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Planetary Exploration Horizon 2061

A Long-Term Perspective for Planetary Exploration

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CHAPTER

2

Solar System/Exoplanet Science Synergies in a multidecadal perspective

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1. Solar System/Exoplanet Science Synergies: a major asset to properly address the key science questions about planetary systems

Since the first discovery of a planet orbiting a main-sequence star (Mayor and Queloz, 1995, rewarded with the Nobel prize in 2019) studies of planetary objects have significantly broadened their scope. Planetary sciences experience the emergence of a new unifying paradigm: the concept of "planetary systems," a class of astrophysical objects that covers and links together the Solar System, giant planets systems, and extrasolar planetary systems.

The Solar System and its giant planets systems (which form a kind of planetary system by their own) on one hand and extrasolar planetary systems on the other hand are observed by different techniques with important differences in measurement resolutions and types. Whereas remote sensing applies to all systems, only the Solar System, in the 21st century, is accessible to the powerful approaches of in situ investigations. Despite this important difference in their accessibility to our observations, there is no doubt that they form *one class* of astrophysical objects. Studying all planetary objects and their systems together in a comparative approach will be a considerable source of new scientific insight, in the same way as what happened to solar and stellar astronomy when they were finally considered as two complementary entries to the same scientific discipline: stellar physics.

This outstanding source of synergies between Solar System and exoplanetary science does not solely apply to the diversity of objects and systems. With the spectacular progress made in telescope observations of circumstellar (e.g., protoplanetary) disks provided by the development of very large aperture telescopes equipped with high-resolution imaging, and of space-based and ground-based telescopes that provide altogether a broad spectral coverage from near-UV through visible, IR, and submillimeter, up to the millimeter domain, our knowledge of the spatial distribution and spectral characteristics of the gas and dust components of these disks has made and will continue to make significant progress in the coming decades. This opens the opportunity for observational access to the complete temporal evolution of these fascinating "planet factories," from the first phase of their formation inside collapsing protostellar clouds to the period when planets form within their disk progenitors. By retrieving their evolutionary sequences with the additional help of advanced simulation tools, some critical information on how our own protoplanetary disk formed and gave birth to all Solar System objects can be inferred (see Lammer and Blanc, 2018, and references therein for more).

This chapter explores the unique potential of synergetic studies of disks, exoplanets, and the Solar System to gain a deeper insight into to the temporal evolution of planetary systems taken as a generic class of astrophysical objects, from their origin and formation, to the emergence of habitable worlds among their constituting objects and possibly of life. To do so, we analyze the way these synergistic studies, which provide a broader perspective on planetary systems, help us to gain deeper insight into the six key science questions about planetary systems introduced in Chapter 1 of this book (Blanc et al., 2021, 2022), which serve as the main scientific guideline of the "Planetary Exploration, Horizon 2061" foresight exercise (http://horizon2061.cnrs.fr/):

Q1: How well do we understand the diversity of planetary systems objects?
Q2: How well do we understand the diversity of planetary systems architectures?
Q3: What are the origins and formation scenarios of planetary systems?
Q4: How do planetary systems work?
Q5: Do planetary systems host potential habitats?
Q6: Where and how to search for life?

We first describe the currently planned and foreseen space missions dedicated to the observation of planetary systems (Section 2). In the following Sections (3 to 7) we explore Solar System/exoplanet synergies in the light of our six key science questions and make suggestions on how to take advantage of these synergies to better address these questions. In Section 9 we summarize our main findings and offer suggestions for future synergistic studies of protoplanetary disks, exoplanets, and Solar System objects.

The contents presented draw heavily on the presentations, discussions, and final report of the forum "Solar System/Exoplanet Science Synergies in a multi-decadal Perspective" jointly organized by the Europlanet Research Infrastructure and the International Space Science Institute (ISSI) in Bern, Switzerland, on February 19 and 20, 2019.

2. Overview of planetary missions in the current space program

Since the mid-20th century, the exploration of our Solar System is driven by technically challenging space missions. Space probes provide remote sensing data from planetary flybys and orbiting missions, as well as data from in situ explorations via landers and rovers. The diverse scientific drivers for future missions are formulated in different terms in the programs of the international space agencies; most of them can be reasonably covered by the six science themes formulated in Section 1. We provide in this section an overview of space missions under development, studied or planned to explore the Solar System and extrasolar planets and planetary systems in the next decades.

2.1 Solar System missions

2.1.1 Missions to the inner solar System

Mercury is the hottest terrestrial planet in the Solar System and the closest analogue for hot terrestrial exoplanets. In 2018, ESA successfully launched its Cornerstone Mission Bepi-Colombo, which will arrive at Mercury in 2025. The main science themes of this mission include its origin and evolution, its interior structure and composition, its magnetic field and tiny magnetosphere, and surface processes. The resulting insights into, e.g., the interior composition and structure of Mercury as well as its formation process will provide meaningful comparisons for future hot terrestrial exoplanets. The question whether the evolution history of Mercury is unique or whether similar objects can be found in other planetary systems remains open to date.

Venus: The diversity of science themes driving Venus exploration includes a better understanding of Venus' geologic and climatic evolution, potential evidence for past water, and the study of water loss processes. Venus is regaining interest because it can provide us with useful lessons to improve our understanding of the evolution of Earth. In addition, Venus serves as a reference case for warm terrestrial exoplanets that became too hot to develop or maintain habitable conditions. NASA as well as ESA have selected three missions in total to visit Venus around 2030, a Russian mission is under study:

- 2026 Venera D (Roscosmos, study) with orbiter and lander, and possibly further long-lived lander and balloon elements from NASA (Zasova et al., 2020)
- 2028 VERITAS (NASA Discovery mission) (Smrekar et al., 2020)
- 2030 DAVINCI+ (NASA Discovery mission) investigating Venus's atmosphere
- 2031 ENVISION (ESA M5 mission) (Ghail et al., 2016)

The study of Venus is important for exoplanet research since Venus provides similarities to warm terrestrial exoplanets at the inner edge of the habitable zone. Processes like dense CO_2-dominated atmospheres, the impact of the runaway greenhouse effect, and conditions for habitability for planets without plate tectonics can be studied in this "lab" in our neighborhood.

The Earth's Moon is of special interest as a track record of the Solar System evolutionary history in the near vicinity of Earth. Moon samples in our laboratories can be investigated via a fleet of modern instruments. The number of current and planned near-future missions to the Moon is steadily increasing, showing the rising scientific interest, as well as the interest to bring back humans to the Moon, and even to use the Moon as a base for further manned Solar System exploration.

Recent and future missions to the Moon include, e.g., the Chinese missions Chang'e-4 with a lander and a rover on the farside of the Moon and the Chang'e5 successful sample-return mission, as well as further sample-return missions and resources exploration in future (Jia et al., 2018; Lu et al., 2021; Qian et al., 2021). The first Israeli Space IL Beresheet commercial lander crashed. India has continued its Moon program with the Chandrayaan-2 (Mathavaraj et al., 2020) operational orbiter and lander (lost just before crash landing), and the Chandrayaan-3 lander and rover due in 2022.

Commercial moon exploration is part of the US NASA CLPS Commercial Lunar Payload Services (starting with Astrobotic & Intuitive Machines missions in 2021), and continuing with three missions to the South Pole in 2022–23, and others to Mare Crisium, Reiner gamma in 2022 and the farside Schrodinger basin in 2024.

The Artemis missions (NASA/ESA) with Orion/ESA service module in cis-lunar orbit in automatic mode launch in 2021, and with crew beyond 2023, will then bring humans on the lunar surface.

NASA has the robotic lander MoonRise mission among its potential candidates for the next New Frontiers mission call, targeting sample return from the South Pole–Aitken basin. Visions going beyond the mid-2020s include manned missions and the set-up of structures suitable for humans, like villages or gateways for future exploration of the Solar System.

The Russian Luna program includes Luna 25 in 2021, Luna 26 orbiter in 2024, Luna 27 lander to characterize lunar ice in 2025, and subsequent missions for lunar resources, e.g., the planned Russian Luna 28 to 31 missions to study technology for a future lunar base in 2027-30. Additional moon exploring nations include South Korea with a planned Pathfinder Lunar Orbiter (KPLO) (launch 2022/23, Sim et al., 2020; Ju et al., 2013) and a Korean Lander Explorer (KLE), South Korea, with orbiter, lander, and rover planned for 2025 (Kim et al., 2016). Russia and China have announced a collaboration for a lunar research base.

While no securely confirmed detections of extrasolar moons have been made yet, such detections are expected for the future with improving detection methods. Recently a circumplanetary disk in the young system PDS 70 has been detected by ALMA (Benisty et al. 2021). Such residual dust could be material from which moons form. Despite this exciting discovery, it will remain challenging to observe exomoons or their progenitors as circumplanetary disks in the near future. Nevertheless, the possibility to compare the Solar System moons with others remains a fascinating goal for future instrument developments. The main value of lunar exploration for exoplanet science, however, lies in the reconstruction of Earth–Moon evolution and enhancing our knowledge of Earth as the prototype of planets capable of developing life.

Mars is at the outer edge of the habitable zone in our Solar System. Its low mass and its fossil crustal magnetic field have implications for atmospheric loss processes that are important for the long-term evolution of its atmosphere (Gronoff et al., 2020). Today, its tenuous atmosphere does not allow for liquid water to be stable at its surface over significant periods of time. Nevertheless, it is now generally believed that Mars had liquid surface water at least during episodes in its early history. This makes Mars the target of a number of space missions to study its surface and atmospheric conditions as well as to search for signs of present or extinct life. Finally, Mars is a target for exploration by humans.

Recent space missions include the three spacecrafts launched in 2020: the Mars2020 (NASA) Perseverance rover, the Hope Mars Mission orbiter (United Arab Emirates) and the TianWen-1mission (CNSA) with Mars Global Remote Sensing Orbiter, a lander, and a rover. Future international missions include European and Russian landers (in 2022, ExoMars Lander and Rover (ESA/Roscosmos, currently on hold), the Mangalyaan 2 orbiter in 2024 (ISRO), and in 2024 the Martian Moons Exploration mission (MMX, JAXA), including a (DLR/CNES) rover on the Martian moon Phobos. The future of Mars studies will bring Mars Sample Return missions and potentially humans on Mars as a goal. All of this will provide us with detailed knowledge about a planet with significant atmospheric escape processes and temporary habitable conditions, which will form our prototype for exoplanets just a bit too small and/or far from their star to be a good target to search for life.

2.1.2 *Missions to small bodies*

Asteroids and comets provide "ground-truth" of the earliest phases of Solar System formation. Their exploration gives access to protoplanetary material, gas/dust and isotopic ratios, mineralogical and chemical compositions, water and volatile fractionation, and their collisional history. Recent and future missions include Hayabusa 2 (JAXA) which arrived at asteroid Ryugu and returned samples of a rare type of asteroid back to Earth. NASA's OSIRIS-Rex mission will bring back samples from asteroid Bennu. 2021/22 will see a number of missions to asteroids, including the LUCY and PSYCHE missions to the Jupiter Trojan asteroids and a main belt object (NASA) as well as DART (Double Asteroid Redirection Test, NASA), a technology demonstration to impact a near-Earth asteroid. The European HERA mission (ESA) serves as technology demonstration in 2024 and is followed by CometInterceptor in 2028 as first mission to a long-period comet.

The planned missions CAESAR and Corsair for sample-return from comets were not selected by NASA in 2019, but samples from comets remain a highly interesting future science goal. The first visit to a Kuiper belt object was made by NASA's New Horizon mission in 2019. Plans for follow-up missions are still under development.

The value of in situ and lab analysis of these pristine objects from the early days of the Solar System is high and serves as a reference for comparisons to proto-planetary disks as well as exo-comets observed in other stellar systems.

2.1.3 Missions to the outer Solar System

The **icy moons** are of particular interest because their subsurface oceans may be a habitat for life. Io, Enceladus, and possibly Europa are active bodies and deliver materials to the surface and surrounding space. A search for tracers of ocean characteristics (e.g., salts) is being undertaken by Earth-based and in situ assets. Science goals for their exploration include the determination of ice crust thickness and composition, the detection of organic molecules in subsurface oceans, and the determination of the salinity, redox state, and chemical composition of subsurface oceans:

- 2023 JUICE (ESA) to study Ganymede and the Jupiter system,
- 2023 Europa Clipper (NASA) to study Europa,
- 2025 Dragonfly (NASA), a drone to study Titan's atmosphere and surface.

Beyond these already accepted missions, several new and important missions are in preparation. A lander mission concept to search for life at the moon Europa is under study by NASA (Hand et al., 2017) and a concept for a joint NASA-ESA mission to Europa has also been formulated (Blanc et al., 2020). ESA's Voyage 2050 report identifies the moons of the gas giants as a theme for a future L-class mission (see Voyage 2050 report for download at https://www.cosmos.esa.int/web/voyage-2050).

Going further out in the Solar System, the ice giants (Uranus and Neptune) have not been investigated in detail since the Voyager 2 flybys. Consequently, plans to investigate ice giants (and their moons) further are currently under discussion in the international scientific community. Given that we now know that planets with the sizes of our ice giants are extremely common in the galaxy (see Fig. 2.1 and comment in Section 3.1), improving our understanding of Uranus and Neptune in terms of their formation mechanism, thermal evolution, internal structure, and magnetospheres is a key scientific objective mandatory to explore the diversity of planets (key question Q1) in the Solar System as well as in other planetary systems.

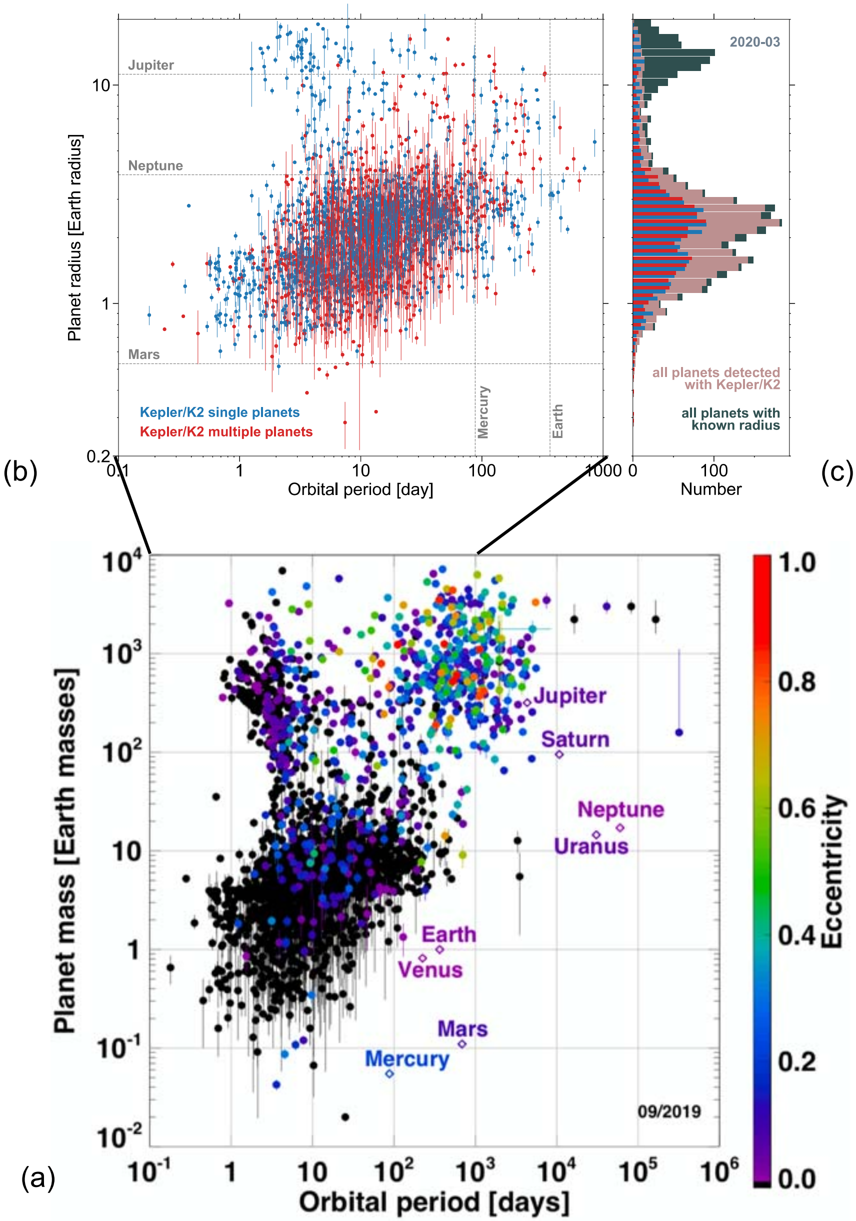

FIGURE 2.1 (Panel A) Mass versus orbital period distribution of all exoplanets for which these parameters have been determined so far; (panel B) inventory of the 2404 planets whose radius has been determined by the Kepler/K2 surveys as a function of their orbital period; (panel C) histogram of their statistical distribution sorted by radius. *Adapted from (Blanc, 2021) and (Deleuil et al., 2020), based on data extracted from exoplanet.org.*

A more detailed description of current, planned, and foreseen space missions to the Solar System is given in Chapter 3 and Chapter 4 of this book (Dehant et al., 2022; Lasue et al., 2022).

2.2 Exoplanet missions

Extrasolar planets allow us to place the Solar System into the more general context of planetary systems, from their formation to the possible emergence of life. Space investigations started with the CoRoT (CNES, Baglin et al., 2016) and Kepler/K2 (NASA) missions (Borucki et al., 2011; Borucki, 2016). The catalogue of short-period planets around bright stars is rapidly growing with the ongoing Transiting Exoplanet Survey Satellite mission (TESS, NASA), launched in 2018 (Ricker et al., 2015), and highly refined radii and other characteristics for known planets are provided by the CHaracterizing ExOplanet Satellite (CHEOPS, ESA) mission (Benz et al., 2021). In the coming decades, exciting new developments are in preparation. The James Webb Space Telescope (JWST, launch 2021) will be able to provide infrared spectra of exoplanets by which molecules (such as H_2O, CO_2, and CH_4) can be detected. A sample of 100 spectra of larger and hotter planets will allow statistical insight into the chemical trends among the targeted planets. The PLAnetary Transits and Oscillations mission (PLATO, ESA) (Rauer et al., 2014, 2016), to be launched in 2026, specifically aims at extending the statistics on planet demographics, particularly for long periods and small planets, thereby providing precise planet mean densities and system ages for a large number of objects via transit, radial velocity, and astroseismology methods. The Atmospheric Remote-Sensing Exoplanet Large-Survey (ARIEL, ESA) mission (Tinnetti et al., 2018), to be launched in 2029, will allow the exploration of exoplanetary atmospheres in transiting planets from hot sub-Neptunes to gas giants. Hence, in future comparative exoplanetology diversity will be possible for a broad range of planetary masses, equilibrium temperatures, and atmospheres. This information can be used to understand better the link between atmospheric composition and the bulk composition and its connection to planet formation and evolution. The Nancy Grace Roman Telescope (formerly WFIRST, to be launched in the mid-2020s) will also further enlarge our statistical coverage of planet occurrences via the microlensing technique. In addition, ESA's Gaia mission will provide a large number of planet detections via astrometry. All these missions are complementary. They address different parameter ranges, with some overlap, and derive planetary characteristics with different uncertainties. In view of the complex processes that shape planets and their environment the characterization of a large parameter range by combining information from all missions will finally be needed.

Exoplanet missions of the next decades will focus on the characterization of atmospheres of small, terrestrial, temperate planets and the search for biosignatures with larger aperture space telescopes. The Large UV/Optical/Infrared Surveyor (LUVOIR), proposed for 2040, and the Habitable Exoplanet Imaging Mission (HabEx), both concept studies by NASA, will explore exoplanet's atmospheres with unprecedented accuracy. The Origin Space Telescope, also part of NASA's decadal survey, would perform transit observations of small planets around M stars. In Europe, a concept for an infrared interferometric mission to detect terrestrial exoplanet atmospheres is being developed (Large Interferometer For Exoplanets, LIFE; Quanz, 2019, 2021). Recently, ESA's new Voyage 2050 program has identified a mission targeting at temperate rocky exoplanets as a potential theme for a future L-class mission (ESA Voyage 2050, recommendations from Senior Commmittee, 2021). Section 8 will describe their objectives and the associated technology challenges. Besides space-based missions, ground-based facilities will also drive key technological developments and offer additional unique opportunities. Extremely Large Telescopes (ELTs) provide and will provide the large aperture and spatial resolution necessary to start studying the atmospheres of Earth analogues around nearby cool stars. Transit spectroscopy, high-resolution spectroscopy, and high-contrast direct imaging on ELTs will make it possible to characterize rocky planets in the habitable zone around small (M) stars at optical to near-infrared wavelengths. In the mid-infrared (10 micron) we will also be able to image rocky planets in the HZ around the nearest solar type stars (Bowens et al., 2021).

In summary, the Solar System as well as exoplanetary systems provide a wealth of data that help us to understand better the formation and evolution of all planets, including the Earth, how they form and evolve and whether life emerged elsewhere than Earth. Missions to Solar System bodies are gaining in complexity, including landers, rovers, drills, drones, balloons, in situ analysis labs, and sample-return mechanisms. For exoplanet characterization, current techniques rely on transiting planets, but direct imaging methods with large-scale telescopes (coronography and interferometry) will be the drivers for future missions. More information about the missions discussed here can be found at the respective space agency web pages and references therein.

3. Diversity of planetary systems objects (Q1)

The past decades of planetary and exoplanetary sciences have revealed exciting new data that will allow us to understand planets and planetary systems as astrophysical objects in more detail in future. Within the Solar System we are able to study eight planets only, although in considerable detail, while exoplanet research has revealed the stunning diversity of thousands of these objects around other stars. Conversely, all types of planetary system objects other than planets (small bodies, moons, rings, dust and magnetohydrodynamic plasma interaction processes, etc.) are accessible to our observations in the Solar System, while only planets have been observed to date in extrasolar planetary systems, with the exception of exo-comets (see Strøm et al., 2020 for an overview) and some debated detection claims of exomoons (Cabrera et al., 2018). Some bright debris disks observed are seen as analogues to the Kuiper belt.

We are now at a stage when exoplanet characterization is improving at a fast pace and can be used to put the Solar System into perspective. There is also a reasonable hope that new categories of objects (moons, rings, etc.) and even radio emissions of exomagnetospheres will be detected in the coming years to decades. Both developments will make synergies between Solar System, giant planet systems, and extrasolar planetary systems increasingly more efficient in addressing our six key science questions.

3.1 Inventory of known exoplanets

During the past 30 years, extraordinary developments in astronomical observations and space exploration have been made in the detection and characterization of exoplanets using a diversity of partly overlapping and partly complementary methods in planetary parameter space, including:

1. radial velocity measurements, which currently reach a precision down to about <1 m/s on stellar radial velocity,
2. the transit method, which can currently observe dips in stellar brightness down to 0.01−0.0001% for ideal targets,
3. microlensing, particularly powerful for the statistical investigation of planet demographics,
4. astrometry, with which one can currently measure the reflex motion of a star caused by a planet with precisions down to 10 micro-arcseconds for bright stars, and
5. finally, direct imaging.

Fig. 2.1 shows the mass and radius versus orbital period distributions of all planets for which these parameters have been determined so far by this diversity of techniques. Panel (a) displays the mass versus orbital period distribution of the more than 4000 exoplanets detected, with the locations of the eight Solar System planets indicated for reference. This observed distribution, though biased by the sensitivity limitations of the different techniques, shows that planets are mainly distributed into three different clusters. A majority of all detected planets belong to a population of low-mass planets (between approximately 0.5 M_{Earth} and 20 M_{Earth}, i.e., up to the masses of Uranus and Neptune) with orbital periods between approximately 1 and 300 days. Two other population clusters can be identified at higher masses: a population of "hot Jupiters" with orbital periods of a few days and masses spreading above and below the masses of Solar System gas giants; and a third population of "warm Jupiters" at larger masses and much longer orbital periods than the "hot Jupiters," ranging from approximately 50 to 104 days. As time progresses and more planet discoveries are confirmed, this distribution will include more and more planets and should likely spread in mass and orbital period as a result of progress in detection and characterization techniques.

Thanks to the successful development of occultation techniques, which provides a direct access to planetary radii, the population of planets with low masses and short orbital periods has been studied more closely and more accurately. The inventory of the 2404 planets whose radii have been determined by the Kepler/K2 surveys is displayed in Panel (b) of Fig. 2.1, distributed as a function of their orbital period. It shows that a broad majority of these exoplanets radii are intermediate between those of Neptune and Earth. The histogram of their statistical distribution, sorted by radius (Panel (c)), in pink, overlaid with the statistical distribution of all planets for which the radius has been determined (in gray), suggests that this radius distribution is bimodal and can be described as the superposition of two partly overlapping populations: one peaking around 1.3 R_{Earth}, referred to as "super-Earths," and a second one peaking near 2.4 R_{Earth}, called the "Sub-Neptunes." These two peaks are separated by a shallow minimum at 1.8 R_{Earth} (Fulton et al., 2017; Owen and Wu, 2017; Jin and Mordasini, 2018,; Fulton and Petigura, 2018; Van Eylen et al., 2018; Ginzburg et al., 2018; Venturini et al., 2020c).

Fig. 2.1 shows that on the basis of the current inventory of exoplanets, none of the Solar System planets are directly comparable in all aspects to exoplanets, being either of significantly lower masses, or located on orbits with significantly higher orbital periods. Some, rare Jupiter analogues are just at the edge of the current detection range in this mass range. At this point, this reflects the observational biases toward larger masses and short periods we still have in the available exoplanet data. This discrepancy places strong limits on direct comparisons between Solar System planets and exoplanets, particularly in terms of their environmental conditions. Nevertheless, except for Mars and Mercury, Solar System planets masses correspond to characteristic masses of the different identified exoplanet clusters, allowing one to use these planets as "templates" to understand the planets of these different clusters, albeit at larger orbital periods.

Progress expected for the coming decades in exoplanet detection and characterization techniques, ground-based and space-based, should progressively reduce these discrepancies. Exoplanet surveys will progressively extend their parameter space coverage toward the right-hand sides and the bottoms of the panels of Fig. 2.1, hopefully ultimately covering the range of masses/sizes and orbital periods in which Solar System planets reside.

To take full advantage of this expected overlap, the accuracy of characterization of Solar System planets should in parallel be improved to provide a useful comparison. This is particularly true for ice giants, the most poorly known of Solar System planets, which could be used as templates for the most abundantly populated exoplanet cluster. Future ambitious ice giants space exploration programs, complemented by observations using the giant space and ground-based telescopes, would bring progress in their characterization.

Our understanding of exoplanets is linked to our capabilities to characterize their host stars, starting with the determination of precise planet parameters, including system ages, up to our understanding on how stellar environments affect planetary diversity and planetary evolution. Detailed monitoring over long periods is essential to advance our understanding of stellar variability and activity on different timescales and of their dependence on star types and ages. First steps were accomplished by the CoRoT, Kepler/K2, and TESS missions and will be continued to widen the range of stellar types and exoplanet systems studied with ESA's PLATO mission. These observational efforts should continue to stimulate theoretical studies ranging from stellar astrophysics to planetary science. In this respect it is important to continue monitoring stellar UV emission because of its impact on, e.g., planetary atmosphere chemistry and loss processes.

Another limit of current exoplanet studies is our insufficient knowledge of their interiors, compositions, and evolutionary histories. Integrated models are needed to link the few observable properties to an improved understanding of planets. In parallel, while it seems hardly possible to overcome all parameter degeneracies for exoplanets (often being a challenge also for Solar System objects), it is important to expand the number of observables. Recently, first measurements of Love numbers (h_2) for exoplanets have been published (Csizmadia et al., 2019; Hellard et al., 2019, 2020), thereby providing an additional observable via the radial velocity and transit techniques (Baumeister et al., 2020). Considering that Love numbers are available for only few Solar System bodies, it will be interesting to study this parameter for a statistical sample of objects once future measurements will provide a larger observational basis.

Recent hints of detection of optical (Cauley et al., 2019) and radio (Vedantham et al., 2020; Turner et al., 2021; Pérez-Torres et al., 2021) emissions produced or induced by exoplanets will ultimately allow us to put constraints on exoplanetary magnetic fields (Hess and Zarka, 2011).

Future measurements of the stellar ages (e.g., PLATO) combined with atmospheric measurements (e.g., JWST, Ariel) can be used to further constrain the planetary bulk composition and internal structure, in particular for gaseous-rich planets. This includes the potential population-wide temporal evolution of some planet types into others (e.g., evolution from sub-Neptunes to super-Earths; Berger et al., 2020).

3.2 A summary of what we know of Solar System objects

Within the Solar System, all families of planetary objects have been visited by spacecrafts at least once and a fraction of them can also be characterized with Earth-based telescopes. Compared to exoplanetary observations, the level of chemical and physical details that can be studied for Solar System objects is orders of magnitudes higher, providing very accurate measurements of the various chemical and physical properties of Solar System planets, including their gravitational and magnetic fields, atmospheric compositions, rotation rates, surface features, etc. Some general findings about Solar System objects include the following: the formation history of Solar System planets is complex and is dominated by the gas giants, including dynamical feedbacks and extreme impact events. The outer planets are very diverse, suggesting that their different characteristics are determined by the specific conditions of their formation and evolution. The formation and cooling histories of terrestrial planets and their interior-atmosphere interactions are also very diverse and are likely influenced by their specific impact history as well as physicochemical processes that are not fully understood. Solar System planets' magnetic fields are very diverse in strength and topology, giving birth to six magnetospheres with very different characteristics. Small bodies and meteorites are remnants from planet formation processes and can provide important information on the physicochemical conditions during the birth of the Solar System.

3.3 Solar System-exoplanets synergies for the decades to come

Understanding the diversity of planetary system objects is a challenging endeavor requiring space missions and adequate technology. For exoplanetary systems, we need to investigate the dependencies of planet demographics on stellar properties (e.g., mass, composition, age, stellar disk at birth) and planet properties (e.g., mass, radius, orbital period, atmospheric characteristics). Exploring each dependency will require mobilization of a large amount of resources and involve the full spectrum of available detection methods. While these methods are partly complementary, they are sensitive to different types of stars, planets, and system architectures. In some cases, the sensitivities of methods do not overlap, which requires statistical modeling to connect the different observed populations. Solar System planets can potentially be used as "templates" of the different exoplanet clusters, to better describe them and to calibrate theoretical models of planet structure, formation, and evolution. In order to take advantage of this synergy, simultaneous order-of-magnitude improvements must be accomplished both in exoplanet detection and characterization techniques and in our knowledge of the most poorly known of Solar System planets, including the two extremes of its range of radial distances to the Sun: ice giants and Mercury. Future synergies between the two target samples will include:

- In Solar System research, access to secondary systems and to the full diversity of their objects (moons, rings, dust and gas, plasmas and charged particles, magnetospheres) provides a "ground truth" to extrapolate their properties to analogue objects likely to be hosted by extrasolar planetary systems, guide for their future detection, and prepare for their characterization;
- In exoplanet research, future detections of new classes of objects (moons, rings, etc.) will in return broaden our understanding of Solar System objects. Knowledge of exoplanets in so far poorly explored parameters ranges (e.g., smallest rocky planets, distant cool planets) will allow one to place the respective analogues in the Solar System into context.

4. Diversity of planetary systems architectures (Q2)

4.1 Comparing Solar System and extrasolar systems architectures

Extrasolar planetary systems are ubiquitous in our galactic neighborhood and diverse in terms of numbers of hosted planets, orbital parameters, period ratios between neighboring planets, planet densities and masses, and stellar properties. Altogether, more than 500 different multiplanet systems are known to date. Available data for this sample indicate a broad diversity in the distribution of planet characteristics (masses, radii, atmosphere properties, stellar illumination, etc.) and orbital parameters: planets are detected on ultrashort orbits of several hours and as far as several hundreds of astronomical units (AUs) from their host stars. Many planets seem to have undergone orbital migration such that they are not detected where they were initially formed.

Fig. 2.2 illustrates this diversity of architectures for a sample of multiplanet systems with at least four planets, extracted from the California Kepler Survey (CKS) by Weiss et al. (2018). They are ordered from top to bottom by decreasing host stellar mass, and horizontally by distance to their host star in AU. Planetary radii are indicated by a color code. Comparison of their radial distributions to the one of inner Solar System planets (line "SOL") shows that most of these already detected planetary systems are grouped closer to their star. This statistical study also revealed a series of regularities in the distribution of planets with respect to mass and stellar distance: (1) neighboring planets tend to have similar masses; (2) neighboring planet pairs tend to have similar separations; (3) distances between adjacent planets tend to increase with planet mass, i.e., less massive planets tend to be more "packed"; (4) these interplanet distances average around 20 mutual Hill radii, and are never smaller than 10 mutual Hill radii: There is an observed lower limit to interplanet distances in the family of systems analyzed in this study. These characteristics are in contrast with the inner Solar System, and this contrast is even more striking if we consider Solar System outer planets as

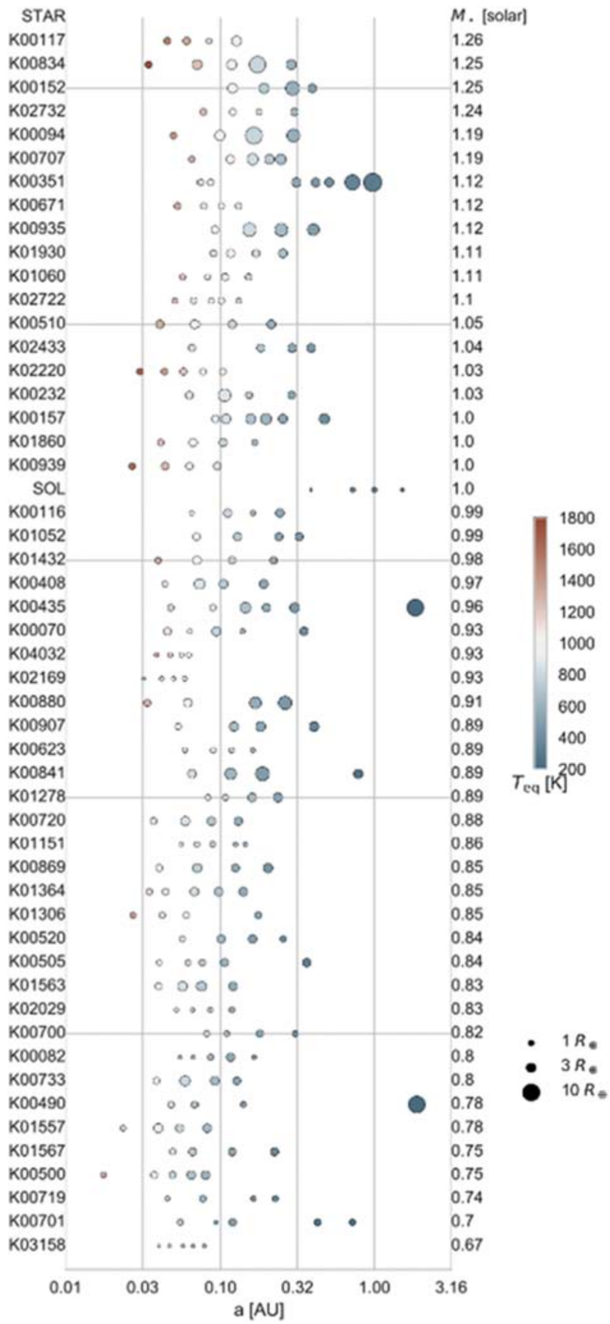

FIGURE 2.2 Architectures of multiplanet systems with at least four planets, ordered by decreasing host stellar mass from top to bottom, extracted from the California Kepler Survey (CKS) which improved the determination of planetary radii, masses, and equilibrium temperatures via a more accurate determination of the host star parameters. Each row corresponds to one planetary system (name on x-axis) and shows the planets semimajor axes (x-axis in log scale). The point sizes correspond to the planet radii, and their colors to their equilibrium temperatures. The inner Solar System is included for comparison. *From Fig. 1 of* Weiss et al. (2018).

well: an architecture similar to our Solar System, characterized by small planets inside the primordial ice line and giant planets outside of it, is not observed to be frequent around other stars.

Another important asset of our Solar System for the comparative study of planetary systems architectures is that it offers five different architectures, summing up the Solar System as a whole, and the four giant planet systems, which can be considered as secondary systems. A broader diversity of objects (rings, moons, dust, gas and plasma tori, etc.) can be observed in the Solar System than around other stars due to the observational biases for exosystems. Reinforcing this (up to now) Solar System singularity, the spatial arrangement of these objects around giant planets also follows very diverse architectures. Considering only regular moons, their mass versus distance to their parent star is presented in Fig. 2.3.

Different trends emerge from this figure: (1) there is a tendency for an increase of moon masses with planetocentric distance, best illustrated by Saturn's moons; (2) the four Galilean moons do not follow this trend, being of comparable masses; (3) the Neptune system appears unlike any other, with only one regular moon, Triton, representing over 90% of the total mass of the moon system. This, together with Triton's retrograde orbit, supports the current interpretation that Triton was initially a Trans-Neptunian object whose capture destroyed Neptune's primordial moon system, if there was any (Banfield and Murray, 1992), and points to the singular interest of this object.

Comparative studies of the architectures of giant planets systems, Solar System, and exoplanet systems provide clues to a deeper understanding of their origins (Q3), working processes (Q4), and habitability (Q5), as illustrated in Fig. 2.4. With its seven planets trapped in mean motion resonances, the TRAPPIST-1 system (center panel) can be compared to the Galilean satellites system (upper panel) within which the Io-Europa-Ganymede system is trapped in a 1:2:4 mean motion resonance called the Laplace resonance (see also the case of the six-planet system TOI-178; Leleu et al., 2021). This resonance and its implications have been studied for a long time by astrometric telescopes and by our space probes. The locations of TRAPPIST-1 planets with respect to their habitable zone can also be compared to those observed for Solar System inner planets (lower planets) and contribute to future studies

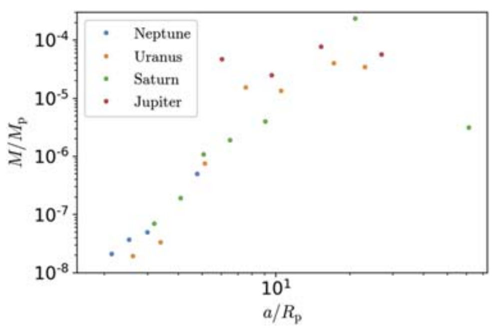

FIGURE 2.3 Architecture of the regular moon systems of the four giant planets. Shown are the masses of the moons (normalized to that of their parent planet) against their semimajor axis (normalized to the radius of their parent planet). Only major moons are reported. *From (Blanc, 2021).*

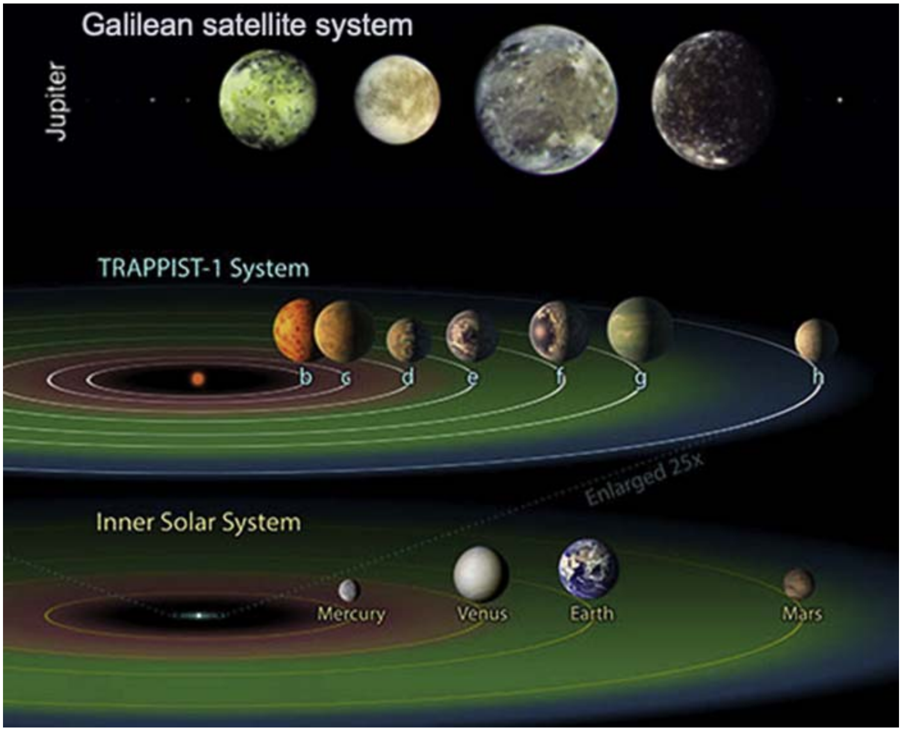

FIGURE 2.4 An illustration of synergies between studies of giant planet systems (represented by the Galilean satellites, *top row*), exoplanet systems (the Trappist-1 system, *middle row*), and the Solar System (*bottom row*). Mean motion resonances can be studied both between the Galilean satellites and the Trappist-1 system, which in turn is an interesting example of a system with several planets in the habitable zone, to be compared to our inner Solar System.

of habitability. Another striking property is the similarity of the Galilean moons-to-Jupiter mass ratio as compared to the TRAPPIST-1 planets to their host star mass ratio.

Finally, planetary systems are also confined, tied together, and protected from their galactic environment by their magnetic fields. The astrospheres (analogue to our heliosphere) shield stars and their systems of planets from energetic particles called galactic cosmic rays (GCRs) that stream from the galaxy. The shielding of GCRs by astrospheres is a fundamental, open question whose answer is critical to assessing the habitability of exoplanets (Herbst et al., 2020; Scherer et al., 2015). But even before we study the shielding properties of other astrospheres to ascertain habitability, we must understand why the only astrosphere known to harbor life, i.e., Earth's heliosphere, does so.

The heliosphere is an immense shield that protects the Solar System from harsh, galactic radiation. With the Voyager 1 data (Stone et al., 2013, 2019) it is known that the heliosphere shields the inner Solar System from 75% of cosmic rays at 1 GeV. This radiation affects not only life on Earth, but human space exploration as well. In order to understand the evolution of the heliosphere's shielding properties, we need to understand its structure and large-scale dynamics. We are now in a position to build a predictive global model of the heliosphere. To date, our best large-scale computer models fail to reproduce critical observations, such as the size of the heliosphere, the plasma speeds and directions, and the width of the heliosheath. Critical advance in heliospheric models is needed. The heliosphere is a template for all other astrospheres, enabling predictions about the conditions necessary to create habitable planets.

Concurrent progress in the astronomical detection of astrospheres around nearby stars (some of which are illustrated in Fig. 2.5) and in the in situ and global characterization of the heliosphere and its interactions with the local interstellar medium is expected for the decades to come. With this progress, synergetic studies of the heliosphere and of astrospheres will move from a mere conceptual connection to real quantitative intercomparisons of data (in situ and remote sensing) and models, and lead to an in-depth understanding of astrospheres, and our heliosphere among them, their interactions with the interstellar medium, their role in the habitability of planets, and our connection to our galactic neighborhood.

4.2 Solar System-exoplanets synergies for the decades to come

In summary, many fruitful synergies between Solar System and exoplanet studies are expected in current and future studies of planetary systems architectures:

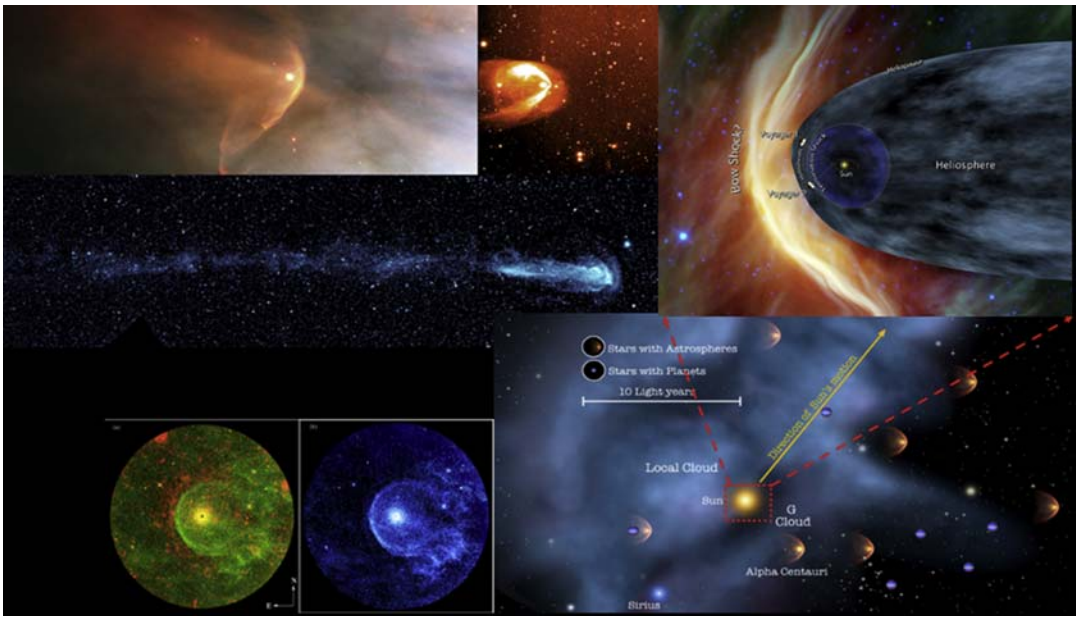

FIGURE 2.5 An illustration of the growing synergies between astronomical studies of astrospheres and in situ studies of the heliosphere, our Sun's astrosphere. Several astrospheres observed in different wavelength ranges (left-hand side of the figure) can be compared to our heliosphere and guide our limited knowledge of its 3D structure. Astrospheres are current attributes of stars in our galactic neighborhood, just as are planets (lower right-hand side panel). *Adapted from Opher, M., 2019. The Heliosphere: Lessons Learned from Voyager, Cassini, IBEX about Our Home in the Galaxy, Planetary Exploration Horizon 2061 Synthesis Workshop, Toulouse.*

(1) five different planetary systems architectures (the Solar System and its four giant planets systems) can be studied in situ and compared to the hundreds of extrasolar system architectures;
(2) the heliosphere, our Solar System's astrosphere, can be investigated in situ up to and beyond its boundaries with the local interstellar medium and provide "ground truth" for generic astrosphere studies.

In return, comparison of the architectures of extrasolar systems, of the distribution of their planets in mass and orbital parameters, of the structures of their astrospheres, with the Solar System and its heliosphere will allow us to understand the connections of planetary systems architectures to their formation histories, evolution mechanisms, workings, and habitability in far more detail. It will tell us to what extent the Solar System is "unique" or generic (see Lammer and Blanc, 2018). Studies of circumstellar disks and their coupling to forming protoplanets will also contribute enormously to a better understanding of the role played by the initial steps of the formation of planetary systems in the shaping of their architecture, as the next section is going to show.

5. Origins and formation of planetary systems (Q3)

5.1 Overview of planet formation

An overview of the main phases of planet formation in the classical sequential bottom-up paradigm (the core accretion theory; Safronov, 1969) is depicted in Fig. 2.6. After the formation of the star and its circumplanetary disk, planet formation starts from micron-sized dust grains that rapidly grow via coagulation to centimeter-sized pebbles (Weidenschilling, 1980). These pebbles drift inward in the disk (Weidenschilling, 1977a,b). Through further coagulation, or more likely through instabilities (Youdin and Goodman, 2005), pebbles accrete further to form kilometer-sized planetesimals, probably at specific places in the disk (Drazkowska and Alibert, 2017). Planetesimals in turn grow into protoplanets, objects on a 1000 km size range (Kokubo and Ida, 2000), via collisions. Some of the protoplanets grow massive enough (a few Earth masses) during the presence of the gaseous nebula (Class I and II disks) to trigger the accretion of a massive gaseous H/He envelope and, with it, the formation of a giant planet (Pollack et al., 1996; Mordasini et al., 2012, Helled et al. 2014). It is now realized that H—He gas can be accreted also when the protoplanet is much smaller than 10 M_{Earth}, which is consistent with the existence of many small exoplanets that are gaseous-rich (e.g., Venturini and Helled, 2017, 2020). Protoplanets embedded in the gaseous disk, depending on the local gas density, can be subject to orbital migration (Lin and Papaloizou, 1986; Dittkrist et al., 2014), causing the initial and final locations of protoplanets to differ (no in situ formation). However, most protoplanets do not grow massive enough to trigger rapid gas accretion. Rather, once the damping influence of the gas is gone (Class III disks) they mutually excite their orbital eccentricities and undergo a series of giant impacts (Benz and Asphaug, 1999), leading to the formation of terrestrial planets. In the final phase, planetary orbits rearrange to reach a configuration that is stable over billions of years (Laskar, 1997). During this time, individual planets undergo a long-term

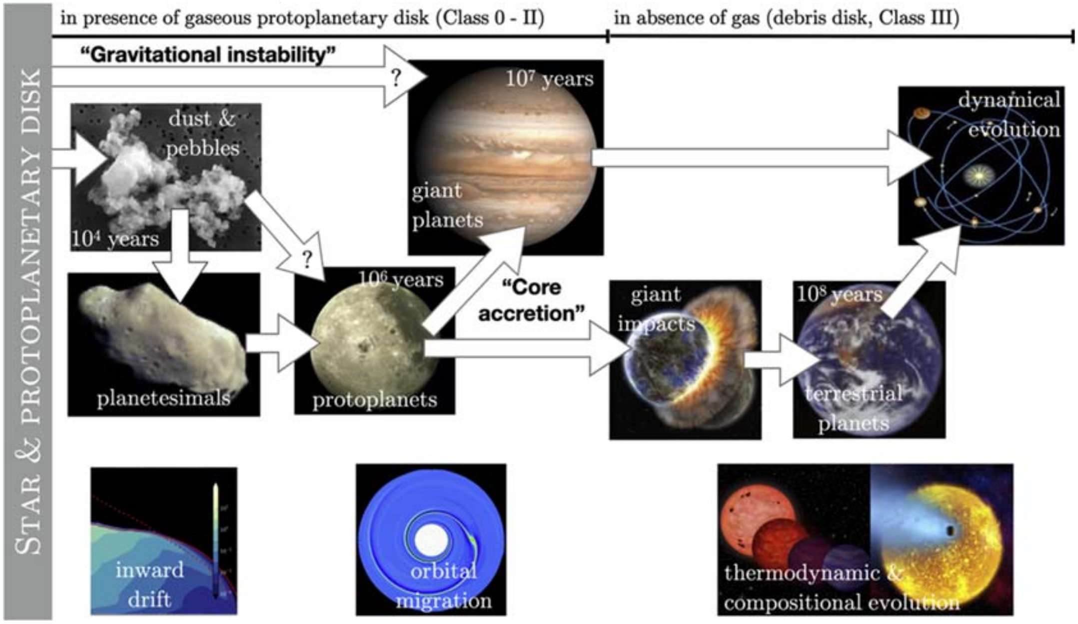

FIGURE 2.6 Overview of planet formation and evolution in the sequential bottom-up paradigm. Arrows indicate the sequence of the phases. Important physical processes acting during different stages are shown at the bottom. *Credit: W. Benz/C. Mordasini (Univ. of Bern).*

thermodynamic and compositional evolution including processes like cooling and contraction (Linder et al., 2019), atmospheric escape (Lammer et al., 2008), or interior–atmosphere interactions like in- and outgassing (Smit and Mezger, 2017).

5.2 Open questions and challenges

The question marks in Fig. 2.6 indicate that even at such a very basic cartoon level, there are fundamental open questions regarding the origin of planetary systems:

- What are the properties of a protoplanetary disk as initial and boundary conditions for planet formation (Birnstiel et al., 2010; Testi et al., 2014)? What drives disk accretion and sets the structure of protoplanetary disks (Turner et al., 2014)? If processes other than turbulent viscosity as conventionally assumed play a role, disk structures and planet formation processes will be very different (Suzuki et al., 2016).
- Do at least some planetary mass companions form by gravitational instability (Boss, 1997; Schib et al., 2021) rather than by core accretion?
- Regarding the accretion of solids: what are the respective roles of pebbles and planetesimals in the course of time, and the importance of their interactions (Alibert et al., 2018)? What is the spatial and size distribution of the planetary building blocks? Recent observations by ALMA show nonhomogenous distributions with pile-ups, rings, and gaps (Andrews et al., 2018), strongly differing from classically assumed smooth MMSN disks.

In addition, the physical properties of the solids (e.g., porosity, fragmentation velocity) at protoplanetary disk conditions are poorly known (Blum, 2018) and affect the outcome of core accretion (e.g., Venturini et al., 2020c).

- What are the expected compositions and internal structure of gaseous-rich planets? Knowing their masses, radii, and ages would put important constraints on the compositions of gaseous planets (Thorngren et al., 2016). This can then be linked to better understand their evolution and origin.
- Regarding the accretion of gas: can predictions made by one-dimensional quasi-static planetary internal structure models (Bodenheimer and Pollack 1986) really be used to predict planetary gas accretion rates? What about the dynamics of the gas (Ayliffe and Bate, 2009)? Significant uncertainties regarding the opacity in protoplanetary atmospheres (Mordasini, 2014), the composition and equation of state of the gas, the distribution of heavy elements (Müller et al., 2020a), and the thermodynamics of giant planet formation (accretion shock physics; Marleau et al., 2019) exist, which affect our ability to understand the gas accretion process.
- How important is orbital migration? Depending on the thermodynamical description of the disk, and on disk as well as protoplanet properties, orbital migration may differ strongly in both direction and speed (Kley and Nelson, 2012; Baruteau et al., 2016). This can lead to different predictions about emerging planetary system architectures (distribution of orbital periods, pile-ups, capture into mean motion resonances, etc.).

Answering these questions is challenging because the processes shown in Fig. 2.6 involve:

- A broad range in spatial scales: dust grains to giant planets (13 orders of magnitude).
- A huge dynamical range in time: from about 10^4 yrs to 100 Myrs dynamical timescales.
- Multiple input physics: gravity, hydrodynamics, radiative transport, thermodynamics, magnetic fields, high-pressure physics, etc.
- Strong nonlinear mechanisms and feedback (e.g., runaway accretion or gas−disk−planet interactions). This means that planets emerge from a highly dynamic and physical system dominated by complex and diverse coupling processes.

The conventional physics approach of conducting laboratory experiments to establish a ground truth is possible in the context of planet formation only for specific aspects (e.g., cosmochemical studies or dust growth/fragmentation experiments) and 3D radiation-magnetohydrodynamic numerical simulations including a realistic number of building blocks are still too computationally expensive. This means that we cannot build a theory on the origins of planetary systems that is based on first principles only: observational guidance is necessary.

5.3 Observational constraints

Our understanding of the origin of planetary systems is based on three classes of observations:

1. *Solar System*. Its detailed observation provides the most comprehensive view of a planetary system we can have today, including its planets but also its minor bodies (comets,

asteroids) that are messengers from the formation epoch (Le Roy et al., 2015). Cosmochemical analyses of meteorites and sample return also offer the unique possibility of dating of events during the formation epoch, like the time of the moon forming impact (Bottke et al., 2015) or Jupiter's growth timescale (Kruijer et al., 2017). Furthermore, Solar System planets are the only ones for which the interior structure (Wahl et al., 2017) and atmosphere can be characterized in great detail (Atreya et al., 1999). Last but not least, the Earth is the currently only known certainly habitable planet.

2. *Exoplanets*. There is typically only little knowledge about an individual extrasolar planet or system, but statistical studies teach us about the diversity of planets and planetary systems (Sections 3 and 4). Large surveys both from the ground (Mayor et al., 2011) and space (Borucki et al., 2011) with a well-controlled detection bias play a key role to understand the scenarios of planet formation. These new results had the consequence that old formation models tailored to the Solar System had to be abandoned. The enormous increase in statistical observational constraints regarding the frequencies of different planet types, the distribution of essential planetary properties (masses, periods, eccentricities (Udry and Santos, 2007; Gaudi et al., 2020)), and the correlations with stellar properties allows to nowadays put formation models to the statistical test. The planetary population synthesis method (Ida and Lin, 2004; Mordasini et al., 2009; Mordasini, 2018) takes advantage of this, making it possible to use the full wealth of statistical constraints that extrasolar planets provide. We showed earlier in Fig. 2.1 a composite of the mass−distance and radius−distance distribution diagrams, color-coding various detection methods. The distribution of planets in these diagrams is of similar importance as the HR diagram for stars.
3. *Protoplanetary disks, and as a recent addition, the observation of forming planets embedded in these disks*. The masses, sizes, lifetimes, and the structure of protoplanetary disks are key initial and boundary conditions that set the stage in which models of the origins of planets must function (Williams and Cieza, 2011). In parallel with the exoplanet revolution, our understanding of protoplanetary disks is also currently undergoing a revolutionary phase, thanks to the high spatial resolution and sensitivity offered by the ALMA observatory and by high-contrast imaging instruments (e.g., Sphere) that provide unprecedented disk images in reflected light and search for embedded and still-forming planets. Compared to the situation a few decades ago, where the reverse-engineered minimum mass solar nebula had to serve as the only available model for the disks, the diversity and statistical properties of protoplanets are now being observed and interpreted at a high rate (Tychoniec et al., 2018).

5.4 Synergies between Solar System and extrasolar planet formation theory

Despite all the data, planet formation theory can still not explain today the observed characteristics and origins of the diversity of planetary systems, including our own, with one coherent picture. In this context, synergies between Solar System and extrasolar planetary system studies must be used whenever possible to make progress. Important examples of synergies can be listed here:

- Adoption of initial conditions for Solar System studies that are not based only on the minimum mass solar nebula alone, but also on the observations of protoplanetary disks (Alibert et al., 2018).
- Inclusion and test of concepts originally developed to understand the origins of extrasolar planets in the context of the Solar System, and vice versa. An important example here is the "grand tack" model (Walsh et al., 2011) that builds on the special orbital migration behavior of two giant planets like Jupiter and Saturn (Masset and Snellgrove, 2001). This leads to the insight that the formation of the Solar System was likely a dynamical process during which the orbits of the planets underwent strong modifications.
- Development of interior, atmospheric, and thermodynamic characterization studies of extrasolar planets that build on ideas and methods developed to characterize Solar System planets. This includes the planetary mass–radius and mass–luminosity relation (Mordasini et al., 2012, 2017) in which typically simpler models developed for extrasolar planets can be tested with plentiful data available for Solar System planets (Linder et al., 2019).
- Development of meaningful connections between planet formation and observable atmospheric spectra (e.g., Oberg et al., 2011; Mordasini et al., 2016).

5.5 Lessons learned from planet formation theory

Early models of the formation of giant planets in the Solar System assumed a static non-integrative picture: the timescales involved in the formation of the planets were either not considered at all (Mizuno, 1980), or at least the temporal evolution of the protoplanetary disks was neglected (Bodenheimer and Pollack, 1986). Planets were also assumed to form in situ, and in isolation, independently of all other protoplanets emerging concurrently in the disk (Pollack et al., 1996). Besides this, very little information was available on the initial conditions, so reference was made to auxiliary and solar system specific concepts like the minimum mass solar nebula. This exceedingly static picture, tailored to the Solar System case, was poor in interactions and dynamical elements and could not explain the diversity that extrasolar planets were found to exhibit.

Extrasolar planets detections, as well as observations of the properties and lifetimes of planet-forming disks (Haisch et al., 2001), made it clear that a modern theory of planet formation must consider that planet formation, planet migration, N-body interactions between the protoplanets, and disk evolution all proceed on similar timescales (Venturini et al., 2020), closely mutually feeding back on each other. This means that the individual processes cannot be treated separately. This was the motivation to develop integrated global models taking into account all currently known governing processes occurring during planet formation in a simplified, but self-consistently linked way. Such global models (Ida and Lin, 2004, Alibert et al., 2005, Mordasini et al., 2012, Benz et al., 2014, Venturini et al., 2020b,c, Emsenhuber et al., 2020a) are able to predict the architecture of an emerging planetary system and the observable quantities of planets based directly on the properties of the nascent protoplanetary disk. In this way, the gap between theory and observation can be bridged.

Important lessons learned from the statistical comparison of the results of such global models with observations include the following points (Mordasini, 2018):

- A centrally condensed or spatially inhomogeneous initial distribution of solids is necessary for rapid planet growth, and to explain the numerous close-in extrasolar planets.
- N-body interactions are key drivers of the final eccentricities and inclinations.
- There is an imprint of the critical core mass for rapid gas accretion at about 30 Earth masses in the observed planetary mass function (Howard et al., 2010; Mayor et al., 2011).
- Planetesimals need to be small for rapid enough growth of giant planet cores. Alternatively, pebble accretion (Ormel and Klahr, 2010) may allow a more rapid growth at larger orbital distances (Lambrechts and Johansen, 2014).
- Orbital migration is at work as shown by planets in or near mean motion resonances, but it seems to be less efficient than predicted by migration timescale estimates for (single) planets (Dittkrist et al., 2014).
- The most important characteristics of a protoplanetary disk in determining the outcome of the formation process is its content of heavy elements. This determines the mean mass of the planets, their number in the system, and the architecture of a planetary system, particularly the distribution of planetary eccentricities (Emsenhuber et al., 2020b).

5.6 Formation and evolution of giant planets

One of the key questions that synergistic studies of Solar System and extrasolar planets will help answer over the coming decades is the formation of gas-giant planets. *In situ* measurements from the Galileo probe provided constraints on the atmospheric composition of Jupiter (Wong et al., 2004) while Cassini measurements provided constraints on Saturn (Flasar et al., 2005). On the exoplanet side, transmission spectroscopy of giant planets (Sing et al., 2016), high-dispersion spectroscopy (Snellen et al., 2010; Hoeijmakers et al., 2018), and spectra extracted from direct imaging of young giant planets (Wang et al., 2018; Greenbaum et al., 2018) can be combined with atmospheric retrieval techniques to estimate atmospheric compositions (see Fig. 2.7). These measured compositions can then be compared with planet formation models (Mordasini et al., 2016; Booth et al., 2017) and protoplanetary disc models

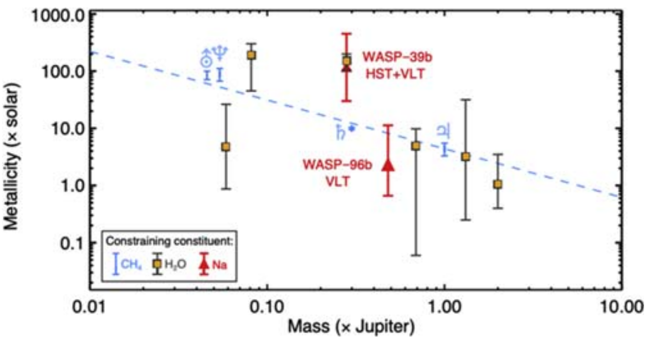

FIGURE 2.7 Mass–metallicity diagram for Solar System planets and exoplanets. Methane (CH_4) and water (H_2O) are the two absorbing constituents used to constrain the atmospheric metallicity of Solar System planets (blue bars) and hot gas-giant exoplanets (orange squares with gray error bars), respectively. Each error bar corresponds to the 1 sigma uncertainty. The blue line indicates a fit to the Solar System gas giants (pale blue symbols indicate Solar System planets). *From (Nikolov et al., 2018).*

(Oberg et al., 2011; Booth et al., 2019), providing insight into the question of the origin and formation–evolution processes of exoplanet atmospheres. However, the giant planets in the Solar System have taught us that their interiors can be much more complex than previously thought (e.g., Helled, 2018). This can affect their evolution and makes the link between observations and theory more challenging (Müller et al., 2020b).

With more detailed results on Jupiter provided by the Juno mission (particularly its oxygen abundance), the combination of JWST with targets provided by TESS increasing the number and quality of transmission spectra of hot gaseous exoplanets and more detailed observed chemical profiles of protoplanetary discs from ALMA, the next few decades should provide the Solar System and exoplanet communities with the leverage to understand the origin and evolution of giant planet atmospheres. It is still unclear, however, whether the atmospheric water abundance reflects the bulk composition, which is important to further constrain planet formation models (e.g., Helled and Lunine, 2014). This is now in particular more relevant given that giant planets are expected to have composition gradients and not be fully mixed.

5.7 Observing planet formation as it happens

Planet formation processes as well as the early temporal evolution of planets and planetary systems have not been directly observed until recently. Instead, between the epoch when planets form and the epoch when they are currently observed, there was typically a gap of several Giga-years in duration that could be bridged by theoretical models only.

In the last few years, however, this has dramatically changed. Three different observational techniques now make it possible to observe planet formation as it happens:

1. Gas kinematics (ALMA; Pinte et al., 2018; Teague et al., 2018). The presence of a protoplanet locally disturbs the Keplerian motion of the gas.
2. Dust dynamics (ALMA; e.g., Zhang et al., 2018). The presence of protoplanets leads to rings and gaps in the spatial distribution of dust and pebbles.
3. Direct imaging of accreting protoplanets in the near-infrared and in observational bands tracing accretion like H-alpha. These observations are made with sophisticated adaptive optics instruments like, for example, SPHERE or MagAO.

Fig. 2.8 shows a composite image (from A. Isella, ESO) of two accreting protoplanets around the 10 Myr-old T-Tauri star PDS 70 (Keppler et al., 2018; Wagner et al., 2018; Haffert et al., 2019). The protoplanetary disk of the star and the circumplanetary disk of PDS 70c are also visible. These observations potentially provide a whole new class of much more direct constraints on planet formation models. Instead of having to infer how planets form from the final outcome (a mature planetary system), we can now observe when, where, and which types of planets emerge in a protoplanetary disk, a constraint of paramount importance for theory. By observing disks (i.e., star forming regions) of different ages, it may even become possible to directly observe the temporal dimension in planet formation. This observation of the stages of the emergence of planetary system may make it possible to constrain the stages shown in Fig. 2.6 and to compare them with cosmochemical constraints from the Solar System. This comparison allows the temporal dating of key events that occurred during its formation.

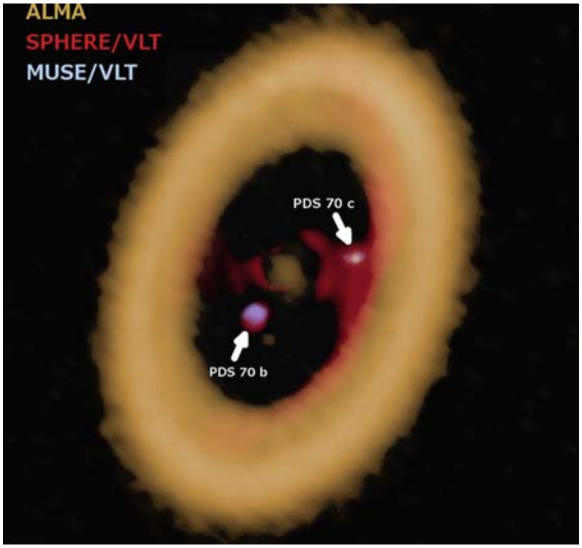

FIGURE 2.8 Composite image of the two accreting protoplanets around the 10-Myr-old T-Tauri star PDS 70 (Keppler et al., 2018; Wagner et al., 2018; Haffert et al., 2019). *From A. Isella, ESO.*

6. How do planetary systems work? (Q4)

For Solar System bodies, space missions can provide detailed in situ measurements of the properties of their atmospheres and surfaces, and even probe their interiors. However, in the case of exoplanets, beyond measurements of their bulk properties (e.g., mass and radius as displayed in Fig. 2.1) only remote measurements of their atmospheres are possible, with some indication that access to Love numbers and magnetic fields via radio emissions for hot giants is within reach (Hellard et al., 2020; Csizmadia et al., 2019; Hess and Zarka, 2011). Here the age of the system is expected to play a major role. This will be better understood once PLATO data are available. The differences in the type of measurements that can be done in Solar System planets versus exoplanets induce severe limitations on the types of coupling and evolution mechanisms that can be compared between Solar System planets and exoplanets. We analyze below three important cases in which comparisons and synergistic studies can be useful.

6.1 Role of star–planet interactions in atmospheric escape and evolution

The interaction of the star with the planetary atmospheres during the system evolution is of major importance. Solar System bodies have experienced ~5 Gyr of evolution and the majority of observed exoplanets are also billions of years old (McDonald et al., 2019). The stellar output can cause atmospheric escape, sculpt the magnetospheres of planets and their moons, as well as control the interaction between the stellar wind and interstellar medium.

Atmospheric escape is believed to play an important role in sculpting the composition of terrestrial planets in our Solar System (Lammer et al., 2008). As typical detected exoplanets are statistically located much closer to their host stars, experiencing fluxes at least 10 and in many cases 1000 times larger than Solar System planets, they provide a unique opportunity to study atmospheric escape under extreme environments (e.g., García Muñoz et al., 2020). Current observations of atmospheric escape in exoplanets are limited to a handful of nearby systems in Ly a or He I (Vidal-Madjar et al., 2003; Ehrenreich et al., 2015; Spake et al., 2018). However, theoretical models have predicted that atmospheric escape should be an important process in sculpting the hydrogen/helium dominated atmospheres of close-in exoplanets (Lammer et al., 2003), causing many to completely lose large primordial hydrogen/helium atmospheres, which could have constituted several 10% of the planet's mass over their lifetimes (Owen and Wu, 2013; Jin and Mordasini, 2018). This loss process results in a bimodal distribution for close-in exoplanetary radii, which has recently been observationally confirmed (Fulton et al., 2017).

Heliospheric research and studies of atmospheres and magnetospheres of Solar System planets provide information for the models of exoplanet–star interactions that are used to interpret optical data. For example, Bourrier and Lecavelier des Etangs (2013) describe how interactions between very close exoplanets and their parent stars can impact the shape of the Ly alpha spectrum observed. Kislyakova et al. (2014), working in a similar manner, also infer the magnetic moment of exoplanets from the shape of the Ly alpha wings during transit phenomena. Details of the Ly alpha detection can be used to infer the velocity distribution of hydrogen atoms in the exosphere of transiting planet. Heliophysics processes such as radiation pressure, energetic neutral atom generation, photo- and electron-impact ionization, solar wind interactions with atmospheres and magnetospheres, etc., may guide the design of coarse models of exoplanet interactions with their parent stars. Atmospheric escape from highly irradiated exoplanets has been studied in detail until now only for hydrogen-dominated atmospheres. This needs to be linked to atmospheric escape models of heavy-element dominated secondary atmospheres, like those of Earth, Mars, and Venus, to understand how exoplanet atmospheres evolve in time. This is particularly important in the context of the search for habitable worlds, as we need to know what type of planets around what type of stars can retain habitable atmospheres (Owen, 2019).

6.2 Prospects for the detection of exomagnetospheres via their radio emissions

Six Solar System planets are permanently magnetized, in addition to Jupiter's moon Ganymede. Magnetospheres create a region of space around the magnetized planet that displays properties differing from the environment of the star. For example, at Jupiter, the magnetospheric plasma is much hotter than the solar wind plasma that flows outside the magnetosphere. Magnetospheres can trap energetic particles and these, in turn, can produce electromagnetic emissions. Relativistic electrons trapped in Jupiter's magnetosphere produce intense synchrotron emissions that can be detected from large distances (Bolton et al., 2001, and references therein). In addition, charged particles accelerated along magnetic field lines generate strong auroral emissions via the Cyclotron-Maser Instability (CMI) mechanism, which has been well documented in the Earth and more recently the Jupiter case (Zarka, 1998; Louarn et al., 2017; Louis et al., 2019). This has led to the suggestion that similar magnetospheres could be detected in exoplanetary systems (Zarka et al., 2001; Zarka, 2007, 2018) using radio telescopes, particularly for close-in exoplanets producing much larger radio power (see Fig. 2.9). While tentative detections have recently been reported for GJ 1151 (Vedantham et al., 2020), Tau Boo b (Turner et al., 2021), and Proxima Centauri (Pérez-Torres et al., 2021), there are not yet robust detections. The Square Kilometer Array will significantly increase our capability to detect these emissions, thus providing an opportunity for comparative studies between Solar System magnetospheres and exoplanetary ones over the coming decades.

6.3 Role of resonances, tidal heating, and magnetospheric particle irradiation: the example of Galilean satellites

Three of Jupiter's Galilean moons, Io, Europa, and Ganymede, are locked in a 4:2:1 orbital resonance called the Laplace resonance. Tidal heating of their interiors, maintained by this resonance, makes these bodies different from most of the colder, ice-rock moons typically found in the outer Solar System. It furthermore drives the spectacular volcanic activity of Io and may play a role in the maintenance of the subsurface oceans of Europa and Ganymede. These two moons are the main targets of the Europa Clipper (NASA) and JUICE (ESA) missions to the Jupiter system, currently planned for launch in 2024 and 2023, respectively. Their surfaces contain still unidentified non-ice materials, which may be salts, hydrated acids, or

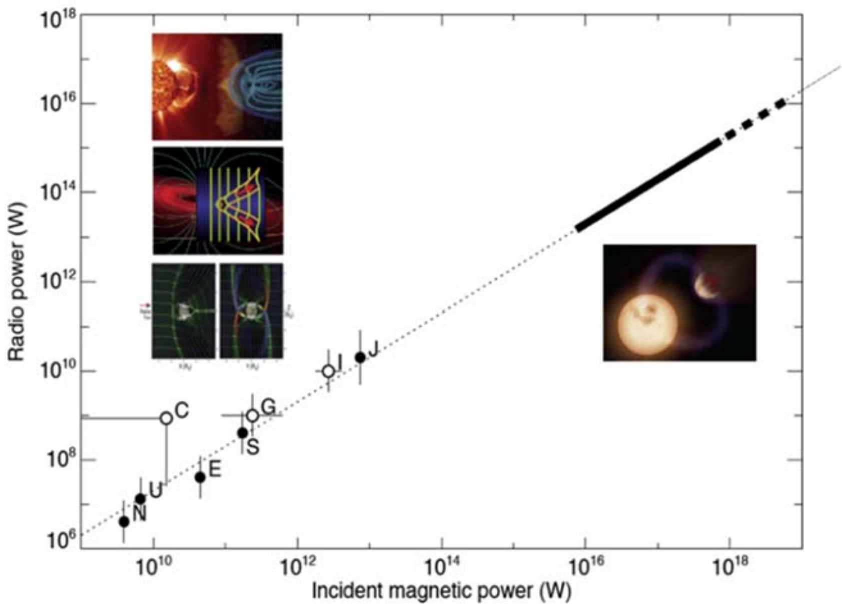

FIGURE 2.9 Scaling law relating magnetospheric (Earth, Jupiter, Saturn, Uranus, and Neptune) and satellite induced (Io, Ganymede, Callisto) average radio power to incident Poynting flux of the plasma flow on the obstacle. Dashed line has slope 1, emphasizing the proportionality between ordinates and abscissae, with a coefficient $\sim 2 \times 10^{-3}$. Note that planetary radio bursts can reach 10× (resp. 100×) the average value ∼10% (resp. ∼1%) of the time. The thick bar extrapolates to hot Jupiters the magnetospheric interaction (solid) and satellite−planet electrodynamic interactions (dashed). *From (Zarka et al., 2015).*

other compounds. Carlson et al. (2009) have documented some of these compounds believed to exist on Europa's surface, and this list was expanded by Ligier et al. (2016 and 2019) who also analyzed ground-based data.

At the present time, the Juno spacecraft is in Jupiter orbit. It can complement ground-based observations in that it can view the satellite poles. Juno has already made advances in surface composition (e.g., Tosi et al., 2020; Mura et al., 2020).

While Europa and Ganymede may have the ingredients for life in their subsurface oceans, their surfaces are inhospitable because of their cold surface temperatures and of the presence of magnetospheric radiation, greater than hundred-of-keV ions and electrons trapped in the Jovian magnetosphere. These particles can alter the surface constituents down to at least 1 meter in the regolith (Paranicas et al., 2009) and over time cause enough ionization to destroy large molecules. Nordheim et al. (2017) have discussed the effects of magnetospheric radiation on the preservation of surface biosignatures at Europa. Schenk et al. (2011) gave some of the earliest illustrations connecting magnetospheric radiation to optical changes on satellite surfaces. Howett et al. (2011) proposed that electron radiation was making ice more compact, based on alterations to the surfaces of the Saturnian satellites observed in their thermal infrared spectrum. On the other hand, irradiation of ices by magnetospheric particles also creates oxidants by radiolysis. These oxidants, if they are transported to the ocean, for instance, by subduction of the ice sheet as proposed by Kattenhorn and Prockter (2014), can contribute to supporting life by supplying chemical (redox) energy.

This example taken from the Galilean moons illustrates the importance of mechanisms like resonances, tidal interaction, and particle irradiation, in determining the surface properties of planets and their moons and even their habitability. Such an example should be kept in mind in the modeling of exoplanet surfaces and the search for biosignatures. In addition, an improved understanding of the moons could be used to further constrain giant planet formation models. The ESA Voyage 2050 program recently suggested a mission to the moons of the giant planets for a future L-class mission. This mission will help with improved knowledge on the Solar System moons, providing further constraints for exoplanet modeling.

7. Do planetary systems host potential habitats? (Q6)

To properly address the potential habitability of a rocky planet, or of the possible emergence of life in its environment, an interdisciplinary approach connecting astrophysical, geophysical, geological, biochemical, and atmospheric sciences perspectives is mandatory, as illustrated by efforts to address the histories of climate and biology on the Earth.

7.1 Environmental conditions on early Earth

We do not yet understand how, when, and where exactly life started on the Earth, but several constraints are available from both the geological record and biochemical studies. Earth's surface (and similarly those of Mars and possibly Venus) changed substantially over time. Critically, the environmental conditions of the early Earth were very different from those reigning at the surface today (Westall et al., 2018; Stueken et al., 2020). Study of the most ancient terrains preserved, as well as modeling, has shown that the early Earth was an anaerobic environment and that, at least at the rock−water interface that was critical for the prebiotic reactions leading to the emergence of life, it was hot. The higher heat flow from a hotter mantle ensured a high degree of volcanic activity and associated hydrothermal activity. This is documented by the abundance of Fe and Mg-rich volcanic rocks, including komatiitic rock types that formed only at the very high temperatures of the early Earth (Arndt, 1994), as well as by the abundant evidence of a global hydrothermal geochemical signature in the early seawater (Hofmann and Harris, 2008; Westall et al., 2018).

7.2 Origin of the organic building blocks

The conditions that are often cited as habitable conditions for life as we know it include the existence of liquid water, the chemical constituents of life (the CHNOPS elements needed to provide the nutrients of life), and energy. The majority of the organic building blocks is believed to be of extraterrestrial origin, having been delivered by volatile-containing rocky and icy materials, such as carbonaceous chondrites and micrometeorites originating from asteroids and comets formed in the outer regions of the Solar System (Maurette, 2006; Alexander et al., 2018; Gourier et al., 2019). Recent analyses of the D/H ratio in different comets, including the Rosetta mission to comet 67P-Churyomov-Gerasimenko, have shown that their compositions are so varied that, while some have D/H ratios similar to Earth, others, like 67P, don't (Meech, 2017; Altwegg et al., 2017). Moreover, despite the truncated mission possibilities for in situ analysis, a wide variety of organic molecules were detected (Grady et al., 2018). It has also been experimentally shown that small icy particles influenced by environmental conditions in space, such as ultraviolet radiation, are a favorable context for the formation of organic molecules, including a suite of sugars such as ribose and related species (Meinert et al., 2016) and, indeed, many of the organic constituents of IDPs (interplanetary dust particles) are presumed to be of presolar origin (Merouane et al., 2012), i.e., formed in the parent molecular cloud of the Solar System. What is also known is the huge variety of organic molecules, more than 10,000 (Schmitt-Kopplin et al., 2010) found in carbonaceous chondrites such as Murchison. However, of this huge variety of molecules, it must be noted that only a restricted quantity is indeed used by life, which somehow points to the idea that some mechanism of molecular selection must be present in the process of the transition from the inert to the living. Only recently have direct traces of these extraterrestrial molecules been documented in terrestrial sediments (Gourier et al., 2019).

Endogenous sources of organic molecules were also available on the early Earth. The formation of such molecules in an early reducing atmosphere à la Stanley Miller (1953) may also have played a role, depending on the mostly unconstrained composition of early Earth's atmosphere (Zahnle et al., 2010). Another source of molecules could have been the upper crust where interactions between circulating hydrothermal fluids and highly mafic/ultramafic rocks produce small organics, such as ketones, CH_4, as well as H_2, all essential ingredients for prebiotic chemistry that are produced by Fischer−Tropsch-type synthesis or from fluid inclusions in ultramafic rocks (Shock et al., 2002; McDermott et al., 2015) or even from recycled meteoritic carbon.

7.3 The role of the interplay between surface and atmospheric environment and chemistry

All of these ingredients cohabited in an early Earth environment that would be classified as "extreme" with respect to the modern environment. They needed to be concentrated on a microscopic scale under conditions in which gradients in temperature, pH, cation concentrations, etc., could drive the prebiotic reactions, catalyzed by reactive mineral surfaces. Rocks and minerals played a fundamental role there. Many of the hypotheses concerning the emergence of life highlight the importance of hydrothermal environments as loci where the combinations of physicochemical factors would have been conducive to prebiotic reactions (Westall et al., 2018; Damer and Deamer, 2020). These environmental conditions were likely common on rocky planets during the early history of the Solar System and could be common on rocky exoplanets offering similar chemical and thermal conditions at their surface. In this perspective, it is possible that biology, viewed as a natural evolution from chemistry, would also be "natural" on any extraterrestrial body offering similar environmental conditions, chemical element, and organic sources as early Earth.

7.4 Atmospheric conditions for the emergence of macroscopic life

While the most elementary forms of life emerged in an anaerobic environment, for human and animal life, or in general for macroscopic life to emerge, oxygen plays a major role as it allows for higher metabolic energy levels and greater diversity in cellular function. But Earth did not always have the same oxygen levels as it has today, and rose in two major steps, each of which increased atmospheric oxygen concentrations by at least an order of magnitude. The last major rise of oxygen concentration about 550 million years ago is linked to the so-called Cambrian explosion, when a huge variety of plant and animal species appeared on the Earth. The first great oxygenation of the atmosphere occurred much earlier, around 2.5 Gyr ago, and has been ascribed to photosynthetic bacteria. However, oxygen was likely produced even earlier but taken up by geochemical reactions at the surface (Lyons et al., 2014). Reactions with fresh basaltic crust may have reduced the atmosphere before the great oxygenation event by releasing hydrogen and methane into the atmosphere (Smit and Mezger, 2017). Plate tectonics may further have influenced the outgassing abundances of different gas species (Mikhail and Sverjensky, 2014). Changing degassing pressures (from submarine to subaerial volcanism) likely also played a role in shaping Earth's atmosphere, linking geophysical processes such as plate tectonics and subduction of ocean water into the mantle with atmosphere evolution (Gaillard et al., 2011). It is yet unclear how reduced or oxidized early Earth's atmosphere actually was (Zahnle et al., 2010), but the implications for prebiotic chemistry are quite clear.

Miller and Urey (1959) already showed that several amino acids—preingredients for life—are more likely to form under reducing conditions, i.e., in atmospheres made of H_2O, CH_4, NH_3, and H_2 rather than of oxidized gas mixtures such as CO_2, O_2, H_2O, and SO_2. Also, the amount of atmospheric nitrogen present likely affected amino acid formation. Gebauer et al. (2020) suggested <420 mb N_2 on early Earth around the time life evolved based on model studies and proxy data. How early Earth evolved from its initial, early hot state is an important focus. Katyal et al. (2020) discussed the influence of the Earth's mantle redox state upon the evolution from the hot magma ocean phase into subsequent habitable conditions. The relationship between the redox state of the surface environment and the gases produced by biology is central to understanding the history of life's complexity. It is therefore also a critical factor to assess for rocky exoplanets.

The atmosphere of a rocky planet is constantly influenced by a) outgassing from the interior via volcanic activity, b) chemical reactions at the crustal layer (e.g., with water), c) weathering cycles at the surface, d) rock formation (e.g., carbonates), e) photodissociation processes in the atmosphere, f) atmospheric erosion to space, and last but not least g) interaction with the biosphere, in particular burial of by-products from the biosphere.

Several of these processes can only be investigated in a very limited way for Solar System planets, since our window into the past is very small, allowing us mostly only indirect probing of the earliest evolution of the Earth, Mars, and Venus. It is still strongly debated, for example, if Venus was ever "Earthlike" at its surface, hence able to have a liquid water ocean with moderate temperatures instead of the hellish climate of today. Mars and Venus both have a CO_2-dominated atmosphere instead of Earth's N_2 and O_2 dominated atmosphere, but this may have been very different in the past. Noble gases in their atmospheres can only give us a clue about their evolution (Lammer et al., 2018). Here atmosphere characterization studies of young exoplanet systems could revolutionize our understanding of atmosphere evolution, especially when observing several exoplanets in the same system but with varying properties (e.g., planet mass, effective surface temperature, volatile content), and shed a better light on the likely evolution of the planets in our own Solar System, especially the potential of a rocky planet to form and harbor life as we know it. Grenfell et al. (2020) reviewed how knowledge of atmospheric evolution from the Solar System could be applied to estimate the atmospheric diversity of rocky exoplanets. Exoplanet modeling studies (e.g., Gebauer et al., 2021) take early Earth parameters (such as atmospheric oxygen evolution) as an example and study how their atmospheric signals would evolve for analogous planets orbiting other stars.

7.5 Summary

Synergies between Earth sciences, Solar System, and exoplanet studies should play a major role to help us better understand the conditions controlling a rocky planet's habitability and the role of its environment in the possible emergence of life, and these synergies work both ways. Lessons from our still limited knowledge of the conditions of emergence and development of life along the history of Earth are essential to help us better formulate the conditions for a planet's habitability. Conversely, progress ongoing and to come in the characterization of rocky planets atmospheres at different ages of their evolution will provide a very important reference to retrieve the unknown history of the evolution of rocky planets atmospheres in our Solar System.

8. Strategies to search for life on exoplanets with future large space telescopes (Q6)

The prior section demonstrates the large number of processes that interact on habitable and inhabited rocky planets. This leads to a desire for detailed information on as many of those planets as possible. Some of this information will come from observations, which could determine orbital properties, atmospheric chemical composition, presence/absence of surface oceans, stellar inputs, and some surface properties. Additional information will be model derived, on the subsurface of these worlds, the gas fluxes from any biosphere that is present, and details on its atmospheric dynamics. The observations themselves are demanding as they require detailed observations of dim planets that are in close proximity to much brighter stars. And the most diagnostic information requires these already-difficult observations to collect enough photons to divide them in spatial and/or temporal bins. The difficulty of this endeavor is why such observations have not yet been made. But years of technology development have placed us on the cusp of these kinds of observations. As a result, the coming decades could bring major advances in our understanding of rocky worlds from two complementary approaches: ground-based and space-based telescopes.

8.1 Searching for habitable conditions and biosignatures from the ground

Extremely Large Telescopes, including the European Extremely Large Telescope (ELT), the US-led Thirty Meter Telescope (TMT), and the Giant Magellan Telescope (GMT), will potentially have the capabilities to search for biosignatures on a relatively limited number of targets. Although the photon collection rate of a telescope of diameter D goes as D^2, the primary advantages of the ELTs are their extremely small diffraction limits ($\sim\frac{\lambda}{D}\sim\frac{1}{30}\frac{\mu m}{m}\sim 0.01$ mas), which, if they can be achieved, provide an advantage of D^4 for background-limited sources.

Whether or not ELTs can achieve their diffraction limit via Adaptive Optics (AO), particularly for wavelengths less than ~1 μm, is not clear. However, if they can reach these goals, they will certainly be powerful machines for a variety of astrophysics studies. In particular, it has been suggested that ELTs could:

- For some select targets, e.g., LHS 1140b, model studies suggest that atmospheric CH_4 could be detected with 20–100 ELT observation hours assuming an Earthlike biomass and low haze loadings (Wunderlich et al., 2020).
- Potentially be sensitive to the thermal emission at ~10 μm from terrestrial planets in the habitable zones of their parent stars, for a handful of systems (Quanz et al., 2015; Bowens et al., 2021).
- Detect and characterize terrestrial planets directly in the habitable zones of the nearest M stars, assuming AO can be achieved with these ELTs thanks to the combination of their exquisite angular resolution and knowing that the contrast ratio between the planets and their host stars is likely accessible to ground-based facilities (NAS Exoplanet Science Strategy).
- Combine high-dispersion spectroscopy and high-contrast imaging to probe the atmospheres of rocky planets orbiting nearby stars, e.g., for the detection of the signature of O_2 in planetary atmospheres (Snellen et al., 2013, 2015; Kasper et al., 2021), a technique whose feasibility could be tested on the VLT with the proposed RISTRETTO instrument (Lovis et al., 2017; Chazelas et al., 2020).

8.2 Searching for habitable conditions and biosignatures in space

There exist two primary groups of target stars that can be searched for life on potentially habitable exoplanets from space. These two groups are delineated primarily by the luminosity of the host stars. The location of the traditional habitable zones of main-sequence stars, i.e., the range of distances from the star where liquid water can be stable on the surface of a rocky planet with the requisite atmosphere, scales as $a_{HZ} \propto L_{*,bol}^{1/2}$. Since $L_{*,bol}^{1/2}$ varies dramatically (by over three orders of magnitude) from the bottom of the main sequence to stars slightly more massive than the Sun,[1] two dramatically different methods are currently used to detect and characterize these two groups of planets, their dividing line residing very roughly between the K and M spectral types.

As described below, surveying for and characterizing potentially habitable planets around low-mass stars typically requires the transit method, and thus such surveys are often referred to as searching for "small black shadows." This may change in future with space interferometers in the mid-infrared range which allow imaging rocky planets also around M dwarf stars. Surveys using the direct imaging method for surveying and characterizing Earthlike planets around Sun-like stars are often referred to as searching for "pale blue dots," a term coined by Carl Sagan based on the famous picture of the Earth taken by the Voyager 1 spacecraft when it was roughly 40 AU from Earth on Valentine's day, 1990 (see Fig. 2.10).

8.2.1 UV/optical/near-IR spectra versus thermal infrared

There are essentially two wavelength ranges within which one can characterize the atmospheres of terrestrial planets and thus determine whether or not they are potentially habitable and search for biosignatures: the UV/Optical/near-infrared, or the thermal emission around 10 μm. For direct imaging surveys ("pale blue dots") in the former wavelength range, one probes the reflected light emission of the planet, which has been filtered through the atmosphere of the planet twice. The latter wavelength range is used to probe the thermal emission from the planet which, given the range of temperatures where liquid water is stable at the surface of such a planet, peaks for a blackbody at ∼10 μm. For transit surveys ("small black shadows") the former wavelength range is where one searches for the imprint of the constituents of planet's atmosphere as starlight emission is filtered through the planet's atmosphere during the transit. The latter wavelength range covers, by definition, the thermal emission peak of a potentially habitable planet, and thus also peaks at ∼10 μm. This regime is best probed by secondary eclipse spectroscopy, where one measures the drop in flux as the planet

[1] Note that main sequence stars considerably hotter than spectral type A, and sometimes even stars hotter than late F, are often not considered when planning surveys to search for potentially habitable planets. This is largely because these stars are rare, have relatively short lifetimes, are hot, and/or are rapidly rotating. In the case of direct imaging, the contrast ratio between a planet in the habitable zone and the host star also increases with increasing host luminosity. All of these features generally make it quite difficult to detect small, terrestrial planets in the habitable zones of these stars using a variety of methods. There are often concerns that their lifetimes are too short to allow for the development of life. Large, space-based direct imaging surveys have some sensitivity to nearby early F and even late A stars, and some such stars often appear on these survey target lists. However, they are typically underrepresented simply because they are rarer and more distant, making the angular separation of their habitable zones from their host stars smaller on average, and therefore more likely to be within the inner working angle of the telescope.

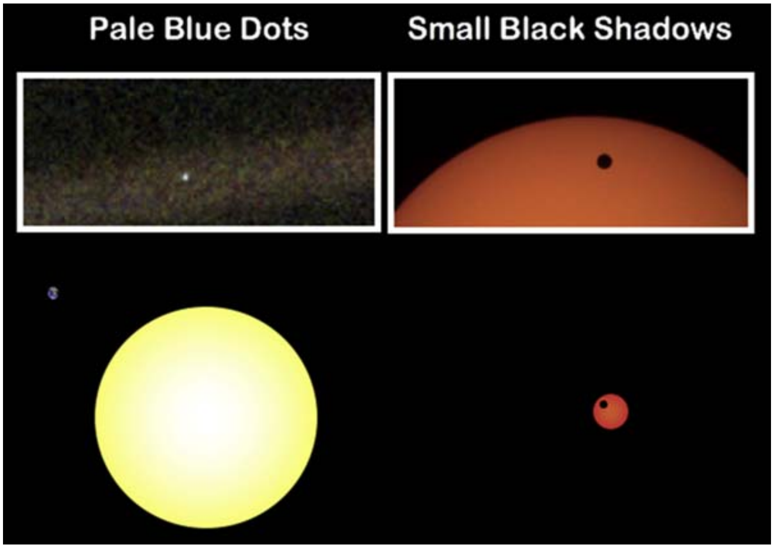

FIGURE 2.10 The two fundamental ways of searching for and characterizing potentially habitable planets, as delineated by the mass and thus bolometric luminosity of their host stars, which dictate the location of their habitable zones and thus the methods that are best suited to these endeavors. In particular, habitable planets around Sun-like stars are more suited to the direct imaging method, whereas planets orbiting low-mass stars are best suited to the transit method, although future IR-interferometers from space, such as LIFE, would allow to image rocky planets in these systems in large numbers. *Credit: NASA/Scott Gaudi.*

passes behind the star. By measuring this drop in flux as a function of wavelength, one essentially measures the planetary emission spectrum, which varies as a function of wavelength due to the varying opacity of the planetary atmosphere with wavelength.

8.2.2 "Small black shadows"

Terrestrial planets in the habitable zones of M stars are most easily discovered with the transit technique, which is highly biased toward such planets because their transit probability is higher, the transit depths are deeper (at fixed planet size), and the duty cycle is larger. Furthermore, these planets are also more easily confirmed with radial velocities. Indeed, the MEarth (Charbonneau et al., 2009) and TRAPPIST/SPECULOOS (Delrez et al., 2018) surveys were designed to find potentially habitable planets around stars at the bottom of the main sequence and have, to date, discovered two systems hosting potential habitable planets (Dittman et al., 2017; Gillon et al., 2017; Luger et al., 2017). NASA's TESS survey is also sensitive to potentially transiting planets around very low-mass stars (Sullivan et al., 2015) and indeed has already discovered one habitable zone Earth-sized planet (Gilbert et al., 2020). One of the most powerful aspects of this technique is that the targets are known *in advance*.

Transiting terrestrial temperate planets orbiting M dwarfs can be spectrally characterized by the James Webb Space Telescope (e.g., Cowan et al., 2015; Rauer et al., 2011; Wunderlich et al., 2020). However, it will be difficult to uniquely identify biosignatures except for

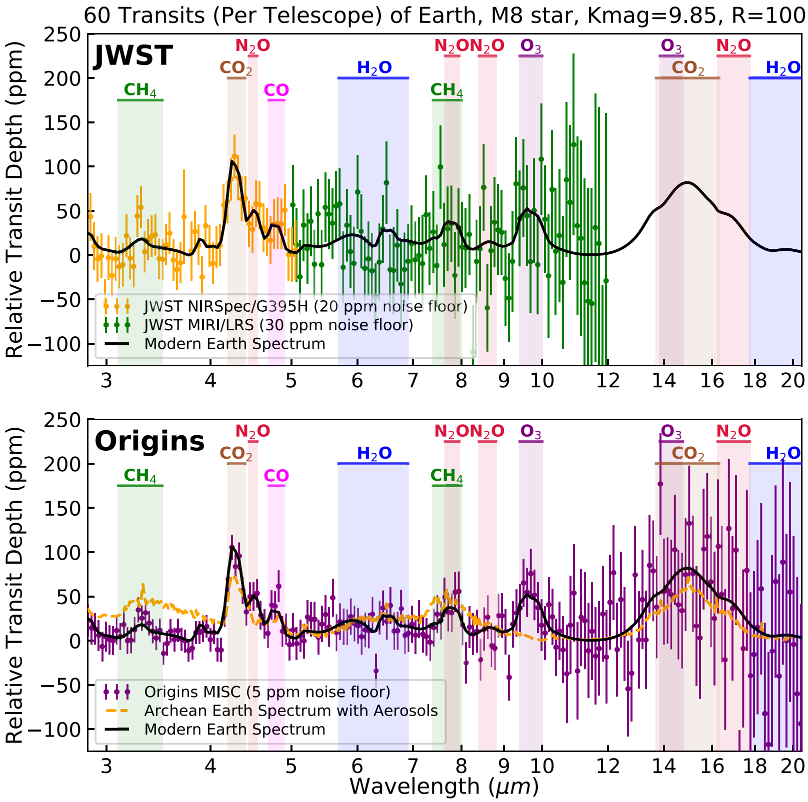

FIGURE 2.11 Transit spectroscopy of the atmosphere of an Earth-radius planet with a modern-day Earth spectrum transiting a planet in the habitable zone of a K 1/4 9.85 M8 star. (Top panel) The expected signal based on 60 stacked transits using JWST. (Bottom panel) The expected signal based on 60 stacked transits using the Origins Space Telescope. Note the longer wavelength coverage of Origins as well as the higher overall signal-to-noise ratio (resulting from the lower systematic noise floor assumed for Origins relative to JWST). Due to its longer wavelength coverage and assumed smaller systematic error floor, Origins will be able to constrain a much larger range of species than JWST and can easily distinguish the spectrum of a modern-day Earth from that of an Archean Earth. *Credit. T. Kataria (JPL).*

exceptionally favorable cases. On the other hand, the *Origins Space Telescope*, one of four large strategic missions being studied by NASA in consideration for the National Academy of Sciences Astro2020 Decadal survey, may be able to identify biosignatures on such systems (see Fig. 2.11). We discuss *Origins*, as well as additional large strategic mission concepts, *HabEx and LUVOIR as well as LIFE*, further below.

8.2.3 "Pale blue dots"

Terrestrial planets in the habitable zones of FGK stars are difficult to discover with the transit method (or the RV method) because of their weak signals and long periods. Rather, these planets are easiest to discover and characterize using direct imaging with large, space-based telescopes, once such telescopes become available. The challenge here is not easy: the reflected light signal of an Earth-sized planet orbiting a solar type star is one part in 10 billion, and the planet is located only ~0.1 arcseconds away for a system at ~10 pc. To illustrate by an analogy, this is akin to trying to detect a firefly roughly 5 feet from an industrial searchlight, at the distance between Los Angeles and New York.[2] Similar challenges occur using the mid-IR range with space interferometers.

Detecting such signals, let alone obtaining a spectrum to look for habitability conditions and even biosignatures, would seem to be impossible. Yet, as we will discuss, technologies have advanced to the point that this goal is likely achievable in the next decade. Indeed, two (LUVOIR and HabEx) of the four large strategic missions that were studied by NASA were designed to be able to detect and characterize Earthlike planets orbiting nearby Sun-like stars in reflected light. And a third (*Origins*) would attempt such characterization via transit spectroscopy. Fig. 2.12 shows the simulated spectrum obtained with a 4m HabEx-like telescope using a technique to suppress the light from its host star by more

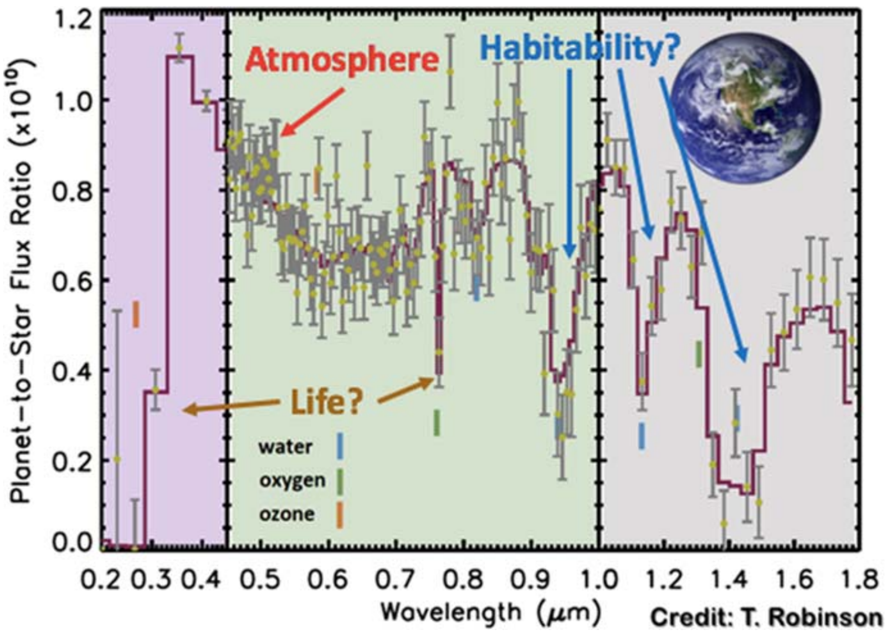

FIGURE 2.12 The reflected light spectrum of a terrestrial planet with an atmosphere identical that of modern-day Earth from the near-UV to the near-infrared (0.2−1.8 μm). The data points with uncertainties are derived assuming the spectrum was taken with a 4 m telescope of an exo-Earth around Beta CVn (Chara), a G0V star at 8.4 pc, assuming 370 h of observations. This yields a signal-to-noise ratio of 10 at 0.55 μm at a spectral resolution of R = 140 in the optical. Signatures of Rayleigh scattering, and absorption by O_2, O_3, CO_2, and H_2O, are readily detectable. *Credit: T. Robinson (NAU).*

[2] This analogy is faulty, however, as a firefly is roughly 1000 times brighter compared to an industrial searchlight than the Earth is compared to the Sun.

than 10 billion at an angular distance of roughly 0.1 arcseconds. The simulated spectrum is that of a modern-day Earth at quadrature around the nearby star beta CVn with 370 h of exposure at 1 zodi.

It is also possible to detect and characterize Earthlike planets orbiting Sun-like stars in the thermal infrared. This would provide critical information on the planet complementary to information that can be obtained in the UV−Visible portion of the spectrum. Thus, it would be ideal if we ultimately have missions that cover both of these wavelength regimes. For terrestrial planets in the habitable zone, this emission always peaks at ∼10 μm. The advantage of working at these wavelengths is that the contrast ratio between the planet and its host star is considerably more favorable than using the reflected light (less than $\sim 10^{-6}$ vs. 10^{-10}). The challenge is that the thermal emission from the sky is exceptionally bright from the ground. For space observations, given the diffraction limit of $\sim\lambda/D$, resolving a planet separated by 0.1 arcseconds from its host star requires either a filled aperture of >25 m, or separate telescopes working together as an interferometer with a separation of ∼25 m. Despite the technological challenge, mission concepts that would meet these requirements and detect the thermal emission of Earthlike planets in the habitable zones of Sun-like stars have been formulated. In particular, a mission concept for a mid-infrared nulling interferometer in space has been submitted to ESA's Voyages 2050 call (Quanz et al., 2015, 2019, 2021).

8.3 Planning for the future

At the beginning of every decade since 1970, the US astronomy community has completed a Decadal Survey, which is a survey administered by the National Academies of Sciences, Engineering, and Medicine, for the purposes of informing NASA, NSF, and DOE of the US astronomy and astrophysics communities' priorities for the next decade. The survey itself is drafted by a relatively small "steering" panel of experts in these communities, who, via input from the broader community, consider a balanced portfolio of priorities for these three national agencies that (hopefully) fits within their fiscal budget. The Astro 2010 decadal survey prioritized the Wide Field Infrared Survey Telescope (WFIRST)[3] as its top-ranked space mission. The national agencies take these recommended priorities quite seriously, and indeed the WFIRST mission is now in Phase B of its development. Of course, the worldwide astronomical community is encouraged to play a role in this process, for example, by submitting white papers for concepts or ideas to the Decadal Survey steering panel committee. This is in line with NASA's long-standing tradition of collaborating with foreign agencies to realize these ambitious space missions.

In preparation for the 2020 Decadal Survey, in early 2016, NASA initiated four large mission concept studies. These four mission concepts are currently named the Origins Space Telescope (*Origins*),[4] the Large UVOIR Surveyor (LUVOIR),[5] Lynx,[6] and the Habitable

[3] Since renamed the Nancy Grace Roman Space Telescope.

[4] https://asd.gsfc.nasa.gov/firs/.

[5] https://asd.gsfc.nasa.gov/luvoir/.

[6] https://wwwastro.msfc.nasa.gov/lynx/.

Exoplanet Observatory (HabEx),[7] respectively. Each study was assigned to a NASA center, and Science and Technology Definition Teams (STDTs) were assembled, each with two co-community chairs. The ultimate succinct goal of these STDTs was to issue a final report that includes a science case with proposed science objectives, a strawman payload, a design reference mission, and a technology development plan required to enable a new mission start. The final reports were submitted in 2019, and the recommendations from the 2020 Decadal Survey were released were in the second half of 2021. The final reports can be found on the websites referenced above.

These study teams, drawn from the broad scientific community and NASA, worked for over 4 years alongside partners in industry and representatives of the international science community. Each team has spent many thousands of person-hours and millions of dollars to create the scientific and technological visions for their missions. As a result, these concepts have reached a level of detailed and rigorous design that is rarely seen for NASA missions at this early stage.

Three of these studies, *Origins*, HabEx, and LUVOIR, would be capable of identifying potentially habitable worlds and looking for biosignatures, e.g., evidence of life.

- The nominal architecture of *Origins* is a telescope with a 5.9 m diameter primary mirror that would be cooled to ~4.5 K. It would be diffraction limited at 30 μm, would have an orbit at L2, and have a lifetime of 10 years. The wavelength range would cover 2.88–588 μm and it would employ three different instruments, with a combination of imaging, low- and high-resolution spectroscopy and spectropolarimetry. *Origins* would look for habitable conditions around terrestrial planets transiting in the habitable zones of low-mass stars ("small black shadows"). The Origins Space Telescope has a predicted yield of roughly 10 Earth analogs for which it could potentially detect signatures of habitability and life.
- The preferred architecture of HabEx is a 4 m monolithic f/2.5 primary, with an off-axis secondary. It would employ two starlight suppression techniques, a coronagraph and a star-shade, each with their own separate devoted instruments. The coronagraphic instrument would operate in the visible and near-IR (0.3–1.8 μm), whereas the star-shade would have a full wavelength range of 0.2–1.8 μm, with the shorter and longer wavelength ranges requiring moving the star-shade. The star-shade would be a separate spacecraft of 52 m in diameter flying in formation with the primary telescope at a distance of roughly 75,000 km. It would suppress the starlight from the target stars by preventing it from ever entering the telescope aperture. HabEx would have a 5-year lifetime, with expendables allowing for a 10-year extended mission. The predicted yield of HabEx is also roughly 10 Earth analogs for which it could potentially detect signatures of habitability and life.
- LUVOIR has two architectures: LUVOIR A, which is a 15 m, segmented, on-axis telescope, and LUVOIR B, which is an 8 m, off-axis segmented telescope. Both architectures would cover the FUV to NIR bandpass (0.1–2.5 μm), and would carry four separate instruments, one of which would be a high-performance coronagraph. LUVOIR would

[7] https://www.jpl.nasa.gov/habex/.

not employ a star-shade. The anticipated yield of LUVOIR is considerably higher than Origins or HabEx.

Both HabEx and LUVOIR are capable of directly detecting and obtaining spectra of Earth analogs, and thereby searching for signs of habitability and perhaps even biosignatures. The primary difference between these two missions with respect to these goals is a question of scope. Acknowledging that the constraints that must be considered by the Astro2020 Decadal Survey, as well as by the larger astronomical community, may be difficult to anticipate or may change over time, the HabEx and LUVOIR studies together present 11 different architectures. All architectures can directly image and characterize exoplanets, although not true Earth analogs for the smallest apertures considered by HabEx.

The LUVOIR concepts will yield a relatively large sample of ExoEarth candidates, enabling a high-confidence constraint on the frequency of potentially habitable worlds with biosignatures, even in the event of a null result. HabEx, on the other hand, will have a smaller sample size, but is designed to nevertheless have a very low probability (<1.4%) of not being able to characterize any potentially habitable worlds.

The European community has expressed great interest in contributing to all of these mission concepts, in particular LUVOIR and HabEx (Snellen et al., 2019).

As mentioned previously, there is also considerable interest by the European community in developing a mission concept for characterizing Earthlike planets via thermal emission using a mid-infrared interferometer (Quanz et al., 2015, 2019). The LIFE[8] initiative is studying the scientific potential and technological challenges of a formation-flying nulling interferometer in space to characterize the atmospheres of dozens of warm, terrestrial extrasolar planets. Such a mission concept would allow to separate the light emitted by the planet from that of its host star by interferometry – a concept that could be applied even for close-in orbiting planets such as Proxima Centauri b (Defrère et al., 2018).[8]

The mission lifetime of LIFE is currently expected to be 5–6 years, split into a search phase (∼2.5 years) and a characterization phase (∼2.5–3.5 year). The current concept of the LIFE interferometer consists of an array of four collector spacecrafts and a fifth beam combiner spacecraft. It is currently planned to cover at least the wavelength range between ∼4 and 18.5 μm with a minimum spectral resolution of R ∼35–50, featuring, for example, absorption bands of key molecules such as CO_2, H_2O, O_3, CH_4, N_2, and N_2O (see Fig. 2.13), and also of PH_3. Depending on the aperture diameter of the collector spacecrafts (1–3.5 m), hundreds of exoplanets, including tens that are potentially habitable, could be detected by LIFE around main-sequence FGK and M stars within 20 pc from the Sun (Quanz et al., 2021). A subsample could be characterized in detail via high SNR thermal emission spectra. LIFE will assess the diversity of exoplanet atmospheres, investigate surface habitability, and search for biomarkers (such as the combination of O_3 and CH_4). Compared to missions focusing on detecting exoplanets in reflected light, probing the object's thermal emission provides direct and strong constraints on their radius and effective temperature.

Recently, the importance of the search for temperate planets, their characterization, and search for biosignatures was highlighted in ESA's Voyage 2050 final report "Final recommendations from the ESA Voyage 2050 senior committee," see: (https://www.cosmos.esa.int/

[8] https://www.life-space-mission.com/.

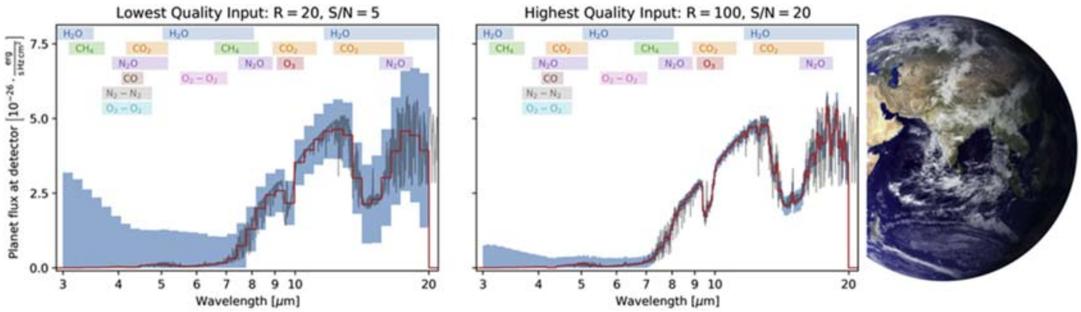

FIGURE 2.13 Examples of thermal emission spectra of modern Earth as used in parameter studies for the LIFE initiative (Konrad et al., submitted). In both panels, a high-resolution spectrum is shown in gray. The red step functions represent binned versions thereof (R = 20 in the left panel; R = 100 in the right panel). The blue shaded regions represent the flux uncertainty for the binned spectra for two fiducial cases (SNR = 5 in the left panel; SNR = 20 in the right panel) that consider relevant astrophysical noise sources such as stellar leakage, emission from the zodiacal dust and emission from an exo-zodiacal dust disk three times as massive as the Solar System zodiacal dust disk. Absorption features of the main atmospheric gases are also indicated.

documents/1866264/1866292/Voyage2050-Senior-Committee-report-public.pdf/e2b2631e-5348-5d2d-60c1-437225981b6b?t=1623427287109.

These recommendations for ESA's long-term science mission planning include the theme of thermal emission from temperate exoplanets among future potential L-class missions. Technical studies are now needed to develop feasible instrument concepts for the next decade.

8.4 Required technology developments

While the Origins Space Telescope, HabEx, and LUVOIR all primarily rely on relatively mature technologies, each of them is enabled by some nascent technologies that will require maturation before these missions can be initiated. The most crucial of these technologies with regard to detecting and characterizing potentially habitable planets are as follows:

- Origins Space Telescope: Low systematic noise detectors.
- LUVOIR: Picometer telescope stability.
- HabEx: Aggregate star-shade technologies.

Each mission concept has developed a well-planned technology roadmap and aggressive technology development schedules. This reduces the risk for the mission development and schedule. Indeed, most of the technology gaps are being addressed through NASA astrophysics technology development programs.

On the European side, the concept of a mid-infrared nulling interferometer (LIFE) is studied. Areas of required investment in further technology studies include in particular:

- Mid-infrared detectors (like for Origins),
- Cryogenic Integrated optics at mid-infrared wavelengths.

In the Voyage 2050 program evaluation, technology studies are recommended in order to investigate the maturity of a space mission for the characterization of temperate exoplanets.

9. Conclusions and recommendations

The Solar System and its giant planets systems on one hand, extrasolar planetary systems on the other hand are observed by different techniques with drastically important differences in measurement resolutions and types: whereas remote sensing using the variety of techniques of astronomy applies to all systems, only the Solar System, in the 21st century, is accessible to the powerful approaches of in situ investigations. Despite this important difference, they form *one class of astrophysical objects: Planetary Systems*. In this chapter, we have explored the power of synergistic studies of these objects, across their different categories, to make progress in the coming decades on our understanding of their evolutionary path, from the formation of protoplanetary disks, through the generation of the diversity of planetary objects and architectures, to the putative emergence of habitable ones and ultimately of life. In the next chapter, Dehant et al. (2022) describe more specifically the detailed scientific objectives of future Solar System studies, and the associated key observations, which can inform the same six science questions guiding the "Planetary Exploration, Horizon 2061" foresight exercise introduced in Chapter 1 (Blanc et al., 2022).

To set the stage of our study, we briefly reviewed the wealth of space missions currently in operation, in preparation or under study that will explore the diversity of planetary systems, with mention of their main scientific objectives. Thanks to the gain in complexity of missions to Solar System bodies, they reach out to more and more challenging destinations and extreme environments and address a very broad spectrum of scientific objectives. Space missions to detect and characterize exoplanets and their atmospheres currently rely on the transit method, but it is expected that a broader variety of techniques, and particularly direct imaging, will appear with the advent of large telescopes in space using coronography or interferometry techniques. This new generation of space telescopes will have the capacity of searching for biosignatures in the atmospheres of potentially habitable planets. Giant optical and radio telescopes on the Earth (ELTs, SKA) will provide other unique observations.

Our understanding of the origins and formation of planetary systems will benefit enormously from these synergies: Solar System observation provides access to all categories of planetary system objects, to an accurate dating of key events in their formation, and to a detailed characterization of planetary atmospheres, magnetospheres, and interiors; extrasolar planets characterization gives access to a rich statistics of planetary masses, distances to host stars, and stellar environment conditions; observations of planet-forming circumstellar disks have recently detected protoplanets as they form. Using this wealth of data, one can better constrain the initial conditions of disk evolution and planetary synthesis models, thus providing deeper insight into our understanding of how the evolution of disks leads to the observed diversity of planetary systems, including our own (see also Blanc et al., 2018; Lammer and Blanc, 2018).

A broad diversity of methods has been developed on the ground and in space to detect and characterize exoplanets and their atmospheres more and more accurately, such as radial velocity, the transit method, microlensing, astrometry, and direct imaging. Furthermore, radio observations seem to take off. In the decades to come these methods will continue to provide an even better statistical and case-by-case view on the diversity of planets and planetary systems architectures, and on their dependence on the properties of their host star. Until this day, the architecture of our own Solar System still appears to be very specific, if not unique. With the coming into service in the coming decade of giant telescopes on the Earth and large space-borne telescopes, many more surprises are awaiting us.

Planets and their moons interact with their external environment via coupling processes involving their atmospheres, their magnetic fields, radiation belts, and magnetospheres. Stellar atmospheres and astrospheres also play a role in the interaction of planets with their galactic environment. All these processes play a key role in the evolution and possible loss of each planet's atmosphere, and ultimately in its habitability. Studies of exoplanets atmospheres have already gone a long way into better understanding this host of processes, but they are until now essentially limited to gas giants. To better inform our understanding of the habitability of Earthlike planets, it is mandatory to conduct a similar effort for significantly lower planetary masses. At the same time, the example of our Solar System gas giants and their "ocean moons," such as Jupiter's Europa and Ganymede or Saturn's Enceladus, tells us that life may also well be hidden inside "ocean moons" orbiting exo-Jupiter's, far away from our investigation capabilities for quite some time.

The heliosphere is the best studied astrosphere and is the benchmark for other astrospheres. While groundbreaking steps were done in the last decade to develop the heliospheric models, much more effort is needed to close the gap between models, theories, and critical observations. It is also critical to bring the heliospheric models to be able to be predictive of the amount of shielding of galactic cosmic rays. This critical step is necessary to allow us to predict other astrospheres and other ISM conditions. Radio observations, on the other hand, should open the possibility for comparative exomagnetospheric studies.

Building on the characterization of potentially habitable worlds, the exoplanet community prepares for a scientifically extremely important, though technically very challenging, objective: the detection of "biosignatures" in exoplanets atmospheres, focusing on terrestrial planets residing within the habitable zone of their host star. There are essentially two wavelength ranges within which one can characterize the atmospheres of terrestrial planets to determine their habitability and search for biosignatures: the UV/Optical/near-Infrared, and the thermal emission around 10 μm. One looks for the detection of atmospheric species believed to be a product of life, such as O_2 or O_3. Then there are two ways to conduct these observations: by transit spectroscopy ("small black shadows"), or by direct imaging of the stellar light reflected by the planet ("pale blue dot") or its infrared emission. While both ways are very promising avenues for the future, they present huge technology challenges for the design of the future space-borne telescopes that will perform these biosignature characterizations. As a result of the preparatory phase of NASA's latest Decadal survey, several promising candidates have been studied to a considerable degree of detail, such as the HabEx and LUVOIR project studies. Their implementation in the coming decade(s) raises the hope that we are on a good track to find signatures of life in exoplanets atmospheres in a not-too-distant future. The importance of the scientific theme of temperate exoplanets and their potential habitability has also been anchored in ESA's Voyage 2050 program. This will result in studies like, e.g., the LIFE interferometric concept in future, enlarging the parameter range addressed.

The joint ISSI-Europlanet Forum hosted by the International Space Science Institute in Bern on February 19–20, 2019, whose presentations and debates guided this chapter, clearly outlined the converging scientific interests of the Solar System and the exoplanet communities

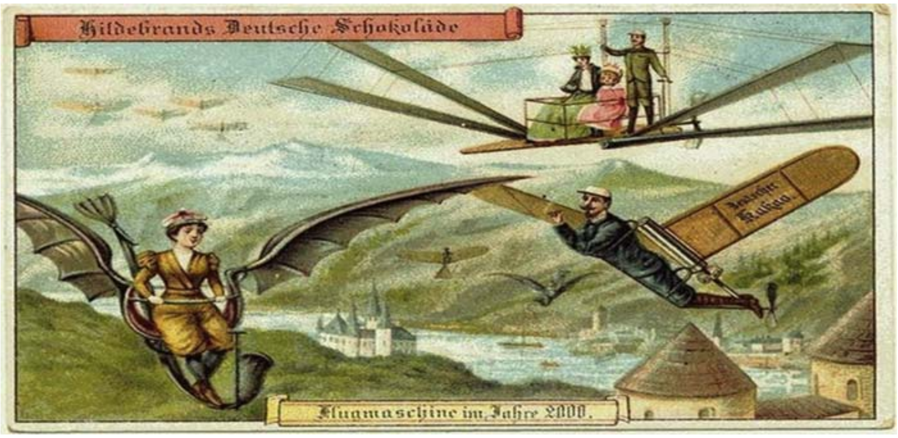

FIGURE 2.14 This beautiful and inspired engraving showing how future flying machines for the year 2000 were anticipated in 1900 reminds us that the future is difficult to predict …. *Hildebrands/Public Domain: https://mashable.com/2017/11/04/life-in-the-year-2000/.*

and the great promises of synergistic studies between the two communities, from the key scientific questions to the planning of future missions. We hope this Forum will inspire follow-on initiatives of the two communities to use the full panoply of ISSI tools, including Workshops, International Teams, Working Groups, or another Forum, to take advantage of these synergies.

Finally, let us not forget that science findings are intrinsically difficult to predict, and that nature is full of surprises (Fig. 2.14). A robust prediction we can make for the 2061 perspective, though, is that many surprises are waiting for us: new discoveries and unexpected results will open new, unexpected scientific questions, requiring innovative interdisciplinary approaches, new theoretical models, and new space missions to address them.

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