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Exoplanets: The Nexus of Astronomy and Geoscience

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**Key Points:**

- Exoplanetary science is rapidly expanding toward characterization of atmospheres and interiors
- Planetary science has similarly undergone rapid expansion of understanding planetary processes and evolution
- Effective studies of exoplanets require models and in situ data derived from planetary science observations and exploration

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# The Fundamental Connections between the Solar System and Exoplanetary Science

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**Abstract** Over the past several decades, thousands of planets have been discovered outside our Solar System. These planets exhibit enormous diversity, and their large numbers provide a statistical opportunity to place our Solar System within the broader context of planetary structure, atmospheres, architectures, formation, and evolution. Meanwhile, the field of exoplanetary science is rapidly forging onward toward a goal of atmospheric characterization, inferring surface conditions and interiors, and assessing the potential for habitability. However, the interpretation of exoplanet data requires the development and validation of exoplanet models that depend on in situ data that, in the foreseeable future, are only obtainable from our Solar System. Thus, planetary and exoplanetary science would both greatly benefit from a symbiotic relationship with a two-way flow of information. Here, we describe the critical lessons and outstanding questions from planetary science, the study of which are essential for addressing fundamental aspects for a variety of exoplanetary topics. We outline these lessons and questions for the major categories of Solar System bodies, including the terrestrial planets, the giant planets, moons, and minor bodies. We provide a discussion of how many of these planetary science issues may be translated into exoplanet observables that will yield critical insight into current and future exoplanet discoveries.

**Plain Language Summary** Thousands of planets have been found outside our Solar System, called "exoplanets," forging a new frontier of planetary exploration. However, studying these planets many light years away requires a deep understanding of the planets nearby so that we can accurately interpret the planetary processes that are occurring on these distant worlds. In this work, we provide a summary of advances in planetary science and describe how the various Solar System bodies enable us to unlock the secrets of exoplanets. These advances include new insights into planetary habitability, and we discuss how diagnosing the evolution of our nearest neighbors can further the search for life in the universe.

## 1. Introduction

Underpinning planetary science is a deep history of observation, and more recently, planetary exploration within the Solar System, from which models of planetary processes have been constructed (e.g., de Pater & Lissauer, 2015; Horner, Kane, et al., 2020, and references therein). Indeed, planetary science as a discipline has greatly benefited from the robotic exploration of the Solar System over the past 60 years. From the early 1960s onwards, we began to explore beyond the Earth–Moon system, with flybys of Venus and Mars (e.g., Fjeldbo et al., 1966; Neugebauer & Snyder, 1966) followed, eventually, by landings on those planets (e.g., Avduevskij et al., 1971; Hess et al., 1977; Keldysh, 1977; Toulmin et al., 1977). At the present time, we have now sent spacecraft past each of the eight planets (e.g., B. A. Smith et al., 1982, 1989); have delivered orbiters to each of the terrestrial planets (e.g., Nakamura et al., 2011; S. C. Solomon et al., 2001), as well as the giants Jupiter and Saturn (e.g., Belton et al., 1996; Spencer et al., 2006); and have also visited several of the Solar System's dwarf planets (e.g., Russell & Raymond, 2011; Stern et al., 2015) and smaller bodies (e.g., Fujiwara

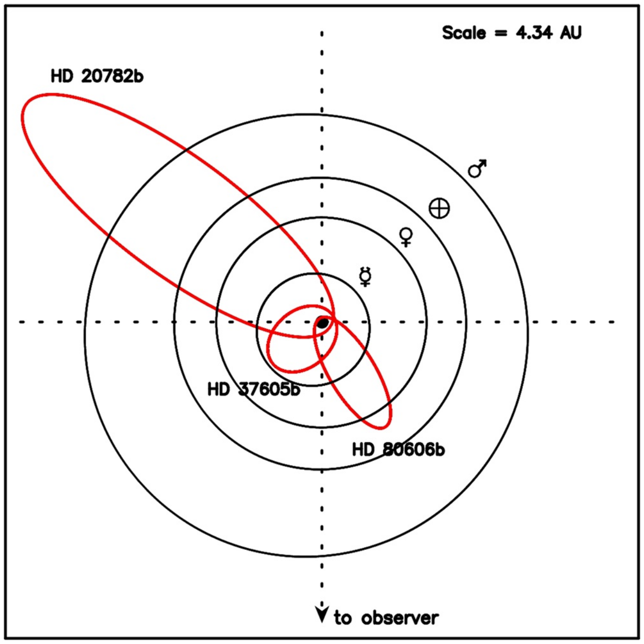


**Figure 1.** Example orbits of highly eccentric exoplanets (shown in red): HD 20782b, HD 80606b, and HD 37605b. These orbits are overlaid on the orbits of the Solar System terrestrial planets, shown in black. The scale of the figure is 4.34 AU along a single side.

et al., 2006; Glassmeier et al., 2007; Krankowsky et al., 1986). The detailed observations and in situ measurements of Solar System bodies provide the basis of fundamental models that describe the origin and evolution of planetary systems, as well as the nature of atmospheric and geological planetary processes (e.g., Goldreich & Soter, 1966; Guillot, 1999; Lodders, 2003; K. Zahnle et al., 2003).

In parallel, the past few decades have seen the rapid expansion of exoplanetary science. At present, the number of known exoplanets has passed 4,300 (https://exoplanetarchive.ipac.caltech.edu/) (Akeson et al., 2013). The current exoplanet inventory contains planets of types vastly different to those in the Solar System, such as super-Earths (Bonfils et al., 2013; Howard et al., 2010; Léger et al., 2009; Valencia, Sasselov, et al., 2007), mini-Neptunes (R. Barnes et al., 2009; Lopez & Fortney, 2014; L. D. Nielsen et al., 2020), and hot Jupiters (Fortney et al., 2008; Mayor & Queloz, 1995; Wright et al., 2012). Furthermore, notable demographic trends have been detected, such as the deficit in planets with radii between 1.5 and 2.0 Earth radii with orbital periods less than 100 days (e.g., Berger et al., 2020; Fulton & Petigura, 2018; Fulton et al., 2017; Van Eylen et al., 2018). Multiplanet systems feature an enormous diversity of architectures (Ford, 2014; Hatzes, 2016; M. Y. He et al., 2019; Winn & Fabrycky, 2015), including compact systems, such as Kepler-11 (Lissauer, Fabrycky, et al., 2011), that demonstrate the capacity of planetary systems to harbor multiple planets interior to a Mercury-equivalent orbit. Furthermore, exoplanetary systems display a broad range of orbital eccentricities compared with the near-circular orbits of the planets in the Solar System. Shown in Figure 1 are the orbits for the exoplanets HD 20782b (Kane, Wittenmyer, et al., 2016), HD 80606b (Bonomo et al., 2017), and HD 37605b (Wang et al., 2012), overlaid on the orbits of Solar System planets. A complete analysis of exoplanetary statistics offers important insight into the question of how typical our Solar System architecture and evolution is (Limbach & Turner, 2015; Martin & Livio, 2015). Furthermore, future observations of terrestrial exoplanet atmospheres have the promise to transform our understanding of the rocky planets in the Solar System (Shields, 2019), with particular astrobiological significance for the study of planets within the Habitable Zone (HZ) of their stars (Kane & Gelino, 2012; Kane, Hill, et al., 2016; Kasting et al., 1993; Kopparapu et al., 2013, 2014).

There are substantial challenges facing an efficient and seamless integration of planetary and exoplanetary science, however, largely related to the language, techniques, and measurables that are prevalent in these respective fields. For instance, planetary science directly studies the atmosphere, geology, and interiors of planets for which we have spatially and temporally resolved and/or in situ data. Yet, at the present time, our knowledge of exoplanet properties is usually not directly obtained since the planets remain invisible to us and is instead inferred from the planet's impact on the host star's orbit or brightness. Knowledge of stellar astronomy then becomes the baseline needed to understand planetary characteristics. Nonetheless, it is clear that the boundaries between these two fields, including language, terminology, methodology, and sharing of results/data, are worth dismantling if a full understanding of planets at the systems level is to be realized. Exoplanetary science provides a statistical insight into planetary architectures and formation scenarios, and planetary science provides detailed planetary models that exoplanetary science relies upon for detailed characterization. For example, a detailed study of the processes governing past and current atmospheric escape for the Solar System terrestrial planets, giant planet moons, and small bodies plays an important role in understanding the survival and evolution of exoplanet atmospheres (Dong, Bougher, et al., 2018; Gronoff et al., 2020; Lammer et al., 2020; Strangeway et al., 2005; Tian, 2015).

There are numerous reasons why the study of Solar System planets and exoplanets in unison is critical for the advancements of both fields, including

1. Terrestrial exoplanets are extremely common (Winn & Fabrycky, 2015) and will form the basis for a large-scale effort toward measurements of planetary atmospheric characteristics (Kempton et al., 2018;

Lustig-Yaeger et al., 2019b), which will, in turn, be applied to understanding Solar System atmospheric abundances (Bean et al., 2017; Martin & Livio, 2015).
2. Studies have shown that giant planets drive the architecture and evolution of planetary systems (Gomes et al., 2005; Morbidelli et al., 2005; Nesvorný, 2018; Raymond et al., 2014; Walsh et al., 2011) and may play a major role in water delivery to terrestrial planets (O'Brien et al., 2014).
3. Planetary (Solar System) science is continually advancing, with frequent and often considerable revisions to our understanding of fundamental processes and to prevailing models of formation, dynamics, atmospheres, surfaces, and interiors (e.g., Adams, 2010; Lodders, 2003; Lunine, 2017; Mitchell & Lora, 2016; Read & Lebonnois, 2018; Tsiganis et al., 2005; R. D. Wordsworth, 2016).
4. Perhaps most importantly is the knowledge that we will not have access to in situ data for an exoplanet within the foreseeable future, such that exoplanet surface conditions will predominantly be inferred from models based on Solar System data.

In this paper, we present a summary of the major bodies within the Solar System, their interiors and atmospheres, major outstanding questions, and the relevance of these worlds to exoplanetary science. In Section 2, we outline the properties of the terrestrial planets, in Section 3 we describe the gas and ice giant planets, in Section 4 we discuss the relevant properties of major icy moons in the Solar System, and in Section 5 we provide the lessons learned from minor planets. Section 6 describes the progress in exoplanetary science, and how discoveries made for worlds in this planetary system will contribute to the interpretation of data for others in the coming years. We provide a brief summary for the overlap between planetary and exoplanetary science along with concluding remarks in Section 7.

## 2. The Terrestrial Planets

The terrestrial planets of the Solar System serve as a foundation for our understanding of rocky planet interiors, atmospheres, and evolution generally. Shown in Figure 2 are schematic cross sections for the four Solar System terrestrial planets, used here to illustrate their relative sizes and known or inferred interior structure. In particular, characterizing the conditions and properties of these worlds help us develop models with which to understand how surface conditions can reach equilibrium states that are temperate and potentially habitable, or hostile with thick and/or eroded atmospheres. Here, we summarize the primary features of the terrestrial planets and some of the outstanding questions that remain regarding their properties.

### 2.1. Mercury

The orbital reconnaissance of the inner Solar System planets was completed by observations returned by the *MESSENGER* spacecraft. Mercury is a world that experienced sustained, widespread effusive volcanism for the first quarter of its life, before interior cooling and global contraction outpaced melt production and the prevailing stress state shut off major volcanic activity around 3.5 Ga (Byrne et al., 2018). *MESSENGER* saw a world heavily scarred by impact bombardment but also surprisingly volatile rich for a rocky planet so close to its parent star-with the planet having an unusually high abundances of S and C (Vander Kaaden et al., 2017) and even evidence for ongoing sublimation of a volatile-rich crust (Blewett et al., 2018). (Note that we do *not* include "water" here as a volatile, which is often a major volatile species in discussions of planetary formation, because the water content of Mercury is poorly constrained.) How a planet in such proximity to the Sun could retain relatively high volatile abundances remains a key outstanding question.

Equally surprising was the discovery with *MESSENGER* data of a remarkably thin silicate portion for Mercury: the core–mantle boundary is only 420 km deep. One possibility is a formation scenario whereby Mercury naturally accreted with much more iron, and much less silica, than the other inner Solar System bodies—although this interpretation presents some substantial chemical challenges (S. Solomon et al., 2018). Alternatively, a single, catastrophic collision (Benz et al., 2007) or several "hit-and-run" impacts (Asphaug & Reufer, 2014; Jackson et al., 2018) may have stripped off much of the outer portion of an originally larger "proto-Mercury." The prospect of a major impact shaping Mercury is supported by evidence for other similar events in early Solar System history, including the formation of the Earth–Moon system. If impact stripping of a proto-Mercury is true, then such dramatic reshaping of the planet happened very early in its history; the

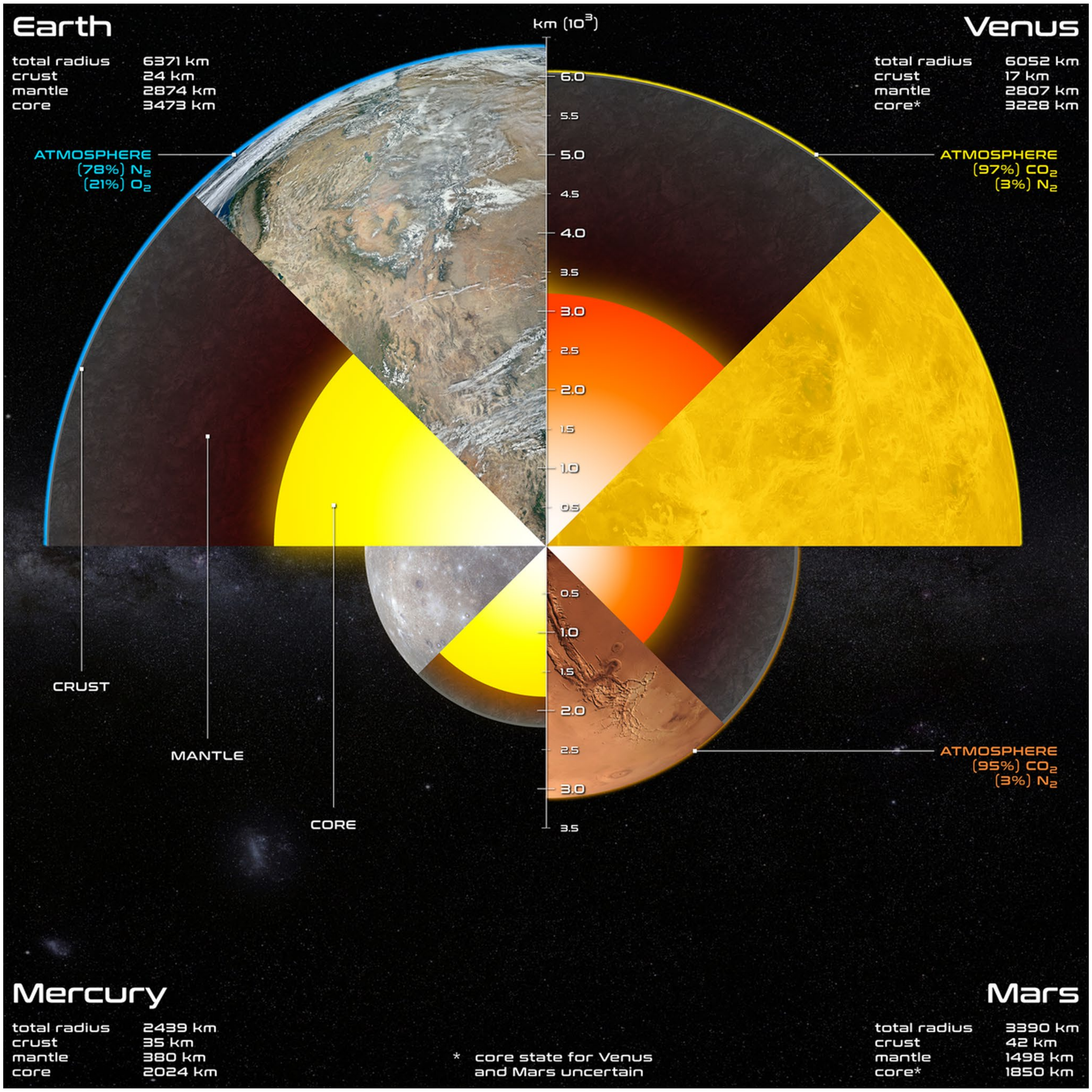


**Figure 2.** Schematic cross sections of the four inner Solar System planets, showing the major internal components (crust, mantle, and core) and atmospheric components. All cross sections are to scale. For simplicity, oceanic and continental crust for Earth are not distinguished nor is the interior structure of Earth's mantle shown. Note that there is considerable uncertainty regarding the state of the cores of Venus and Mars and specifically whether there is a liquid and solid component, as for Earth's core, and so they are shown with orange fill instead of yellow. The interior structure for Earth is from Dziewonski and Anderson (1981). For Venus, the crust–mantle depth and mantle–core depth values are from James et al. (2013) and Aitta (2012), respectively. For Mars, those values are from Goossens et al. (2017) and Plesa et al. (2018), respectively, and for Mercury are from Padovan et al. (2015) and D. E. Smith et al. (2012), respectively. The exosphere of Mercury is not shown.

oldest preserved terrain on the planet is 4.1 Ga (Marchi et al., 2013), with most of the earlier history of the planet likely buried by major volcanic and impact ejecta deposits (S. Solomon et al., 2018). Although impact stripping may deplete a planet's volatile inventory, and thus seem incompatible with Mercury's apparent enrichment in moderately volatile elements such as S and C, impact modeling suggests that such volatiles might be retained in a vapor cloud to later recondense on the planet (e.g., Ebel & Stewart, 2017).

The relevance of Mercury to exoplanetary science lies in both its chemical make-up and its interior structure: how can a rocky world with high volatile abundance and an outsize core form so close to its star? It may be that such compositions are possible in the inner portions of the protoplanetary disk. Or, perhaps, giant impacts are not all that unusual. For example, Bonomo et al. (2019) noted that the planets Kepler-107b and Kepler-107c have almost identical diameters (both ∼1.5–1.6 $R_{Earth}$) but significantly divergent densities (∼12.6 g $cm^{-3}$ for Kepler-107c vs. ∼5.3 g cm¯3 for Kepler-107b). Improving our knowledge of how Mercury came to form with its present interior structure will provide valuable information with which to assess which of these scenarios—initial accretion, or subsequent impact stripping—may apply to Kepler-107b.

Some key questions of Mercury relevant to exoplanetary science include (but are by no means limited to)

1. Did Mercury form with its large core, or did giant impact(s) strip away much of its silicate material (e.g., Benz et al., 2007; Ebel & Stewart, 2017)?
2. What effect, if any, has the proximity of Mercury to the host star had on the planet's abundances of moderately volatile elements such as C and S (e.g., Vander Kaaden et al., 2020)?
3. What does the current surface geology tell us of the interior structure and thermal history of a planet with such a large core and relatively modest mantle mass fraction (e.g., Byrne et al., 2018)?
4. How has the composition and geology of Mercury's airless surface being affected by its proximity to its host star (e.g., Chapman et al., 2018)?

In terms of exoplanet science, perhaps more than anything else Mercury offers us a natural laboratory for understanding how a rocky planet close to its star can form with—and retain over geological time—substantial inventories of moderately volatile species such as C and S, which might have been expected to be absent given the planet's distance to the Sun. Additionally, determining how Mercury attained its outsize core will in turn tell us what role, if any, giant impacts play in the formation of such planetary interior structure. Detecting and observing small rocky planets close to their host stars remains technically challenging, but Mercury is a useful basis with which to interpret similarly sized and structured close-in worlds elsewhere.

### 2.2. Venus

Venus is often referred to as Earth's "sibling," because it is the Solar System world most alike to Earth in terms of size and bulk composition. However, it has a ∼92-bar atmosphere comprising 96.5% $CO_2$ and 3.5% $N_2$ and a surface temperature of ∼735 K. The surface of Venus has a surprisingly young average age of ∼750 Ma, based on crater counts (e.g., Schaber et al., 1992), and may be in a "stagnant lid" state (e.g., Herrick, 1994), although subduction may still occur today (Davaille et al., 2017; Smrekar et al., 2018). The standard explanation for the present atmospheric state of Venus is a past progression into a runaway greenhouse (Walker, 1975) that occurred when incident solar radiation (insolation) exceeded the limit on outgoing thermal radiation from a moist atmosphere (Goldblatt & Watson, 2012; Ingersoll, 1969; Komabayasi, 1967; Nakajima et al., 1992), evaporating any oceans present. The possibility of past oceans on the surface of Venus is not a new concept (e.g., Grinspoon, 1993; Kasting, 1988; Kasting et al., 1984). However, recently Way and Del Genio (2020) suggested an alternative scenario for surface water retention, in which ocean evaporation was not dominated by effects related to secular changes in insolation, based on cloud decks forming at the substellar point. Instead, these authors argued, the emission into the atmosphere of amounts of $CO_2$ greater than could be drawn down into the surface and a putative ocean, most likely by major volcanic eruptions, would have triggered a moist greenhouse scenario. If so, then the fundamental difference in climate between Venus and Earth may be more stochastic, and less inevitable, than previously assumed. The explanation for this difference relies upon a deeper understanding of the relative contributions of $CO_2$ outgassing compared with the physical properties of clouds that determine albedo.

In any case, once a moist greenhouse effect was underway, it is likely that water loss by hydrogen escape followed, evident in high D/H relative to Earth (de Bergh et al., 1991; Donahue et al., 1982). Complete water loss for Earth-equivalent oceans would take a few hundred million years (Kasting, 1988; Kasting et al., 1984; Watson et al., 1981; K. J. Zahnle & Kasting, 1986), depending on extreme ultraviolet (XUV) flux and potential throttled by oxygen accumulation (R. D. Wordsworth & Pierrehumbert, 2013). Moreover, the Venusian nitrogen inventory is poorly known and may hold important clues to the atmospheric and mantle redox evolution (R. D. Wordsworth, 2016). Notably, massive water loss during a moist and runaway greenhouse has been suggested as producing substantial $O_2$ in exoplanet atmospheres (Luger & Barnes, 2015; R. Wordsworth & Pierrehumbert, 2014), but the present Venus atmosphere does not show this tracer of ocean loss and potential false positive for an oxygen biosignature. Hydration and oxidation of surface rocks (e.g., Matsui & Abe, 1986) and top-of-the-atmosphere loss processes (Chassefière, 1997; Collinson et al., 2016) may have removed any $O_2$ that was produced by early ocean loss, although it is uncertain how the present atmospheric loss processes would operate for a different (younger) Venus atmosphere, potentially in the presence of a stronger magnetic field (Curry et al., 2015; Luhmann et al., 2008; Persson et al., 2020). Thus, Venus is an ideal laboratory to test hypotheses for abiotic oxygen production and loss processes.

The evolutionary history of Earth's sibling is of crucial importance to understanding not only both the past and future of our world but the analysis of terrestrial exoplanet atmospheres more generally (Ehrenreich et al., 2012; Lustig-Yaeger et al., 2019a; Schaefer & Fegley, 2011). This consideration is particularly important in the current era of exoplanet detection, from which the discovery of potential Venus analogs is expected to become the prime targets for detailed follow-up observations (Kane, Barclay, et al., 2013; Kane et al., 2014; Ostberg & Kane, 2019). An example of a potential exoplanet analog to Venus is Kepler-1649b (Angelo et al., 2017), for which climate simulations predict rapid water-loss scenarios and possible progression through a runaway greenhouse (Kane et al., 2018). However, the relative lack of knowledge regarding the dynamics and chemistry of middle and deep atmosphere of Venus presents a barrier to detailed modeling of surface environments of terrestrial exoplanets (e.g., Forget, 2013; Forget & Leconte, 2014). Thus, Venus is a particularly important object of study within the Solar System as a possible template for the expected challenges in characterizing the evolution and atmospheres of terrestrial exoplanets in or near the HZ (Kane et al., 2019; Lustig-Yaeger et al., 2019a). Examples of outstanding questions regarding Venus are as follows:

1. What is the interior structure and composition of Venus (Gillmann & Tackley, 2014; Gülcher et al., 2020; O'Rourke, 2020)?
2. What has been the history of tectonics, volatile cycling, and volcanic resurfacing (Ivanov & Head, 2011)? Was the delivery of volatiles to the atmosphere from the surface and interior gradual, episodic, or catastrophic?
3. What is the detailed composition and atmospheric chemistry that exists within the Venusian middle and lower atmosphere (Bierson & Zhang, 2020; Krasnopolsky, 2012), and how does the lower atmosphere interact with the surface?
4. What drives the Venus atmospheric circulation (Fukuhara et al., 2017; Horinouchi et al., 2017), and in particular the superrotation on this slowly rotating planet (Horinouchi et al., 2020; Lebonnois, 2020; Lebonnois et al., 2010)? How can the atmospheric dynamics of Venus be used to model tidally lock exoplanets (e.g., Heng et al., 2011; Yang et al., 2019)?
5. Where did Venus' water go, and what processes are most important for $O_2$ loss from terrestrial planet atmospheres? Was hydrogen loss and abiotic oxygen production prevalent, or did surface hydration dominate (Kasting et al., 1984; Lichtenegger et al., 2016; Watson et al., 1984)?
6. Did Venus have a habitable period (Way & Del Genio, 2020; Way et al., 2016)? That is, did Venus ever cool after formation (Hamano et al., 2013)? If Venus had a habitable period, how long did it last—and when did it end?
7. What is the nature of the unknown UV absorber in the Venus atmosphere (Esposito, 1980; Molaverdikhani et al., 2012; Pérez-Hoyos et al., 2018), responsible for absorbing half of the insolation into Venus' atmosphere, and could it have astrobiological significance for Venus and exoplanets (Limaye et al., 2018)?

Many of the remaining questions regarding Venus have strong overlap with the community goals of understanding the evolution of exoplanets. For example, the nature of water delivery to Venus remains uncertain (Gillmann et al., 2020), a factor that determines long-term habitability (Way et al., 2016). Additionally, atmospheric mass loss (e.g., Howe et al., 2020; Kane, Roettenbacher, et al., 2020) and water loss from the top of the atmosphere (R. D. Wordsworth & Pierrehumbert, 2013) depend on XUV flux from star, which in turn depends on spectral type (Dong, Jin, et al., 2018; J. E. Owen, 2019). Moreover, the relative lack of knowledge regarding the bulk composition of Venus makes it difficult to infer the mineralogy of exoplanets based on stellar abundances (Hinkel & Unterborn, 2018). Most importantly, the evolution of Venus potentially represents a pathway from habitable to uninhabitable conditions, a pathway whose nature may be common for terrestrial planets (Foley, 2015; Foley & Driscoll, 2016; Way & Del Genio, 2020). Thus, the study of planetary habitability will benefit from understand which of the myriad of differences between Venus and Earth dominated the divergence in their planetary evolutions (Kane et al., 2019).

### 2.3. Earth

In the discussion of life beyond the Solar System, a great majority of the focus lies on finding exoplanets that may be similarly habitable to Earth. In many ways, it makes sense to focus our efforts on planets of a similar size, mass, and insolation flux to Earth, because Earth is the only known globally habitable and inhabited planet. For that reason, studies of Earth are of critical importance in shaping the future direction of exoplanetary science (e.g., Fan et al., 2019; Groot et al., 2020; Horner & Jones, 2010; Unterborn et al., 2016). One of the great challenges that such a focus on Earth-similar planets poses is the determination of which factors in Earth's characteristics and history are universally required for habitability and life (Meadows & Barnes, 2018). It is natural to look at Earth and ascribe our existence to any and all of our planet's peculiar and unique features, from the presence of our anomalously large satellite, to its internally generated magnetic field and magnetosphere, to the relatively benign impact regime our planet has experienced, at least for the past few billion years. It is worth noting that ascribing known life to fundamental Earth properties may, in some cases, present an erroneous line of reasoning that requires further investigation to properly resolve.

There have been numerous studies regarding the role of the Moon in stabilizing the spin axis of the Earth (e.g., J. W. Barnes et al., 2016; Ćuk et al., 2016; Laskar et al., 1993; Lissauer et al., 2012), including suggestions that the such stabilization may have moderated the Earth's climatic variability (e.g., Waltham, 2004), and therefore habitability (Armstrong et al., 2014; Colose et al., 2019; Heller et al., 2011; Spiegel et al., 2009; Williams & Kasting, 1997). As such, the possible requirement of the presence of a substantial moon for long-term habitability continues to be used as an argument toward the potential scarcity of habitable planets in the Universe. The reason for that assertion is that the formation of the Moon is thought to have been a stochastic event, the result of a giant collision between "proto-Earth" and a Mars-sized object (colloquially referred to as "Theia" [e.g., Benz et al., 1986; Canup & Asphaug, 2001; Reufer et al., 2012]). However, such stochastic events do not necessarily mean that analog Earth–Moon systems are rare (Elser et al., 2011). Additionally, it has been demonstrated that the Earth may possibly maintain long-term obliquity stability without the presence of the Moon (G. Li & Batygin, 2014; Lissauer et al., 2012), reducing the dependence of climate evolution on its presence.

Similarly, the origin of the Earth's volatile budget is still a point of some discussion (Dauphas, 2017; Marty, 2012; Marty et al., 2016; Peslier et al., 2017; Wu et al., 2018). Theories for the hydration of Earth fall into three broad groups: *endogenous hydration*, in which the water was accreted from material local to the Earth from the solar nebula (Ikoma & Genda, 2006), typically in the form of hydrated silicates (e.g., Drake, 2005); *early exogenous hydration*, where volatile material was delivered from beyond the "ice line" as Earth was still accreting, in the form of asteroids and comets flung inward by the giant planets (possibly as the latter migrated) (e.g., Morbidelli et al., 2000; Petit et al., 2001); and *late exogenous hydration* (otherwise known as the "late-veneer" family of models), which invokes the delivery of water from the outer Solar System toward the end of Earth's accretion, or even some time after the formation of the planet was essentially complete (e.g., T. Owen & Bar-Nun, 1995).

A common feature of many of these models is the implicit assumption that all of the terrestrial planets received similar amounts of volatile material and that the isotopic abundances of the volatiles delivered to them ought to have been the same from one planet to the next. However, dynamical studies have shown that the different terrestrial planets likely received different amounts of material from different reservoirs of volatiles—at least in the case of the exogenous delivery of those volatiles (e.g., Horner et al., 2009; T. Owen & Bar-Nun, 1996; Raymond et al., 2004), a result that has been replicated in studies of planet formation around other stars (e.g., Ciesla et al., 2015). This finding has implications, for example, for the volatile inventory of Venus and its similarity (or not) with that of Earth (e.g., Way & Del Genio, 2020).

The composition of Earth's earliest atmosphere is poorly known, although life may have evolved during the earliest phase of Earth history, the Hadean (>4.0 billion years ago) (Nutman et al., 2016). Since life arose, atmospheric abundances of biosignature gases (e.g., $O_2$, $O_3$, $CH_4$, and $N_2O$) have varied by orders of magnitude over our planet's billion year history (Schwieterman et al., 2018; K. Zahnle et al., 2007; K. J. Zahnle et al., 2020), with major implications for the detectability and interpretation of the presence of these gases on exoplanets. These changes in atmospheric composition have also featured in the most dramatic changes in Earth overall environmental history. In the Archean eon (4.0–2.5 billion years ago), Earth's atmosphere is thought to have been relatively anoxic (Lyons et al., 2014), though evidence exists for an earlier oxygen-rich atmosphere (Ohmoto, 2020). Because the Sun then was only 70%–80% as luminous as today, enhanced greenhouse warming was necessary, and perhaps sufficient to keep Earth clement during this time period. These greenhouse gases likely included carbon dioxide ($CO_2$) and methane ($CH_4$), and when present together in large quantities, can indicate a biological atmospheric disequilibrium (Krissansen-Totton, Olson, et al., 2018). Methane in the Archean may have been 2–3 orders of magnitude more abundant than today (Pavlov et al., 2000), possibly occasionally forming a Titan-like atmospheric organic haze (Arney et al., 2016; Trainer et al., 2006; Zerkle et al., 2012). Similar to the cloud decks of Venus, such hazes may make characterization of the surface environments of exoplanets challenging, especially for transit transmission observations (e.g., Gao et al., 2020). Because of the long path length slant viewing geometry inherent to transit transmission observations, even hazes that are transparent to the surface in the shorter path lengths relevant to direct imaging can become opaque at elevated altitudes in transit observations (e.g., Fortney, 2005).

The start of the Proterozoic (2.3 billion years ago to 541 million years ago) marked the rise of an oxygenated atmosphere, irreversibly altering the redox state of the atmosphere, although oxygen abundance during the middle Proterozoic may only have been present at low abundances (Planavsky et al., 2014, e.g., 0.1% of the modern atmospheric level). The rise of oxygen also meant the rise of its photochemical byproduct, the UV-blocking ozone layer, with profound implications for the surface habitability of our planet. Understanding the chemical, geological, and even biological interplay between Earth's volatile inventories and its secular atmospheric composition, therefore, represents an important path toward ensuring accurate interpretation of measurements of exoplanet atmospheres and assessments of their prospective habitability. Other important issues relevant to exoplanetary science include

1. How long did Earth's magma ocean period last, what was the nature of the earliest crust on the planet, and how long did it take for the oceans to form (e.g., Katyal et al., 2019; Monteux et al., 2020)?
2. When did life originate and evolve on Earth (e.g., Dodd et al., 2017; Mojzsis et al., 1996)? How have abiotic factors including (but not limited to) petrology and degassing at the ocean floor contributed to a changing atmospheric composition (e.g., Lyons et al., 2014)?
3. How important was the Moon-forming collision for the interior structure and composition of Earth and the subsequent evolution of life here (e.g., Canup, 2012)?
4. What is the role of volatiles (e.g., liquid water) in continental plate subduction and the carbon cycle (e.g., Bercovici, 2003; Regenauer-Lieb et al., 2001; van der Lee et al., 2008), and how critical is this process for the sustained habitability of terrestrial exoplanets (e.g., Lammer et al., 2009; Noack & Breuer, 2014; Valencia, O'Connell, et al., 2007)?
5. How has the composition of the Earth's atmosphere changed with time due to the influence of biology (e.g., Reinhard et al., 2017)?
6. How has the depth of the oceans, and the amount of continental freeboard, changed through time (e.g., Korenaga et al., 2017), and how do the interaction of continents and ocean depth influence planetary habitability (e.g., Cowan & Abbot, 2014; Glaser et al., 2020)?
7. What aspects of life's impact on Earth's current and past environments are potentially detectable on an exoplanet (e.g., Kaltenegger et al., 2007; Robinson, Ennico, et al., 2014; Rugheimer et al., 2015; Sagan et al., 1993; Schwieterman et al., 2018)?

In the context of exoplanets, Earth is invaluable as the planet we have by far the most data for, and as the only known planet with a biosphere. Understanding which processes are—or are not—necessary for habitability and the origin of life on our own planet will help us understand the potential for habitability and life on worlds with different histories and characteristics. Our modeling efforts of habitable exoplanets often starts with planets analogous to Earth. This is for good reason: grounding and validating these models in the characteristics of our planet is a necessary step to ensure their accuracy before they can be extended to exoplanets. Further, understanding the diversity of ways a planet can maintain habitability over long time periods can, together with remote sensing of our own planet "as an exoplanet," provide a useful starting point for future interpretations of potentially habitable exoplanets. Exoplanet science is rapidly moving toward a regime where observations and characterization of such potentially habitable worlds will be possible, and Earth is the best starting point we ever will have for interpreting the data we obtain from these distant worlds.

### 2.4. Mars

The surface of Mars today boasts a variety of features we recognize from Earth and other planets, including impact craters, tectonic structures, and volcanoes and their products (including the largest such examples in the Solar System) (e.g., Werner, 2009). But also preserved on this rocky world is evidence for a different, early Mars, when ~3.5–4.0 billion years ago liquid water carved valley networks (e.g., Ehlmann & Edwards, 2014; Grau Galofre et al., 2020; Grotzinger et al., 2014), and atmospheric pressure was much higher than the 6 mbar today (Carr, 2012). An early dynamo indelibly marked the ancient crust (Acuna et al., 1999), dying before the valley networks formed (e.g., Lillis et al., 2008).

In terms of exoplanetary science, Mars represents a case study for a world that was once more geologically active than today, and perhaps even once habitable, that underwent a major change in internal and surface properties as its interior cooled and its atmosphere was lost to space (e.g., Ehlmann et al., 2016). It is possible that Mars is at or near the minimum size of a rocky world that makes this transition, since widespread geological activity ended much earlier on smaller Mercury and the Moon, but continues to the present on larger Earth and (probably) Venus (e.g., Byrne, 2020, and references therein). Mars with its tenuous atmosphere has been considered in the context of exoplanet atmospheric escape (Brain et al., 2016; Dong, Lee, et al., 2018). This is particularly important because many exoplanets orbit very closely to their stars and/or their stars exhibit high levels of activity that may be sufficient to strip significant fractions of an atmosphere. A modeling study of Mars atmospheric escape over geologic time, validated by MAVEN observations, has suggested that 100 bars of atmosphere can be lost from a Mars-like exoplanet orbiting in the HZ of a M-dwarf star over 4 billion years (Dong, Lee, et al., 2018). Other important science questions for understanding Mars in the context of exoplanetary science include

1. What is the current internal structure and activity of Mars (e.g., Banerdt et al., 2020), and how does that activity relate to surface geology (e.g., Giardini et al., 2020), as a sub-Earth-size rocky world that is several billion years old?
2. To what extent was early Mars really "warm and wet" in contrast to the cold and dry planet we see today (e.g., Grau Galofre et al., 2020; Ramirez & Craddock, 2018)?
3. How do the Red Planet's histories of dynamo generation, atmospheric loss, and habitability interrelate, and what we can learn from them for planetary habitability in general (e.g., Kite, 2019)?
4. What is the lower size limit for sustained planetary habitability (e.g., Ehlmann et al., 2016)?

In the exoplanetary context, Mars offers us a fascinating insight into the kind of planet that could, potentially, be mistaken for an "Earth-like," habitable world. It offers a cautionary tale—showing us how planets can evolve from being eminently habitable (as it seems was the case for the warm, wet, young Mars) to one whose habitability is, at best, borderline or questionable (e.g., Bishop et al., 2018; Ramirez et al., 2020). Mars also stands testament to the vagaries of the chaotic and violent latter stages of planet formation, with some studies suggesting that its relatively small size (compared to Earth and Venus) is the result of significant collisional attrition, and others arguing that it might be more representative of the oligarchs that precluded the final collisional growth of the two largest terrestrial planets (e.g., Brasser et al., 2017; Bromley & Kenyon, 2017; Izidoro et al., 2015). The chaoticity of Mars' obliquity, and the variability in its orbit, combines to give the planet a far greater level of climatic variability than is seen for Venus or the Earth (e.g., Jakosky et al., 1995; Mischna et al., 2013; Ward, 1973). Once again, this behavior can act as an illustration of the different factors that could render a given "potentially habitable exoplanet" more, or less, suitable for life to develop and thrive—and as such, will help guide our efforts to select the best exoplanets to target in the search for life beyond the Solar System. Finally, studies of the Martian interior give us an insight to a planet with failed plate tectonics—offering ground truth for studies that model the range of planetary outcomes for which such tectonic activity is feasible.

## 3. The Giant Planets

The giant planets of the Solar System have long been the subject of fascination and scientific investigation. Similarly, many of the earliest confirmed that exoplanets were also giant, owing largely to the biases associated with most methods of exoplanet detection (Fischer et al., 2014). Giant planet. also hold most of the planetary mass and angular momentum of their respective planetary systems, making them key players in determining the final architectures of planetary systems generally (e.g., Childs et al., 2019; Kane, Turnbull, et al., 2020; Morbidelli et al., 2007). Schematics of the interiors of the Solar System's giant planets are shown in Figure 3 and indicate why these worlds are termed "gas giants" and "ice giants." Most of Jupiter and Saturn consist of some form of H and He, including metallic hydrogen, with traces of heavier gases and possibly even some rock and ice at their centers. Uranus and Neptune have much higher abundances of volatiles like water and ammonia than the gas giants but do not have internal pressures sufficient to generate metallic hydrogen. Instead, these ice giants may feature subcloud "oceans" of a slushy mix of mainly water and ammonia ices (e.g., Wiktorowicz & Ingersoll, 2007).

The presence of giant planets has often been suggested to influence the habitability of terrestrial planets within the same system (Georgakarakos et al., 2018; Sánchez et al., 2018). Such influence could include offering shielding from an impact regime that would otherwise render the planet sterile (e.g., Quintana et al., 2016). However, several studies have revealed that the situation is likely far more complex (e.g., Grazier, 2016; Grazier et al., 2018; Horner & Jones, 2008, 2009, 2012; Lewis et al., 2013), with giant planets acting as a source of potential impact threat. Yet such a role may be advantageous, as several models of the origin of Earth's water invoke an exogenous source, requiring the migration of giant planets to deliver volatiles during Earth's youth (see Section 5). Thus, the effects of impacts can have positive (volatile delivery) and negative (extinction events) consequences for terrestrial planets. At the same time, the influence of giant planets, or other significant perturbers, on the system orbital evolution may play an important role in shaping the climatic variability of potentially habitable worlds by influencing their Milankovitch cycles (e.g., Deitrick, Barnes, Bitz, et al., 2018; Deitrick, Barnes, Quinn, et al., 2018; Horner, Vervoort, et al., 2020; Kane, Vervoort, et al., 2020; Wolf et al., 2020).

Here, we address separately the two major classes of Solar System giant planet, the gas giants (Section 3.1) and the ice giants (Section 3.2) followed by a summary of open questions for giant planets (Section 3.3). The exploration of both groups is key to furthering our understanding of exoplanetary systems.

### 3.1. Gas Giants

Numerous spacecraft have visited the mighty gas giants, Jupiter and Saturn. Missions such as *Voyager 1* and *2*, *Galileo*, *Cassini–Huygens*, and *Juno* have directly explored the interiors, atmospheres, magnetospheres, rings, and satellites of these worlds and have discovered immense complexity. Rather than being a centrally condensed planet with distinct internal layers, Jupiter likely has a diluted, silicate-rich core that may extend to a substantial fraction of its radius (Wahl et al., 2017). Saturn may also have compositional gradients (Iess et al., 2019), despite evidence for a rocky core with mass ∼15 $M_\oplus$ (Movshovitz et al., 2020). Understanding the relation between interior complexity and bulk composition for gas giants is pivotal in interpreting exoplanet observations, which only yield the latter of properties. For example, Thorngren et al. (2016) found that the bulk heavy element masses of their sample of 47 giant planets only modestly changed when assuming different equations of state.

Exploration of the atmospheres of Jupiter and Saturn has also provide invaluable information for the interpretation of direct or indirect observations of exoplanet atmospheres. The Galileo entry probe measured

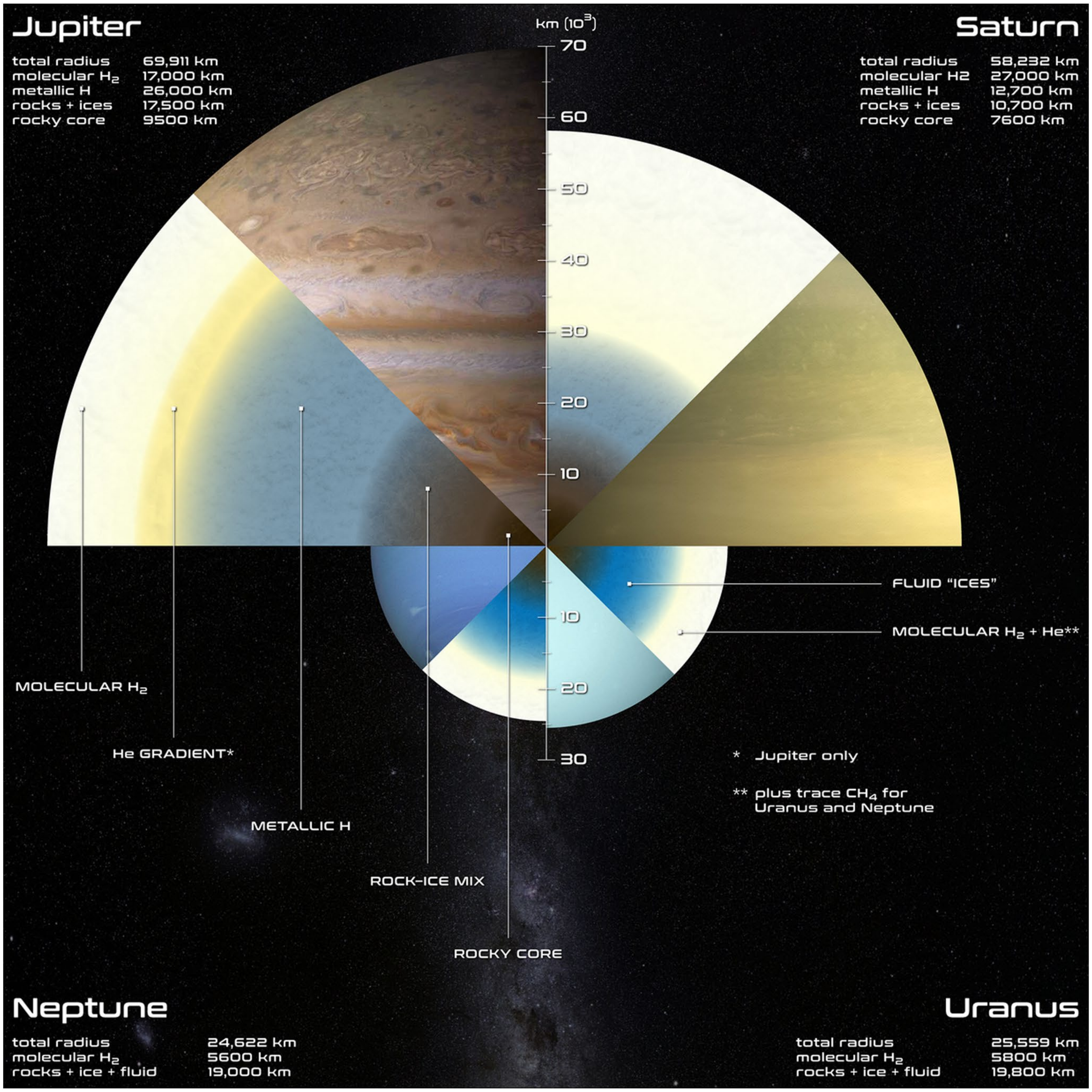


**Figure 3.** Schematic cross sections of the four giant planets of the Solar System, showing the major internal components. All cross sections are to scale, but the thickness for each component layer is only approximate (Spiegel et al., 2014). Those layer thicknesses are shown to the nearest 100 km for schematic purposes, but we emphasize that the interior structure of these words is not known to that level of precision. For this illustration, fluid "ices" are shown within Uranus and Neptune; other interior models are possible with available geophysical and spectroscopic data for these planets. Even so, note the substantial differences between the interiors of the "gas giants," Jupiter and Saturn, and those of the "ice giants," Uranus and Neptune.

the abundances of various gas species in Jupiter's atmosphere including He, which was necessary to interpret the thermal evolution of the planet (e.g., von Zahn et al., 1998). The probe measured abundances of heavy elements C, N, S, and P and the heavy noble gases Ar, Kr, and Xe that were enhanced relative to solar by a factor of 2–4 (Mahaffy et al., 2000; Wong et al., 2004), measurements that are critical for understanding Jupiter's formation (Gautier et al., 2001; Mousis et al., 2019; T. Owen et al., 1999). Remote-sensing measurements suggest that Saturn is enriched in C (Lellouch et al., 2001), S (Briggs & Sackett, 1989), and P (Fletcher et al., 2009) by a factor of 10–12 relative to solar but N is only enriched by a factor of ∼2 (Fletcher et al., 2011) which could have important implications for the formation of Saturn (K. Mandt, Mousis, Lunine, et al., 2020; K. E. Mandt, Mousis, & Treat, 2020). The *Galileo* probe showed that Jupiter is depleted in He and Ne because helium likely precipitates as droplets in the deep atmosphere (Stevenson & Salpeter, 1977a) with neon being sequestered in these droplets (Wilson & Militzer, 2010). Saturn is also depleted in He by the same process, but no Ne measurement is available because noble gases heavier than He can only be measured by a probe (Mousis et al., 2014). The *Galileo* probe also found a depletion in oxygen (Mahaffy et al., 2000), frequently interpreted to mean that the probe sampled a meteorologically anomalous region of Jupiter's atmosphere (Orton et al., 1998). The *Juno* mission instead discovered deep currents that circulate ammonia and water around the planet (Bolton et al., 2017; C. Li et al., 2017, 2020). The in situ measurements from the *Galileo* probe have been most valuable for providing tools that can be used to determine how giant planets formed and evolved since formation (e.g., K. Mandt, Mousis, Lunine, et al., 2020; K. E. Mandt, Mousis, & Treat, 2020, and references therein). In situ observations of the giant planets are important for exploring giant exoplanet formation and evolution. In particular, comparisons of the relative abundances of heavy elements (e.g., C/N) provide a direct comparison for Solar System analog exoplanets—or at the very least a necessary starting point for models of more exotic (e.g., highly irradiated) giant exoplanets for which no direct analog exists in the Solar System.

### 3.2. Ice Giants

The so-called ice giants, Uranus and Neptune, are particularly notable in regards to exoplanets because they represent examples of what seems to be the most common type of exoplanet yet detected. By size, the majority of exoplanets within 100 days orbital period have radii between that of Earth and those of Uranus and Neptune (e.g., Fulton & Petigura, 2018). Importantly, this class of exoplanet does not occur among the ranks of the Solar System, and there appear to be significant differences between their composition and formation compared with the Solar System ice giants (Lee, 2019; J. E. Owen & Wu, 2017). Even so, there remain many questions as to how mass, radius, and bulk density affect or are related to the interior structure of the ice giant planets. Further challenges in modeling the ice giant interiors relate to the nondipolar and nonaxisymmetric nature of their magnetic fields (Nellis, 2015; Ruzmaikin & Starchenko, 1991), particularly in relation to the dynamics and chemistry of their upper and deep atmospheres (Redmer et al., 2011; Stanley & Bloxham, 2004). Uranus and Neptune (and the Earth) bookend a much larger demographic that includes rocky and gaseous planets. Coming from the large end of this transitional regime, Uranus and Neptune are best windows we have to most common class of exoplanet yet known (Kane, 2011; Wakeford & Dalba, 2020).

Uranus and Neptune have only been the subjects of flybys by the *Voyager 2* spacecraft and of Earth-based observation (e.g., Fletcher et al., 2014; Lindal, 1992; Lindal et al., 1987; B. A. Smith et al., 1986, 1989; Tyler et al., 1986). They have not yet been explored with orbiters or entry probes, despite compelling planetary and exoplanetary motivation (e.g., Atreya et al., 2020; K. Mandt, Mousis, Lunine, et al., 2020; K. E. Mandt, Mousis, & Treat, 2020; Mousis et al., 2020; Wakeford & Dalba, 2020). Such a mission could provide much needed context for to the growing number of mass, radius, and atmospheric abundance measurements being acquired for exoplanets. One aspect of the ice giants fundamental to understanding exoplanets is their interior structures. A three-layer model of rock, ice, and H–He gas is often employed in studies of these worlds but yields results that are at odds with the expected interior ice–rock ratios of Uranus and Neptune (Nettelmann et al., 2013). Furthermore, the formation and migration of Uranus and Neptune are key points for comparison with exoplanets that may have either formed closer to their host star through different mechanisms or experienced substantially different migration histories. Had Uranus and Neptune formed via core accretion (Mizuno, 1980; Pollack et al., 1996) at their current orbits, the time scale of their formation would be longer than the lifetime of the protosolar nebula (Pollack et al., 1996). This complication can be overcome with various assumptions involving planetary migration (e.g., Dodson-Robinson & Bodenheimer, 2010), but accurately reproducing the measured properties of Uranus and Neptune requires very finely tuned conditions (Helled & Bodenheimer, 2014). On one hand, planetary migration likely accounts for the wide diversity of exoplanets similar in size and mass to Uranus and Neptune since, as described by Helled and Bodenheimer (2014), the mass and solid-to-gas ratios are sensitive to the birth environments of the planets. On the other hand, this freedom in parameter space necessitates that specific information for Uranus and Neptune be obtained with which to constrain prospective formation scenarios; that information can be attained by future exploration of the Solar System's ice giants (K. Mandt, Mousis, Lunine, et al., 2020; K. E. Mandt, Mousis, & Treat, 2020; Mousis et al., 2020).

### 3.3. Outstanding Questions

The giant planets are important analogs for a large number of known exoplanets. Exploring the four giant planets in our Solar System allows us to better understand the formation and evolution of both gas and ice giants as well as the opportunity to explore how giant planets migrate after formation. Observations that have provided important advancements in understanding the giant planets as exoplanet analogs include the *Galileo* probe measurements (e.g., Atkinson et al., 1998; Folkner et al., 1998; Niemann et al., 1998; Sromovsky et al., 1998; von Zahn et al., 1998; Wong et al., 2004) and *Juno* and *Cassini* gravity measurements (e.g., Buccino et al., 2020; Duer et al., 2020; Folkner et al., 2017; Guillot et al., 2018; Iess et al., 2019; Kaspi et al., 2017; Moore et al., 2017; Movshovitz et al., 2020; Stevenson, 2020; Wahl et al., 2017). Some of the most significant remaining science questions for understanding the giant planets in the context of exoplanetary science include

1. How did the giant planets in our Solar System form and how did they evolve internally after formation? How has this affected the composition of the observable atmosphere (e.g., Atreya et al., 2020; Bodenheimer & Pollack, 1986; Dalba et al., 2015; Fortney & Nettelmann, 2010; Helled & Bodenheimer, 2014; Koskinen & Guerlet, 2018; Mizuno, 1980; Nettelmann et al., 2013; Pollack et al., 1996; Stevenson & Salpeter, 1977b)?
2. Did the giant planets migrate after formation and how did this migration impact the architecture of the Solar System (e.g., Clement, Kaib, et al., 2019; Goldreich & Tremaine, 1980; Gomes et al., 2005; Ida & Lin, 2004; Lin & Papaloizou, 1986; Morbidelli, 2010; Tsiganis et al., 2005; Walsh & Morbidelli, 2011; Walsh et al., 2011)?
3. Why are the magnetic fields of the ice giants so drastically different from any other magnetic fields in our Solar System and what does that mean for the interiors of the ice giants (e.g., Connerney, 1993; Helled et al., 2010, 2020; Jacobson, 2009, 2014; Stanley & Bloxham, 2004, 2006; Warwick et al., 1986, 1989)?
4. How would the phase curves of the four giant planets compare to what future direct imaging missions will observe in exoplanetary systems (e.g., MacDonald et al., 2018; Madhusudhan & Burrows, 2012; Mayorga et al., 2016; Mendikoa et al., 2017)?

Understanding how our own giant planets formed and evolved and how this has impacted the composition of the atmosphere is important for interpreting measurements of giant planet atmosphere composition and connecting these measurements to the history of that planetary system. Furthermore, we are only beginning to understand the role that the migration of giant planets plays in the architecture of a planetary system and the delivery of volatiles, particularly water, to planets that formed inside the water ice line. Understanding magnetic fields is fundamental to interpreting the near space environment of an exoplanet and how its star influences its atmosphere. The least understood and most surprising magnetospheres in our Solar System are those of Uranus and Neptune, which demonstrate how little we truly understand about giant planet magnetospheres. Until we have a better understanding of them, we will be limited in what we can learn about exoplanets. Finally, observations of the phase curves of all four giant planets (including polar perspectives for comparison to face-on, directly imaged systems) are critical for interpreting the phase curves that we will eventually measure for exoplanets.

## 4. Icy Moons

Given the prevalence of satellites within the Solar System, substantial effort is being devoted to the search for moons orbiting exoplanets (e.g., Heller et al., 2014; Hill et al., 2018; Hinkel & Kane, 2013; Kipping et al., 2013). Furthermore, formation of regular moons, such as those in the Galilean system, may serve as analogs of compact exoplanetary systems in terms of their formation and architectures (Batygin & Morbidelli, 2020; Dobos et al., 2019; Kane, Hinkel, et al., 2013; Makarov et al., 2018). However, there are numerous questions that remain regarding the wide array of moons in the Solar System, including their geology and, in some cases, atmospheres. The icy satellites of the giant planets may serve as small-scale analogs for low-mass, water-rich exoplanets, that is, so-called "ocean planets." Ocean planets are a class of terrestrial exoplanets with substantial water layers that may be common throughout the galaxy (Ehrenreich & Cassan, 2007; Léger et al., 2004; Raymond et al., 2006; Sotin et al., 2007), and which are likely to have $H_2O$ contents at least an order of magnitude greater than Earth's ∼0.1% $H_2O$ content. Ocean planets may exist in one of a variety of climactic states including, ice-free, partially ice covered, and completely frozen (Quick et al., 2020; Tajika, 2008); those with highly eccentric orbits may well also possess substantial amounts of internal energy owing to tidal heating from their host stars. As liquid water and energy are both necessary ingredients for life, ocean planets represent prospective habitable environments beyond typical Earth-like environments in the traditional HZ (Glaser et al., 2020). Indeed, even those such worlds that are mostly ice covered may have considerable regions of unfrozen land near their equators or small, equatorial regions of salt-rich water where life could flourish (Del Genio et al., 2019; Olson et al., 2020; Paradise et al., 2019).

Shown in Figure 4 is a representation for the interior structures of the icy moons of our outer Solar System's giant planets, highlighting the diversity of internal structures. Studying the interiors, tidal properties, and evolution of these moons may provide similar key insights into the properties of ocean planets (Barr et al., 2018; Ehrenreich & Cassan, 2007; Henning & Hurford, 2014; Journaux et al., 2020; Luger et al., 2017; Noack et al., 2016; Sotin et al., 2007; S. Vance et al., 2007; Yang et al., 2017). Owing to their similar internal structures, geophysical processes operating on ocean planets with ice-covered surfaces may be similar to geophysical processes operating on the moons of the giant planets and may include ice tectonics (Fu et al., 2010; Hurford et al., 2020; Levi et al., 2014), and cryovolcanism (Levi et al., 2013; Quick et al., 2020). Although the specular reflection of starlight, or "glint," on the surfaces of ocean-covered planets will make them fairly easy to detect at visible and near-IR wavelengths (Lustig-Yaeger et al., 2018; Robinson et al., 2010; Visser & van de Bult, 2015; Williams & Gaidos, 2008), the high albedos of ocean planets with ice-covered surfaces will make them far more detectable than rocky planets in reflected light (Wolf, 2017). Many ocean planets may resemble Saturn's largest moon Titan (Figure 4), where the presence of a dense atmosphere allows for the maintenance of liquid at its surface (Lora et al., 2015). With its active methane cycle (Dalba et al., 2012; Hörst, 2017; Levi & Cohen, 2019; Turtle et al., 2011), Earth-like shorelines (Lunine & Lorenz, 2009), diverse geological processes (Jaumann et al., 2009), and the potential for prebiotic chemistry (C. He & Smith, 2014; Neish et al., 2009), Titan serves as an analog for ocean planets that are similar to Earth in nature. Haze in the atmospheres of Titan-like exoplanets could be detected by next-generation space telescopes (Checlair et al., 2016; Lora et al., 2018; Robinson, Maltagliati, et al., 2014), thereby revealing the atmospheric compositions of numerous ocean planets.

### 4.1. Minor Planets

Our Solar System informs our understanding of volatile distribution and planet migration, especially from careful study of its minor bodies: asteroids and Edgeworth–Kuiper belt objects. Asteroids, and the meteorites that sample them, map out the distribution of water in our protoplanetary disk. For excellent reviews of different meteorite types, and their connections to asteroids, we refer the reader to Weisberg et al. (2006) and DeMeo et al. (2015). Asteroids are categorized by their reflectance spectra. Three main types are E-type asteroids, at ≈1.9–2.1 AU; S-type asteroids, at ≈2.1–2.7 AU and beyond; and C-type asteroids, at 2.7–3.5 AU, though some lie interior to these distances (Binzel et al., 2019; Gradie & Tedesco, 1982). Meteorites from unmelted asteroids are termed chondrites and are categorized according to major elemental distributions as well as isotopic anomalies (Weisberg et al., 2006) and are presumed to come from parent bodies sampling a variety of heliocentric distances in the protoplanetary disk. The different asteroids are spectrally associated with the three main types of chondrites: enstatite chondrites (ECs), associated with E-type asteroids; ordinary chondrites (OCs), with S-type asteroids; and carbonaceous chondrites (CCs), with C-type asteroids (Binzel et al., 2019; Gaffey et al., 1993). Generally, CCs are the most volatile rich, with abundant hydrated phases equivalent to a few wt% $H_2O$ in CO and CV CCs, up to 13 wt% in CM and CI CCs (Alexander et al., 2013). ECs are the least volatile rich, with no hydrated phases, and sulfides and other reduced miner-

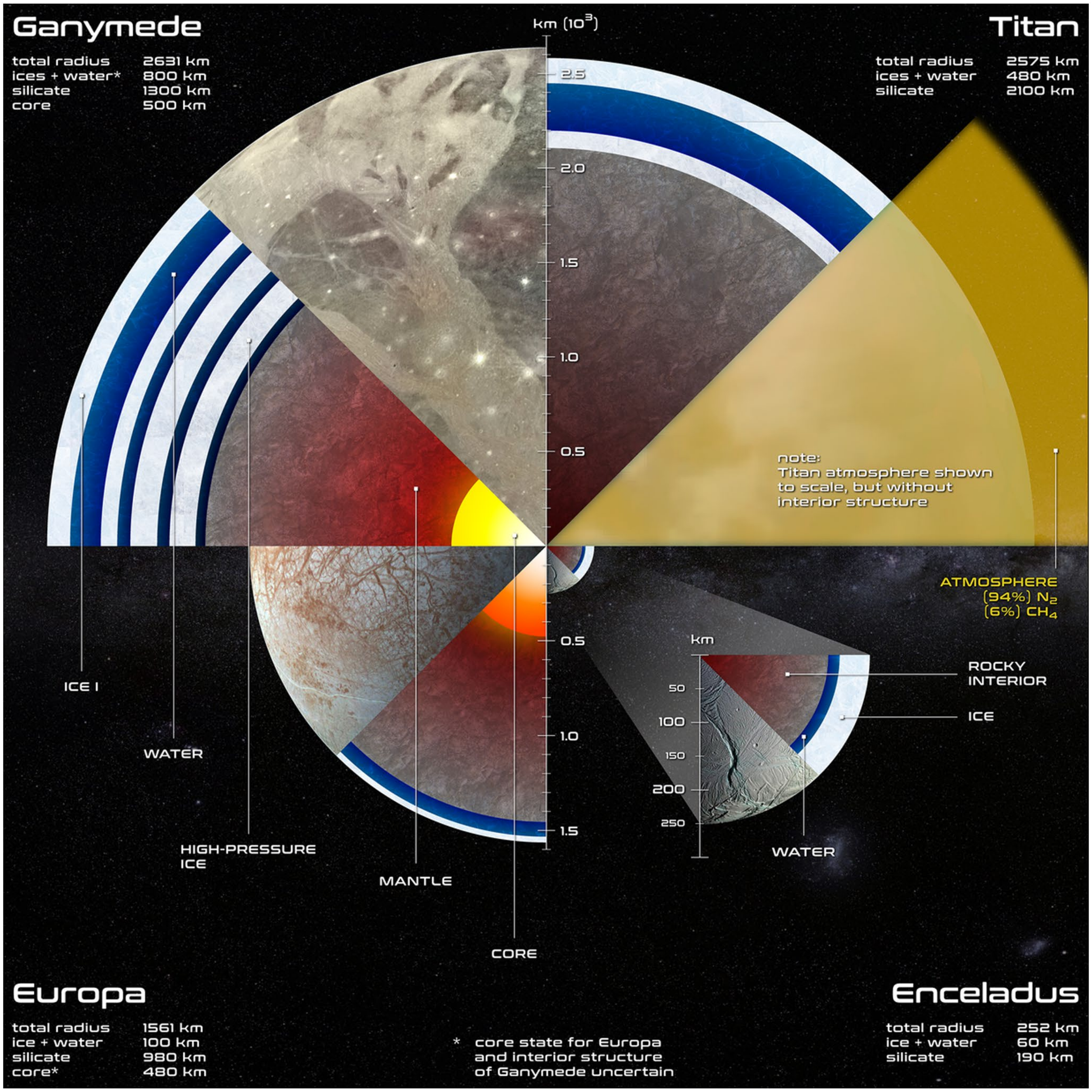


**Figure 4.** Schematic cross sections of four of the Solar System's major icy moons, showing the major internal components. All cross sections are to scale, but the depths to each component layer are only approximate (based on the interior structure models of S. D. Vance et al. [2018]). Depths are given to the nearest 10 km, such that aggregate depths may not match known planetary radii values. For this illustration, the interior of Ganymede is shown with interleaved oceans and (high-pressure) ice layers, but other internal arrangements are possible.

als that would have been destroyed by water on the parent body. OCs have ~0.1–1 wt% $H_2O$, indicating that they formed outside the $H_2O$ snow line, but in a region with much lower water ice abundance than where most CCs formed. C-type asteroids appear to have been scattered into their present orbits from beyond Jupiter, but E-type and S-type asteroids seem to have formed in place (Walsh et al., 2011). This places the snow line between where ECs and OCs may have formed, that is, at 2 AU, at the time they formed, about 2 Myr (Desch et al., 2018).

Earth formed inside the snow line (Raymond et al., 2004; Wetherill, 1990) but acquired water by accreting materials from beyond the snow line. From an elemental and isotopic perspective, Earth resembles a mix of about 71% ECs, 24% OCs, and 5% CCs, of type CO or CV (Dauphas, 2017). Assuming the 29% of its mass that is OCs and CCs had ~1 wt% $H_2O$, Earth would have roughly 0.003 $M_{\oplus}$ of $H_2O$ (or about 12 oceans' worth of water), a good match to the inferred amounts of hydrogen in Earth's core, mantle, and surface, equivalent to about 0.002 $M_{\oplus}$ (Wu et al., 2018). But Earth could have had much more water if it had accreted a larger fraction of material from beyond the snow line, or especially if the material just beyond the snow line was more water rich. OCs, despite forming in a region cold enough for water ice to condense, ended up containing only 0.1–1 wt% water, instead of the few to 13 wt% $H_2O$ seen in CCs. Morbidelli et al. (2016) explained this in terms of a "fossil snow line," in which Jupiter formed and grew large enough to open a gap in the disk (more precisely, create a pressure maximum in the disk outside its orbit), while the snow line was exterior to Jupiter; later, even as accretion waned, the disk cooled and the snow line formally moved inward, ice could not follow because most of it was bound in large (cm-sized) particles that remained trapped in the pressure maximum. Similar ideas were invoked by Kruijer et al. (2017) to explain the isotopic dichotomy of the Solar System and by Desch et al. (2018) to explain the distribution of calcium-rich, aluminum-rich inclusions in chondrites. In both models, Jupiter must grow to 20–30 $M_{\oplus}$, to create a pressure maximum by about 0.4–0.9 Myr. The detailed disk model of Desch et al. (2018), which includes accretion heating and is tailored to fit multiple constraints from 18 different meteorite types, predicts the snow line at 2 Myr should have been at 2 AU and conforms to the fossil snow line model of Morbidelli et al. (2016).

In our Solar System, the snow line in the protoplanetary disk stage was at 2 AU (Rubie et al., 2015), just beyond the (future) HZ at about 1 AU, leading Earth to be a habitable, but relatively volatile-poor (0.025 wt% surface $H_2O$) planet. The relative positions of the HZ and snow line would be different in exoplanetary systems around other stars, since they have different dependencies on the luminosity and effective temperature of the host star. For example, the HZ planets orbiting the late M star TRAPPIST-1 may be more volatile rich than the Earth. The masses and radii of planets f and g, orbiting in the HZ of TRAPPIST-1, seem to demand ≈50 wt% $H_2O$ (Unterborn et al., 2018). These planets likely formed much farther (perhaps 4 times farther) from their host star, beyond the snow line, and then migrated inward (Unterborn et al., 2018). Migration is supported by the fact that all the planets are nearly in mean motion resonances, with period ratios supportive of convergent migration (Steffen & Hwang, 2015). For the Solar System, both the inward and outward migration of the giant planets is strongly signposted by the distribution of the Solar System's small body populations—with such migration having sculpted the Asteroid and Edgeworth–Kuiper belts (e.g., DeMeo & Carry, 2014; Hahn & Malhotra, 2005; Levison et al., 2008; Minton & Malhotra, 2009; Morbidelli et al., 2010) and resulted in the capture of the Jovian and Neptunian Trojans (e.g., Lykawka & Horner, 2010; Lykawka et al., 2009; Morbidelli et al., 2005; Pirani et al., 2019) and the Plutinos (e.g., Malhotra, 1993, 1995).

While the rocky planets in our Solar System do not appear to have migrated, minor bodies strongly indicate that the giant planets migrated. The asteroid belt today has only about 0.1% of the rocky mass that probably existed between 2 and 3 AU during the protoplanetary disk phase, and S-type and C-type asteroids are commingled in this region, both facts possibly explained by Jupiter's migration (Minton & Malhotra, 2009; Walsh et al., 2012). Meteorites appear to record several large impacts in the Solar System around 5 Myr, including the impact of the ureilite parent body (Amelin et al., 2015) and the CH/CB parent body (Krot et al., 2008). Presumably, the outward migration of Jupiter in either model would have depleted the asteroid belt and scattered the C-type asteroids into the asteroid belt. Large-scale migration of Jupiter is not necessarily demanded to mix C-type and S-type asteroids in the asteroid belt (e.g., Raymond & Izidoro, 2017), but it is a common feature of dynamical models of the early Solar System (Clement, Raymond, et al., 2019; Tsiganis et al., 2005). The models of both Walsh et al. (2011) and Desch et al. (2018) rely on the rapid (~$10^5$ years) migration of Jupiter and Saturn while <10 $M_{\oplus}$, then slower (>$10^6$ years) migration after growing to masses large enough to open a gap in the disk, as commonly theorized for growing planets (e.g., Bitsch et al., 2015). Thus, studies of Solar System minor bodies reveal important lessons for understanding rocky exoplanets and the role of Jupiter analogs and suggest that the majority of systems may have more volatile-rich rocky exoplanets but might be characterized by even more orbital migration.

## 5. Exoplanets and Observables

While the Solar System is our best studied example of a planetary system, observations of exoplanets have expanded our horizons to reveal planets and planetary system architectures that are unknown in our home system. These alien systems have helped reveal key planetary processes that refine our understanding of how our own planets and planetary system might have formed and evolved. In particular, the discovery of planetary types not found in the Solar System, including hot Jupiters, sub-Neptunes, and volatile-rich terrestrials, has helped us better understand fundamental processes such as atmospheric loss and planetary migration that have also sculpted our own planets. Shown in Figure 5 are four examples of exoplanets shown to scale but spanning a broad range of size, density, interiors, and atmospheres. These include Kepler-1647b, a Jupiter analog orbiting a binary star (Kostov et al., 2016), HD 149026b, a dense, giant planet with large core (Sato et al., 2005), GJ 1214b, a water-rich mini-Neptune (Charbonneau et al., 2009; Rogers & Seager, 2010), and TRAPPIST-1f, a potential ocean-planet in the HZ (Gillon et al., 2017; Unterborn et al., 2018). Though super-Earth and mini-Neptune planets are not represented in the Solar System, GJ 1214b and TRAPPIST-1f may represent two examples of ocean worlds, possibly similar to icy moons of the Solar System, described in Section 4.

The observing techniques used to study exoplanets are currently most sensitive to planets that are close to (via transit and radial velocity) or very far from their stars (via direct imaging and astrometry) and the region in between where most of the Solar System planets would reside is currently relatively inaccessible. This lack of overlap makes it more difficult to place our Solar System in its true cosmic context but nonetheless provides an excellent opportunity to study planetary systems very unlike our own that challenge long held concepts. These include systems, some orbiting G dwarfs like our Sun, where multiple planets are found within the equivalent of the orbit of Mercury (Lissauer, Ragozzine, et al., 2011), speaking to the importance of planetary migration as a fundamental system process (e.g., Gillon et al., 2017; Luger et al., 2017; Ramos et al., 2017; Unterborn et al., 2018; Walsh & Morbidelli, 2011), and also highlighting the likely importance of gravitational interactions and tidal heating, seen primarily in the giant planet satellites in our system, to close-in exoplanets. Extrapolations of the likely demographics in the not yet fully explored regions of exoplanet systems also hint at the relative rarity of Jupiters, with only about 10% of solar type stars and 3% of M dwarfs harboring giants inside of 10 AU (Wittenmyer et al., 2016, 2020; Zechmeister et al., 2013). Upcoming observations, including the Roman Space Telescope microlensing survey, will detect many more planets at similar distances to their star as our planets and provide the statistics needed to better understand how common planetary Systems like the Solar System are in our galaxy (Penny et al., 2019). The direct imaging capabilities of Roman will be able to access analogs of both Jupiter and Neptunes, providing rare insights into the atmospheres of ice giants external to the Solar System (Lacy et al., 2019).

After over a decade of giant exoplanet characterization, the field is on the brink of terrestrial exoplanet atmosphere observations. We have obtained transmission spectra of a suite of hot Jupiters, revealing a diversity of giant worlds with a range of different atmospheric compositions, clear or cloudy atmospheres, and temperature profiles with strong stratospheric inversions or none at all (Sing et al., 2016). Observations of exo-Neptunes are now state of the art (Crossfield & Kreidberg, 2017), revealing flat to water absorption dominated spectra that show possible trends in composition with size, with the smaller planets having a higher fraction of elements heavier than hydrogen. These trends are similar to those seen in atmospheric composition for Solar System giants. But perhaps the most exciting advances of all are the first observational constraints on terrestrial-sized worlds. Transmission spectroscopy of the Earth-sized TRAPPIST-1 planets rule out cloud-free, $H_2$-dominated atmospheres (de Wit et al., 2016, 2018; Wakeford et al., 2019), and a combination of laboratory work and modeling suggests that the atmospheres of these worlds, if they exist are also unlikely to be $H_2$-rich and cloudy (Moran et al., 2018). These combined constraints suggest that these terrestrial worlds may have high-molecular-weight atmospheres like the terrestrial planets in our own system, although the data are also consistent with no atmospheres at all. With the launch of the James Webb Space Telescope, observations of the TRAPPIST-1 system and other nearby terrestrial worlds will have the capability to detect the presence and composition of atmospheres (Lincowski et al., 2018; Lustig-Yaeger et al., 2019b; Morley et al., 2017; Wunderlich et al., 2019), potentially revealing past processes like atmosphere and ocean loss (Lincowski et al., 2018, 2019; Lustig-Yaeger et al., 2019a). These observations may also provide our first opportunity to search for signs of life, such as $CH_4$ in combination with other

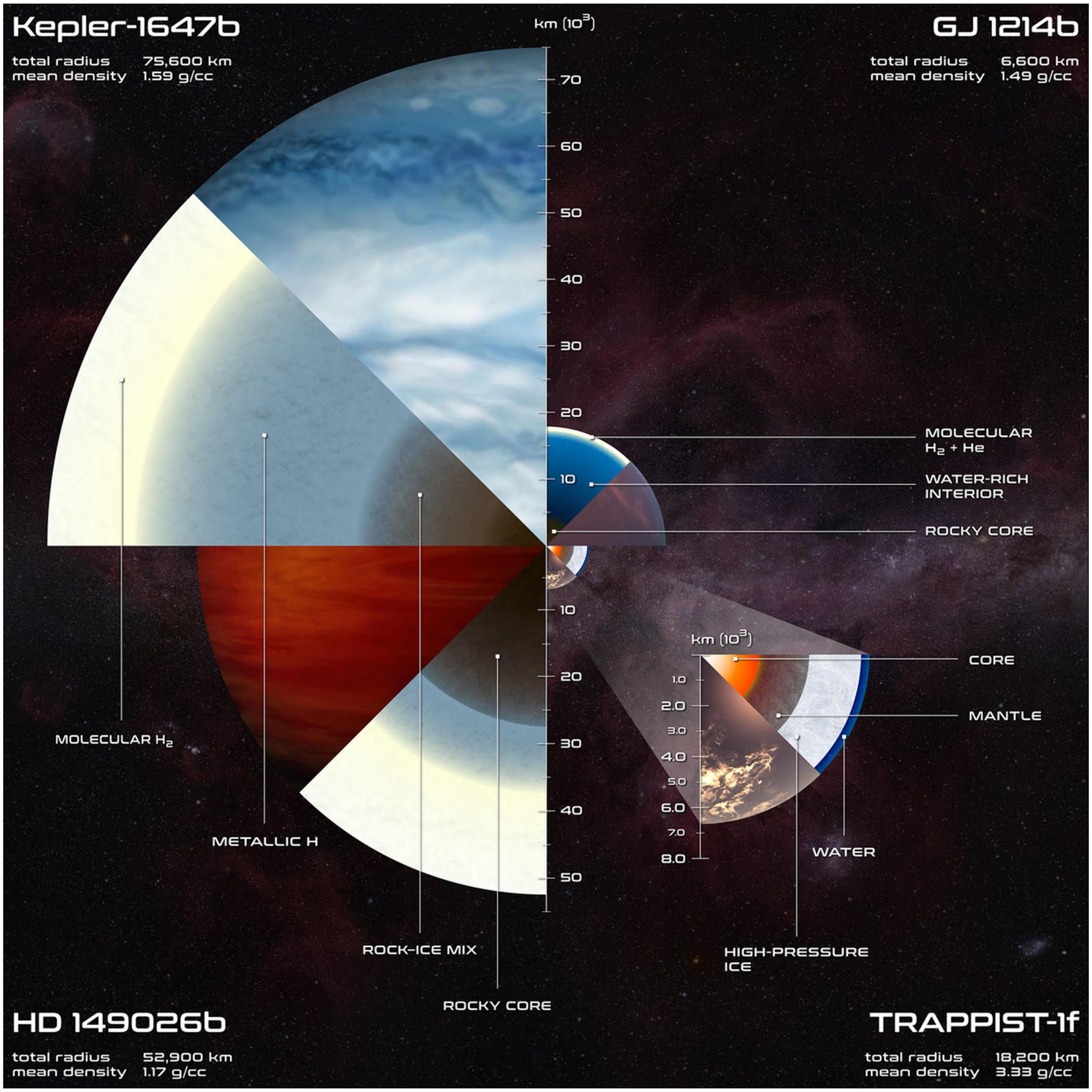


**Figure 5.** Schematic cross sections of four selected exoplanets that span a broad range of sizes and predicted interior structures and compositions: Kepler-1647b, HD 149026b, GJ 1214b, and TRAPPIST-1f. All cross sections are qualitatively to scale, but the structure and composition of these interiors, and of these planets' atmospheres, are uncertain and are shown here for illustrative purposes only. Kepler-1647b and HD 149026b are analogous to the Solar System gas giants and TRAPPIST-1f may be analogous to Venus and/or Earth. GJ 1214b is likely a water-rich mini-Neptune that represents a size regime between that of Earth and Neptune. The radii and density values are from the NASA Exoplanet Archive (Akeson et al., 2013).

biosignatures, in the atmosphere of a terrestrial exoplanet (Krissansen-Totton, Garland, et al., 2018; Wunderlich et al., 2019), and complement observations from the ground with extremely large telescopes that will search for $O_2$ using high resolution spectroscopy (López-Morales et al., 2019; Lovis et al., 2017).

Arguably, the overarching goal of exoplanetary science is to find reliable pathways toward accurate characterization of exoplanet atmospheres, surfaces, and interiors. Fundamental exoplanet observables such as mass and radius can be used to determine density, which in turn constrains planetary bulk composition. Transmission observations and direct imaging can reveal atmospheric composition, and in the case of direct imaging, potentially surface composition as well. However, correct interpretation of all of these data relies upon models of planetary processes that are best developed and validated using in situ or remote-sensing observations of Solar System bodies (Fujii et al., 2014). Similarly, observations of Solar System bodies, even very fundamental ones like phase-dependent photometry of the Jovian planets (Mayorga et al., 2016), or simulated transmission observations of Titan (Robinson, Maltagliati, et al., 2014) or the Earth (Macdonald & Cowan, 2019) can help inform planning and interpretation of exoplanet observations and help us train predictive (forward) and retrieval (inverse) models for exoplanets.

Both the exoplanet and Solar System planetary communities are moving toward a more systems and processed-based approach to understanding planet formation, evolution, habitability, and biosignatures. These approaches require the synthesis of observations, theory, and laboratory work from multiple disciplines, and it is very clear that the two communities can benefit greatly from the knowledge and perspectives provided by both of their fields. As described above, planetary science forms the foundation, both in terms of data and models, from which exoplanet observables may be interpreted. In turn, exoplanet observables provide vast numbers of exoplanets from which demographic studies can inform the studies of planetary system formation and evolution in general (e.g., Barclay et al., 2017; Clanton & Gaudi, 2016; E. L. Nielsen et al., 2019). Measurements (both direct and indirect, respectively) from planetary science and exoplanet observables feed into the inferred properties of planetary bodies generally and, in particular, the potential surface conditions of a terrestrial exoplanet that may have temperate surface conditions. Models that are well validated on Solar System bodies, especially Earth, will be particularly critical for the difficult task of inferring the presence of life on an exoplanet from possible observed biosignatures. Indeed, this may be the most challenging task faced by planetary scientists in the coming decades when spectral observations of potentially habitable terrestrial planets become possible, and interdisciplinary collaborations of scientists will be essential to its success.

The pathway forward therefore lies in identifying the key measurables from Solar System bodies, through in situ observations with spacecraft missions and those taken on and in orbit of Earth (Jiang et al., 2018; Robinson et al., 2011), needed to correctly interpret exoplanet observables and infer their properties. In the near-term, the most critical data needed from planetary science are atmospheric measurements that can constrain composition, chemistry, dynamics, and evolutionary history, particularly for poorly understood atmospheres such as those of Venus (Kane et al., 2019), Titan (Checlair et al., 2016), and the ice giants (Wakeford & Dalba, 2020). Beyond modeling the nature of exoplanet atmospheres and inferring possible surface conditions lies the complex task of modeling how the interior and surface have previously, and are currently, interacting with the atmosphere. In particular, a major challenge lies in distinguishing between biotic and abiotic processes that yield gases of biological significance (e.g., $CH_4$, $CO_2$, and $H_2O$), the signatures of which can be detected from studying atmospheric abundances (Fujii et al., 2018; Harman et al., 2018; Meadows, 2017; Wogan & Catling, 2020).

## 6. Conclusions

In the current era, there are two separate but complementary fields: planetary science and exoplanetary science. Historically, the reason for the separate pathways of the two fields resulted from exoplanet detection primarily being a task of stellar characterization by stellar astronomers, from which the presence of a companion of planetary size and/or mass may be inferred, whereas planetary science has focused on specific worlds within the Solar System. However, discoveries of terrestrial exoplanets have provoked further discourse between the disciplines as we strive toward a common objective of leveraging Solar System data toward a deeper understanding of the exoplanet observables. In time, we may come to understand planetary bodies at the systems level, with perhaps the ultimate goal to understand where else in the cosmos we might search for, and find, life.

Planetary science has an exceptionally long history of ground and space-based observations of Solar System bodies, along with robotic exploration and in situ analysis of atmospheres, surfaces, and interiors. These data have provided the foundation for our fundamental understanding of planetary processes and the signatures that those processes produce. In this work, we have provided a brief overview for some of the research highlights of planetary science, particularly as these discoveries relate to exoplanets. Although we have presented this information in categories of terrestrial planets, giant planets, moons, and minor bodies, there is clearly substantial overlap between these classes of objects in their formation, structure, evolution, and interaction with each other. Additionally, we have outlined some key questions that remain for various Solar System bodies, the answers of which will further inform the models used in the interpretation of exoplanet observations.

Given the increasing rate of exoplanet discoveries and the rapid expansion of exoplanet characterization studies, the trajectory of exoplanetary science in the years ahead is expected to require detailed modeling of planetary atmospheres and their interaction with surface and interior processes. As described in this work, near-term testing of exoplanet models will rely on Solar System data, and indeed the design of many recent Solar System exploration proposals is incorporating science goals that specifically benefit anticipated studies of exoplanets. Furthermore, laboratory experiments are being conducted that provide the framework for interpreting molecular absorption in exoplanet atmospheres (C. He et al., 2020; Hörst et al., 2018; Moran et al., 2020; Tennyson & Yurchenko, 2017). Therefore, it is expected that the continuing reliance of exoplanetary science on Solar System exploration will provide enormous benefits for both fields of research as the vast data provided by the plethora of exoplanets answer significant questions regarding the context and uniqueness of the Solar System and, ultimately, the prevalence of life in the universe.

## Data Availability Statement

Data were not used nor created for this research.

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