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Observed Properties of Extrasolar Planets

Andrew W. Howard

Observational surveys for extrasolar planets probe the diverse outcomes of planet formation and evolution. These surveys measure the frequency of planets with different masses, sizes, orbital characteristics, and host star properties. Small planets between the sizes of Earth and Neptune substantially outnumber Jupiter-sized planets. The survey measurements support the core accretion model, in which planets form by the accumulation of solids and then gas in protoplanetary disks. The diversity of exoplanetary characteristics demonstrates that most of the gross features of the solar system are one outcome in a continuum of possibilities. The most common class of planetary system detectable today consists of one or more planets approximately one to three times Earth’s size orbiting within a fraction of the Earth-Sun distance.

Extrapolation of the known number of detected extrasolar planets can be estimated to be in the range of 7000 to 10,000 within one astronomical unit (AU) of the host star. This extrapolation assumes a uniform distribution of planets per star and a flat distribution of stars at all distances from the Sun. The observed properties of extrasolar planets are consistent with a model in which most giant planets form in the outer regions of their host star’s protoplanetary disk and migrate inward due to interactions with lower-mass planets (or other planets, such as Jupiter or Saturn). The migration of a giant planet can cause a net inward migration of the Sun-like star’s planets, leading to a wider range of orbital separations and eccentricities in the inner regions of the host star’s disk.

The planet’s orbital period is the time interval between consecutive transits, and the orbital distance (semi-major axis) can be inferred from Kepler’s third law. The mass of a transiting planet can be measured from follow-up Doppler observations if the host star is bright enough and the Doppler amplitude large enough. Masses can also be measured in special cases from precise timing of consecutive transits, which deviate from strict periodicity when multiple planets orbiting the same star gravitationally perturb one another.

Transiting planets also offer the opportunity to measure the stellar obliquity—the angle between the stellar spin axis and a planet’s orbital axis—as well as characteristics of the planet’s atmosphere. Obliviqities have primarily been measured as the transiting planet alternately blocks blue-shifted and red-shifted portions of the rotating stellar disk causing apparent Doppler shifts (the Rossiter-McLaughlin effect). In an observational survey, a large number of stars are searched for planets and the statistical properties of the detected population are studied in order to infer mechanisms of planet formation and evolution. Surveys count planets and naturally produce number distributions of planet parameters (such as the number of detected planets versus planet mass), but these distributions can systematically hide planets that are more difficult to detect. To measure planet occurrence—how commonly planets with a particular characteristic exist in nature—surveys must estimate their sensitivity to planets with different values of that characteristic and statistically correct for their incomplete sample of detected planets.

Abundant Close-In, Low-Mass Planets

Planets intermediate in size between Earth and Neptune are surprisingly common in extrasolar systems, but notably absent from our solar system. The planet size and mass distributions (Fig. 2) show clearly that these small planets outnumber large ones, at least for close-in orbits. Two separate Doppler surveys (14, 15) of nearby, Sun-like stars have shown that planet occurrence rises significantly with decreasing planet mass (Msin i) from 1000 M_E (3 Jupiter masses) down to 3 M_E. In the Eta-Earth Survey, an unbiased set of 166 nearby, G- and K-type stars in the northern sky were observed at Keck Observatory (14). The RV of each star was measured dozens of times over 5 years, and the time series RVs were searched for the signatures of planets with orbital periods P < 50 days. (The restriction of P < 50 days for solar-type stars is equivalent to

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restricting orbital distances to $<0.25$ AU, inside of Mercury’s 0.4 AU orbit.) In total, 33 planets were detected orbiting 22 of the 166 stars. Low-mass planets ($M_{\text{sin}} = 3$ to $30 M_{\oplus}$) were detected more frequently, in spite of their weaker Doppler signals. After correcting for survey incompleteness, the planet mass distribution was fit with a power-law model that rises steeply toward low mass. The probability of a star hosting a close-in planet scales as $M_{\text{sin}}^{-0.48}$. In absolute terms, 15% of Sun-like stars host one or more planets with $M_{\text{sin}} = 3$ to $30 M_{\oplus}$ orbiting within 0.25 AU, and by extrapolation, another 14% of stars host planets with $M_{\text{sin}} = 1$ to $3 M_{\oplus}$.

The HARPS (High Accuracy Radial velocity Planet Searcher) survey measured the RVs of 376 Sun-like stars in the southern sky with somewhat better sensitivity to low-mass planets (15). It confirmed the rising planet mass function with decreasing mass and extended it to 1 to $3 M_{\oplus}$ planets (Fig. 2). It also demonstrated that low-mass planets have small orbital eccentricities and are commonly found in multi-planet systems with two to four small planets orbiting the same star with orbital periods of weeks or months. The HARPS survey found that at least 50% of stars have one or more planet of any mass with $P < 100$ days.

The Kepler mission has substantially refined our statistical knowledge of planets between the size of Earth and Neptune by revealing thousands of these planets, compared with the dozens detected with the Doppler technique. The distribution of planet sizes (radii) measured by the Kepler telescope (Fig. 2) follows the same trend as the mass distribution, with small planets being more common (16, 17, 18). However, the Kepler telescope size distribution extends confidently down to Earth size for close-in planets, whereas the mass distribution is uncertain at the 50% level near 1 Earth mass. The size distribution is characterized by a power-law rise in occurrence with decreasing size (17) down to a critical size of $\approx 2.8$ Earth radii ($R_{\oplus}$), below which planet occurrence plateaus (16). Earth-size planets orbiting within 0.25 AU of their host stars are just as common as planets twice that size. The small planets detected by the Kepler telescope ($<2 R_{\oplus}$) appear to have more circular orbits than those of larger planets (19), suggesting reduced dynamical interactions.

The Kepler telescope is sensitive to sub-Earth-size planets around stars with low photometric noise and has detected planets as small as the Moon ($0.3 R_{\oplus}$) (20). However, survey sensitivity remains uncertain below $1 R_{\oplus}$ with current data, even for orbital periods of a few days. Although the occurrence plateau for 1 to $2.8 R_{\oplus}$ with a steep fall-off for larger planets is not well understood theoretically, it offers an important observed property of planets around Sun-like stars that must be reproduced by planet formation models.

The high occurrence of small planets with $P < 50$ days likely extends to more distant orbits. As the Kepler telescope accumulates photometric data, it becomes sensitive to planets with smaller sizes and longer orbital periods. Based on 1.5 years of data, the small-planet occurrence distribution as a function of orbital period is flat out to $P = 250$ days (with higher uncertainty for larger $P$). That is, the mean number of planets per star per logarithmic period interval is proportional to $P^{-0.11 \pm 0.05}$ and $P^{-0.10 \pm 0.12}$ for 1 to $2 R_{\oplus}$ and 2 to $4 R_{\oplus}$ planets, respectively (21).

Of the Kepler telescope’s planet-host stars, 23% show evidence for two or more transiting planets (3). To be detected, planets in multi-transiting systems likely orbit in nearly the same plane, with mutual inclinations of a few degrees at most, as in the solar system. The true number of planets per star (transiting or not) and their mutual inclinations can be estimated from simulated observations of model planetary systems constrained by the number of single, double, triple (and so on) transiting systems detected with the Kepler telescope (22, 23). One model finds an intrinsic multi-planet distribution with 54, 27, 13, 5, and 2% of systems having 1, 2, 3, 4, and 5 planets with $P < 200$ days, respectively. Most multi-planet systems (85%) have mutual inclinations of less than $3^\circ$ (22). Comparisons of the Kepler telescope and HARPS planetary systems also suggest mutual inclinations of a few degrees (24). This high degree of coplanarity is consistent with planets forming in a disk without substantial dynamical perturbations capable of increasing inclinations.

Orbital period ratios in multi-transiting systems provide additional dynamical information. These ratios are largely random (25), with a modest excess just outside of period ratios that are consistent with dynamical resonances (ratios of $2:1$, $3:2$, and so on) and a compensating deficit inside (26). The period ratios of adjacent planet pairs demonstrate that $>31$, $>35$, and $>45$% of two-, three-, and four-planet systems, respectively, are dynamically packed; adding a hypothetical planet would gravitationally perturb the system into instability (27).

**Fig. 1.** Schematic illustration of a planetary orbit and the variations in stellar brightness and RV that it causes. (A) A planet orbits its host star and eclipses ("transits") the star as seen by a distant observer. (B) Planets are detectable during transit by the decrease in stellar brightness (solid white line). Transit depth is proportional to the blocked fraction of the stellar disk. The stellar obliquity can be measured during transit by anomalous Doppler shifts (the Rossiter-McLaughlin effect; solid yellow line) in the RV time series as the planet blocks portions of the rotating stellar disk. A low-obliquity system with $i = 3\sim 30^\circ$ (with higher uncertainty for larger $i$) is observed. (C) Over many orbits, planet properties including the size, mass, orbital period, eccentricity, and orbital inclination can be measured from detailed analysis of time-series photometric and RV data.

**Masses, Radii, and Densities**

Although mass and size distributions provide valuable information about the relative occurrence...
of planets of different types, it remains challenging to connect the two. Knowing the mass of a planet does not specify its size, and vice versa. A planet the mass of Earth could have a variety of sizes, depending on the composition and the extent of the atmosphere.

This degeneracy can be lifted for ~200 planets with well-measured masses and radii (Fig. 3), most of which are giant planets. The cloud of measurements in Fig. 3 follows a diagonal band from low-mass/small-size to high-mass/large-size. This band of allowable planet mass/size combinations has considerable breadth. Planets less massive than ~30 $M_{E}$ vary in size by a factor of 4 to 5, and planets larger than ~100 $M_{E}$ (gas giants) vary in size by a factor of ~2. For the gas giants, the size dispersion at a given mass largely is due to two effects. First, the presence of a massive solid core (or distributed heavy elements) increases a planet’s surface gravity, causing it to be more compact. Second, planets in tight orbits receive higher stellar flux and are statistically more likely to be inflated relative to the sizes predicted by atmospheric models (the “hydrogen” curve in Fig. 3). Although it is clear that higher stellar flux correlates with giant planet inflation (28), it is unclear how the stellar energy is deposited in the planet’s interior. Energy deposited in a planet’s outer layers is quickly reradiated unless it is somehow circulated to the interior.

Low-mass planets have an even greater variation in size and inferred compositional diversity. The planet Kepler-10b has a mass of 4.6 $M_{E}$ and a density of 9 g cm$^{-3}$, indicating a rock/iron composition. With such a high density, this planet likely has little or no atmosphere (29). In contrast, the planet Kepler-11e has a density of 0.5 g cm$^{-3}$ and a mass of 8 $M_{E}$. A substantial light-element atmosphere (probably hydrogen) is required to explain its mass and radius combination (30). The masses and radii of intermediate planets lead to ambiguous conclusions about composition. For example, the bulk physical properties of GJ 1214b (mass 6.5 $M_{E}$, radius 2.7 $R_{E}$, density 1.9 g cm$^{-3}$) are consistent with a several compositions: a “super-Earth,” with a rock/iron core surrounded by ~3% H$_{2}$ gas by mass; a “water” world planet, consisting of a rock/iron core, a water ocean, and atmosphere that contribute ~50% of the mass; or a “mini-Neptune,” composed of rock/iron, water, and H/He gas (31). For this particular planet, measuring the transmission spectrum during transit appears to have lifted the degeneracy. The small atmospheric scale height of GJ1214b favors a high mean molecular weight atmosphere (possibly water) but is also consistent with an H$_{2}$ or H/He atmosphere rendered featureless by thick clouds (32).

**Gas Giant Planets**

The orbits of giant planets are the easiest to detect by using the Doppler technique and were the first to be studied statistically (33, 34). Observations over a decade of a volume-limited sample of ~1000 F-, G-, and K-type dwarf stars at Keck Observatory showed that 10.5% of G- and K-type dwarf stars host one or more giant planets (0.3 to 10 Jupiter masses) with orbital periods of 2 to 2000 days (orbital distances of ~0.03 to 3 AU). Within those parameter ranges, less massive and more distant giant planets are more common. A fit to the giant planet distribution in the mass-period plane shows that occurrence varies as $M^{-0.31 \pm 0.2} P^{0.26 \pm 0.1}$ per logarithmic interval dlog$M$/dlog$P$. Extrapolation of this model suggests that 17 to 20% of such stars have giant planets orbiting within 20 AU ($P = 90$ years) (35). This extrapolation is consistent with a measurement of giant planet occurrence beyond ~2 AU from microlensing surveys (36). However, the relatively few planet detections from direct imaging planet searches suggest that the extrapolation is not valid beyond ~65 AU (37).

These overall trends in giant planet occurrence mask local pile-ups in the distribution of orbital parameters (38). For example, the number distribution of orbital distances for giant planets shows a preference for orbits larger than ~1 AU and to a lesser extent near 0.05 AU, where “hot Jupiters” orbit only a few stellar radii from their host stars (Fig. 4A). This “period valley” for apparently single planets is interpreted as a transition region between two categories of planets with different migration histories (33). The excess of planets starting at ~1 AU approximately coincides with the location of the ice line. Water is condensed for orbits outside of the ice line, providing an additional reservoir of solids that may speed the formation of planet cores or act as a migration trap for planets formed farther out (39). The orbital period distribution for giant planets in multi-planet systems is more uniform, with hot Jupiters nearly absent and a suppressed peak of planets in >1 AU orbits. The giant-planet eccentricity distribution (Fig. 4B) also differs between single- and multi-planet systems. The eccentricity distribution for single planets can be reproduced quantitatively with a dynamical model in which initially low eccentricities are excited by planet-planet scattering.

![Fig. 2. The (A) size and (B) mass distributions of planets orbiting close to G- and K-type stars. The distributions rise substantially with decreasing size and mass, indicating that small planets are more common than large ones. Planets smaller than 2.8 $R_{E}$ or less massive than 30 $M_{E}$ are found within 0.25 AU of 30 to 50% of Sun-like stars. (A) The size distribution from transiting planets shows occurrence versus planet radius and is drawn from two studies of Kepler telescope data: (16) for planets smaller than four times Earth’s size and (17, 59) for larger planets. The inset images of Jupiter, Neptune, and Earth show their relative sizes. The mass (M$_{\text{sin}i}$) distributions (B) show the fraction of stars having at least one planet with an orbital period shorter than 50 days (orbiting inside of ~0.25 AU) are from the Doppler surveys from (14) (white points) and (15) (yellow points), whereas the histogram shows their average values. Inset images of Earth, Neptune, and Jupiter are shown on the top horizontal axis at their respective masses. Both distributions are corrected for survey incompleteness for small/low-mass planets to show the true occurrence of planets in nature.](www.sciencemag.org)
Multi-planet systems likely experienced substantially fewer scattering events. One interpretation is that eccentric, single-planet systems are the survivors of scattering events that ejected the other planets in the system.

Although hot Jupiters (giant planets with \( P < 10 \) days) are found around only 0.5 to 1.0% of Sun-like stars (41), they are the most well-characterized planets because they are easy to detect and follow up with ground- and space-based telescopes. However, they have a number of unusual characteristics and a puzzling origin. In contrast to close-in small planets, hot Jupiters are commonly the only detected planet orbiting the host star within observational limits (Fig. 4) (42). Many have low eccentricities, primarily because of tidal circularization. The measured obliquities of stars hosting hot Jupiters display a peculiar pattern: Obliquities are apparently random above a critical stellar temperature of \( \sim 6250 \) K, but cooler systems are mostly aligned. In situ formation is unlikely for hot Jupiters because of insufficient protoplanetary disk mass so close to the star. Rather, they likely formed in the disk at several AU, were gravitationally perturbed into orbits with random inclinations and high eccentricities, and were captured at \( \sim 0.05 \) AU by dissipation of orbital energy in tides raised on the planet. For systems with sufficiently strong tides raised by the planet on the star (which depend on a stellar convective zone that is only present below \( \sim 6250 \) K), the stellar spin axis aligns to the orbital axis (12).

**Planet Formation**

Metal-rich stars (43) are more likely to host giant planets within 5 AU. This “planet-metallicity correlation” was suggested in 1997, when the first four Doppler-discovered giant planets were all found to orbit stars with higher iron abundance than that of the Sun (44). Initially, this correlation was seen as an artifact of stellar self-pollution from accretion of metals onto the stellar atmosphere during planet formation. Today, it provides evidence for the core accretion model of planet formation (45). In this model, a high density of solids in the protoplanetary disk is required to form giant planets, which pass through two key phases. Protoplanets must grow to masses of \( \sim 10 M_{\oplus} \) by accretion of solids (dust and ice) from the disk. The protoplanet then undergoes runaway gas accretion, increasing its mass by an order of magnitude, but only if the protoplanetary gas has not yet dissipated. Giant planet formation is a race against dispersal of gas from the protoplanetary disk on a time scale of \( \sim 3 \) to 5 million years (46). This theory predicts that giant planets should be more common around massive and metal-rich stars whose disks have higher surface densities of solids.

The planet-metallicity correlation was validated statistically by Doppler surveys of \( \sim 1000 \) stars with masses of 0.7 to 1.2 solar masses (\( M_{\odot} \)) and uniformly measured metallicities, which were highly sensitive to giant planets (47, 48). The probability of a star hosting a giant planet is proportional to the square of the number of iron atoms in the star relative to that in the Sun, \( p(\text{planet}) \propto N_{\text{Fe}}^2 \) (47). A later Doppler study spanned a wider range of stellar masses (0.3 to 2.0 \( M_{\odot} \)) and showed that the probability of a star hosting a giant planet correlates with both stellar metal content and stellar mass, \( p(\text{planet}) \propto N_{\text{Fe}}^{1.2} \pm 0.2 M_{\odot}^{1.0 \pm 0.3} \) (49). The planet-metallicity correlation only applies to gas giant planets. Planets larger than \( 4 R_\oplus \) (Neptune size) preferentially orbit metal-rich stars, whereas smaller planets are found in equal numbers around stars with a broad range of metallicities (50). That is, small planets form commonly in most protoplanetary disks, but only a fraction grow to a critical size in time to become gas giants.

Although the planet-metallicity trends support the basic mechanism of the core accretion model, many statistical features of the observed planet population cannot yet be explained in detail. In particular, the population of low-mass planets inside of 1 AU is difficult to reproduce in conventional models. Population synthesis models attempt to follow the growth and migration of sub-Earth-size protoplanets in a protoplanetary disk to predict the planet masses and orbital distances after the disk dissipates (39, 51). These models reproduce the giant planet population well, but struggle with low-mass planets. In population synthesis models, low-mass planets form primarily near and beyond the ice line (several AU) and migrate to close orbital distances through interactions with the disk. The prescriptions for migration and growth in these models produce “deserts” of reduced planet occurrence precisely where Doppler and transit surveys detect a great abundance of planets.

An alternative model is in situ formation of close-in, low-mass planets with minimal subsequent planet migration (52, 53). Although this model correctly reproduces several observed properties of close-in planets (the mass distribution, multi-planet frequencies, and small eccentricities and inclinations), it is still in the early stages of development. One challenge is that in situ formation requires \( \sim 20 \) to 50 \( M_\oplus \) of protoplanetary disk material inside of 1 AU, which is poorly constrained by observations.

**Earth-Size Planets in the Habitable Zone**

The detection of planets the size or mass of Earth remains a prominent observational goal. Using the Doppler technique, one such planet has been detected: a planet with \( M_{\text{Earth}} = 1.1 M_\oplus \) orbiting the nearby star α Centauri B with an orbital separation of 0.04 AU that renders it too hot for life (54). The Doppler signal from an Earth-mass planet orbiting at 1 AU is smaller by a factor of five, beyond the reach of current instrumentation and possibly hidden in
Fig. 4. Orbital characteristics of giant planets (M\textsubscript{Jup} > 0.2 Jupiter masses) detected by Doppler surveys (\emph{A}, \emph{B}). (\emph{A}) The number distribution of semi-major axes shows that apparently single planets (blue) preferentially orbit at distances of ~0.05 AU and at ~1 to 3 AU from their host stars. These preferred orbits are dimmed in multi-planet systems (red). The decline in number of detected planets for orbits outside of ~3 AU is not significant; fewer stars have been searched for such planets as compared with the closer orbits. (\emph{B}) The distribution of orbital eccentricities for apparently single planets (blue) span the full range, with low-eccentricity orbits being more common. Giant planets in multi-planet systems (red) have orbits that are more commonly close to circular (eccentricity = 0). The larger eccentricities of single planets suggest that they were dynamically excited from a quiescent, nearly circular origin, perhaps by planet-planet scattering that resulted in the ejection of all but one detectable planet per system.

Doppler noise from the star. Nevertheless, Doppler planet searches continue. If a planet the size or mass of the Earth is detected orbiting in the habitable zone of a nearby star, it would be a milestone for science and could catalyze the development of instruments to image and take spectra of such planets.

The Kepler telescope has detected dozens of Earth-size planets, although these planets orbit interior to their stars’ habitable zones (16, 18). The habitable zone—the set of planetary orbits consistent with liquid water existing on the planet’s surface—is challenging to define precisely because it depends on the detailed energy balance for a planet with an often poorly constrained composition and atmosphere (35). Nevertheless, the Kepler telescope has also detected planets slightly larger than Earth (1.4 and 1.6 times Earth size) in the classically defined habitable zone (56). The primary goal for the Kepler telescope in its extended mission is to detect individual Earth-size planets in the habitable zone and to estimate their occurrence rate. Not all of the Earth-size planets detected by the Kepler telescope will be 1 M\textsubscript{Jup}, however. Measuring the densities of several Earth-size planets (not necessarily in the habitable zone) will offer some constraints on the typical compositions of Earth-size planets.

Targeting low-mass stars offers a shortcut in the search for planets the size and mass of Earth. Planets are more detectable in Doppler and transit searches of lower-mass stars. The habitable zones around such stars are also closer, owing to the reduced brightness of low-mass stars. Small planets may be more common around low-mass stars as well (17) [an opposing view is available in (18)]. An analysis of planets detected with the Kepler telescope orbiting M dwarfs suggests a high rate of overall planet occurrence, 0.9 planets per star in the size range 0.5 to 4 R\textsubscript{E} in P < 50 day orbits. Earth-size planets (0.5 to 1.4 R\textsubscript{E}) are found in the habitable zones of 15±4\% of the M dwarfs in the Kepler telescope sample (57). As the Kepler telescope’s sensitivity expands during the extended mission, we will likely learn how common Earth-size planets are in the habitable zones of Sun-like stars.