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Abstract:

The solar system and its giant planets systems on one hand, extrasolar planetary systems on the other hand are observed by different techniques which offer 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 in their accessibility to our observations, there is no doubt that they form *one class of astrophysical objects: Planetary Systems*. In this short article we explore the potential of performing 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 to the generation of the diversity of planetary objects, and among these objects to the emergence of potentially habitable ones and ultimately of life.

Solar System/Exoplanet Science Synergies in a multi-decadal Perspective – Report on the Second ISSI-Europlanet Forum (February 19th -20th, 2019)

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Abstract

The solar system and its giant planets systems on one hand, extrasolar planetary systems on the other hand are observed by different techniques which offer 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 in their accessibility to our observations, there is no doubt that they form *one class of astrophysical objects: Planetary Systems*. In this short article we explore the potential of performing 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 to the generation of the diversity of planetary objects, and among these objects to the emergence of potentially habitable ones and ultimately of life.

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) studies of planetary objects have spectacularly broadened their scope, and planetary sciences experience the emergence of a new unifying paradigm: the concept of "planetary systems", a class of astrophysical objects which covers and links together the solar system, giant planets systems and extrasolar planetary systems.

The solar system and its giant planets systems (5 "realizations" of planetary systems within our own) on one hand and extrasolar planetary systems on the other hand are observed by different techniques which offer 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 XXIst century, is accessible to the powerful approaches of in situ investigations. Despite this importance difference in their accessibility to our observations, there is no doubt that they form *one class of astrophysical objects*, as illustrated by the "cartoon" of Figure 2. 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 physics when they were finally considered as two complementary entries to the same scientific discipline: stellar physics.

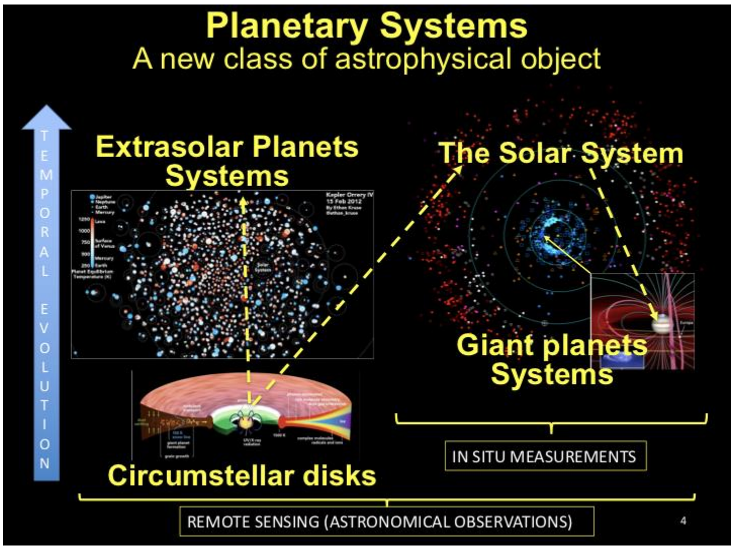


Figure 1: by studying Planetary Systems as a new class of astrophysical objects, in the perspective of their evolution, from their formation inside circumstellar disks to the possible emergence of habitable worlds within them, one can bridge the "observational gaps" currently existing between disks, solar system objects and exoplanets and take advantage of considerable synergies to better address key scientific questions about them.

This outstanding source of synergies between solar system and other planetary systems does not solely apply to the diversity of objects and systems, illustrated in the upper part of Figure 1 (e.g., the "space domain"). With the spectacular progress made in telescope observations of circumstellar (e.g. protoplanetary) disks provided by the development and coming into operation 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 spectacular progress in the coming decades. This opens serious hopes to access to the temporal evolution of these fascinating "planet factories", from the first phase of their formation inside collapsing proto-stellar clouds to the period when planets form and sometimes open gaps within them. Hence, with the fantastic support of circumstellar disk studies, we can observe in our galactic neighborhood objects similar to the protosolar Nebula out of which all solar system planets formed. While retrieving their evolutionary sequences with the additional help of advanced simulation tools, one can also infer some critical information on how our own protoplanetary disk formed and gave birth to all solar system objects (see Blanc et al., Space Science Series of ISSI Volume 56 "From Disks to Planets – the making of planets and their early atmospheres", 2018, and Lammer and Blanc, 2018 therein, for more).

Thus, building on the synergies between disks, exoplanet and solar system studies, one can gain a deeper insight into to the temporal evolution of planetary systems taken as a generic class of astrophysical objects (Figure 1), from their origin and formation, to the emergence of habitable worlds among their constituting objects, and lay the foundations for the search for alien life throughout the whole class of planetary systems, as has been proposed in the "Planetary Exploration, Horizon 2061" foresight exercise (http://horizon2061.cnrs.fr/).

This general science goal can be formulated in the following concise way:

Study the formation and evolution processes leading to the growth of complexity, and ultimately to the possible emergence of life, through the diversity of planetary systems:
(1) the growth of molecular complexity, from the Interstellar medium (ISM) to planetary and moons environments;
(2) the growth of planetary environments complexity, and the conditions under which their evolutionary paths may lead them to become "habitable".

Developing this general goal into more specific questions addressing the different sequences of planetary systems evolution including their current workings, one can come up along the "tree of evolution" of planetary systems with six key science questions illustrated by the cartoon of Figure 2, which can be applied in the same way to the solar system, giant planets systems and extrasolar planetary systems.

1. What is the origin of planetary systems?
2. How does their formation scenarios produce the diversity of their architectures?
3. How well do we understand the diversity of their constituting objects?
4. How do planets and planetary systems work?
5. Where and under which conditions does their evolution lead to the emergence of potentially habitable worlds?
6. How to search for and recognize life in these habitable worlds?

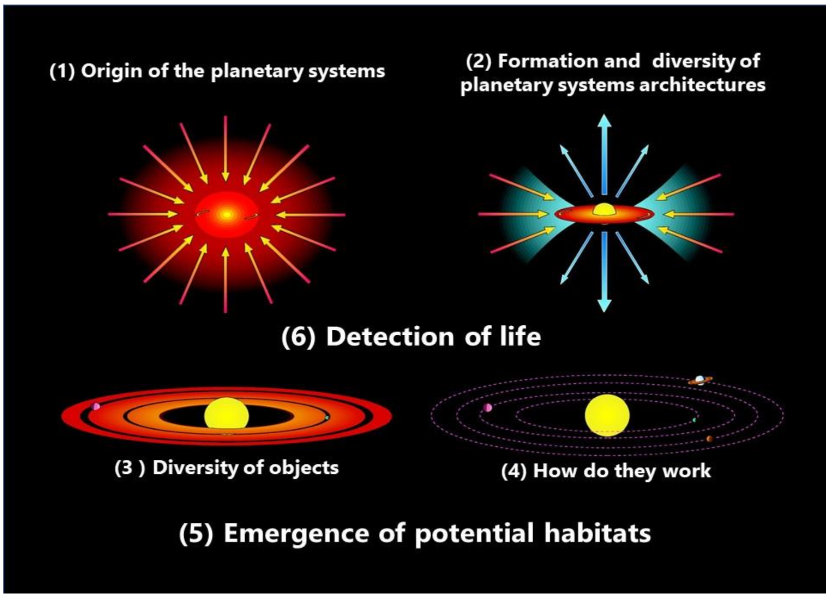


Figure 2:

Six key science questions about planetary systems

In this article, 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 8 we summarize our main findings and offer suggestions for future synergistic studies of protoplanetary disks, exoplanets and solar system objects.

2. Overview of planetary missions in the current space program

2.1. Introduction

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 fly-by´s and orbiting missions, as well as data from in situ explorations via landers and rovers. The diverse scientific drivers for future mission are formulated in different terms in the programs of the different 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.

2.2. Solar system missions

2.2.1. 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 BepiColombo, which will arrive at Mercury in 2025. The main science themes include the origin and evolution of a planet close to its parent star, its interior structure and composition, magnetic field and surface processes.

Venus: study science themes include a better understanding of Venus' geologic and climatic evolution, potential evidence for past water and the study of water loss processes. Venus is re-gaining interest also to clarify what lessons can be learned for the evolution of Earth. Beyond this, we want to understand similarities to warm terrestrial exoplanets, like the impact of stellar distance and geophysical effects (e.g. the runaway greenhouse, habitability conditions on planets with no plate tectonics). These issues are addressed by a number of missions currently under study (launch dates given):

- 2025/2026 **VERITAS** (NASA Discovery candidate)
- 2025 **Venera D** (Roscosmos, study) with orbiter, lander and balloon
- 2032 **ENVISION** (ESA M5 candidate)

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 labs can be investigated via a wide range of modern instruments. The number of current and planned near-future missions to the Moon is steadily increasing, showing the rising scientific interest, but also the interest to bring back humans to the Moon, and even to use the Moon as a base for further manned solar system exploration.

Current and future missions to the Moon include e.g.:

- 2019 Chang'e-4 (CNSA) with a rover landing on the night side of the Moon
- 2019 Chandrayaan-2 (ISRO), including a lander and rover
- 2019/20 Chang'e 5 and Chang'e 6 (CNSA) are planned sample-return missions
- 2020 Korea plans to launch a Pathfinder Lunar Orbiter
- 2021- 23 The Russian Luna program (from Luna 25 in 2021 to Luna 27 in 2023) explores the use of natural resources on the lunar surface.
- 2024 -27 Luna 28 to 31 to study technology for a future lunar base
- 2025 MoonLander (Korea) with orbiter, lander and rover
- 2026 Chang'e 8 (CNSA) South pole lander
  MoonRise (NASA) sample return from South Pole–Aitken basin

In addition, there are a number of planned privately funded missions to the Moon, e.g. in the U.S. with Lunar Scout, EM-1, and Peregrine planned for launch in 2019/20, or the planned German ALINA mission in 2020. 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.

Mars is at the outer edge of the habitable zone in our solar system. Its low mass implies that atmospheric loss processes are important for the long-term evolution of its atmosphere. 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. Upcoming space missions include:

- 2020 Mars2020 (NASA)
  ExoMars (ESA)
- 2024: Martian Moons Exploration mission (MMX, JAXA), including a (DLR/CNES)
  rover on the Martian moon Phobos.

Planned missions to Mars:

- 2020: Hope Mars Mission (United Arab Emirates)
  Mars Global Remote Sensing Orbiter (CNSA) with a lander and a rover
  Mars Terahertz Microsatellite (JAXA)
- 2022: Mangalyaan 2 (ISRO)

2.2.4. Small bodies

Small bodies (**asteroids and comets**) provide ´ground-truth´ of the earliest phases of solar system formation. Their exploration gives access to proto-planetary material, gas/dust and isotopic ratios, mineralogical and chemical compositions, water and volatile fractionation, and their collisional history.

- 2019/20 Hayabusa 2 (JAXA) arrived at asteroid Ryugu and will bring samples back to Earth.
- 2018 – 23 OSIRIS-Rex (NASA) arrives at asteroid Bennu and brings samples
  back to Earth
- 2021/22 LUCY mission to the Jupiter Trojan asteroids (NASA)
  PSYCHE mission to a main belt object (NASA)
- 2028 CometInterceptor (ESA F-Mission) to a long-period comet

Planned missions include DART (Double Asteroid Redirection Test) by NASA and HERA (ESA). The planned mission CAESAR (NASA) for sample-return from comets was 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.

2.2.4. The outer Solar System

The **icy moons** are of particular interest because their sub-surface oceans may be a habitat for life. The science goals of their exploration include ice crust thickness and composition, detection of organic molecules in sub-surface oceans, salinity, redox state and general composition of oceans:

- 2022 JUICE (ESA) to study Ganymede and the Jupiter system
- 2023 Europa Clipper (NASA) to study Europa and the Jupiter system
- 2025 Dragonfly (NASA), a drone to study Titan’s atmosphere and surface

Going further out to the solar system, relatively little is known. The **ice giants** (Uranus and Neptune) have not been investigated in detail since the Voyager 2 flybys. Consequently, plans to investigate the gas and ice giants (and their moons) in more detail are currently under discussion in the scientific community.

2.3. Exoplanets

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 (see section1). Space investigations started with the CoRoT (CNES) and Kepler/K2 (NASA) missions and are ongoing with NASA´s TESS mission. A number of space telescopes are under current development to detect and characterize exoplanets, in addition to studies for further investigations of their atmospheres, in particular for small, terrestrial planets.

- 2019 CHEOPS (ESA) to better determine planetary radii
- 2026 PLATO (ESA) to detect terrestrial planets around solar-like stars in their habitable zone
- 2028 ARIEL (ESA) to characterize exoplanetary atmospheres

In addition, ESA´s Gaia mission and NASA´s WFIRST will provide a large number of further planet detections via astrometry and microlensing techniques, respectively. JWST (NASA/ESA) will be the key instrument for atmosphere spectroscopy of transiting exoplanets.

Planned future exoplanets missions then focus on the characterization of small planets' atmospheres. These require larger aperture space telescopes. Studies currently under development focus on missions with coronographic techniques (e.g. LUVOIR, HABEX in the US). For cool terrestrial planets, interferometric techniques in the thermal infrared provide the best means to search for spectroscopic biosignatures. Studies in that direction should be continued as a long-term perspective to investigate planets similar to Earth, as will be described in detail in section 7.

2.4. Summary

The solar system as well as exoplanetary systems provide a wealth of data which help us to better understand how Earth developed and whether life may have also emerged elsewhere. Missions to solar system bodies gain 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 (cornography and interferometry) will be the driver for future missions with large-scale telescopes. More information about the missions discussed here can be found at the respective space agency web pages and references therein.

3. Origins and formation of planetary systems

3.1. Overview of planet formation

An overview of the main phase of planet formation in the classical sequential bottom-up paradigm (the core accretion theory, Safronov 1969) is depicted in Figure 3. After the formation of the star and its circumplanetary disk, planet formation starts from micron-sized dust grains that rapidly grow via coagulation to cm-sized pebbles (Weidenschilling 1980). These pebbles drift inward in the disk (Weidenschilling

1977). Either through further coagulation, but more likely through instabilities (Youdin & Goodman 2005), the pebbles form km-sized planetesimals, potentially preferentially at specific places in the disk (Drazkowska & Alibert 2017). The planetesimals grow via a collisional growth into protoplanets, objects on a 1000 km size range (Kokubo & Ida 2000). Some of the protoplanets grow massive enough (about 10 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 (giant planet formation, Pollack et al. 1996). Protoplanets embedded in the gaseous disk are subject to orbital migration (Lin & Papaloizou 1986), causing the initial and final location of protoplanets to differ (no in-situ formation). 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 & Asphaug 1999). This leads to the formation of the terrestrial planets. In the final phase, the orbits of the planets rearrange to reach a configuration that is stable over billions of years (Laskar 1997).

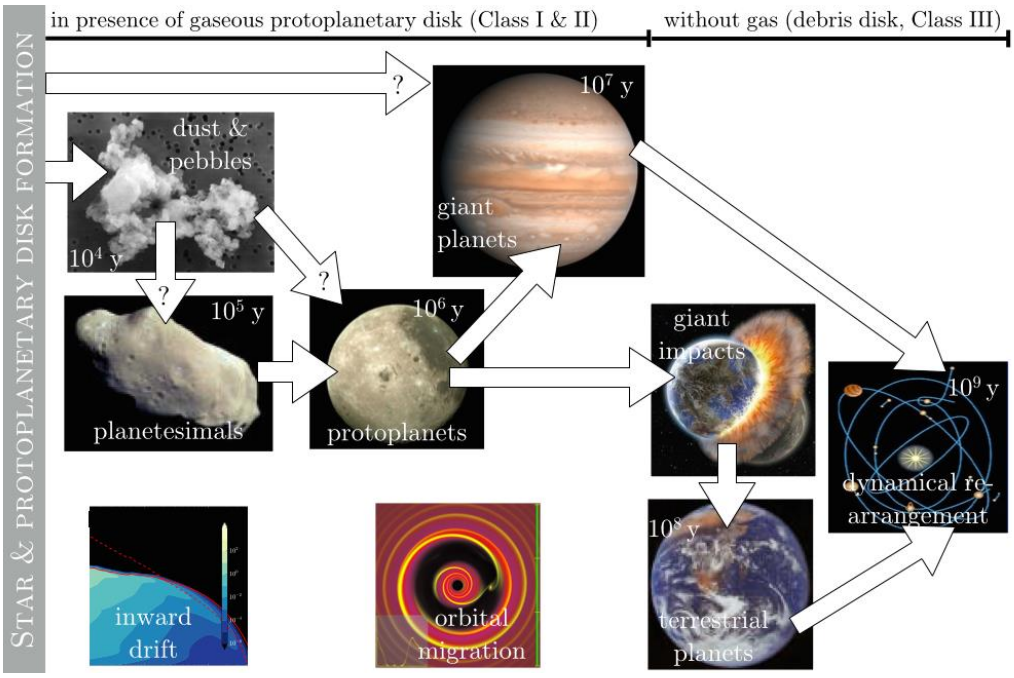


Figure 3: overview of planet formation

3.2. Open questions and challenges

The question marks in Fig. 3 indicate that even on such a very basic cartoon level, there are fundamental open questions regarding the origin of planetary systems:

- What are the properties of protoplanetary disk as initial and boundary conditions for planet formation (Testi et al. 2014)? What drives disk accretion and sets the structure of protoplanetary disks (Turner et al. 2014)? If processes other than the turbulent viscosity as conventionally assumed play a role, the disk structures will be very different and thus also the planet formation process (Suzuki et al. 2016).
- Do at least some planetary mass companions form by gravitational instability (Boss 1997) and not core accretion?
- Regarding the accretion of solids: what size is dominant at which stage? Pebbles, planetesimals or both, interacting (Alibert et al. 2018)? What is the

spatial and size distribution of the planetary building blocks? Recent observations by ALMA seem to suggest non-homogenous distributions with pile-ups, rings, and gaps (Andrews et al. 2018), strongly differing from classically assumed smooth MMSN disks.

- Regarding the accretion of gas: can predictions made by 1-dimensional quasi-static planetary internal structure models (Bodenheimer & Pollack 1986) really be used to predict planetary gas accretion rates? What about the dynamics of the gas (Ayliffe & Bate 2008)? Significant uncertainties regarding the opacity in protoplanetary atmospheres (Mordasini 2014), the composition and equation of the state of the gas (Venturini et al. 2018), and the thermodynamics of giant planet formation (accretion shock physics, Marleau et al. 2019) also represent uncertainties that strongly affect our ability to understand the gas accretion process.
- How strong is orbital migration? Depending on disk and protoplanetary properties, orbital migration differs strongly in both direction and speed (Kley & Nelson 2012), leading to different predictions about emerging planetary system architectures (distribution of orbital periods, pile-ups, capture into mean motion resonances, …).

Answering these questions is challenging, because the processes shown in Figure 3 involve

- a huge range in spatial scales: dust grains to giant planets (13 orders of magnitude).
- a huge dynamical range in time: 10 to 100 Myrs dynamical timescales.
- Multiple input physics: gravity, hydrodynamics, radiative transport, thermodynamics, magnetic fields, high-pressure physics, etc.
- Strong non-linear mechanisms and feedback (e.g., runaway accretion or gas disk-planet interaction). This means that planets emerge from a highly dynamic and strongly inter-coupled physical systems.

The conventional approach in physics of conducting laboratory experiments to establish a ground truth is possible in the context of planet formation only for special aspects (e.g., cosmo-chemical studies) and 3D radiation-magnetohydrodyamic 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. Instead observational guidance is necessary.

3.3. Observational constraints

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

1. The detailed constraints from our solar system. It provides in a unique way a comparatively complete view of a planetary system of not only the planets but also its minor bodies (comets, asteroids) that are messengers from the formation epoch (Le Roy et al. 2015). The 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, the solar system planets are the only ones for which the interior structure (Wahl et al. 2017) and the 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 there is the statistical aspect teaching us

about the diversity of planetary system. Since the discovery of the first extrasolar planet around a solar-like stars (Mayor & Queloz 1995), our understanding about the properties and the diversity of planetary systems was revolutionized by the detection of several thousand exoplanets. 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 statics of planet formation. The 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 & Santos 2007), and the correlations with stellar properties allows to nowadays put formation models to the statistical test. The planetary population synthesis method (Ida & Lin 2004, Mordasini et al. 2009) takes advantage of this, making it possible to use the full wealth of statistical constraints that the extrasolar planets provide. Figure 4 shows the mass-distance diagram, color-coding various detection methods. The distribution of planets in this diagram 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 on the origins of planets must function (Williams & 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. 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).

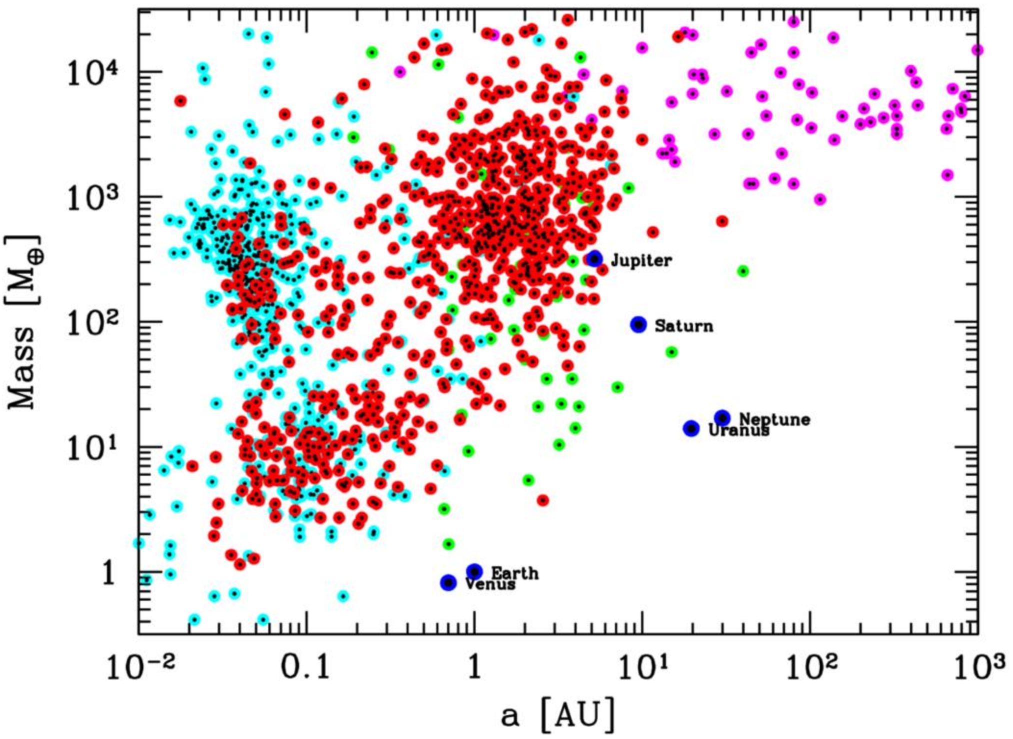


Figure 4: mass-distance diagram of already detected exoplanets. In this diagram the observations performed using different techniques are colored coded and overlaid.

3.4. Synergies between solar system and extrasolar planet formation theory

Despite all the data, today planet formation theory can still not explain the observed characteristics with one coherent picture. Furthermore, it is clear that a satisfactory theory must be able to explain the origins of both the solar system and the extrasolar planets. This underlines the importance of synergies between solar system and extrasolar planet studies.

Important examples of synergies include here

- the adoption of initial conditions for solar system studies that are not only based on the minimum mass solar nebula alone, but also on the observations of protoplanetary disk (Alibert et al. 2018).
- the inclusion and test of concepts originally developed to understand the origins of extrasolar planet 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 & Snellgrove 2001). This leads to the insight that the formation of the solar system was likely a dynamical process where the obits of the planets underwent strong modifications.
- The beginning interior, atmospheric, and thermodynamic characterization of extrasolar planets that builds on ideas and methods developed to characterize planets in the solar system. This includes the planetary mass-radius and mass-luminosity relation (Mordasini et al. 2012, 2017) where the typically simpler models developed for extrasolar planets can be tested with plentiful data available for solar system planets (Linder et al. 2019). Another example that will gain importance in the coming years regards the following important question: can we meaningfully connect planet formation and observable atmospheric spectra (e.g., Öberg et al. 2011, Mordasini et al. 2016).

3.5. 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 & Pollack 1986). The 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 recurrence was made to auxiliary and solar-system specific concepts like the minimum mass solar nebula. It is clear that such a static and tailored picture that is poor in interactions and dynamical elements could not explain the diversity that extrasolar planets were found to exhibit.

Especially the detection of extrasolar planets, but also observations of the properties and in particular the lifetimes of planet-forming disks (Haisch et al. 2001) has since made it clear that a modern theory of planet formation must take into account that planet formation, planet migration, N-body interactions between the protoplanets, and disk evolution all proceed on similar timescales, 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 that take into account all currently known governing processes occurring during planet formation in a simplified, but self-consistently linked way. Such global models like the Bern model (Alibert et al. 2005, Mordasini et al. 2012, Benz et al. 2014) are able to predict the architecture of an emerging planetary system, and the observable quantities of the 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 for 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 & Klahr 2010) may allow a more rapid growth at larger orbital distances (Lambrechts & Johansen 2014).
- Orbital migration is at work as shown by planets in or near mean motion resonances but is seems to be less efficient than predicted by migration timescale estimates for (single) planets (Dittkrist et al. 2014).
- The most important characteristic of a protoplanetary disk determining the outcome of the formation process is its content of heavy elements. It determines the mean mass of the planets, their number in the system, and the architecture (eccentricity) of a planetary system.

3.6. Observing planet formation as it happens.

The planet formation process itself, and the early evolution of planets and planetary systems in time was until recently not directly observable. Instead, between the epoch when planets form, and the epoch when they are observed with astronomical observations, 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 disturbes the Keplerian motion of the gas.
2. Dust dynamics (ALMA; e.g., Zhang et al. 2018). The presence of a 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.

Figure 5 shows a composite image (from A. Isella, ESO) 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). The protoplanetary disk of the star, and the circumplanetary disk of PDS 70c, are also visible.

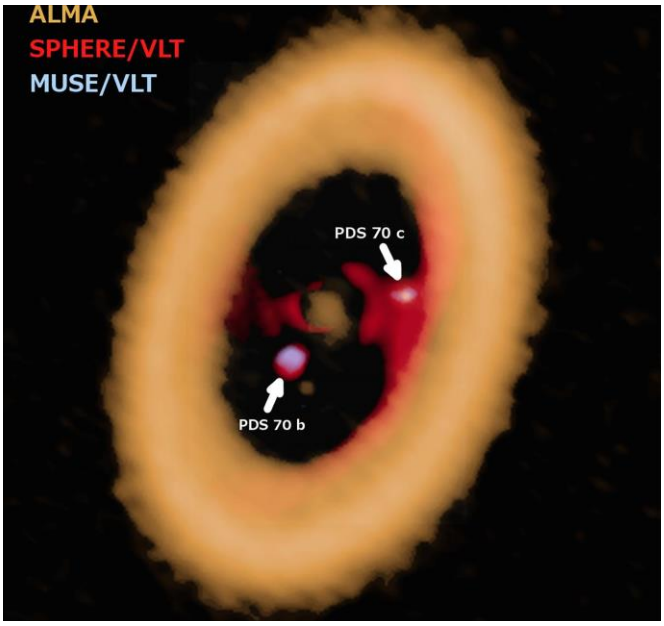


Figure 5: composite image (from A. Isella, ESO) of the two accreting protoplanets around the 10 Myr old T-Tauri star PDS 70 (Keppler et al. 2018, Wagner et al. 2018, Haffert et al. 2019).

These observations have the potential to put 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 which 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 observationally constrain the stages shown in Fig. 3. The temporal dimension also represents a synergy to the solar system, where the temporal dating of key events during the emergence of our own planetary system is made with cosmochemical methods.

4. Diversity of planets and planetary systems architectures

4.1 Overview

The past decades of planetary and exoplanetary science have revealed exciting new data that allow us to better understand planets as astronomical objects. Within the solar system we were able to study in detail a limited number of specific planetary objects, while exoplanetary research has revealed a stunning diversity of planets and planetary systems around other stars. We are now at a stage where exoplanets characterisation is possible and can be used to place the solar system in perspective. At the same time, unlike exoplanets for which we typically have access only to basic parameters such as mass and radius, we have very accurate measurements of the various chemical and physical properties of the planets in the solar system, including their gravitational and magnetic fields, atmospheric compositions, rotation rates, surface features, etc. Overall key open questions in the field include:

4.2. How do planets form and evolve?

How do formation and evolution processes shape the diversity of planet composition and internal structure? What determines the planetary system architectures? How common are planetary systems like our own? These are the questions we address in this section.

Current state of the research

During the past 30 years, extraordinary developments in astronomical observations and space exploration have been made. Planetary objects within the solar systems have been visited by spacecrafts and are also characterised from the ground. For exoplanets, various methods were developed to detect and characterize exoplanets such as radial velocity[1], the transit[2], microlensing[3], astrometry[4], and direct imaging[5].

Some of the most important insights about our stellar neighborhood can be briefly summarized as follows: Most stars host planets and the most common planets are larger than Earth (super-Earths) and smaller than Neptune (mini-Neptunes). Planetary systems are ubiquitous and diverse in terms of the number of hosted planets, orbital parameters, period ratios for neighboring planets, planet densities and masses, and stellar properties. Planets are detected on ultra-short orbits of several hours and as far as several hundreds of astronomical units (AU). Many planets seem to have undergone orbital migration such that they are not detected where they were initially formed.

Compared to exoplanetary observations, the level of chemical and physical details that can be studied for solar system objects is orders of magnitudes higher. The 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 which are not fully understood. 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.

[1] *with a precision down to about 1 m/s on stellar radial velocity*

[2] *with observable dips in stellar brightness down to 0.01 percents for ideal targets*
[3] *that is useful for the statistical investigation of planet demographics*
[4] *measuring the reflex motion of a star caused by a planet with precisions down to 10 microarcseconds for bright stars*

4.3. Future developments

In the coming decades, exciting developments in astronomical observations are in preparation. The James Webb Space Telescope (JWST, launch 2021) will provide infrared spectra of some terrestrial- size exoplanets by which molecules (such as H2O, CO2, and CH4) can be detected. A sample of 100 spectra of larger and hotter planets will allow statistical insights into the chemical trends among the targeted planets. The Atmospheric Remote-Sensing Exoplanet Large-Survey (ARIEL, launch 2028), the Large UV/Optical/Infrared Surveyor (LUVOIR, proposed for 2040), and the Habitable Exoplanet Imaging Mission (HabEx, conceptualized) will allow the exploration of exoplanetary atmospheres. For the first time, comparative exoplanetology with the focus on atmospheric diversity will be possible for a broad range of planetary masses and equilibrium temperatures.

The catalogue of short-period planets around bright stars is rapidly growing with the ongoing Tran- siting Exoplanet Survey Satellite mission (TESS, launched 2018), and highly refined radii for confirmed planets will be provided by CHaracterizing ExOplanet Satellite (CHEOPS, launch 2019). The PLAne- tary Transits and Oscillations mission (PLATO, launch 2028) specifically aims at extending the statistics on planet demographics, specifically for long-periods and small planets. The Wide-Field Infrared Survey Telescope (WFIRST, launch mid-2020s) will further enlarge the statistical understanding of planet occurrences by probing long-periods and small planets. Besides space-based missions, ground-based facilities are indispensible for technological developments and other unique opportunities. Very Large Telescopes (VLTS) and Extremely Large Telecopes (ELTs) provide and will provide the large aperture and spatial resolution necessary to start study the atmospheres of Earth-analogues around nearby stars. Transit spectroscopy, high-resolution spectroscopy, and high-contrast direct imaging on ELTs can characterize rocky planets in the habitable zone around small (M) stars at optical to near-infrared wavelengths.

The understanding of exoplanets is linked to our capabilities to characterise their host stars. Detailed and long-term monitoring are important to advance our understanding of stellar variability and activity and how they depend on different time scales and vary between star types and ages. Observational efforts stimulate theoretical studies ranging from stellar astrophysics to planetary science and high-pressure physics. Exoplanet science is a highly interdisciplinary endeavor. Observational constraints on planetary properties are limited in their information content about the interior of exoplanets, their compositions and structures, and evolutionary histories. Integrated models are needed to link the (generally few) observable properties to an improved understanding of planets. In order to interpret the observed planetary properties, we must understand how the stellar environment affects planetary diversity and planetary evolution.

For the solar system, many missions are ongoing (i.e., the Jupiter mission JUNO, Mercury mission BepiColombo, Lunar lander Chang'e 4, Solar satellite SolO, etc.) and are scheduled to get further insights on the Sun, planets and moons, and small objects. To give some examples: The JUpiter ICy moons Explorer (JUICE, launch 2022) will study Ganymede, Callisto, and Europa, partly with the aim to investigate their potential of habitability. Europa will also be visited by the Europa Lander and Clipper mission to search for biosignatures at the subsurface. Lucy (launch 2021) will visit a target-rich environment of Jupiter's mysterious Trojan asteroids, and Psyche (launch 2023) will study a unique metal asteroid which could represent the iron cores of terrestrial planets. There are mission concepts to even place a lander on Mercury and on Venus to provide better constraints for comparative planetology of terrestrial planets. Also planned are unmanned and crewed missions to the Moon and Mars (e.g., Mars rover ExoMars). In addition, there are ongoing efforts to design a mission dedicated to the exploration of Uranus and Neptune, the farthest planets in the solar system which were only visited only once during the Voyager 2 flybys of 1986 and 1989. Given that we now know that planets with the sizes of our ice giants are extremely common in the galaxy, improving our understanding of Uranus and Neptune, better understand their origin and further constrain their internal structures is a very important scientific objective to address the six science questions about planetary systems identified in section 1.

4.4. Disciplinary synergies for the decades to come

Understanding planets and planet system architectures is a challenging endeavor by nature. Investigations of this topic requires space missions and well-developed 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 to mobilize 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.

Understanding the diversity of planets and how formation and evolution processes shaped their masses, compositions and structures is a many-step process. Solar system planets allow us to calibrate theoretical models of planet formation and evolution, but at the same time, we still have not observed any exoplanetary systems that resemble our own.

Science findings are hard to predict, and we have already learned that nature is full of surprises. A robust prediction we can make for the 2061 perspective it is that many mysteries lie ahead of us. We will have new discoveries and unexpected results for both extrasolar systems and solar system objects which will require new theoretical models and interdisciplinary approaches.

5. Interactions between solid, liquid and gas/plasma components of a planet and early life

When it comes to the question of potential habitability of a rocky planet, or the question of the possible origin of life, interdisciplinary efforts are needed from astrophysical, geophysical, biochemical and atmospheric sciences.

We do not yet understand how, when and where exactly life started on Earth, but several constraints are available from both the geological record and biochemical studies. Earth's surface (and similarly also for 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). Study of the most ancient terranes preserved, as well as modelling, 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 the abundant evidence of a global hydrothermal geochemical signature in the early seawater (Hofmann and Harris, 2008).

The conditions which are often cited as habitable conditions for life as we know it include the existence of liquid water, building blocks (CHNOPS elements), nutrients, and energy. The majority of the organic building blocks are believed to be of extraterrestrial origin, having been delivered by volatile-containing 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). 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 rations similar to that of the Earth, other do not, e.g. 67P (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 shown experimentally that small icy particles influenced by environmental conditions in space are a good context for the formation organic molecules, including precursors of sugars (Meinert et al., 2016) and, indeed, many of the organic constituents of IDPs (interplanetary dust particles) are even of presolar origin (Merouan et al., 2012). What is also known is the huge variety of organic molecules, more than 10,000 (Schmitt-Kopplin et al., 2010) found in carbonaceous chondrites. However, of this huge variety, only a restricted quantity of the molecules are used by life.

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 (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 would have been the upper crust where interactions between circulating hydrothermal fluids and highly mafic/ultramafic rocks produces small organics, such as ketones, CH4, as well as H2, elements essential for prebiotic chemistry and produced by Fischer-Tropsch-type synthesis or from fluid inclusions in ultramafic rocks; cf. Shock et al., 2002; McDermott et al., 2015) or even from recycled meteoritic carbon.

All of these ingredients co-habited in an early environment that would be classed as "extreme" in respect to the modern environment. They needed to be concentrated on a microscopic scale under conditions where gradients in temperature, pH, cation concentrations etc. could drive the prebiotic reactions, catalysed by reactive mineral surfaces. Again, it appears that rocks and minerals played a fundamental role here. Most of the hypotheses concerning the emergence of life highlight the importance of hydrothermal environments as loci where the combinations of physico-chemical factors would have been conducive to prebiotic reactions (Westall et al., 2018). These environmental conditions would be common on rocky planets during the early history of the Solar System and could be common on exoplanets. In this perspective, it is possible that biology, viewed as a natural evolution from chemistry, would also be "natural" on extraterrestrial bodies.

While life emerged in an anerobic environment, for human and animal life, or in general for macroscopic life, oxygen plays a major role as it allows for higher energy levels and more cell diversity. But Earth did not always have the same oxygen levels as it has today. The last major rise about 550 million years ago is linked to the so-called Cambrian explosion, when a huge variety of plant and animal species appeared on 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 (e.g. Lyons T. W. et al., 2014, Nature, 506, 307-315). Also, reactions with fresh basaltic crust may have reduced the atmosphere before the great oxygenation event by releasing hydrogen and methane into the atmosphere (Smit M. A. and Mezger K., 2017, Nature Geosciences, 10, 788-792). Plate tectonics may further have influenced the outgassing abundances of different gas species (Mikhail S. and Sverjensky D. A., 2014, Nature Geosciences, 7, 816-819). 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 the atmosphere evolution (Gaillard F. et al., 2011, Nature, 478, 229-232). 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 already showed in 1959 (Miller S. L. and Urey H. C., 1959, Science, 130(3370), 245-251) that

several amino acids - pre-ingredients for life - are more likely to form under reducing conditions, that means atmospheres rather made of H_2O, CH_4, NH_3 and H_2 than oxidized gas mixtures such as CO_2, O_2, H_2O and SO_2.
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.

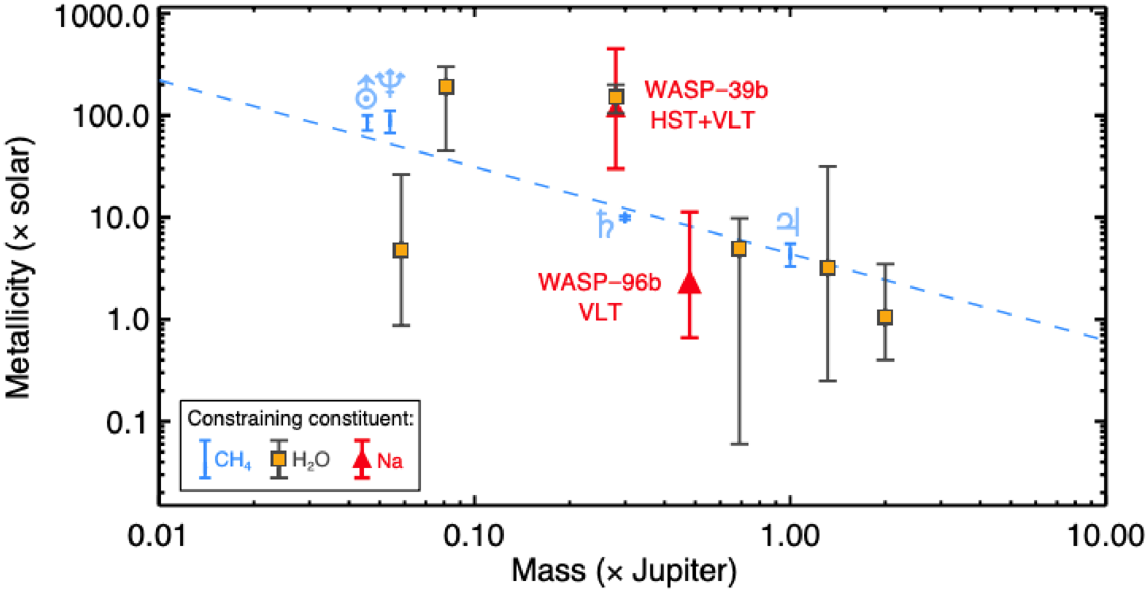
Several of these processes can only be investigated in a very limited way for solar system planets, since our window into the past is very small, allowing us mostly only indirect probing of the earliest evolution of Earth, Mars and Venus. It is still strongly debated, for example, if Venus was ever "Earth-like" 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 H. et al., 2018, Astron Astrophys Rev, 26:2, 1-72). 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, and especially the potential of a rocky planet to form and harbour life as we know it.

6. The role of atmospheres, plasma envelopes, magnetospheres, stellar outputs and astrospheres in the evolution of planetary environments

For Solar-System bodies space missions can provide detailed in-situ measurements of the properties of their atmospheres, surfaces and even interiors. However, in the case of exoplanets, beyond measurements of their bulk properties (e.g. mass and radius) only remote measurements of their atmospheres are possible. Therefore, understanding the origin and evolution of planetary atmospheres and how it is affected by the host star is perhaps the only way to link our detailed and specific knowledge of Solar-System planets with the statistical knowledge exoplanets provide. This will allow us to gain insights into critical processes that govern their evolution and perhaps the origin of life.

One of the key questions that could be answered over the coming decades is the formation of gas-giant planets. In situ measurements from the Galileo probe provide constraints on the atmospheric composition of Jupiter (e.g. Wong et al. 2004) while Cassini measurements provide constraints on Saturn (e.g. Flasar et al. 2005). On the exoplanet side, transmission spectroscopy of giant planets (e.g. Sing et al. 2016), high dispersion spectroscopy (e.g. Snellen et al. 2010, Hoeijmakers et al. 2018) and spectra extracted from direct imaging of young giant planets (e.g. Wang et al. 2018, Greenbaum et al. 2018) can be combined with atmospheric retrieval techniques to estimate the atmospheric compositions (e.g. Figure 6, Nikolov et al. 2018, Fisher & Heng 2018). The measured atmospheric compositions can then be compared with planet formation models (e.g. Mordasini et al. 2016, Booth et al. 2017) and protoplanetary disc models (e.g. Oberg et al. 2011, Booth et al. 2019), providing insight into the question of the origin and formation-evolution processes of exoplanets atmospheres. With more detailed results on Jupiter, (particularly its oxygen abundance) to be provided by the JUNO mission, the combination of TESS and JWST increasing the number and quality of transmission spectra of giant 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.

Figure 6:_Mass-metallicity diagram for Solar System planets and exoplanets. Methane (CH4) and water (H2O) 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 grey error bars), respectively. Each error bar corresponds to the 1sigma uncertainty. The blue line indicates a fit to the Solar System gas giants (pale blue symbols indicate Solar System planets). The figure is taken from Nikolov et al. (2018).



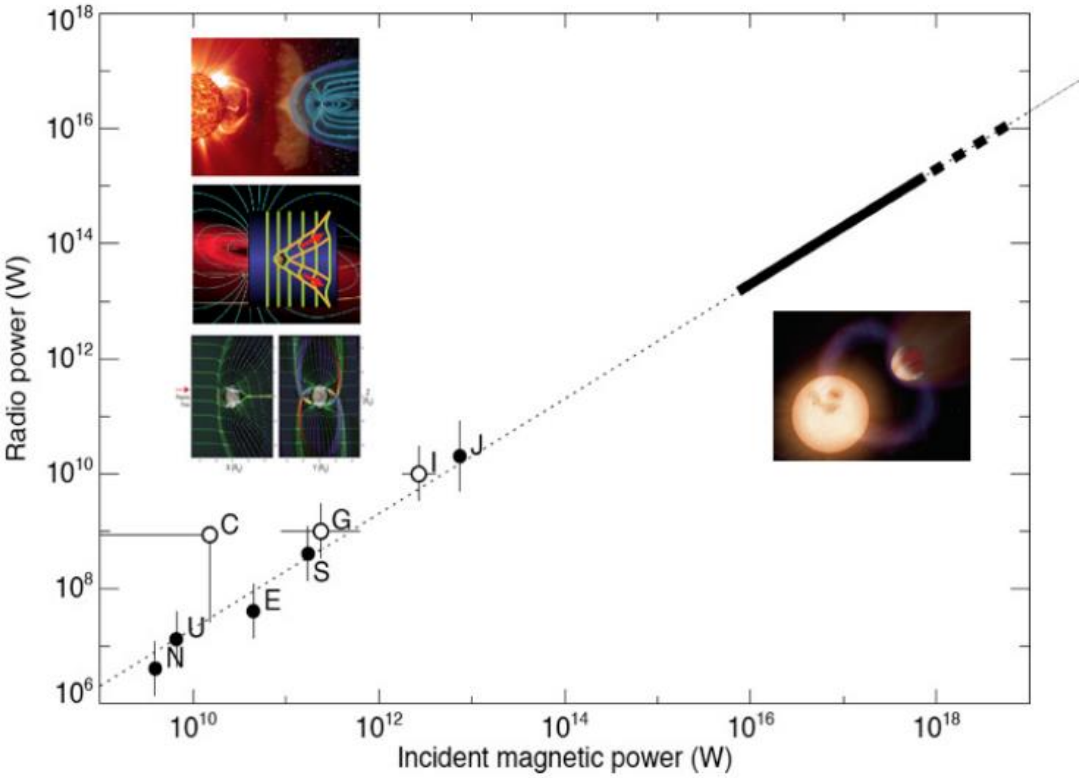
The effect of the stellar output on the evolution of planetary atmospheres is critical to understand. Solar-System bodies have experienced ~5Gyr of evolution already and the majority of observed exoplanets are also billions of years old (e.g. McDonald et al. 2019). The stellar output can cause atmospheric 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 (e.g. Lammer et al. 2008). However, with typical exoplanets experiencing fluxes at least 10 and in many cases 1000s time stronger than Solar-System planets they provide an opportunity to study atmospheric escape under extreme environments. Current observations of atmospheric escape in exoplanets are limited to a handful of nearby systems in Ly a or He I (e.g. 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 (e.g. Lammer et al. 2003), causing many to completely lose large primordial hydrogen/helium atmospheres which could have constituted several 10%s of the planet’s mass) over their lifetimes (e.g. Owen & Wu, 2013). This loss process results in a bimodal distribution for close-in exoplanetary radii which has recently been observationally confirmed (e.g. Fulton et al. 2017). Another aspect of the subject is that heliospheric, atmospheric, and magnetospheric research informs models of exoplanet-star interactions that are used to interpret optical data. For example, Bourrier & Lecavelier des Etangs (2013) describe interactions between very close exoplanets and their parent stars and how this can impact the shape of the Ly a spectrum that is observed. Kislyakova et al. (2014) working in a similar manner, also infer, for example, the magnetic moment of the exoplanet from the shape of the Ly a wings during transit phenomena. It is believed that the details of the Ly a detection can be used to infer the speed distribution of the hydrogen atoms in the exosphere of the planet. Heliophysics principles, such as radiation pressure, energetic neutral atom creation, photo- and electron-impact ionization, solar wind interactions with atmospheres and magnetospheres, etc., are invoked as guiding ideas to make coarse models of exoplanet interactions with their parent stars.

One important consideration for the future is that atmospheric escape from highly irradiated exoplanets has only been studied in detail for hydrogen-dominated atmospheres. This needs to be linked to atmospheric escape models of heavy-element dominated secondary atmospheres in order 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 (e.g. Owen, 2019).

Six solar system planets are permanently magnetized, in addition to Jupiter's moon Ganymede. Magnetospheres create a region of space around the magnetized planet which displays properties differing from the environment of the star. For example, at the planet Jupiter, the magnetospheric plasma is much hotter than the solar wind plasma that flows outside the magnetosphere. In addition to these properties, magnetospheres can trap energetic particles and these, in turn, can have their own emissions. Jupiter has intense synchrotron emissions originating from relativistic electrons trapped in its magnetosphere which can be detected from large distances, (e.g., Bolton et al. 2001, and references therein). This has led to the suggestion that similar magnetospheres could be detected in exoplanetary systems (e.g. Zarka, 2007, 2018) using radio telescopes, particularly for close-in exoplanets where the emitted radio power may be much larger (e.g. Figure 7, Zarka et al. 2015). While there are no current confirmed robust detections, the SKA will provide an opportunity for comparative studies between Solar-System magnetospheres and exoplanetary ones over the coming decades.

Figure 7: 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 ∼ 2 × 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). The figure is taken from Zarka et al. 2015.



Jupiter's satellites are instructive because of the 4:2:1 orbital resonance of Io, Europa, and Ganymede (the so-called Laplace resonance). The tidal heating of the interiors makes these bodies different from the colder, ice-rock bodies typically found in the outer solar system. Europa and Ganymede are the targets of a concerted search for a subsurface ocean by the Europa Clipper (NASA) and JUICE (ESA) missions to the Jupiter system, both of them planned for a launch in 2022. The surfaces of both of these moons contain non-ice materials and it is debated whether these are salts or hydrated acids (e.g., Carlson et al. 2009). Carlson has documented some of the constituents believed to exist on Europa's surface. The list of possible constituents was expanded by the work of Ligier et al. (2016) who also analyzed ground-based data.

While two of the Jovian moons seem to have the ingredients for life, they are inhospitable in terms of their cold surface temperatures and the presence of magnetospheric radiation (mostly hundreds of keV ions and electrons that are trapped in the magnetosphere). These particles can alter the surface constituents, certainly destroying large molecules, down to at least one meter in the regolith (e.g., Paranicas et al. 2009). Nordheim et al. (2017) have discussed the issue of magnetospheric radiation and the preservation of biosignatures relevant to the moon Europa. Some researchers, alternatively, believe the radiation can be a mechanism to create materials that can work to support life (e.g., oxidants) or that can supply energy deeper into the ice. 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. These issues illustrate some of the complexities in exoplanet modelling and the search for biologically relevant materials.

7. Strategies to search for life on exoplanets future large space telescopes

7.1 Searching for Habitable Conditions and Biosignatures from the Ground

Extremely Large Telescopes, including the European Extremely Large Telescope (E-ELT), and US-led Thirty Meter Telescope (TMT) and 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 ($\sim \frac{\lambda}{D} \sim \frac{1\mu m}{30m} \sim 0.01$ 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:

- Use very high-resolution spectroscopy ($R \gtrsim 100{,}000$) and cross-correlation techniques: studies of bright stars with transiting planets at optical wavelengths would allow for the detection of the signature of O_2 in the planetary atmospheres (Snellen et al. 2013)
- 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).

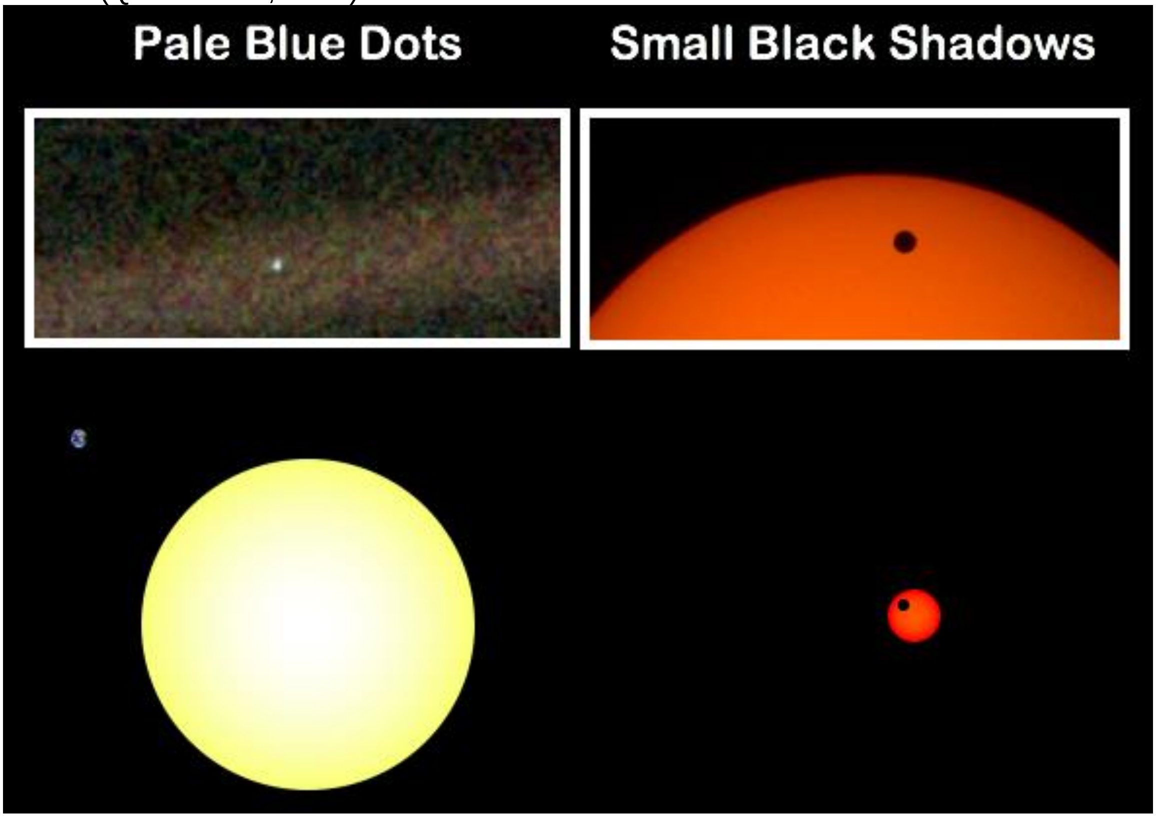


Figure 8. The two fundamental ways of searching for and characterizing potentially habitable planets, as delineated by the mass and thus bolometric luminosity of their host stars, which dictate the location of their habitable zones and thus the methods that are best suited to these endeavours. In particular, habitable planets around sun-like stars are more suited to the direct imaging method, whereas such planets orbiting low-mass stars are best suited to the transit

- Direct detection and characterization of terrestrial planets 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 that the contrast ratio between the planets and their host stars is likely accessible to ground-based facilities (NAS Exoplanet Science Strategy).

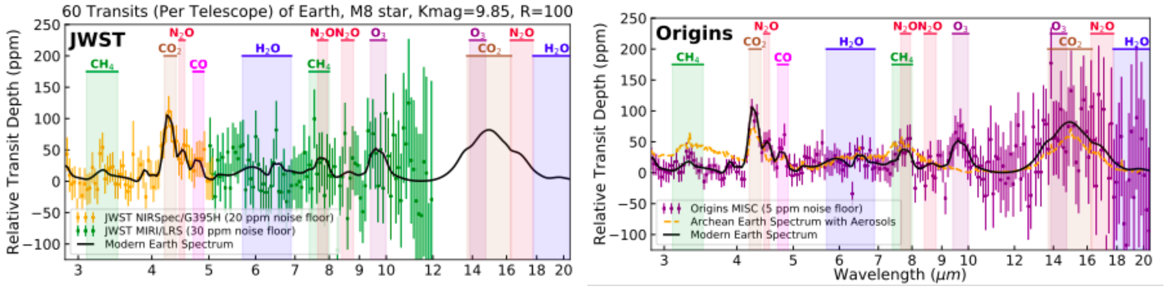


Figure 9. Transit spectroscopy of the atmosphere of an Earth-radius planet with a modern-day Earth spectrum transiting a planet in the habitable zone of a K=9.85 M8 star. (*Left*) The expected signal based on 60 stacked transits using JWST. (*Right*) The expected signal based on 60 stacked transits using 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. Kitaria.

7.2 Searching for Habitable Conditions and Biosignatures in Space

7.2.1 Two Paths You Can Go By

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 (see Figure 8).

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 is distinct from, but in analogy to, the classic direct image method required for surveying and characterizing Earthlike planets around suchlike stars. These surveys are often referred to as searching for “pale blue dots,”, a term coined by Carl Sagan based on

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[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, relatively short lived, hot, and/or 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’s 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.

the famous picture of the Earth taken by the Voyager 1 spacecraft when it was roughly 40 years from Earth on Valentine's day, 1990 (See Figure 8).

7.2.2 UV/Optical/near-IR spectra versus Thermal Infrared

There are also essentially two wavelength ranges within which one can characterize the atmospheres of terrestrial planets, determine whether or not they are potentially habitable and search for biosignatures: the UV/Optical/near-Infrared, or the thermal emission around 10µm. For direct imaging surveys ("pale blue dots"), one probes the reflected light emission of the planet, which has been filtered through the atmosphere of the planet twice, in the former wavelength range. 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 ~10µm. For transit surveys ("small black shadows") the former wavelength range is where one searches for the peak of the starlight emission as it 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 ~10µm. It is best probed by eclipse spectroscopy, where one measures the drop in flux across the planetary spectrum, which varies as a function of wavelength due to the varying opacity of the planetary atmosphere with wavelength, as the planet passes behind the star.

7.2.3 "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 (Gillon et al. 2017) 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). NASA's TESS survey is also sensitive to potentially transiting planets around very low-mass stars (Sullivan et al. 2015). 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 (Cowan et al. 2015), however it will be difficult to uniquely identify biosignatures safe for exceptionally favorable cases. On the other hand, the *Origins Space Telescope*, one of four large strategic mission 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 Figure 9). We discuss *Origins*, as well as two additional large strategic mission concepts, *HabEx and LUVOIR*, further below.

7.2.4 "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 in reflected light using direct imaging with large, space-based telescopes. The challenge here is not easy: the reflected light signal of an Earth-sized planet orbiting a solar type star is one part in ten billion, and the planet is located only ~0.1 arcseconds away for a system at ~10 pc. To illustrate by an analogy, this is like trying to detect a firefly roughly five feet from an industrial searchlight, at the distance between Los Angeles and New York[2].

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

Detecting such a signal, 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 of the four large strategic missions being studied by NASA are designed to be able to detect and characterize Earthlike planets orbiting nearby sun-like stars in reflected light. Figure 10 shows the simulated spectrum obtained with a 4m telescope using a technique to suppress the light from its host star by more 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 170h of exposure at 1 zodi.

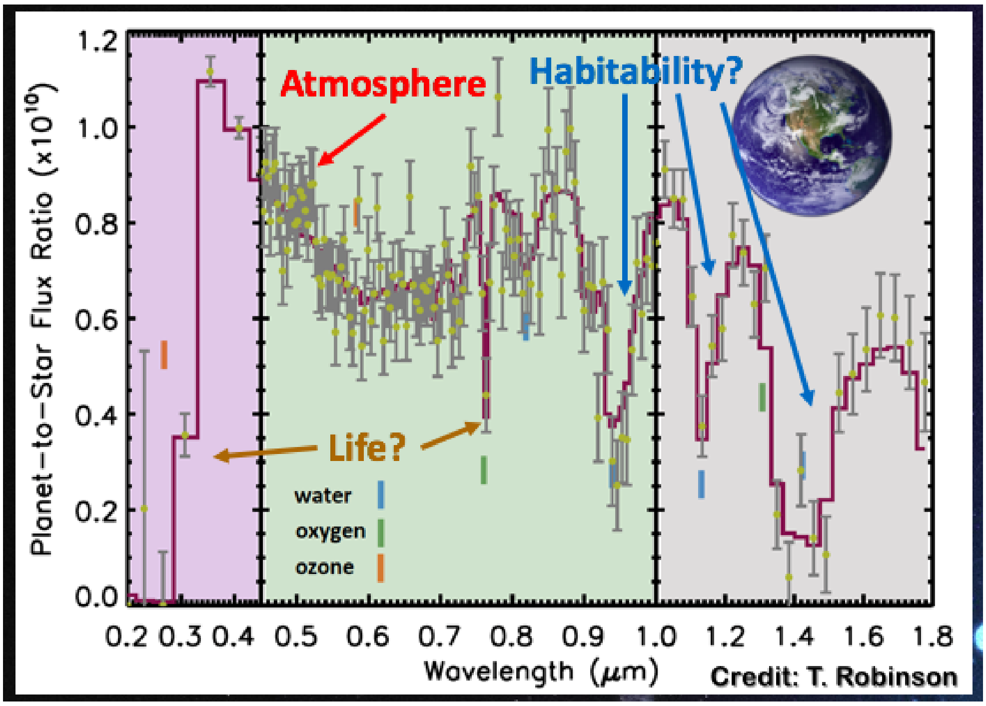

Figure 10. The reflected light spectrum of a terrestrial planet with an atmosphere identical that of modern-day Earth from the near UV to the near infrared (0.2-1.8µm). The data points with uncertainties are derived assuming the spectrum was taken with a 4m telescope of an exo-Earth around Beta CVn (Chara), a G0V star at 8.4 pc assuming 230h of observations. This yields a signal-to-noise of 10 at 0.55 µm at a spectra 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.

It is also possible to detect and characterize Earthlike planets orbiting sun-like stars in the thermal infrared, as previously mentioned. For terrestrial planets in the habitable zone, this emission always roughly 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 (~10^{-6} versus 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 ~λ/D, resolving a planet separated by 0.1 arcseconds from its host star requires either a filled aperture of 10^2 m, or two separate telescopes working together as an interferometer with a separation of ~10^2 m. Despite the technology challenge, mission concepts that would meet these requirements and detect the thermal emission of Earthlike planets in the habitable zones of sunlike stars have been formulated. In particular a mission concept for a laser interferometer in space has been submitted to ESA's Voyages 2050 call (the Laser Interferometry For Exoplanets concept, Quanz et al. 2015).

7.2.5 Planning for the Future

At the beginning of every decade since 1970, the U.S. 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) as its top-ranked space mission. These national agencies take these recommended priorities quite seriously, and indeed the WFIRST mission in 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 longstanding tradition of collaborating with foreign agencies to realize these ambitious space missions.

In preparation for the upcoming 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*)[3], the Large UVOIR Surveyor (LUVOIR)[4], Lynx[5], and the Habitable Exoplanet Observatory (HabEx)[6], 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 are due on August 22nd, 2019.

These study teams, drawn from the broad scientific community and NASA, have worked for over three 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.

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

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

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

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

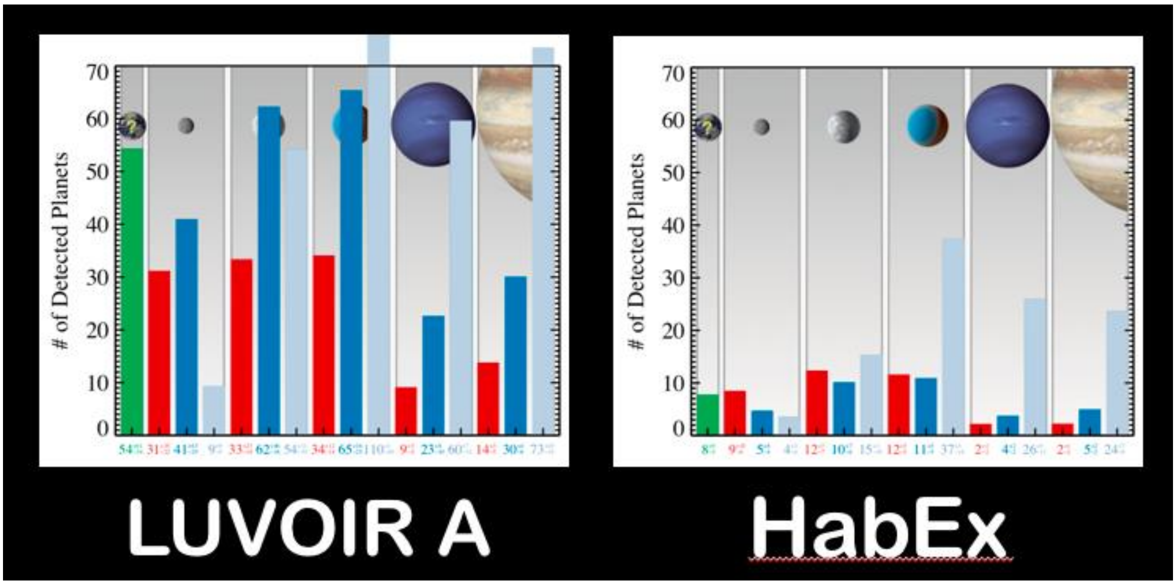

Figure 11: *(Left) The predicted exoplanet yields from the preferred HabEx architecture (4m Hybrid) for different classes of planets over a wide range of planetary radii: Rocky Planets, Super Earths, Mini-Neptunes, Neptunes, and Gas Giants, and surface temperatures: hot (red), warm (blue) and cold (ice blue). (Right) Same for LUVOIR A (15m). We note that the fractions of characterized planets (planets with full spectra and orbits) differ between these two plots due to the different methods used by HabEx and LUVOIR to characterize planets. Credit: C. Stark (STScI).*

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

- The nominal architecture of *Origins* is a telescope with a 5.9m diameter primary mirror that would be cooled to ~4.5K. 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 spectro-polarimetry. *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 4m 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 (0.3-1.8μm), 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 52m 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 five-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 15m, segmented, on-axis telescope, and LUVOIR B, which is an 8m, 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 not employ a star-shade. The ancipated yield of LUVOIR is considerably higher than Origins or HabEx, as illustrated in Figure 11.

Both HabEx and LUVOIR are capable of directly detecting and obtain 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 eleven 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. HabEx, on the other hand, will have a smaller sample size, but is designed to nevertheless have a very low probability (<1.4%) of detecting no potentially habitable worlds. Figure 11 shows the yield of the HabEx preferred architecture compared to the most ambitious LUVOIR A architecture.

The European Community has expressed great interest in contributing 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.

7.2.5 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 regards 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.

8. Conclusions and recommendations for future collaborative activities between the two communities, including ISSI meetings and Europlanet activities

The solar system and its giant planets systems on one hand, extrasolar planetary systems on the other hand are observed by different techniques which offer 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 XXIst century, is accessible to the powerful approaches of in situ investigations. Despite this importance difference in their accessibility to our observations, there is no doubt that they form *one class of astrophysical objects: Planetary Systems*. In this short article we have explored the potential of performing 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 to the generation of the diversity of their objects, and among these objects to the emergence of potentially habitable ones and ultimately of life.

To set the stage of our study of solar system/exoplanets synergies, we briefly reviewed the wealth of space missions currently in operation, in preparation or under study which 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 make it possible to 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.

Our understanding of the origins and formation of planetary systems can and will benefit enormously from synergies between observations of the solar system (which provides access to all categories of objects produced by planetary systems formation, to an accurate dating of key events in the formation process, and to a detailed characterization of planetary atmospheres and interiors), of extrasolar planets (which gives access to a rich statistics of planetary masses, distances to their host stars, and stellar environment conditions) and of planet-forming circumstellar disks, within which it has recently become possible to directly observe 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.

A broad diversity of methods have been developed on the ground and in space to first detect, then characterize exoplanets and their atmospheres more and more accurately, such as radial velocity, the transit method, microlensing, astrometry and direct imaging. They have provided and will continue to provide in the decades to come an even better statistical and case-by-case view on the incredible diversity of planets and planetary systems architectures, and on their dependence on the properties of their host star. Until this day, however, the architecture of our own solar system still appears to be very specific, if not unique, in this perspective. With the coming into service of giant telescopes on Earth and large space-borne telescopes in the coming decade, many surprises are awaiting us in our exploration of the diversity of planets and planetary systems.

Planets and their moons interact with their external environment via coupling processes involving their atmospheres, their intrinsic or induced magnetic fields, radiation belts and magnetospheres. At the scale of each planetary system the stellar astrosphere also plays a role in the way planets interact 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 and probability of harboring life. Studies of exoplanets atmospheres have already gone a long way into better understanding this host of processes but are until now essentially limited to gas giants. To better inform our understanding of the habitability of Earth-like planets, it is mandatory to conduct a similar effort for planetary masses significantly lower than the ones of the gas giants. 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 be well hidden inside “ocean moons” orbiting exo-Jupiter’s, far away from our investigation capabilities for quite some time.

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 whether or not they are potentially habitable and search for biosignatures: the UV/Optical/near-Infrared, or the thermal emission around 10µm. In the former wavelength range one looks for the detection of atmospheric species believed to be a product of life, such as O_2 or O_3. In the latter wavelength range one looks for spectral signatures of biomarkers (molecules produced by life) in the thermal emission spectrum of the planets. 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"). While both ways are very promising avenues for the future, they present huge technology challenges for the design of the future space-borne telescopes which will have the needed capabilities to perform these biosignature characterizations. As a result of the preparatory phase of NASA's upcoming 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 trajectory to find signatures of life in exoplanets atmospheres in a not-too-distant future.

This joint ISSI and Europlanet Forum very clearly outlined the common interests of the solar system and the exoplanet communities, as well as the extremely promising synergetic possibilities for both communities, by discussing the relevant scientific questions and challenges from both perspectives and incorporating the others' views into the planning of future missions. This Forum could only be a first step in this direction. ISSI offers a variety of formats for deepening the connection between these two communities, including ISSI Workshops, International Teams, Working Groups or another Forum. The conveners and participants of this Forum are encouraged to consider such future ways of cooperation; given a good science case and focus, they can expect enthusiastic support of ISSI.

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