Planet Occurrence: Doppler and Transit Surveys

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Abstract Prior to the 1990s, speculations about the occurrence of planets around other stars were based only on planet formation theory, observations of circumstellar disks, and the knowledge that at least one seemingly ordinary star is the host of four terrestrial planets, two gas giants, and two ice giants. Since then, Doppler and transit surveys have been exploring the population of planets around other Sun-like stars, especially those with orbital periods shorter than a few years. Over the last decade, these surveys have risen to new heights with Doppler spectrographs with a precision better than 1 m s\textsuperscript{-1} precision, and space telescopes capable of detecting the transits of Earth-sized planets. This article is a brief introductory review of the knowledge of planet occurrence that has been gained from these surveys.

Introduction

If, in some cataclysm, all our knowledge about exoplanets from Doppler and transit surveys were to be destroyed, and only one brief sentence passed on to the next generation of astronomers, what statement would contain the most helpful information? Here is one possibility:

At least a third of Sun-like stars have several Earth-to-Neptune-sized planets – and a tenth have giant planets – orbiting between 0.05 and 1 AU.

If we could preserve a mathematical function instead of a sentence, we might choose

\[ \frac{dn}{d\log P} \approx C P^{\beta} \left[ 1 - e^{-(P/P_0)^{\gamma}} \right], \]  \hspace{1cm} (1)
along with the values of the constants $C$, $\beta$, $\gamma$, and $P_0$ that apply to planets of different sizes \cite{Howard2012}. When integrated from $\log P_1$ to $\log P_2$, this function gives the average number of planets per star having orbital periods between $P_1$ and $P_2$. The function is an example of an occurrence rate density, in which the average number of planets per star ($n$, the occurrence rate) is differentiated with respect to chosen characteristics of the system (making it a density).

Even more helpful to astronomers starting from scratch would be a computer program that produces random realizations of the key properties of planetary systems that are statistically consistent with everything we have learned from our surveys (see, e.g., \cite{He2019}). Ideally, such a “generative model” would include planetary properties besides $P$ such as planetary mass and orbital eccentricity, as well as stellar properties like mass, metallicity, and age. The model would also take into account that the occurrence of one type of planet depends on the properties of the other planets in the system, i.e., it would incorporate conditional occurrence rates.

Transmitted in any of these forms to our descendants, the occurrence information would dispel any prejudice that all planetary systems should resemble the Solar System, help them design their instruments to detect exoplanets, and inspire their theories for planet formation. However, the real point of this thought experiment is to convey that occurrence is a topic of central importance in exoplanetary science and that it can be treated at many levels of sophistication. The subject of this introductory review is the knowledge we have gained about planet occurrence from Doppler and transit surveys. The details of the Doppler and transit techniques themselves are left for other reviews, such as those by \cite{Lovis2010}, \cite{Winn2010}, and \cite{Wright2018}. Here, we will simply remind ourselves of the key properties of the Doppler and transit signals:

\begin{align}
K &= \frac{0.64 \text{ m s}^{-1}}{\sqrt{1-e^2}} \left( \frac{P}{\text{1 day}} \right)^{-1/3} \frac{(M/M_\oplus) \sin I}{(M_*/M_\odot)^{2/3}}, \quad (2) \\
\delta &\approx 8.4 \times 10^{-5} \left( \frac{R/R_\oplus}{R_*/R_\odot} \right)^2, \quad p_{\text{tra}} = 0.0046 \left( \frac{R_*/a}{R_\odot/1 \text{ AU}} \right) \quad (3)
\end{align}

where $K$ is the radial-velocity semi-amplitude; $\delta$ is the fractional loss of light during transits; $p_{\text{tra}}$ is the probability for a randomly-oriented orbit to exhibit transits; $a$, $P$, $e$, and $I$ are the orbital semi-major axis, period, eccentricity, and inclination; $M$ and $R$ are the mass and radius of the planet, and $M_*$ and $R_*$ are those of the star.

The next section describes methods for occurrence calculations and is followed by two sections on the results. Because the surveys have revealed major differences in occurrence between giant planets and small planets, with a dividing line just above $4 R_\oplus$ or $20 M_\oplus$, the results for small planets and giant planets are presented separately. After that comes a review of what is known about other types of stars, and a discussion of future prospects.
Methods

Life would be simple if planets came in only one type and we could detect them unerringly. We would search $N$ stars, detect $N_{\text{det}}$ planets, and conclude that the occurrence rate is $n \approx N_{\text{det}}/N$, with an uncertainty dictated by counting statistics. Unfortunately, detection is not assured: small signals can be lost in the noise. If the detection probability $p_{\text{det}}$ were the same for every star that was searched, then effectively we would only have searched $N_{\text{eff}} = p_{\text{det}} N$ stars, and the estimated occurrence rate would be $n \approx N_{\text{det}}/(p_{\text{det}} N)$.

In reality, $p_{\text{det}}$ depends strongly on the characteristics of the star and planet (see Figure 1). Detection is easier for brighter stars, shorter orbital periods, and larger and more massive planets. For this reason we need to group the planets according to orbital period and other salient characteristics for detection: the radius $R$ for transit surveys and the minimum mass $M$ for Doppler surveys. Actually, for Doppler surveys the observable quantity is $M \sin I$ rather than $M$, but this is a minor issue for occurrence studies if we are willing to assume that planetary systems are oriented randomly relative to our line of sight, implying $\langle \sin I \rangle = \pi/4$. Transit surveys have a more serious complication: most planets produce no signals at all, because $I$ needs to be very close to 90° for transits to occur. With this consideration in mind, our estimates for the occurrence rate become

$$n_i \approx \frac{N_{\text{det},i}}{N_{\text{eff},i}} \quad \text{where} \quad N_{\text{eff},i} = \frac{\sum_{j=1}^{N} p_{\text{det},ij}}{\sum_{j=1}^{N} p_{\text{det},ij} \times p_{\text{tra},ij}}$$

for Doppler surveys, and

$$n_i \approx \frac{N_{\text{det},i}}{N_{\text{eff},i}} \quad \text{for transit surveys}.$$  (4)

where the index $i$ refers to a group of planets sharing similar characteristics, and the index $j$ specifies the star that was searched.

This conceptually simple method has been the basis of many investigations. The results of Doppler surveys are sometimes presented as a matrix of occurrence rates for rectangular bins in the space of $\log M$ and $\log P$ (e.g., Figure 1 of Howard et al. 2010). For transit surveys, the bins are in the space of $\log R$ and $\log P$ (e.g., Figure 4 of Howard et al. 2012). Ideally, the bins should be large enough to contain many detected planets, and yet small enough that the occurrence rate density and the effective number of searchable stars do not vary too much across the bin. When the number of detected planets in each bin is modeled as a Poisson random variable, the maximum-likelihood estimate of the occurrence rate in each bin is $n_i = N_{\text{det},i}/N_{\text{eff},i}$ (Tabachnik and Tremaine 2002). More careful handling is needed when there are substantial uncertainties in $N_{\text{det},i}$ arising from uncertainties in the relevant planetary and stellar characteristics (Foreman-Mackey et al. 2014).

Another approach is to posit a parameterized function for the occurrence rate density, such as Equation 4 but often in two or more dimensions. For example, Doppler surveyors have often chosen a double power law in mass and period:

$$\frac{\partial^2 n}{\partial \log M \partial \log P} = C M^\alpha P^\beta,$$  (5)
Fig. 1 Idealized Doppler and transit surveys. The top panel shows the results of a Doppler survey in which 100 Sun-like stars are each observed 50 times over one year with 1 m s$^{-1}$ precision. The bottom panel shows the results of a transit survey in which $10^4$ stars are observed continuously for a year with a photometric precision corresponding to $3 \times 10^{-5}$ per 6 hours of data. Each star is assumed to have one planet on a randomly-oriented circular orbit, with random properties drawn from log-uniform distributions between the plotted limits. Colored points are planets detected with a signal-to-noise ratio (SNR) exceeding 10. Gray points are undetected planets. In the Doppler survey, the threshold mass scales as $P^{1/3}$ for periods shorter than the survey duration. For longer periods, the threshold mass increases more rapidly, with an exponent depending on the desired false-alarm probability (Cumming 2004). The transit survey includes more stars, because they can be monitored simultaneously, but detects a smaller fraction of the planets and is more strongly biased toward short periods. For periods shorter than survey duration, the threshold radius varies as $P^{1/6}$ (Pepper et al. 2003). For longer periods it is impossible to observe more than one transit, making any detections more ambiguous.
where $C$, $\alpha$, and $\beta$ are constants that are estimated by maximizing the likelihood of drawing planets from the distribution that match the number and characteristics of the detected planets. For details on this approach, see Tabachnik and Tremaine (2002), Cumming et al. (2008), and Youdin (2011). Subsequent authors have increased the level of sophistication by applying methods from Bayesian hierarchical inference (Foreman-Mackey et al. 2014), and “likelihood-free” approximate Bayesian computation (Hsu et al. 2018).

Most studies report the occurrence rate density as a function of the properties of a planet, regardless of any other planets in the system. More difficult is quantifying the multiplicity of planetary systems, the number of planets that orbit together around the same star. For Doppler surveys, one problem is that the star is pulled by all the planets simultaneously. As a result, the detection probability for a given planet depends on the properties of any other planets — especially their periods — and on the time sampling and total timespan of the Doppler observations. For transit surveys, the detectability of one planet is nearly independent of any others because transits only rarely overlap (Zink et al. 2019). Instead, the main problem is a degeneracy between multiplicity and the mutual inclinations between orbits. A star with only one detected transiting planet might lack additional planets, or it might have several planets only one of which happens to transit. This degeneracy can be broken — with difficulty — by modeling transit durations (He et al. 2019) or transit-timing variations (Zhu et al. 2018), or by combining the results of a transit survey with a Doppler survey of similar stars (Tremaine and Dong 2012; Figueira et al. 2012).

Doppler surveys have discovered on the order of $10^3$ planets. Among the most informative surveys for planet occurrence were based on observations with the High Resolution Echelle Spectrometer (HIRES) on the Keck I 10-meter telescope (Cumming et al. 2008; Howard et al. 2010) and the High Accuracy Radial-velocity Planet Searcher (HARPS) on the La Silla 3.6-meter telescope (Mayor et al. 2011; Fernandez et al. 2019). Each instrument was used to monitor $\approx 500$ stars for about a decade, with a precision of a few meters per second. Additional information comes from a few lower-precision and longer-duration surveys (see, e.g., Lovis and Fischer 2010). Another valuable resource is the California Legacy Survey (CLS; Rosenthal et al. 2021), a meta-survey of 718 stars based on $\sim 10^5$ archival Doppler measurements spanning several decades.

For transits, surveys with ground-based telescopes have discovered several hundred planets, but they are not often used for occurrence studies because the limitations of ground-based data make it difficult to characterize the sample of searchable stars and calculate the detection probabilities. Instead, our most important resources are the NASA space-based surveys Kepler, K2, and the Transiting Exoplanet Survey Satellite (TESS). Kepler used a 1-meter space telescope to measure the brightness of about 150,000 stars from 2009 to 2013 (Borucki 2016). The typical photometric precision over a 6-hour time interval was on the order of $10^{-4}$, which was sufficient to detect about 4,000 planets (Lissauer et al. 2023). K2 used the same telescope to survey 19 fields along the ecliptic in 80-day increments from 2014 to 2018 (Howell et al. 2014). Since 2018, TESS has been surveying the entire sky in month-long campaigns with four 0.1-meter cameras (Ricker et al. 2015). Although K2 and TESS
data have been used to discover several thousand planets and planet candidates, the Kepler mission was more sensitive to planets with longer periods and smaller sizes. Therefore, our knowledge of transiting planet demographics is still anchored by Kepler, with K2 and TESS providing supplementary information by searching stars with a wider variety of masses, ages, and locations within the galaxy.

**Giant planets**

**Overall occurrence** For giant planets, some key references are Fulton et al. (2021), who computed planet occurrence based on the CLS, Wittenmyer et al. (2020), who did the same for the 18-year Anglo-Australian Planet Search, Santerne et al. (2016) and Petigura et al. (2018), who used the Kepler transit survey, and Fernandes et al. (2019), who combined the Doppler results of Mayor et al. (2011) and the Kepler results of Santerne et al. (2016). Although these studies differ in detail, their overall message is that approximately one-tenth of Sun-like stars have giant planets with orbital distances smaller than 1 AU. For orbital distances from 1–10 AU, the fraction rises to about one-third, and there is tentative evidence that $dn/d\log a$ has a broad peak centered at about 3 AU (see Figure 2). This peak might be related to the location of the “snow line” in protoplanetary disks, which plays an important role in the theory of giant-planet formation via core accretion; beyond this line it is cold enough for water to freeze, increasing the mass of solid material that is available to help a growing planet achieve the critical mass for runaway gas accretion (Pollack et al. 1996; Lecar et al. 2006). For periods shorter than a few years, the distribution of planet masses, $dn/d\log M$, appears to be roughly constant between about 30 and 1,000 $M_\oplus$ (Fernandes et al. 2019; Fulton et al. 2021).

![Fig. 2](image-url) Occurrence rate density of giant planets, expressed as the average number of planets per 100 stars within each bin of either period (left) or semi-major axis (right). The data at left were derived from the Kepler transit survey by Santerne et al. (2016). The data at right were derived from the Doppler-based California Legacy Survey by Fulton et al. (2021).
Metallicity

The earliest Doppler surveys found the occurrence of giant planets to be associated with a high heavy-element abundance of the host star (Gonzalez 1997). Fischer and Valenti (2005) found $\frac{dn}{dZ} \propto Z^2$, where $Z$ is the mass fraction of “metals” (elements heavier than helium). Another valid description of the data is that giant-planet occurrence is low and independent of metallicity for $Z \lesssim Z_\odot$, and rises steeply with metallicity for $Z \gtrsim Z_\odot$ (Santos et al. 2003; Fulton et al. 2021).

This “metallicity effect” is widely interpreted as supporting evidence for the core accretion theory of giant planet formation. The logic is that the rapid assembly of a massive solid core — an essential step in the theory — is easier to achieve in a metal-rich protoplanetary disk. Santos et al. (2017) found the occurrence of companions more massive than $4 M_{\text{Jup}}$ to be independent of metallicity and suggested that such objects form by gravitational instability rather than core accretion. Schlaufman (2018) reached a similar conclusion and went so far as to say that companions more massive than $10 M_{\text{Jup}}$ should not be considered planets. Complicating the interpretation, Buchhave et al. (2018) found that giant planets with $a > 2$ AU and low eccentricities are not preferentially found around high-metallicity stars, suggesting that the metallicity effect is related to giant-planet migration rather than formation.

Hot Jupiters

Easy to detect, but intrinsically rare, hot Jupiters have an occurrence rate of 0.5–1% for periods between 1 and 10 days. They are even rarer for periods shorter than one day (Howard et al. 2012; Sanchis-Ojeda et al. 2014). There is a 3σ discrepancy between the rate of 0.8–1.2% measured in Doppler surveys (Wright et al. 2012; Mayor et al. 2011) and 0.6% measured using Kepler data (Howard et al. 2012; Petigura et al. 2018). This is despite the similar metallicity distributions of the stars that were searched (Guo et al. 2017). While we should never lose too much sleep over 3σ discrepancies, an interesting explanation was offered by Moe and Kratter (2021): giant planet formation is suppressed in binary star systems with separations less than about 10 AU. Transit surveys include many such close binaries in their search samples (Bouma et al. 2018), but Doppler surveys generally exclude them, which could boost the inferred occurrence of hot Jupiters in Doppler surveys by a factor of 1.5–2.

Conditional occurrence rates

Given the existence of a close-orbiting giant planet, what is the chance of finding another planet around the same star? Many authors have attempted to measure such conditional occurrence rates because they might provide clues about the formation and evolution of giant planets. For example, Huang et al. (2016) used Kepler data to show that hot Jupiters ($P = 1–10$ days) are “lonelier” than warm Jupiters ($10–100$ days), in that they have a lower occurrence rate of companions with periods shorter than 50 days and radii larger than $2 R_\oplus$. However, hot and warm Jupiters have similar occurrence rates of more distant giant planets (Schlaufman and Winn 2016; Bryan et al. 2016; Zink and Howard 2023). These results suggest that the formation of a hot Jupiter involves events that destroy or suppress the formation of any other planets within $\approx 0.5$ AU, as expected in the theory of high-eccentricity migration (Rasio and Ford 1996).
Other properties The giant-planet population is distinguished by other features. Their orbital eccentricities range from zero to nearly unity with a mean value of about 0.3 (Kipping 2013). Their occurrence seems to fall precipitously for masses above \( \approx 10 M_{\text{Jup}} \), at least for orbital distances smaller than a few AU. Because of this low occurrence, the mass range from 10–80 \( M_{\text{Jup}} \) is often called the “brown dwarf desert” (Grether and Lineweaver 2006; Sahlmann et al. 2011; Santerne et al. 2016; Triaud et al. 2017). Occasionally, we find two giant planets in a mean-motion resonance (Wright et al. 2011). The rotation of the star can be grossly misaligned with the orbit of the planet, especially if the star is more massive than about 1.2 \( M_{\odot} \) (Albrecht et al. 2022).

Smaller planets

Overall occurrence At least a third of Sun-like stars have “miniature Solar Systems” consisting of several planets with periods shorter than a year and sizes in between those of Earth and Neptune. Planet formation theories generally did not predict this profusion of close-orbiting planets. Indeed, some of the most detailed theories predicted that such planets would be especially rare (Ida and Lin 2008). Their surprisingly high abundance led to new theories in which small planets can form in short-period orbits, rather than forming farther away from the star and migrating inward (see, e.g., Hansen and Murray 2012; Chiang and Laughlin 2013).

Doppler surveys provided our first glimpse at this population of planets. For periods shorter than 50 days and masses between 3 and 30 \( M_{\oplus} \), two independent Doppler surveys found the occurrence rate to be \((15 \pm 5)\%\) (Howard et al. 2010) and \((27 \pm 5)\%\) (Mayor et al. 2011). Soon after, the Kepler mission revealed this population in more vivid detail (Howard et al. 2012). For example, Zhu et al. (2018) used Kepler data to show that \((30 \pm 3)\%\) of Sun-like stars harbor several planets with periods shorter than 400 days and sizes between 1 and 4 \( R_{\oplus} \). Any association between their occurrence and the metallicity of the host star is weaker than for giant planets (Buchhave et al. 2012; Mulders et al. 2016; Winn et al. 2017; Wilson et al. 2018; Petigura et al. 2018).

Size and period Within the innermost AU of planetary systems, planets with sizes between 1 and 4 \( R_{\oplus} \) are about an order of magnitude more abundant than planets with sizes between 4 and 16 \( R_{\oplus} \). The occurrence rate density \( dn/d\log P \) of 1–4 \( R_{\oplus} \) planets rises with period out to about 10 days and is nearly flat between 10–400 days. The left panel of Figure 3 shows the occurrence rate densities derived by Petigura et al. (2018) using Kepler data, for two different size categories.

Orbital spacings As noted above, small planets frequently occur in closely-spaced systems. Zhu et al. (2018) found the typical system to consist of three planets having periods shorter than 400 days. The ratios of orbital periods between adjacent planets tend to be in the range between 1.5 and 5 (Fabrycky et al. 2014). With reference to the mutual Hill radius (relevant to dynamical stability),
Fig. 3 Occurrence rate density of small planets, expressed as the average number of planets per 100 stars within each bin of either period (left) or radius (right). The period distributions are from Petigura et al. (2018), with best-fit functions of the form given by Equation 1. The radius distribution is from Fulton et al. (2021) and refers to planets with periods shorter than 100 days. The dip at $1.7 R_{\oplus}$ appears to separate solid “super-Earths” from gas-sheathed “sub-Neptunes”.

\[ a_H \equiv \left( \frac{M_{\text{in}} + M_{\text{out}}}{3M_\star} \right)^{1/3} \left( \frac{a_{\text{in}} + a_{\text{out}}}{2} \right), \]  

(6)

the typical spacing is 10–30 $a_H$ (Fang and Margot 2013). At the lower end of this distribution, the systems flirt with instability (Deck et al. 2012; Pu and Wu 2015). A few percent of the Kepler systems are in or near mean-motion resonances, suggesting that the orbits have been sculpted by planet-disk gravitational interactions. Resonant and near-resonant systems offer the gift of transit-timing variations (TTVs), the observable manifestations of planet-planet gravitational interactions. In some cases, modeling the TTVs leads to precise constraints on planet masses, eccentricities, and inclinations (see, e.g., Carter et al. 2012 and Agol et al. 2021), although there are often degeneracies between these quantities (Lithwick et al. 2012). Analyses of TTVs, and other lines of evidence, have shown that the compact multiple-planet systems tend to have orbits that are nearly circular (Hadden and Lithwick 2014; Xie et al. 2016; Van Eylen and Albrecht 2015) and coplanar (Fabrycky et al. 2014).

**Radius gap** For planets with periods shorter than 100 days, the occurrence rate density $dn/d\log R$ shows a dip centered at $R \approx 1.7 R_{\oplus}$ (Fulton et al. 2017; Van Eylen et al. 2017; see the right panel of Figure 3). The location of this dip is often used as the dividing line between “super-Earths” and “sub-Neptunes”. Super-Earths tend to have lower densities, suggestive of a rocky planet with an outer layer of hydrogen-helium gas constituting a few percent of the total mass. Possibly, super-Earths are sub-Neptunes that lost their atmospheres due to the host star’s high-energy radiation (Owen and Wu 2013; Lopez and Fortney 2013) or the gradual leakage of the rocky planet’s heat of formation (Ginzburg et al. 2018).
Both Doppler and transit surveys found a very low occurrence rate for planets with periods shorter than a few days and sizes between 2 and 6 $R_\oplus$ or masses between 10 and 100 $M_\oplus$ (Szabó and Kiss 2011; Mazeh et al. 2016). This “hot Neptune desert” may be another consequence of atmospheric erosion. Those few hot Neptunes that do exist are strongly associated with metal-rich stars and tend to have planetary companions in closely-spaced coplanar orbits, making them similar to giant planets and unlike smaller planets (Dong et al. 2018).

**Conditional occurrence rates** Two super-Earths or two sub-Neptunes orbiting the same star tend to have more similar sizes than two planets of the same category drawn from the entire collection of planetary systems. Their similar sizes (and regular spacings) cause planets within a given system to resemble “peas in a pod” (Weiss et al. 2018; Millholland and Winn 2021). It seems logical that planets forming in a similar environment should resemble each other; for more on this phenomenon and its interpretation, see Weiss et al. (2023).

Another interesting conditional occurrence rate is that of distant giant planets around stars that harbor short-period super-Earths and sub-Neptunes. By combining the results of Doppler and transit surveys, Zhu and Wu (2018) found that the existence of a compact inner system boosts the odds of finding a giant planet with a period of a few years from about 10% to 30%. Similar results were obtained by Bryan et al. (2019). Complicating the situation, Rosenthal et al. (2022) found evidence for a weaker boost and Bonomo et al. (2023) found no evidence for any boost, seemingly contradicting the earlier results. A possible resolution is that the boost is specific to metal-rich stars (Zhu 2023).

**Earth-like planets** A goal with broad appeal is measuring the occurrence rate of Earth-sized planets orbiting Sun-like stars within the “habitable zone”, the range of distances from the star where the surface temperature of a rocky planet could plausibly allow for oceans of liquid water. The Kepler mission provided the best available data for this purpose. However, even Kepler was barely sensitive to such planets. The number of detections was on the order of 1–10, depending on the definitions of “Earth-sized”, “Sun-like” and “habitable zone”. The desired quantity can be written

$$\eta_\oplus \equiv \int_{R_{\min}}^{R_{\max}} \int_{S_{\min}}^{S_{\max}} \frac{\partial^2 n}{\partial \log S \partial \log R} \ d \log S \ d \log R,$$

where $S$ is the flux the planet receives from the star, and the integration limits are chosen to select planets likely to have a solid surface with a temperature and pressure suitable for liquid water (Kasting et al. 2014; Kopparapu et al. 2014).

The Kepler team published a series of papers reporting steady advances in quantifying the efficiency of planet detection, eliminating false positives, understanding instrumental artifacts, and improving the characterization of the stars that were searched. The most recent study, by Bryson et al. (2021), summarized previous work on this topic and found $\eta_\oplus$ to be between $0.37^{+0.25}_{-0.21}$ and $0.88^{+1.28}_{-0.51}$. These two estimates are based on different assumptions made in extrapolating the occurrence rate from larger planets and shorter periods.
Other types of stars

Almost all of the preceding results pertain to main-sequence stars with masses between 0.5 and 1.2 \( M_\odot \), i.e., spectral types from late K to late F. Stars with masses between 0.1 and 0.5 \( M_\odot \), the M dwarfs, are not as thoroughly explored, especially near the low end of the mass range. However these stars are very attractive for planet surveys. Their small masses and sizes lead to larger Doppler and transit signals, all other things being equal. Furthermore, planets in the habitable zones of M dwarfs have short orbital periods that make transits more likely and are convenient for observers (Gould et al. 2003; Nutzman and Charbonneau 2008).

The occurrence rate of giant planets with \( a \approx 1 \) AU is lower around M dwarfs than FGK dwarfs by at least a factor of a few (Endl et al. 2006; Cumming et al. 2008; Johnson et al. 2010b; Bonfils et al. 2013; Bryant et al. 2023; Gan et al. 2023). On the other hand, super-Earths and sub-Neptunes with \( a \approx 1 \) AU are several times more common around M dwarfs than FGK dwarfs (Howard et al. 2012; Muiders et al. 2015; Dressing and Charbonneau 2015). An implication is that the nearest habitable-zone planets are probably around M dwarfs, and indeed, Doppler surveys have turned up two potentially habitable planets around very nearby M dwarfs: Proxima Cen (1.3 pc; Anglada-Escudé et al. 2016) and Ross 128 (also known as Proxima Vir; 3.4 pc; Bonfils et al. 2018). As is the case for FGK dwarfs, the small planets around M dwarfs are often organized into compact systems of multiple planets (Muirhead et al. 2015; Gaidos et al. 2016; Ballard and Johnson 2016). There is also evidence that the planet population around M dwarfs exhibit both the hot Neptune desert and the radius gap (Hirano et al. 2017), although the nature of the planets above and below the radius gap is debated. Luque and Pallé (2022) argued that the sub-Neptunes around M dwarfs are not gas-ensheathed rocky planets, but are instead “water worlds” with a high abundance of volatile elements, while Rogers et al. (2023) argued that there is not yet conclusive evidence for a population of water worlds.

Beyond the scope of this review, but nevertheless fascinating, are the occurrence rates that have been measured in Doppler and transit surveys of other types of stars: A stars (Zhou et al. 2019; Beleznay and Kunimoto 2022), evolved stars (Johnson et al. 2010a; Reffert et al. 2015), stars in open clusters (Mann et al. 2017; Christiansen et al. 2023) and globular clusters (Gilliland et al. 2000; Masuda and Winn 2017), binary stars (Armstrong et al. 2014), brown dwarfs (He et al. 2017), thick-disk and halo stars (Zink et al. 2023), and white dwarfs (Fulton et al. 2014; van Sluijs and Van Eylen 2018). Even neutron stars have been surveyed, using the Doppler-like technique of pulsar timing (Kerr et al. 2015; Behrens et al. 2020; Niţu et al. 2022).
Future Prospects

Improving upon the state of the art in Doppler and transit surveys will not be easy, but efforts are underway. Surveys of M dwarfs are being conducted with stabilized high-resolution infrared spectrographs, a relatively new technological development (see, e.g., Mahadevan et al. 2012; Sabotta et al. 2021). With a new generation of optical Doppler spectrographs, such as MAROON-X (Seifahrt et al. 2016), ESPRESSO (Pepe et al. 2021), EXPRES (Jurgenson et al. 2016), KPF (Gibson et al. 2020), and the planned HARPS3 (Thompson et al. 2016) and G-CLEF (Szentgyorgyi et al. 2018), it might be possible to detect Earth-mass planets with orbital periods approaching a year. In addition to finding potentially habitable planets, the results from these facilities will provide more overlap between Doppler-based occurrence measurements as a function of mass and transit-based occurrence measurements as a function of radius. This combination will improve our understanding of the compositions of small planets, the eccentricities of their orbits, and the mutual inclinations between their orbital planes.

Meanwhile, the PLATO mission Rauer et al. (2016] is scheduled for launch in 2026 by the European Space Agency. PLATO will perform a transit survey using 26 × 0.2 m optical telescopes with an combined instantaneous field of view of about 2,300 square degrees. The current plan is to monitor two fields for two years each, with a top-level goal of finding ~10 habitable-zone Earth-sized planets around Sun-like stars. A China-based collaboration is proposing a space-based transit survey called Earth 2.0 (Ge et al. 2022) that would monitor a field that encompasses the original Kepler field.

In the years to come, the domains of all the planet detection techniques — including astrometry, gravitational microlensing, and direct imaging — will begin overlapping. Some efforts have already been made to determine occurrence rate densities based on data from different techniques (see, e.g. Montet et al. 2014; Clanton and Gaudi 2016). We can look forward to a more holistic view of the occurrence of planets around other stars, barring any civilization-ending cataclysm.

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