The Structure of Exoplanets

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The hundreds of exoplanets that have been discovered in the past two decades offer a new perspective on planetary structure. Instead of being the archetypal examples of planets, those of our Solar System are merely possible outcomes of planetary system formation and evolution, and conceivably not even terribly common outcomes (although this remains an open question). Here, we review the diverse range of interior structures that are known to, and speculated to, exist in exoplanetary systems — from mostly degenerate objects that are more than 10 times as massive as Jupiter, to intermediate-mass Neptune-like objects with large cores and moderate hydrogen/helium envelopes, to rocky objects with roughly the mass of the Earth.

Introduction

How can we, from many light years away, learn about the interior structure of exoplanets? Radial velocity (RV) observations provide minimum masses of exoplanets; transit observations provide planet radii. Taken singly, neither is terribly informative about planet structure. However, when we know both the mass and the radius of a planet we may learn much more about the interior structure. The *Kepler* satellite [1, 2] is a space-based, transit-detecting mission that, as of early 2013, has identified of order ~100 planets and roughly 3000 planet candidates, of which the vast majority are almost certainly real [3, 4]. Thanks to *Kepler* and ground-based efforts such as the HAT and Super-WASP transit surveys [5, 6], there are now more than 200 known planets with measured masses and radii, spanning a range of irradiation conditions.

Figure 1 portrays how planet radii relate to masses and incident fluxes, among the known planets (including the Solar System planets) and the *Kepler* candidates (*Kepler objects of interest* – KOI) [7, 8]. Several trends are apparent in the data: planets with the largest radii tend to be near Jupiter's mass and highly irradiated; and, *Kepler* seems to find low-radius planets at a wide range of orbital separations, including some small planets that are extremely highly irradiated.

In the remainder of this paper, we discuss what is known of the structure of the most massive planets ("Gas Giants"), of intermediate-mass planets ("Neptunes"), and of low-mass planets ("Terrestrial and Ocean Planets"). We conclude by considering how our knowledge of exoplanet structure might improve over course of the next decade.

Gas Giants

Jupiter and Saturn are essentially giant spheres of hydrogen and helium ("H/He") with smaller contributions from heavier elements and complex molecules. Many of the known exoplanets have similar mass and similar radius to our local gas giants, and probably have roughly similar bulk structure. The atmosphere, or weather layer, of such an object is a thin outer region that is of roughly the same relative depth as the skin of a grapefruit, and is typically defined as the region above the radiative-convective boundary,[1] which can be

at pressures of order ~kilobar for the most strongly irradiated planets and which occurs in the vicinity of ~1 bar in gas giants subjected to lower irradiation, such as Jupiter and Saturn. Below the radiative-convective boundary, there is a deep envelope extending almost the entire radius of the planet in which opacities are high enough that heat must be transported via convection; this region is presumably well-mixed in chemical composition and specific entropy. Some gas giants have heavy-element cores at their centers, although it is not known whether all such planets have cores.

Gas-giant planets of roughly Jupiter's mass occupy a special region of the mass/radius plane. At low masses, liquid or rocky planetary objects have roughly constant density, and suffer little compression from the overlying material. In such cases, $R_p \propto M_p^{1/3}$, where R_p and M_p are the planet's radius mass. At high masses, for objects that have had time to cool, electron degeneracy pressure becomes significant, and the mass/radius relation changes such that the radius scales as $R_p \propto M_P^{-1/3}$. Note that the "H/He comp." curve in Fig. 1 does not display this behavior at low masses, because this curve is calculated for highly irradiated objects that are a mere 0.045 AU from their Sun-like star, which prevents them from reaching their "zero-temperature radius" in 3 Gyr (three billion years). For cold spheres of H/He, it has long been appreciated that the maximum in the mass/radius relation occurs near four times Jupiter's mass [9, 10], with a broad peak at just over 1 R_J (where R_J is Jupiter's radius), extending from ~a tenth of Jupiter's mass to ~100× Jupiter's mass. For a planet to be smaller than the H/He minimum radius requires the presence of a significant heavy-element component, in the form of a core in the object's center or high-metallicity material well mixed throughout the envelope (where "metals" is taken to mean elements heavier than helium). For a planet to be larger than the zero-temperature radius (~1 R_J) requires it to have a high enough temperature that pressure from ions becomes a significant fraction of that due to electrons.

Prior to the discovery of transiting planets, it was assumed that ~billion-year-old planets — even ones on close-in orbits around their stars (so-called "hot Jupiters," with orbits lasting ~a week or less) — would have cooled and shrunk to near their asymptotic radius [11, 12]. However, the discovery of transiting hot Jupiters such as HD 209458b [13] with its $\gtrsim 1.3$ R_J

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[1] The radiative-convective boundary is the region bounding the convective interior of a planet in which heat transport is dominated by convective eddies. This boundary occurs essentially where the vertical temperature gradient becomes subadiabatic and therefore stable against convection.
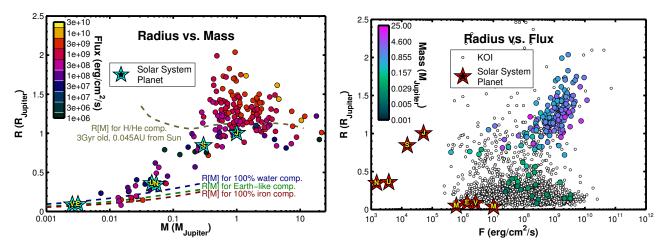
Fig. 1. Radius vs. mass (left panel) and vs. incident irradiating flux (right panel) for the confirmed exoplanets, the *Kepler* candidate planets (*Kepler* objects of interest — KOI), and the planets of our Solar System. The ∼200 confirmed planets in this figure are represented with filled large circles; KOI (in the right panel) are represented with small white circles; Solar System planets are represented with large pentagrams. For comparison, the left panel shows the radius-vs.-mass relationship for Earth-like composition, which precisely matches the (mass,radius) values for Venus and Earth [26]. Planets span masses from less than Earth's to tens of times Jupiter's, radii from less than Earth's to more than double Jupiter's, and incident fluxes from nearly 0 — in the case HR 8799b, at ∼70 AU [27] — to nearly 10^{12} erg cm^{-2} s^{-1}. The planets with the largest radii tend to be close to Jupiter's mass and highly irradiated.

radius, suggested that some planets are a good deal puffier than expected [14]. Many mechanisms have been suggested in the literature to explain the apparently inflated radii of some of the hottest hot Jupiters [15, 16]; what these mechanisms all have in common is that they increase the bulk entropy of the planet above what might have been expected from naive cooling models.[2] This increase can come either from (*i*) retarding the evolutionary cooling (via enhanced atmospheric opacity or modified atmospheric thermal profiles [19, 20, 21]), or (*ii*) from additional power added in the planet's deep interior (via tidal [22, 23] or Ohmic [24, 25] dissipation).

It remains uncertain whether a single inflation mechanism predominates. For the most highly-inflated objects, however, mechanisms of type (*i*) might not work. Close-in planets are presumably tidally locked (although see [28]) and have a permanent nightside through which they cool more efficiently [19, 29]; accounting for the enhanced night-side cooling efficiency suggests that mechanisms that merely reduce the cooling rate might not be able to explain the highly inflated planets, and some power must be deposited in the deep interior [30]. Despite the lack of a consensus mechanism, it is clear that objects must either be quite young [31] or very highly irradiated [32, 33] (see Fig. 1) in order to have significantly inflated radii. The lowest irradiation experienced by any planet with a radius more than 1.5× Jupiter's is the ∼10^9 erg cm^{-2} s^{-1} incident on Kepler-12b, which still exceeds the solar flux upon Jupiter by a factor of 10^4.

One of the key structural uncertainties for many of the known gas-giant planets is whether they have cores in their centers. (It is also not known, at present, whether Jupiter has a heavy-element core at its center, although Saturn must have one.) The presence or absence of cores is of interest both as it relates to our knowledge of the the planets themselves and because it bears upon their formation mechanism — whether by a runaway process of accreting gas onto ∼10-$M_\oplus$ cores [34] or via gravitational instability of the protoplanetary gas disk [35]. Unfortunately, it is essentially impossible to learn whether the extremely inflated planets have cores (though, if they do, the larger the core mass, the greater the additional power that is required to explain their radii). Some of the known transiting gas giants, however, have smaller radii (at

their known masses) than a H/He composition can produce. These planets must have a significant heavy-element component. The inferred metal fraction appears to be correlated with the metallicity of the planet's host star [36, 20], suggesting that more metal-rich protoplanetary environments lead to more metal-rich planetary compositions, perhaps in the form of rocky cores.

Some exotic objects orbiting other stars do not have direct structural analogs in our Solar System. One planet that falls between our local archetypcal categories is the enigmatic HD 149026b [37]. Although 20% more massive than Saturn, its radius is 22% *smaller*, which suggests that its heavy-element content is greater than the entire mass of metals (outside the Sun) in the Solar System, in the range of ∼60–110-$M_\oplus$ of metals [38, 20]. In this respect, despite its greater-than-Saturn mass, this planet is perhaps more similar in structure to Uranus- and Neptune-like planets, the subject of the following section.

Neptunes

Giant planets where most of the planet's mass is composed of heavy elements, rather than mostly H/He gas, begin our transition to our next class of planets. These so-called "Neptune-class" planets still have a thick H/He envelope, but the light-element envelope does not comprise the majority of the planet's mass. In our Solar System, Uranus (14.5 $M_\oplus$ and 4.0 $R_\oplus$), and Neptune (17.1 $M_\oplus$ and 3.9 $R_\oplus$) are our examples of these planets. Figure 2 portrays how the bulk structure of a Neptune-class planet differs from that of either a Jupiter or an Earth (which we will address in the next section).

Uranus and Neptune are generally known for their bluish color and are often lumped together as two "ice giants" because most structure models find that the majority of the planetary mass is in a deep fluid ionic sea probably consisting predominantly of water, and also containing ammonia and methane. While the planets appear outwardly very similar,

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[2] There are some uncertainties in the proper equation of state for H/He/metals mixtures [17, 18], but the attendant uncertainties in radius are insufficient to explain the very large radii ($\gtrsim$1.5 R_J) occasionally seen.
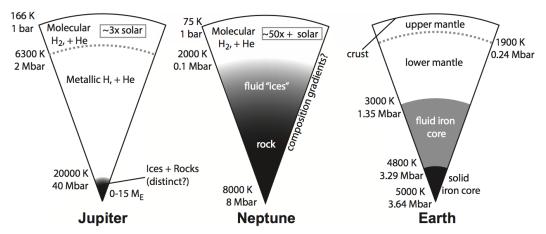
Fig. 2. Pie-slice diagrams of a representative gas-giant (Jupiter), ice-giant (Neptune), and terrestrial (Earth) planets. Jupiter's outer ~20% in radius consists mostly of molecular hydrogen. Pressures and temperatures quickly increase inside the planet and the bulk of Jupiter is made of liquid metallic hydrogen, a form of liquid hydrogen that is highly electrically conductive. At its center there may be a concentration of heavier elements, but constraints are not firm. The visible atmosphere, and perhaps the entire H/He envelope is enhanced in metals by a factor of 3-5 compared to the Sun. Within Neptune, most or perhaps all of the hydrogen is found in molecular form, while the bulk of the planet's mass, the "middle" gray layer, is composed of fluid conducting molecules and molecular fragments probably consisting of H_2O, NH_3, and CH_4. Constrains on the interior rock-to-ice ratio are not firm, and it is not clear how distinct the layer boundaries actually are. The visible atmosphere is enhanced in carbon by a factor of ~50 compared to the Sun, but there is little constraint on other elements. Within the Earth the mantle is composed of silicates whose mineralogy differs between the upper and the lower mantle. The distinct core is mostly iron-nickle, with small admixtures of unknown lighter elements. The solid core is currently growing at the expense of the liquid core. Most of the interiors of all of the planets are thought to be convective.

there is ample evidence that the planet's interiors are quite different. The diversity within our two Neptune-class planets should be a clear reminder that this class of exoplanets should harbor tremendous diversity.

First, both planets do *not* simply have homogeneous three-layer structures with an H/He upper envelope, water-dominated middle envelope, and rocky core. Neither planet is as centrally condensed as this often-suggested but too-simple picture would imply. Uranus is more centrally condensed that Neptune. More dramatically it also has a heat flux from its deep interior that is no more than 10% that of Neptune, which may be due to deep composition gradients that suppress large-scale convection. Uranus is also flipped over on its side with its spin axis nearly in its orbital plane, which might imply that the stochastic nature of giant collisions near the end of the planet-formation era plays a major role in determining the structure of this class of planet. Even today, much of our knowledge of the structure and evolution of these planets remains uncertain and provisional [39, 40, 41].

Both planets have H/He atmospheres that are strongly enriched in metals. Only the carbon abundance (in methane) can be measuredly fairly definitively via spectroscopy, and requires a carbon enhancement of about $50\times$ solar in each planet [42]. Indirect evidence suggests that oxygen may be several hundred times solar in Neptune [43]. This suggests a framework where the relatively thin H/He envelopes of Neptune-class planets may well be extremely enhanced in metals compared to their parent stars.

Whether Neptune-class exoplanets are true "ice giants" (meaning that much of their mass is made up of water and other fluid "planetary ices") is an open question. If planets form beyond the "ice line" where water has condensed (like all of our giant planets), then a substantial fraction of the mass of Neptune-class planets is probably water. However, planets may also form within the ice line, in which case they would have rock/iron interiors with an accreted gaseous envelope.

The first Neptune-class exoplanet with a measured mass and radius was the transiting "hot Neptune" GJ 436b, which is 22.2 $M_\oplus$ and 4.3 $R_\oplus$ [44, 45]. The planet's location on the mass/radius diagram implies that the planet must have a substantial H/He envelope and is not composed only of water, for instance. The relative mass fractions of H/He, water (and other icy components like ammonia and methane), rock, and iron cannot be ascertained from mass and radius alone. Even with the assumption of a fixed rock:iron ratio, one can mix a wide array of 3-component compositions of rock/iron, water, and H/He. For instance, one could model the planet with only H/He and rock, or with only H/He and water, ignoring a third component. Another complication is that one needs to be able to model the thermal evolution of the planet to understand the deep interior temperatures and densities of the possible components of this several-Gyr-old planet. Degeneracy in inferred composition for Neptune class exoplanets will always be the rule [46, 47].

Diversity in exo-Neptune interior structure can be seen from a comparison of GJ 436b to Kepler-30d. Models of GJ 436b generally suggest an interior that is 80-90% heavy elements (similar to Uranus and Neptune). However, Kepler-30d has nearly the same mass (23.1 $M_\oplus$) but a radius twice as large (8.8 $R_\oplus$) [48]. This suggests that the planet is only 30% heavy elements, and 70% H/He gas, thereby already breaking our "rule" that planets of this class (mass-range) should not be made predominantly of hydrogen!

Kepler data show a dramatic increase in planetary occurrence from 6 $R_\oplus$ to 2 $R_\oplus$, indicating that "sub-Neptunes" from 2-3 $R_\oplus$ are a very common planetary type [4, 49]. Such planets also generally need a H/He envelope, but one that comprises perhaps only ~1-5% of the planetary mass. Several of these objects have masses in the 3-10 $M_\oplus$ range, indicating that even relatively small planets can accrete and maintain gaseous H/He envelopes, even despite ongoing evaporative mass loss [50].

While the majority of *Kepler* planets are around distant, faint stars, there is also a relatively nearby example of this

class of sub-Neptune planet, named GJ 1214b. This $\sim$500-K transiting planet orbits its cool star in a close-in orbit, and its mass (6.5 $M_\oplus$) and radius (2.7 $R_\oplus$) are well determined [51] and seem to imply a gaseous component atop a liquid/solid core [52, 53]. A series of observational campaigns have attempted to characterize the visible H/He atmosphere of the planet. This would perhaps allow the composition of the entire H/He envelope to be constrained. However, the observed transit-radius spectrum has been nearly featureless [54, 55]. This suggests either that cloud material is obscuring the atmosphere or that the atmosphere is quite compact, so that it imprints little signal on the stellar transmitted light. If the planet's atmosphere is strongly enriched with metals, at a level even higher than Uranus and Neptune, this could greatly increase the mean molecular mass and reduce the atmosphere's vertical height, although such a high atmospheric mean-molecular weight is disfavored by the observed mass and radius [53]. Once the atmospheres of more of these planets have been probed in more detail, we can begin to make firmer connections that could link the composition of the H/He envelope with planetary mass and orbital location.

Below some mass ($\lesssim$3–5 $M_\oplus$?), cores are small enough that they either do not accrete nebular H/He gas, or the gas that is accreted is quickly lost. Such objects are true terrestrial or water planets, often called super-Earths. We now turn our attention to these larger cousins of Earth and Venus.

Terrestrial and Ocean Planets

The search for "Earth-like," terrestrial planets is a major objective in the study of exoplanets. Terrestrial planets are objects such as Mars, Venus, and Mercury that are composed predominantly of elements such as Si, Mg, Fe, O, and, perhaps in some cases, C [56]. Now that exoplanets have been discovered that are roughly the size of Venus or Earth, one key question is whether a given terrestrial exoplanet is more similar to Venus or to Earth, as discussed in §**Terrestrial Planets** below. However, other types of planets or satellites may be habitable and, in some sense, Earth-like. In the Solar System, Enceladus and Europa share with the Earth the rare characteristic of possessing an ocean that is in contact with a rocky interior. It is not known whether there is life on Enceladus or Europa, but their existence motivates the study of exoplanets that would have a large fraction of H_2O, known as ocean planets [57]. As discussed in §**Ocean Planets**, it might be difficult to determine unambiguously that an exoplanet actually is an ocean planet, because such worlds could occupy the same region of the M_p/R_p plane as planets consisting of rocky cores surrounded by atmospheres of H/He [58].

Terrestrial Planets. Venus and Earth have about the same mass and radius, and Venus's slightly smaller density could be explained by its smaller mass. That is, the uncompressed density is the same for the two planets. But Venus and Earth have evolved to present-day conditions so different as to invite the question of whether distance to the Sun is the only parameter that drives such a different evolution.

Among the major differences between Venus and Earth is the lack of current plate tectonics on Venus, as revealed by the geological analysis of radar images acquired by the Magellan mission [59, 60]. Plate tectonics plays an important role on Earth, providing a very efficient way of cooling the Earth's interior. It also provides an exchange mechanism between the interior, the surface, and the atmosphere: at subduction zones, hydrated minerals and sediments are carried back to the mantle; at mid-ocean ridges, new crust and volatiles contained in the mantle are released into the atmosphere (Fig. 3). Whether such a cycle [61] is required for life to form [62] and evolve on a terrestrial planet is debated. Still, since the only world where life has been identified has plate tectonics, it is crucial to understand what controls tectonic dynamics.

Plate tectonics occurs in response to convective motions in the mantle (Fig. 3). The main features are the formation of instabilities at the thermal boundaries located at the core-mantle transition and at the surface (Fig. 3). Hot plumes are common features of Venus and Earth (e.g. [63]). Venus is in the so-called stagnant-lid regime — cold plumes form at a cold thermal-boundary layer, deep below the surface, at the base of the "stagnant lid" through which heat is transferred by conduction. The stagnant lid regime is not efficient in removing heat from the interior [64]. The tectonic regime (plate tectonics or stagnant lid) depends on a number of parameters, including the size of the planet, the surface temperature, the presence of water at the surface, and more generally the history of the planet [65]. The reason why Venus and Earth have evolved so differently pathways remains uncertain [66].

Convective stresses scale with the vigor of convection. Some authors argue that larger planets have larger convective stresses and, therefore, are more likely to experience plate tectonics [67, 68]. However, the yield strength depends on more than just the size of the planet. Recent work has shown that the depth dependence of the crustal yield strength, a poorly constrained parameter, is critical in determining the convective regime and the likelihood of plate tectonics [65]: the more the yield strength increases with depth, the lower the probability of plate tectonics. The yield strength and its variation with depth depend on surface temperature, the presence of liquid water, the geological history of the planet (such as whether large impact craters have weakened the lithosphere), and the presence of light, Earth-like continents (Fig. 3), at whose border the lithosphere is weaker. Other geological properties, such as the temperature dependence of viscosity, the amount of interior heating, and mineralogical transformations in the mantle, also influence the propensity for plate tectonics. Furthermore, episodic regimes in which stagnant-lid periods alternate with active-lid periods may also exist [65]. One hypothesis that has been proposed to explain Venus's global resurfacing is a transition from a plate-tectonics regime to a stagnant-lid regime about 1 Gyr ago [66].

Definitively determining whether a planet around another star undergoes plate tectonics will be extremely difficult. Still, as our understanding of geology on Earth and elsewhere in the Solar System improves, we might be better able to estimate the likelihood of exoplanetary plate tectonics.

Ocean Planets. Water is a key ingredient for the formation and development of life.[3] "Follow the water" has, therefore, been a motto for Mars exploration. Although H_2O is known to exist in ice and vapor form on Mars, subsurface liquid water has not yet been identified. On the other hand, geophysical observations (magnetic field and gravity field) by the Galileo mission and the Cassini mission strongly suggest the presence of water under the icy crust of Callisto, Ganymede, Europa, Titan, and Enceladus. This has inspired several studies about the possibility of ocean-dominated exoplanets.

Ocean exoplanets are not known to exist, but some of their possible properties have been theoretically explored. For a given mass, a planet that is 50% (by mass) H_2O and 50% Earth-like composition would have a radius $\sim$25% larger than that of a terrestrial exoplanet [57]. As illustrated in Fig. 1,

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[3]It is also possible that having too much water might hinder the development of life, because it might both dilute important nutrients and disrupt geochemical thermal regulation processes.
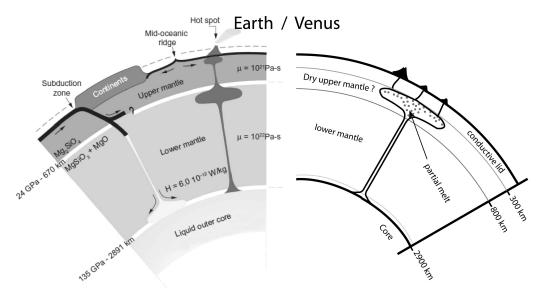
Fig. 3. Schematic representation of the interior structure and dynamics of the Earth (left) and Venus (right). On both planets, hot plumes form at the core/mantle boundary, although the heat that comes out of core is a fraction (∼25% for the Earth) of the total heat released at the surface. The mineralogical transformation at the upper/lower mantle interface may or may not be a barrier to convection: the left panel depicts a hot plume that would be stopped at this interface; whereas the right panel shows how the plume moves up to the bottom of the conductive lid. The depth of this interface on Venus is larger than that of the Earth because the gravity on Venus is lower. On Earth (left), the oceanic lithosphere (black) forms at the mid-ocean ridges and is recycled in the mantle at subduction zones (adapted from [72, 63]).

several exoplanets have (M_p, R_p) values that lie in the vicinity of the $R_p[M_p]$ relationship for Earth-like composition. Recent work has examined the structure of ocean planets with a variety of water fractions and found, generically, that ocean planets have $R_p[M_p]$ relations that are somewhat larger at a given mass than Earth-like planets [26, 69, 70, 53], with the degree of increased radius depending on the water fraction. However, there are degeneracies: for instance, a planet whose (M_p, R_p) location is consistent with being an ocean planet could also have a silicate (terrestrial) core veiled by a H/He rich atmosphere [58]. This degeneracy can be resolved if the atmospheric composition can be discerned [71].

An ocean planet's habitability could be affected by whether its liquid water is in contact with a rocky core. Planets with large amounts of H_2O might develop a high-pressure ice layer between the core and the liquid layer [26], similar to the structure proposed for Ganymede, Callisto, and Titan. Counterintuitively, more massive planets might have thinner oceans, because they have greater pressure gradients and, therefore, their oceans more quickly enter the high-pressure ice-layer regime. In order to have contact between the ocean and the rocky core, the fraction of H_2O has to be small, as is the case on Earth (2×10^{-4}) and Europa (7×10^{-2}). However, in some circumstances, even if the planet has a large water fraction, there can still be contact between a fluid water layer and a silicate layer. This would occur if the temperature at the top of the H_2O layer is high enough that the envelope's temperature gradient yields a temperature at the base of the water layer that is that is still in the fluid regime, and might be a natural outcome in Neptune-class planets with or without the loss of their primordial H_2-He atmospheres.

Conclusions

Observational campaigns in the next decade will help us to refine our knowledge of the structure of planets both in our Solar System and beyond. The Juno Mission [73] will provide crucial new insights into Jupiter's internal structure, and should help resolve the longstanding question of how much water is in Jupiter. Beyond the Solar System, the recently approved *Transiting Exoplanet Survey Satellite* (*TESS*) will identify many planets around stars close enough and bright enough that the planets are amenable to follow-up observations from the ground or with the *James Webb Space Telescope* (*JWST*). Learning about both the masses (via RV measurements) and about the atmospheres of these planets will inform our understanding of their bulk compositions and structures.

Finally, in some cases, giant exoplanets that are sufficiently far from their stars and sufficiently self-luminous, such as those in the HR 8799 system [27], may be directly imaged with new, high-contrast imaging techniques. These direct observations of young objects are sensitive to planets' initial conditions and, therefore, might help us (*i*) to distinguish between formation mechanisms of widely-separated, young jovian objects [74, 75, 76], and (*ii*) to learn about their interior structures. The ground-based programs that will undertake such surveys include the Gemini Planet Imager (GPI, [77]), the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) on the Very Large Telescope [78], and more. Exoplanetary observations have revealed unanticipated structures in planets both large and small, and so the prospect of a flood of upcoming data promises more surprises and new insight into comparative planetology.

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