How Complete Are Surveys for Nearby Transiting Hot Jupiters?

Samuel W. Yee ©, Joshua N. Winn ©, and Joel D. Hartman ©
Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Princeton, NJ 08544, USA; swyee@princeton.edu
Received 2021 July 12; revised 2021 September 16; accepted 2021 September 21; published 2021 November 15

Abstract
Hot Jupiters are a rare and interesting outcome of planet formation. Although more than 500 hot Jupiters (HJs) are known, most of them were discovered by a heterogeneous collection of surveys with selection biases that are difficult to quantify. Currently, our best knowledge of HJ demographics around FGK stars comes from the sample of ≈40 objects detected by the Kepler mission, which have a well-quantified selection function. Using the Kepler results, we simulate the characteristics of the population of nearby transiting HJs. A comparison between the known sample of nearby HJs and simulated magnitude-limited samples leads to four conclusions. (1) The known sample of HJs appears to be ≈75% complete for stars brighter than Gaia $G \lesssim 10.5$, falling to ≲50% for $G \lesssim 12$. (2) There are probably a few undiscovered HJs with host stars brighter than $G \approx 10$ located within $10^3$ of the Galactic plane. (3) The period and radius distributions of HJs may differ for F-type hosts (which dominate the nearby sample) and G-type hosts (which dominate the Kepler sample). (4) To obtain a magnitude-limited sample of HJs that is larger than the Kepler sample by an order of magnitude, the limiting magnitude should be approximately $G \approx 12.5$. This magnitude limit is within the range for which NASA’s Transiting Exoplanet Survey Satellite can easily detect HJs, presenting the opportunity to greatly expand our knowledge of hot-Jupiter demographics.

Unified Astronomy Thesaurus concepts: Exoplanets (498); Hot Jupiters (753)

1. Introduction
Hot Jupiters—planets with masses exceeding $0.1 M_J$ and orbital periods shorter than 10 days—are rare. The probability that a Sun-like star has a hot Jupiter has been variously estimated as 0.4%–1.2% (Mayor et al. 2011; Wright et al. 2012; Fressin et al. 2013; Masuda & Winn 2017; Petigura et al. 2018). Despite this low probability, many of the earliest discovered planets were hot Jupiters, including 51 Pegasi b (Mayor & Queloz 1995). Today, hot Jupiters constitute more than 10% of the sample of confirmed exoplanets. This is because hot Jupiters are relatively easy to detect, producing strong radial-velocity signals and having conveniently short orbital periods. They also have high transit probabilities, and when they do transit, the fractional loss of light is relatively large.

The discovery of hot Jupiters was unexpected because giant planets were supposed to form in orbits wider than a few AU, according to the prevailing core-accretion theory for giant planet formation (e.g., Lissauer 1993, although see also Struve 1952). There are three categories of responses to this theoretical challenge, as reviewed by Dawson & Johnson (2018) and Fortney et al. (2021). One scenario is that hot Jupiters did form in very close orbits, i.e., a sufficiently massive core was able to form within the inner disk despite the low surface density of solids (Rafikov 2006; Batygin et al. 2016; Lee & Chiang 2016). In the other two scenarios, giant planets form in wide orbits and then move inward. The inward migration might be caused by torques from the protoplanetary disk (Goldreich & Tremaine 1980; Lin et al. 1996; Baruteau et al. 2014), or by eccentricity excitation followed by tidal circularization (Rasio & Ford 1996; Fabrycky & Tremaine 2007).

It might be possible to figure out how often each of these processes takes place by examining the properties and statistics of hot Jupiters. For example, migration through a disk would lead to an inner boundary for the orbital distances of hot Jupiters corresponding to the inner edge of the disk, while for high-eccentricity migration the inner boundary should occur at roughly twice the Roche radius. Indeed, a possible pileup of hot Jupiters at an orbital period of ≈3 days was first noted by Cumming et al. (1999) and Udry et al. (2003). Nelson et al. (2017) examined the semimajor axis distribution of the hot Jupiters discovered by the HAT and WASP surveys, arguing that it showed evidence for multiple populations, with 85% of hot Jupiters residing in a component consistent with having formed through high-eccentricity migration, while the remaining 15% were consistent with disk migration.

Other trends in the population of known hot Jupiters include an increasing occurrence rate with stellar metallicity (Santos et al. 2004; Valenti & Fischer 2005), and possibly also with stellar mass (Johnson et al. 2010), although Obermeier et al. (2016) argued that the current sample size is too small to draw a robust conclusion. When the planet radius/period distribution is examined for periods shorter than 10 days, there appears to be a deficit of planets with radii between about 2 and 9 Earth radii, with the lower limit increasing with orbital period. This is the so-called “hot-Neptune desert” separating hot Jupiters from smaller and mainly rocky planets (Szabo & Kiss 2011; Mazeh et al. 2016).

Despite these advances, our knowledge of the demographics of hot Jupiters remains fuzzy. Paradoxically, we have better knowledge of the demographics of smaller planets with periods ranging out to several months, because of the large and well-understood sample of thousands of such planets that resulted from NASA’s Kepler mission (Borucki 2016). In contrast, the Kepler sample includes only 40 confirmed and 19 candidate hot Jupiters orbiting FGK stars. Radial-velocity surveys have discovered 44 hot Jupiters, also a relatively small sample, and it is difficult to interpret the results because different surveys used different selection procedures, such as a preference for high-metallicity stars, and different detection biases. Two of the most statistically well-understood radial-velocity samples are those analyzed by Cumming et al. (2008) and Rosenthal et al. (2021), which contained only 12 and 14 hot Jupiters,
respectively. More than three quarters of the total observed sample of $\approx$500 hot Jupiters comes from a heterogeneous collection of wide-field ground-based photometric surveys such as WASP (Pollacco et al. 2006), HAT (Bakos et al. 2004, 2013), KELT (Pepper et al. 2007), and NGTS (Wheatley et al. 2018). While these surveys have been very successful in detecting hot Jupiters and have made important contributions to the field, they suffered from complex and severe biases due to irregular data sampling, nonstationary noise properties, limited knowledge of the properties of the stars that were searched, and inability to perform the necessary follow-up observations of many transit candidates. Thus, despite the large sample size, it has proven difficult to use the results of the wide-field surveys for demographics. The Kepler sample of hot Jupiters is probably the most homogeneous sample that is currently available. The Kepler telescope observed about $2 \times 10^5$ stars for 4 yr, with a sensitivity high enough to be nearly 100% complete for hot Jupiters. The results from Kepler provided many new insights, such as a clearer view of the connection between radius inflation and stellar irradiation (Demory & Seager 2011), constraints on the frequency of nearby companion planets (Steffen et al. 2012), and the finding that the period pileup is only evident when the sample is restricted to metal-rich stars (Dawson & Murray-Clay 2013). New questions were also raised, such as the reason for the apparent factor-of-two discrepancy between the occurrence rate of hot Jupiters from different surveys (Wright et al. 2012). However, as noted above, the Kepler sample includes only 40 confirmed and 19 candidate hot Jupiters orbiting FGK stars, limiting the power of statistical studies.

The work reported in this paper was undertaken to gauge the completeness of the existing samples of hot Jupiters in the solar neighborhood, and estimate the number and stellar host properties of the hot Jupiters that would need to be detected in order to enlarge the statistically useful sample from 40 to 400. We focused on transit detection, rather than radial-velocity detection, to take advantage of the homogeneity and completeness of the Kepler sample of transiting planets and to set expectations for the large number of hot Jupiters that are detectable using data from the NASA Transiting Exoplanet Survey Satellite (TESS) mission (Ricker et al. 2015). Prior work by Beatty & Gaudi (2008) had a similar goal, to predict the number of transiting hot Jupiters that would be discovered in wide-field transit surveys as a function of magnitude and galactic latitude. Our work incorporates the knowledge we have gained since then about hot Jupiters and their properties. We used the Kepler sample to estimate the number of transiting hot Jupiters we should expect in a magnitude-limited sample of FGK stars (Section 2), and compared this to the known sample (Section 3). Because the results suggested that the current sample is reasonably complete down to a Gaia magnitude of 10.5, we took the opportunity to compare this subsample of hot Jupiters with the independent Kepler sample (Section 4) and assess the level of agreement in their observed properties.

2. Completeness of the Sample of Nearby Transiting Hot Jupiters

To gauge the completeness of the current sample of transiting hot Jupiters (HJs), we wanted to estimate how many would have been detected in a magnitude-limited survey of nearby FGK stars. To set expectations for more complicated models, let us start with a simple model. In an idealized magnitude-limited transit survey of a population of identical Sun-like stars isotropically and uniformly distributed in space, the expected total number of detections is

$$N(m_{\text{lim}}) = np_{\text{tra}} \times \frac{4\pi}{3} d_{\text{ref}}^3 \times 10^{0.6(m_{\text{lim}}-m_{\text{ref}})},$$

(1)

where $m_{\text{lim}}$ is the limiting apparent magnitude, $n$ is the number density of stars, $f$ is the fraction of stars with HJs, $p_{\text{tra}}$ is the average geometric transit probability, and $m_{\text{ref}}$ is the apparent magnitude of a Sun-like star at an arbitrarily chosen reference distance $d_{\text{ref}}$.

Based on the Gaia Catalog of Nearby Stars (Gaia Collaboration et al. 2021b), a reasonable estimate for the number density of stars with absolute magnitudes between 3.5 and 6.5 (roughly the spectral types F6 through K4) is 0.007 stars pc$^{-3}$. For $n$, we adopt a hot Jupiter occurrence rate of 0.6% based on the analysis by Petigura et al. (2018) of the Kepler sample. A reasonable estimate of $p_{\text{tra}}$ is 0.1, corresponding to an orbital distance of about 0.05 au around a Sun-like star. Further choosing $d_{\text{ref}} = 116$ pc and $m_{\text{ref}} = 10$ as appropriate for the Sun, we obtain

$$N(m_{\text{lim}}) \approx 25 \times 10^{0.6(m_{\text{lim}}-10)}.$$  

(2)

The current sample of hot Jupiters includes 19 with host stars brighter than $G = 10$, suggesting that it may be $\approx75\%$ complete down to that magnitude. For $m_{\text{lim}} = 8$, this formula predicts $N \approx 1.6$, and there are two known HJs (HD 209458b and KELT-11b) with host stars with $G < 8$ and spectral types between F6 and K4. This formula also predicts that to obtain a magnitude-limited sample of 400 hot Jupiters, the required limiting magnitude is 12.0.

We wanted to go beyond this crude approximation in order to:

1. Take into account the uncertainties arising from Poisson fluctuations and the uncertainty in the hot-Jupiter occurrence rate.
2. Investigate completeness as a function of galactic latitude, to see if the practical problems associated with detecting and confirming planets in crowded star fields have led to lower completeness near the galactic plane.
3. Account for stars of different stellar types and possible variation in hot-Jupiter occurrence rate with stellar mass.
4. Use the statistics of Kepler transit detections directly, instead of relying on an inferred occurrence rate and a typical transit probability.

The latter goal is complicated by the fact that Kepler was not a magnitude-limited survey. The stars for which data are available were selected based on various criteria related to planet detectability, which depended on stellar effective temperature, radius, and the surface density of nearby stars on the sky (Batalha et al. 2010).

Our chosen method builds on similar work by Masuda & Winn (2017), who calculated the expected number of detections of transiting HJs in the globular cluster 47 Tucanae. In short, we constructed a sample of Kepler stars for which any transiting HJs would have been detected. We then used the Gaia catalog to construct a magnitude-limited sample of stars spanning the same range of colors and luminosities as the Kepler sample—the “local” sample—and matched each local star with a star of similar color and luminosity in the Kepler sample. Whenever a local star was matched to a Kepler star that...
hosts a transiting hot Jupiter, we assigned the local star a planet with the same properties. We then counted the total number of transiting planets in this “matched” catalog, and compared it to the number of HJs actually detected in the “local” sample. By repeating this process many times, we derived the statistical uncertainty in this estimate arising from Poisson fluctuations and the limited number of HJs detected by Kepler.

The underlying premise of this method is that planet occurrence in the solar neighborhood is the same as in the Kepler sample. As we noted in the introduction, Kepler HJ statistics appear to differ from those found by radial-velocity surveys by 2–3σ, which may be due to differences in the underlying stellar distribution. Our matching procedure attempts to correct for differences in stellar population in color–magnitude space, but not directly for other factors that may affect the HJ occurrence rate, such as stellar metallicity, multiplicity, and age. We discuss the validity of our assumptions later in Section 4.2. In the rest of this section, we outline our data selection and matching procedure in greater detail.

2.1. Target Selection

2.1.1. Planet Properties

The occurrence rates reported in the literature are sometimes based on different definitions of hot Jupiters. For our work, we consider a planet to be a hot Jupiter when it has a radius between 0.8 and 2.5 times that of Jupiter, and an orbital period shorter than 10 days. Using this criterion, we found ≈500 confirmed and candidate hot Jupiters when querying the NASA Exoplanet Archive; however, not all of these planets orbit main-sequence FGK stars. Below, we describe our stellar selection process.

2.1.2. Kepler Stars

To select the stars in the Kepler sample, we used the Gaia–Kepler Stellar Properties Catalog (Berger et al. 2020), a homogeneous set of stellar properties derived using an isochrone analysis with Gaia parallaxes and broadband photometry. This catalog includes almost all of the ≈200,000 stars observed by Kepler, subject to cuts based on the quality of parallax measurements and photometry from the 2MASS survey to exclude nearly equal-brightness binaries. We obtained Gaia EDR3 photometry (Gaia Collaboration et al. 2021a; Riello et al. 2021) for all the members of the catalog. To correct the Gaia photometry for reddening and extinction, we used a standard extinction law $R_V = 3.1$ and the extinction coefficients for Gaia filters derived by Casagrande & Vandenberg (2018; Table 2), together with the $A_V$ extinctions derived by Berger et al. (2020). Figure 1 shows the extinction-corrected $M_G$, $G_{BP} - G_{RP}$ color–magnitude diagram for this sample.

We then selected FGK main-sequence stars using synthetic photometry from the MESA Isochrones and Stellar Tracks (MIST; Choi et al. 2016; Dotter 2016). We defined a region in the Gaia color–magnitude diagram bounded by the zero-age main-sequence and terminal-age main-sequence isochrones in MIST for stars with masses between 0.7 and 1.2 $M_\odot$. We used isochrones spanning initial [Fe/H] metallicities from $-0.2$ to $+0.2$, and used the union of the regions bounded by these isochrones as our final stellar selection criterion. This cut on stellar colors and absolute magnitudes led to a sample of 112,203 Kepler targets.

We also wanted to restrict our Kepler sample to stars around which any transiting hot Jupiters would have been detected. For each star we calculated the Multiple Event Statistic (MES),

$$\text{MES} = \frac{T_{\text{obs}}}{P_{\text{orb}}} \frac{(R_p/R_\star)^2}{\sigma_{\text{CDPP}}(T_{\text{ra}})},$$

where $T_{\text{obs}}$ is the total timespan of observations for a given star, $P_{\text{orb}}$ is the orbital period, $R_p$ is the planetary radius, $R_\star$ is the stellar radius, and $\sigma_{\text{CDPP}}$ is the robust root-mean-squared combined differential photometric precision (Christiansen et al. 2012) on a timescale equal to the maximum possible duration of a transit for a planet on a circular orbit,

$$T_{\text{ra, max}} \approx 13 \text{ hr} \left( \frac{P_{\text{orb}}}{1 \text{ yr}} \right)^{1/3} \left( \frac{\rho_\star}{\rho_{\odot}} \right)^{-1/3},$$

where $\rho_\star$ is the mean density of the star. The final version of the NASA Kepler pipeline used a minimum MES threshold of 7.1 to identify Threshold-Crossing Events (Twicken et al. 2016; Thompson et al. 2018). We computed the MES for each Kepler target assuming $R_p = 0.8 \, R_{\text{Jup}}$ and $P = 10$ days, the most difficult hot Jupiter to detect according to our definition of hot Jupiters. We used the stellar properties of Berger et al. (2020) and set $T_{\text{obs}} = (\pi/4) T_{\text{ra, max}}$ to account for averaging over possible transit impact parameters. The value of $\sigma_{\text{CDPP}}$ was computed for various fixed timescales based on Kepler DR25 (Twicken et al. 2016); we used linear interpolation to compute $\sigma_{\text{CDPP}}$ for our desired transit duration.

Given the calculated MES values for the detection of a hot Jupiter around each target, we excluded those for which MES is less than 7.1. We also excluded stars for which the observation duration $T_{\text{obs}}$ was less than 30 days, given that at least three transits needed to be observed for a secure detection.

Only 13 of the stars in our Kepler sample were excluded by these criteria. Increasing the MES threshold from 7.1 to 10 or 17 changed the number of stars in our final sample by less than one percent. Thus, this exercise served to confirm that Kepler could have detected a transiting hot Jupiter around essentially all of the stars it observed during its 4 yr primary mission. This reinforces our notion that the hot Jupiters detected by Kepler represent the most complete and well-understood sample of such planets currently available.

Around the stars meeting our selection criteria, Kepler detected a total of 40 confirmed hot Jupiters, and 19 candidate transit signals for which the reported light-curve properties are consistent with hot Jupiters. We excluded planets with grazing transits (impact parameters $>0.9$) because of their lower detectability, larger uncertainties in planet radius and other parameters, and higher likelihood of being false positives. This left us with a sample of 36 confirmed and six candidate hot Jupiters. Each of the six candidates was assigned a false-positive probability (FPP) by Morton et al. (2016). By assigning each of the confirmed planets a weight of 1.0, and each of the candidates a weight of 1-FPP, we arrived at an effective sample size of 41 transiting hot Jupiters drawn from a sample of 112,203 stars. We will refer to this Kepler sample by the symbol $S_K$. 

1 https://doi.org/10.26133/NEA12
2.1.3. Magnitude-limited Sample

We then constructed a magnitude-limited sample using data from Gaia EDR3 (Gaia Collaboration et al. 2021a). We queried the Gaia archive for all stars brighter than $G < 12.5$ to obtain the photometric and astrometric observations, using a standard quality cut on the parallax ($\varpi/\sigma_\varpi > 5$) to remove suspect data. We also used the geometric distances from Baier-Jones et al. (2021) to compute absolute $G$-band magnitudes. Although most of these bright stars are relatively nearby and do not suffer significant dust extinction, we nonetheless corrected their Gaia $G$, $G_{BP}$, and $G_{RP}$ magnitudes using the mw_dust Python package (Bovy et al. 2016). In particular, we used the Combined19 dust map, which combines the maps from Green et al. (2019), Marshall et al. (2006), and Drimmel et al. (2003) to provide full sky coverage. The majority of our stellar sample received only small corrections, with $90\%$ of stars having $E(G_{BP} - G_{RP}) < 0.15$.

To select main-sequence FGK stars, we applied the same cut in the extinction-corrected color–magnitude diagram (ersus $G_{BP} - G_{RP}$) as we did for the Kepler sample. We did not make any further cuts on astrometric fit quality, out of concern that hot Jupiters may be preferentially associated with stars with wide-orbiting companions (e.g., Ngo et al. 2016) that would affect the quality of the Gaia astrometric fits (Belokurov et al. 2020; Moe & Kratter 2020). This procedure yielded 1,073,225 stars in our magnitude-limited “local” sample, which we denote by the symbol $S$. According to the NASA Exoplanet Archive, there are 154 transiting hot Jupiters known to exist around the stars in this sample. The right panel of Figure 1 shows the color–magnitude diagram for the stars and hot Jupiters in this sample. The two stellar populations are different: Kepler target stars were chosen to maximize the number of small planets that could be detected (Batalha et al. 2010), leading to a dominance by G-dwarfs; meanwhile, the Gaia magnitude-limited sample is dominated by early F stars because they are more luminous and can be seen to a greater distance at fixed apparent magnitude (Malmquist bias). If the hot Jupiter occurrence rate varies according to stellar type, then our matching procedure should account for these differences. This was the motivation for the process described in the following section.

2.2. Matching Procedure

We performed our matching procedure to generate a synthetic catalog of transiting hot Jupiters around the stars in $S$. First, we drew stars, with replacement, from $S_K$, to generate a new sample $\tilde{S}_K$ that has the same number of members as $S$. This step accounted for the Poisson fluctuations in the number of planets in the Kepler sample. We then associated each star in $S$ with a star in the resampled set, $\tilde{S}_K$. To account for the differences in the underlying stellar populations of the two samples, and any possible variation in hot-Jupiter occurrence with stellar type, we wanted to match the stars in $S$ with stars of similar spectral types in $\tilde{S}_K$.

We defined a metric in color–magnitude space,

$$d = \left( \frac{\Delta\text{mag}}{\sigma_{\text{mag}}} \right)^2 + \left( \frac{\Delta\text{color}}{\sigma_{\text{color}}} \right)^2,$$

where $\Delta\text{mag}$ is the difference in absolute magnitude, $\Delta\text{color}$ is the difference in the $G_{BP} - G_{RP}$ color, and $\sigma_{\text{mag}}$ and $\sigma_{\text{color}}$ are the standard deviations of the distributions of absolute magnitude and color of the entire sample. Then, for each star in $S$, we drew a proposed match in $\tilde{S}_K$, and accepted this proposal with probability $P(d) \propto e^{-d}$. Whenever a proposed match was rejected, we proposed a new matching star from $\tilde{S}_K$ until all stars in $S$ were successfully matched.

The choice of 3 as the factor in the exponent of $P(d)$ was made after some experimentation to balance two effects: if set too small, the resulting distribution would not resemble the target distribution; too high, and the sparsity of hot-Jupiter hosts in the Kepler sample would mean some stars in $S$ would never be matched with a planet-hosting star in $\tilde{S}_K$. We arrived at 3 by computing the distances between each Kepler hot Jupiter hosts and its five closest counterparts, and fitting the resulting distribution of distances with an exponential distribution. In this way, all stars in $S$ had a nonzero probability of being matched with a hot Jupiter host in $\tilde{S}_K$.

This process generated a “matched” catalog of stars, denoted $S_M$, which is comprised of real Kepler stars with a distribution...
in color–magnitude space that is similar to that of the local magnitude-limited sample. Figure 2 compares a single realization of a matched catalog to the distribution of stars in the Gaia sample $\mathcal{S}$, illustrating the desired agreement in stellar properties.

We then assigned each transiting hot Jupiter around a star in $\mathcal{S}_M$ to its matched counterpart in $\mathcal{S}$. Given that each star is only matched to a similar star, any corrections for changes in transit probability due to differing stellar densities are minimized, and were neglected in our subsequent calculations. The end result was a synthetic catalog of transiting hot Jupiters around a magnitude-limited sample of nearby stars from Gaia, based on their occurrence statistics in the Kepler sample. We repeated this process to generate 1000 realizations of this catalog in order to estimate sampling uncertainties in the results.

3. Results

The results from this matching process are shown in Figure 3. Based on these results, we expect that a complete survey of nearby FGK stars brighter than $G < 12.5$ will contain $424^{+38}_{-36}$ transiting hot Jupiters with impact parameters $b < 0.9$—assuming that the Kepler hot Jupiters are representative of the nearby population of hot Jupiters. For comparison, 154 hot Jupiters have actually been confirmed around such stars, leaving several hundred more hot Jupiters undiscovered around nearby stars. Figure 3 also shows that the apparent magnitude distribution of known hot Jupiters is consistent with being 75% complete down to a limiting Gaia $G$-band magnitude of 10.5. For $G < 12.5$, the estimated completeness falls to $36^{+9}_{-7}$%.

Recall that the simpler calculation presented at the beginning of Section 2 predicted that 400 hot Jupiters could be found down to a limiting magnitude of $G < 12$. Our sample-matching procedure suggests that the actual limiting magnitude needs to be 12.4 to reasonably expect to detect 400 transiting hot Jupiters. The differences in the results are due to the simplifying assumptions that were made in the earlier calculation as well as our restriction in the sample-matching procedure that the planets need to show nongrazing transits. We can correct for the latter effect by multiplying the expected number of hot Jupiters in our simulated samples by a factor of 1/0.9, as would be appropriate for isotropically oriented planetary orbits. This simple correction leads to an expectation of $472^{+44}_{-40}$ transiting hot Jupiters for an apparent magnitude limit of $G = 12.5$.

One of the simplifying assumptions that was made in the basic calculation leading to Equation (1) was that stars are distributed isotropically in space around the Sun. In reality, the number density of stars varies strongly as a function of galactic latitude, and the number density of stars also affects the detectability of transiting planets. The crowded star fields near the galactic plane lead to various practical difficulties. Having multiple stars within a photometric aperture reduces the amplitude of the transit signal and increases the noise level due to Poisson fluctuations and variations in the point-spread function. A separate issue is that the incidence of “false-positive” signals is higher in crowded fields, due to the higher density of background eclipsing binaries whose eclipses can be mistaken for planetary transits. Furthermore, the radial-velocity observations and other spectroscopic follow-up observations that are necessary for planet confirmation are made more difficult in the presence of nearby bright stars.

Figure 4 shows that for a limiting magnitude of 10.5, most of the “missing” hot Jupiters are probably to be found within $10^\circ$ of the galactic plane. This strip at low galactic latitudes subtends 17% of the sky and is home to 21% ± 2% of hot Jupiters in our simulated samples, but it only contains 6.5% (10 out of 154) of the sample of known hot Jupiters. If we restrict ourselves only to stars with $|b| > 10^\circ$, then the estimated completeness of the $G < 10.5$ magnitude-limited sample of hot Jupiters rises to $99^{+3}_{-33}$%. Our simulations also suggest that there are a handful (1–4) of hot Jupiters orbiting stars brighter than 10th magnitude waiting to be discovered by those without fear of treading within the galactic plane.
The fraction of hot-Jupiter hosts with flux contamination ratios (a measure of the crowdedness of the star field) larger than the value of the x-axis, for the stars in our synthetic catalogs (blue) and confirmed hot Jupiter hosts (orange), in both cases with an apparent magnitude limit of $G = 12.5$. The confirmed hot Jupiter hosts are biased toward lower flux contamination ratios and lower crowdedness. If we exclude stars close to the galactic plane (green line), the distribution for the synthetic catalogs is more similar to the confirmed population.

≈80 HJs with orbital period $P \leq 5$ days would be found in a magnitude-limited survey of Sun-like stars down to $V \leq 12$. Indeed, when we restrict our synthetic catalogs to $P \leq 5$ days and $V \leq 12$, we obtain an expected yield of $88_{-18}^{+15}$ planets. This good agreement is in part due to those authors’ use of occurrence rates from the OGLE-III survey (Gould et al. 2006), which found a hot Jupiter occurrence rate of 0.45%, similar to the low occurrence rate found by Kepler (see Section 4.2). Our work differs from their analytic study by performing a numerical matching of stars in the all-sky and Kepler catalogs, accounting for possible variation of occurrence rates with stellar and planet properties, and producing synthetic catalogs of transiting planets that we can examine the properties of, as we do in the next section.

4. Discussion

4.1. Comparison of Possibly Complete Samples

Based on the comparison between the apparent magnitude distribution of the hosts of known hot Jupiters and the distribution one would expect based on the incidence of transiting hot Jupiters in the Kepler survey, we are currently aware of about 40% of the hot Jupiters with host stars brighter than $G = 12.5$. However, for a magnitude limit of $G = 10.5$, the total number of known hot Jupiters is consistent with the expected number, once we exclude the region of the sky within $5^\circ$ of the galactic plane. Our Kepler-matching procedure predicts $33 \pm 7$ transiting hot Jupiters, in agreement with the 33 transiting hot Jupiters that have been found. This suggests that we might already be in possession of a nearly complete magnitude-limited sample of hot Jupiters down to $G = 10.5$.

Thus, we took the opportunity to compare this “possibly complete” subset of hot Jupiters—which should be less biased in planet properties than the known hot Jupiter population as a whole—with the sample of 42 Kepler hot Jupiters. Figure 6 compares the period and radius distributions of both of these real samples of hot Jupiters. There are some hints of possible differences in these distributions, despite the fact that we expect both samples to be nearly complete. The period distribution of Kepler hot Jupiters exhibits a pileup at $\approx 3$ days, as first noted by Latham et al. (2011) in an early catalog of Kepler objects of...
The two populations appear to have differing properties, but this discrepancy is reduced when we resample the transiting HJ population to match the stellar distribution of Kepler targets (green). The error bars on the green histogram reflect the 1-σ widths of the distribution based on 1000 resampled catalogs.

> Figure 6. Period and radius distributions of transiting hot Jupiters in the Kepler (blue) and magnitude-limited sample (orange). The two populations appear to have differing properties, but this discrepancy is reduced when we resample the transiting HJ population to match the stellar distribution of Kepler targets (green). The error bars on the green histogram reflect the 1-σ widths of the distribution based on 1000 resampled catalogs.

These results must be interpreted with caution, due to the small sizes of the two samples. Our resampling process showed that due to the small number of planets, features in the period and radius distributions cannot be identified conclusively, especially when considering possible differences in stellar type. Furthermore, our claim that the $G < 10.5$ magnitude-limited sample is “possibly complete” is based only on the total number of detections as a function of apparent magnitude. To check if this is really the case, one would need to understand and model the selection function for the surveys for nearby transiting hot Jupiters, a much larger effort which we did not attempt.

4.2. Comparison with Previous Occurrence Rates

As a check on the matching procedure described in Section 2, we used this same procedure to estimate the occurrence rate of hot Jupiters in the Kepler sample. We did so by simply matching $S_K$ with itself. This yielded many realizations of catalogs of transiting hot Jupiters that we used to estimate the sampling uncertainty. To find the total occurrence rate of hot Jupiters, rather than the rate of transiting hot Jupiters, we weighted each transiting planet by the product of $R_p/a$ (the inverse transit probability) and the factor 1/0.9 that accounts for our restriction on the transit impact parameter. The result was an estimated occurrence rate of $0.38\% \pm 0.06\%$. This is in line with the estimate of $0.43^{+0.07}_{-0.06}\%$ by Masuda & Winn (2017), who used a similar procedure. Other studies of
the Kepler hot Jupiter population have also arrived at similar results. Santerne et al. (2016) found an occurrence rate of 0.47% ± 0.08%, and Petigura et al. (2018) found a rate of 0.57% ± 0.13% based on a more limited subset of the Kepler stars. These Kepler occurrence rates are a factor of ~2 lower than those derived from other studies, albeit with modest statistical significance. Cumming et al. (2008) found a hot-Jupiter occurrence rate of 1.5% ± 0.6% from the Keck radial-velocity surveys, although the parent stellar sample was not constructed blindly with regard to planet host status. Wright et al. (2012) used a cleaner sample from the Lick and Keck planet searches, finding an occurrence rate of 1.2% ± 0.4%. This is consistent with the result of 0.89% ± 0.36% reported by Mayor et al. (2011) based on the HARPS and CORALIE radial-velocity searches. This discrepancy is not limited to comparisons between transit and radial-velocity surveys. Based on the CoRoT transit survey, Deleuil et al. (2018) reported a hot-Jupiter occurrence rate of 0.98% ± 0.26%, higher than the Kepler results and consistent with the radial-velocity results.

Many authors have investigated possible reasons for the discrepancies in occurrence rates.

1. Wang et al. (2015) argued that 12.5% ± 0.2% of hot Jupiters in the Kepler sample were likely misidentified as smaller planets due to flux contamination by nearby stars or errors in the estimated stellar radius, but this would be insufficient to account for a factor-of-two difference in measured occurrence rates.

2. Guo et al. (2017) investigated whether the strong association between stellar metallicity and hot-Jupiter occurrence could be responsible for the discrepancies. Through spectroscopic observations, they found that Kepler stars are more metal-poor by about 0.04 dex than the stars in the Lick and Keck radial-velocity surveys, whereas a full resolution of the discrepancy between the point estimates of the hot Jupiter occurrence rates would have required a metallicity difference of 0.2–0.3 dex.

3. Bouma et al. (2018) used simple analytic models to argue that the observational biases arising from unrecognized binaries in the Kepler sample are not large enough to resolve this discrepancy.

4. Moe & Kratter (2020) advanced a hypothesis that binarity is responsible for the discrepancies after all, due to an astrophysical effect. Hot Jupiters may not be able to form around a star with a close stellar companion (a < 100 au). Because close binaries are systematically excluded from radial-velocity surveys, the inferred occurrence rate of hot Jupiters would be higher than in transit surveys that do not exclude close binaries. This would still leave unexplained the relatively high occurrence rate derived from CoRoT survey (Deleuil et al. 2018).

If the true occurrence rate of hot Jupiters around FGK stars is higher than has been inferred from the Kepler sample, than the matching procedure we used in this study would underestimate the number of hot Jupiters that we expect to find around nearby bright stars. In that case, the “possibly complete” sample that we discussed in Section 4.1 would be farther from complete than it originally appeared.

5. Summary and Conclusions

To better understand the origins of hot Jupiters, it would help to have a better census of their properties: the distributions and correlations between their periods, radii, masses, orbital parameters, host star parameters, and occurrence of companion planets and companion stars. Currently, the census that is easiest to interpret statistically is the sample of about 40 hot Jupiters found by the Kepler mission, which was capable of detecting transiting hot Jupiters with >99% probability around more than one hundred thousand FGK stars. The total number of known hot Jupiters is an order of magnitude larger than the number in the Kepler sample, but demographic studies cannot yet take full advantage of this much larger sample size because the unknown and undoubtedly complex selection functions of the many surveys that have found hot Jupiters.

We did not attempt to model these selection functions. Instead, based on the simpler considerations of the distribution of apparent magnitudes and the occurrence of transiting hot Jupiters in the Kepler survey, we have shown that the current sample of transiting hot Jupiters is consistent with being complete down to a limiting apparent magnitude of 10.5, if we exclude the region of the sky within 10° of the galactic plane. We compared this subsample of hot-Jupiter hosts with the Kepler sample to compare the distributions of orbital periods and planet radii, which are indistinguishable at this stage, after accounting for differences in the color–magnitude distribution of the host stars. If there are any differences, or if the longstanding discrepancies between the hot-Jupiter occurrence rates measured in different surveys turn out to have interesting astrophysical origins, then only larger samples of planets will reveal them.

We showed that our current knowledge of hot-Jupiter demographics is far from complete. We quantified the limiting magnitude and galactic latitudes of stars around which we need to search for hot Jupiters, finding that many planets remain to be found even around relatively bright stars, which should be easily detectable by the TESS, and which are also nearby and bright enough to appear in many other all-sky surveys, such as the Gaia astrometric survey and the APOGEE spectroscopic surveys. The overlap of these surveys may allow us to discover new connections between hot Jupiters, the properties of their host stars, and the presence of wide-orbiting companions.

To increase the size of the statistically useful sample of hot Jupiters by an order of magnitude, we should aim for a complete sample of hot Jupiters down to a limiting apparent magnitude of about $G = 12.5$. Around such stars, we expect $(420 \pm 68)$ transiting (and nongrazing) hot Jupiters, of which 154 are already known, leaving approximately 250 to be discovered and confirmed. This would represent a significant effort but also a major advance in our understanding of hot Jupiter origins. TESS presents an immediate opportunity to perform this task, thanks to its nearly all-sky coverage, 27-day observing baseline, and high photometric precision, enabling the construction of a nearly complete sample of HJs down to 12th magnitude (Sullivan et al. 2015; Zhou et al. 2019), while the homogeneous and continuous data will make it possible to understand the selection function much better than those of previous ground-based transit surveys.

This research made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. The work also made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia...
Data Processing and Analysis Consortium (DPAC; [https://www.cosmos.esa.int/web/gia/dpac/consortium](https://www.cosmos.esa.int/web/gia/dpac/consortium)). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. Work by S.W.Y. and J.N.W. was funded by the Heising-Simons Foundation and the TESS project (NASA contract NNG14FC03C). J.H. acknowledges support from the TESS GI Program, programs G011103 and G022117, through NASA grants 80NSSC19K0386 and 80NSSC19K1728.

Facility: Exoplanet Archive.

Software: astropy (Astropy Collaboration et al. 2013, 2018); numpy (Harris et al. 2020); scipy (Virtanen et al. 2020); matplotlib (Hunter 2007).

**ORCID iDs**

Samuel W. Yee [https://orcid.org/0000-0001-7961-3907](https://orcid.org/0000-0001-7961-3907)

Joshua N. Winn [https://orcid.org/0000-0002-4265-047X](https://orcid.org/0000-0002-4265-047X)

Joel D. Hartman [https://orcid.org/0000-0001-8372-6166](https://orcid.org/0000-0001-8372-6166)

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