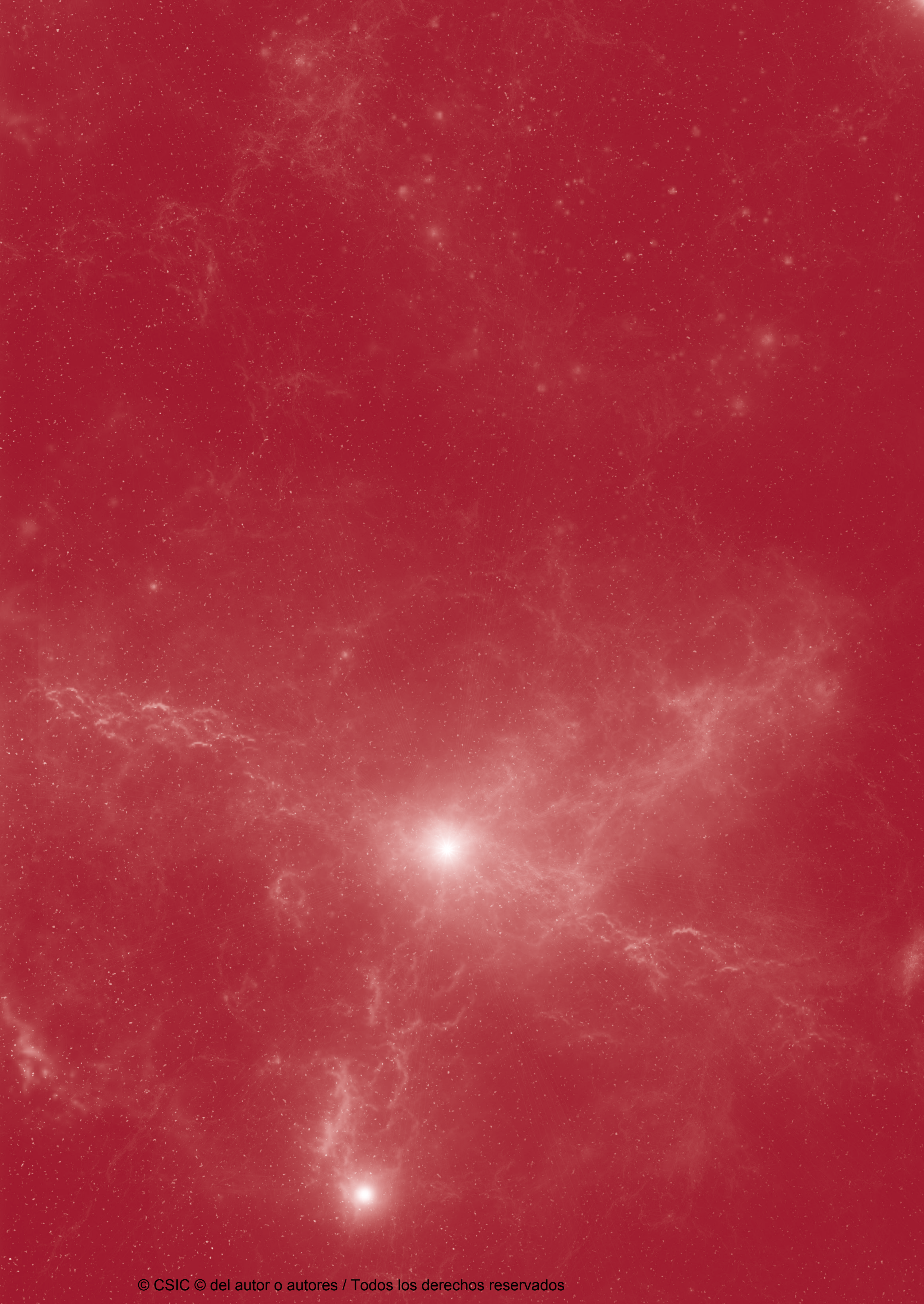

## ABSTRACT

The exploration and colonization of the outer space represents a foreseeable future for the Humanity. This endeavour involves deepening our knowledge about the formation and evolution of the solar system, of other planetary systems, emergence of life (and its prospects once it exists), the interaction between Earth and Space (particularly with its Sun) and the impact of space conditions (radiation, gravity, etc.) on Earth-borne organisms. Materialization of this exploration and colonization currently drives technological developments in several fronts as optics, electronics and sensors just to mention a few. Other aspects as well law & ethics, psychology, biology, etc., cannot be discarded.



## KEYWORDS

solar system bodies | artificial intelligence | energy supply | life | extremophiles | biochemistry | protoplanetary disks | (exo)planetary systems | geophysics | space weather | paleoclimate | climate change | the sun | impact hazards | extra-terrestrial human settlements | biology | psychology | health | altered gravity | radiation

# OUR FUTURE? SPACE COLONIZATION AND EXPLORATION

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## EXECUTIVE SUMMARY

Humanity undoubtedly feels the need to explore and discover. On the metaphysical side, there are no boundaries to knowledge and science endeavour is thus endless. On the physical side, however, there are few places on Earth that cannot be reached, and Humanity has naturally set its eyes to the ultimate boundary: Space. Infinite, mostly unknown, utterly challenging, it has fascinated Humanity since its very beginning.

In what Space Science is concerned, CSIC is in a good position to tackle some of the most interesting challenges. The wide variety of its research institutes and the efficiency of its personnel are strong assets for such a multidisciplinary goal. That being said, any prospective attempt in the identification and definition of Challenges and Global Objectives for the near future, as well as for long-term, must have in mind that Spain is an active member of the European Space Agency (ESA) contributing to its policies and strategies of research. Even in practical terms, access to space and/or ground-based facilities is unavoidably mediated and facilitated by ESA or by other space Agencies through international collaboration.

In an effort to organize the huge diversity of research lines involved in Space Science, this document gathers 6 main challenges. Each of them puts the light on a specific section of that big picture but should, by no means, be considered a watertight compartment.

The use of space resources for exploration, in particular the **In Situ Resource Utilization** (ISRU) may be possible thanks to recent advances in knowledge of the Moon, Mars and near Earth asteroids, and the emergence of new technologies and increased participation of private sector in space activities. By 2030, the potential of lunar resources will have been established and space resources will be used to obtain water, oxygen, metals and other materials from ice stored in the polar caps and regolith on the surface of the Moon. New technologies for this will have been developed and demonstrated. Human presence at the Moon, sustained by local resources is expected by 2040.

In addition to Mars and the Moon which are clear targets for Human exploration, other bodies will be the destination of unmanned **Voyages to the Solar System**. Venus is our closest neighbour in the Solar System. Despite its similarity with Earth in size and mass, its atmosphere is radically different which makes it an objective of choice for planetary modelling. Icy moons, like for instance Europa, Ganymede or Titan are also quite different from rocky bodies like Earth. Some have been proven to shelter deep oceans under an icy crust providing some of the key elements (water, heat and chemical elements) for extra-terrestrial life to emerge and be sustained. Characterizing geological activity and phenomena like cryomagmatism or tidal heating, is of particular importance. Deciphering the origin of the solar system is a goal sustained by these space missions but also by the study of terrestrial analogues.

Earth, as every body of the Solar System, strongly interacts with its environment. **Space-Earth interaction** produces threats and opportunities for our Society. Space Weather is a discipline whose goal is to forecast the effects of ionizing particles coming from Space (mostly from the Sun but also from deep space). Such effects could be very deleterious to our modern technology. Radiation from the Sun and from the outer space (as the galactic cosmic rays) also induce atmospheric changes that can have relevant Climate effects. Increasing our understanding of these phenomena involves considerable observational and modelling challenges of the Sun, the Atmosphere and the magnetic fields that mediate these interactions. In addition, monitoring and detection of potentially hazardous asteroids is another topic addressed by this challenge: not only because of the collision risk but also because asteroids are a worthwhile object of study per-se as they are remnants of the early phases of the solar system, the building blocks of the planets and the source of the water (essential for the emergence of life) on our planet.

**Sustaining Human life in Space** is a requirement for long-term exploration and extra-terrestrial human settlements. Space is a harsh environment that can have strong consequences on health. Gravity and radiation can impact tissues, brain development, the reproduction function, aging processes etc. Understanding these impacts and finding proper countermeasures is thus fundamental. As well, sustainable food is also of utmost importance. Basic food sources, both vegetal and animal, have to be adapted from Earth. The same can be said for microorganisms that perform a set of valuable functions: sewage, food fermentation, soil adaptation... Most of these aspects will require thorough molecular biology studies. This enormous amount of -omics (genomic, epigenomics, proteomic, etc.) information shall be gathered in a structured database.

The challenge entitled "**In search of Life**" addresses several aspects from the most fundamental to the most practical ones. The question of the origin of life in the universe is closely related to the development of molecular complexity (see Volume 9 of this series), and this challenge focuses mostly on the emergence of biological precursors. The search of Life beyond the solar system is mostly based on the study of exoplanets and the characterization of their habitability conditions. A deeper knowledge of extremophiles and Earth analogues allows to refine the boundaries of these habitability conditions, though the search of life forms should also envisage the possibility of evolution of life based on silicon, ammonia, and sulphur. Finally, the search for extinct and extant life in the solar system can rely on direct exploration missions, closely related to the second challenge described above. It is an ambitious and pluri-disciplinary approach that involves expertise in different fields: astrobiology, astrophysics, biophysics, (astro)chemistry, geology, mineralogy, geobiology, palaeontology, microbiology, lichenology, phycology, botany, and mycology, among other.

The purpose of the last challenge is to assess how to contribute with breakthrough materials and components to the new challenges imposed by the future space programs. Taking into account CSIC global mission and its internal strengths, we identified research axes where CSIC could significantly contribute to **push the limits of several space technologies**, thus enabling novel space-related studies and missions. These challenges are i) increasing the sensing and detection ranges, ii) ensuring functional safety in the data storage and analysis on-board systems, iii) optimizing the energy generation and management, iv) controlling the radiation impact on personal and equipment. To address these challenges, we need to coordinate multidisciplinary teams specialized in materials science, optics, high energy physics, micro-nanoelectronics, biophysics or astrophysics. These challenges also require the industry to actively participate in a collaborative frame and not only in the commercial one.

CHALLENGE 1

# IN-SITU RESOURCES UTILIZATION

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## 1. INTRODUCTION

In-situ resource utilization (ISRU) is the practice to generate own products with local material, thinking in humans or robots working or staying on other solar-system bodies, like asteroids, the Moon or Mars.

The development of ISRU methods for the deep exploration of space and in particular for the exploration of Mars will become increasingly important in the following decades. As it is impossible to transport from Earth the required amount of some critical commodities, raw products need to be collected and transformed, in-situ, through new processes that are yet to be defined and tested.

Some of the most important products that need to be produced include oxygen, water, and methane as well as construction and radiation shielding materials. Among the new technologies that are being considered, additive manufacturing (or 3D printing) of lunar and Martian regolith is a possibility. The regolith is the layer of loose, heterogeneous surface deposits covering the solid rock. It includes dust, soil, broken rock and other related material present in all the planetary surfaces. Other efforts focus on extracting volatiles from the regolith, and this requires, in turn, new processing technologies and an extensive effort on mapping where the most critical resources (water, regolith with useful volatiles, metals, salts) may be concentrated and at reach.

The ISRU will require processes such as drilling, collection, storage, sorting, and chemical processing of lunar/asteroid/martian regolith to synthesize oxygen, water, and metals. Those extracted resources can be used as fuels for propelling rockets, life support consumables and building materials for a lunar/martian base. Concentration rates of those resources in the regolith are affected by the particle size. Regolith on the Moon, Phobos, Deimos (both are natural satellites of Mars) and Mars or asteroids is also of high interest. In particular, the lack of wind and water on Moon for example, allows regolith dust grains to maintain sharp and jagged edges, which increases its abrasiveness compared to powders we are familiar with.

Promising locations on the Moon, for example, for ISRU are those with ice: water can be used for life support and fuel, and ice is very easily separated from rock. The first lunar ISRU missions are focused near the Moon's south pole. A widespread presence of water ice has been detected in the permanently shadowed areas of the Polar Regions in the Moon. These deposits could be a valuable resource of hydrogen and oxygen for life support and fuel[1]. They aim to solve operational problems in the extreme cold of permanent shadow and determine the distribution of volatiles, including non-ice volatiles like hydrogen or carbon dioxide.

Mining proposals are focused on purely robotic flights. Space mining will likely start with extraction of water from the Moon and accessible near-Earth asteroids (NEAs). It's estimated that the Moon contains amounts of water contained in ice sheets found in 'permanently shaded craters'. Within about 40 of these craters, there are 600 million metric tons of water ice[2] this amount would be enough to launch one space shuttle per day for 2.200 years. Hydrogen can be extracted from water to be used as jet fuel, or to be used to drink and produce food, as well as to provide radiation protection.

In addition, the lunar soil is that 40% of it is made up of oxygen. This makes the Moon a very attractive option to host a space refuelling station, and in fact, there are multiple proposals to this effect. While companies are looking at extracting water from regolith, the exploration community is also interested in its insulating properties and how well it can provide protection from cosmic rays.

However, ISRU is not limited to water. Metals mined from extra-terrestrial bodies can be used to 3D print spaceship components. In fact, 3D manufacturing in space started in 2014, when the International Space Station's (ISS) 3D printer produced its first product. The primary goal of the project was to verify that a 3D

1 https://www.esa.int/About_Us/Business_with_ESA/Business_Opportunities/Water_and_oxygen_made_on_the_Moon
2 NASA Radar Finds Ice Deposits at Moon's North Pole' (NASA) www.nasa.gov/mission_pages/Mini-RF/multimedia/feature_ice_like_deposits.html

printer could function in a microgravity environment and developing materials strong enough to withstand space's vacuum, not achieved up to now. It remains to be seen whether metals extracted from space will be suitable for 3D printing. This kind of printing offers a potential means of facilitating lunar settlement with reduced logistics from Earth. As an example, the lunar material must be mixed with magnesium oxide. This turns it into 'paper' to print with. Then for the structural 'ink' a binding salt is applied to convert material to a stone-like solid. The current printer builds at a rate of around 2 m per hour, while a next-generation design should attain 3.5 m per hour, completing an entire building in a week[3].

On the other side, microgravity environments allow precise control of liquid and gas convection. The space vacuum also allows the creation of very pure materials, minimizing their defects. In addition, extreme temperatures in space, often necessary in the manufacturing process, are available.

ISRU philosophy to use the material on an extra-terrestrial body (i.e. for construction, isolation, fuel provision) can be divided in various actions: Prospection, Preparation or Exploration, Extraction, Construction and finally, Protection of the environment. In this chapter we want to present the state of the art on the ISRU, and discuss how CSIC as a national research institution can get involved on in a short, medium and long terms.

## 2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

The Exploration Roadmap of ESA and NASA to fulfil Human and Robotic exploration of Mars have been defined, and the first steps are now being implemented. However, the requirements on propellant mass do not allow for large landed missions. The future Mars Ascent Vehicle for humans will require about 7.0 mega tons of methane ($CH_4$) and 22.7 mega tons of oxygen to lift-off from Mars, back to Earth, with four crewmembers. This represents about 80% of the weight of the spacecraft, and this is to date one of the most critical problems that inhibit the human exploration of Mars. In addition to propellants, such as $CH_4$, water is another critical product, both for life-support systems and its possible transformation into hydrogen ($H_2$) and oxygen ($O_2$) for propulsion or again for life-support systems. ISRU is thus a new research activity which is being supported both by NASA and ESA.

3 http://www.esa.int/Enabling_Support/Space_Engineering_Technology/Building_a_lunar_base_with_3D_printing

CSIC scientist should participate in this kind of missions in the future. Nowadays, they are participating in building hardware and producing software of some instruments presents in mission to Mars, Mercury, Jupiter, asteroids and comets. This participation also needs getting involved in the interpretation of the data acquired by those instruments. From the scientific point of view, CSIC scientist should get involved in more missions to data acquisition on the Moon, Mars and asteroids/comets with the final idea to have first access to the data on where the key material abundances are present in the surface or sub-surface of those bodies.

**2.1. Economic Impact**

Space resources will play a critical role in future in-space economies. Incorporation of space resources into exploration missions will reduce costs and improve their economic viability. Space resources technology has multi-sector, near-term commercial value in existing terrestrial markets.

Using space resources is expected to create socio-economic benefits in three major areas. The first refers to the space resources utilization industry itself. The second area includes development of knowledge and technology in technical domains, such as materials science, manufacturing, additive manufacturing, robotics, and data analysis, which are expected to provide indirect benefits of the order of 2.5 B€ over 50 years. Third area refers to expected contribution to wider effects with a strong contribution to social and strategic benefits by enabling space exploration and development, and with some contributions to environmental benefits by lessening dependence on Earth's finite resources. Finally, a broader contribution to social and environmental benefits is expected by decreasing dependence on Earth's finite resources.

Exploitation of resources in situ, such as water, regolith or metals present on the Moon, Mars or nearby asteroids and comets, requires the establishment of new supply chains for effective activation. Although the first operational applications are expected to be ready in the next decade, preparatory steps are being taken today to develop enabled technologies and obtain prospective information on future exploitable space resources.

Companies, space agencies and other organizations must detect opportunities and anticipate future needs to create value chains in the use of space resources for their successful development. Although the use of in-situ space resources still has uncertainties, analysis of the different value chains reveals promising important aspects for the future of the industrial sector.

A recent study commissioned by the Luxembourg government[4, 5] has analyzed the potential economic impact of space resources utilization through an assessment of the associated future markets and value chains. The report concludes that market revenues of 73-170 B€ are expected from space resources from 2018-2045 supporting 845 thousand to 1.8 million full time employee years. Potential exploration cost savings (or equivalent cost of activities that would otherwise not have been undertaken) to end-users are estimated to be 54-135 B€. Technology and knowledge spill overs are estimated to be of the order 2.5 B€ over 50 years, which might be considered conservative based on recent interactions with terrestrial industry. Additional benefits are predicted based on industrial clustering, development of new standards with contributions to social, strategic benefits, environmental benefits.

Preparing space resource utilization will only be achieved through the combined efforts and resources of a broad and diverse community of actors. Cross-sector community will be involved in ISRU, including robotics, construction, engineering industries, geology mining or biotech companies.

ESA will have to actively engage with actors from different sectors and different scales, from Start Ups to large multinationals; from universities to public sector agencies, from industry on Earth to industry in Space. ESA will facilitate their participation and integration in the community and will ensure the effective construction of networks and communications within the community.

On the other hand, Spain, as an active member of ESA, should also get involved in it. It is of particular interest for the CSIC to actively participate in this development process, generating knowledge and new technological developments for its transfer to the space industry and also scientific participation on instruments/mission to the mentioned bodies.

Meanwhile, research and technology development are required on Earth. In parallel, flight opportunities across several missions in an ISRU preparation campaign. This is likely to be driven by the availability of flight opportunities, the capabilities of international and commercial missions and the timeliness of payload development and readiness for flight.

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4 Opportunities for space utilisation: future markets and value chains, study, (2018).
5 https://space-agency.public.lu/dam-assets/publications/2018/Study-Summary-of-the-Space-Resources-Value-Chain-Study.pdf

## 3. KEY CHALLENGING POINTS

### 3.1. Prospection

Space resources will be a major international topic in the next decade. ESA's position as a leader and an enabler for European science and industry would ensure that Europe has a role to play in the medium to long term utilization of resources in space, whilst delivering social and economic benefits in the near term here on Earth, in accordance with the international legal framework.

In that context, which are the most probable candidates for doing ISRU?

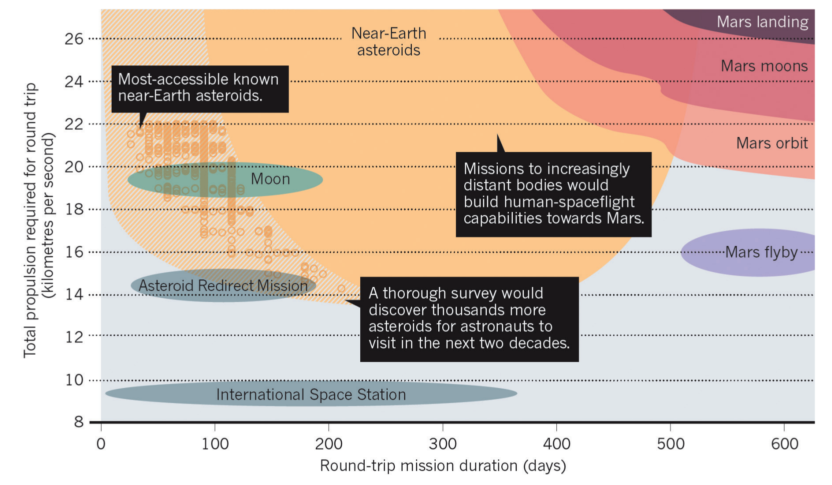
The most immediate candidates to be colonized are the Moon, some near Earth asteroid and Mars. Figure 1 presents the viability to reach each target. It is represented the total propulsion required for a round trip to the target versus the duration in days. The total propulsion is directly related to the cost of the mission.

As can be seen, the most accessible place in space is the International Space Station (ISS). Astronauts aboard the ISS today receive regular cargo shipments from Earth with food, air, water, rocket fuel, and spare parts. Then, there are a few, for the moment, NEAs that can be reached. Also, investing in asteroid discovering surveys can identify more small NEAs to be reached in short missions. The next, large body, with mineral resources, which can be used, is our Moon and in a long-term vision, Mars is the preferred target.

NEAs are easy to reach, in some cases, but still difficult to stay on target and extract materials. Once we are on the surface of the NEAs, the main problem is to anchor the ship to an object of one to several kilometres in size and install the mining machinery. Mars has the opposite problem, it is easy to install the mining machinery but it is still difficult or expensive to reach and stay there.

In this sense, the first utilization of space resources contemplated by the European Space Agency (ESA) will be on the Moon; a source of water, oxygen, metals and other materials. The strategy covers the period up to 2030, by which time the potential of lunar resources will have been established through measurements at the Moon, key technologies will have been developed and demonstrated and a plan for their introduction into international mission architectures will have been defined. Priorities for investments will be based on the available materials at the Moon, their applications in exploration and the demonstrated interest from terrestrial industries to partner and co-invest.

**FIGURE 1–**Adapted from Binzel (2014).




The resources of Mars and asteroids are also important considerations and activities at the Moon should prepare the way for future utilization at these locations.

In particular, the specific objectives of the ESA Space Resources Strategy, focusing on the Moon, for the period 2020-2030 are:

- Confirm whether space resources can enable sustainable space exploration and which resources are of primary interest for this purpose.
- Identify and create new scientific and economic opportunities for European industry and academia in the area of space resources and position European science and industry to take de advantage of these opportunities should they arise.
- Create benefits in the areas of technology and processes innovation for sustainability in Space and Earth
- Engage new industrial actors in the space endeavour
- Establish ESA's role as part of a broader community of international, public and private actors and create new international and commercial partnerships.

***The Targets***
What kind of material can be found in Mars, the Moon or the asteroids?

Mars and the Moon are basaltic differentiated bodies, composed by a metallic nucleus, an olivine mantle and a basaltic surface. Asteroids are shattered remnants of planetesimals, bodies that never grew up to became planets or fragments of larger bodies that suffered catastrophic collisions. Those, asteroids can be perfect testers of the interior of larger bodies, a unique opportunity to be in contact of a planetary nucleus or mantle. On Mars and the Moon, we will only have access to the surface or sub-surface of the bodies, the first kilometre from the surface, meanwhile, the surface of asteroids can be samples of any part of a shattered body or a pristine rock from the beginning of the solar system formation.

There are metallic asteroids that sampled the iron nucleus of a differentiated body like Mars or the Earth. This is an excellent opportunity to obtain minerals formed at high pressure and temperature like into the nucleus of a planetary body. Also, asteroids could be part of the hydrated mantle of a body like Ceres, where the interior models indicate the presence of a liquid ocean in the interior.

The extraction of material from the surfaces of Mars or the Moon are limited to those related to basaltic formation or deposited into the surface along millions of years. On the sub-surface of Mars, we are expecting to find hydrated materials formed when Mars has a liquid ocean on the surface. Also, the water and carbon mono(dio) oxide can be extracted from the polar regions.

In summary, in the near future investment on discovering new and easily reached NEAs is mandatory to have more targets in the list. At the same time, and as is currently doing by different space agencies is the detailed research on the characterization of the surface of the Moon. And finally, in the long term, the surface and sub-surface characterization of Mars need to be studied in detail, where a manned mission is planned in the next 20 years.

## 3.2. Preparation and Exploration

For the preparation of the site to be explored, we have our own reference that is our own Earth. The knowledge on the internal (shallow and deep) structure of the Earth as well the exploration of Earth's resources relies on a multitude of different geophysical and geological measurements and subsurface imaging approaches. Data acquisition, processing, structural imaging and interpretation techniques are essential and constantly improving. They provide us with new constraints, such as needed for fundamental understandings on geodynamic processes, geo-risks, and exploration of resources.

Similar strategies can be applied on any extra-terrestrial body. After decades of observation and study of the planets and bodies from the distance either from the Earth or from orbiting instruments the main challenge in the next decades will be the exploration of the sub-surface, difficult to assess from the distance. The best way to study in detail the surface and more important the sub-surface of a body is to put appropriate instruments on the surface of the targets. Radar technology and radio frequencies instruments installed on in-orbit satellites can also be used to characterize the sub-surface in remote mode.

Right now, in 2020, the sub-surface structure of the NASA mission's InSight landing site on Mars is being studied using different direct, in situ geophysical investigations. For instance, the magnetic field at the landing site is ten times stronger than was predicted from satellite data (Banerdt et al. 2020). Its interaction with solar winds affects surface environments and is being used to study the magnetic weather, crustal magnetization, and dynamo, among others. Further, with InSight for the first time a seismometer has been placed on the surface of another planet. The first seismic measurements reveal many small magnitude Marsquakes that together with the seismic response from dust devils are now being used to constrain the very shallow and crustal structure of Mars (Lognonne et al 2020). Seismic wave speeds and attenuation of energy permit to constrain the seismic structure and to compare it to Moon and Earth. Different structural discontinuities are being revealed and mapped owing to the identification of reflected waves. Seismicity is low compared to Earth. In the first 10 months, about 460 events (quakes, landslides, etc.) have been detected of which 174 have been studied more into depth.

At present, revealing the interior structure and dynamics relays on robust single-station approaches. The problems to tackle are non-unique, and data might be limited due to unfavourable deployment and environmental conditions. For instance, at the InSight landing site temperatures vary during a martian day over 70 $^{o}$C and winds are shaking the lander and instruments. Thermal stresses and lander modes are being recorded and can mask smaller signals in the acquired data. New capable methods for the exploration of extra-terrestrial bodies need to be developed and extensively tested to image and monitor the subsurface with less ambiguity and higher resolution to efficiently guide any further exploration or resources.

*Exploring the subsurface*

First direct information on the rocks and composition of the Moon, asteroids, and Mars came from surface samples collected in the frame of the first landed missions. Those surface samples are part of the so-called regolith, the uppermost layer covering the surface. But regolith samples mainly represent the altered and unconsolidated surficial horizon that is not necessarily representative of the composition of the rocks in the sub-surface. Therefore, the exploration of the sub-surface is necessary to learn on the actual structure and composition of the planets and bodies under investigation. Also, we should be ready to face many open questions on the present-day activity and active geodynamic processes (active faults, plate tectonics, volcanic activity) and the evolution in each case, as we already known this can be different for the different bodies. Most of these should be proven during the exploration of the internal structure and dynamics.

As of today, we can envisage the sub-surface exploration will progress by applying geophysical methods based on our experience in exploration of the Earth's sub-surface but considering the specific constraints and particular and specific environmental conditions on different planets and exploration objectives. Specific conditions like temperature, gravity, magnetic field and presence (or absence) of fluids in the sub-surface will be a major constrain for the applicability of some of the standard geophysical exploration methods and existing instrumentation. Therefore, it will be necessary to implement innovative instrumentation to achieve these challenges.

The common approach and steps using available methodologies for Earth exploring would be to start obtaining a big picture of the sub-surface and then go to the detail, using large coverage methods first (remote sensing and satellite info), then geophysical surveys from close to the surface (e.g. drone surveys), from the surfaces with instruments deployed on the ground and finally achieving direct measurements by drilling, borehole logging and sampling and borehole monitoring.

We can envisage following these steps and the specific techniques that could be applied, from the use of remote sensing exploration methods (e.g. satellite based) as first step a second and next step would be the direct exploration from the proximity of the surface (i.e. low-frequency geo-radars, spectrometers) and finally directly from the surface: all three steps are complementary and provide us with different types of data:

- Surface geophysical measurements and monitoring applying seismic, magnetic, electromagnetic, gravity and temperature geophysical methods, where applicable. Both airborne (when possible) and also using equipment and instrumentation deployed on the surface of the planet or body investigated would provide us with indirect measurements of the sub-surface and with a first picture on the structures and layers underlying the regolith. These methods of exploration are used always in the first phases of the sub-surface exploration on Earth because large areas and volumes of rocks are investigated and help to identify anomalies in the sub-surface and possible targets and objectives for drilling, the next step. This is the general approach when the exploration targets are sub-surface resources (e.g. hydrocarbons and mineral resources).
- Drilling and borehole/down-hole sampling, geophysical logging down-hole logging and imaging and down-hole monitoring are direct types of tools and measurements for investigation of the subsurface applied on the Earth. It is expected that first planetary drillings will cover the first meters of the sub-surface but future drilling should reach hundreds to thousands of meters, following the evolution of planetary drilling technologies. As it has been stated in recent attempts to drill in Mars, the drilling techniques should be improved and refined in the next year in order to achieve successful sub-surface drilling and sampling. At the same time new borehole logging and monitoring tools will be developed and adapted for the exploration of planetary sub-surfaces. These tools would be used inside the boreholes for continuous measurements, profiling and imaging (with optical and hyperspectral cameras) to map mineral content, textures and composition of the rocks at depth and also on possible fluids and gases. And specific instrumentation would be dedicated to monitoring.

Borehole instrumentation is somehow protected from surface extreme conditions and this would be an advantage for the quality and reliability of the measurements performed, usually less noise and more stable conditions during extreme environmental changes experienced during day and night and in case of storms.

It is convenient to highlight at this point that, even in case of successful drilling and logging, we would be able to reach only the first meters or kilometres as drilling capabilities are nowadays in the range of 12 km (vertical or horizontal) on the Earth. To investigate and learn more on the structure and composition of deeper levels we would need to apply again indirect geophysical methods to investigate the deep structure and composition using methods like seismic monitoring.

***Scale and scope***

Using the tools and methods presented, the exploration would offer the first big pictures of the sub-surface and an outline of large structures (plates, sutures, major faults and faults systems, large volcanoes and major boundaries between layers of different composition). Also, the possibility to detect large ore bodies rich in mineral resources, based on geophysical anomalies characterized and interpreted by experts. This would be the large-scale scope of the exploration. Then by drilling and logging in boreholes we would obtain direct and detailed mineral composition, gases and fluids as well as rock textures, structures and geo-mechanical properties can be defined in detail, and also confirm or refine the geophysical interpretations and models obtained from geophysical methods.

Sub-surface planetary exploration has already started and we know about first results obtained from the sub-surface. Seismic sensors were deployed on Mars (InSight mission) detected possible on-going seismic activity (Banerdt et al., 2020) that could be related to active geologic processes in the subsurface. Also, recently subsurface imaging was achieved using geo-radar instrumentation deployed by the Chinese rover Yutu-2, mission operating for months on the Moon's far side (Chunlai Li et al 2020). These recently published results were obtained using a 500 MHz LPR (Lunar Penetrating Radar) and revealed the layered structure of the first 40 m section of the lunar sub-surface. These results indicate the presence of granular and porous rocks and outline a layered structure of rock bodies underlying the 12m thick regolith, homogenous and mostly composed by fine materials. Also, the internal textural properties consisting of heterometric boulders embedded in finer grain granular material. This can be considered one of the first and successful exploration achievements and first results of exploration using conventional techniques developed and used on the Earth as "ground penetrating radar". Chang-4 successfully landed on the eastern floor of Von Karman crater within the South Pole Aitken Basin. The Lunar Penetrating Radar (LPR) was on-board the Yutu-2 rover. The radar is a dual frequency GPR system, operating at 60 Mhz (low frequency) and 500 Mhz (high frequency), with a frequency band of 40 to 80 Mhz and 250 to 750 Mhz, respectively (Chunlai Li et al, 2020).

### 3.3. Extraction

The possible sources of extraction of resources are the regolith present on the surfaces (i.e. Moon, asteroids, Mars), dust and gases from the atmospheres if present. After the prospection of the place to understand the resources and determine how abundant is, and the distribution of the resources also with the hetero/homogeneity we need to determine the energy required to evolve or separate the resource. Martian and Lunar regolith contain valuable elements for many applications. Some examples are iron (Fe) and magnesium (Mg) for aerospace applications, silicon (Si) for solar cells, sodium (Na) or Mg for the preparation of binders' form cement like materials, oxygen (O) for the life support or propellant. Terrestrial mining technology to recover metals from metal oxides is very mature. But processes generally use large volumes of chemicals that are often caustic or corrosive or thermal methods that require high-energy inputs.

How can we extract all these materials from the regolith? In 2018 the European Space Agency organized a workshop called "Towards the use of Lunar Resources" where participants identified potential technologies that are of interest for producing oxygen and/or water from lunar regolith:

- **Hydrogen reduction:** The hydrogen reduction process has some appeal in ISRU because hydrogen is available as a gaseous reagent on the Moon and at other destinations that also harbour water. In its first stage of development, the process aims at reducing available minerals such as Ilmenite ($FeTiO_3$) found on the Moon to produce oxygen. Extract oxygen from regolith by high-temperature reaction of iron oxides in the regolith followed by water electrolysis. The reaction is limited to iron oxides, which forces the selection of a soil where these oxides are abundant and/or the use of techniques to beneficiate the regolith to obtain a soil with a larger portion of iron oxides. The simplicity and the relatively low operating temperatures of this technology make it a good candidate for early demonstrations of oxygen extraction on a limited scale during robotic space missions.
- **Carbothermal reduction**: This is a mature terrestrial technology using carbon to reduce metal oxides (ores) to produce metals such as iron in blast furnaces and metallurgical grade silicon. The same process can be used to reduce minerals containing various metallic oxides in the lunar and other asteroidal or planetary regolith to produce oxygen.
- **The FFC Cambridge process:** This process is an electrochemical method in which solid metal compounds, like oxides, are cathodically reduced to the respective metals or alloys in molten salts.

- **Molten electrolysis:** This is the process used to extract aluminium from bauxite, an ore, which also contains impurities such us iron oxide and silicon dioxide. Until now, only laboratory studies with lunar regolith simulants have been published (Ellery et al. 2017) among others. They formulated a concept to link the molten salt electrolysis with additive manufacturing of the metals produced. Molten salt electrolysis is used industrially for the production of aluminium, lithium, magnesium and other metals such as rare earth metals.
- **Ionic liquid (IL) electrolysis:** organic salts are molten at or near room temperature. Being entirely composed of ions, ILs have a number of properties that makes them attractive for in-space use, including electrochemical and thermal stability, low vapour pressures, and high ionic conductivity.
- **Vacuum pyrolysis:** this method is the decomposition of materials at elevated temperatures in an inert atmosphere. The focus of these pyrolyses related techniques is the production of oxygen from the regolith. Just to mention a few of them are the solar concentration, solar heating of regolith, resistive heating of regolith, sintering, regolith boiling, and more. Vapour phase pyrolysis, in principle, only requires regolith and concentrated sunlight, but faces difficulties in the separation of metals, metal oxides and oxygen in the gas stream.

Novel approaches to oxygen production are still being proposed (e.g. ionic liquids processing of regolith. It is likely, with the increased focus on lunar exploration, that new processes will be identified and the performance of the existing processes improved, taking inspiration and knowledge from other industrial and research sectors (e.g. metallurgy research for terrestrial smelting, semiconductor processing methods). There is a technological challenge in realising such processes in-situ (Schluter and Cowley, 2020).

***Extraction of elements***

In practice water ice in the inner solar system space is scarce, with exception of high latitude hidden regions in Lunar and Martian craters.

Water ice is now widely considered to be present on the lunar surface in specific locations. Using near infrared spectroscopic data from the Moon Mineralogy Mapper instrument on board the Chandrayaan-1 spacecraft, Li et al. (2018) claim to have found direct evidence for water ice at the surface of lunar polar, permanently shadowed regions. They state that the ice content dispersed in the regolith could be up to 30 wt%. These water deposits, if accurate and accessible, represent a tantalising resource that could enable many ISRU processes.

Hurley et al. (2016) estimated the total amount of hydrogen in the lunar polar volatiles to be $10^{11}$ kg. However, they also state that the radar data does indicate that the hydrogen is present either in ice grains <10 cm, or found as "hydrated minerals, adsorbed molecules, pore-filling ice, and small ice grains mixed with regolith", which would complicate the mining and processing in terms of immediate accessibility.

Water can also be extracted from phyllosilicates. Clay minerals are composed of sheets of FeO/OH, MgO/OH, or AlO/OH in octahedral configurations forming sheets with connected $SiO_4$ tetrahedral. These are common in carbonaceous chondritic asteroids, Mars and probably some Moon regions. For example, in Mars a clay common mineral is smectite. It has a layer of $H_2O$ molecules bound to Na or Ca sandwiched in between the metal-bearing sheets and adsorbed $H_2O$ on all surfaces. Such adsorbed water is released at temperatures ~100-150 °C and the bound water can be harvested by heating to ~300 °C. Once released the water or hydroxyl is easy to get oxygen by electrolysis.

In carbonaceous asteroids it was identified different types of phylo-silicates that might be source of water. The meteorite specimens of the most hydrated CI, CM and CR chondrite groups contain up to a 12% of water in mass, but that is an (probably biased) upper limit. In general, the abundance is 1-4% in mass (Trigo-Rodríguez et al., 2019 and references therein). Volcanic glasses in the Moon and Mars also contain water, so their well-localized deposits could be an additional source of water.

Oxygen can be obtained by $H_2$ reduction of ilmenite (Fe,Ti oxide), producing Fe, $TiO_2$ and water (again by electrolysis we can get $H_2$ and $O_2$). Oxygen also can be obtained from some phylo-silicates and oxides present in the regolith. In basalt-rich Lunar and Martian terrains the water is available as the (hydroxyl)-bearing phase: apatite - $Ca_5[PO_4]_3(OH,F,Cl)$.

Another source of oxygen is the lunar regolith itself, as it contains approximately 45% of oxygen per weight. As regolith is ubiquitous to the lunar surface, oxygen can be extracted from it essentially everywhere, although the composition varies considerably. The most abundant oxide is $SiO_2$, ranging from 40.7 to 47.1 wt%.

To extract oxygen from the minerals in the lunar regolith, the metal oxides present therein have to be reduced to the corresponding metals. The iron content in the lunar regolith is notably location-specific. In mare basalts, the iron content can be in the range of 14–17 wt%. Xia et al. (2019) used the Interference Imaging Spectrometer on the Chang'e_1 orbiter to determine a detailed map of the six major oxides ($SiO_2$, $Al_2O_3$, CaO, FeO, MgO and $TiO_2$) and Mg# with a resolution of 200 m/pixel. It needs to be mentioned that lunar regolith melts incongruently. Its solidus temperature, below which all of it is solid, varies between 1050 ºC and 1150 ºC and its liquids temperature, above which all of it is molten, range from 1150ºC to 1400ºC.

Water can be extracted also from apatite, but this mineral is also a useful raw material for the production of phosphorus (P) and phosphoric acid. This is because the apatite can be pyro-metallurgically treated using carbon (C) to extract P without fluxing at temperatures exceeding 1800 °C. In addition, the resulting slag phases allow the extraction of REEs.

Specific minerals are an opportunity. Rare Earths Elements (REEs) are also common in some undifferentiated bodies. On the Moon, for example, the KREEP-rich region underlies the Oceanus Procellarum and Imbrium Basin region contain the "KREEP" material: impact breccia and basaltic rocks enriched in Potassium (K), Rare-earth elements, and Phosphorus (P). The majority of lunar samples (Apollo, Luna, or meteoritic samples) contain REE-bearing minerals as trace phases, e.g., apatite and/or merrillite. Some carbonaceous chondritic asteroids contain significant amounts of REEs.

Helium-3 ($^3He$), and Helium-4 ($^4He$), plus other light chemical elements transported by the solar wind which have been implanted in the lunar regolith, so they could be also extracted, preferentially from the fine-grained component.

Organic compounds with significant amount of C are common in carbonaceous chondrites, and localized regolith-rich regions in Mars and the Moon. In C-rich asteroids is not only forming organic compounds generated by aqueous alteration-driven catalysis because metamorphosed materials have significant amorphous carbon. This is because of being heated and de-hydrated as consequence of impacts. Sometimes C-rich projectile collisions produce extremely rich clasts.

### *Conclusion*

Water can be used for life support and fuel. Oxygen can be obtained from regolith and using sunlight as power source. Hydrogen and oxygen from water will provide habitable conditions for the astronauts to breathe "quasi-atmospheres". Other minerals like phosphorous, carbon, and REE also can be obtained using different techniques.

Development of new strategies based on the use of ISRU for protection from cosmic rays (analyses of electromagnetic properties of regolith to study its feasibility as protection from cosmic rays) is recommended.

Finally, the analysis and optimization of fertility of lunar and other regoliths to achieve more self-sustaining agriculture systems at future bases need to be considered.

As an example, Alex Ignatiev (Lunar Resources, Inc., Houston, Texas) and colleagues presented the latest ideas for how to make solar cells directly on the lunar surface. A rover with a wheelbase on the order of 1–2 meter and weighing about 200 kilograms could be equipped to produce a glassy substrate a few millimetres thick on which silicon and aluminium vapours are deposited to make thin film solar cells.

Both autonomous and tele-operated robots will have a key role as far as materials extraction is concerned. Whether in combination with manned bases or as autonomous robot colonies, ISRU sites will likely have a mine and an automated mineral processing facility. Space mining robotics (and, more in general automation in process control technologies) will benefit from spinning-in/spinning-out effects from terrestrial mining technology. Specific challenges are detailed in section 4. In particular, mining and robotics technologies are mentioned in the "ESA Space Resources Strategy"[6] as enabling technologies that need research activities on Earth.

**Attention is claimed to all techniques related to extract purified minerals from a component like lunar, asteroid and martian regoliths, given priority for the lunar case in the next twenty upcoming years.**

Construction advancements in additive manufacturing or 3-D printing, may make it possible to use regolith harvested on the Moon, Mars and its moons,

6 https://sci.esa.int/documents/34161/35992/1567260390250-ESA_Space_Resources_Strategy.pdf

and asteroids to construct habitation elements on extra-terrestrial surfaces, such as living quarters and storage facilities.

Gravitational force on the Moon is 1/6 of that on Earth. In addition, the sieve system requires periodic cleaning of accumulated particles on the sieve to prevent clogging, and so the system requires a mechanical cleaning system which will make the system more complex and increase the failure risk because small regolith particles easily enter gaps in the mechanical system. Therefore, a new type of the size sorting system that reliably works in the Moon environment is necessary.

One important issue to face is a size sorting system required to increase fluidization of particle motions and increase the surface area of particles and reaction rate for the improvement of the ISRU performance (Sander and Larson, 2013). An electrostatic size sorting system has been developed (Kawamoto and Adachi, 2014). This system utilizes an electrostatic traveling wave that transports regolith particles by utilizing the Coulomb force and a dielectro-phoresis force. The travelling wave was mainly used for the cleaning of regolith particles deposited on surfaces of solar panels and optical lenses (Calle et al. 2011). While the particles were transported using the travelling wave, size sorting of the regolith was conducted by using a balance between the electrostatic and gravitational forces acting on particles, which depends on the particle diameter. In a previous study (Kawamoto and Adachi, 2014), a demonstration of particle size sorting using the electrostatic systems were experimentally conducted in a low vacuum environment (=10 [Pa]). Although the system could sort small particles less than 20 μm in diameter from the bulk of the regolith in the vacuum environment, the analysis of the particle dynamics in the electrostatic field was not enough. In particular, the effect of the particle charges, which largely affects the particle motion, was not investigated. Later, in 2016, the researchers measured the charge of each particle, and the effect of those charges on particle movements was investigated by conducting a model experiment and a numerical calculation based on the distinct element method. In addition, it was experimentally demonstrated that particles less than 20 μm in diameter were sorted from the bulk of a lunar regolith simulant under moderate vacuum conditions (~1.5×10-2 [Pa]). Masato et al (2016) developed a particle-size sorting system of lunar regolith using an electrostatic force for ISRU on the Moon to extract indispensable resources from the regolith and realize long-term explorations. The system utilizes only the electrostatic force, and it does not need gas, liquid, or even mechanical moving parts.

***Particle handling on Mars***

Dust particles on Mars have an effective radius of 1.0 μm over much of the atmospheric column below 40 km throughout the Martian year. This includes the detached tropical dust layers detected in previous studies. Effective radii range from > 3 μm below 20 km to near 1.0 μm at 40 km altitude.

The martian atmosphere typically contains 10-400 billion metric tons of dust particles ranging in diameter from <1 to >10 μm, but it is too dispersed to be acquired by rover sampling systems. Most of the particles on Mars are ferrous, susceptible to a magnetic trapping effect. The Curiosity rover includes a tool, known as the Collection and Handling for Interior Martian Rock Analysis (CHIMRA) to collect and sort samples from the Martian surface. This tool, has a system of chambers and labyrinths used to sort, sift, and portion samples. Curiosity sorts samples by flexing the wrist joint on its arm to position the turret, while using a vibration device to move material through the chambers, passages, and sieves. The vibration device also creates the right portion size for dropping material into the inlet ports on the rover deck for rock-analysing instruments (SAM and CheMin) inside the rover's body. However, it is uncontrolled manipulation of the particles, which demand new devices based on the vibration concept.

***Robotics and Artificial Intelligence technologies***

There is an increasing interest for ISRU (but also Resource exploitation for Earth) in the space community. This would allow longer and sustainable missions. In fact, to date, all that is needed (oxygen, water and other consumables for life support, propellant and materials for construction and manufacturing) needs to be transported from Earth to space. This will be especially critical for long-termed human missions.

Working in space, however, is a critical issue. Extremely harsh environmental conditions, exposition to radiations and other hazards will impose to human's minimal exposition to the external environment. Therefore, robots (both autonomous and tele-operated) will be key tools for resources discovery, extraction and transportation, as well as for (semi) automated constructions of structures such as human shelters and docking stations.

Key technologies and research topics related to these scenarios are listed below.

*Tasks*

- **Autonomous exploration/mapping** for assessment before human settlements. Prior to the landing of humans, detailed maps (including geological and meteorological features) are needed. Teams of robots can perform this task for the preparation of human arrival, but also during their stay (e.g. in search for resources, see above).
- **Automated and/or tele-operated building/assembly** of structures. Some infrastructure may already be in place before arrival of humans, assembled by autonomous robots. Additionally, tele-operated robots may be of great help in order to perform operations supervised by in-situ operators, with the purpose of reducing risks (exposition to radiations etc.). The use of locally available resources shall be considered, which connects this topic with ISRU.
- **Autonomous and/or tele-operated vehicles for logistic** (transportation of materials). Same as above.

*Technologies*

- **Autonomy**. The lack of high bandwidth and real-time communications with human operators makes autonomy and intelligence a key feature of the systems. This includes the capability of understanding their surroundings, self-localization, situational awareness, motion planning, as well as high level task/mission planning and self-awareness.
- **Multi-robot coordination.** Also related to autonomy is robot coordination. Many tasks will carry out in a more efficient ways by teams of robots that shall coordinate their activities.
- **Modularity** and (self-?) **re-configurability** for improved resilience.
- **Locomotion** in harsh environments. Legged locomotion as an alternative to wheels, especially for mining robots. Need to consider low gravity.
- **Tele-operation**. In-situ human operators to remotely operate mobile robots and/or other manipulation stations on the planet for logistics (loading/downloading/local transportation), but also for exploration/production (such as foraging or mining).
- **Energy**. (Re-)charging for underground operations or in absence of direct sunlight (e.g., the dark side of the moon).
- Geo-physical sensors for ore detection.

Construction technologies on the lunar surface are different from terrestrial ones. The community identified several technologies:

Sintering or melting of regolith: solar, microwave, laser, resistive heating. Solid structures can be built out of sintered lunar regolith and molten regolith can provide additional air tightness to the edifice.

- Regolith consolidation using binders: chemical, polymer, bio-based binders (e.g. enzymes). Most of the binders would have to be brought from Earth and space environment conditions can adversely affect binders (outgassing, radiation-induced degradation), but can also be used at their advantage (e.g. binder curing with radiation).
- Additive manufacturing (3D-printing) with extracted metals or lunar regolith was found promising as a versatile technology for construction or metallic hardware manufacturing.
- 3D-printed materials, inflatable or foldable structures could all take part in the architecture and design of the habitats.
- Basic technologies: Digging and compaction of dust to produce blocks could also be considered.

It is worth noting that the above-mentioned enabling technologies are common to other ISRU applications, like planetary exploration and mining robots.

***Health issues to be addressed***

The current noise control and vibration technologies should be adapted to undertake new challenges concerning aerospace exploration and maintain safety of structures and staff in space mission.

Any on-orbit laboratory or space mission with a long-term person occupation presents a significant acoustic challenge considering the equipment that may create a noisy environment. It is important to maintain reasonable noise levels not only for hearing loss of the technical staff, but also for acoustic comfort and habitability, and for avoiding risks associated to reduced speech intelligibility between staff and the ground or between the crew members. The main goal would be to explore the sustainable integration of acoustic materials designed to be both absorbing and insulating in order to reduce interior noise annoyance for vehicles in missions or for permanent settings of personal staff.

Also, lightening of structures is one of the fundamental strategies for improvement of performance in the aerospace industry. They can be found in various applications such as fuselages, arrays of solar panels or antennas for satellite.

The mass density reduction leads to increase the transmitted vibrations that may result in vibroacoustic fatigue up to the limit of fracture. It constitutes then a danger for the integrity of the components or equipment's to be transported. The use of vibro-acoustic materials will mitigate the transmission and also contribute to reduce vibrations of the instruments for space observations.

The Lunar regolith offers diverse relevant products, but the effects of dust particles (size < 200 μm) should be addressed before any human activity.

These particles have potential for coatings, on seals, gaskets, optical lens, suits, windows, electrical components, etc. However, they are harmful, causing physiological effects on humans, especially with respect to the lungs, the lymph system, and potentially the cardiovascular system, in the case of extremely fine particles.

### 3.3. Protection

***Legal Framework***

International law applicable to outer space activities lags behind rapid technological advances. There is currently no clear answer to the legal questions posed by space mining. There remains significant legal uncertainty about how to proceed in mining on the Moon and asteroids under existing international and national law. International agreements state that no government can claim outer space or celestial bodies as their own. Private companies interested in investing in space see these uncertainties as a major impediment to the future commercial development of space. These companies argue that the absence of property rights is an impediment to obtaining external financing, hinders the protection of their investments in space and the guarantee of adequate income on their investments.

The Treaty on the Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Organs, "Outer Space Treaty", is the founding text of international space law.[7] It entered into force in 1967 and has been signed and ratified by more than 100 nations.

Article I provides: " *the exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries...Outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind,*

7 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 27 January 1967, 18 UST 2410, 610 UNTS 205.

*on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies."* The Treaty does not clearly address whether the extraction of space resources is lawful.

The Treaty present a problem, there is not a single definition of celestial bodies, if this category includes asteroids (see Article II and Art VI of the Treaty). If they are not defined as celestial bodies, then the prohibition of the Outer Space Treaty on national appropriation of the Moon and other celestial bodies would not apply to them.

The International Institute of Space Law considers that, while the Outer Space Treaty does not create an express right to extract space resources, it also does not prohibit such action.[8] In particular, Article I provides for the free exploration and use of celestial bodies in outer space without discrimination. However, the Treaty does not clarify the free use of non-renewable natural space resources.

The Outer Space Treaty is the 'constitution' of international space law; other treaties also bear on commercial space mining ventures:

Moon Treaty: addresses resource extraction from the Moon, and likely also applies to asteroids. It declares that the Moon and other celestial bodies in the solar system, as well as their natural resources, are the 'province of all mankind', the 'common heritage of all mankind' (Marboe 2016 and Roth 2015). The Moon Treaty has been signed by fewer than 20 countries and was not signed by the United States or other space-faring nations. Some regard the Moon Treaty is obsolete and it could present a significant barrier to private space mining.

The Liability Convention: on International Liability for Damage Caused by Space Objects[9] includes the Agreement on the Rescue and return of Astronauts and Objects Launched into Outer Space ('***Rescue Agreement'***)[10] and the Convention on Registration of Objects Launched into Outer Space ('***Registration Agreement'***)[11]. The Liability Convention creates a liability framework for damage cause by spacecraft and establishes a strict liability standard for accidents on the Earth's surface and a negligence standard for accidents elsewhere. Where disputes arise, they are resolved through the Claims Commission. However, because Claims Commission decisions are only binding with

8 Position Paper on Space Resource Mining' (International Institute of Space Law, 20 December 2015) www.iislweb.org/docs/SpaceResourceMining.pdf

9 Convention on International Liability for Damage Caused by Space Objects, 29 March 1972, 24 UST 2389, 961 UNTS 187.

10 Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space, 22 April 1968, 19 UST 7570, 672 UNTS 119.

11 Convention on Registration of Objects Launched into Outer Space,14 January 1975, 28UST695,1023 UNTS 15.

the consent of the parties. Any space-mining mission would have to meet the requirements of these international agreements.

Article III of the Outer Space Treaty states that States Parties shall conduct activities in outer space 'in accordance with international law'. At present, the relationship between traditional international law and space law remains unsettled. There is some uncertainty about how activities should be carried out in space "in accordance with international law". Some government and industry representative's advocate requesting an amendment to the Outer Space Treaty to provide private companies with legal clarity (Foust 2017). Specifically, they point out that the Treaty was drafted at a time when commercial space mining was unthinkable. However, the opening of the Treaty for the amendment and attempt to reach broad international consensus would be risky and difficult. Others are opposed to seeking amendments to the Treaty.

The Hague International Space Resources Governance Working Group ('Working Group') seeks to address this uncertainty for resources development in outer space. The goal of the Working Group is to 'assess, on a global scale, the need for a regulatory framework for space resource activities and to prepare the basis for such regulatory framework'. The Working Group prepared draft set of 'building blocks' for a regulatory framework for the development of resources in space in 17 September 2017 to "create an environment conducive to space resource activities that takes into account all the interests and benefits of all countries and humanity". To this end, the Working Group supports the pillars of international law, including the idea that the development of space resources should be solely for peaceful purposes, and for the benefit and interest of all countries and humanity independently of its degree of economic and scientific development. The Working Group believes that implementation of the international framework should be monitored on the basis of reports of states and intergovernmental organisations. It recommends that States and intergovernmental organizations take responsibility for the development of resources in outer space by creating laws to authorize and regulate these activities, as well as products generated by these activities; the legal framework created by the State or intergovernmental organization must be consistent with international legal principles.

As was mentioned before, the United Nations developed the Moon Agreement in 1979. Only 16 countries have entered into the Moon Agreement – and the parties do not include key industrialised countries like China, Russia or the United States. The Moon Agreement describes the Moon as 'the common heritage of mankind'. However, the Outer Space Treaty refers to outer space as 'the province of all mankind', but not as its 'common heritage'. Thus, the countries who are parties to the Outer Space Treaty, but not the Moon Agreement, have not adopted the view that outer space should be treated in a manner analogous to the deep seabed.

***Planetary protection***

The COSPAR (Committee on Space Research) Planetary Protection (PP) Panel defines a policy that is a scientific guidance framework for space exploration. This Policy is defined and upgraded by agreement between the scientific community and space agencies in compliance with the United Nations Outer Space Treaty. The different space exploration planetary protection categories (I-V) reflect the level of interest and concern that biological contamination can compromise future investigations or, for sample return missions, the safety of the Earth. The categories and associated requirements depend on the target body and mission type combinations. This categorisation is revisited when new scientific results challenge the current perception and indicate the necessity for updates or when challenges appear from new players in the space field or new requests. It is foreseen that the PP policy will have to be reviewed periodically in the following decades. The COSPAR Planetary Protection policy places lander missions to Mars under Category IV, which requires stringent bioburden control and reduction mechanisms. Furthermore, any mission dedicated to the search of present or past life on Mars is assigned Category IVb which requires that the entire landed system is restricted to a surface bioburden level of ≤ 30 spores per $m^2$ or levels of bioburden reduction driven by the nature and sensitivity of the particular life-detection experiments. Any subsystem of the lander system that is involved in such a mission must also be subjected to a bioburden control of ≤ 30 spores per $m^2$. The challenge is now the preparation for the human exploration and sample return missions and the potential intersection with activities devoted to finding signatures of life of Mars, which may be compromised by the aerial dispersal/spreading of bioburden from landed robotic platforms and then, in the future, from human-crewed missions. Also, new detection protocols for clean rooms need to be defined, as nowadays, only cultivable organisms are detected by swab-sampling and agar growth. However, most of the microorganisms cannot be detected this way, and the resistance of them to the sterilisation procedures that are now in place is also unknown.

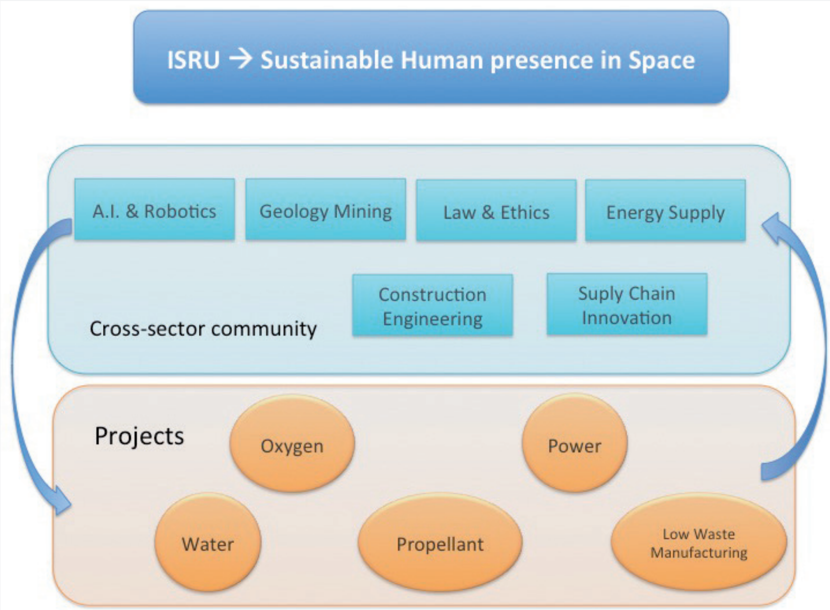
## 3.4. Conclusions

The exploitation of Moon resources is an important and immediate point. Kornuta et al. (2019) and Jones et al. (2019) have examined whether materials from the Moon can be manufactured into propellant for spacecraft and whether a commercial business case can be made. In many cases, ISRU missions propose finding water ice or hydrated minerals and extracting the water to be electrolyzed into its constituent components of hydrogen and oxygen, or reducing the oxides in the regolith for oxygen. These components are then cooled, liquefied, stored, and utilized as propellant for rockets in cislunar space. Fundamental research into lunar materials and the underlying science of resource utilization is needed in addition to technology development. **Fundamental scientific research at the Moon, asteroids and Mars is important to better understand the resources we are aware of and to identify opportunities we are not aware of yet whilst delivering near term benefits for science.**

The NASA 2020 Mars Rover mission that has landed at Jezero Crater, Mars, will collect and cache geological samples for their future return to Earth. The transportation to Earth will require a sample-retrieval mission and an Earth return mission. ESA is now developing both of them. An international team of 77 researchers (International MSR Objectives and Samples Team, iMOST) has prepared a white paper describing the potential goals of the Mars Sample Return (MSR) mission. This team has reviewed the state of the art of the latest scientific and engineering discoveries about Mars and its exploration plans, to define the scientific objectives, the samples of interest, their amount, the requirements on sampling, and the analytical methods that would be applied to the Martian samples once on Earth. These suggestions were adapted to the realities of the NASA 2020 Mars Rover sampling system. The objectives of the sample studies required to improve our understanding of the Martian history, present state and future exploration risks and potentials of Mars are classified as 1) Geological environments; 2) life; 3) Geochronology; 4) Volatiles; 5) Planetary-scale geology; 6) Environmental Hazards and 7) In-Situ Resource Utilization (ISRU).

Independently of the technological challenges associated with this mission architecture, the future scientific challenges related to Mars Sample Return will mostly concern the development of high accuracy instrumentation, and protocols to maximise the analysis of these samples with the regard to the 7 goals detailed above. This includes the development of life-detection protocols that need to be applied as a pre-screening before the samples are released to laboratories that do not have the highest standards of bio-security. Also, it is unclear yet which organisations will receive the samples, for curation and then for storage. International cooperation and participation within European initiatives are desired.

**FIGURE 2–**Sustainable human presence in space. All the activities included in the cross-sector community are related with all the projects connected on the extraction of materials using ISRU.




On the other hand, it is important to recommend studying, developing and improving the technology to extract any of the mentioned minerals from the regolith on different bodies. Recommendations are needed also to solve problems with those technologies: power supplies, communications, hardware problems.

Technology development is needed in areas related to energy production and storage; resource extraction; material production and metallurgy; manufacturing and construction; regolith excavation, handling and processing; accessing and operating in extreme environments. In figure 2 it is represented the relation between all the material productions like water, oxygen and power and the cross-sector community that may be interested in ISRU.

The European Space Agency is seeking innovative ideas for exploring lunar caves, though an ESA's Open Space Innovation Platform (OSIP), which provides individuals and businesses with the opportunity to collaborate with ESA experts and contribute to the future of space research. It is run through

Discovery & Preparation, which lays the groundwork for ESA's short- to medium- term future activities.

In parallel, the NASA's Space Technology Mission Directorate has established a Lunar Surface Innovation Initiative. It is a technology development portfolio to enable human and robotic exploration on the Moon and future operations on Mars. The activities will be implemented through a combination of unique NASA work and public-private partnerships.

High on the list are technologies for in-situ resource utilization to generate products using local materials, such as technologies for converting lunar ice into drinkable water and other important resources.

Technology development and demonstrations will mature the following capabilities:

- Utilizing the Moon's resources;
- Establishing sustainable power during lunar day/night cycles;
- Building machinery and electronics that work in extreme environments, like super-chilly permanently shadowed craters;
- Mitigating lunar dust;
- Carrying out surface excavation, manufacturing and construction duties;
- Extreme access which includes navigating and exploring the surface/ subsurface

An urgent need exists for high fidelity, quality assured analogies and simulants for technology development and testing. (ESA outcome Workshop ISRU, 2018).

Last, but no least, legal framework on the outer space is still not defined and a lot of discussion and work to define all the points necessary for mining on the Moon, asteroids or Mars. In short, companies and governments are working to develop technologies that allow the extraction of space resources under conditions other than Earth. While there is some legal uncertainty around the ground, consensus appears to be growing among nations affecting the area that the extraction of trade resources is compatible with international law. International law provides a framework for resource development in outer space, and existing treaties and proposed regulations and laws borrow heavily from the principles of international law. Still, outer space is not the sea, and an asteroid is not an island or a distant land. Over time, the law of space will evolve in its own direction.

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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 20$^{th}$ 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.

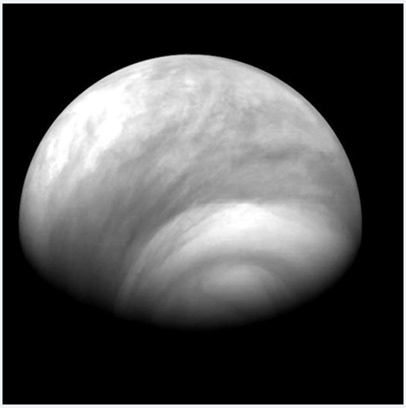
The challenges associated to the brightest light in our sky and centre of our system, the Sun, deserves a full separate chapter (see Challenge 3) and is not taken into account in this Chapter.

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.

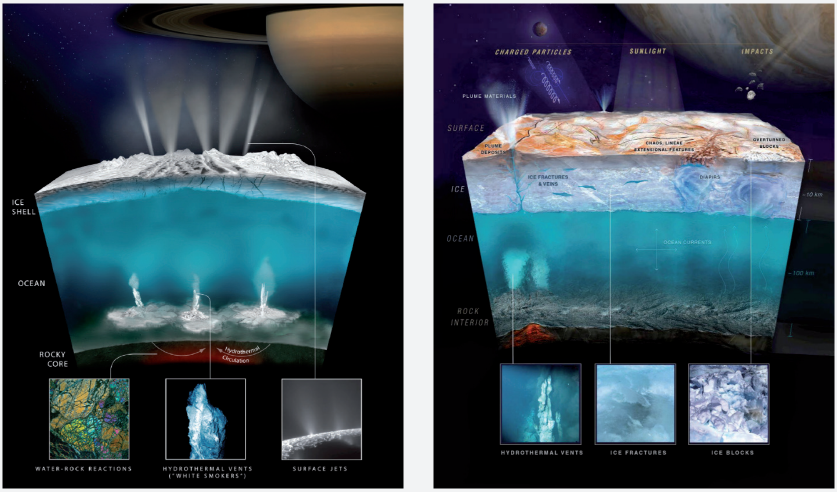
The only two Venus missions in the 21st century have, however, significantly improved our knowledge about this planet. Venus Express has, among many other results, improved the characterization of the temperature structure, the atmospheric dynamics, the atmospheric composition and the ion escape from 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.

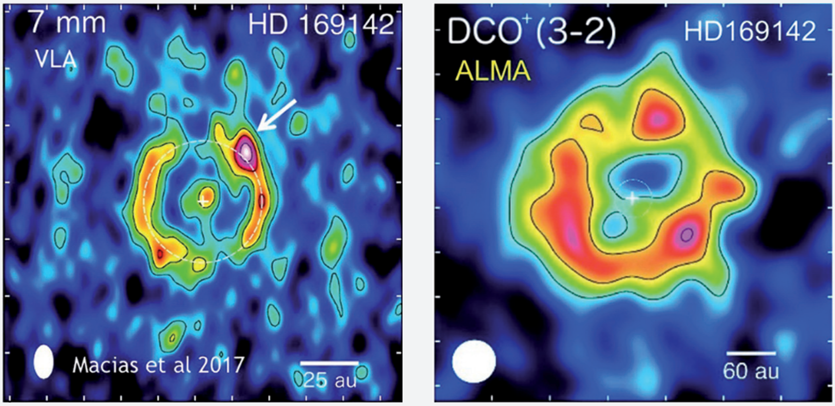
### *What are the signs of planet formation in the protoplanetary disks?*

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

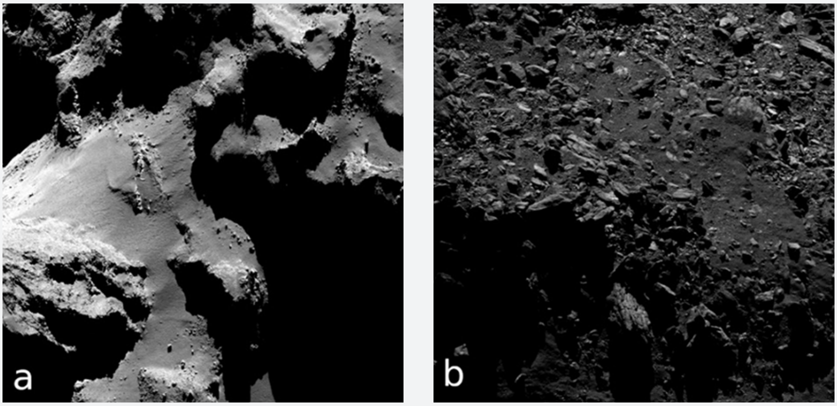
***How was the formation and evolution of comets and trans-neptunian objects?***

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).

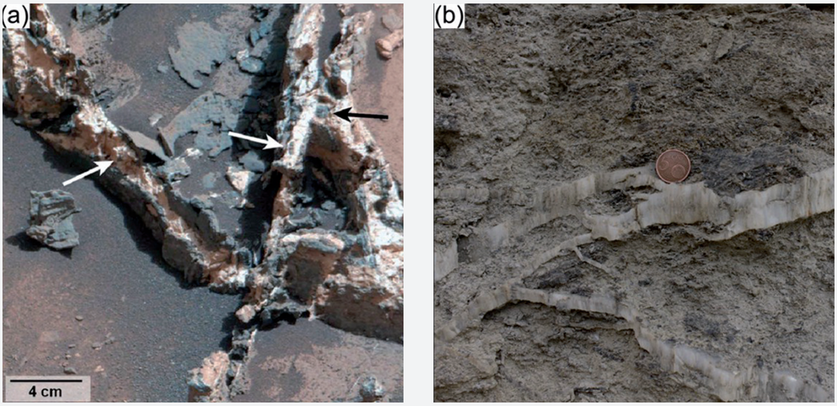
***Local features interpretation (e.g. fractures) by analogy***

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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CHALLENGE 3

# SPACE OPPORTUNITIES AND THREATS FOR SOCIETY: PREDICTING THE SPACE-EARTH INTERACTION

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## 1. INTRODUCTION AND GENERAL DESCRIPTION

Earth and human life are exposed to a highly variable space environment. Space weather driven by impulsive phenomena in the solar corona induces short-term variation from minutes to weeks in the upper atmosphere and ionosphere, impacting technology and human health. Solar activity variations on decadal to centennial time scales influence Earth's climate. The influx of extra-terrestrial material on Earth, mainly in the form of interplanetary dust, meteoroids, asteroids and comets, has relevance in many different aspects: from the creation of metal layers in the upper terrestrial atmosphere to the potential local damage caused by Megaton-class impacts to even the destruction of the civilization from large impacts capable of causing massive extinctions and temporal modification of climate. On the other hand, anthropogenic climate change is expected to alter the near-space environment populated by low-orbiting satellites and space debris.

This challenge deals with Space-Earth interactions, from space weather phenomena to the Earth's surface, with the mediating role of the upper and middle atmosphere, where these phenomena are felt the most and their signals can subsequently propagate to the Earth's surface.

Integrated understanding of this complex system, in particular coupling of the middle atmosphere with the troposphere, is key for future climate projections and enhancing skills of subseasonal-to-seasonal and potentially decadal climate predictions. In addition, they would further enable anticipation and preparedness to environmental and technological hazards by extreme events caused by extreme space weather and worst-case events such as asteroid impacts or solar superstorms.

### 1.1. Space weather

The Sun is not a static body, but the amount of energy emanating from it varies with time. Impulsive phenomena in the solar corona expel huge amounts of energetic solar material into interplanetary space, substantially increasing the density and velocity of the solar wind. Under these conditions, a great variety of phenomena such as geomagnetic storms, auroral and substorm activity, or thermospheric and ionospheric storms does occur.

Space weather (SWe) refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of spaceborne and ground-based systems and services or endanger property or human health. Space weather deals with phenomena involving ambient plasma, magnetic fields, radiation, particle flows in space and how these phenomena may influence man-made systems. Because our society is becoming increasingly dependent on those technological systems, the ionosphere, its electrodynamics, and its coupling with the lower atmosphere, the neutral upper atmosphere and the magnetosphere are a matter of intensive research. This research seeks to determine to what extent valid predictions of those phenomena and their effects can be made [e.g. Richmond, 1996]. In addition to the Sun, non-solar sources such as galactic cosmic rays (GCRs) can be considered as space weather elements since they alter space environment conditions near the Earth.

#### *Solar processes and interplanetary space*

Most space weather phenomena are ultimately driven by the Sun. More specifically, solar coronal mass ejections (CMEs) and co-rotating interaction regions (CIRs), which are at the root of most severe geomagnetic storms have a solar magnetic field origin. The same occurs with flares, medium to high radiative energy releases that alter the conditions of the interplanetary medium and the solar wind, triggering, for example, solar energetic particles (SEPs) fluxes. These are also driven by borrowing energy from magnetic fields. Twisting and subsequent reconnection of magnetic fields are thought to be the energy supply for all those solar phenomena relevant to space weather. Indeed, the magnetic field shapes and couples the various atmospheric layers from the photosphere to the corona and gives rise to the so-called solar activity. That solar activity and magnetic field entangling vary at all spatial scales from the smallest observable (0.”1 - 0.”2) and shorter times (of the order of less than 1 min; e.g., Requerey et al. 2017) to the whole solar disk and years.

The still insufficient knowledge of the solar magnetic fields and their variability hampers our capability to predict flares, CMEs, CIRs, SEPs, and other space-weather phenomena. A better characterization of the Sun’s magnetic field, in particular, of its outermost layers, the chromosphere and the corona, is mandatory to understand the essential building blocks of space weather.

### *Impacts on magnetosphere, ionosphere and MLT atmospheric composition*

During extreme Space Weather events (SWe), solar flares abruptly release huge amounts of energy that promptly change the ionospheric structure in the sunlit hemisphere. The intense ultraviolet and x-ray radiation, after a propagation time of about 8 minutes, hits the dayside of the Earth and is absorbed by atmospheric constituents, raising them to excited states and knocking electrons free in the process of photoionization. The low-altitude ionospheric layers (D and E regions) immediately increase in electron density over the entire dayside, a process known as sudden ionospheric disturbances (SIDs). Short radio waves (in the HF range) are absorbed by the increased particles in the low altitude ionosphere, causing a complete blackout of radio communications. In the higher latitudes, the solar wind energy dissipation triggers geomagnetic storms and consequently, ionospheric storms following gradually the impact of geoeffective phenomena of solar surface origin: CMEs and “coronal holes” that emit high-speed solar wind streams (HSSs) and CIRs under the interaction of HSSs with preceding low-speed solar wind. Numerous experimental and theoretical studies show that the behaviour of the ionosphere during geomagnetic storms is greatly influenced by the coincident thermospheric storm. The changes in neutral air winds and composition result in changes to rates of production and loss of ionization. The modified electron densities in turn alter the ion drag on the neutrals. Disturbed neutral winds also cause F region electric fields by the disturbance dynamo mechanism. These electric fields redistribute the plasma, affecting production and loss rates. Apart from large scale ionization enhancements or depletions, the storm-related electric fields may also destabilize the plasma, producing irregularities. Spread F condition, particularly at the equatorial and at high latitudes, and bubbles in the equatorial zone lead to additional perturbations in the electron density, which are more pronounced as the ionospheric electron density increases.

Atmospheric gravity waves launched by high-latitude sources such as Joule heating, Lorenz forces, or intense particle precipitations, are detected in the form of Large Scale Travelling Ionospheric Disturbances (LS-TIDs), propagating from high to middle latitudes. The solar proton events (SPE) cause abnormal ionization in the ionospheric D-region that absorb radio waves in the HF and VHF bands, the so-called polar cap absorption (PCA) events.

This complex physical system is the source of many scientific, operational, societal, and environmental challenges that affect the smooth and uninterrupted operation of technological systems such as radio communication and geolocation systems, ground and satellite-based augmentation systems, and space-based communications as well as communications between the Earth and ground stations (or rovers) at Moon, Mars, and other planets, low-frequency radio astronomy and Synthetic-Aperture Radars.

Currently, the available ionospheric models provide forecasts of large-scale effects in the critical ionospheric characteristics up to few hours, i.e. only when the solar wind characteristics at L1 are known. The forecast of irregular structures is even more uncertain, because of their local character. Irregularities such as scintillations, bubbles and travelling ionospheric disturbances (TIDs), can be only nowcasted or forecasted by 1 hour ahead. In general, current ionospheric forecasting capabilities severely lag behind users' requirements. There are two reasons: a) the complexity of the physical mechanisms acting in the ionosphere and the regional character of ionospheric perturbations; and b) the very short-term notice given for the expected perturbations in the characteristics of the solar radiation environment and solar wind plasma, and in the interplanetary magnetic field (from minutes to few hours) that drive the ionospheric forecasting models.

### *Worst case events*

Worst case SWe events may cause severe impacts on the Earth environment. Several such events are known historically, as the strongest white-light flare and geomagnetic storm of 1859 (Carrington event) and the solar radiation storm of 775 AD, which may serve as an upper estimate of solar events (Usoskin et al. 2017). So far, possible future extreme events of this magnitude have not been considered in climate assessments and only a limited number of studies deal with the potential technological impacts of such worst case events. Despite the rather low probability, their consideration is relevant due to the expected magnitude of socio-economic impacts. A comprehensive assessment of the occurrence probability is still missing due to the difficulty to reconstruct past extreme events from proxy data. The study of bright flares on other Sun-like stars (Maehara et al., 2012) could be a way to make progress in the future.

## 1.2. Influence of solar activity on climate

Together with volcanic activity, solar activity variations are an important source of naturally forced climate variability. On timescales of years to decades, relevant solar variations include the 11-year solar cycle and sustained periods of anomalously high and low solar activity, known as grand solar maxima and minima, respectively. Solar effects in the middle atmosphere, particularly those related to the 11-year solar cycle are well documented, whereas near-surface impacts are more controversial and subject to debate. Uncertainties and challenges include the limited observational record of solar forcing changes, discrepancies in their reconstruction over the pre-satellite era, the generally small radiative forcing associated with recent solar variations, and our limited understanding of the mechanisms whereby solar signals in the middle atmosphere could propagate to Earth's surface and its representation in climate models.

### *Past, present, and future solar activity*

Solar activity on decadal and longer timescales is driven by the solar dynamo, by which the dynamical interactions of flows and magnetic fields in the solar convection zone lead to cyclic reversals of polarity of the solar magnetic field with a quasi-static period of 11 years. One of its consequences is the emergence of regions with enhanced magnetic fields, namely sunspots, whose numbers are the most widely known proxy of solar activity for the last centuries. Sunspots provide reliable estimates of Total Solar Irradiance (TSI), which is key for quantifying the solar contribution to past climate variability as well as for constraining the evolution of future solar activity and associated climate impacts. Changes in TSI, such as those associated with the 11-year solar cycle, do not distribute uniformly through the solar spectrum. Instead, they involve larger irradiance variations in short wavelengths (e.g. ultraviolet, UV) than over the visible part of the spectrum. Quantification of these spectral solar irradiance (SSI) changes is of paramount importance to elucidate the pathways of solar influences on climate. Observational-based assessments of the last solar cycle suggested larger SSI variations in UV wavelengths than previously thought. However, instrument sensitivity drifts and unrealistic ozone responses to these UV changes have also been reported. Due to the limited availability of accurate satellite measurements, SSI variations are often inferred from empirical models (e.g. Matthes et al. 2017 and references therein). While TSI variations since the 1970s are relatively well known from direct spaceborne observations and, to a lesser extent, from ground-based observations since the late 19th century, their reconstruction for the past centuries from sunspots, is rather complicated and uncertain. On longer timescales, solar variability can only be reconstructed using cosmogenic isotope proxies (mostly $^{14}C$ and $^{10}Be$ in natural stratified archives), allowing estimates of the solar modulation of cosmic rays, ultimately driven by solar magnetic activity. Geomagnetic activity, i.e. disturbances of the magnetosphere, caused by solar transients and solar wind, are monitored by ground-based magnetometers since the mid-19th century or by qualitative historical auroral records for several centuries, but should be reconstructed on longer time scales. Isotope-based reconstructions of sunspots are fed in solar irradiance models to retrieve a suite of solar forcing reconstructions of TSI and SSI for the last millennia (Jungclaus et al. 2017), in support of the IPCC. Notable discrepancies (one order of magnitude) exist in long-term variations of solar activity, with e.g. TSI relative changes from the Late Maunder Minimum (LMM, 1675-1715 CE) to present days ranging from 0.06% to 0.25%.

Despite recent advances of physical models of the solar magnetic dynamo, "true" predictions of solar activity are currently not possible beyond one cycle. Estimates of future solar activity are thus restricted to probabilistic assessments based on the present conditions and statistics of past variations, which suggest that the recent solar activity decline will continue during the upcoming decades. Plausible future scenarios based on such statistics are included, for instance, in recent recommendations of solar forcing for climate model projections informing the upcoming IPCC assessment report (Matthes et al. 2017), which includes a best-guess future scenario of solar forcing, as well as an extreme scenario of low level of solar activity during the 21st century, comparable to the Maunder Minimum. Single modelling studies have also quantified the effects of a near-future grand solar minimum in climate change projections, using a considerable spread of solar forcings, which allows testing the sensitivity of the response to the amplitude of solar variations. However, a complete probabilistic evaluation of the possible range of future solar forcing is to date still missing.

In summary, despite recent progress, significant uncertainties remain in understanding and modelling solar irradiance variations. The most critical issues are the variability of solar irradiance in the UV part of the spectrum between 200 and 400 nm and the lack of reliable constraints on the magnitude of the centennial variations.

### *Climate impacts*

Direct heating of the Earth's surface by solar radiation in the Visible and Infrared represents the most obvious mechanism by which solar energy enters the climate system. Although the variability of the TSI hardly exceeds 0.1% over the 11-year solar cycle, several studies have suggested different mechanisms whereby this small signal can be amplified. The so-called bottom-up mechanism involves heating of the subtropical sea surface temperatures (SSTs) from solar variations in visible wavelengths, amplified by air-sea coupling in the tropical Pacific. Another mechanism is associated with well-known temperature variations in the upper tropical stratosphere induced by ozone absorption of UV radiation. According to this mechanism, the ozone-induced warming of the upper tropical stratosphere during solar maxima strengthens the climatological circumpolar westerly winds of the winter stratosphere (stratospheric polar vortex) through enhanced meridional temperature gradient, thereby promoting stratosphere-troposphere coupling (see below). This interaction between radiation, chemistry and dynamics is also referred to as the top-down mechanism, and has been suggested to propagate solar signals from the polar winter stratosphere downwards to the extratropical troposphere and the ocean, being particularly important for regional climate variability. Both, top-down and bottom-up solar mechanisms may work in tandem to amplify solar signals, which complicates the attribution and quantification of their relative impact on climate.

In addition, recent studies have paid attention to potential impacts of energetic particle precipitation (EPP) on climate. EPP is strongly linked to the solar cycle, either directly by CMEs producing sporadically large fluxes of solar energetic particles or, indirectly, by the quasi-continuous impact of the solar wind on the Earth's magnetosphere, as well as by the shielding of GCR fluxes by the solar magnetic field (see, e.g. Mironova et al., 2015, for an overview). EPP-induced ionization initiates the production of odd nitrogen and odd hydrogen, both of them destroying ozone via catalytic cycles.

SPEs caused by CMEs are particularly frequent around the maximum of the solar cycle and produce transient alterations of the chemistry in the polar mesosphere and stratosphere. Energetic electron precipitation is associated with geomagnetic storms and occurs mainly in the polar auroral and sub-auroral regions. Such geomagnetic perturbations occur throughout the solar cycle with an intensity being largest about 2 years after the maximum of the solar cycle, in phase with the acceleration of the solar wind. Processes that occur in the outer radiation belt typically generate mid-energy electron (MEE) precipitation affecting the atmosphere at altitudes of 50–100 km. Auroral electrons, originating principally from the plasma sheet, affect the lower thermosphere (95–120 km). Odd nitrogen produced by precipitating electrons is long-lived during polar winter and is regularly transported down from its source region in the mesosphere and lower thermosphere into the stratosphere, to altitudes well below 30 km (e.g., Funke et al., 2014) where it interacts with the ozone layer. Satellite observations of the last two decades have provided a clear picture of this EPP indirect effect occurring regularly during polar winters. Between the surface and 25–30 km, cosmic rays are the main source of atmospheric ionization, exhibiting highest levels during solar minima. GCR-induced ozone alterations have been postulated by several model studies, although, no observational evidence has been provided to date.

EPP-induced ozone changes are thought to modify the thermal structure and winds in the stratosphere, which, in turn, modulate the strength of the Arctic polar vortex. The introduced signal could then propagate down to the surface, introducing significant variations of regional climate, particularly in the Northern Hemisphere (NH; see, e.g. Sinnhuber and Funke, 2020, for a recent review). However, despite the recent advances in the investigation of EPP impacts on the middle atmosphere and their potential climate impacts, many open questions and issues still remain. Most of them are related to current limitations of available observations and climate model capabilities. Others are caused by the lack of process understanding, particularly of processes related to the possible mechanisms that could lead to energetic electron impacts on regional surface climate.

The climate system exhibits a wide spectrum of persistent internal modes of variability such as the dominant atmospheric circulation patterns in the NH and Southern Hemisphere (SH), i.e., the annular modes (Northern Annular Mode, NAM, and Southern Annular Mode, SAM, respectively), and their regional manifestations (i.e. the North Atlantic Oscillation, NAO). Other examples include the coupled atmosphere-ocean circulation patterns like the El Niño Southern Oscillation (ENSO) phenomenon, and SST modes of variability, such as the Atlantic Multidecadal Variability (AMV). All of them play a substantial role in regional weather and climate. Natural forcing from the decadal-scale solar cycle has been proposed to synchronize the NAO, the inter-to multi-decadal variability in the Atlantic and Pacific oceans, and the ENSO-related Pacific Walker circulation. However, convincing and systematic evidence is still missing. An intense topic of recent research has focused on the influence of the 11-year solar cycle on the winter NAO, which largely dictates climate anomalies over the Euro-Atlantic sector. Several studies have argued that positive phases of the NAO, associated with warmer and wetter winters in northern Europe, are more likely during solar maxima, therefore representing a window of opportunity for decadal predictability in extratropical regions of the NH. Modelling evidence supports a lagged response of the NAO to the solar cycle, although this is often weaker than in the observations and is not robust across models. A more recent study reports the absence of any solar signal prior to the mid-1960s in various observation-based datasets and suggests that internal variability alone is capable of generating decadal NAO variations as those observed in the more recent period. Current limitations to detect robust regional solar signals include the assessment of the relative roles of solar forcing and internal variability under different background conditions and external forcings, i.e. past (no anthropogenic forcing) versus present and future (increasing anthropogenic forcing). Moreover, a reliable quantification of solar of solar effects in regional regional surface climate requires a better understanding of the middle atmosphere and its coupling with the troposphere, and of atmosphere-ocean interactions. These issues are partially hampered by the short length of dense observations before the mid-20$^{th}$ century, and the model ability to capture the climate responses to external forcing (e.g. an apparent underestimated response of the NAO to solar forcing, see also Challenge 2 in Volume 7).

The Space-Earth system integrates a complex array of components, some of them representing a promising source of predictability in subseasonal to decadal, with potential benefits for both weather and space weather predictions.

In particular, substantial skill in subseasonal-to-seasonal (S2S) forecasts arises from atmospheric coupling of the lower, middle and upper atmosphere. This coupling is evidenced in wintertime with a strongly perturbed boreal stratospheric polar vortex or just the opposite, strong vortex events. The most salient examples associated with weakening of the stratospheric polar vortex are Sudden Stratospheric Warmings (SSWs), extreme phenomena characterized by an abrupt temporary warming of the polar winter stratosphere (see also Challenge 5 in Volume 7). Their effects propagate above and below the stratosphere, materializing as extensive changes of the whole atmosphere, even across both hemispheres. For example, the strong negative anomalies of the NAM in the middle stratosphere produced by SSWs propagate downwards to the troposphere, thereby causing temperature and precipitation anomalies persisting from weeks to months. Moreover, SSWs eventually lead to polar winter elevated stratopauses formed at mesospheric altitudes, that alter the upward propagation of atmospheric waves to the thermosphere. They also produce considerable variations of the thermosphere and the ionosphere across the globe, i.e., appreciable reductions of upper-thermospheric density, low-latitude electron density anomalies with a magnitude similar to those caused by moderate geomagnetic storms or tidal variations affecting the equatorial electrojet and the current system.

The S2S predictability skill associated with stratosphere-troposphere coupling is mainly confined to periods of SSWs, being otherwise low. The modulation of the stratospheric polar vortex and SSWs by internal modes of atmospheric variability may further extend predictability of the stratosphere (see Challenge 5 in Volume 7). However, this requires that prediction models simulate adequately these phenomena, their teleconnections to the polar stratosphere and the whole atmosphere coupling.

Traditional model limitations to the predictive skill from the stratosphere include low model tops, poor vertical resolution, the lack of internally-generated QBO, unrealistic gravity wave parameterizations and tropospheric biases. In order to further improve predictions In order to further improve predictions and to extend them to the whole atmosphere, there is also a need for i) a better modelling of stratospheric ozone as an additional source of predictibility, ii) improved data assimilation for initialization, and iii) a comprehensive knowledge of vertical coupling processes.

Major sources of seasonal-to-decadal (S2D) predictability in current forecast systems mainly rely on SST anomalies that are predictable beyond a season, such as ENSO and AMV. As discussed above, decadal solar variations may also excite stratosphere-troposphere coupling and influence internal modes of variability on these time scales, therefore providing additional skill in S2D forecasts. However, realizing this potential predictability will require better understanding of the response of stratosphere-troposphere coupling to solar variations and the separation of this externally forced signal from internal variability.

### 1.3. Meteoroid population

The Zodiacal Dust Cloud (ZDC) is a circumsolar debris disk centered at the ecliptic plane, composed by dust particles originated from the collision of asteroids and disintegration of comets. ZDC particle accretion constitutes the dominant source of interplanetary material to the inner Solar System planets. In contrast to the relatively fresh cometary trails originating well-known meteor showers, the orbital characteristics of zodiacal particles have evolved significantly since ejection, which makes it impossible to establish a direct link to their specific parent bodies. However, they can be generally classified in relation to a source family using ground-based radar and optical observations of atmospheric entry events.

The so-called Sporadic Meteor Complex (SMC) consists of six directional enhancements of the meteor radiants. These apparent sources are known as the North and South Apex, composed mainly of dust from long period comets; the Helion and Anti-Helion, originating from short period comets; and the North and South Toroidal, which have been linked to Halley-family comets (Janches et al. 2017 and references therein). Dynamical models of dust evolution from different cometary families have been constrained with spaceborne impactor data (LDEF) and infrared dust emission observations (IRAS and Planck). These modelling efforts indicate that the ZDC is dominated by small (~10 µg) and slow (<15 km $s^{-1}$) particles, originating mainly from the Jupiter family of comets (JFC) (Nesvorný et al. 2010).

Coupled orbital dynamics and atmospheric entry modelling has been used to interpret a wealth of ground based observations, including the micrometeorite record population, high performance-large aperture radar meteor rates, accumulation rate of meteor smoke particles (MSPs) in ice cores and lidar density measurements of the mesospheric Na, Fe and Ca layers. This has enabled estimating the interplanetary dust input to Earth to be around 40 tons $day^{-1}$ and to derive also estimates for Mars and Venus (Carrillo-Sánchez, 2020).

These estimates are broadly consistent with the independent interplanetary meteoroid flux density model by Grün et al. (1985). Nevertheless, important discrepancies regarding some key ground-based observations remain, which points to an incomplete understanding of the physics of atmospheric entry.

### 1.4. Climate change impacts on the upper atmosphere and geospace

While man-made greenhouse gas emissions trigger global warming in the troposphere, a cooling response has been observed in the middle atmosphere. This is thought to be related to increased carbon dioxide ($CO_2$) concentrations in the middle and upper atmosphere that have been recently reported. If the mesosphere - lower thermosphere (MLT) region cools down, then atmospheric contraction reduces the density in the thermosphere. The underlying picture is further entangled by the modulation of such contraction by the solar cycle, and also by hemispheric asymmetries and additional horizontal inhomogeneities.

The lower and middle atmosphere further affect the upper atmosphere via the upward propagation of atmospheric waves, including planetary waves, atmospheric tides, and gravity waves. As these waves propagate upward, their amplitudes grow due to the decreasing density with height, until they eventually break and deposit their energy and momentum into the ambient atmosphere, driving large-scale circulations. This might be observed also in the variability of the Earth's ionosphere which can be caused by both solar/geomagnetic activity and meteorological effects (Altadill and Apostolov, 2003). Both the excitation of atmospheric waves in the lower atmosphere, and their upward propagation through the middle atmosphere, are dependent on the conditions in the background atmosphere and are therefore likely to be affected by climate change. A long term increase in gravity wave forcing of the upper atmosphere would result in additional cooling and cause more turbulent mixing, thereby enhancing the downward transport of thermospheric atomic oxygen and thus amplifying the reduction of mass density.

All objects in low Earth orbits experience an atmospheric drag which is proportional to the ambient atmospheric density. This drag acts to lower the object's orbit and will eventually cause it to fall back to the Earth's surface. This is the main way in which space debris is removed from the near-Earth space environment. Any long-term change in the density of the upper atmosphere will therefore have a significant impact on the time evolution of the space debris population.

Also the meteoroid environment influences the upper atmosphere. The atmospheric processing of Fe, Mg and Si atoms ablated from micrometeoroids results in re-condensation of meteoric material as nm-sized MSPs. These act as condensation nuclei of noctilucent clouds (NLCs), which were reported for the first time in 1885 and have been since growing brighter and spreading to lower latitudes. NLCs appear at the high latitude summer mesopause (around ~85 km), where the temperature falls below 150 K and water vapour then spontaneously forms ice particles. NLCs are a long-term indicator for climate change due to the increase of $H_2O$ in the middle atmosphere resulting from the oxidation of anthropogenic methane. The occurrence frequency and brightness of NLCs may be impacted on decadal time scales by changes in $H_2O$ and $O_3$, and in the dominant meridional circulation in the mesosphere. Temperature is crucial too, although there is no clear evidence of a temperature decrease at the particular altitude of the mesopause due to increased $CO_2$.

## 2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

### 2.1. Towards an integrated understanding of the Space-Earth system

A major expected impact is to interconnect Spanish and international research communities addressing solar physics, minor bodies of the Solar system, atmospheric and ionospheric physics, and climate sciences to jointly advance our understanding of the entire impact chain of Space-Earth interactions in a holistic manner and generate new integrated knowledge. This implies the coordinated development of synergistic space mission concepts and observational strategies, as well as the generation and sharing of multidisciplinary datasets and community data analysis tools addressing all aspects of the Space-Earth system. The joint effort of presently disconnected disciplines is expected to enhance the CSIC visibility and leadership in the international basic science panorama.

The designing and provision of an organized access to experimental facilities, Findable, Accessible, Interoperable, Re-usable (FAIR) data, standardized data products, and training and innovation services will impact in the progress of basic science and in societal benefits. This, in turn, will drive the way for new observing technologies, procedures and tools for the end-to-end transition of research models to applications tuned to meet the requirements of the technologies concerned, and linking best-in-class facilities to provide seamless multi-technology services.

### 2.2. Societal benefits of enhanced predictability

*Space weather forecasts*

Monitoring and forecasting space weather in an accurate and timely manner is important to protect critical infrastructures from interruptions or indeed long-term damage by adverse SWe. The implications of space weather on numerous aspects of life in our planet, including socio-economic activities of developing countries, are well-known and recognized. Some examples follow:

- The total electron content (TEC) of the ionosphere may increase substantially during strong ionospheric storms, causing variability in the propagation conditions of electromagnetic waves. SPEs, for instance, can cause episodes of enhanced absorption of radio waves in the Earth's polar caps (PCA events), thereby restricting (if not disabling) transpolar high-frequency (HF) radio communications. Commercial airlines are potentially affected by these disruptions when they overfly the polar zones, being obliged to deviate from their projected shortest routes towards lower latitudes.
- The accuracy of single frequency receivers signals of Global Navigation Satellite Systems (GNSS) can also be affected by intense TEC enhancements and ionospheric scintillations produced by irregularly structured regions, as these signals suffer from unknown delays and scattering.
- High-energy SPEs and GCRs can also expose astronauts to radiation levels above the safety limits, especially those working in the exterior of their spacecraft or in unprotected areas, due to lack of atmospheric shielding. Particle solar radiation can also incur damages in satellite-borne equipment.
- Temperature-induced inflation of the thermosphere during geospheric storms can cause low Earth orbit (LEO) satellites to reduce its speed and even fall prematurely due to enhanced drag with this part of the upper atmosphere.
- Strong currents flowing at the ionosphere of relatively high magnetic latitudes during geomagnetic storms and substorms produce strong and highly variable magnetic fields at the Earth's surface, giving rise to induced electric fields in the solid earth. Because electrical power grids are grounded, these electric fields act as a voltage source for the

high-voltage power transmission grids, thus introducing a substantial direct current (DC) signal in the network. The related currents, known as geomagnetically induced currents (GICs), may disrupt or damage the transformers of those grids, which are set up for alternating current (AC) flow, thus potentially affecting the final user. This is perhaps the space weather threat of most concern in our era. At lower latitudes, the main mechanism of GIC generation is rather related to the direct impact of the solar wind onto the magnetosphere, namely the sudden impulse (SI) in the magnetic field produced by the abrupt increase of the magnetopause currents caused by the bulk of incoming solar plasma. Although one generally expects that at those latitudes the magnitude of GICs is one order of magnitude lower than that at high latitudes, recently there has been a great wealth of studies on the vulnerability assessment at those middle to low latitude grids. To be efficient, such vulnerability analyses must benefit from the following: i) the knowledge of the geomagnetic field variations at each node of the grid; ii) the knowledge of the Earth's geoelectrical structures beneath the network. Abrupt site-to-site differences in the derived geoelectric field can show geographically distributed differences up to a factor of 1000; iii) the knowledge of the topology and the relative resistances of the power grid elements in the precise instant of the geomagnetic storm.

- There also exists evidence that intense GICs can hamper rail traffic by disturbing signaling and train control systems. Such a threat concerns long railway segments and is primarily caused by high-latitude geomagnetic disturbances driven by the auroral electrojet, but also by SI and pulsations, which can affect a higher range of latitudes.

Reliable and accurate monitoring and forecasting requires large heterogeneous data sets, detailed theoretical models and advanced data processing techniques. Recent advances in machine learning now offer great potential to uncover the characteristics of the Sun-Earth system, to use this knowledge to predict solar activity and its terrestrial impacts on timescales ranging from hours to days, and to improve the accuracy of interplanetary propagation models.

### *Climate projections and sub-seasonal to decadal prediction*

Sub-seasonal to decadal timescales are considered most relevant by policy makers and drive decisions in terms of, e.g., infrastructure investments or land use. As to date, weather forecast systems exhibit reasonable skills out to several weeks. On the other hand, climate variations are well represented in Earth system models on centennial scales. Bridging the gap in the intermediate timescales requires identification and understanding of sources of predictability, as well as its adequate representation in forecast models.

Better prediction of the solar and geomagnetic evolution, with their inherent 11- year variations, improved understanding of the mechanisms whereby they affect weather and climate, and a better representation in forecast systems represent major steps to assess the benefits from these potential sources of predictability in subseasonal-to-decadal scales. If realized, they might bring added value to forecasts as "windows of opportunity", i.e. periods of enhanced predictability conditioned on skillful phenomena, with potential benefits to many sectors of society.

Regarding climate projections on longer timescales, one of the current limitations concerns the lack of probability estimates of future solar forcing variations, which limits the design of model sensitivity experiments within the Coupled Model Intercomparison Project (CMIP) that supports the IPCC. Although recent progress has been made regarding the consideration of plausible and extreme future solar forcing, they do not represent the full range of scenarios and even less the occurrence of low-probability worst-case events. A better quantification of solar impacts on global and regional climate would also represent an important step to improve knowledge of past climate, and hence to better constrain climate sensitivity, which represent a key source of uncertainty in the climate projections that ultimately guide the measures required to meet the ambitious global surface temperature targets agreed under the COP21 Paris Agreement.

### 2.3. Adaptation to extreme events

*Extreme SWe*

Intensive efforts are presently dedicated to forecasting GIC with some lead time in order to benefit decision making. When it comes to evaluate the performance of a given model, one is faced with the question of what is the most suitable method to compare it with real observations (in the case of GIC in power grids, the currents measured directly in the transformer neutrals by using Hall effect transducers; or those indirectly obtained by differential magnetometry under power lines). The broader community studying extreme SWe impacts is actively discussing how to evaluate model performance across a variety of prediction domains. This includes predictions of the ground magnetic perturbations leading to GIC. Efforts are done also to develop warning and mitigating capacities of SWe effects in the ionosphere: a) to detect and track ionospheric disturbances that might degrade technological systems based on radio-telecommunications in order to provide warnings and to create strategies to mitigate such a deleterious effects; b) to develop back-up communications systems to maintain the flow of critical information under failure of other communications systems that might be caused by natural or anthropogenic threats; and c) to prove the integrity of radio-communication systems technologies under the effects of certain scenarios.

***Meteor showers***

The detection of large bolides should concentrate monitoring efforts in order to identify the sources of hazard to humans. In the lower range of particle diameters, cometary meteoroid streams and younger dust trails encountering the Earth can produce a significant fraction of millimeter- to centimeter-sized projectiles that could require palliative measurements to avoid satellite impact hazard.

The dynamic linkage between a meteoroid orbit and that of a comet or asteroid has been also reinforced using powerful backward integrators like e.g. Mercury 6. As a consequence, the links are established on the basis of a long temporal scale comparison between the orbits of the parent bodies and that of each meteoroid. Such a procedure avoids false associations with meteoroids belonging to the sporadic background, casually showing similarity at the epoch of their encounter with Earth.

A close encounter with a comet is very unlikely, but the atmospheric consequences of a comet flyby similar to Siding Spring's passage near Mars (140000 km) would cause an increase of the input of extra-terrestrial dust to the upper atmosphere, which would perturbate significantly both atmospheric chemistry and dynamics. The consequences would range from destruction of ozone and water in the middle atmosphere to a perturbation of stratospheric aerosol as a result of the injection of cometary sulfur (Gómez Martín et al., 2017). Besides climate impacts, such an encounter would have a large impact on the ionosphere, creating a metal ion E layer with the potential of disrupting space-to-ground communications. Encounters with long period comets are difficult to predict, e.g. Siding Spring was observed for the first time about 20 months before its encounter with Mars.

***Adaptation to climate change impacts on geospace***
Predicting the middle and upper atmosphere long-term temperature and density changes resulting from trends in greenhouse gases and the dependency of those trends on the solar cycle will influence international space policy for the rest of this century and beyond. It will be a major factor in the satellite insurance and reinsurance industry, particularly when considering that monitoring the location of all known space debris objects to avoid collisions, even when no avoidance manoeuvres are needed, comes at considerable cost to satellite operators.

## 3. KEY CHALLENGING POINTS

### 3.1. Observational challenges

***Sun and interplanetary space***
*Polar observations of the Sun:* Seen from Earth or Earth-bound orbits, the poles of the Sun are hardly accessible to observation but are responsible for the large scale structure of the coronal magnetic field. In this sense, efforts to exploit the results coming from the excellent vantage point provided by ESA's Solar Orbiter will be key during the next 10 - 15 yr to understand the changes of solar activity at the poles of the Sun. The unique orbit of Solar Orbiter, inclined from the ecliptic up to 32 degree, will provide an unprecedented view of polar magnetic fields. Solar Orbiter is going to provide another unique observational capability, namely, the observation of the whole-Sun magnetic field by combining the PHI (Polarimetric and Helioseismic Imager) magnetographic data with those coming from the Earth (or Earth-bound orbit) when the spacecraft and our planet are in opposition with respect to the Sun. These global measurements will be key to gauge the prediction capabilities of current models of solar activity variability that have never been checked observationally.

*Synergistic operational monitoring of the solar corona, the solar wind and the interplanetary magnetic field* is key for early and reliable predictions of arrival times and characteristics of space weather events. ESA has recently initiated Phase-A studies for Lagrange, a mission concept specifically devoted to space weather. Designed to monitor the Sun from the Lagrange's L5 point, it will be the greatest herald of space-weather, Earth-directed phenomena with due time advance, thanks to the 60 degree angle that the spacecraft and Earth form as seen from the Sun. Among its payload, as is currently normal in every space weather effort, a magnetograph is included. PMI (Polarimetric and

Magnetic Imager) will hence provide crucial 24/7 monitoring of the photospheric magnetic field. When combined with proper extrapolations, its measurements will increase our forecasting capabilities of CMEs, CIRs, SEPs and flares.

*Accurate and extended satellite measurements of SSI variations*, covering the 11-year solar cycle, are of paramount importance to quantify solar effects in climate and unveil the underlying mechanisms. Observations of the last solar cycle showed larger SSI changes in UV wavelengths than hitherto believed, and climate models prescribing them revealed stronger climate responses to solar cycle, with regional climate impacts that were promising for subseasonal-to-decadal forecasts. These observations were later suggested to be biased by drifts in satellite instruments. Current estimates of SSI changes employed in climate models are based on empirical or semi-empirical irradiance models, with substantial differences in the magnitude of SSI changes over the 11-year solar cycle, which prevent more definitive answers on the controversial debate about solar impacts in climate.

*High spatial resolution measurements of the solar magnetic fields* are expected to benefit from the state-of-the-art features of the DKIST, which has recently seen first light at Haleakala Observatory, in the Hawaiian island of Maui, and EST (European Solar Telescope) to be erected in one of the Canarian observatories. Those telescopes, and the third edition of the Sunrise stratospheric mission, will provide new capabilities for observing the chromosphere and the corona.

However, a *global picture of the coronal magnetic field* does not appear in the plans of space agencies, although we only know the properties of the Sun's global photospheric and chromospheric field. If high resolution is crucial to understanding the detailed physics, global, moderate-resolution observations of the corona are paramount to predict the arrival of CMEs to Earth. A long term goal would be to pursuing the development of a space mission devoted to monitoring the global coronal magnetic field.

***Magnetosphere and ionosphere***

*Spectrally and pitch angle resolved measurements of electron fluxes*. A good knowledge of the vertical shape of the atmospheric ionization profile is crucial for constraining direct and indirect atmospheric impacts of energetic electron precipitation. This is particularly relevant in the MLT region, where dynamical factors such as the interplay between diffusion and advection induce huge variations of the magnitude of particle-induced composition changes as a result of only small variations in the vertical distribution of ionization. The existing MEPED instrument on POES suffers from poor energy resolution, directly translating into poor vertical resolution of the derived atmospheric ionization. Further issues of these instruments are contamination by medium-energy protons and uncertainties in terms of the fraction of precipitation observed. Current instrumentation has also poor coverage of relativistic electrons (>1 MeV), resulting in poor knowledge of direct EPP impacts in the upper stratosphere. Furthermore, there is a lack of pitch angle resolved measurements over a wide angle range, which prevents from a true measurement of the fluxes of all electrons precipitating into the atmosphere. These issues need to be addressed in future space mission concepts.

*Detection and tracking of ionospheric irregularities* caused by Space Weather is key for the study of ionospheric irregularities phenomena, expanding the understanding of the dominant energy distribution and momentum transfer mechanisms in the ionosphere and thermosphere, and, in turn enabling the development of advanced warning and mitigation applications for systems relying on predictable ionospheric radiowave propagation. For this purpose, ground-based networks of sensors probing the ionosphere are mandatory. However, even denser networks of sensors are needed for a more accurate and precise detection and tracking of ionospheric irregularities (e.g. Altadill et al., 2020). Moreover, although significant advances in our understanding of ionospheric irregularities have been made to date, a complete picture is yet to emerge. This is why research into ionospheric disturbances phenomena remains an important topic for the ionospheric community. New observational methods, both from Space and ground, will be key for future progress.

***Atmosphere***

*Continuous monitoring of the dynamical and compositional state of the atmosphere.* The "Golden Age" of spaceborne Earth observation of the past two decades has offered a unique opportunity to advance our knowledge of naturally and anthropogenically forced atmospheric composition changes and associated dynamical variations. However, roughly two decades of observations are not sufficient for capturing long-term changes of both, the direct chemical impacts (caused by changes of the irradiance and ionization levels related to decadal and secular variations of the Sun) and the dynamical coupling of these impacts to the stratosphere (due to changing circulation patterns as consequence of greenhouse gas forcing). Perspectives for the future are not promising: several space missions targeting middle atmosphere observations have recently ended or are phasing out in the next few years, with no replacements planned in the near future. As a consequence, an observational gap is expected that will seriously harm the continuity of long-term observational records of ozone and related chemical agents, temperature, and dynamical tracers such as water vapor, carbon monoxide and methane. The promotion of future space instrumentation targeting the continuation of the monitoring of middle atmospheric key variables is thus of utmost importance.

*Generation of consistent long-term climate records.* Multi-decadal climate data records from combined satellite datasets and their integration in numerical models are key for the detection and attribution of long-term trends in the atmosphere. Improved and extended datasets are also required for the evaluation of Earth System Models as well as for verification of hindcasts in subseasonal-to-decadal forecasts. Mandatory steps include the critical assessment of methods for merging, homogenising and testing disparate measurement series, as well as the implementation of ways of providing quantitative and traceable uncertainties of merged datasets and their systematic comparison. Standardised products for community use need to be developed and improved, including tools to access the merged datasets, for its use in data assimilation schemes employed in reanalyses, and forecasts whose skill strongly depends on initialization state.

*The thermosphere is the poorest known atmospheric region,* despite its importance for linking Geospace with the atmosphere where we live. Remote sensing observations of the thermosphere are extremely difficult to perform with current instrumentation and, as a consequence, temperature and CO2 measurements in this region are sparse. Atomic oxygen, a key parameter that largely controls the energy budget of this region through chemical recombination, as well as its cooling by CO2 and NO emissions, has never been measured globally. As the thermosphere is expected to be significantly affected by increasing CO2 concentrations which, in turn, has unforeseen effects on the LEO satellite orbits and space debris, the future continuous monitoring of its CO2 and atomic oxygen concentrations and temperature are fundamental for understanding the future evolution of the Space-Earth system.

*High resolution observations of critical chemical parameters in the MLT region:* Trace gas measurements in the middle atmosphere are difficult, particularly in its upper part, where most of the solar-induced composition changes occur. Except for isolated in situ measurements by instrumentation on rockets this region is accessible only by remote sensing techniques from space and ground. Limitations of these techniques with respect to spatial sampling, dependence on illumination, and vertical resolution often make it difficult to draw robust and/or quantitative conclusions about the magnitude and spatial variability of chemical changes. This is particularly the case for nitric oxide observations in the MLT region because of its large vertical gradients and its pronounced variability caused by energetic particle precipitation. Future progress in sensor technology and miniaturization, together with the development of new observational strategies (e.g., satellite constellations), is hoped to overcome current limitations.

***Meteoroid and asteroid environment***

New fireball networks have been created during the last few decades using new high-sensitive digital cameras. As a consequence, the atmospheric volume monitored has increased, and applying new detector techniques, including digital CCD and video imaging (Trigo-Rodríguez et al., 2013), have allowed the discovery of new sources of meteoritic activity. Such an effort has ended in 112 recognized meteoroid streams, plus a working list of 685 additional streams that remain to be confirmed (https://www.ta3.sk/IAUC22DB/MDC2007/). Most of these meteor showers are associated with comets, but others are linked with asteroids or transitional objects in near-Earth space. The later are more challenging as they might contain meter-sized rocks that can produce meteorite falls, or even excavate small craters like e.g. Carancas.

Additional effort is required to understand the ability of these challenging meter-sized bodies to penetrate in Earth’s atmosphere. The development of new mathematical approaches is the key to decipher the implications of m-sized meteoroids in impact hazard (Moreno-Ibáñez et al., 2020). To quantify and identify the effects it is needed to increase the fireball monitoring effort using high-resolution temporal and spatial detector systems. Increasing astrometric measurements will get better quality of orbital parameters.

New technological developments are also required to enable *interplanetary dust collection devices* to be deployed on board of orbital platforms for in situ analysis or return missions that do not involve altering the collected samples by high-speed collisions. Further afield, evidence of micrometeorites on the Martian surface and cometary return missions analogue to Osiris-REX would be highly desirable.

### 3.2. Models and methodological developments

***Sun and interplanetary space***

In spite of recent advances, our current understanding of the solar cycle progression is still poor. Improved magnetohydrodynamic (MHD) modeling of the solar dynamo is needed to allow for solar activity forecasts beyond the ongoing solar cycle and as a tool for SWe event prediction. Still more important are the techniques for combining those forecasts with future observational data (in particular those from Lagrange). Further, an effort to use our current good knowledge of the past to extrapolate the future is needed.

***Space weather and Ionosphere:***

Most current forecasting techniques of SWe effects on Earth are based on empirical models driven by solar wind data or by solar/geomagnetic activity indices which are able to warn for a few hours or fractions in advance. This is a significant gap for SWe products. In addition, ionospheric forecasting products, which can be tailored for a given region, as Europe, or to provide global forecasting, have a forecast horizon limited from minutes to few hours ahead. Therefore, it is needed to forecast ionospheric perturbations triggered by SWe much earlier in advance. To improve this, a better knowledge and more accurate storm-time electrodynamics is needed to be able to better forecast ionospheric irregularities. The analyses and exploration of additional physical magnitudes which can serve as proxies of plasma clouds arrival, in order to anticipate a SWe event much earlier in advance, are the key challenges for providing improved forecasting techniques and models capable of extending the forecasting horizons of disturbances caused by SWe up to several days.

While many ionospheric models are based on the linear regression approach and dependent on a limited number of variables, the correct relation between drivers and response parameters is still a state-of-art solution. The main advancement of contemporary models is the introduction of delayed reaction of ionosphere to the driver forcing. Moreover a progress is needed from predicting climatology to describing the real-time weather conditions in the ionosphere.

***Atmosphere and Climate:***

*Parameterized processes in climate modelling*. The dynamics of the mesosphere and lower thermosphere is driven largely by small scale waves, which are not explicitly considered in most climate models owing to limitations of horizontal resolution. Although resolved planetary waves are critical for the stratosphere, its circulation is also strongly sensitive to small scale waves, in particular orographic and non-orographic gravity waves. Parameterizations are often implemented to account for the impact of such waves in climate models and forecast systems. Deficiencies of these parameterizations are, for instance, the likely cause of the mismatch between modeled and observed NOx descent during dynamically perturbed NH winters, and an important factor of current model biases and the spread of future climate projections in the stratosphere. Currently, large efforts are being made to improve these parameterizations. Future progress will also benefit from the growing computing power, allowing the increase of horizontal model resolution, and hence, possibly allowing for explicit simulation of small scale waves and their propagation through the entire atmosphere.

*High vertical resolution and climate model lid height.* Recent progress in modelling and computing facilities has allowed higher vertical resolution and extending vertically the upper boundary of climate models above the stratopause. This has fostered international initiatives evaluating the beneficial role of an explicit well-resolved representation of stratospheric dynamics (the so-called high-top models; e.g. SPARC), and interactive chemistry (e.g. CCMI). The latter is of paramount importance for future projections foreseeing competing and interactive effects between the expected recovery of the ozone layer and increasing concentrations of greenhouse gases. Benefits have been tremendous, including an improved representation of stratosphere-troposphere coupling, the spontaneous simulation of internally-generated phenomena (e.g. the QBO), reduction of model biases, or an enhanced skill in subseasonal-to-seasonal forecasts. However, there are still large avenues for further improvements to fully exploit the added value of the middle atmosphere in upcoming generations of climate models. While there is no theoretical understanding regarding minimum requirements for the vertical resolution and model lid heights, coupling of the stratosphere with upper layers of the atmosphere is still not fully understood, as well as their potential benefits, which represents an endeavour to integrate in a holistic way the Space-Earth system and simulate their interactions.

*Advanced statistical analysis methods.* Solar signals in observations and/or model studies have been usually attributed using statistical methods such as multilinear regression, optimal fingerprints or superposed epoch analysis. These have a strong explanatory power, are easy to implement and have allowed advances in detection and attribution of climate change to climate forcing with large signal to noise (e.g. greenhouse gases concentrations or volcanic eruptions). However, the assumptions required for these standard methods (e.g., linearity, normality of the error distribution, regressor orthogonality, and so forth) are often not fulfilled in the climate system, which may result in biases or may even lead to erroneous conclusions. Currently, a robust detection and attribution to solar forcing is often elusive, particularly in paleoclimate, where additional uncertainties add to those of solar forcing reconstructions. As such, the attribution of past climate changes to solar variations is inconclusive even on hemispheric scales and for periods of well-known solar variations such as the Maunder minimum. Advances in statistical learning analysis methods developed in other fields may have the potential to overcome the aforementioned limitations and need therefore to be explored. Machine learning has recently been successfully employed in climate problems to e.g. uncover cause-effect relationships in this nonlinear highly complex system (so-called causal networks). Promising results can be anticipated for the identification of skilful predictors in statistical forecasts and the separation of superposing drivers of stratosphere-troposphere coupling that suffer from aliasing effects (e.g., solar vs. volcanic forcing)

***Meteoroid and asteroid environment***

Meteoroid ablation models need to implement the new insights into the composition and structure of cometary dust obtained by the Rosetta mission. Fragmentation of micrometeoroids as a result of vaporization of the interstitial organic matter is possibly the clue to reconciling apparently diverging ground observations. The potential of remote spectro-photo-polarimetric observations of the Zodiacal Cloud to determine the different dust populations should be fully developed. This involves a better understanding at a fundamental level of the interaction between radiation and particulate matter, and identifying light scattering spectro-photo-polarimetric features that may assist in quantifying the relative contribution of different populations, e.g. asteroidal vs cometary.

Meteoroid engineering models and atmospheric entry models require a better characterisation of the sporadic meteoroid complex regarding composition, structure, density, and tensile strength. Recent space missions to comets like e.g. Stardust (NASA) and Rosetta (ESA) have provided a significant insight into the heterogeneous nature of mm-sized meteoroids associated with comets. These particles initially forming meteoroid streams are fragile aggregates that fragment over time due to solar irradiation, and also suffer non-gravitational effects and collisions that make them lose progressively dynamical affinity with their parent bodies. We know that in time-scales of tens of thousands of years they are fragmented into micron-sized dust that forms the Zodiacal Dust. To increase the fireball monitoring effort using a multidisciplinary approach could be the key to increase our knowledge in these areas.

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CHALLENGE 4

# SUSTAINING HUMAN LIFE IN SPACE

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## 1. INTRODUCTION AND GENERAL DESCRIPTION

On 20th July 1969, the Fresnedillas Control Station, near Madrid, received the first words of a human from the surface of the Moon. "That's one small step for [a] man, one giant leap for mankind", was the historical sentence recorded from Neil A. Armstrong, commander of the "Apollo XI" mission. Nowadays, fifty years after Armstrong's epic achievement, space exploration by humans is commonly recognized as a highly exciting and attractive challenge and a powerful booster for scientific and technological progress in order to improve the human life on Earth. This is true despite some criticisms (minority, but significant) that question the high costs that it entails (Rinaldi 2016). The establishment of permanent settlements in the Moon and Mars is becoming a realistic venture day by day. After a decade of successful rover explorations to the surface of Mars, both ESA and NASA, and more recently the agencies from growing economies in Asian countries, are working to promote a manned mission, first to the Moon, and then to Mars. The European Space Agency (ESA), of which Spain is an active member, adheres to these objectives and is strongly committed in supporting and participating in these programs.

The main aim of space life science is to understand how the space environment, and specifically altered gravity and radiation, affects the morphology, physiology and behaviour of living organisms, and to design countermeasures to enable terrestrial life, and particularly human life, to develop outside Earth. That is, how they perceive and respond to gravity and radiation and adapt to the space environment. There is a variety of disciplines, such as genetic, molecular, anatomical or physiological fields, which use a range of technologies to address these issues. In order to understand adaptations at the functional level it is necessary to identify and study adaptations at cellular and tissue levels. Also, basic research analysing biomolecules, cells and model organisms is necessary to progress towards exploration subsystems or bioregenerative life support systems. Figure 1 shows a scheme of the synergism between space biology and human research from NASA life sciences translational research (taken from Alwood et al., 2017). Thus, life science space research moves from biological systems to human health in order to support successful human exploration; through the horizontal integration of research between basic and applied researchers, along with vertically-integrated teams.

The main aim of the present chapter is to identify CSIC research teams that can contribute at any level on space life science research and how they can do this contribution. The goal is to engage researchers within the current open science program approaches in order to optimize resources and facilitate translational research (see Figure 2).

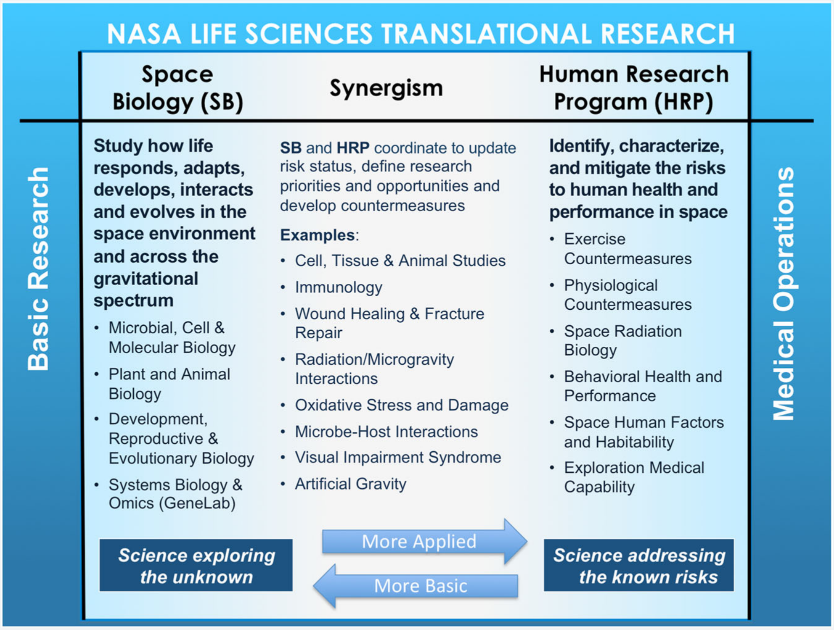
Although we do contemplate life science for space as a global research endeavour, the contents of this challenge can be gathered in three main categories:

***Biomedical implications of space exploration: Human and animal space biology***

The establishment of human colonies in space does not only depend on the appropriate technological developments, but also on the biological capacity of humans to live in a different environment. A return to the Moon, expeditions to Mars and beyond, and a rise in space tourism will lead to an increasing number of human spaceflights. Thus, it is crucial to consider the challenges to human health in space during long-term space missions and physiological changes that can take place during short-term altered gravity conditions. In addition, it is necessary to consider the possible influence of space radiation, available countermeasures and potential applications on Earth of knowledge gained when considering these issues.

For example, the establishment of the adult pattern of brain circuitry depends on various intrinsic and extrinsic factors, whose modification during development can lead to alterations in cortical organization and function. Since the

**FIGURE 1–**Space Biology and Human Research Bi-directional Synergism. Basic Space Biology research is done mainly with lower-level model organisms, cells, and tissues. The HRP conducts biomedical science mainly with humans. They synergistically and bi-directionally collaborate in maximizing opportunities for translating a subset of that knowledge to optimize the health and safety of the crew via applications supporting medical operations (taken from Alwood et al., 2017)




brain has evolved over millions of years in the presence of a constant terrestrial gravitational field, this environmental parameter may affect cortical development and the processing of information of the neurons and circuits exposed to space flights.

As well, the effect on human fertility will require careful consideration together with the necessity of ensuring human reproduction in long-haul missions of colonization. The capacity of humans to reproduce in space or in stations in other planets, under a variety of conditions of life with hypergravity or microgravity, and during or after exposure to radiation, represent new challenges which will determine the likelihood of success in these endeavours.

Few studies have been done about aging/health changes in long-duration space flights, due to the low number of missions (8) that have lasted more than 300 days in the space (Garrett-Bakelman et al. 2019). In humans, exposure to microgravity caused aging-like changes, such as cognitive disturbance, bone density loss, mild hypothyroidism, increased stress hormones, decreased sex steroids, insulin resistance, impaired anabolic response to food intake, anorexia, altered mitochondrial function, and systemic inflammatory response (Garrett-Bakelman et al. 2019; Wang et al. 2009). Thus, space's impact on aging (by boosting the onset of diseases) is a growing research field, and alternative therapies and counter-measures are necessary to avoid or delay the onset of these aging-like changes described to date.

Besides, crews on space missions have to be self-sustained, which also implies medical treatment beyond aging mitigation. Diseases or injuries that humans face on Earth are a challenge in extra-terrestrial missions. Medical infrastructure must be reliable and it must cover as many clinical scenarios as possible and, preferentially, it has to be operated in a semi-automated manner for the lack of specialized personnel. Simplicity is another requirement as the space for medical equipment is limited. Additive manufacturing technologies can be used for manufacturing personalized tools including the manufacturing of surgical tools under demand.

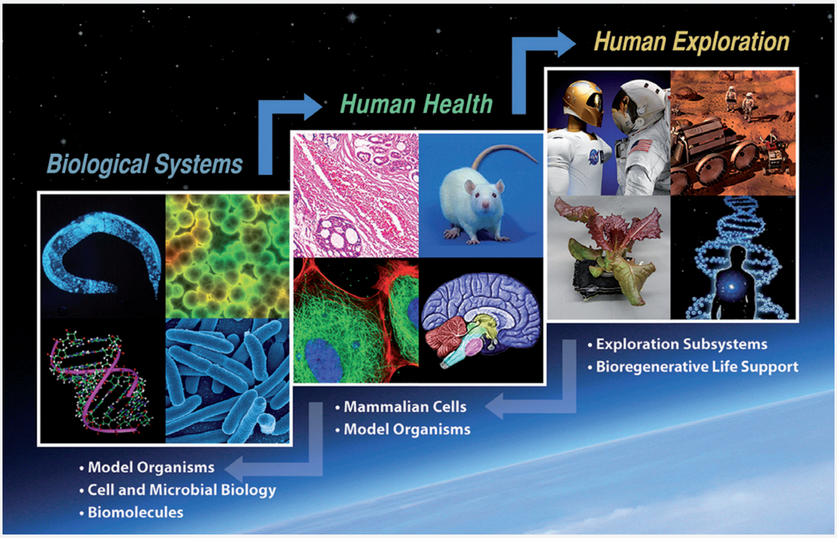
***Bioregenerative Life Support Systems (BLSS): Plant space Biology***

Plants are a necessary companion of Humans in Space Exploration.

https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Research/Plants

The objectives of deep space exploration by humans, including the Moon and Mars, require the implementation of a complex system of life support for space explorers, capable of supplying the elements necessary for sustaining their life (oxygen, food, moisture...) and of removing their waste products. The system needs to be bioregenerative, i.e. the components need to self-regenerate, without the addition of new elements brought from the Earth, and energetically efficient, only using the power sources available in space. Plants are a candidate to occupy a key position in these Bioregenerative Life Support Systems (BLSS). They indeed are being used in all the initiatives tested up to now, such as MELiSSA (Häder et al. 2018). There is no doubt that plants must accompany humans in space exploration ventures, since they offer the potential to provide food, replenish the air, filter water, and improve the mental health of the crew during long-duration missions in space. The achievement

**FIGURE 2**—The NASA Life Sciences Translational Path. It moves from basic research to human exploration applications with bi-directionality options. As knowledge is applied along this path (top arrows) questions may arise that can best be addressed by more basic research (bottom arrows) in order to support further progress toward successful human exploration (taken from Alwood et al., 2017).




of a true "space agriculture" is a fundamental objective of this global enterprise and it requires a full knowledge of the effects of the space environment on the plant biological mechanisms and the adaptive processes and countermeasures necessary to guarantee plant survival in these alien environments (Medina 2021; Figure 3).

In addition to the use of plants, human life support can greatly benefit from an adequate protein supply of animal origin. However, while seeds of different plant species are feasible to transport in space aircrafts to be seeded when necessary, transport of farm animals or embryos with the objective to raise a farm in the space, is not as easy task. A promising alternative to this problem would be the introduction of adequate animal species rich in protein content and having the ability for efficient waste processing. In addition to this, the animal farming model should be able to utilize inedible parts of plants to meet its nutritional requirements, everything integrated in a bioregenerative life support system.

A third approach to provide life support in space is by using food fermentation, the oldest way to preserve food in the Earth. It extends shelf-life, enhances palatability, increases nutritional value (e.g. vitamin production, increase nutrient bioavailability) and it may also deliver bioactive compounds and beneficial microorganisms (probiotics) (Marco et al., 2017). Fermented foods are essentially the result of microbial growth on a particular substrate and enzymatic conversions of food components. Lactic acid bacteria (LAB) are the main microorganisms involved in the fermentation of raw products. They are natural inhabitants of plants and the mammalian gut from where they have access to raw food and promote its fermentation. Currently, selected LAB are intentionally added to start fermentation and are generally known as "starter cultures" or simply "starters". Specific LAB strains are regarded as probiotics because consumption of viable cells exerts a positive effect on human health by improving human gut microbial homeostasis, including mental health through the interactions with the gut-liver-brain axis.

*Microorganisms in Space exploration*

Microorganisms are major players ruling the maintenance and functioning of ecosystems on Earth and influence the development of plants and animals, including humans. Microorganisms rule the behaviour and well-being of plants and animals, including humans. Today, it is well known that the human microbiome rules human physiology and psychology. Similarly, microorganisms interact with plant growth and it is well known the role of plant-growth promoting microorganisms and their role in the rhizosphere. Plants and animals are not such independent living creatures; rather they live through a continuous interaction with their microbiomes, the microbial communities living on, or around, them. Consequently, space settlements will have to consider the presence of microorganisms which are required for humans, plants and animals' life. How these microbial communities are affected by different factors in space are gaps that need to be filled. Confinement, potential radiation, different gravity, nutrient and waste cycling, use of biofertilizers and probiotics, etc., are some factors to be considered on maintaining adequate microbiomes in plants and animals. There is even a potential to sustain human nutrition entirely out of microorganisms and current examples are represented by starting-up initiatives on the consumption of microalgae, yeasts, and numerous microbialy-generated nutritive complements. A support for the provision of vitamins and probiotics, as examples, which could be produced by microorganisms. The role of biotechnology of microorganisms in space would represent a major achievement for the adaptation of sustainable processes in human settlements beyond our planet.

The microorganisms also carry out some essential steps required for the complete cycling of elements such as denitrification, nitrification, sulphate reduction, methanogenesis, oxidation and reduction of metals, among others. These capabilities are highly valuable to generate sustainable human settlements. Thus, microorganisms are of relevance to be able to build sustainable support systems in space and other planets.

Microorganisms could be a tool for the transformation of planets or large-scale environments to be used either for human habitability or to carry out different processes. An example of this has occurred naturally on Earth. It is the great oxygenation event based on the massive growth of cyanobaceria on earth about 2500 billion years that resulted in an oxygenated atmosphere as we know it today. Environments appropriated for bioleaching processes to extract metals could also be generated by using microorganisms such as the case of Rio Tinto (Huelva) where metal transformations are naturally carried out by microorganisms (Garcia-Moyano et al. 2008) and, at present, these microbes and conditions are used industrially. Thus, the transformation of environments for different purposes is a future challenge for human development in space.

However, in space and on the surface of other planets of interest for the establishment of human colonies, such as the Moon or Mars, conditions are unfavourable for most microorganisms that could be used in life support systems. For instance, radiation exposure is much higher than on Earth, due to the absence of a protective atmosphere and magnetosphere. Besides that, on Mars the soils may contain toxic compounds such as perchlorate and toxic metals such as lead, cadmium or arsenic. Some microorganisms found on Earth can develop under aerobic (in the presence of oxygen) or anaerobic (in the absence of oxygen) conditions which result in the possibility to inhabit almost any imaginable habitat in our planet. Microorganisms, and especially extreme microorganisms (i.e., extremophiles), are a major natural resource to design long-term support systems which must be sustainable. So far, the extremophiles are the organisms that define the currently known limits of life. Thus, when bioprocesses need to be developed under unfavourable conditions (from the human perspective), the extremophiles (i.e., thermophiles, phychrophiles, acidophiles, halophiles, etc.) are the resource to look at for genes, proteins and enzymes (biocatalysts), mechanisms and potential solutions (Elleuche et al., 2014) to be used in long-term space support systems.

## 2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

### 2.1. Biomedical implications of space exploration. Human and animal space research

Understanding the effects of space environment on the brain will reveal if long periods in space would induce significant structural changes. As the neocortex is the site of higher brain functions, the structural plasticity induced by microgravity may be of particular relevance for future prolonged human spaceflights. Also, generating models and simulations of the cortical circuits under situations of microgravity could particularly be relevant to model the effects of future prolonged human spaceflights that for technical reason cannot be performed experimentally. Providing a new understanding of brain plasticity will trigger interesting medical applications.

In a similar manner, the study of human reproduction in space and the associated technology that would be developed will found a direct application on Earth. The impact of food, or other environmental factors, on female and male fertility, and in offspring, will have to be implemented. There will also be a need to organize gamete, embryo and somatic tissue banks as an insurance against possible negative impacts of space conditions on fertility. Ethics and politics related to development and monitoring of reproductive issues will also be required.

The impact of aging-associated diseases is also specially relevant when thinking in future long duration space travel and other planets colonization.. Space-driven developmens to cure or delay aging-related diseases could have enormous social and economic impact. Besides an improvement in health and longevity in the elderly population, other social groups could be benefited. This is the case of patients suffering from premature aging diseases, cancer patients who are treated with agents that induce premature senescence of tumour cells, and old people suffering acute diseases (such as acute lung injury; ALI, and acute respiratory distress syndrome; ARDS).

Regarding space missions, the fact of being treated (vaccinated) against the onset of diseases that plague old age would reduce the consumption of medicines and health expenses, and would significantly improve the health and longevity of the older travellers. These aspects are especially important when thinking that these people will be confined in closed and reduced places for a long time or perhaps the rest of their life.

As well, developments in regenerative medicine based on tissue and organ bioprinting can find a direct application on Earth: i) The production of new generation of bioinks biologically active for capturing tissue-matrix properties, ii) clinical treatments for a variety of musculoskeletal defects caused by trauma or degenerative pathologies, iii) Personalised Medicine with Custom-made bioprinted Tissue Engineered Constructs (TEC) tailored specifically to the needs of each individual patient, iv) new platforms for testing radiation effects, drugs and cosmetics to accelerate the transition from animal to non-animal-based research and safety testing of new drugs for the treatment of numerous diseases. Space exploration offers a unique opportunity for making tissue engineered products a real choice for clinicians on earth. Added benefits include the possibility of providing remote heath assistance to low income or remote areas where the lack of specialized medical personnel is common.

### 2.2. Bioregenerative Life Support Systems (BLSS) to sustain human life in space

The foreseen achievements of the study of plant biology in space are: i) to provide possible systems of food production in outer space, ii) to promote sustainable production of nutrients under extreme stress conditions, iii) to select crops and varieties adapted to environmental conditions out of the current ranges of our agricultural areas, iv) to increase resource use efficiency in plants for cultivation under minimal availability of resources, v) to achieve limited biosphere where humans can be integrated in a cycling system that allows a circular and sustainable food supply. These developments could allow the implementation of stable human colonies in the outer space or in extreme environmental conditions of the Earth. As a side effect, investigations to be performed with these objectives could be used in scenarios other than space application (poor soil conditions, extreme temperature, etc...), and put to good use to achieve the underarching objective of sustainable agriculture on Earth.

The same sustainability target can be achieved with the development of an adequate high-quality protein supply for astronauts and space settlers along big timeframes. It would provide with an easy-to-handle animal rearing technology integrated into bioregenerative life support systems capable to use plant wastes and human urine for animal feeding through highly efficient fermentative processes. Being able to reproduce the most appreciated organoleptic experiences of human culinary culture would have a positive impact in the social development of permanent, big lunar/Martian colonies.

Microorganisms can also contribute to the sustainability of bioregenerative life-support systems by the integration of an additional food supply. Overlapping with the ongoing research on the impact of gut microbiota and health, there is a window of opportunity to design food fermentation strategies as a dietary source of beneficial microorganisms to restore homeostasis of gut microbiota and mitigate associated risks to long-term human space settlements. The knowledge gained to modulate human gut microbiota to improve crew health could also be used in Earth-based applications.

### 2.3. Microorganisms in Space exploration

As commented above, long-term human settlements need to be designed based on sustainability. Microbial-based processes are an ideal solution for the recycling of wastes and the production of goods following green and circular strategies. Because of the major influence of microorganisms and microbial diversity on the maintenance of living beings, farming systems, and extra-terrestrial environments, the role of microbial diversity needs to be monitored and extensive utilized. Only in this way we will be able to avoid undesired biases of essential microbial systems and to achieve a successful, long-term habitability beyond Earth. The study of extremophiles will allow to improve the ability of life support systems to withstand the conditions of space and the surface of Mars and the Moon, to make possible the permanence of humans for long periods of time on space travel and planetary bases.

Soil bioremediation, treatment of health-hazardous residues, and other processes mediated by microorganisms that have to be developed for long-term human settlements in space will also undoubtedly find an application on Earth and help mitigating the conditions resulting from a possible climate change scenario, in which heat waves increase, producing higher UV radiation doses and droughts.

## 3. KEY CHALLENGING POINTS

### 3.1. Biomedical implications of space exploration. Human and animal space research

***Effects of space environment on brain***

In the brain, the main structure involved in the processing of cognitive information from a sensory perception is the cerebral cortex. The information from the outside world arrives into the cortex via thalamic afferent fibers and the information is processed to produce a response. The final product results from an interaction between three types of information: external, intrinsic and stored. The main neuronal type involved in this process is the pyramidal cell, whose dendritic spines play an integral role in the activity of spiny cells (reviewed in Yuste, 2010). Thus, our understanding of the synaptic organization of the neocortex largely depends on the knowledge available regarding synaptic inputs to pyramidal cells. In addition, dendritic spines are key elements in brain plasticity. Therefore, it is extraordinarily important in functional terms to know the distribution, size and proportion of cortical synapses.

Previous results in postnatal developing rats subject to microgravity conditions during a 16 days space flight (Neurolab mission) showed that microgravity leads to changes in the number and morphology of cortical synapses in a laminar-specific manner (DeFelipe et al., 2002). However, in this study only conventional electron microscopy and stereological techniques were used to estimate the density of synapses in a particular region of the cerebral cortex, the hindlimb cortex of rats. Methods have been developed to overcome these difficulties, for instance by means of dual-beam electron microscopy, where a focused ion beam (FIB) is used in combination with scanning electron microscopy (SEM). Moreover, other cellular and subcellular elements can be easily identified and traced through the series of images and thus all the components of the neuropil (axons, dendrites, synapses, glial processes, mitochondria, synaptic vesicles, etc.) can be studied at the same time as synapses.

To enable the next steps of human exploration such as cruises to reach destinations beyond low Earth orbit, it is critical to perform a more comprehensive study of possible microgravity-induced alterations of neuronal morphology and organization of synaptic circuits in various cortical areas, including the effects of longer duration space flights on brain neuronal circuits. Understanding the effects of space environment on the brain will expand previous results and reveal possible further changes in the design of the dendritic geometry of pyramidal neurons and synaptic connectivity, for a variety of sensory, motor, associational and memory-related regions. This will enable to find whether changes are selective for those cortical areas related to somatosensory and motor processing, whether there are certain critical periods of development in which they are more prominent, and to what extent synaptic plasticity occurs in the mature cerebral cortex in a microgravity environment. Furthermore, the modelling of neurons and circuits will enable to probe the distinct processing of information of the neurons and circuits exposed to space flights.

### *Human reproduction in space*

Many genetic and environmental factors affect human reproduction with impacts on fertility and offspring health. Extended travel in deep space presents potential hazards to the reproductive function of female and male astronauts, including exposure to cosmic radiation, microgravity, hypergravity, psychological stress, physical stress and circadian rhythm disruptions. Only a few studies have examined the effects of microgravity on female reproduction (Mishra and Luderer 2019). They have found disrupted oestrous cycling and follicle development, which are a cause for concern. Exposure to microgravity during space flight and to simulated microgravity on Earth disrupts spermatogenesis and testicular testosterone synthesis in rodents. Studies performed on Earth in rodents exposed to experimentally generated high charge and energy (HZE) particles have shown a high sensitivity of ovarian follicles and spermatogenic cells to these particles (reviewed by Mishra and Luderer 2019).

In mice exposed to microgravity or artificial gravity at the International Space Station (ISS) and returned to Earth, only a decrease in accessory gland weight was detected in relation to control mice caged on Earth. There were no overt microscopic defects or changes in gene expression in the reproductive organs as determined by RNA-seq. Spermatozoa from mice kept at the ISS could fertilize oocytes in vitro at levels comparable to control males. Development of these fertilized eggs to birth and postnatal growth or fecundity of offspring showed no significant difference in relation to controls. Thus, short-term stays in outer space do not seem to cause apparent alterations in male reproductive function and offspring viability.

There has been little work carried out on human semen yet. Frozen sperm samples subjected to space-like microgravity conditions appeared to be as viable as those that remained on Earth. Mobility, vitality and DNA fragmentation was not altered when compared to its properties in conditions of gravity on Earth. A more detailed study on human (and bull) sperm function (NASA Micro-11 mission) allowed for live sperm assessments in spaceflight using several fertility biomarkers used clinically on Earth. Cryopreserved sperm were thawed at the ISS and several functional tests were carried out to assess motility and the ability of sperm to develop fertilizing capacity. Overall, results suggest that sperm functions related to fertility are altered in spaceflight. Studies on fresh human sperm are lacking. So far, research has apparently been carried out comparing semen samples collected before and after space flight, but no studies are available yet with semen samples collected at the ISS because astronauts seem to refuse to supply the samples. Future results should further explore sperm function in space with a view towards automated sperm analysis systems and the establishment of sperm banks outside Earth and also examine impacts on sperm DNA integrity.

Sex in space would be difficult and dangerous for a series of reasons. There are mechanical challenges and the threat to fertilization and the developing embryo posed by cosmic radiation. The development of appropriate space suits that could allow for conception in low gravity and aid pregnancy will be required. Altogether, many gaps require attention, including the effects of microgravity, hypergravity and radiation on the male and female reproductive tracts, hypothalamic-pituitary regulation of reproduction and prenatal development of the reproductive system, as well as the combined effects of the multiple reproductive hazards encountered in space.

***Human aging and cellular senescence***

In recent years it has been shown that the cause of the main diseases associated with aging is the accumulation of senescent cells in different tissues. These cells are metabolically hyperactive, and with harmful effects when they accumulate in the body in a chronic way. Importantly, it has been described that simulated microgravity promotes cellular senescence in neural rat cells and human intervertebral disc cells (Wang et al. 2009). Thus if the microgravity is a trigger of cellular senescence (as radiation does as well), and due that these cells play a causal role of several aging-associated diseases, it could explain some physiological aging-related changes described in astronauts.

An emerging and exciting approach is the clearance of senescent cells. It was recently demonstrated that elimination of senescent cells delays the onset of aging-related disease, thus establishing for the first time a direct role for cellular senescence in the onset of disease. No side effects were observed in mice during progressive elimination of senescent cells, demonstrating that age-dependent accumulation (continuous presence) in the organism is not essential. However, this strategy is based on genetic interventions, which cannot be used in humans. Pharmacological approaches, by using drugs that selectively kill or "silence" senescent cells (senolytics and senomorphics, respectively), are another strategy, although based on a chronic treatment scheme, which in some cases has led to negative side effects. A possible approach to solve this problem would be the targeted and progressive clearance of senescent cell accumulation by stimulating the adaptive immune response (vaccine development or targeted immunotherapy). Immunotherapy is defined as the stimulation of the immune system to recognize and kill disease-associated cells and recent data demonstrated that vaccination (T-cell response) in spaceflight was not affected, unlike other processes (Garrett-Bakelman et al. 2019). Such a vaccine could prove successful for the natural aging process, by improving health and increasing longevity, and important for microgravity-related environments. On the basis of the accumulated experience in this field, senescent cells are ideal targets for directed immune therapies. Importantly, there are no published data about the effect of immunotherapy on senescent cells, thus highlighting the novelty of this approach.

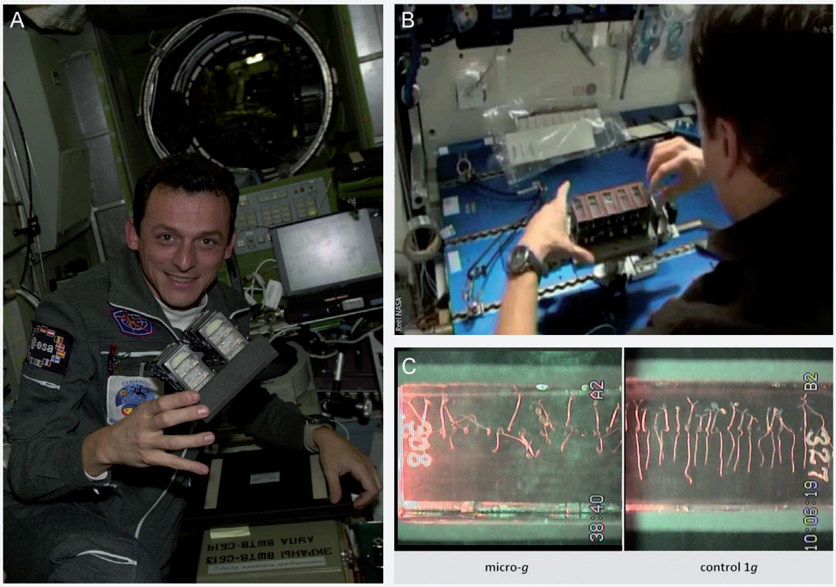
***Countermeasures for regeneration of tissue and organ damage in space***
The future challenge to improve the medical autonomy of the crew is the use of bioprinting, an additive manufacturing technology that will allow to grow human tissues in space, to treat various pathologies such as severe burns or complex bone fractures.

Bioprinting involves the use of bioinks, materials that combine biological and hosting materials. Hydrogels are normally used as the hosting material for bioinks. They are mostly appropriate for soft tissues but they do not present the required mechanical properties for hard tissues such as bone or cartilage, where other more complex approaches are needed.

Current technologies in development for bioprinting on Earth are:

- *Extrusion*: viscous materials are pushed through a nozzle and deposited on strands following the designed pattern. Physical and chemical processes are required to shift the viscoelastic nature of the material to stabilize the structure. The shift can be triggered by the addition of ions, variations in temperature or pH, solvent evaporation or photocrosslinking.
- *Inkjet:* droplets of low viscous liquids are directly deposited onto a substrate. The work with solid materials in powder forms requires the use of a resin that acts as binder.
- *Selective laser sintering (SLS):* a laser beam is directed across a powder bed to raise temperature and melt “a path”. Ceramic, metallic or polymer substrates can be used. Laser-induced forward transfer (LIFT) requires ultrashort laser pulses to induce vaporization on a metallic layer acting as a mask. The mask protects cells from the high power beam and results in droplet formation that is collected on a substrate.

**FIGURE 3—**Images of Spanish biological experiments in the International Space Station (ISS), originated in CIB Margarita Salas – CSIC research center. A: The Spanish ESA astronaut Pedro Duque during the Cervantes Mission (2003) showing an experimental container of one of the Spanish experiments. Credit: ESA/Pedro Duque. B: Processing of samples in space corresponding to one of the runs of the NASA-ESA Seedling Growth Project (2013-2018) on plant biology. Credit: NASA. C: An experimental image of the Seedling Growth Project. Seedlings of the plant model species Arabidopsis thaliana germinated and grown for 6 days under microgravity, in space (micro-g), compared with control seedlings grown in the same conditions, but under terrestrial gravity (control 1g). Credit: F.J. Medina (CIB-CSIC).




- *Stereolithography:* similar to SLS. Here the laser is used to obtain local polymerization on organic substrates. 2-photon stereolithography can write 3D structures inside a monomer solution within a submicron range.

For space applications, gravity is an important factor determining not only the material and technology requirements, but also the three-dimensional growing of tissues and organs. Reduced gravity has shown to cause dramatic physiological changes. Cardiovascular, musculoskeletal, nervous, gastrointestinal and immune systems respond to microgravity in a similar way to changes associated with ageing. Recent microgravity experiments found that human thyroid cancer cells and human endothelial cells form multicellular spheroids rather than the flat single-cell layers typical on Earth (Bradock, 2019). In microgravity, spheroids can develop into tubular structures resembling the intima of rudimentary blood vessels, even without scaffolds. However, for more complex tissues this self-assembly methodology is not enough, and another technique (like 3D bioprinting) is required to mimic the tissue environment.

In the ISS, Russian researchers have just started to use a magnetic levitating technology to create spheroids of mouse thyrocytes, to imitate a thyroid gland, and chondrocytes to produce cartilage. Both sort of construct showed living cells with a normal morphology. Also, a Biofabrication Facility (BFF) with a bioprinter has been recently installed by the US at the ISS to test different biomaterials for tissue engineering. These are likely to be the first steps in using microgravity studies to create tissues for transplantation or drug development. It also provides new research lines that enable the testing of bioinks created on Earth, opening new opportunities for bioprinting researchers and institutions.

### 3.2. Bioregenerative Life Support Systems (BLSS) to sustain human life in space. Food supply

***Plant growth in space***

Growing plants successfully in space requires a full understanding of the biological mechanisms of response and adaptation to the conditions of the spaceflight environment. It provides conditions that are inaccessible on Earth, such as growth in microgravity and exposure to cosmic radiation, providing a unique opportunity to dissect responses under conditions that plant biology has not encountered during its evolutionary history (Figure 3). Additional challenges of spaceflight experiments come from limited access and available space on orbiting platforms.

The culture of plants on planets and satellites other than the Earth, such as the Moon or Mars, necessarily requires the creation of a “greenhouse” in which the plant is provided with the necessary environmental elements to enable its development. These elements include light, water, temperature, oxygen, $CO_2$, aeration, and nutrients. Furthermore, microorganisms are required to achieve a fully functional and sustainable environment for plants. In addition, plants need a substrate capable of anchoring the root and sustaining root development. There are published experiments that demonstrate that terrestrial plants can grow in an analogue of lunar soil or Martian soil, provided that this substrate is supplemented with additional elements and substances that provide the plant with water, mineral salts and nutrients that it needs for its survival and development. In this regard, the example of potato cultivation on Mars described in the movie “The Martian” (2015) is very illustrative. It is certainly science fiction, but it raises with rigor and solid scientific and technological arguments the problems and their possible solutions. Regarding gravity, centrifugal culture at 1*g* does not seem technically feasible and, with respect to radiation, available shields do not seem to achieve 100% shielding, as evidenced from the data obtained in the ISS (Maalouf et al. 2011; Medina et al. 2015).

The first space experiments, more than 50 years ago, showed that plants could survive and grow in space, although alterations were soon reported. Major improvements in culture facilities, mostly after the assembly and operation of the International Space Station (ISS), have allowed concluding that microgravity itself does not prevent plant growth and reproduction. This occurs despite the alteration of fundamental cellular and molecular processes that have been reported to take place at the early developmental stages and/or as an early response to the microgravity environment. They include alteration of cellular processes, changes in gene expression and epigenetic modifications, which should produce significant effects on the plant growth and development (Herranz and Medina 2014). The experimental evidence of the achievement of a full seed-to-seed life cycle in space means that plants should trigger immediate adaptive responses to overcome the stress conditions of spaceflight throughout the successive developmental stages (Zupanska et al., 2019). However, the physiological mechanisms by which plants overcome and counteract the adverse environmental factors of space, specifically gravity alteration and increased radiation are still unknown. The investigation on these adaptive processes and mechanisms is one of the most important and decisive challenges of space plant biology in the coming years. In particular, the research efforts focused on the effects of spaceflight on the plant genome will be considered under a further separate heading in this document. Additionally, how the microgravity condition changes gene and protein expression by using the novel repertoire of -omics methodologies will be also explained here.

An alternative approach in space plant research has consisted of the *in situ* direct production of vegetable crops in ISS, which may serve as fresh food to supplement the packaged diet of astronauts. This has been (and still it is) a specific objective of NASA with the Veggie (Vegetable Production System) and APH (Advanced Plant Habitat) facilities. For instance, to study the effects of space conditions, red romaine lettuce was successfully grown in three tests in the Veggie incubator with two different harvest methods, and yields were comparable to growth on Earth, as well as different physiological markers analyzed and the microbial communities associated to plants.

Selection of crops for stable agricultural systems can be carried out primarily by choosing species adapted to wide ranges of conditions in the Earth, assuming that they are more adaptable to new situations than the crops that cannot prosper in extreme environments of the Earth; and, second, with crops able to grow with minimum requirements of soil, nutrients and other inputs. Indeed, some crops are able to produce edible organs without soil and with limited availability of resources, such as lettuce (*Lactuca sativa L.*) or tomato (*Solanum lycopersicum L.*). In addition, this crop selection should ideally cover most of the Human nutritional needs.

The role of microbial communities for plant growth is also a factor to be investigated to enhance plant productivity and to solve some of the stresses of plant growth under space conditions.

The global challenge thus consists in releasing crop varieties adapted to the target conditions – ranging from outer space to human settlements on other planets – for a sustainable production of food.

***Human food supply: animal protein***

Some animal candidates for space protein source have already been discussed in the scientific literature, namely aquatic animals (fish species, snail, and amphipods) poultries, mammals and insects such as silkworms. However, none of them has met the necessary requirements to be used for this purpose.

Yellow mealworm (*Tenebrio molitor L.*) is a kind of coleopterous belonging to *Tenebrionidae* family. During its larval and pupal stages is rich in protein and it is easy to rear. In China it has become a popular dish for human consumption, whereas in Europe its main use has been limited to provide a protein source for animal feeding (Gasco et al., 2019, Motte et al., 2019).

Previous research has been already carried out concerning analysis of the amino acid composition of *Tenebrio molitor*. According to this, this insect contains all the essential amino acids needed for human nutrition and, in most cases, those contents are above the requirements proposed by FAO/WHO/UNU (FAO/WHO/UNU, 1985). It has been reported that the essential amino acid content of yellow mealworm is higher than that of pork, lamb and bean, and close to that of beef and fish (Li et al., 2013). However, some studies are still needed to characterize, beyond its amino acid composition, the identity and nature of yellow mealworm proteome. We need to go forward the simple compositional analysis by implementing high throughput Omic approaches allowing performing a detailed proteomic, lipidomic and metabolomic profiling of yellow mealworm.

Most common feeding sources in yellow mealworm farms are wheat bran together with various kinds of vegetables and fruits. In bioregenerative life support systems it is common to produce a certain amount of wheat bran and around 3 to 5 times the amount of rice and/or wheat straw. On the other hand, it is known that anaerobic fermentation contributes to increase the digestibility and protein content of straw. Consequently, production of fermented straw could become, together with other alternatives, an interesting feeding source for yellow mealworm in the space, contributing to the improvement of life cycle closure. Previous studies have shown that the growth rate of larval *T. molitor* is lower when plant wastes (fermented straw) was included into the feeding regime as compared to feeding with a conventional diet containing wheat bran and cabbage leaves. The explanation could be the low nitrogen content in the fermented straw (Li et al., 2013). This model would be improved considering the potential use that astronauts could give to excrements of yellow mealworm larvae as plant fertilizer.

***Human food supply: fermentation processes***

Certain microorganisms are currently applied in bioregenerative life-support system (BLSS) for in situ regeneration of resources to support long-term space explorations. An example of such BLSS is the Micro-Ecological Life Support System Alternative (MELiSSA) pilot plant located in Barcelona and developed by the MELiSSA consortium where bacteria are used for organic waste and water recycling: http://www.esa.int/Enabling_Support/Space_Engineering_Technology/ ELiSSA_life_support_project_an_innovation_network_in_support_to_space_exploration

In parallel, several research groups are studying the so-called "spaceflight syndrome" using model bacteria to understand bacterial physiology under spaceflight conditions (Morrison et al., 2019). The majority of these experiments have been carried out with either model bacteria or pathogens that represent a threat to human health. Nonetheless, due to the growing interest on the potential role of probiotic bacteria on astronaut's health, preliminary ground-based space simulation experiments have already started with some LAB. Therefore, one can anticipate that the body of knowledge will develop in the near future to provide further evidence for the intended use of these bacteria to sustain human life in the space.

### 3.3. Microorganisms in space exploration

Extremophilic microorganisms have developed complex molecular mechanisms to adapt to the conditions of extreme environments on our planet, such as high radiation doses, high and low temperatures, high salinity and toxic compounds such as perchlorate and heavy metals, among others. Molecular inventions developed by extremophilic microorganisms could be transferred to other microorganisms and plants to expand their capability to adapt to the particular extreme conditions of space during manned missions, to the surface of the Moon, or of other planets such as Mars.

For instance, microorganisms used to produce fermented foods and to recycle waste, and plants could be modified to resist higher doses of UV and ionizing radiation. In this way, their level of cellular stress and the frequency of mutations in their genomes would be reduced, optimizing their performance in spatial conditions. These organisms would be modified with genes involved in the radiation resistance of bacteria, archaea or algae naturally exposed to high doses of UV (e.g. Andean highlands) or ionizing radiation (e.g. uranium mines and nuclear power plants), such as genes related to DNA damage repair, production of pigments or in protection against oxidative damage.

Another limitation for the human colonization of other planets is the composition of the soil, which for example on Mars contain toxic compounds such as perchlorate and heavy metals could be harmful to plant growth. Therefore, food plants, microorganisms that promote plant growth or those used in soil bioremediation could be modified to resist and/or degrade toxic compounds. Bacteria and archaea resistant to perchlorate and others that also reduce it to chloride have been isolated from various extreme saline environments, such as Big Soda Lake (USA) and hypersaline soils. On the other hand, microorganisms (including unicellular algae) resistant to high concentrations of toxic metals and metalloids have been identified in acid mine drainage environments, such as in the Rio Tinto (Spain) (García-Moyano et al., 2008). Genes involved in resistance to perchlorate, or to toxic metals and metalloids from microorganisms of those environments could be used to modify other organisms that facilitate human exploration and eventual settlement on Mars.

The molecular mechanisms of resistance to some of the extreme conditions that can limit the maintenance of life outside our planet, such as radiation, perchlorate, toxic metals and metalloids, have not yet been well characterized in the microorganisms most resistant to these conditions. In addition, there is an important bias in the mechanisms that are known, since they have been studied mainly in microorganisms that can be cultured in laboratory conditions.

To better understand microorganisms and their capabilities it is necessary to complement culture-independent and -dependent techniques. Cultures allow to grow and evaluate metabolic processes whereas -omics (genomics, transcriptomics and proteomics) and molecular biology permit the analysis of the genomes and their regulatory mechanisms. The retrieval of genetic information, preferentially from extremophiles (showing highly stable biomolecules), to be expressed in microbial model systems is a procedure to achieve large-scale expression of selected genetic information (genes and their regulation), use of microorganisms or their enzymes as biocatalysts and achieve biotechnological processes for sustainable human settlements beyond our planet.

The use of microorganisms and their enzymes in biotechnological processes in space will require accurate and rapid monitoring systems which, at present, are barely available. These systems could include, for example, fluorescence lifetime correlated techniques which can provide quick, sensitive, *in situ* evaluation of the status of microbial and enzymatic processes. Ideally, the combination of biological, genetic and physiological, tools complemented with engineering design will aim to final applications for sustainable strategies for the settlement of humans in space.

### 3.4. Space –omics. Use of spaceflight generated biological datasets

In the next couple of decades spaceflight life-support systems will require to generate and exploit all the knowledge from space biology experiments performed in microgravity and cosmic radiation conditions from human bones to plant biology effects. The objective to promote more efficient and safe environments to support our settlements out of Earth will be realistic thanks to the scientific activities that began on board the ISS twenty years ago. Scientists who have had the opportunity to develop biological experiments in the space environment have collected a significant amount of biological samples and scientific results but the limitations on Space Research on experimental design made quite complicated to compare the results and reach similar conclusions. In addition, not all the samples have been processed and the results published conveniently, as stated at scientific meetings by our European colleagues. They have compiled more materials than they can analyse and complementary biological information for spaceflight experiments is not usually made available to the community. In the case of the genome scale -omics techniques, while results are usually deposited in the databases by publisher's request, data does not use to be processed following a single scientific criterion.

NASA has paved the way in answering such needs by implementing the GeneLab database (Ray et al. 2019). The GeneLab initiative was launched in 2014 and has positioned the American scientific community working with NASA at a clear advantage, as their work is more readily accessible and usable than the work from scientists who depend on the ESA for storing information. GeneLab has been prioritizing the deposition of data obtained in spaceflights. However, samples and data which are spaceflight-relevant are also collected, covering a full range of adverse experimental conditions, either in space experiments or by simulation in terrestrial analogues. To list a few examples: experiments with various levels of gravity, with high radiation, with extreme temperatures and suboptimal composition of the atmosphere and culture media (nutrients, pH, humidity...). GeneLab is considering extending the database to other types of data, such as datasets obtained from other astrobiology analogues with similar suboptimal environments, or from a more diverse range of ionizing radiation. Finally, GeneLab has launched in early 2018 the Analysis Working Groups (AWG), divided in four topics: Plants, Microbes, Animals-Humans, and Multi-Omics. AWGs are now comprised of ~120 scientists across four different countries (including CSIC researchers), and members meet monthly to: establish and adopt standards for sample processing and data analysis for space omics; to discover new biology from mining this large array of data; and to publish jointly in peer-reviewed journals.

There exists a need to promote a unified criterion for the incorporation of all scientific data obtained at the European level in a single database to homogenize all the ESA projects, including highly valuable samples that have been exposed to spaceflight environments and preserved without proper analyses.

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CHALLENGE 5

# IN SEARCH OF LIFE

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## 1. INTRODUCTION AND STATE-OF-THE-ART

The search for life in the universe and its origin is one of the most fundamental questions of human knowledge and science. The question "When and where the chemical complexity existing on Earth appeared, especially that related to the origin of life" expands now far beyond the Earth and the solar system pushing the human kind for exploring the universe in an unprecedented inter- and multi-disciplinary approach as it will be shown in this chapter.

Solar system objects with many and diverse environments have and have had the possibility to host life nowadays or in their past history. The possible existence of large subsurface liquid water reservoirs in several icy satellites is one of the promising lines of future research in the search of life in the solar system. This search will require multidisciplinary approaches to detect and analyse organic and chemical features as well as morphologic and sedimentary structures that could be related to life. This study crosscuts different research disciplines and technologies.

While the origin of life on Earth is still based on a number of working hypotheses, the search for evidence of life in the solar system is related to the search of the presence of water either on the surface or at the subsurface of the planets, moons and asteroids. This has been the first approach based on our knowledge of life conditions on Earth. Discoveries based on research on Earth environments and life have proven the existence of life in so called "extreme environments". Potential habitable environments in other planets are under conditions similar to some extreme environments on Earth. Therefore, the study of extremophiles and Earth analogues is now and will be in the next decades crucial to assess the possibilities of life in the solar system. Earth's history and extinguished forms of life in the past are also a source of potential scenarios to be considered.

On the other hand, the search for life on exoplanets is mostly limited to finding planets where the conditions on their surface are not too hostile to the delicate equilibriums required to develop complex biochemistry. Still, the parameter space of all possible chemistries of all possible imaginable lives is vast, so for practical reasons the searches are limited to Earth-like life footprints that we can identify remotely. More in particular, the best prospects for remote detection of life on exoplanets are on the detection of combinations of atmospheric species that would not exist in a purely abiotic setup.

The search for extinct and extant life in universe is an ambitious and pluridisciplinary approach that involves expertise in different fields: astrobiology, astrophysics, biophysics, (astro)chemistry, geology, mineralogy, geobiology, paleontology, microbiology, lichenology, phycology, botany, and mycology, among others. Therefore, it happens in three broad areas, namely: Solar System exploration, Exoplanets and their host stars, and Interstellar medium and Astrochemistry. We make a review of the state-of-the-art in these three areas, and then proceed to identify key challenges to be addressed in the next decades.

### 1.1. Solar System exploration - Mars, Icy Moons and Titan

**Chemistry and laboratory experiments** have taught us that the basic "biochemical" building blocks of life can be obtained from simple molecules and gases. However, we still don't know how to make informative polymers from them, or how to obtain polymers with catalytic activities. This is one of the widest gaps in the steps for the origin of life. Experimentation, simulation and modelling in the "test tube" is essential. In building macromolecular and supra-macromolecular structures for life, the chirality of the basic elements as well as compartmentalization processes played critical roles. Understanding primitive metabolisms and primitive bio-catalysts will shed light to this still dark part of the origin of life.

**The chemistry of meteorites** (especially of carbonaceous chondrites) shows a rich composition in amino acids and precursors of nucleobases, and, as the sensitivity and resolution of astrochemical instruments (both in space and on Earth) is improving, newer and more complex molecules are being discovered in the interstellar space. Since the discovery of extremophiles several decades ago, we have learnt how diverse, robust, and versatile can be the biochemistry that allows microbes thriving at the limit, under extreme physicochemical parameters. Microbial life thrives on Earth in all places where there is a minimum water activity. Due to extreme physicochemical parameters (e.g., temperatures from -20 to 113º C, pH ranges from 0 to 12, high salt, high or low pressure) dominating in those places, they can be considered as analogues of current or ancient environments in other planetary bodies in the solar system.

**Mars** is the first priority in the way of searching for life outside the Earth. The advances on the metabolism of extremophiles together with the somewhat controversial, potential martian microbial fossil in the ALH84001, boosted the planetary science community to retake the exploration of Mars. Several NASA orbiters, landers and rovers together with ESA's orbiters have provided valuable information in the last 20 years. Mars was warmer and wetter than it is today and had liquid oceans, an active magnetic field and a thicker atmosphere by the time (3.5-3.8 billion years ago) life arose on Earth. Given the similarity between the two planets, it seems reasonable to think that whatever steps led to life on Earth could also have occurred on Mars. We assume that life originated on Earth, however, this might not be true or it might have occurred in other planetary environments too. The solar system has offered since its origins a variety of scenarios where, at least a complex prebiotic chemistry might have taken place.

**The geophysical study of Mars subsurface** (and of any other body of the solar system with a solid surface) where life could be harboured is achieved by indirect geophysical methods from the distance. Subsequent approaches include the installation of geophysical instrumentation on the surface, as has been done already on the Moon and Mars. This surface geological experiments combined with surface seismometers (NASA's Insight mission, in operation) and surface *georadar* techniques, are revealing the internal structure of the planet, and will provide a first exploration of the soil composition at relatively shallow depths (<100m).

Mars is a good example to illustrate how exploration helped to understand the main constraints and conditions for the possibility of life. The first photographs provided by the cameras on Viking landers and orbiters showed that geological features formed on Mars resulted from combinations of internal and external processes. Orbital sensors and robotic analyses of Martian minerals subsequently have identified a variety of water-containing clays, sulfate minerals precipitated from briny solutions, ice in the regolith, and subsurface hydrogen that is presumably water-ice. In rocks and surface materials, extensive hematite ($Fe_2O_3$) deposits have been identified more recently by the Mars Exploration Rover Opportunity.

**The story of Mars exploration** illustrates how the process of finding evidence for live in other Solar System sites will also develop. The first surface photographs provided by the cameras on Viking landers and orbiters, showed that geological features formed resulted from combinations of internal and external processes. Orbital sensors and robotic analyses of Martian minerals subsequently identified a variety of water-containing clays, sulphate minerals precipitated from briny solutions, ice in the regolith, and subsurface hydrogen that is presumably stored in abundant water-ice. Very recently, evidence of water in liquid state has been reported using radar observations from orbit using data from ESA's Mars Express.

**Icy moons**: Several decades of space missions to the outer solar system have proven that there are many moons beyond planet Mars with large volumes of liquid water in their interiors (Prieto-Ballesteros et al., 2019). Europa and Enceladus moons achieve the main requisites of planetary habitability in addition to liquid water: chemical elements essential for life, and available energy to maintain metabolisms. These two ocean worlds have a rocky seafloor, which is probably geologically active, in contact with the liquid water. The interaction between them may provide energy and chemical species to the aqueous solvent. In both there are evidences of endogenous features that connect the ocean and the surface, i.e., the plumes that expose materials on the surface that come from the interior, including the biosignatures of subsurface life, if any. In addition to the rise of materials by this mechanism or other types of cryovolcanism, subduction processes are thought to be occurring on Jupiter's moon Europa, supporting the hypothesis of endogenous dynamics able to recycle chemical elements such as carbon or sulfur. Considering the terrestrial life case, chemolitotrophic metabolisms, and a very low biomass of cells affected by extreme physico-chemical parameters like the acidity or the redox state are expected in this deep environment. So far, the best terrestrial analogues considered to better understand the geochemistry and the habitability of these dark hypothetical niches are: aphotic systems where serpentinization or other type of aqueous-rock interaction occur, deep cold brines, and subglacial liquid-water environments.

**The Saturn moon Titan**, on the other hand, possesses a large inventory of organic molecules at different physical state on the surface but not evidence of a link between the surface and its deep ocean. Titan is a target to studying the prebiotic chemistry and the origin of life, offering an organic alternative to the liquid water to act as the solvent that supports life. Indeed, it is predicted that if life emerges in Titan, it would be different than the one we know on Earth.

### 1.2. Exoplanets and their host stars

**The search, characterization and study of exoplanets** is a prominent branch of the search for life beyond Earth in nowadays science. Among them, those with bulk properties like our own world are the ones with higher astrobiology interest. Currently, we have the capabilities to detect planets sharing some properties with Earth —especially around stars smaller than the Sun, or red dwarfs—, but no true Earth analogue has been identified yet. Also, the information that we can learn from exoplanets is much more limited than the one we can obtain from Solar System bodies. Essentially, and in the most favourable scenarios, we can measure the masses and sizes of these planets, and we will be able to infer whether they have atmospheres and identify the presence of key molecules in some of them.

The discovery of the hot Jupiter 51 Peg b by Mayor and Queloz (1995) (Nobel prize in Physics in 2019) is considered the kick-off of *modern* exoplanet science. At the current time today, there are about 4000+ exoplanet candidates listed (http://exoplanets.eu). About 1000 of them have been found using the radial velocity technique, and about 3000 by using the transit method using ground-based surveys (such as super-WASP) and space-based surveys (like NASA's Kepler mission, Borucki et al. 2010).

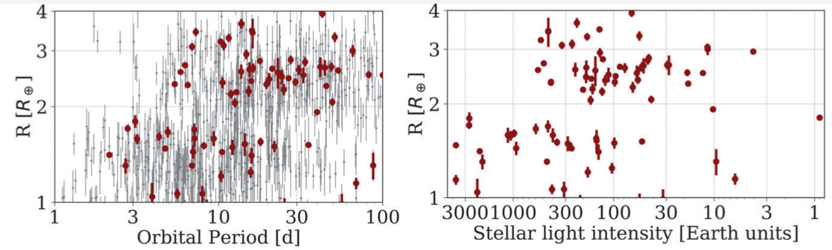
In the meantime, the direct imaging method has also been developing but remains mostly usable to self-luminous giant planets around young stars (ages below 30 Myr) as it entails major technological challenges. Other methods such as microlensing and astrometry have yielded smaller numbers (few tens) but they probe different areas of the parameter space. The niche case of long period gas giants is likely to dramatically change with the final data release of the Gaia/ESA astrometry mission by >2022 when thousands of new giant exoplanet detections are likely to be reported using astrometry. Concerning the detection of planets more like Earth, the two leading techniques (photometry and radial velocities) remain as the most likely ones to lead the discoveries in the next decade. These two methods are also yielding the detections of exoplanets that are likely to be characterized more in detail.

**Planetary interiors and geological composition are also important for habitability.** Not only the surface, atmosphere, and interactions between both play an important role to define an exoplanet as habitable. Firstly, there are aspects of planetary interiors such as the need for plate tectonics which continuously recirculate material thus maintaining a rich dynamic chemistry, and aspects related to the presence of a liquid mantle resulting in a powerful quasi dipolar magnetic field protecting the atmosphere and surface from harmful high energy radiation and particles (stellar and galactic). Secondly, there must be a strong dependence of the atmosphere to the initial planetary composition. The range of water content on exoplanets is expected to cover the range between less than a thousandth as on Earth to the several percent found in the icy moons of the Solar System. For example, in planetary systems that are more carbon rich, most of the oxides will be in the form of $CO_2$ gas forming thick atmospheres, while in others like in the Solar System most of the oxygen is likely to be bound to Silicon ($SiO_2$) and other metals, which is a solid (quartz). This kind of considerations make important differences that need to be addressed from an interdisciplinary approach.

In summary, there is substantial landscape to be explored on theoretical grounds that will mostly be needed to interpret near future exoplanet observations. This is needed to both help interpretation of atmospheric chemistries that shall be obtained soon and anticipate possible non-Earth like habitable conditions to guide searches with new planned facilities.

**Our knowledge of the host stars,** i.e the physical parameters as mass and radius, is fundamental for determining the exoplanet characteristics. An obvious example is that the stellar radius is needed to good precision (better than few %) to produce reliable size estimates for transiting exoplanets. Also, dating the star is the only way to determine the age of exoplanets and its potential life harbouring capabilities. Several methods can be used, depending on the available data. But in the last decade, particularly with the Kepler mission

**FIGURE 1—**Planet radii vs orbital period (left panel). Red symbols show exoplanets with radii determined from asteroseismically measured stellar radii. Grey symbols are based on spectroscopic and astrometric (Gaia) data. Right panel shows radii as a function of stellar irradiation received by planets. The radius valley around 2 Earth radii is apparent in the data.




(NASA), asteroseismology has emerged as the tool best suited to accomplish this task. In combination with astrometric data from Gaia, it has now become possible to determine stellar masses and radii for exoplanet host stars with precisions of just 2 or 3% (Serenelli et al. 2017) with comparable accuracy (Zinn et al. 2019), and ages to about 10%.

The quality of the asteroseismic results has opened the path for precision exoplanet science. An example is shown in Fig.1, which confirms the existence of the theoretically predicted radius valley in rocky planets due to the loss of the planet atmosphere induced by the stellar irradiation (Van Eylen et al. 2018). Analogously, the combination of precise exoplanets masses and radii allow tests of mass-radius theoretical relations.

With very good asteroseismic data, it is also possible to determine the angle between the star's rotation angle with respect to the observer by measuring the relative amplitude of the components of dipole triplets, enabling the characterization of the orbital-stellar spin axis alignment. The next big revolution in asteroseismology will happen with the launch of PLATO, in 2026, the ESA M3 mission for exoplanet and stellar characterization. PLATO is the first mission that, by design, will incorporate asteroseismic analysis as part of its standard pipeline. It will observe tens of thousands of stars as part of its core program dedicated to characterization of the exoplanet-host star (FGKM) system. CSIC has a strong participation in the preparation of PLATO and its exoplanet and stellar science programs through several institutes.

**Stellar non-thermal emission** is dictated primarily by the activity level of a star. This is ultimately related to the presence, strength, and topology of magnetic fields on the star which, in turn, are the interplay of timescales of stellar convection and stellar rotation. Characterization of non-thermal radiation can be done, for example, by observations in radio, in extreme UV and X-rays. Low mass stars —which are the targets where terrestrial planets can be found more easily— retain high levels of activity for much longer than more massive stars, and it is likely to have a strong impact on habitability conditions for such red-dwarf planets. The habitability condition of exoplanet atmospheres needs to consider the past evolution of the star to the current day. A deeper understanding of the non-thermal radiation requires the development of simulations of magnetic field generation in stars, which is a very underdeveloped field. Probably the best example is the —yet unsolved— paradox of the faint young Sun according to which the young Earth had to be in a snowball state, contrary to what fossil and geological evidence show.

**Planetary magnetic fields** are also key elements in understanding the evolution and state of planetary atmospheres. Despite our incomplete understanding of Earth's magnetic field long-term behaviour, we know that its uninterrupted presence, detectable by paleomagnetism during the last 3.5 Gyr at least has been and still is a fundamental piece in the biosphere. Planetary magnetic fields provide shielding against cosmic rays and solar wind and (at the very least) is essential to provide a safe harbour to current Earth life. The key factors that allow a long-living magnetic field on terrestrial planets need to be identified in order to assess the best Earth-like candidates. One requisite is arguably the presence of strong heat fluxes, which could maintain a long-lived dynamo, so that long-thermal magneto-thermal evolutions, considering the thermal-magnetic interactions, could shed light on this issue. However, the main problem is that terrestrial planets are intrinsically more difficult to detect, and so are the signals of their magnetic fields: it is unlikely to detect radio emission from Earth-like planets or infer their inner structure in the foreseeable future. Radio emission from magnetic exoplanets has been proposed long ago, in analogy with Jupiter, known since 1955 to be the major planetary source of radio signals below 40 MHz. The observed auroral emission is thought to come from the cyclotron-maser instability and depends on the magnetospheric interaction with the Solar wind and/or the planetary rotation. Since many M-dwarf stars have large magnetic fields, it is possible that the interaction between the host star and the exoplanet may yield measurable radio emission at significantly larger frequencies, where current and future radio interferometers, e.g., the SKA, may crucially contribute. Auroral radio emission, in the last two decades at least, has been proposed as one of the most interesting possible exoplanetary observables.

**Star formation and the study of protoplanetary disks** is another topic closely related to the origin of life as it includes the processes transporting matter from the interstellar medium to the planets. In the past two decades, there have been significant advancements in both observational and theoretical arenas. A theoretical understanding of the growth and migration of solids in gas-rich protoplanetary disks is emerging from advanced numerical modelling of high-resolution dust observations with long-baseline radio interferometers such as ALMA. General model predictions are qualitatively sound, but quantitative estimates of dust evolution timescales are hampered by simplistic assumptions about gas small-scale substructure (Andrews and Birnstiel, 2018). Dust coagulation barriers at centimetre scale are surmounted by pebble traps and gravitational collapse of pebble clouds (Blum, 2018) which are generated by instability mechanisms consistent with the formation of large-scale structures observed in disks around young stars. As planetesimals start to form they also collide and grow to larger objects, with further help of turbulence. Additionally, accretion of pebbles from the disk may facilitate the formation of planetary embryos. These then may migrate, with the outcome (outwards or inwards migration) depending on the viscous properties of the disk (Nelson, 2018)

In terms of finding evidence of intelligent life, Drake's equation could be updated by the addition of one term quantifying our ability to detect and identify (intelligent?) life as such. To quantify this term, one would need to examine more broadly the parameter space search in dimensions what we might not even consider. In these searches, the general strategy is looking for features are not commonly shared by the rest of the observed sample or by our theoretical expectations. Given that radio is the most energy efficient way to transmit information over long distances, the mainstream branch of these *Searches for Extraterrestrial Intelligence* (or SETI, see Tarter 2001) consists of scanning stars for anomalous radio emission. Along these lines, there are several initiatives (mostly privately funded) that have been operating for some decades now. Other SETI approaches consist in searching from excesses of infrared radiation from stars (and even galaxies), which could be indicative of civilizations operating at star-system (or galaxy) level from space (infrared radiation would be the waste product of such activity). In summary, and despite the fringe nature of the field, SETI searches is an active research. These programmes are also very popular and their use to engage the public into scientific discussion should not be underappreciated.

### 1.3. Interstellar Medium and Astrochemistry

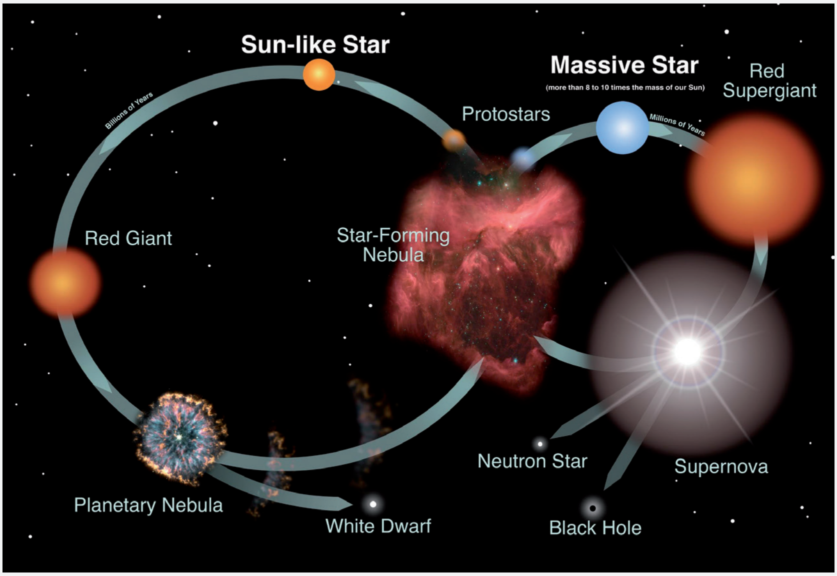
The life cycle of molecules in the interstellar medium (ISM) begins in stars. Most chemical elements are transported and created there by stellar winds and (sometimes) by supernova explosions and its aftershocks. The material dispersed from these processes forms diffuse clouds that eventually coalesce into denser dark (also called dense or molecular) clouds, where new stars and solar systems are formed, ready for the next cycle (see Figure 2)

While molecular complexity builds up at each stage of the Sun-like star formation process (Caselli and Ceccarelli, 2012), it is unclear whether the building blocks of life (i.e., prebiotic species) are inherited from the dense and cold molecular core material prior to the Sun's formation; or they are products of the different physical processes undergoing within the solar nebula protoplanetary disk. On the other hand, it is well known that massive and low-mass protostars undergo the so-called hot core/corino phase, with T~100-200K, that displays a very rich chemistry in interstellar complex organic molecules (iCOMs) because of the evaporation of ices from dust grain mantles. This raises the question of what happens to prebiotic species during the next evolutionary stage.

We know that there are many polyatomic molecules in the ISM. Contrary to early beliefs, the diffuse ISM is chemically rich, albeit dilute. Many ion-molecule reactions and radiative association processes proceed without energy barriers and are important mechanisms of molecule formation in the ISM. Since the first detection of molecules in space in the late 30 's, currently around 200 molecules have been discovered in space thanks to the advent of radio astronomy (see Cologne Database for Molecular Spectroscopy, CDMS), indicative of the rich chemical complexity of ISM. A very significant part of unidentified lines in survey spectra of dense clouds are certainly due to vibrationally excited states and/or isotopologues of COMs and molecules with low-lying vibrational states and/or large amplitude can give raise to hundreds of lines, many of them not yet identified in the laboratory.

**The search for prebiotic species in the ISM** has been a huge effort over the last few years. Key species for the development of life of increasing complexity, such as formic acid (HCOOH), glycolaldehyde ($HOCH_2CHO$), amino

**FIGURE 2**—Diagram illustrating the life cycles of Sun-like and massive stars. ( Credit: NASA and the Night Sky Network )




acetonitrile ($NH_2CH_2CN$), formamide ($NH_2CHO$), urea ($NH_2CONH_2$) or phosphorus-bearing species (PN and PO) have also been detected in massive star-forming regions and in Solar-type systems, mainly in the so-called hot core/hot corino phase (e.g., Fuente et al. 2014, Rivilla et al. 2020). Cold chemistry on ice surfaces, and the processing of ices and dust grains by shocks and radiation are thought to be largely responsible for the COM production.

**There is a number of key molecules** that are subject to intensive research in relation to the origin of life. One of them is glycine ($NH_2CH_2COOH$ ), which is the simplest amino acid that plays a role in the synthesis of proteins in known living organisms. Although it has not been detected in the ISM (yet), glycine and other simple amino acids have been found in meteorites and comets Regarding the phosphorus-bearing molecules, phosphorus (P) is a crucial chemical biogenic element for the development of life (Maciá, 2005) as it is one of the key components of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), phospholipids (the structural components of all cellular membranes) and the adenosine triphosphate (ATP) molecule, which transports chemical energy within cells (Pasek and Lauretta, 2005). Therefore, phosphorus plays a vital role in three essential aspects (replication, structure, and energy transfer), and it could also be fundamental for life in other planets besides Earth. Phosphorus is thought to be synthesized in massive stars and injected into the ISM by supernova explosions. As shown by Jiménez-Serra et al (2018), PN and PO molecules can be formed in quiescent and cold gas, although it remains undetected toward solar-type system precursors.

**The delivery process of chemically complex material** into planets and their survival through the protoplanetary phase remains unclear. However, comparisons of the C, N, O isotopic fractionation in the ISM and meteorites or pre-solar dust grains suggest that, at least, some material of interstellar origin has been delivered to Earth.

**The study of pristine meteorites**, like e.g., the carbonaceous chondrites, provides additional insight on the delivery of water (Trigo et al., 2019) and organics to the early Earth. Some of these meteorites have preserved ancient chemistry clues in the interior of their fine-grained matrixes and are also a source of valuable information studying other high temperature produced components like e.g. chondrules, refractory inclusions, clay minerals, etc... Carbonaceous chondrites retained water as hydrous minerals and organics in the fine-grained matrix that compacted the rest of chondritic components during the consolidation of these rocks. The organic compounds arrived in these meteorites are not so simple, as they include amino-acids, nucleobases, etc.

## 2. KEY CHALLENGES

### 2.1 Solar System exploration

**Understanding the chemistry in different bodies** ranging from planetesimals to icy worlds is important. For example, what is the minimum size to generate heat and stable liquid water? What is the role of salts? And radiation? How many different scenarios for the origin of life could have been created? How feasible could have been a second genesis of life elsewhere in the Solar System? Understanding the biochemistry and the biodiversity under such extremes is one of the major challenges of microbiology and molecular biology.

The exploration about the interior, surface, atmosphere, and interaction with the interplanetary medium faces many open questions nowadays for every rocky planet with a gaseous envelope. For instance, what is the current climate on Mars and how has it changed along its history? How wet and hot was the early Mars 3.8-3.5 Ma? Did life have the chance to thrive on early Mars? Is it there still today? What fingerprints did it leave? What lessons can we learn from terrestrial analogue environments? To address these questions new investigations and instrumentation must be developed.

In the 50 's of the 21st century, it is foreseen the samples from Mars will be brought to Earth. To achieve this, technological challenges and planetary protection protocols must be established. Whether in-situ robotic exploration on the surface on Mars or through a Mars sample return, the CSIC can (and must) be an active part of this exciting chapter of science and human knowledge.

**Liquid water is essential to Earth-like life**, but this liquid water must have a minimum of physical-chemical conditions for supporting the development of physiological processes. These physicochemical minima are not well understood, requiring a considerable multi/inter-disciplinary effort to decipher them. The sensitivity of astrobiology-dedicated instruments must be high enough to guarantee the detection of a limited number of cell-like morphologies as well as low concentrations of biomolecules. Besides, studies on terrestrial analogues deploying instrument suites are critical to better understand what kind of morphological and biochemical diversity could be expected on other planets and moons of the solar system.

**Plans of future biological exploration of ocean worlds** (i.e., the icy moons at the outer Solar system) consider successive steps that advance by accessing the plume materials, exploring the subsurface by drilling the icy crust, and even bringing materials back to Earth for analysis. Underwater exploration would include reaching the seafloor where organisms could potentially concentrate around foci of hydrothermal activity. Drilling in the subsurface of any Solar System body different from the Earth will be the forthcoming challenge for the in-situ exploration searching for life (also on Mars). First attempts to drill within the regolith in Mars revealed the technological difficulties, and the needs for improved specific drilling equipment adapted to the actual geology and conditions at each target based on preliminary assessment by geophysical methods. Seismic sensors were deployed on Mars and have detected ongoing seismic activity (Giardini et al., 2020) are likely related to active geologic processes in the subsurface.

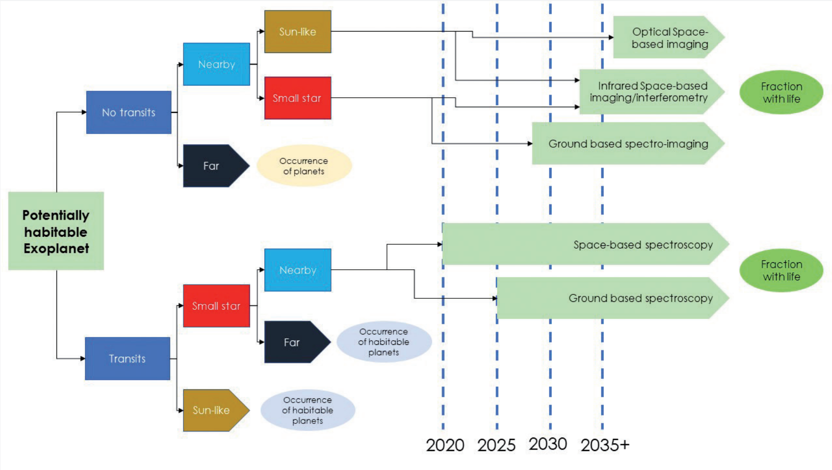
Data obtained by the Lunar Penetrating Radar have revealed a layered structure of the first 40 m section of the lunar subsurface (Li et al., 2020). These results indicate the presence of granular and porous rocks and outlines a layered structure of rock bodies underlying the 12m thick regolith on the Moon. Also, the internal textural properties consist of heterometric boulders embedded in finer grain granular material. This can be considered one of the first and successful exploration achievements and first results of exploration using conventional techniques developed and used on the Earth as *ground penetrating radar*. Following these advances in drilling, new downhole logging, sampling, and monitoring instrumentation will be necessary to extract new information, samples, and data.

### 2.2. Exoplanets and their host stars

**Radial velocities and transits** are, and will likely remain, the two most relevant techniques in the discovery of terrestrial exoplanets in the liquid-water habitable zone of stars. While Doppler spectroscopy can efficiently be done from the ground, transit searches are now being executed by space-photometry missions (like NASA's Kepler & TESS, and ESA's CHEOPS and PLATO). In addition, the traditional separation between Doppler spectrometry surveys and transit planet searches is blurring, as transit missions combined with coordinated ground-based spectroscopy follow-up are becoming an efficient way to nail down the most valuable planets for characterization. A scheme of the observational roadmap towards detection and characterization potentially habitable exoplanets for the next decades is shown in Figure 3.

**In terms of radial velocity** measurements, there are numerous visible and near-infrared high-resolution spectrometers from many countries (incl. Spain) at various stages of development, to the extent that it is difficult to keep track. Europe has had a clear leadership in this arena since the beginning. In the European landscape, several facilities in operation demonstrated ~1 m/s level precision on a sizeable sample of targets like HARPS (ESO), HARPS-N (Italy and others, incl. Spain), CARMENES (Spain + Germany) and ESPRESSO (ESO), the latter having reached precisions of tens of cm/s and thus allowing, in principle, for the detection of true Earth twins. Operational facilities outside Europe include HIRES at the Keck-1 telescope, APF at Lick Observatory, PFS at Las Campanas/Magellan-II, IRD at the Subaru Telescope, MINERVA-Australis, EXPRES at the 4.2-m Discovery Channel Telescope, Veloce and Veloce Rosso at the AAT, NEID just to mention the most relevant ones. It is also becoming clear that the gain to expand into the infrared is modest because of the diminished radial velocity content, and therefore the optical and far-red appear sufficient to reach down to

**FIGURE 3–**Decision tree for exoplanet detection and expected methodologies to become relevant in terms of characterization in the next two decades.




planetary close to the substellar domain boundary. To achieve the necessary long-term precision and stability in Doppler spectroscopy, ultraprecise devices such as Laser Frequency Combs has been developed and adapted to astronomical applications. Hardware innovation and filtering techniques based on Fabry-Perot interferometers, fibres, etc., are needed to overcome difficulties in terms of optimal spectral line densities and secure long-term (year scale) stability.

**Regarding characterization**, the most immediate big leap in exoplanet characterization is likely to happen on small transiting exoplanets around red dwarf stars observed with space observatories like the Hubble Space Telescope, JWST/NASA (launch planned in fall 2021), and possibly with ESA's Ariel mission (>2026). The same spectrometers used in precision radial velocity searches are also being used for atmospheric characterization, so investing on their development is also an investment in future relevant research. In the future (e.g. ESO's E-ELT instrumentation), the combination of adaptive optics with high-resolution spectroscopy could reach sufficient contrast ($10^9$-$10^{10}$) to allow for the measurement of atmospheric components of planets in the habitable zone of nearby stars. **High contrast large missions from space** for direct imaging of exoplanets in the optical and infrared are also being planned in the timeframe of 2030+, including the LIFE project (Quanz et al. 2019, mid-infrared interferometry, ESA context) and LUVOIR (Snellen et al. 2019, optical imaging, US/NASA + ESA context). It is key that CSIC keeps involvement in the international consortia being organized around these concepts.

Experiment and theory to obtain molecular opacities at the high temperatures of most known exoplanets are needed: laboratory observations at high spectral resolution test and validate the more extensive calculated line lists and can lead to improvements in the calculated line lists by empirical adjustment of the potential energy and dipole surfaces used in the calculations. It must be noted however, that the calculated line lists are far less accurate regarding line positions, while they can be more reliable regarding line strengths. Line positions should be validated in the extreme ranges of quantum numbers and temperatures. Data are needed for pressure-induced (collisional) effects: broadening coefficients for perturbers other than $N_2$ and $O_2$, as for example, $H_2$, $CO_2$, $H_2O$, $CH_4$, in broad temperature (70-2000 K) and pressure (up to 100 bar) ranges, way beyond HITRAN's (the most widely spread database for molecular line lists) coverage. This information is currently very scarce and encompasses a huge laboratory effort that may take decades to complete. Collision Induced Absorption (CIA, i.e., absorption through normally forbidden transitions induced by transient dipole moments occurring under frequent collisions), has been mainly studied for $N_2$ and $O_2$ under conditions relevant to Earth's atmosphere, and it should be extended to absorptions induced in $H_2$, $N_2$, $CO_2$, $O_2$ by collisions with relevant background gases in general exoplanetary environments such as $H_2$, He, $N_2$, $CO_2$, $O_2$, $H_2O$, $CH_4$, CO and $NH_3$. Even in the case of temperate atmospheres, since information about exoplanets atmospheric properties comes from interpretation of their spectra, efforts like the ExoMol computed line lists (Tennyson et al. 2016) are being developed.

Experimental and theoretical efforts in gas collision rates and their effects are also needed. JWST will likely produce a large amount of data in the near to mid-IR on the atmospheres of exoplanets (mostly hot planets, a handful of temperate ones). The spectral retrieval codes used in the interpretation of the observations need collision rates as input to cope with the far from equilibrium conditions in the outer layers of the atmospheres. Despite of their great importance, they are difficult to obtain experimentally, difficult to calculate and they are often neglected resulting in extrapolations to conditions too far from the experimental ones and scaling laws not fully validated. Experimental groups at CSICs IEM and theoretical experts at CSICs IFF have developed strategies to accurately measure or validate state to state rates in $H_2$:$H_2$, $H_2O$:He, $N_2$:$N_2$, and other relevant molecules. Efforts are currently underway to extend these measurements to higher temperatures.

**Chemistry and atmospheric dynamics** are often coupled, and therefore including chemistry in General Circulation Models is key for future characterization of exoplanets. Atmospheres targeted for transit are typically hot (500 K – 2500 K), with UV photochemistry influencing their disequilibrium chemistry. Room temperature photo-absorption cross-sections usually underestimate exoplanet UV photo-absorption and photo-dissociation rates. Thus, high temperature UV photo-absorption cross sections of key species such as $CO_2$, CO, $CH_4$ and $H_2O$ are required (see e.g. Venot et al., 2018). Similarly, reaction rate constants for conditions not found on modern Earth (high and low temperatures, reducing atmospheres) are poorly constrained. There is a lack of data for reactions of elements other than C, H, O and N, some of them biologically important elements such as P and S. Data for heavier organic molecules and ions are also lacking. It is also important to obtain reaction rates for key species by exposing them simultaneously to VUV photons. While the supersonic expansion technique enables wall-less experiments in the very low temperature range (see Douglas et al., 2018; Ocaña et al., 2019), laboratory measurements of absorption cross sections and reaction rate constants at high temperatures are experimentally challenging and require substantial engineering and support.

**Computational models** should be used to expand the range of pressure and temperature covered by laboratory experiments also to include interactions between gas and solid phases. In-house expertise in computation of *ab-initio* spectra and photochemistry exists at several institutes of the CSIC. Hazes play central roles in the dynamics, radiative transfer, and chemistry of planetary atmospheres. Understanding formation chemistry and thermal stability of photochemical hazes is essential to interpret future spectroscopic data (Madhusudhan, 2019). This requires new advances in ion-neutral chemistry, gas-to-particle conversion, particle growth and loss rates, chemical and thermal stabilities of particles and coupled volatile-refractory chemistry under UV irradiation. The chemical coupling of CHON elements and more refractive elements such as S, P, Na, Si, Mg, Fe, etc. can generate particles whose properties are poorly known. Refractory condensates formed in high temperature atmospheres (500 K — 2000 K; $10^{-3}$ — 10 bar), such as magnesium silicates or iron are also poorly understood. There are essentially no laboratory experiments of grain growth under relevant exoplanet conditions: vapor pressures of refractory materials are needed to estimate formation of condensate clouds, and data is required to infer gas-to-particle conversion pathways and obtain surface reaction rates, for a wide range of conditions including temperature, pressure, metallicity, etc. There are suitable facilities at CSIC to study physical and chemical properties of hazes and aerosols. However, some engineering challenges will have to be addressed, including e.g., in-situ measurements of ice particles. Progress in this field can benefit from synergies among different existing laboratories within CSIC.

**In terms of models for biosignatures,** approaches in search for features related to life are based on the study of the photometric, spectroscopic and/or polarimetric properties of potentially habitable worlds. Schwieterman et al. (2018) classify features potentially useful to infer the presence of living processes into three broad categories: gaseous, surface, and temporal biosignatures. All of them are inevitably based on our knowledge of life on Earth, so substantial work needs to be done to extrapolate them outside Earth conditions. Typical surface biosignatures refer to vegetation and, together with atmospheric $O_2$, surface reflectance of vegetation is one of the most robust planetary scale biosignatures. The models to anticipate these signatures are based on identifying the metabolic process where light is transformed into chemical energy and used to drive biosynthesis of organic matter from $CO_2$. Pigments are a key component of that process and remotely detecting their spectral signature at 690-740 nm (red edge region) would allow speculating on expressions of life these worlds. However, new chlorophylls absorbing in different areas of the spectrum as well as other pigments should be also investigated, such as carotene and xanthophyll that are also structural elements of the photosynthetic apparatus related with photo-protection presenting distinctive absorption features. Models designed to understand light interaction with vegetation, can relate to other Radiative Transfer Models already available to simulate the planet's atmosphere and rock/soil background. This way we can add potential confounding factors to the planetary-scale surface biosignature so the spectral signal detected by ongoing or future space-based and ground-based missions could be interpreted with respect to environmental context.

**Concerning the identification of biosignatures**, there is a doubtless convergence between Earth and Space observation, including the study of chlorophyll fluorescence or sun induced fluorescence (SIF), a fast-responding regulatory mechanism that helps keeping the energy balance of the light-absorbing complexes (plant photosystems). For example, Chlorophyll exhibits SIF emission spectrum in the red and near-infrared regions characterized by two peaks at approximately 685 nm (red region) and 740 nm (far-red region) which are already used on Earth observation methods and can be searched during the spectroscopic characterization of exoplanets.

**Magnetic fields in exoplanets** (as well as in the solar system planets) are crucial to protect the planet of the harmful environment and could prevent the development and long-term survival of superficial life. Their detection can only come after the detection of the planets themselves, something that currently is happening at a steady pace. The expectation is that with current facilities we should be able to start detecting magnetic fields of hot giant planets, and slowly move towards detecting similar effects in smaller and more habitable ones. One key observational ingredient to discriminate between stellar and planetary emission is the polarized emission as for the exoplanet-star system will be generally unresolved. Cyclotron maser instability radiation is strongly circularly/ elliptically polarized and beamed anisotropically whereas stellar plasma radiation is basically unpolarized. Therefore, measurements at low frequencies (<=3 GHz) with circular or full *Stokes* polarization observations with the new era of low-frequency radio telescopes will represent a significant leap forward in the field.

### 2.3. Interstellar medium and Astrochemistry

The advent of the current centimetre and millimetre instrumentation opened the possibility to detect many species of biochemical interest in several astrophysical environments. The cutting-edge of radio interferometers such as Square Kilometre Array (see review on the topic in Acosta-Pulido et al. 2015) soon will open a new window to perform high-sensitivity molecular line observations toward the earliest stages of star formation pre-stellar cores on the verge of gravitational collapse. Data to be acquired with SKA, James Webb Space Telescope, Extremely Large Telescopes (ESO and others), etc., need more complete databases for rotational spectroscopy. To this end, increased efforts in developing sophisticated experiments to prepare and study highly reactive species (molecular ions, radicals), sensitive detection techniques, trained personnel and long-time commitment are needed.

The interpretation of the observations relies on laboratory experiments, simulations, and theoretical calculations, providing information about the respective astrophysical environments of gas, dust, and ices. The success of astrophysics is bonded to the development of Laboratory Astrophysics, and, specially, of spectroscopic techniques, to enable the full exploitation of the observational resources. Line frequencies, cross sections, and collisional data, rate coefficients of many chemical reactions over a large range of conditions (phase, temperature, pressure), *ab-initio* calculations of energy levels and spectra, and reaction rates and collision theories are needed. Many of these laboratory studies, experiments and computer models are similar (or made by the same groups) as those discussed in the previous section so they will not be repeated here for briefness.

It is the entanglement of astrophysics and spectroscopy what has led to the identification of more than 200 molecular species in the ISM. The study of exoplanet atmospheres is revealing their most abundant constituents, including water, and, of course, our own solar system has shown evidence of complex molecules in many objects beyond Earth. Paraphrasing the Nobel laureate *Harry Kroto*, a natural question arises: "*Where molecules are, can life be far behind?*"

**As a closing remark,** we want to highlight that the *search for life beyond Earth* is a hot and rapidly expanding topic, and it is likely to be one of the main driving forces shaping near and long-term instrumentation, international collaborations, and missions. CSIC has numerous teams working on different aspects of this endeavour. Maintaining leadership will require support and possible expansion to keep up at the cutting edge of this exciting field.

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CHALLENGE 6

# PUSHING THE LIMITS OF SPACE TECHNOLOGY

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## 1. INTRODUCTION AND GENERAL DESCRIPTION

Current technology ecosystem surrounding space-related activities is an adapting scenario. It is a response to the realities of worldwide commercial and highly competitive marketplace, on the one hand, while adds to the traditional public cooperative projects for global security, environmental protection, and space exploration programs, on the other. Technology challenges are identified for specific components and systems in each one of these sectors. In most cases, the main constraint is cost, similar to on-Earth applications. Yet, there is an increasing trend on also assessing their sustainability. For instance, Clean Space initiative consists in technical analyses to identify knowledge-gaps, such as introducing eco-design, green technologies, space debris remediation. However, baseline targets for technology evolution continue to be higher reliability of materials (systems lifetime, radiation hardness, thermal management, self-protection, self-healing...) or higher efficiency and capabilities of devices (sensitivity, processing power, data management power, frequency ranges...).

Today, numerous new projects and missions have already been scheduled by the different Space agencies and private companies. Space missions require huge, continuous development of a number of advanced technologies. For instance, the ESA-JAXA BepiColombo mission, launched in 2018, aims at a comprehensive study of Mercury, including the characterization of its magnetic field, magnetosphere, and both inner and surface structure. In this case, 80% of the technologies used to equip the whole spacecraft (including solar cells, electronic devices, shielding, antennae, scientific instrumentation...) had technology requirements specific to this mission. Yet, new developments are not always mission-exclusive, and e.g. part of BepiColombo technologies have been replicated for the Solar Orbiter mission launched in 2020. Without the large efforts done for developing their new technologies, these two missions would have not been possible.

Public research institutions, e.g. CSIC, can bring their expertise to carry out exploratory, high risk and longer-term investigations, for instance offering breakthrough technologies based on new materials or on novel devices and systems concepts. On one side, earth and deep space observation requires more and more sensitive and precise sensing systems. On the other hand, space missions shift more and more from orbital missions to in situ missions or colonization missions that need to cope with their related harsh environments. Novel technologies as well as a better understanding of the operation conditions are necessary to enable such missions to succeed. In this scenario, sensing, together with telecommunications and energy management are definitively three pillars of the future space science and development.

Consequently, the exploration of breakthrough sensing technologies for monitoring and instrumentation is needed for both public services like weather forecast, navigation, disaster management, and for space exploration, which includes deep space observation, planetology, astrophysics, among others. If we have a closer look to the currently planned Space missions of the different agencies for the next 10-15 years, we can identify a first set of technology requirements, as starting points. As an example, in Annex 1 are listed some of the scheduled scientific missions by ESA and other agencies, including the type of instrumentation planned to be integrated to the spacecraft. We can identify by this way which kind of materials and components technologies will be needed for instrumentation and anticipate longer term needs.

Novel space applications also require search for novel sensing, processing, communication and energy management technologies able to operate in harsh environment with a high reliability. Today's satellites have already got much smarter, and in space as on Earth, end-users are demanding more and more processing power. Space-borne applications related equipment (ground-based, satellites, spacecraft...) are mainly built with semiconductor-based electronics systems. It may represent up to 70% of the payload in satellites and un-crewed spacecraft. Satellites and Spacecraft use hundreds of microchips to control their navigation in space, and to be able to convert the signals measured by all the instruments on board into useful information. Complex integrated circuits act as the brains that process all the incoming and outgoing data in the spacecraft. Sophisticated circuit design tools and commercial manufacturing technologies used to produce microchips for terrestrial applications (inside home computers, mobile phones, etc.) have been adapted for their use in space applications. However, future space instrumentation requires increasing computing capabilities which need to cope with stringent requirements like reduced size, mass, power consumption and high tolerance to radiation. It involves the development of a new generation of digital processing units for space instrumentation. For instance, a new generation of Digital Processing Units (DPUs) based on powerful FPGA or ASIC devices and brand-new space processors can simplify the DPU designs without compromising on efficiency and increasing significantly its capabilities. Together with these new advanced developments, it is very important to carry out dedicated and optimized control software for the chosen architecture by balancing the design options for error protection and computing performance.

Clearly, the main obstacle for the reliable operation of the on-board electronic systems in a spacecraft is radiation. Electronics for space applications usually have very high functional safety requirements. In most missions, the involved cost is so high that failure is simply not an option. As a result, the electronic components that may end up in space have to undergo stringent qualification processes. These are expensive processes that verify the functional integrity of the components under pre-determined radiation and temperature scenarios, but also of all the mechanical bonds under severe vibrations. Moreover, with the advent of ultimately scaled CMOS integrated circuits, radiation failure anticipation will create a need for modelling effort. This requires the development of improved radiation-hardening strategies, both at low-level (from the circuit topology to its layout) and at high-level (with system-level approaches such as error-correcting codes, approximate computing, clever redundancy schemes, etc.).

Definitively, the fundamental study of radiation effects on equipment but also on humans is crucial for the future space missions. Outside Earth's protective atmosphere, radiation is everywhere: high-energy particles from the Sun, protons, electrons and ions are attracted by Earth's magnetic field and cosmic rays bombard us from beyond the Solar System. Radiation levels in space are up to 15 times higher than on Earth and radiation can have severe health consequences for humans. Effect of cosmic radiation on living cells is one of the main health hazards associated with space travel and exploration. In humans, overexposure to radiation can cause cancer, damage to the foetuses of pregnant women and heritable genetic disorders that can be passed onto future generations. Consequently, in the shorter term, radiation is going to be a crucial issue when it comes to planning the future human exploration, of the Moon and Mars. ESA experience of radiobiological effects in the space environment comes mostly from manned spaceflight in Low Earth Orbit (LEO). For long-duration interplanetary missions, most of the radiation dose will arise from cosmic rays, solar particle ions and secondary particles against which future spacionaute will need to be sheltered. This will probably be the most important challenge for the future crewed space missions.

In addition, in many future missions, the correct operation of the electronics on-board in Space environment must be also guaranteed at extreme temperatures and often for long mission durations, where on-board parts repair or replacement is not an option.

In this scenario, the emergence of novel dedicated materials and devices technologies for efficient sensing, data processing and energy management able to operate under harsh environment would have a significant impact on future Space applications.

## 2. IMPACT IN BASIC TECHNOLOGY PANORAMA AND POTENTIAL APPLICATIONS

The main sectors where next generation Space technologies are being pursued are:

- Public services, e.g. weather forecast, satellite-assisted navigation, disaster management.
- Commercial services, e.g. telecommunications, broadcasting and multimedia, traffic management, applications of earth observation.
- Space science, e.g. astrophysics, planets exploration, exoplanets search, deep space understanding.
- Low Earth Orbits and outer space transportation, e.g. future re-usable systems, small expandable launchers, balloons.
- Living in Space, e.g. life sustainability, space infrastructures, crew transportation, logistics.

Both Space Science and Public services require advanced technologies for optical surveillance and imaging science. Optical surveillance is the primary method for surveillance and tracking of objects and satellites in higher terrestrial orbits because this task does not require high temporal resolution in the image acquisition. However, surveillance of objects in low earth orbits requires sub-millisecond accuracy in the image acquisition. Optical surveillance in LEO regions has recently emerged thanks to the availability of high-resolution low-noise sensors, with global electronic shutter, that feature high temporal resolution (Żolnowski,2019). However, short exposure times translate in large amount of noise and the generation of huge amounts of mostly redundant data. This vaste amount of data demands very large communication bandwidth and power at the sensor output. Furthermore, these data must be further processed for object detection and tracking requiring high computation capabilities of the processing system.

Additionally, the discovery of habitable exoplanet candidates and most-distant galaxies require the development of new, sophisticated technology, which is definitively a challenge for optics and other research fields. In the case of optics devoted to the near and far infrared, there are scheduled missions, such as ESA's ARIEL, planned for 2028, where the observations of a set of exoplanets will be done in the wavelengths from 2 to 8 microns. In this case, the development of optics for such wavelengths, are basic for its success. Other missions such as Athene or Lisa will also require optical technologies which have yet to be developed, also for infrared observation. Briefly, the currently available CCD-based optical sensors are not well suited for neither far nor near infrared observations. Thus, new sensing devices, both sensor and also optics, should be developed for this wavelenght range. Along with this, stable mounts and compact designs will be required, such as photonic integration of the different optical components, which will be interesting for increasing accuracy and stability of the optical systems both in earth and in space missions.

Concerning Astronomy, ground-breaking discoveries in this field are usually linked to the development of state-of-the-art detectors. Particularly, the mm/sub-mm/Far-IR range is strongly constrained by the sensitivity and the size/number pixels of array detectors. For instance, radiation detectors based on superconductors display revolutionary performances, which are making them essential elements in a variety of next generation instrumentation, both in space and ground-based astronomy. Their key advantage is related to the much lower characteristic excitation energy, which is of the order of the meV for low temperature superconductors, three orders of magnitude below typical bandgaps in semiconductors. Thus, these cryogenic detectors can provide single photon detection combined with spectroscopic capabilities, low dark count rates and excellent sensitivity, over a wide energy range. These achievements are specially suited for photon-starved science cases. For instance, the Kinetic Inductance Detectors (KID) technology exhibits a huge potential for building very sensitive large cameras with more than 1000 pixels with a simple multiplexed readout, like in the ESA's NIKA2 and CORE instruments (de Bernardis, 2018). Besides, Transition Edge Sensors (TES) is another promising technology. Impact of TES in basic science can be evaluated from the fact that they are considered already essential to access new science, and thus incorporated in very complex and revolutionary instruments, such as X-IFU, the high resolution X-ray spectrometer onboard Athena, ESA's next X-ray telescope. TES arrays constitute the detectors of the HIRMES instrument on the stratospheric observatory SOFIA, and are under development for ground telescopes and other underground instruments, among them: ACTPol, BICEP2, CRESST, HOLMES, and are being considered for axion search (IAXO). They also start to be in use in materials science and security, and constitute one of the technologies in consideration for quantum communications.

Regarding solar physics, the technological development of harsh environment sensing and electronic systems would constitute the heart of the instrumentation that will contribute to solve scientific questions related to the magnetic field coupling of the different layers of the Solar atmosphere, to further investigate the magnetic field in both the chromosphere and in the corona or to understand the evolution of the solar structures. Another application field can be found in the space weather discipline where understanding the influence of the solar magnetic field is a key point. This knowledge will allow a better forecasting of some solar events that are crucial form life and security on Earth.

Besides, planetary science missions will continue to revolutionize our understanding of the origin and history of the Solar System. New instruments with more advanced and sensitive sensors will gather data to help scientists understand how the planets formed, what triggered different evolutionary paths among planets, what processes have occurred and are sill active, and how Earth among the planets became habitable.

All this current and future space instrumentation demand increasing computing capabilities and advanced data systems which need to cope with specifications like size, mass and power consumption and high tolerance to radiation. Hardware and software building blocks for control and data systems (fault-tolerant computers, support ASICs, standard interface controllers, etc.) are required for future exploration missions, as well as for the next generation of commercial satellites and spacecraft. In this sense, Digital Processing Units (DPUs) based on powerful Field Programmable Gate Arrays (FPGA) or Application Specific Integrated Circuit (ASIC) devices could play an important role in different scientific challenges based on instrumental development and novel spacecraft electronic management, which usually involves the execution of complicated algorithms on board. As mentioned before, applications can be found in several scientific cases for different areas like solar physics, asteroseismology, or planetary science missions.

However, current submicronic densely packed ICs generations used for Space component technologies are more and more sensitive to Space-environment effects (radiation, electrical discharges, temperature gradients...). Standard electronics developed for Earth applications is mainly based on silicon technology. This implies a typical operation temperature range between -55ºC and 125ºC, atmosphere pressure operation, a medium lifetime of 10 to 15 years, and basic cosmic ray protections, among other limitations. Radiation and temperature stresses are real issues for all the electronic systems designed for Space application with this silicon technology. A direct approach to reduce the performance gap between components used on Earth and those used in Space is to re-use components developed for Earth application (the so-called COTS, Components Of The Shelf) without other hardening process than extra shielding. With such a strategy, the burden is shifted from specific circuit development to qualification, with special emphasis in the analysis of radiation effects in the performance. Indeed, several candidates of similar performance must be qualified to have a chance of finding one that meets the specifications. The development of Rad-Hard Application-Specific Integrated Circuits will likely remain the preferred path for critical systems. That being said, the COTS strategy is gaining momentum, because some large volume markets (like for instance automotive) demand components with very high functional safety requirements. It has been reported that muon Single Event Effect may induce a non-negligible soft error rate at Earth surface in ultimately scaled CMOS. This may be good news for space applications since it would trigger a lot of effort in the development of state-of-the-art rad-hard circuits.

Another relevant part of a space equipment is the power system which is in charge of supplying energy to all the active systems of the satellite, spacecraft or ground based. The current power systems, typically developed for earth applications are heavy, bulky, not efficient enough and, due to their design/technology specificities have even more difficulties than low power electronics to operate in extreme environments. Advanced power electronics, with enhanced lifetime and reliability under extreme temperature ranges and radiation environment would have a considerable impact on high power robotics, crew electric propulsion missions and in-situ resources utilization missions, as well as nanosatellites and small planetary probes. It will enable novel missions to solar system planets like Mercury, Mars, Venus, Jupiter etc., and allow longer term near sun observation missions. Predictions from different electronics roadmaps indicate that in 2030, 80% of the consumed energy on earth will pass through power converters, and by essence, through power semiconductor electronics. The optimisation of these power devices is then fundamental to reduce energy losses in converters used everywhere. This is even more critical in space application, were energy consumption must be optimised as much as possible to ensure operation lifetime of the systems.

Importantly, all these technologies can also be derived to on-earth applications like human health, energy management, oceans exploration, exploration of the Earth's interior, transportation, telecommunications, among other.

## 3. KEY CHALLENGING POINTS

In this panorama, focusing on the harsh environment technologies required to build efficient sensing and data/energy processing space systems on one side, and the CSIC research groups competences on the other side, we can identify and evaluate the new challenges CSIC is fully prepared to face.

### 3.1. Challenge 1: Development of advanced optic, optical and image sensors to enable more precise and deeper observation imaging

As mentioned earlier, several issues are still present with conventional optical sensors when used for space surveillance: resolution, limited dynamic range, noise, large amount of data, etc. Despite the recent advances, there are still challenges to be tackled in the next 10-15 years. First, the current dynamic vision sensors are not optimized for space applications. Second, algorithms targeted and optimized for the detection of different object of interest in space, such as stars, satellites, debris objects, etc., using the output of the optimal sensors should be developed, such as neuromorphic sensors. In addition, low power neuromorphic processing hardware optimized for space use and for space objects detection and optimized for radiation tolerance are compulsory to meet future requirement of long life missions.

One direction to tackle these issues is to develop research on Dynamic vision sensors (DVSs). DVS are a new type of bioinspired vision sensing devices which are based on a different acquisition paradigm than conventional CCDs and CMOS Active Pixel Sensors (APS). In a DVS, each pixel detects the changes in the illumination impinging on that pixel in an asynchronous, continuous, and autonomous way. Each pixel adapts its response time to the local illumination conditions. Furthermore, as the sensor generates outputs only when there is a temporal change in the illumination, only the moving objects in the scene produce an output, while the static background parts remain silent. Thus, the sensor output information can be sparse and highly compressed compared to the output of conventional conventional image sensors. This information compression reduces the bandwidth and power consumption of the sensor communication output channel and allows output post-processing for real-time detection and tracking of target objects using low power embedded or neuromorphic processors (Mead, 1990). The high parallelism of neuromorphic computing systems promises to make them more resilience to local radiation events. These systems will be appropriate to develop smart and low power neuromorphic computation on-site systems reducing the amount of information communication.

Another direction is to use advanced optics technologies for IR observation with high stability and accuracy. Research on materials which can be used in this range, with improved performances, new concepts or tools to reach the desired wavelengths is necessary. For instance, the atmospheric transmission window called M-band is interesting for making observations for terrestrial exoplanets, but there are, to date, not integrated optic devices suited for this band or others at longer wavelengths. Additionally, observations for astrophysics, solar physics, and atmosphere physics communities at key spectral lines in the far and extreme ultraviolet (FUV, EUV) require challenging coating and optics developments. A promising option is to investigate on optical coatings for the FUV-EUV in the main wavelength range of 40-200 nm. Coatings include mirrors, filters, and polarizers. Also, lighter and cheaper medium diameter optical mirrors for space-borne and ground-based observatories would be desirable. New materials could be the way to mass-produce them.

### 3.2. Challenge 2: Define novel radiation detectors concepts and technologies for scientific instrumentation and safety control

Radiation detectors for electrons, protons, neutrons, X-ray, light ions and heavy ions will be a key technology in the future space exploration and manned missions. Again, current technologies based on Silicon are highly limited and other approaches are required. The accessibility of cryogenic temperatures and the potential advantages of low temperature electronics are likely to boost superconducting detectors and electronic devices as an alternative to Silicon. Cryogenic detectors with superconductors are a Key Enabling Technology which will see in the coming years a widening of their application range, for specific targets. The fabrication and readout (multiplexing) of large arrays is a crucial aspect for some applications.

Today, Transition Edge Sensors (TES) are the most mature cryogenic detectors technology: they constitute very versatile, ultra-sensitive radiation detectors, able to detect from gamma-rays to microwaves and particles with energy resolving power, very low dark count and efficiency close to 100% (Irwin, 2005). For instance, the search for biosignatures in exoplanets will require telescopes operating in the ultraviolet, visible, and near-infrared bands. Since biosignature detection is a photon-starved science, this requires detectors with nearly zero dark counts and moderate spectral resolution. TESs is a most interesting technology in this field because they meet these requirements and offer the prospect of non-dispersive imaging spectroscopy. In spite of the relative maturity and excellent performances achieved, there are still open questions regarding fundamental aspects of the operation of these devices. Fully understanding them should result in approaching their theoretical limits. In the range of visible-UV, of especial interest for planetary exploration, current research is focused on improving efficiency to values as close to 100% as possible (values >90% have been achieved by different groups). Also, for biosignature search, improvement of the spectral resolving power up to at least a value R=100, which is considered achievable.

On the other hand, Kinetic Inductance Detectors (KIDs) is another approach to be considered (Calvo, 2016). The main advantage of KIDs is their intrinsic multiplexing capability in frequencies due to the sensitive element to the radiation, the inductor. This allows to manufacture thousands of resonators with different resonance frequencies which can be readout in the frequency domain through a single line. Future space mission to study the Cosmic

Microwave Background (CMB) will require cameras with large number of detectors, very good sensitivity and polarization selectivity. KIDs are the ideal candidates to be used as they exhibit very good sensitivity and they are intrinsically multiplexable which allows the frequency multiplexing of thousands of pixels through a single transmission line. However, KIDs still need further key developments to fulfill all the requirements of future space missions. Among them, the development of new materials for the detection of low frequencies (50 to 100 GHz) and the design of new geometries for improving the polarization sensitivity and cross-polarization, are key requirements that should be improved to meet the mission baseline. KIDs intrinsic advantages will be also exploited outside the limits of millimetre astronomy and reach shorter wavelengths such as visible light and x rays, and particle detection through the so-called phonon mediated detection. The KID technology that is being developed will not only provide a dramatic increase in mapping speed for broad band imaging, but it could also enable novel applications in spectro-polarimetry and hyperspectral imaging. Additionally, future space science and Earth observation missions are limited by the availability of high sensitivity large imaging detector array technology for the mm-FIR wavelength range. KIDs can be used as alternative technology that still have some critical aspects that need to be demonstrated or optimized. Regarding the detector performance, the polarization response is at a very early stage of development, the beam shape on the sky still shows mid to high level side-lobes, and the best sensitivity achieved so far is below that required for a background limited spectroscopic space missions with a cold aperture (<10 K) in the FIR range. Design of new geometries for improving the polarization sensitivity and cross-polarization are key aspects that should be faced.

Additionally, it would be interesting to develop a new family of uncooled radiation semiconductor detectors as well. A new disruptive technology could be developed based on robust wide bandgap device/technology, and even combined with the versatility of novel 2D materials, such as graphene. Wide bandgap semiconductors typically have a better collection of charges induced by several types of radiation, making them attractive for detectors applications. Silicon Carbide (SiC) or SiC-2D technologies (graphene, $WS_2$, $MoS_2$...) could address two complementary issues: radiation tolerance and thermal management, while keeping excellent sensing performance or incorporating novel operation principles. For instance, it is foreseen that WBG microdosimeters can be further developed for space application, so that we might better understand the biological effects of space radiation and its effects on human cells in long range crewed mission for future space colonization.

### 3.3. Challenge 3: Development of a new generation of digital processing units (DPU) for space instrumentation and extreme radiation environment

As it has been pointed out in the previous sections, the development of Digital Processing Units (DPU) based on FPGAs, comprising hardware, firmware and software are a key technology to solve a wide variety of space science challenges. These challenging DPUs based on FPGAs must enable the execution of complex algorithms (image compression, image stabilization, etc.) in real time or almost real time. This is essential to solve some scientific problems which are required to be performed on board due to the limited storage resources as well as the reduced bandwidth available, which does not allow the data transmission to Earth to perform the calculations on ground. Additionally, these DPUs will be the perfect candidate for long-duration missions thanks to their adaptability and fault-tolerant capabilities that will allow them to work under very harsh environments. Despite the excellence reached with the already developed solutions, there is still a wide field to explore regarding innovative architectures and configurations for the new systems based on FPGAs. The computationally highly demanding algorithms to be implemented imply to squeeze at maximum the available resources and this task can only be undertaken by developing new technics for re-configurability and architecture optimization. This challenge is linked with the needs and specifications for control electronics and data treatments of sensing systems driven by challenges stated in Chapters 1 and 2.

It is now widely assumed that conventional CMOS scaling, the well-known Moore's law, is coming to an end. However, it is also fairly clear that CMOS circuit will not disappear in the mid-term. One path to continue functional scaling is 3D integration, which poses significant challenges for concurrent errors due to a single cosmic ray traversing the stacked layers. Another path is that ultimately scaled CMOS platforms are likely to be complemented with some "exotic" technologies to increase application capabilities. As an example, Spin-Transfer-Torque Magnetic RAM (STT-MRAM) modules are readily produced on CMOS compatible processes and it is only a matter of time that an embedded version appears as an option in standard commercial processes. Other technologies like silicon photonics, memristors, graphene or other two-dimensional layers, may also be adapted for their use as a back-end CMOS process option. Roadmapping beyond short to midterm is quite challenging because the global semiconductor market is orders of magnitude larger than the space electronics market. Not all the possible technologies will make their way to mainstream production and space applications will have to take advantage of the global scale winners, even if others would have been more suitable. Anyhow, the inclusion of new "exotic" technologies will trigger a lot of research in qualification for space, developing appropriate models for temperature, radiation, magnetism, etc.

The variability of ultimately scaled CMOS and the advent of "exotic" technologies is also fostering the research of unconventional computing architectures that depart form Von Neumann's. In-memory computing, spiking neural networks, approximate computing, etc., are all interesting concepts that may find a perfect application in space. Indeed, these computing architectures are thorught to cope with the intrinsic high variability of the technologycal parameters of the devices and imperfect yield, taking advantage of massive parallelism rather than perfect matching. They could thus be inherently resilient to radiation impact or other environmentally induced drifts. Besides, AI applications, which also rely on these architectures, will be a hot topic for space missions in the coming years, be it for computer vision, smart sensing or control applications.

### 3.4. Challenge 4: Development of harsh environment electronics enabling future long range exploration missions

As already mentioned, two of the main constraints on current semiconductor microsystems employed in on-board electronic are their thermal operation limits and radiation hardness, which worsen to meet the reliability and compactness specifications required by the application. Creating KETs based on new emerging rad-hard materials for low and high temperatures is a requisite to enable these space technology demands. As a consequence, temperature and radiation hard Micro-/nano-technologies and the resulting microsystems are of strategic importance to European space exploration strategy, potentially impacting all areas of activity.

To achieve these goals, a first objective should be to target new family of Rad-hard, High-Reliability microsystems, focusing initially on cosmic radiation monitoring and on energy management of onboard electronic systems. These microsystems could integrate customized sensors for in-situ monitoring and protection, and control front-end electronic circuits by means of heterogeneous approaches. Such complexity requires novel concepts and tailored fabrication processing approaches, as well as specifically designed packages, involving new materials and architectures.

Additional measures for space applications concern energy management through power devices. The relevancy of the power system in a spacecraft is not negligible as it can represent up to 30% of the total mass. As a consequence, novel approaches must be found to reduce power systems mass and volume, increasing power density (reducing losses). One of the main targets would be a fourfold reduction of the system volume and mass, safely lasting over 30 years without replacement and being capable of operating in a vacuum in extreme temperatures and radiation fields. Another objective would be to break the 170°C junction temperature barrier of current power devices. Overcoming this limit will expand the scientific mission span ambitioned by ESA and, therefore, will contribute to answer the main quests in space sciences. For this purpose, wide bandgap material-based power semiconductor devices for operation at high temperature and high power-density are the only candidates for the viability of future missions. These semiconductors are also more resistant to radiation. SiC MOSFETs, GaN High Electron Mobility Transistor (HEMT) and current limiters are identified in both ESA and H2020 roadmaps and should be our first targets for the short term (10 years). Such devices require novel concepts and fabrication processing approaches (e.g., thin-film-based technologies) to overcome their current thermal limits. Moreover, these semiconductor devices will provide their maximum potential only with a specifically designed package involving new materials and architectures to operate under the aforementioned conditions. Besides, development and validation of specific characterization and reliability tests adapted to the stringent space specifications are still needed and compulsory. For the longer term (15-30 years), other less mature WBGs like Diamond and Gallium Oxide should be explored.

In general, we need to acquire a fundamental understanding of radiation effects on humans, materials and equipment. The limitations of knowledge of the space radiation environment impact on the space science and exploration is affecting the design and operation of future missions and spacecraft. A more fundamental approach consisting in deeply studying the radiation effects on electronics systems and look for mitigation techniques at design and technology levels is compulsory. Space travellers will be irradiated with cosmic rays to a dose rate considerably higher than that received on Earth. In order to make sensible judgements about space exploration, the risks to health of such radiation need to be assessed. Part of the assessment of risk is to allow for the enhanced biological effectiveness of high LET radiations with respect to others. In order to meet these goals, radiation sources must be assessed in order to focus the studies on the worst-case radiation scenario (i.e. higher cosmic ray and solar particle events dose). Then, transfer trajectories minimizing interplanetary radiation should be identified and modelized. Shielding provides a way to prevent astronauts from being exposed to the harsh radiation environment of space. Beyond that, radiation doses can be mitigated by parallel methods such as accurate knowledge of transfer trajectories, definition of an acceptable effects dose threshold and space weather monitoring and warning systems. The development of solid state microdosimetry and nanodosimetry for space applications would allow a better understanding of the biological effect of space radiation and quantify microdose and LET in order to create a RBE model for long-duration space travels. Microsensors of the smallest effective volume developed in semiconductors will establish a new standard for the absorbed microdose measurements. For instance, diamond has some important advantages compared with the often-used silicon, e.g. a better radiation resistance and tissue equivalence. On the contrary, it is very difficult to get high quality material to be used as detector and the Micro-Electro-Mechanical System (MEMS) fabrication is a challenge.

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The exploration and colonization of the outer space represents a foreseeable future for the Humanity. This endeavour involves deepening our knowledge about the formation and evolution of the solar system, of other planetary systems, emergence of life (and its prospects once it exists), the interaction between Earth and Space (particularly with its Sun) and the impact of space conditions (radiation, gravity, etc.) on Earth-borne organisms. Materialization of this exploration and colonization currently drives technological developments in several fronts as optics, electronics and sensors just to mention a few. Other aspects as well law & ethics, psychology, biology, etc., cannot be discarded.

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