Document prepared by the solar system panel

Francesca Esposito (INAF, Rome, Italy),
Luisa M. Lara (IAA-CSIC, Granada, Spain) (co-chair),
Inge Loes ten Kate (Utrecht University, Utrecht, Netherlands),
Benoit Lavraud (LAB, Pessac, and IRAP, Toulouse, France),
Jorrit Leenaarts (Institute of Solar Physics, Stockholm, Suède),
Javier Licandro (IAC, La Laguna, Spain),
Matteo Massironi (University of Padova, Italy),
Markus Roth (KIS, Freiburg, Germany),
Beatriz Sanchez-Cano,(University of Leicester, Leicester, United Kingdom),
Frans Snik (Leiden University, Netherlands),
Nicole Vilmer (Paris Observatory, CNRS, PSL, Meudon, France (chair),
Tom Van Doorsselaere (KU Leuven, Leuven, Belgium)

with contribution from Natalie Krivova (MPI für Sonnensystemforschung,
Göttingen, Germany)

Solar system review panel

A Heliospheric Plasmas, Solar Physics, and Space Weather

The Earth is embedded in the heliosphere, the bubble carved out in the interstellar medium by the solar wind. We are orbiting the Sun, in astronomical terms, at a close distance. This unique vantage point allows us to study astrophysical plasma processes in-situ, with spacecraft launched to the interplanetary medium. We can study the physics of the Sun, from dynamo-action, via the sources and variability of the solar wind outflow, to explosive energy release in the outer solar atmosphere, in great detail. Finally, an emerging field of research concerns the understanding of the chain or processes that controls the interaction of the solar wind with planets, their atmospheres and magnetospheres: a domain coined planetary Space Weather.

A1 What does the heliosphere teach us about astrophysical plasma processes?

The Universe is filled with plasma and most remote-sensing signatures result from plasma processes that produce bulk plasma heating and/or radiation from charged particle acceleration. Plasma heating and acceleration occur through a range of plasma processes such as magnetic reconnection, turbulence, and shock waves. Because the solar system is within our reach, it is the only place where fundamental astrophysical processes can be studied in detail through the unique combination of remote-sensing and in-situ measurements. The Sun, from its deep interior to the corona, the planetary magnetospheres, and more generally the interplanetary medium are pristine natural laboratories for studying plasma processes.

Understanding fundamental plasma processes

A fundamental property of plasmas is that their dynamics are driven by complex processes that couple to each other through different spatial and temporal scales. These scales are typically associated with large-scale structures, on the one hand, where energy is being injected and which can often be described through a fluid description (e.g. magnetohydrodynamics), and on the other hand with the kinetic scales associated with ions and electrons, where energy dissipation actually occurs. In order to comprehensively study plasma processes and associated energy conversion, dissipation and particle energization, observations have to cover multiple scales at the same time. This strategy has been used in the past using measurements from multi-spacecraft constellations with different inter-spacecraft separations, with in particular the Cluster and MMS (Magnetospheric Multiscale) missions sampling plasmas respectively at separations close to the ion and electron scales.

However, a major qualitative jump in understanding the fundamentals of astrophysical plasma processes requires to probe the dynamics of the plasma at all relevant scales at the same time. This is because the workings of all processes involve intricate, inextricable couplings between all these scales. It has been shown that, in order to fully cover the characteristic plasma scales in the 3D space, at least 7 properly instrumented spacecraft with appropriate inter-spacecraft distances are required. Europe has a strong heritage in this field, from the Cluster era, and thus would be in a prime position for leading such a next generation space mission, with or without international cooperation.

Exploring the outer heliosphere
Near-Earth plasmas only cover a limited range of astrophysical properties. Reaching out to other media is critical to confront our understanding of astrophysical plasma processes elsewhere. The exploration of the outer regions of the heliosphere, of the boundaries that separate the solar system from the interstellar medium, and of the interstellar medium itself, are an obvious next step for understanding the properties and dynamics of our home, the solar system, and how it interacts with its surrounding environment. The dynamics of this system shall also be contrasted with the interactions of other known planetary systems, and constitutes the best prototype from which we may extrapolate on the nature of other « astrospheres ». Exploring the confines of our solar system requires a dedicated space mission - an interstellar probe. A strong push for such an endeavor is currently being made in the USA and China, and proposals for contributing to these ambitious missions have been made within Europe to ESA and national space agencies. There is no doubt that this next step has to be taken, and we believe that it is the right time to shape such missions and have them fly in the next few decades.

A2 How does the solar magnetic field drive solar variability at all scales?

The magnetic field is the driver of solar variability at all scales. It links and provides the energy for all plasma processes, while it originates from the dynamo process involving convection and rotation. Due to this dynamo process, the solar magnetic field is continuously reconfigured, generated and destroyed on timescales from seconds to decades, and fills the whole heliosphere. Understanding the solar dynamo inside the Sun, the effects of the magnetic fields on the solar atmosphere, and finally the resulting consequences of the magnetic field variability on the whole heliosphere remains a challenge for solar (and in the broader context stellar) and heliospheric physics. Indeed, the plasma physics behaviour in the heliosphere is determined by long-term Space Weather and intermittent solar storms, which are notoriously hard to predict. The major open questions in solar physics remain the precise workings of the solar dynamo, how the magnetic field heats the outer solar atmosphere, and how it drives solar flares, coronal mass ejections and associated events.

Dynamo
Even if a lot of progress has been achieved this last decade on the way the solar dynamo works, e.g., through the achievement of sophisticated numerical simulations, a 3D view of the processes is still missing. In particular, getting a polar view of the magnetic field and flows will be a great achievement to better constrain dynamo models. Some first constraints of this type will be obtained with Solar Orbiter. In the long-term planning, a mission focusing on a view of the solar poles from high helio-latitudes (above 70°) has been proposed to study the interior of the solar polar regions in order to uncover the key role of magnetic flux transport in the solar cycle.

From the ground, full disk observations of surface oscillations and magnetic field are needed to further constrain dynamo modelling and serve as boundary conditions for Space Weather forecasting. Such continuous observations can be carried out either in space by a single observatory (such as SDO/HMI) or on the ground in the form of a network of observatories (such as GONG). In the case of a ground-based network, the telescopes need to be geographically distributed such that gaps from the night time, bad weather and instrumental interruptions are minimized. Ideally the individual observatories are equipped with nearly-identical observing instruments to ease the data merging and analysis. The success of this strategy is that small-aperture telescopes with a large field-of-view provide important observations of the Sun, and can be operated for a long time.

GONG is currently providing solar magnetic field measurements since the 90s. However, addressing the questions of solar physics and Space Weather research requires higher spatial and temporal resolution and an improved spectral coverage, and thus the outdated technology of GONG is to be replaced in the coming decades with a state-of-the-art ground-based network. The importance of such a new global network was already pointed out by the ASTRONET Roadmap 2008 and has gained in relevance since then. With SPRING (Solar Physics Research Integrated Network Group) a preliminary design for such a new network for advanced synoptic observations is completed in Europe by 2023.

High-resolution observations
The driver of solar activity is the magnetic field. Measuring the magnetic field is a difficult task, because the polarization signals from which the field is determined are generally weak, and thus require high signal-to-noise ratio observations, which is daunting to do while simultaneously observing at diffraction-limited resolution and at a time cadence that freezes the time evolution of the atmospheric plasma.

A major goal for solar physics in the coming decade is to routinely measure the magnetic field simultaneously at multiple heights in the solar photosphere and chromosphere at the highest spatial and temporal resolution. This requires telescopes with a larger aperture than the current 1-m class telescopes, such as the German GREGOR telescope and the Swedish 1-m Solar Telescope. The American Daniel K. Inouye Solar Telescope (DKIST), which is starting its science operations in 2021, has an aperture of 4 m, which is a major step forward in light-collecting area to reach high polarimetric sensitivity and spatial resolution (to probe the smallest possible spatial scales).

A 4-m class ground-based solar telescope in Europe to complement DKIST is of the highest priority for European solar physics. This has been recognized for a long time, and plans for the European Solar Telescope are at an advanced stage. A full design study will be ready by the end of 2022, so that construction can commence as soon as funding is secured. EST's optical design facilitates extreme polarimetric sensitivity and precision, and is designed with maximum throughput in mind to be able to obtain the highest signal-to-noise at fixed spatial and temporal resolution. It's planned instrument suite will consist of several integral-field spectropolarimeters, an instrument-development field where Europe is currently leading.

Together with the American DKIST, EST will fill a gap that is not covered by any other existing or upcoming instrument: it will be able to examine magnetic coupling in the solar atmosphere from the deepest layers of the photosphere to the highest layers of the chromosphere. This allows to uncover the thermal, dynamic and magnetic properties of the sun's plasma at high spatial and temporal resolution. According to the 2012 Science Vision update by ASTRONET, the EST is the infrastructure to meet these requirements. EST was included in the ESFRI (European Strategy Forum for Research Infrastructures) Roadmap in 2015, and preparations have started for construction of the European Solar Telescope (EST, with 4m aperture) on the Canary Islands, Spain. The project requires now the strongest support in order to realize its construction.

Another challenge in the field is to measure the magnetic field in the corona. This can be done from space by measuring polarization at EUV wavelengths. Such measurements of the coronal magnetic field could be complemented by ground-based observations from EST to build a complete 3D picture of the magnetic field from the visible solar surface to the corona. Radio observations could also provide quantitative values of the chromospheric and coronal magnetic field through future circular polarization measurements with ALMA of the millimeter emission from active regions. In the microwave domain, quantitative magnetic field measurements in the low corona can be obtained from gyroresonance/gyrosynchrotron emissions and future observations with SKA could provide crucial contributions in this area with its unprecedented image quality and dynamic range.

The American DKIST telescope has a capability to measure coronal fields from the ground using spectral lines in the IR, owing to its off-axis design that leads to low straylight contamination from the solar disk. However, DKIST can only do this off-limb, and the method suffers from line-of-sight integration effects. Another way forward is to measure intensity and Doppler-shift oscillations caused by localised, high-frequency coronal waves, that allow access to the coronal magnetic field information through coronal seismology. Both these measurements of the coronal magnetic field are to be complemented with numerical simulations, to study the magnetic field evolution in less accessible parts of the solar atmosphere. The combination of the simulations with forward modelling helps to more precisely constrain the solar atmospheric magnetic field.

A particularly powerful approach to probe both various heights in the atmosphere and different physical parameters is to combine simultaneous observations from multiple observatories to increase coverage of the spectrum. Combinations of observations with for example ALMA, optical ground-based telescopes and space-based (E)UV telescopes such as SDO/AIA, IRIS, and Hinode are now common. New ground-based observations in the radio domain such as the ones provided by LOFAR will lead e.g. to new insights into the fundamental physics of the solar corona through e.g. a combination of spectroscopic measurements and high-resolution imaging of solar radio bursts.

Future solar ground and space-based observatories should carefully consider synergies. In the coming decade, such synergies will be achieved through the combination of observations from Solar Orbiter and other space missions and ground –based observations, thus providing a stereoscopic vision of the different phenomena.

A3 What is the impact of the Sun on the heliosphere and on planetary environments?

Multi point observations in the inner heliosphere

The coming decade will see a fleet of spacecraft flying in the inner heliosphere (Solar Orbiter, Parker Solar Probe, Bepi Colombo) providing measurements of the solar wind, of its perturbations such as coronal mass ejections (CMEs), and of solar energetic particles (SEPs) at different distances from the Sun and different longitudes. This will bring a better understanding on the origin of solar transients, their variability and propagation in the heliosphere as well as on the source, characteristics and propagation of SEPs in the inner heliosphere.

Observations from ground-based radio-observatories such as LOFAR should also provide in the near-future crucial remote-sensing measurements of the solar wind parameters and even of magnetic field in interplanetary coronal magnetic ejections. These measurements will complement satellite measurements and will strongly contribute to an improved understanding of the evolution of the solar wind and coronal mass ejections through the inner heliosphere and to better constrained space weather models.

In the coming future, there would be a strong advantage for understanding the physics of the Sun and the heliosphere from the new space mission Vigil (formerly known as LAGRANGE) to be brought to the Lagrange point 5 (L5). Such a scientific mission needs to be considered thoroughly in the space plasma and solar physics communities in Europe. The L5 point gains attraction because it offers a side view of the Sun-Earth line. This allows to measure the speed of CMEs impinging on Earth with higher accuracy. Furthermore, stereoscopic and coronographic views of CMEs combined with numerical simulations of their propagation would permit a better forecast of the propagation of solar storm to Earth. Besides this, such a mission allows an early view on the Sun’s surface and its sunspots that are the sources of flares and CMEs. As the Sun rotates towards the Earth, the detection and prediction of these events is improved. Multi-point in situ measurements from L1 and L5 will provide essential insight into the nature of SEP events. This should be complemented with numerical simulations of their generation and propagation in the heliosphere.

Planetary environments, Space Weather and Space Climate

Understanding how the solar wind interacts with a planet is critical to determine the properties of the near-planet environment, and in turn to determine its habitability. This is because this interaction controls, among many other factors, atmospheric escape (such as Mars' dehydration over time), energy dissipation (such as auroral processes and radio signal absorption), or the shielding of harmful radiations from the surface. The solar wind interaction with planets first occurs at high altitude with their magnetospheres and upper atmospheres. In particular, for planets with an atmosphere (i.e., all except Mercury), the ultimate region where the energy of the solar wind is dissipated is the ionosphere (the solar photoionized part of the upper atmosphere). This is common for all planets, moons and comets that have a surrounding gas. In the case of Mercury and other bodies with no atmosphere (including the moon), the energy of the solar wind is ultimately dissipated at the surface of the planet.

Understanding the chain of processes that control Space Weather and Space Climate at planets, i.e. the impact of the solar wind on the planets near-environment on various time scales, is essential to accurately forecast and thus prevent hazardous situations for spacecraft and humans.

It is now understood that solar storms impacting Earth can severely damage electronics onboard spacecraft, threaten the lives of astronauts, inflict strong damage in power lines and transformers on the ground, sometimes leading to electrical blackouts. Numerous national monitoring schemes have been put in place for Space Weather forecasting on Earth. Although large efforts have been made in the last few decades, we need significantly more efforts in terms of theory and numerical modeling, to increase our understanding of the full chain of processes, as well as much more real-time (in situ as well as remote-sensing) data, to propose truly accurate space-weather warning services in the future. Space Weather is not unique to Earth! It will very soon become a necessary service at other planets where robotic exploration is significantly rising, especially at Mars on the eve of its human exploration.

A main goal to accomplish in the next few decades is to be able to forecast accurate upper atmospheric responses to Space Weather events at least for terrestrial planets, although it would be desirable to have some level of monitoring at giant planets as well. At Earth, accurate and real-time data are mandatory, and at the terrestrial planets (particularly at Mars) a continuous solar wind monitoring platform to provide timely and accurate Space Weather information is also essential (but not available so far). Accurate forecasts are only possible if sufficient and appropriate data both upstream in the solar wind and in-situ at the magnetosphere and ionosphere-thermosphere levels are continuously available.

In addition to upstream solar wind monitors, we need multi-spacecraft observations of the coupling between the many layers of planetary environments (magnetosphere – ionosphere -thermosphere) in the solar system, which would give us a more complete picture of plasma processes and their importance in driving Space Weather. At the moment, multi-spacecraft plasma missions are only available near Earth with missions such as Cluster, THEMIS, Swarm, and MMS. At Mars, prototype multi-spacecraft studies have been completed using initially independent missions (Mars Express, Mars Global Surveyor, Rosetta and MAVEN (Mars Atmosphere and Volatile EvolutioN)), and in the coming years Bepi Colombo will perform coordinated observations at Mercury with two spacecraft. Nevertheless, dedicated multi-spacecraft studies with high temporal resolution, capable of making simultaneous and coordinated observations of the different plasma regions and their coupling on both day and night sides (i.e. solar wind, magnetosphere, ionosphere, and atmosphere), would enable the much-needed understanding and forecast ability of upper atmospheric and magnetospheric conditions.

Increasing our knowledge of the solar wind impacts on planetary plasma environments is a key to future planetary science and exploration, which has notable implications beyond the solar system. A better understanding of the solar wind interaction with planets in our solar systems is a required stepping-stone to understanding Space Weather and Space Climate impacts at other astrophysical systems beyond reach, and in the first place Exoplanetary systems, for which much fewer observations are available.

Solar impact on planetary environments is not limited to solar wind nor to energetic particles. The variability of solar total (i.e. integrated over the entire spectrum, TSI) and spectrally-resolved (SSI) irradiance is among the main uncertainties hindering reliable assessment of the solar influence on Earth's climate, as pointed out by the Intergovernmental Panel on Climate Change (IPCC) reports. Furthermore, understanding solar irradiance variability is key to understanding the variability of other Sun-like stars as well as their impact on exo-planets and their detectability. Key open questions are the magnitude of irradiance changes on time scales longer than the solar cycle and the spectral distribution of this variability, most critically the amplitude of the SSI variability in the UV and the phase of the variability in the visible range. One critical aspect is the continuity of TSI and SSI measurements. Past experience teaches us that having just one single operating TSI experiment at a time often brought the continuity of the TSI record into danger and is the main reason of the currently existing significant uncertainties in the amplitude of the variability on time scales longer than the life time of a single mission. The over 20-year long (since 1996) record from VIRGO on SoHO became a crucial bone of the current TSI record covering more than 40 years. The shorter (2010-2014) record from PREMOS on PICARD has contributed to resolving the discrepancy in the absolute calibration between the SORCE/TIM measurements and all earlier experiments. Since then, no other European experiment regularly monitoring the solar irradiance variability was operating. The only currently operating experiment is TSIS-1 on ISS to be succeeded by TSIS-2, both led by LASP, USA, cannot guarantee the continuity and reliable cross-calibration of the record. Radiometers measuring TSI are usually light-weight and comparatively low-cost experiments that can be placed on many space-based platforms. Therefore, including a radiometer on a suitable future mission would be beneficial. The existing spectral irradiance record is even more uncertain, being patchy in both temporal and spectral coverage and partly with huge uncertainties. At the same time, UV irradiance is of special interest for Earth as it controls the chemistry of the terrestrial atmosphere, which urgently calls for long-term monitoring of the irradiance variability in the UV and visible.

B The early history of the solar system

The origin and formation of the solar system encompasses complex processes divided in a series of steps whose knowledge has recently benefited from the discovery of a large number of protoplanetary disks and extrasolar planets. Observations, simulations and theory have to proceed hand-in-hand in order to identify the main formation and evolution paths of exoplanetary systems, as well as clarifying the main reasons for the apparent rarity of system like ours.

Key questions concern the physical state of the circumstellar disk at the origin of our planets like its temperature profile that determines the location of the snow line beyond which icy dust can condense and form the core of giant planets, the dust and gas density distributions that influence the planetesimal formation process.

The advances in understanding phenomena such as dust particle accretion, the potential pebble concentration processes and their role on the fast formation of the giant planets as well as the early-stage planetary migrations, have provided explanations for some peculiar characteristic features of our Solar System (e.g. the existence of Jupiter Trojans and the dynamical structure of the Kuiper Belt). In the next decade, it is expected that additional theoretical work, mostly based on numerical simulations, will shed new light on the kind of instabilities present in a circumstellar disk that may help the pebble accumulation process possibly leading to a coherent model of planetesimal formation able to predict their initial size distribution and composition at different radial distance.

B1 Dynamical properties of small body populations and families

The wide-field high-sensitivity sky surveys has allowed the cataloguing of a very large number of asteroids and comets thus pushing forward our ability to reconstruct the collisional history of the Main Asteroid Belt through a refined classification in asteroid families. For comets, the history of the Oort

Cloud through models and simulation on a grander scale, has led to a better knowledge of the influence of stellar encounters and of the galactic tide. The dynamics of the trans-neptunian region needs deeper surveys in order also to ascertain the existence of any further planet in a large heliocentric orbit.
Aiming to a deeper understanding of the dynamical evolution of the small solar system bodies has strong implications not only for the planning of exploration mission but also for properly addressing the associated data analysis for either science or applications.

A striking example is represented by the Near-Earth Object (NEO) population, which will greatly profit from the dynamical models, based on the extremely precise GAIA astrometry, thus allowing the study of finer and finer dynamical perturbations, thus pushing forward the horizons of predictability for objects in chaotic orbits. This, in turn will allow to greatly support the Planetary Defence initiatives started at worldwide level (notably in the US and in Europe) for protecting our planet from the impact hazard by providing impact monitoring services directed to a large spectrum of stakeholders ranging from civil protection agencies to the citizens. The harvesting of extraterrestrial resources relies alsop on the accessibility of the small bodies of the solar system.

B2 Study of the non-gravitational forces

The small body populations represent an important constraint in the validation of the models for the evolution of the Solar System: therefore, the non-gravitational perturbations play a paramount role in determining their dynamical history that led to the presently observed situation.
The high precision astrometry coming from ground-based surveys, coupled with the lengthening of the observed arcs, has allowed the detection of the tiny non-gravitational forces affecting the motion of small asteroids passing close to our planet. The development of the associated theoretical modelling has, in turn, led to a better understanding of the long-term evolution of these bodies, unveiling in detail the role of mean motion and secular resonances.in shaping the dynamical paths followed.
In particular, the Yarkowsky and the YORP effect influence, respectively, the orbital and rotational evolution of a small body close to the Sun. Moreover, the coupling between the two mentioned effects can enhance or hinder the efficiency of the mobility of a small body through the solar system. Beyond the orbital evolution of the bodies, the non-gravitational perturbations are responsible also for sculpting the size distribution of the small body populations closer to the Sun (NEAs and Main Belt). Namely, the YORP effect is responsible for the rotational disruption of small bodies possibly down to a limiting size representing the building blocks of the observed rubble pile objects.

Therefore enhanced theoretical models and numerical simulations of the small bodies evolution (including the transient populations of the Centaurs) coupled with extended large observation campaigns of small Main Belt objects (more affected by the non gravitational perturbations) shall help in refining the theoretical models of the evolution of the small bodies in the region both in terms of orbital distribution (e.g., asteroid families evolution and dating) and in terms of size distribution.

B3 Small bodies of the Solar System

Small bodies are the remnants of the early stages of formation of our solar system, the building blocks from which planets were created, and therefore contain information on the materials and conditions prevailing in the solar nebula during its early stages. Small bodies are rocky and/or icy objects, usually ranging in size from a few meters to 1-2 thousand kilometres. Their physical nature, distribution, formation, and evolution are fundamental to understand how the solar system formed and evolved and ultimately, how planetary systems are formed and evolve in other stars.
Small bodies of the Solar System populate three main fossil structures that characterize our star: the main asteroid belt (MB); the trans-Neptunian belt (TNB, also known as Kuiper belt); and the Oort Cloud. The main concentration of asteroids (currently 800.000 are known) is located in the main belt, a ring-shaped region between the orbits of Mars and Jupiter (2.0 - 3.5 au) where we can find mainly bright asteroids composed of silicates and metal and dark (primitive-class) asteroids with a high content of carbon compounds and hydrated minerals. Beyond the orbit of Neptune (30 au) and up to 48 au we find the second ring-shaped concentration of objects (2500 known), the Kuiper Belt. The trans-

Neptunian objects (TNOs) are composed largely of ices, such as water, methane, or nitrogen mixed with silicates and refractory non-volatile species and its most famous member is Pluto. The third, outermost, and largest concentration of icy-bodies is the Oort Cloud. It starts as a disk-shaped structure at its innermost region (a few hundred au) and becomes spherical as we move outwards, extending up to 50,000 – 200,000 au.

Similar belts of rocky and icy-bodies have been detected around other stars in the form of debris disks. In fact, the most recent studies refer to a two-component temperature debris disk, where a combination of two blackbodies at different temperatures is sufficient to reproduce the entire spectral energy distribution from the mid-infrared to millimetre wavelengths. In this scenario, the disk will be a combination of a trans-Neptunian belt analogue and an asteroid belt analogue closer to the star. Such belts have been marginally resolved for some systems, such as Epsilon Eri and HD 107146

There are also other populations, such as NEAs, comets and Centaurs, Jupiter's Trojans (JT) and Hildas. NEAs are objects that move in the terrestrial planet region in dynamically unstable orbits with short lifetimes, needing to be replenished by the inner zone of the main belt. Comets and Centaurs are icy-objects scattered from the trans Neptunian belt and the Oort Cloud. Centaurs orbits are in the region of the Giant Planets, while comets moves in very elliptical orbits that can cross the terrestrial planets region. When close to the Sun, comets sublimate ices and present the well know coma and tails also observed in some Centaurs and a very few main belt asteroids. Cybeles, Hildas and Trojas are the three main stable populations immediately outside the Main Belt, and its origin is under debate: originated in situ or TNB objects scattered in the early stages of the Solar System and captured in their present orbits?

NEAs' proximity makes them ideal candidates for exploration with spacecraft, in addition to being a source of material resources that in a not too distant future may be exploited through asteroid mining or In-situ Resource Utilization (ISRU)for the production of fuels, drinking water, habitats, and communications devices. In addition, they constitute impact hazards. In particular,. NEAs that approach less than 20 times the Earth-Moon distance and whose diameter is greater than 140 meters are called potentially dangerous, or PHAs because of their catastrophic global effect in case of collision. However, smaller objects (a few meters) can produce catastrophic local effects too. Discovery, orbit follow-up (in particular of PHAs and small virtual impactors), physical characterization (including Earth-based observation and space mission), and dynamical studies are crucial to understand the nature of asteroids and its relation with the evolution of life on Earth as well as to develope an effective strategy for Planetary Defense and for future space exploitation.. Dedicated Earth-based telescopes, Space telescopes to look for PHAs in regions not observable from Earth, and missions like DART and HERA are thus a priority.

Cometary science has been revolutionized after ESA's Rosetta mission. It showed that the composition of comet 67P/Churyumov- Gerasimenko is rich in organics and has a different water isotope ratio to Earth's; that its nucleus structure is stratified and surface morphology controlled by seasonal activity, with starkly contrasting areas dominated by erosion via sublimation and by fall back; and that the comet's inner coma is highly dynamic, changing in time and space. However, Rosetta also raised important new questions that need to be tackled in the next decades. Some of these questions relate to the primordial properties that reflect the process of comet formation; to the evolutionary features and their control of cometary activity; to the differences in composition seen in the coma and how the solar wind interacts with it; to the nucleus evolution and changes on the surface driven by insolation weathering which leads to pervasive fracturing, fragmentation, and mass wasting, such as collapsing cliffs; to non-gravitational forces, which develop as activity-induced torques and affect the rotational parameters of comets; etc.

The bulk of our knowledge of the ice composition of comets comes from studying the gas of the coma. The detailed compositional measurements that are only possible in situ provide crucial information on the provenance of cometary material. The two distinct D/H ratios in the water of 67P, derived from HDO/H2O and D2O/HDO, suggest a cold-temperature origin of the ices in the Interstellar medium (ISM). The D/H ratio of a less evolved object may give some insight into outgassing-related fractionation processes, which will help in interpreting differences or similarities between remote and in situ D/H measurements. Pre-solar signatures have been observed in the isotopes of 67P's volatiles while similar bulk abundances of the volatile molecules were observed at comet C/1995 O1 Hale-Bopp and in objects in the ISM. One of the surprising results of Rosetta was the abundant molecular oxygen observed in the coma. Circumstantial evidence for O2 was also found in comet 1P/Halley. Several formation mechanisms have been discussed, from radiation of water ice and cold temperature chemistry in the ISM to various in situ formation mechanisms. However, this remains as a key open question that spans several research fields. It is obvious that processes in the interior, subsurface, surface and gas and dust envelope of a comet need to be analysed in a multi/interdisciplinary approach, being Europe in a privileged position to lead these studies.

The link between primitive-class asteroids and carbonaceous chondrite meteorites is undoubtedly determined: they are the parent bodies of this kind of meteorites that have a high content of complex organics molecules (including amino acids). Compositional and dynamical studies of primitive asteroids is crucial to have a map of the abundance of these materials in the Solar System and its role in the development of life on Earth. Observations in the near-infrared regions that are very difficult from Earth are needed to study ices and organics. The James Webb Space Telescope (JWST) capabilities in the 3-8 micron region represent a unique opportunity for a big step in this field.

The physical properties and dynamical links among TNOs are still poor as we need larger facilities to study these objects which orbit too far from Earth. A window of opportunity is open with the new generation of giant telescopes and, in particular, with the launch of JWST. Additionally, the study of TNO in extreme orbits and its possible link with the existence of a planet ~100au (and its search) has been of high interest for the community.

The old separation between asteroids (inactive) and comets (active objects) disappeared in the last decade, there are clearly comet-asteroid transitional bodies called active asteroids (ACOs). Several objects move as asteroids and show cometary behaviour (active asteroids, AAs), and objects that move as comets but show no cometary-like activity (asteroids in cometary orbits, ACOs) have been discovered. We still have to understand the mechanism that ejects dust in AAs and why ACOs do not sublimate ices like comets.

During the last years, big surveys like SMASS and WISE allowed to make a nice map of the compositional distribution of the MB. The combination with dynamical simulations and laboratory studies allowed a much better understanding of the collisional evolution of the MB, the formation of collisional families and the number, size and composition of their parent bodies that populated the early solar system. The compositional distribution of the asteroid belt and its parent bodies is of fundamental importance to understand the origin of the solar system

In the first 2 yrs of operation of the Large Synoptic Survey Telescope (LSST) (now named Rubin Observatory), the number of minor bodies will increase in a factor of ten or more. This will have a high impact in the study of the currently known populations providing astrometry and color photometry (i.e., composition) in particular of their smaller members. However, it will likely discover new types of bodies that, not surprisingly, will produce another revolution in the field as the one produced by the surveys in the 90s.

B4 Interstellar planetesimals

The planetesimal population of the young solar system was very numerous initially but the majority of the objects ended up ejected due to gravitational perturbations with the planets and other external perturbers. Numerical simulations indicate that many other planetary systems would have experienced a similar evolution, yielding to an interstellar space filled with ejected planetesimals. In this scenario, 1I/‘Oumuamua is the first interstellar interloper discover with PanSTARRS with no evidence of outgassing. The second object discovered so far is 2I/Borisov with an unquestionable cometary composition, reassuring us that a population of icy interstellar planetesimals exists.

Current computations on the number of interstellar planetesimals that can be trapped in these environments indicate that many of them will be incorporated to each star- and planet-forming disk. The interest of these trapped planetesimals is that they could have sizes large enough to rapidly grow into larger bodies, via the direct accretion of the sub-cm sized dust grains in the protoplanetary disk, before the planetesimals drift toward the star due to gas drag, overcoming the meter-size barrier that challenges the growth of cm-sized pebbles into km-sized objects, an unsolved problem in planet formation theories. This suggests that the trapping of interstellar bodies in these environments should be considered in future planet formation models but require a better characterization of the population of interstellar planetesimals, particularly its background density, size, and velocity distributions.

C Exploration of terrestrial planets

Last decades have been characterized by a growing worldwide interest and investment in space economy that turned into a boost in space exploration programs. The retrieved amount of data is enormous and is going to exponentially increase in the years to come. Of particular relevance for the future will be the integration of data from different missions to favouring comparative planetology. In this perspective any kind of data interpretation needs to be carried out under the light of experimental analysis, modelling and analogue studies both in the field and in the laboratory.

C1 Mercury

Mercury, explored by Mariner 10 in the seventies and more recently by MESSENGER (2008-2015), is an enigmatic body being a small planet with a remarkably large metallic core, a magnetic field, a volcanically dominated surface and numerous evidences of volatile rich materials at its surface. All these peculiar characters pose numerous issues on where and how Mercury formed and evolved, which is in turn strictly related to the solar system evolution in terms of planetary accretion and differentiation, orbital migration and collisional history. The coupling of a high metal/silica ratio and a volatile rich composition are severe constraints on any formation theory of planet Mercury either being related to orderly processes by early accretion from the protoplanetary disk or to chaotic later collisional events. In the meantime the long lived effusive and explosive volcanism and the significant radius contraction by cooling rise issues on the way magmatism and tectonism coexists on a small terrestrial body, which experienced important collisional events forming large basin structures. The Mercurian harsh environment will give unparalleled opportunities of investigating unique magnetosphere and exosphere interactions with the solar wind, radiations and interplanetary dust as well as of exploring the surface materials behaviour under high diurnal thermal variations, and the enhanced space weathering, sputtering and regolith production due to faster collisional speeds. On the other hand, its high orbital axis inclination allows extensive permanently shadowed areas in the polar region where water ice and organic volatiles storage is maintained at stable cryogenic temperatures even on this warm planet close to the Sun. All these peculiar aspects make Mercury the ideal planet for answering key questions of planetary sciences. In addition, the Mercury close proximity to the Sun, whose mass causes distortion in space-time, enables testing of the Einstein's theory of General Relativity.

The ESA-JAXA BepiColombo mission, launched in 2018, has the aim of solving these open issues providing simultaneous measurements from two spacecraft from December 2025 onwards

C2 Venus

At the early stage of space exploration, Venus was the most visited planet, but after the last US mission Magellan in 1994, it became a forgotten planet for many years, until the launch of the ESA Venus Express mission in 2005 and, soon afterwards, the JAXA mission Akatsuki.

Despite Earth and Venus have similar size and bulk composition, they show a dramatic difference in environment, being the CO_2 dominated Venus atmosphere able to reach an average temperature of with 470° C and a pressure of 90 atm at the planet surface. In this framework a key aspect to be addressed is to understand Venus' early evolution, potential habitability and how much of the geologic history is preserved on its surface, considering also the present-day couplings between the surface and atmosphere.

The relatively young surface of Venus implies that the planet is geologically active, but it does not show evidence of plate tectonics. However, the current geodynamical regime, surface chemistry and mineralogy, interior and thermal evolution remain indeed poorly understood and consequently Venus' geological history remains enigmatic. Venus could have maintained a habitable environment with liquid water oceans for billions of years, a significant longer period than Mars, and detectable signatures of this ancient epoch could await discovery by new missions.

In conclusion Venus has all the ingredients for a habitable planet (geologic activity, a massive secondary atmosphere, possible past surface water, possibly a past dynamo, similar size and gravity of Earth), but despite it all, something happened during its planetary evolution that made Venus a hell and its surface the most inhabitable site in the solar system. Future missions will have to address when and why Venus and Earth's evolutionary paths diverged, if Venus ever hosted habitable conditions or even past signs of life, or if the Earth could follow the same destiny of Venus in future.

C3 Mars

Mars is the most widely explored extra-terrestrial planet in the Solar System. Its surface shows clear evidence of an early stage environment very similar to the terrestrial one, with a complex system of flowing liquid water in the form of rivers, lakes and seas. In similar conditions, the Earth assisted to the emergence of life. Due to the crustal recycling related to plate tectonics, the geological records of that early period are lost on the Earth; they are instead well preserved and still accessible on Mars. On those records, it is also possible to unveil the climate changes that brought the planet from a warm and wet past, dominated by the formation and deposition of hydrated minerals, to the present cold arid desert through an intermediate stage characterised by evaporite precipitation. The main climate transition is thought to have taken place between the Noachian and the Hesperina at around 3.5 Ga and the possible driver causes are still to be unveiled. In the present era, only a fraction of the water present at the very early stages has been detected. It can be found in the form of ice or embedded in the structure of water-bearing materials. There are also good evidences of active ground water systems that occasionally interact with the surface. Polar caps hide systems of subglacial saltwater lakes and should record the Martian recent climate variability which is thought to be paced by orbital forcing. However how orbital parameters affect climate on Mars is still to be deciphered. An important aspect to investigate is also the feedback of atmospheric dust on the characteristics and circulation of the atmosphere and on the past and present climate, habitability and geologic history. Mars today is still a dynamical world and is a key target of next exploration. It will help to understand the formation and evolution of inner planets, the path that leads a planet to be habitable and the processes that determine the emergence and the destiny of life. Moreover, the study of Martian satellites will provide important information about the formation processes of terrestrial planets' satellites. In particular, some recent literature suggests that Phobos and Deimos could represent the present state of a dynamical and evolving process following a giant impact on Mars. This should be studied and compared with the Earth-Moon system origin and evolution. Europe has been developing in the last years the ExoMars programme. It includes two missions: the Trace Gas Orbiter, orbiting Mars since October 2016 to monitor atmospheric trace gases including methane, and a rover and a Surface Platform which was planned to be launched in the late summer of 2022. The current status of the ExoMars programme is stated in https://www.esa.int/ExoMars_suspended The programme addresses astrobiological, surface, near-surface and atmospheric studies. Next frontier will include the very ambitious Mars Sample Return program, in which Europe is deeply involved, and the preparation to human exploration. This last step would still require filling some knowledge gaps on the planet, that could be covered through some additional dedicated explorations.

C4 Moon

Other than as a privileged base for the observation of the universe and the future exploration of the Solar System, Moon itself is also an interesting target from the scientific point of view. Indeed, several scientific missions have been and are nowadays operative on the Moon with orbiters, landers and rovers exploring the lunar environment and many others are in preparation. The major still open questions about the Moon Science cover planetary science with special emphasis on: an in-depth study of the surface, subsurface layering and voids, and interior; the dust dynamics and the plasma environment; the calibration of methods for absolute chronological dating of planetary surface; the origin and accumulation mechanisms of volatiles and water on the Moon; the In Situ Resource Utilization materials for sustainability of human settlements and potential exploitation; the physiology, survivability, and habitability in Space; the origin of the Earth-Moon system. Furthermore, it is of relevant importance the implementation of Radio, Optical, Infrared and Cosmic ray astronomy from the Moon. The path for human exploration to Mars includes the development of several space missions with growing complexity that will eventually bring to the long term human return to the Moon. The NASA Artemis program, which will land the first woman and the next man on the Moon by 2024, the ESA projects under study (the Cislunar Transfer Vehicle and the European Large Logistic Lander), and the articulated Lunar Exploration program from China, Russia and other countries will surely make the Moon closer than ever.

D Jupiter, (Saturn), Neptune and Uranus: planets and their systems.

D1 The Jovian and Saturnian systems

Our knowledge of the large gas giants has enormously grown in the last decades. The Cassini-Huygens mission (NASA-ESA-ASI) scrutinized the Saturnian system (planet, rings and satellites) to an unprecedented level. The discoveries are almost endless, being almost impossible to list all here. It is worth mentioning the first view ever of Titan’s surface showing a landscape similar to a river bed on the Earth at the Huygens probe landing site; icy plumes on Enceladus containing water and other molecules likely coming from an ocean beneath the surface; active and dynamic ring system; Titan was revealed as Earth-like world with methane and ethane rain, rivers, lakes and seas responding to seasons; an extremely dynamic atmosphere on Saturn developing massive storms and a jet stream with hexagon shape at the both poles with giant hurricanes; dual bright-dark surface spots on the moon Iapetus is due to a combined effect of body’s long rotation and swept of reddish dust along the orbit; etc.

The scientific community is lacking knowledge of the Jovian system as the one achieved with the Cassini-Huygens mission at Saturn. The Galileo mission changed the way we look at our solar system, and it witnessed the impact of the comet Shoemaker-Levy 9 with the planet. The mission lasted for 14 years, discovering an intense radiation belt above Jupiter's cloud tops, helium in about the same concentration as the Sun, extensive and rapid resurfacing of the moon Io because of volcanism and a magnetic field at Ganymede. The mission ended when the probe carried by the orbiter plunged into the planet’s atmosphere to measure the water (and other molecular and atomic species) abundance in deep layers to be compared with the solar values and thus shedding light on the origin and evolution of the planet and processes in the early solar system. On the other hand, the Juno mission has exclusively devoted to study the atmosphere (storms, lightning, weather, water abundance four times higher than solar values) and its interior (displacement of huge masses induced by weather processes, strong magnetic field also displaces with respect to the north pole), key aspects of the planet itself and crucial questions related to the habitability of the icy satellites as Europa, Ganymede and Callisto remain unsolved. To remediate this, ESA will launch the JUICE mission in 2023. The mission is conceived to characterise the potential habitable worlds Ganymede, Europa and Callisto (hosting pre-requisites already established by the Voyager and Galileo -NASA- missions); to provide a complete spatio-temporal characterisation of the giant, rotating magnetosphere, and of the meteorology, chemistry and structure of Jupiter's gaseous atmosphere; to study coupling processes inside the Jupiter system, with emphasis on the two key coupling processes within that system: gravitational coupling, which ties together Jupiter and its satellite system, and electrodynamic interactions which couple Jupiter and its satellites to its atmosphere, magnetosphere and magnetodisc.

By investigating Jupiter, its moons and the Jovian system in all its complexity JUICE will address many more goals than the NASA Juno mission, whose focus is the giant planet. In the study of the giant planet itself, JUICE will give new insights due to broader spectral range, its emphasis on global mapping, the long temporal baseline offering the opportunity to study spatial/temporal variability, the even dayside and night side coverage, and its focus on sounding of the stratosphere and thermosphere. In addition, JUICE will provide much more, by achieving a full exploration of Ganymede, with very focused investigations of Europa and Callisto, by exploring new regions of the magnetosphere never reached by any other spacecraft, and by assessing the coupling processes of the entire system. The recent geological activity in some of the Jovian 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. In a broader perspective, the search for primordial life forms in the ocean worlds necessarily passes through the Jupiter and Saturn systems. While their distance from the Earth imposes minimum cruise times of some years for a spacecraft, and for Saturn also the need to rely on radioisotope thermoelectric generators (RTGs), the long-term vision foresees to return to Enceladus, Europa and Titan through a series of missions that can ultimately shed light on the actual presence of elementary life forms in the watery environments of those worlds.

D2 Icy giants: Uranus and Neptune

The ice giants Uranus and Neptune and their satellite systems remain to date largely unexplored, with most of our understanding of these worlds relying on the data provided by the brief visits of the Voyager 2 mission more than 30 years ago. The very existence of these planets poses a conundrum when considered in a broader context of the known family of planets in our Galaxy. Their limited gaseous envelopes have long been interpreted as an indication that their formation occurred close to the dissipation of the solar nebula, which prevented them from accreting larger quantities of nebular gas like Jupiter and Saturn. However, such a limited temporal window for their formation is at odds with the large abundance of planets similar to Uranus and Neptune among the discovered exoplanetary population. The exploration of Uranus and Neptune is therefore a critical step to understand their origins and shed light on the formation process on one of the most abundant classes of planets in our Galaxy. Moreover, while the two planets are considered members of the same planetary class based on their shared characteristics, each of them is unique in many respects. The limited internal heat flux of Uranus results in a sluggish atmosphere, while Neptune's atmosphere is extremely dynamic and characterized by powerful winds. Both ice giants have complex magnetic field configurations, but the large obliquity of Uranus allows for unique interactions with the solar wind. Neptune's satellite system has been completely reshaped by the capture of Triton, a geologically active former trans-neptunian object, while Uranus may be host to a primordial satellite system that, however, shows evidences of a violent past. The exploration of these planets and their satellites would therefore allow to address scientific questions over a number of disciplinary domains in both planetary and exoplanetary sciences.

Such central importance of Uranus and Neptune to advance our understanding has been highlighted over the last 10 years by the rapidly growing number of mission proposals and white papers submitted by the European and international communities, as well as international studies performed by space agencies to assess the feasibility of the different proposed mission scenarios (NASA Pre-Decadal Ice Giants Study 2017; ESA CDF Ice Giants Study 2019; ESA EPIG CDF Study 2019, ESA White Papers Voyage 2050, Planetary Science and Astrobiology Decadal Survey 2023-2032). Independently on the different scientific goals of the proposed mission scenarios, all studies agree that a mission to the ice giants is the logical next step in the exploration of the outer Solar System. Two additional elements of consensus are present among all studies performed up to date. First, to address the most fundamental science questions concerning the origins and nature of Uranus and Neptune, the ideal mission scenario for the exploration of one of these two planets should combine an orbiter with an atmospheric probe for in situ measurements. Second, due to the unique characteristics of each of these two planets and their satellite systems, the comparative exploration of both ice giants is critical to understand which characteristics are primordial and shared by ice giants and which are the result of their different and individual histories. Comparative exploration using twin or dual spacecraft has been assessed as feasible in the framework of a single mission by both ESA and NASA, at the cost of not being able to accommodate an atmospheric probe in the mission scenario. As a result, achieving a full and detailed characterization of both planets and their satellite systems within the next two decades requires international collaborations between leading space agencies.

However, although these two planets contain many the clues to understanding the evolution of the solar system, Uranus and Neptune remain poorly investigated. There are striking differences between these two planets, and also between them and the other two massive planets. They represent a class of planet that is not well understood, and which is fundamentally different from the gas giants (Jupiter and Saturn) and the terrestrial planets. Ice giants are, by mass, about 65% water and other so-called “ices,” such as methane and ammonia. In spite of the “ice” name, these species are thought to exist primarily in a massive, super-critical liquid water ocean. No current model for their interior structure, including the nature of the planetary dynamo, is consistent with all observations.

The elemental composition of the atmosphere of Uranus and Neptune has to be ascertained as it can shed light on early processes in the solar system. It is still under debate if the core accretion or the gravity instability model explains the interiors of the giant planets. Available measurements in Jupiter, few ones in Saturn and virtually none in Uranus and Neptune are not conclusive. Something similar happens to the knowledge of elemental atmospheric composition, being crucial to know the abundance of carbon, oxygen, nitrogen and noble gases (He, Ne, Ar, Kr and Xe) and their corresponding isotopes.

The wind regime in Uranus and Neptune is dramatically different to the one on Jupiter and Saturn. The icy planets have broad retrograde equatorial jet and nearly symmetric prograde jets a high latitude. The origin of this pattern is unknown and none of the current models can explain it.

Both planets have satellites whose surface is strikingly new. Whereas Triton (a Kuiper Belt Object captured by Neptune) shows cryovolcanic activity, the reason for Ariel and Miranda (natural satellites of Uranus) having new surfaces is an open question. Furthermore, Ariel and Miranda could host potential sub-surface oceans (in addition to the Jovian and Saturnian satellites).

Characterising the structures and temporal changes in the rings, the interior and surface composition of the satellites, the atmosphere of Triton, the solar wind-magnetosphere-ionosphere interactions, etc are also by themselves key science topics in the exploration of the outer solar system.

In situ investigations of the Uranus and Neptune systems must represent a milestone for Europe when aiming at the understanding of the solar system as a whole and in context with other planetary systems discovered in our Galaxy.

E Astrobiology, linking the Solar System to Exoplanets

Astrobiology is the study on the origin of life on Earth and the potential for life elsewhere. Astrobiology also includes the search for extraterrestrial life. In this search there are several key questions that need to be resolved to ensure an unambiguous detection:
How do we define what we are searching for?
Where should we look for life in the solar system?
How do we correctly interpret our findings?
How can we extend our search to exoplanets?

To define what we are searching for we need to look here on Earth, as Earth is the only place currently known to harbour life. The first step is to study the Earth as an exoplanet through field work and laboratory research. Biosignatures include biologically produced gases in the atmosphere and reflection signatures, but also mineralogy only produced through or in the presence of life and organic remnants in a planet's surface and subsurface materials. Earth is the best place to grasp the full breadth of potential biosignatures. In addition, dedicated space instrumentation shall allow us to observe the Earth-as-an-exoplanet, compressing all our reflected and emitted light into a single "dot" (to paraphrase Carl Sagan), and test our retrieval methods for atmospheric and surface properties, the presence of continents and liquid-water oceans, vegetation, a large range of other biomarkers and technosignatures. Future missions to land on or orbit the Moon (except landing on the far side) constitute an ideal platform for such observations, as the Earth is always up in the lunar firmament, and is being illuminated by our star at all phase angles within a month. Also, e.g., the ISS and deep-space missions could and should be used to obtain crucial benchmark data of our living planet. Strong links between astronomers, Earth scientists and biologists are necessary and many have already been established. It is important to keep fostering these collaborations.

The currently most promising locations within our Solar System to study the possibility for life and its potential presence are Mars, Enceladus, Europa, Venus, and Titan. Each of these bodies has its own niches and, in addition, Venus and Mars represent cases at the extremes of the canonical habitable zone, both with possible past life. On Mars missions studying the potential for extinct life should focus on locations where water used to be present. For extant life caves, subsurface water bodies, and locations with current water activity have been identified as the most target locations. Enceladus and Europa, the icy moons with large oceans under a thick ice crust, have an outer surface very hostile to life. The moons' rocky surfaces underneath the oceans may, however, support similar conditions as Earth's current or early oceans. In the near future the compositions of the oceans can be studied through analyzing the plumes and geysers erupting through the ice crusts. First steps have already been made by the Cassini mission, investigating Enceladus' plumes. Near-future missions should continue to focus on analyzing the composition of the plumes. In the mean time preparatory studies should be carried out on the potential for probing the ice crust and the oceans below. Recent findings, combining findings on terrestrial microbes with observations of the Venusian atmosphere have once again spiked interest in the potential for life in the clouds of Venus. Before we can make any assumptions on observations of compounds in Venus' atmosphere, a dedicated Venusian clouds mission shall ensure a much better insight in the chemical and physical conditions of and processes playing a role in these clouds. Titan will be visited soon by DragonFly that will already put some additional constraints on the potential for life in its liquid hydrocarbon lakes.

Now we have identified how to define what we are searching for and where to search in our solar system, the next big step to take is to correctly interpret our findings. Life produces many signals that individually may hint towards life, but may also have many other sources. To avoid misconceptions that can easily arise through the multidisciplinary approach of the search for extraterrestrial life, potentially leading to false claims of life detection, to pave the way for optimal interpretation of (near)-future findings, and to eventually identify extraterrestrial life, we need an overarching unambiguous interpretation of terrestrial data and data that we will receive in the next years with upcoming Solar System missions and exoplanet detection and characterization missions. An interpretation that will be accepted by all scientific disciplines. For this we need to develop a common language and classification of biosignatures that is agreed upon by all participating disciplines.

The solar system is only one of very many planetary systems that we can observe. By merging the fields of planetary science and exoplanetary astronomy (see chapter X) we can extend our search for life to exoplanets. Most notably in the form of "comparative planetology", putting new exoplanetary discoveries in the context of the solar system as a whole, and also specific solar-system planets. The solar system seems to be an atypical case, even among the already huge diversity of exoplanetary systems currently accessible to detections. And of course, the solar system harbors the only planet currently known to harbor life. However, and rather thanks to our privileged position to observe this particular planetary system from within in great detail, solar-system studies remain of vital importance for exoplanetary astronomy and the search for life.

First, indirect exoplanet detection approaches (both the radial velocity and transit methods) are now fundamentally limited by stellar activity that can mimic or obfuscate the signals of the presence of exoplanets in starlight. Studying and understanding the Sun-as-a-star is therefore crucial to mitigate these effects and discover small, rocky exoplanets on long orbits around Sun-like stars that can potentially harbor life.

Second, observations of solar-system planets can prepare us for future observations of exoplanets, whether they are fully comparable or not. Third, conditions for life may also be present elsewhere in the solar system, for instance in subsurface water oceans of icy moons like Europa and Enceladus, and possibly also in Titan's liquid hydrocarbon lakes. This would greatly expand the available search space for life in exoplanetary systems. Dedicated observations of and missions to those moons should inform the observational strategies of exomoons and associated exorings.

More generally, solar-system studies and exoplanetary research are converging to address fundamental questions about habitability, the origin and evolution of life, and how diverse and widespread life could be. Observations of young and mature exoplanetary systems will soon probe AU-scales, and thus provide essential insights into the formation of our own planetary system, and the conditions and ingredients for (early) life on at least one of its planets. Vice versa, understanding the conditions for (possible) life in all unlikely places on Earth and elsewhere in the solar system is crucial to prepare us for the search for life on exoplanets and/or exomoons. In particular, we need to understand (through observations, lab experiments and simulations) to what extent harsh environments (e.g. due to stellar flares and space "climate") can be ruled out for life, and which stabilizing factors (shepherding planets, stabilizing moons, planetary magnetic fields, atmospheric absorption, etc.) provide sufficient comfort for life to evolve.

Most importantly, being able to ask relevant questions about the possibility of extraterrestrial life in the solar system and/or beyond demands a fundamentally interdisciplinary approach. This research does not only bring together astronomers and planetary scientists, but also Earth scientists (climate/atmospheric scientists, geoscientists, etc.), chemists, biologists, ecologists (applied) physicists, engineers, etc. It is therefore crucial to form new interdisciplinary research and educational structures to learn each others' languages and to learn how to ask really relevant questions that address all pertinent aspects. Moreover, the possibility of detecting first signs of extraterrestrial life demands an intimate collaboration and public engagement with scholars in the humanities, philosophers, artists, and indeed society-at-large, to instil the significance of such a ground-breaking discovery in the broadest possible sense for all of humankind.