

WARM JUPITERS ARE LESS LONELY THAN HOT JUPITERS: CLOSE NEIGHBOURS

CHELSEA HUANG^{1,2}, YANQIN WU³, AMAURY H.M.J. TRIAUD^{1,3,4}*Draft version April 29, 2016*

ABSTRACT

Exploiting the *Kepler* transit data, we uncover a dramatic distinction in the prevalence of sub-Jovian companions, between systems that contain hot Jupiters (periods inward of 10 days) and those that host warm Jupiters (periods between 10 and 200 days). Hot Jupiters, with the singular exception of WASP-47b, do not have any detectable inner or outer planetary companions (with periods inward of 50 days and sizes down to $2R_{\text{Earth}}$). Restricting ourselves to inner companions, our limits reach down to $1R_{\text{Earth}}$. In stark contrast, half of the warm Jupiters are closely flanked by small companions. Statistically, the companion fractions for hot and warm Jupiters are mutually exclusive, particularly in regard to inner companions.

The high companion fraction of warm Jupiters also yields clues to their formation. The warm Jupiters that have close-by siblings should have low orbital eccentricities and low mutual inclinations. The orbital configurations of these systems are reminiscent of those of the low-mass, close-in planetary systems abundantly discovered by the *Kepler* mission. This, and other arguments, lead us to propose that these warm Jupiters are formed *in-situ*. There are indications that there may be a second population of warm Jupiters with different characteristics. In this picture, WASP-47b could be regarded as the extending tail of the *in-situ* warm Jupiters into the hot Jupiter region, and does not represent the generic formation route for hot Jupiters.

Subject headings:

1. FOREWORDS

The origin of hot Jupiters (HJs, period inward of ~ 10 days) has remained an unsolved issue. Although multiple scenarios have been proposed (disk migration, planet scattering, secular migration, etc.), none seem capable of satisfying all observational constraints. The recent discovery of two low-mass planetary companions (Becker et al. 2015) close to the hot Jupiter WASP-47b (Hellier et al. 2012) further obfuscates the picture. Motivated by the large population of low mass, closely-packed planets at small distances away from their host stars (Mayor et al. 2011; Howard et al. 2012; Borucki et al. 2011; Lissauer et al. 2011), and by the realization that some of them could have accumulated enough mass to undergo run-away gas accretion (Lee et al. 2014), Boley et al. (2016); Batygin et al. (2015) argue that WASP-47b, and possibly all hot Jupiters, were formed *in-situ*, instead of somehow transported inward. Only a tiny fraction of super-Earths need follow this path to be able to match the occurrence rate of hot Jupiters.

While this seems a reasonable proposal for WASP-47b, could it explain the majority of hot Jupiters? To answer this, we focus on the following issue: is WASP-47b a generic hot Jupiter in terms of co-habiting with other planets? Currently, this question is best addressed by exploiting the *Kepler* data to look for small transiting bodies in systems hosting (either confirmed or candidate)

hot Jupiters. If we find that WASP-47b is truly unique among all hot Jupiters, it may suggest that the formation of hot Jupiters can have multiple pathways, with a minority being formed *in-situ*.

There is a second goal to our paper: understanding the warm Jupiters (WJs). By this term we refer specifically to those giant planets orbiting between 10 days and 200 days in period. Unlike the hot Jupiters (inward of 10 days), they are too far out to have experienced little if any tidal circularization and therefore may be difficult to migrate inward by mechanisms that invoke high-eccentricity excitation. On the other hand, they live inward of the sharp rise of giant planets outside $\sim 1\text{AU}$ – in fact, the period range of warm Jupiters corresponds to the so-called ‘period-valley’, the observed dip in occupation in-between the hot Jupiters and cold Jupiters (e.g., Mayor et al. 2011; Wright et al. 2012; Santerne et al. 2016). In contrast with hot Jupiters, no theories have been proposed to explain the existence of this class of objects. So in this paper, we hope to gain some insights by studying their companion rates.

There have been multiple past claims that hot Jupiters lack sub-Jovian (and Jovian) close companions, by using the Radial Velocity data (Wright et al. 2009), by inferring from (the lack of) transit timing variations in these objects (Steffen & Agol 2005; Gibson et al. 2009; Latham et al. 2011; Steffen et al. 2012), and by searching for other transiting companions in the same systems (Steffen et al. 2012). The last study, in particular, is the closest to our work in spirit. Using preliminary candidates resulting from the first four months of the *Kepler* Mission (63 HJs and 31 WJs, defined differently from here), Steffen et al. (2012) found a difference between the two populations: while none of the HJs have any transit-

¹ Centre for Planetary Sciences, University of Toronto at Scarborough, 1265 Military Trail, Toronto, ON, M1C 1A4, Canada

² Dunlap Institute, University of Toronto, Toronto, ON, M5S 3H4, Canada

³ Department of Astronomy & Astrophysics, University of Toronto, Toronto, ON, M5S 3H4, Canada

⁴ Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, United Kingdom

ing companions, five of the 31 WJ candidates do. These led them to suggest that HJs and WJs may be formed differently. However, due to the limitation of the short baseline of early stage *Kepler* data, and their crude criteria for candidate selection, their companion fractions are largely uncertain. For instance, among the five WJ candidates that were claimed to have companions: Kepler-18d, with a radius of $0.6R_J$, is actually a hot Neptune (Lithwick et al. 2012); KOI-190.01 is a diluted eclipsing binary (Santerne et al. 2012); and KOI-1300.01 is an eccentric eclipsing binary (Ofir & Dreizler 2013). This highlights the possible confusion ensued when selecting candidates based on early *Kepler* light-curves. Fortunately, four years down the road, we not only have the full four-year *Kepler* dataset at our disposal, we also have a large number of confirmed Jovian planets to inform us on the selection of candidates. We use both of these to our advantage and revisit the issue of companion fractions for close-in Jovian planets.

Our paper proceeds as follows. We first describe how we select our samples of hot and warm Jupiters from the *Kepler* data and how we evaluate our selection completeness in Section §2; the companion fractions of the two population are estimated and presented in Section §2.3. We discuss the implication of our result in Section §3 on the formation paths of hot Jupiters and warm Jupiters.

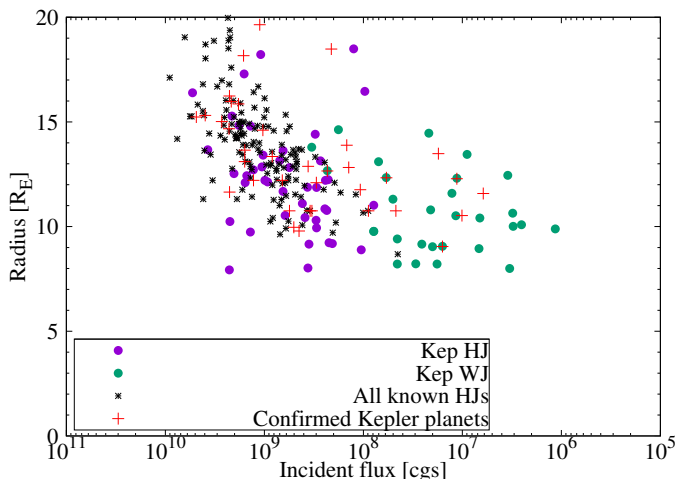


FIG. 1.— The radius of our selected planets versus the incident irradiations they receive, compared with all the known transiting hot Jupiters (black *) and confirmed *Kepler* giant planets (red crosses). We separated our sample into two groups, the hot Jupiters ($P < 10\text{day}$) are in purple dots, and the ones with longer orbital periods (warm Jupiters) in green dots.

2. COMPANION FRACTIONS IN *KEPLER*

2.1. Sample selection

We aim to construct a clean and complete giant planets sample with period range from 0.5 to 200 days from the full set of *Kepler* data. We select the planet candidates with shorter period range (0.5 to 34 days) from the Kepler Object of Interests (cumulative table), and then compensate the list of longer period planets from existing literatures studying *Kepler* giant planets. We ensure a uniform selection of all candidates by making the same selection threshold as presented below on planet candidates from both origins.

We start with all the candidates with radii between $8\text{--}20 R_E$. We then restrict ourselves to those around stars with more reliable stellar parameters in the Kepler Input Catalog (with stellar effective temperatures between 4500 and 6500K). To reduce the false positive rate in the sample, we also require each of the planetary candidate to have a fitted impact parameter smaller than 0.9, and a fitted stellar density from transit parameters between 0.2 g cm^{-3} and 5 g cm^{-3} (Seager & Mallén-Ornelas 2003). We further remove candidates that have detectable secondary eclipses, or ellipsoidal variations, or centroid shifts during transit events.

The completeness and robustness of the *Kepler* candidates decrease for giant planets with longer orbital periods. A few teams released their own catalogs of long period planetary candidates discovered within the *Kepler* data (Wang et al. 2013, i.e.). In particular, Dawson et al. (2015) selected 31 KOIs with orbital periods longer than 34 days by using the combined catalog from all available sources (we refer to their Appendix A for their selection details).

We include the 22 candidates from Dawson et al. (2015) that have orbital periods between 34 day and 200 day to complement our above selection, but reject five planetary candidates from that sample because of their V-shaped transits and/or anomalously large radius (also see “exceptional candidate treatment” section of Dawson et al. 2015). These warm Jupiters matched our selection criterion for the KOIs with shorter orbital periods. Therefore combining both samples preserves a uniform selection. We refer to our sample as the *Kepler* giant planet sample in the text hereafter and do not specifically distinguish in the text between the concept of “planets” and “planet candidates”.

We present our final sample in Tables 3 & 4. This sample includes all of the 40 confirmed giant planets from the catalog summarized by Santerne et al. (2016) matching our designed planet period and stellar properties range. With our definitions of hot Jupiters and warm Jupiters, our sample includes 45 HJs (28 confirmed), and 27 WJs (12 confirmed). It does not, however, include the hot Jupiter WASP-47b, since it is not observed by the *Kepler* main mission.

In Fig. 1, we compare the sizes of these objects with known Jupiters, as a function of their incident irradiations. They appear to fall into similar region, suggesting that the fraction of false positives in our sample is small. More quantitatively, Morton (2012) developed a statistical frame work to quantify false positive probabilities of *Kepler* candidates. Judging by his values for the unconfirmed objects in our sample (Tables 3 & 4), the majority have negligible probabilities to be false positives.

2.2. Search and completeness of small-sized planets

We seek additional companions in systems hosting our selection of giant planets. To address the possibility that the giant planet transit signals would influence the detrending process and the transit search algorithm, we first removed all of their transits from the *Kepler* raw (simple aperture, SAP) light curves. For each expected giant planet transit, this is done by creating a data gap in the light curve with a width $1.1\times$ the fitted transit duration and centred on the transit epoch. We then

detrended the light curves following Huang et al. (2013) and searched for additional transit signals using a Box Least Square (BLS) algorithm. Any BLS peaks detected with transit dip significances (signal-to-noise of the transit signal) higher than 10 are investigated to check if they are due to planet signals.

Moreover, we can also calculate the completeness of detection for a planet of a given size and at a given period, based on the estimated signal-to-noise ratio,

$$\text{SNR} = \frac{\delta}{\text{CDPP}} \times \sqrt{N_{\text{transit}}} . \quad (1)$$

Here, δ is the expected transit depth for the planet, N_{transit} the number of transits in the entire *Kepler* light curve, and CDPP the combined differential photometric precision of the light curve over the transit duration time-scale. Fressin et al. (2013) reported that 99.9% of the *Kepler* candidates with a signal-to-noise ratio (SNR) larger than 10.1 will be detected by the *Kepler* pipeline. When calculating the completeness, we define a planet as detectable if its SNR is greater than 10. A histogram of the 6.5-hour CDPP values for host stars in our sample is shown in Figure 2. The host stars of HJs and WJs have similar noise properties in their light curves. So we expect similar detection completeness in these two groups.

We report the detection completeness thus estimated in Figure 3, averaged over the cohorts of HJ and WJ systems separately. As expected, they look rather similar. We further verify this estimation by performing a signal-injection-and-recovery experiment. We inject into the HJ light curves transit signals by planets of orbit period around 10 days and of various sizes ($2R_{\text{Earth}}$, $1.5R_{\text{Earth}}$ and $1R_{\text{Earth}}$). We obtain recovery rates of 100%, 93% and 51% at these sizes. These match the above estimates using light curve CDPPs.

Also shown on Fig. 3 are the positions of the two small companions of WASP-47b. If present, they should be trivially detected around any of the giant planets in our sample.

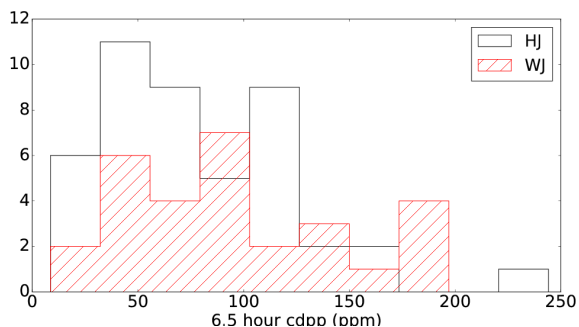


FIG. 2.— Histogram of the 6.5 hour CDPP for the light curves of the host stars in our *Kepler* giant planet sample. Those with hot Jupiters are shown in black, while those with warm Jupiters are shown in red. The two populations have similar noise properties.

2.3. Results

We summarize our search results in Table 1. We find that, while none of the HJs have any transiting companions, 11 (out of 27) of the WJs do. All of these companions have also been reported by the *Kepler* candidate

group	total	N_{multi}	Inner	Outer
HJ	45	0	0	0
confirmed HJ	28	0	0	0
WJ	27	10	10	3
confirmed WJ	12	7	7	2

TABLE 1
SUMMARY OF TRANSITING COMPANIONS FOR *Kepler* GIANT PLANETS.

catalog. We display the orbit architectures of these multiple systems in Figures 4 & 5.

Assuming all companions to the giant planets transit, we can estimate simply the companion fractions using results in Table 1. We focus on companions inward of 50 days and larger than $2R_{\text{Earth}}$, since this population should be detected nearly completely ($> 90\%$), and since most of the companions we find do fall in this range. We term these “close” companions. We treat the problem as an estimation of the distribution of the event success rate p for a binomial distribution having observed s successes in n trials, for which each system is assumed to have equal weight. We imply a conjugate prior (Beta(0.5, 0.5)) on p . The posterior distribution of p can be expressed as Beta($s+0.5, n-s+0.5$). We thereby obtain a multiplicity rate of hot Jupiters of $0.52^{+5.0}_{-0.52}\%$, while that for warm Jupiters is $37.2^{+18.6}_{-16.3}\%$. Throughout this work, we present results in terms of the median of the distribution and their 90% confidence interval.

If we only use the confirmed planet systems, the estimated multiplicity rate for hot Jupiters is Beta(0.5, 28.5) = $0.8^{+7.7}_{-0.8}\%$, and for warm Jupiters is Beta(8.5, 4.5) = $58.1^{+23.9}_{-26.9}\%$. This latter value, however, should be taken with caution as the confirmed systems are likely to bias towards multiple systems. As an example, they are usually prioritized during radial velocity follow-up observations. Other confirmation methods, such as transit timing variation (Xie 2013, i.e.), or making use of low false positive rate of the *Kepler* multiply systems (Rowe et al. 2014, i.e.), also prefers to confirm multiple systems.

2.3.1. Monte Carlo Simulation

To have a more realistic estimation that takes into account of a multitude of observational uncertainties, we perform a Monte Carlo Markov Chain simulation with emcee (Foreman-Mackey et al. 2013) to constrain the rate of multiplicity.

For our standard MCMC model, we again assume all companions transit (a flat system), and we adopt a false positive rate of 50% for the unconfirmed planets in our sample. We continue to focus on “close” companions for which our detection capacity is nearly complete. We also account for the scatter of the Neptune population into our sample. The details are laid out in Appendix A and the results are shown in the top panel of Figure 6. We obtain that hot Jupiters have a multiplicity rate of $1.1^{+13.3}_{-1.1}\%$, and warm Jupiters have a multiplicity rate of $55.7^{+27.0}_{-31.1}\%$, largely unchanged from our previous estimates.

In the following, we relax or alter some of the assumptions in our standard model. Results of all these experiments are summarized in Table 2.

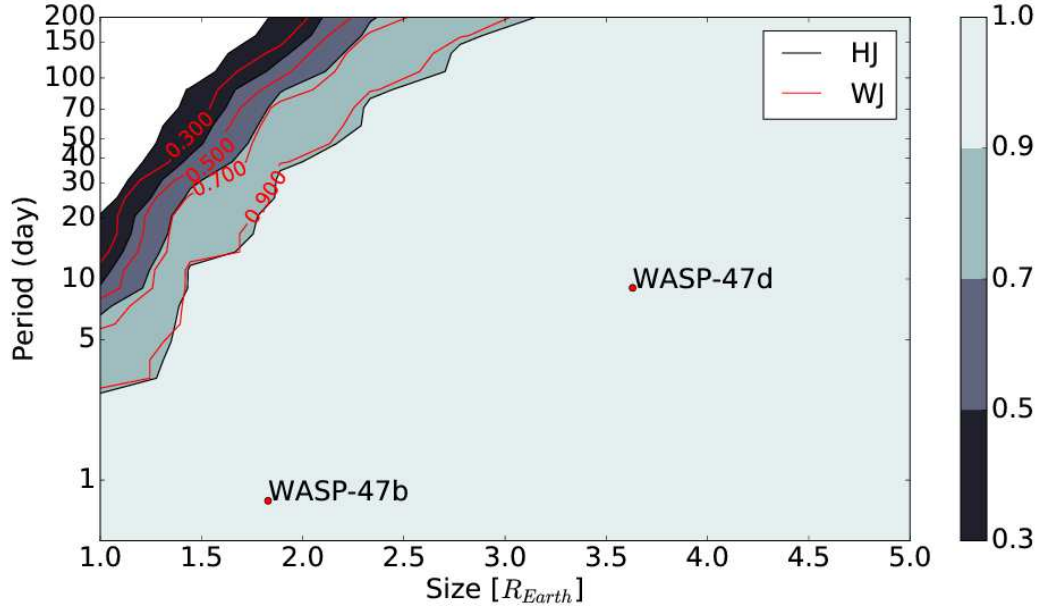


FIG. 3.— The detection completeness as a function of planet size (in Earth radius) and orbital period (in day) for our systems. The contours (and black lines) show the averaged completeness of all HJ systems, while the red lines show that for the WJ systems. They are similar. For planets larger than $2R_{\text{Earth}}$, we are $> 90\%$ complete out to 50 days; while for those larger than $1R_{\text{Earth}}$, we are $> 90\%$ complete out to ~ 3 days. The latter places stringent constraint on the inner companions of HJs. The interior and exterior companions of WASP-47c are noted here. They are trivially detectable around all systems.

TABLE 2
THE PROBABILITY FOR A GIANT PLANET TO HAVE AT LEAST ONE “CLOSE” COMPANION IN THE SYSTEM. ^a

group	candidate fp	mutual inclination	HJ rate (%)	WJ rate (%)
1	0	0	$0.5^{+5.0}_{-0.5}$	$37.2^{+18.6}_{-16.3}$
2	10%	$\sigma_\mu = 1.8^\circ$	$0.98^{+9.4}_{-0.98}$	$58.1^{+31.7}_{-31.0}$
3	10%	uniform	$8.4^{+46.4}_{-8.0}$	-
4	50%	0	$1.1^{+13.3}_{-1.1}$	$55.7^{+27.0}_{-31.1}$
5	50%	$\sigma_\mu = 1.8^\circ$	$1.6^{+19.5}_{-1.6}$	$69.5^{+24.2}_{-30.8}$
6	50%	uniform	$9.1^{+45.8}_{-8.6}$	-
7	100%	0	$0.8^{+7.7}_{-0.8}$	$58.1^{+23.9}_{-26.9}$

^aFor case 1,4 and 7, “close” companion refer to those with period smaller than 50 days. For case 2,3,5 and 6, only the interior companion of the giant planets are considered.

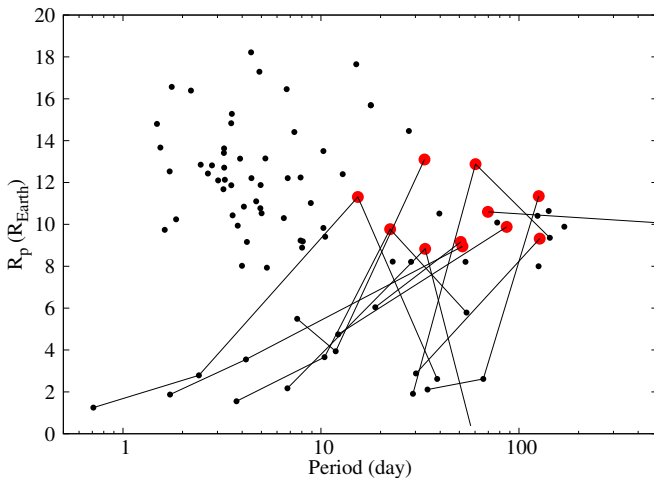


FIG. 4.— Periods and radii for our sample of giant planets and their neighbours. The giant planets that have companions are marked out in red and are connected to their companions by lines. Only warm Jupiters appear to belong to multiple systems.

2.3.2. Impact of false positives

Fig. 6 compares the results when different false positive rates for the unconfirmed systems are adopted. The overall effect of a smaller false-positive rate is to reduce the companion fraction for WJs, since the confirmed WJs have a higher multiplicity than the unconfirmed ones.

We note that the false positive rate we adopt for our standard model ($fp = 50\%$) is likely too pessimistic for our sample. This value is derived by Santerne et al. (2016) for all giant candidates in the entire *Kepler* candidate sample, while we benefit from additional filtering based on follow-up measurements and additional vetting on the light curves. In fact, the individualized false-positive rates (Morton et al, 2016, in prep) for the unconfirmed objects in our sample are in general low. We regard an optimistic value of $fp = 10\%$ as calculated from the above work to be more suitable for our WJ candidates. We will present more results for this false positive rate below.

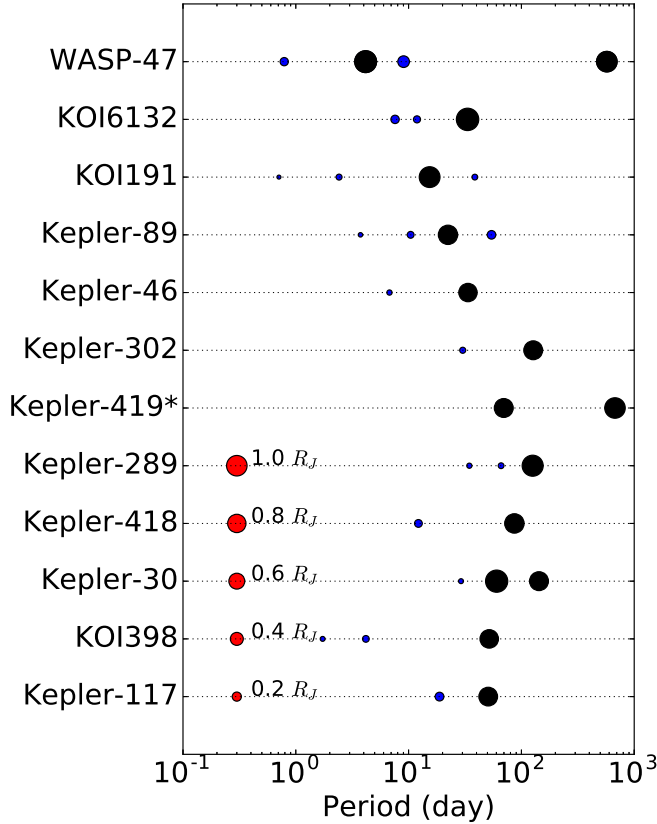


FIG. 5.— Similar to Fig. 4 but showing more clearly the architectures of our multiple systems (around warm Jupiters). The planets are laid out in $\log P$, with the size of the dot representing the size of the planet. The confirmed systems are noted by their *Kepler* names. **Kepler-419** system is counted as a single warm Jupiter system in our calculation, given the companion is far away.

2.3.3. Impact of mutual inclination

So far, we have assumed that the companions always transit. Fabrycky et al. (2014) found that the *Kepler* multiple systems are indeed quite coplanar (also see Figueira et al. 2012; Fang & Margot 2012; Tremaine & Dong 2012). Assuming that the mutual inclination (μ) dispersion follows a Rayleigh distribution, the inferred dispersion σ_μ typically lies in the range 1.0° – 2.2° . We investigate how this affects our results.

We consider only the possibility that the giant planet systems to have a non-transiting companion interior to the giant planet. As the transit probability is now a function of orbital period, we need to assume a period distribution for the companion. The occurrence rate of sub-Jovian planets is roughly flat in the log period space, and falls off for short periods (Howard et al. 2012; Dong & Zhu 2013). We assume the companion occurrence rate is flat in $\log P$ for WJs, with a inner cut-off period of 1 day, and a period power-law dependence for HJs, with a inner cut-off period of 0.5 day. We simulate the rate of a interior companion assuming the prior for the mutual inclination follows a Rayleigh distribution with $\sigma_\mu = 1.8^\circ$ for both the HJs and WJs. To explore the extremes, we also simulate the rate of interior companion for HJs assuming the $\cos \mu$ distribution is uniform between 0 and 1. The distribution of interior companion rate is constrained as in Figure 7, upper panel

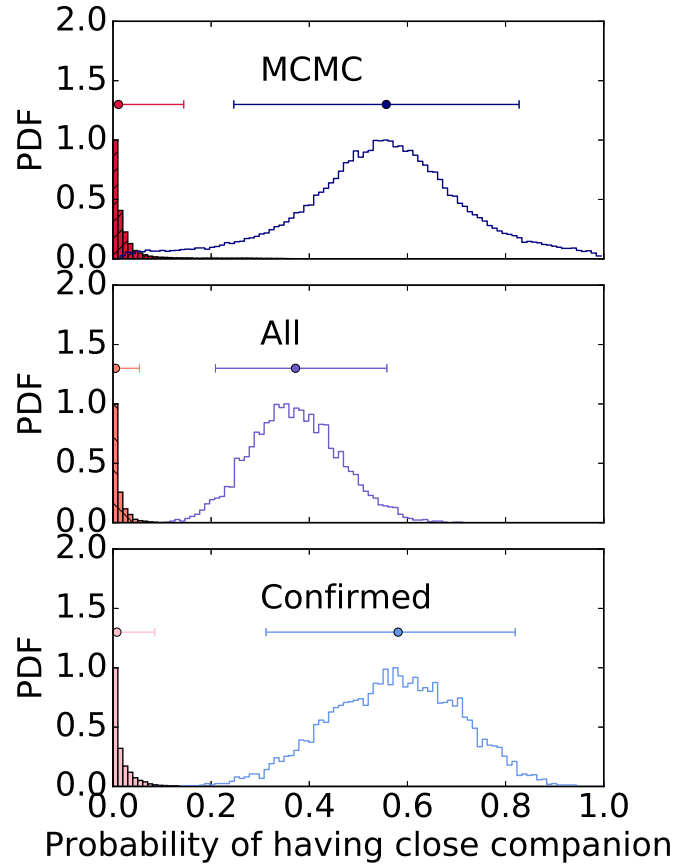


FIG. 6.— The probability density distributions for giant planets to have “close” companions, defined as inward of 50 days and larger than $2R_{\text{Earth}}$. Here we assume that all planets in a given system transit. The top panel compares the companion rates for hot Jupiters (blue) and warm Jupiters (red) in our standard Monte Carlo model where the candidate false positive rate is assumed to be 50%. Points with error-bars indicate the median of the distribution and its 90% confidence interval. The middle panel assumes that all unconfirmed candidates are real planets ($fp = 0$), whereas the bottom panel assumes that they are all false positives ($fp = 100\%$) and only confirmed planets are included. The two populations of giant planets are incompatible in all cases.

using a false positive rate of 50%. We show that assuming the same mutual inclination distribution, the median of the multiplicity rate distribution of HJs and WJs both shift to a higher value, but their 90% confidence interval do not overlap with each other. Even with the extreme case that the HJ companions have a uniform cosine mutual inclination distribution, the 90% confidence interval of its distribution exclude the median of the WJ companion rate distribution. The conclusion holds with a 10% false positive rate (lower panel of Figure 7). If we assume instead a uniform $\log P$ distribution for the HJ companions, similar to that of the WJ’s, the conclusion will be stronger since it allows less non-transiting companions.

For interior companions of HJs, we are able to constrain the detection of planets with sizes larger than $1.5 R_{\text{Earth}}$ to be complete up to 10 days. However, this conclusion can be extended to $1R_{\text{Earth}}$ if we correct for detection completeness assuming $df/d\log R$ is constant between 1 – $3 R_{\text{Earth}}$ (as suggested by Petigura et al. (2013)). In reality, the majority of the HJs have orbital period smaller than 5 days, allowing us to have almost complete

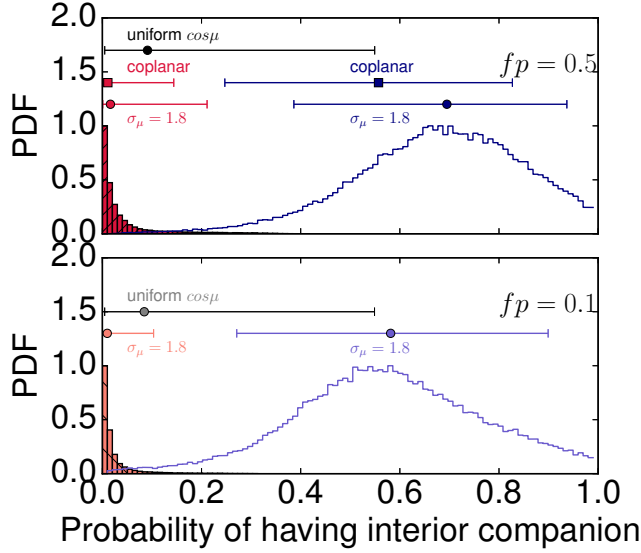


FIG. 7.— Same as Fig. 6 but demonstrating the impact of mutual inclinations, considering only inner companions. The top panel compares the inner companion rates using our standard priors, with the histograms corresponding to a case where the mutual inclinations is a narrow Rayleigh distribution with a dispersion of $\sigma_\mu = 1.8^\circ$ – compare these to the co-planar case. The extreme case, marked with “uniform $\cos\mu$ ” for the HJ only, is one where we assume that the orbital planes for hot Jupiters and their inner companions are un-correlated. The bottom panel shows the same content but for a smaller false positive rate of $fp = 10\%$, a value that we deem more plausible for our sample.

detection to $1 R_{\text{Earth}}$ regardless of the size distribution.

The rate of exterior companions is extremely sensitive to the distribution of mutual inclinations, as such it is difficult to obtain a good constraint. If we assume every giant planet with interior companion also have an exterior companion, and that the interior and exterior companions have the same mutual inclination distribution (a Rayleigh distribution with $\sigma_\mu = 1.8^\circ$), the observed number of systems with exterior companion is expected to be a quarter of those with interior companions due to the transit probability and detection completeness. This is not in contradiction with the current observations.

3. DISCUSSIONS

Our main results (Fig. 6 and 7) that HJs have a companion fraction consistent with zero, while about half of WJs have close neighbours, reveal much about their respective formation mechanisms.

3.1. Two populations of Warm Jupiters?

Two previous works have suggested that warm Jupiters are not all the same beasts. Using RV data, Dawson & Murray-Clay (2013) suggested that eccentric WJs tend to orbit around metal rich stars, while planets around metal poor stars have predominately circular orbits. Later, also based on RV data, Dong et al. (2014) showed that more than half of the eccentric WJs ($e > 0.4$) have distant, Jovian companions, while the low-eccentricity WJs tend to be ‘single’. Taken together, these suggest that more Jovian planets are produced around metal-rich stars, and this somehow raises the eccentricities of WJs (via either secular perturbations or planet-planet scatterings). Recently, Bryan et al. (2016)

confirmed the above finding with a larger sample. In addition, they reported that WJs have a lower occurrence rate of distant giant companions (defined as with masses between $1\text{--}20 M_J$, and at orbital distances of $5\text{--}20 \text{ AU}$), compared to what they found regarding the HJs, suggesting that dynamic processes due to giant planetary companions are less important in the WJ systems.

Our study of the *Kepler* transit data adds a further dimension to the picture. At least half of the WJs in our sample are flanked by close, small companions. Most likely, they are nearly coplanar with these companions (to maximize transit probability), and are also nearly circular (to prevent dynamical instability in such closely packed systems). RV counter-parts to these objects have been found, e.g., HIP 57274c (Fischer et al. 2012) which is a nearly circular WJ with a small mass neighbour interior to its orbit, and GJ 876c (Rivera et al. 2010), and 55 Cnc-b (Endl et al. 2012). However, due to limits on RV precision, most of these WJs will in general be observed as ‘singles’ on largely circular orbits.⁵

How are the warm Jupiters formed? For those with low-mass neighbours, we postulate that they are formed *in-situ*, i.e., they undergo run-away gas accretion locally, and that the abundant, closely packed, super earth population discovered by *Kepler* are the cores enabling the accretion. This hypothesis is supported by the following arguments.

- Small planets (sub-Jovian) are common around stars, and their frequency rises outward steeply at just the inner edge of our WJ zone (Howard et al. 2012), and it remains flat in logarithmic period beyond this cut-off (Petigura et al. 2013; Silburt et al. 2015).
- Measured masses for some of these small planets are available (e.g. Weiss et al. 2013; Hadden & Lithwick 2014), with some reaching beyond $10 M_{\text{Earth}}$ in solid mass.
- Such massive cores can retain a heavy enough atmosphere and undergo run-away gas accretion, at the observed locations for these WJs (e.g. Rafikov 2006). Recent theoretical studies of accretion of such an envelope (Lee et al. 2014; Batygin et al. 2015) further argue that cooling can be sufficiently fast to allow *in-situ* formation of giant planets at these distances.
- As the WJ grows in mass, it can keep the planetary configuration largely intact.⁶ As a result, we observe them today still flanked by small neighbours.

Alternative theories such as disk migration, whereby these WJs are formed at larger distances and migrated inward by interaction with the protoplanetary disk, and high-eccentricity migration (such as Kozai migration, planet-planet scattering, etc), face the challenge of explaining the presence of small neighbours.

⁵ In other words, the transit technique is uniquely capable of revealing these small neighbours.

⁶ It will be able to destabilize some of the closest neighbours and ingest them in the process.

What about the other WJs, the ones that have no transiting companions? Studies mentioned above argue that these may be a distinct population. However, it needs to be firmly established that these WJs indeed always have distant Jovian companions, and/or are largely eccentric, and/or only reside around metal-rich stars. At the moment, their origin remains an enigma.

Assuming that the lonely WJs in our sample are from a distinct population, we can estimate the relative proportions of these two groups of WJs. Among the WJs, 10 out of 27 are in multiple systems, or $37^{+19}_{-16}\%$ of WJs. However, this value can rise to $58^{+31}_{-31}\%$ if the mutual inclination dispersion of the system follows a Rayleigh distribution peaked at 1.8 deg. In other words, at least half of all WJs are formed *in situ*.

3.2. Formation of Hot Jupiters

We were initially motivated by the discovery of close companions around the hot Jupiter WASP-47b (Becker et al. 2015). After having established the general pattern among hot and warm Jupiters, we return to reflect upon the existence of this particular system.

WASP-47b was first identified by ground-based photometry, and then verified with radial velocity measurements (Hellier et al. 2012). Thanks to this detection, it was proposed as a target for the K2 mission. In the meantime, the radial-velocity monitoring of the system unveiled a second, long period gas giant (Neveu-VanMalle et al. 2016). Becker et al. (2015) analyzed the K2 data and announced the presence of two super-Earths, one inner to the hot Jupiter, and one between both gas giants. The two low-mass companions of WASP-47b were discovered in a targeted observation, so it is difficult to ascertain their statistical importance. However, we can set an upper limit on the frequency of such objects, based on the absence of neighbours in our hot Jupiter sample. This is $1.0^{+9.5}_{-1.0}\%$ among all hot Jupiters, assuming a candidate false positive rate of 10% and a mutual inclination dispersion of 1.8 deg (Table 2).

This leads us to believe that WASP-47b is a rather unique system among hot Jupiters, themselves rare systems. Based on our discussion above, we further speculate that since more than half of WJs may be formed *in-situ*, this path may find its way into the period domain of HJs. Or, WASP-47b is also formed *in-situ* (Boley et al. 2016; Batygin et al. 2015), and is a tail of the *in-situ* WJs. Given the relative numbers of hot Jupiters (one, WASP-47b) and warm Jupiters (7 out of the confirmed sample of 12) in multiple systems, and the lower transit probability of WJs, this would suggest that the *in-situ* process is increasingly difficult for closer-in planets, with WASP-47b being the hottest representative of the warm Jupiter population.

Where do majority of the hot Jupiters come from then? We turn to the observations for answer. Many of the dynamical migration processes that are invoked to explain hot Jupiters invariably produce the so-called 3-day pile up, an excess of HJs near 3-day orbital period. Such a pile-up, originally discovered among RV population (Wright et al. 2009), but then found to be absent in the *Kepler* transit data (Howard et al. 2012), and then re-discovered recently through careful RV falsification of the transit candidates Santerne et al. (2016), now seems

here to stay. Hot Jupiters went through dynamical migration also led to destructions of any inner planetary systems naturally (Mustill et al. 2015). This lends support to the hypothesis that hot Jupiters are products of violent dynamical processes.

4. CONCLUDING WORDS

When we set out on this project, we wondered whether WASP-47b is a common-place hot Jupiter in terms of small neighbours. By examining the *Kepler* hot Jupiters, we found that systems such as WASP-47b are rare among the hot Jupiters – among our statistical sample of 45 (28 confirmed) hot Jupiters, none show small companions, either inner or outer.

In contrast, we found that among our warm Jupiter sample, half or more have nearly coplanar, small companions. Most of these are inner companions, and given the fact that exterior companions are less likely to transit, the data give the impression that they are at least as common as the inner ones (Table 1).

So not only do hot Jupiters and warm Jupiters appear to be separated in their period distributions (Santerne et al. 2016), they are also distinct in their respective fractions of close neighbours.

Motivated by this discovery, and by recent theoretical progress in understanding gas accretion, we propose that a significant fraction of warm Jupiters are formed *in-situ*. The prevalence of multiple low-mass planets in close proximity to one another and to the star can, in a fraction of the cases, permit some of the planets to accrete enough envelope and to trigger run-away growth. This process can operate in the warm Jupiter locale, but appears to become increasingly difficult towards the hot Jupiter region, explaining the rarity of systems like WASP-47b.

We outline future directions below ,

- The true neighbour fractions of warm Jupiters is sensitive to the inclination dispersion in the system, as well as the false positive rate of our warm Jupiter sample (Table 2). Both could be improved. Specifically, further photometric and Radial Velocity monitoring of the confirmed warm Jupiters discovered by ground based transit surveys, such as HAT-P-15b (Kovács et al. 2010), HATS-17b (Brahm et al. 2016), are likely to reveal the presence of companions, if current statistics holds.
- Masses for these close companions are interesting. They may yield the critical mass above which run-away gas accretion occurs.
- Multiple lines of evidences suggest that there may be a second population of warm Jupiters. But data are inconclusive at the moment. Studies of warm Jupiter eccentricity distribution, host star metallicity distribution, presence of giant planet companions, etc. may help answer whether there is a second pathway to form warm Jupiters.
- The *in-situ* warm Jupiters accrete their gas inward of the ice-line. As such, their envelope water content should not be depleted by condensation. This may contrast with those that accrete their gas beyond the iceline (barring core erosion

in these bodies) and may be testable by transmission spectroscopy.

- Using transit data, we can exclude inner neighbours of hot Jupiters, but the constraint is less stringent for the outer neighbours, especially if they may be highly misaligned (Batygin et al. 2015). Radial velocity study is necessary.
- If outer neighbours are indeed also absent among hot Jupiters, theoretical study is needed to explain the rarity of *in-situ* formation for hot Jupiters, vs. that of warm Jupiters.

ACKNOWLEDGEMENTS

The Dunlap Institute is funded through an endowment established by the David Dunlap family and the University of Toronto. References to exoplanetary systems were obtained through the use of the paper repositories,

ADS and arXiv, but also through frequent visits to the exoplanet.eu (Schneider 2011) and exoplanets.org (Wright et al. 2011) websites. This paper includes data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission directorate. Some of the data presented in this paper were obtained from the Multimission Archive at the Space Telescope Science Institute (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. This research has 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.

APPENDIX

STATISTICAL FRAME WORK

The observed giant planet multiplicity systems $N_{\text{obs},m}$ can arise from four origins: the confirmed multiple planet systems $N_{\text{obs},p,m}$, candidate multiple planet systems $N_{\text{obs},gc,m}$ with at least a giant planet, candidate multiple planet systems with the most massive planet being Neptune nature $N_{\text{obs},nc,m}$, and false positive multiple systems due to binary contamination $N_{\text{obs},s,m}$. We assume the contribution to the multiple system with a giant planet from false positives ($N_{\text{obs},s,m}$) to be negligible (Lissauer et al. 2014).

$$N_{\text{obs},m} = N_{\text{obs},p,m} + N_{\text{obs},gc,m} + N_{\text{obs},nc,m}. \quad (\text{A1})$$

The individual terms above can be expressed as the following:

$$N_{\text{obs},p,m} = N_p f(g, m) f(d), \quad (\text{A2})$$

in which, N_p is the total number of confirmed system we have, $f(g, m)$ is the rate of giant planet system having a close-in companion, $f(d)$ is the probability for this companion to be detected.

The number of multiple systems originated from “Jupiters” and “Neptunes” can be estimated as:

$$N_{\text{obs},gc,m} = N_{pc} f(g) f(g, m) f(d), \quad (\text{A3})$$

and

$$N_{\text{obs},nc,m} = N_{pc} (1 - f(g)) f(n, m) f(d), \quad (\text{A4})$$

in which $f(g)$ is the fraction of giant planets in the our selected radius range, $f(g, m)$ and $f(n, m)$ is the probability a Jupiter/Neptune size planet having a close-in companion. N_{pc} is the number of planetary candidates that has planet nature,

$$N_{pc} = (N - N_p) \times (1 - fp), \quad (\text{A5})$$

with fp denote the false positive rate of a unconfirmed KOI.

The problem can be summarized as a Bayesian problem, in which N_m is observable, and $f(g, m), f(n, m), f(FP), f(g)$ as parameters we want to constrain given the data. We can do this by sampling the posterior space:

$$p(\hat{f} | w_{\text{obs}}) = p(\hat{f}) \times p(w_{\text{obs}} | \hat{f}). \quad (\text{A6})$$

The likelihood $p(w_{\text{obs}} | \hat{f})$ can be expressed as $B(N_{\text{obs},m} - N_{\text{obs},nc,m} | f(g, m), N_p + N_{pc,g})$, in which $B(s | x, N)$ indicate the probability of observing s success given N observations with success rate x .

The priors $p(\hat{f})$ are assumed (estimated) as below.

- We use a conjugate prior for the multiplicity rate of giant planet $f(g, m)$.
- $f(g)$ is the probability of an unconfirmed planet to be a giant planet. We use the posterior of the radius distribution of the candidate to decide the probability of a candidate to have a radius smaller than $8R_{\text{Earth}}$. We derived the average probability of a unconfirmed HJ to be a Neptune to be Beta(2.06, 15.9), and for warm jupiter is Beta(2.65, 18.4).

- We use the multiplicity rate for the super Neptunes ($4R_{\text{Earth}} < R_p < 8R_{\text{Earth}}$) within our designed stellar parameter and period range, in the entire KOI sample (25 out of 140), as a prior for $f(n, m)$. We note that this rate is quite uncertain, (Mayor et al. 2011) report the multiplicity rate for small planets are $\sim 70\%$ with an unclear statistic significance. Given the rate of $f(g)$ is small, the choice of $f(g)$ do not impact the final result significantly.
- We use two sets of false positive rate. We first use the false positive rate from (Santerne et al. 2016) to estimate the false positive rate of an unconfirmed candidate fp . Santerne et al. (2016) identified 46 false positives out of 100 KOIs in the effective temperature and period range we use. For hot Jupiters, the FP rate is 42.8%, and 49% for warm Jupiters. This is lower than the overall false positive rate reported by Santerne et al. (2016), since the authors found that the false positive rate around stars with T_{eff} higher than 6500 K is generally higher, which are not included in our sample. We apply a beta distribution prior for the false positive rate. Due to our additional selection on our candidates, the actual false positive rate can be even lower. We use the astrophysical false positive rate estimated by Morton et al (in prep) to obtain a more optimistic value (10%).
- We do not attempt to factor in the actual value of the detection completeness $f(d)$ for our estimation of the final rate since the size distribution of small planets have big uncertainties. We note that the detection is complete to $2R_{\text{Earth}}$ with orbital period less than 50 days for both HJs and WJs. While for interior companions, it is complete for HJs to $1.5R_{\text{Earth}}$. We are able to prove that our conclusions are not changed if extend this size limit to $1R_{\text{Earth}}$ by assuming $df/d\log R$ is constant between $1-3 R_{\text{Earth}}$ as suggested by Petigura et al. (2013). Our experiment found out that counting smaller planets is equivalent to assume a more dispersed mutual inclination distribution for both HJs and WJs. Unless the occurrence rate of planet has a steep rise towards small size, it does not impact the companion rate of HJs much, while the companion rate of WJs may shifts to a higher value.

To take into account the effect of mutual inclination angle dispersion, we compute an averaged transit probability for HJs and WJs separately on a mutual inclination grid with $\cos \mu$ from 0 to 1. We later on interpolate on this grid to obtain the transit probability at an arbitrary mutual inclination angle in our simulations. Since the inclination angle of the giant planet i_g is usually loosely constrained by the transit fit, we assume that $\cos i_g$ has a uniform probability as long as the planet transit. We also integrate over the possible period range the companion could take.

$$\bar{f}_{\text{tran}}(\mu) = \frac{1}{N} \int f_{\text{tran}}(\text{period}, i_g, \mu) P(\text{period}) P(i_g) d\text{period} di_g \quad (\text{A7})$$

For the probability of the companion occur at a certain orbital period, we use the formalism from Howard et al. (2012) for the HJs.

$$df/d\log(\text{period}) \propto \text{period}^\beta (1 - e^{-(\text{period}/7.0\text{day})^\gamma}), \quad (\text{A8})$$

in which, $\beta = 0.27 \pm 0.27$, $\gamma = 2.6 \pm 0.3$. For period $< 10\text{day}$, this can be approximated with $f(\text{period}) \propto \text{period}^2$. We use the latter in our calculation. For WJs, we assume $df/d\log(\text{period}) = C$ instead with a cut-off inner period at 1 day.

The likelihood expression can be revised as $B(N_m | f(g, m) f_{\text{tran}}, N_p + N_{\text{pc,g}})$ as a conditional Binomial problem. Here we are assuming that the covariance between $f(g, m)$ and f_{tran} are 0.

We choose two type of priors for the mutual inclination of HJs, a Rayleigh distribution with $\sigma_\mu = 1.8$ and a uniform distribution for $\cos \mu$ between 0 and 1. We only use the Rayleigh distribution prior for the WJs.

REFERENCES

- Almenara, J. M., Damiani, C., Bouchy, F., et al. 2015, A&A, 575, A71
- Batygin, K., Bodenheimer, P. H., & Laughlin, G. P. 2015, arXiv:1511.09157
- Becker, J. C., Vanderburg, A., Adams, F. C., Rappaport, S. A., & Schwengeler, H. M. 2015, ApJ, 812, L18
- Boley, A. C., Granados Contreras, A. P., & Gladman, B. 2016, ApJ, 817, L17
- Bonomo, A. S., Hébrard, G., Santerne, A., et al. 2012, A&A, 538, A96
- Bonomo, A. S., Sozzetti, A., Santerne, A., et al. 2015, A&A, 575, A85
- Borucki, W. J., Koch, D. G., Basri, G., et al. 2011, ApJ, 736, 19
- Brahm, R., Jordán, A., Bakos, G. Á., et al. 2016, AJ, 151, 89
- Bruno, G., Almenara, J.-M., Barros, S. C. C., et al. 2015, EPJWC, 101, 06014
- Bryan, M. L., Knutson, H. A., Howard, A. W., et al. 2016, ApJ, 821, 89
- Buchhave, L. A., Latham, D. W., Carter, J. A., et al. 2011, ApJS, 197, 3
- Cabrera, J., Csizmadia, S., Lehmann, H., et al. 2014, ApJ, 781, 18
- Dawson, R. I., Johnson, J. A., Morton, T. D., et al. 2012, ApJ, 761, 163
- Dawson, R. I., & Murray-Clay, R. A. 2013, ApJ, 767, L24
- Dawson, R. I., Murray-Clay, R. A., & Johnson, J. A. 2015, ApJ, 798, 66
- Deleuil, M., Almenara, J.-M., Santerne, A., et al. 2014, A&A, 564, A56
- Dong, S., Katz, B., & Socrates, A. 2014, ApJ, 781, L5
- Dong, S., & Zhu, Z. 2013, ApJ, 778, 53
- Endl, M., Caldwell, D. A., Barclay, T., et al. 2014, ApJ, 795, 151
- Endl, M., MacQueen, P. J., Cochran, W. D., et al. 2011, ApJS, 197, 13
- Endl, M., Robertson, P., Cochran, W. D., et al. 2012, ApJ, 759, 19
- Esteves, L. J., De Mooij, E. J. W., & Jayawardhana, R. 2015, ApJ, 804, 150
- Fabrycky, D. C., Lissauer, J. J., Ragozzine, D., et al. 2014, ApJ, 790, 146
- Faigler, S., Tal-Or, L., Mazeh, T., Latham, D. W., & Buchhave, L. A. 2013, ApJ, 771, 26
- Fang, J., & Margot, J.-L. 2012, ApJ, 761, 92
- Figueira, P., Marmier, M., Boué, G., et al. 2012, A&A, 541, A139
- Fischer, D. A., Gaidos, E., Howard, A. W., et al. 2012, ApJ, 745, 21
- Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306
- Fressin, F., Torres, G., Charbonneau, D., et al. 2013, ApJ, 766, 81

TABLE 3
KEPLER HOT JUPITER SYSTEMS

KIC	Period [day]	R_p [R_{Earth}]	M_p [M_{Jup}]	R_{star} [R_{\odot}]	fp rate ^a	Other Name/Reference ^b
9115800	4.454194338	12.21 ^{+7.19} _{-1.6}	n/a	0.915 ^{+0.539} _{-0.12}	6.5e-5	KOI-421.01
8544996	4.082275068	10.85 ^{+4.31} _{-0.81}	n/a	0.707 ^{+0.316} _{-0.06}	2.1e-6	KOI-913.01
7832356	7.886631104	9.23 ^{+3.33} _{-1.62}	n/a	1.135 ^{+0.409} _{-0.199}	1.3e-11	KOI-1456.01
4076098	3.990106229	8.02 ⁺³ _{-0.69}	n/a	0.9130 ^{+0.341} _{-0.079}	9e-5	KOI1323.01
9643874	8.027680595	8.89 ^{+3.39} _{-0.63}	n/a	0.887 ^{+0.338} _{-0.063}	1.1e-3	KOI1457.01
7585481	8.098887986	9.19 ^{+4.66} _{-0.85}	n/a	1.064 ^{+0.54} _{-0.098}	8.4e-9	KOI890.01
3351888	1.625522200	9.74 ^{+3.88} _{-1.24}	n/a	1.057 ^{+0.421} _{-0.135}	5.8e-7	KOI801.01
9141746	6.491684259	10.30 ^{+6.12} _{-1.24}	n/a	1.13 ^{+0.67} _{-0.14}	3.2e-4	KOI-929.01
8255887	4.708326542	11.10 ^{+4.17} _{-2.41}	n/a	1.21 ^{+0.46} _{-0.26}	4.9e-5	KOI908.01
11138155	4.959319451	11.88 ^{+4.91} _{-1.08}	n/a	1.025 ^{+0.424} _{-0.093}	1.7e-2	KOI-760.01
10019708	3.268695154	12.13 ^{+7.48} _{-1.4}	n/a	1.171 ^{+0.722} _{-0.135}	1.3e-10	KOI-199.01
11414511	2.816504852	12.82 ^{+4.94} _{-1.39}	n/a	0.9650 ^{+0.371} _{-0.105}	5.8e-4	KOI-767.01
9595827	3.905081985	13.14 ^{+0.86} _{-0.49}	n/a	0.8870 ^{+0.058} _{-0.033}	8.1e-4	KOI-217.01
12019440	3.243259796	13.63 ^{+6.16} _{-1.23}	n/a	1.0290 ^{+0.465} _{-0.299}	1.7e-3	KOI-186.01
8323764	6.714251076	16.46 ^{+6.05} _{-1.79}	n/a	0.8 ^{+0.29} _{-0.084}	3.4e-2	KOI-3767.01
6849046	4.225384512	9.00 ^{+1.76} _{-0.66}	n/a	1.05 ^{+0.21} _{-0.08}	0	KOI-201.01 (Sa12)
7778437	5.014234575	10.31 ^{+7.57} _{-1.54}	n/a	1.31 ^{+0.26} _{-0.26}	0	KOI131.01 (Sa12)
7017372	5.240904530	12.84 ^{+6.69} _{-2.52}	n/a	1.41 ^{+0.59} _{-0.24}	0	KOI-3689.01 (Sa12)
757450	8.884922680	11.30 ^{+0.66} _{-0.66}	9.9 ^{+0.5} _{-0.5}	0.88 ^{+0.04} _{-0.04}	0	Kepler-75b (Bo15)
4570949	1.544928883	14.92 ^{+1.32} _{-1.32}	2.01 ^{+0.37} _{-0.35}	1.32 ^{+0.08} _{-0.08}	0	Kepler-76b (Fa13)
5357901	3.797018335	10.73 ^{+0.24} _{-0.24}	0.25 ^{+0.08} _{-0.08}	0.86 ^{+0.02} _{-0.02}	0	Kepler-425b (He14)
5358624	3.525632561	11.85 ^{+0.33} _{-0.33}	1.27 ^{+0.19} _{-0.19}	0.80 ^{+0.02} _{-0.02}	0	Kepler-428b (He14)
5728139	5.334083460	15.91 ^{+1.76} _{-1.76}	2.82 ^{+0.52} _{-0.52}	2.26 ^{+0.25} _{-0.25}	0	Kepler-433b (Al12)
5780885	4.885488953	17.78 ^{+0.11} _{-0.11}	0.44 ^{+0.04} _{-0.04}	1.96 ^{+0.07} _{-0.07}	0	Kepler-7b (La10)
6046540	7.340714746	10.53 ^{+0.22} _{-0.22}	0.63 ^{+0.12} _{-0.12}	1.12 ^{+0.04} _{-0.04}	0	Kepler-74b (Bo15)
6922244	3.522498573	15.58 ^{+0.55} _{-0.66}	0.59 ^{+0.13} _{-0.12}	1.45 ^{+0.12} _{-0.13}	0	Kepler-8b (Je10)
7529266	8.600153301	21.84 ^{+1.98} _{-1.98}	0.84 ^{+0.15} _{-0.15}	3.21 ^{+0.3} _{-0.3}	0	Kepler-435b (Al12)
7877496	1.720861324	14.70 ^{+0.44} _{-0.55}	0.94 ^{+0.12} _{-0.02}	1.29 ^{+0.04} _{-0.04}	0	Kepler-412b (De14)
8191672	3.548465405	15.69 ^{+0.44} _{-0.55}	2.11 ^{+0.07} _{-0.09}	1.75 ^{+0.14} _{-0.15}	0	Kepler-5b (Ko10)
9305831	3.246732651	11.96 ^{+0.77} _{-0.77}	1.00 ^{+0.1} _{-0.1}	1.35 ^{+0.08} _{-0.08}	0	Kepler-44b (Bo12)
9410930	1.855557540	11.41 ^{+0.44} _{-0.44}	0.56 ^{+0.10} _{-0.09}	1.02 ^{+0.03} _{-0.03}	0	Kepler-41b (Es15)
9631995	7.891448474	12.62 ^{+1.21} _{-1.21}	0.43 ^{+0.13} _{-0.13}	1.24 ^{+0.12} _{-0.12}	0	Kepler-422b (En14)
9651668	2.684328485	13.17 ^{+0.77} _{-0.77}	0.72 ^{+0.12} _{-0.12}	0.99 ^{+0.05} _{-0.05}	0	Kepler-423b (En14)
9818381	3.024092548	13.39 ^{+0.77} _{-0.66}	3.23 ^{+0.26} _{-0.26}	1.38 ^{+0.05} _{-0.03}	0	Kepler-43b (Es15; Bo15)
10264660	6.790121599	12.46 ^{+0.59} _{-0.59}	8.4 ^{+0.19} _{-0.19}	2.05 ^{+0.08} _{-0.08}	0	Kepler-14b (Bu11)
10619192	1.485710952	14.59 ^{+0.44} _{-0.44}	2.47 ^{+0.10} _{-0.10}	1.17 ^{+0.09} _{-0.09}	0	Kepler-17b (Bo12)
10666592	2.204735365	15.69 ^{+1.2} _{-1.2}	1.741 ^{+0.028} _{-0.028}	2.00 ^{+0.01} _{-0.02}	0	HAT-P-7b (Pa08; Va13)
10874614	3.234699312	14.26 ^{+0.22} _{-0.33}	0.67 ^{+0.04} _{-0.04}	1.29 ^{+0.09} _{-0.10}	0	Kepler-6b (Es15)
11017901	7.794301316	18.10 ^{+6.47} _{-6.47}	1.37 ^{+0.48} _{-0.48}	1.03 ^{+0.16} _{-0.16}	0	Kepler-447b (Li15)
11359879	4.942783399	10.54 ^{+0.66} _{-0.77}	0.66 ^{+0.08} _{-0.09}	0.98 ^{+0.16} _{-0.06}	0	Kepler-15b (En11)
11804465	4.437963030	19.20 ^{+0.33} _{-0.44}	0.43 ^{+0.05} _{-0.05}	1.42 ^{+0.30} _{-0.24}	0	Kepler-12b (Es15)
11446443	2.4706133738	13.05 ^{+0.27} _{-0.27}	1.253 ^{+0.052} _{-0.052}	1.0 ^{+0.036} _{-0.036}	0	Tres-2b (Od06; So10)
11502867	3.217518593	11.96 ^{+0.33} _{-0.33}	0.34 ^{+0.08} _{-0.08}	0.92 ^{+0.02} _{-0.02}	0	Kepler-426b (He14)
9941662	1.763587569	16.57 ^{+0.44} _{-0.44}	9.28 ^{+0.16} _{-0.16}	1.74 ^{+0.04} _{-0.04}	0	Kepler-13b (Sh11)
8359498	3.578780551	10.53 ^{+0.22} _{-0.22}	0.43 ^{+0.03} _{-0.03}	0.99 ^{+0.02} _{-0.02}	0	KOI127.01 (Ga13)

^a The false positive rate for individual system fp is from the NASA Exoplanet Archive Kepler false positive probability table based on Morton et al (in prep).^a We assign 0 to the confirmed candidates.

^b Reference abbreviations used in this table and the next are as follows. Al12:Almenara et al. (2015); Bo12:Bonomo et al. (2012); Bo15:Bonomo et al. (2015); Br15:Bruno et al. (2015); Bu11:Buchhave et al. (2011); Ca14:Cabrera et al. (2014); Da12:Dawson et al. (2012); De14:Deleuil et al. (2014); En11:Endl et al. (2011); En14:Endl et al. (2014); Es15:Esteves et al. (2015); Fa13:Fagler et al. (2013); Ga13:Gandolfi et al. (2013); He14:Hébrard et al. (2014); Je10:Jenkins et al. (2010); Ko10:Koch et al. (2010); La10:Latham et al. (2010); Li15:Lillo-Box et al. (2014); Ne12:Nesvorný et al. (2012); Od06:O'Donovan et al. (2006); Pa08:Pál et al. (2008); Sa12:Sanchis-Ojeda et al. (2012); Sa12:Santerne et al. (2012); Sa12:Santerne et al. (2016); Sc14:Schmitt et al. (2014b); Sc14b:Schmitt et al. (2014a); Sh11:Shporer et al. (2011); St10:Steffen et al. (2010); So10:Southworth (2011); Ro14:Rowe et al. (2014); Va13:Van Eylen et al. (2012); We13:Weiss et al. (2013).

^a<http://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=koifpp>

TABLE 4
KEPLER WARM JUPITER SYSTEMS

KIC	Period	Rp	Mp	Rstar	fp rate	Other Name/Reference
	[day]	[R_{Earth}]	[M_{Jup}]	[R_{\odot}]		
7984047	77.63425713	$10.09^{+1.35}_{-0.91}$	n/a	$0.755^{+0.101}_{-0.068}$	8.8e-3	KOI-1552.01
7811397	169.49954	$9.89^{+2.26}_{-0.81}$	n/a	$0.719^{+0.164}_{-0.059}$	0.71	KOI-1477.01
8672910	39.64317811	$10.52^{+4.46}_{-0.81}$	n/a	$0.833^{+0.355}_{-0.064}$	3.6e-4	KOI-918.01
7504328	53.71797107	$8.21^{+2.73}_{-1.59}$	n/a	$1.151^{+0.383}_{-0.222}$	0.46	KOI-458.01
6471021	125.62887621	$8^{+1.14}_{-0.34}$	n/a	$0.897^{+0.128}_{-0.038}$	2.2e-4	KOI-372.01
6061119	27.807562927	$14.46^{+6.63}_{-1.08}$	n/a	$0.791^{+0.363}_{-0.059}$	7.7e-2	KOI-846.01
4760746	15.068059056	$17.65^{+5.88}_{-1.64}$	n/a	$0.96^{+0.32}_{-0.089}$	0.8	KOI-1455.01
10656508	124.03590546	$10.41^{+6.91}_{-1.14}$	n/a	$1.137^{+0.754}_{-0.125}$	7.9e-3	KOI-211.01
7950644	10.290993755	13.776 ± 2.35	0.29 ± 0.09	1.35 ± 0.2	0	Kepler-427b (He14)
4164994	10.506825646	$9.41^{+1.89}_{-0.64}$	n/a	$0.784^{+0.157}_{-0.054}$	7.5e-4	KOI-1320.01
11194032	28.511205250	$8.21^{+6.23}_{-4.56}$	n/a	$1.741^{+1.322}_{-0.966}$	0	KOI-348.01
7499398	23.020303180	$8.22^{+3.19}_{-0.68}$	n/a	$0.95^{+0.368}_{-0.079}$	9.4e-3	KOI-1473.01
7368664	12.874711418	$12.40^{+2.85}_{-1.98}$	$2.86^{+0.35}_{-0.35}$	$1.38^{+0.13}_{-0.13}$	0	Kepler-434b (Al12)
7951018	52.75875577	$9.04^{+5.84}_{-1.04}$	n/a	$1.154^{+0.746}_{-0.132}$	8.5e-4	KOI-1553.01
9025971	141.24164672	$10.64^{+4.02}_{-0.85}$	$0.55^{+0.02}_{-0.02}$	$0.913^{+0.345}_{-0.073}$	0	KOI-3680.01 (Sa12)
5812701	17.855219698	$15.69^{+1.43}_{-1.43}$	n/a	$1.63^{+0.15}_{-0.15}$	0	KOI-12.01 (Bo15)
10723750	50.79034619	$9.16^{+5.55}_{-1.14}$	$1.84^{+0.18}_{-0.183}$	$1.183^{+0.716}_{-0.147}$	0	Kepler-117c (Ro14; Br15)
	18.795900480	$6.04^{+3.66}_{-0.75}$	$0.094^{+0.03}_{-0.03}$		0	Kepler-117b (Ro14; Br15)
7109675	33.601220660	$8.83^{+0.46}_{-0.5}$	n/a	$0.93^{+0.048}_{-0.053}$	0	Kepler-46b (Ne12)
	57.011	n/a	$0.376^{+0.021}_{-0.019}$		0	Kepler-46c (Ne12)
	6.76652078	$2.17^{+0.11}_{-0.13}$	n/a		0	Kepler-46d (Ne12)
6462863	22.342969585	$9.77^{+2.03}_{-1.5}$	$0.333^{+0.036}_{-0.036}$	$1.297^{+0.27}_{-0.199}$	0	Kepler-89d (We13)
	10.423677765	$3.66^{+0.76}_{-0.56}$	0.030 ± 0.015		0	Kepler-89c (We13)
	54.31998605	$5.79^{+1.21}_{-0.89}$	0.1101 ± 0.045		0	Kepler-89e (We13)
	3.743175556	$1.55^{+0.32}_{-0.24}$	0.02 ± 0.02		0	Kepler-89b (We13)
5972334	15.358768403	$11.31^{+4.78}_{-1.04}$	n/a	$0.87^{+0.368}_{-0.08}$	4.1e-4	KOI-191.01 (St10)
	2.418405445	$2.79^{+1.17}_{-0.26}$	n/a		3e-3	KOI-191.02 (St10)
	0.708620008	$1.25^{+0.52}_{-0.12}$	n/a		1.0	KOI-191.03 (St10)
	38.6519976	$2.62^{+1.11}_{-0.24}$	n/a		1.3e-3	KOI-191.04 (St10)
5629353	33.319916700	$13.10^{+7.22}_{-3.66}$	n/a	$1.63^{+0.897}_{-0.456}$	2e-2	KOI-6132.01
	7.5844126	$5.49^{+3.03}_{-1.53}$	n/a		3.8e-4	KOI-6132.02
	11.8674823	$3.94^{+2.17}_{-1.1}$	n/a		3.7e-3	KOI-6132.03
9946525	51.84688575	$8.95^{+2.07}_{-0.65}$	n/a	$0.838^{+0.252}_{-0.061}$	4.43-3	KOI-398.01
	4.18004955	$3.55^{+1.07}_{-0.26}$	n/a		3.8e-7	Kepler-148c
	1.729366467	$1.87^{+0.56}_{-0.15}$	n/a		0.88	Kepler-148b
3832474	143.2063518	$9.36^{+0.99}_{-0.37}$	$0.073^{+0.008}_{-0.008}$	$0.867^{+0.092}_{-0.034}$	0	Kepler-30d (Sa12)
	60.32488611	$12.88^{+1.36}_{-0.51}$	$2.01^{+0.16}_{-0.16}$		0	Kepler-30c (Sa12)
	29.1598615	$1.91^{+0.2}_{-0.07}$	$0.036^{+0.004}_{-0.004}$		0	Kepler-30b (Sa12)
3247268	86.67855186	$9.88^{+4.67}_{-1.02}$	$1.1^{+1.1}_{-0.0}$	$1.043^{+0.494}_{-0.107}$	0	Kepler-418b
	12.218278	$4.75^{+2.25}_{-0.49}$	n/a		2.0e-4	KOI-1089.02
7303287	125.8518	$11.35^{+0.19}_{-0.19}$	$0.41^{+0.05}_{-0.05}$	$1.00^{+0.02}_{-0.02}$	0	Kepler-289b (Sc14b)
	34.5438464	$2.11^{+0.1}_{-0.1}$	n/a		0	Kepler-289c (Sc14b)
	66.063	$2.62^{+0.16}_{-0.16}$	$0.013^{+0.003}_{-0.003}$		0	PH-3c (Sc14b)
12365184	69.7546	$10.6^{+1.4}_{-1.3}$	$2.5^{+0.3}_{-0.3}$	$1.75^{+0.08}_{-0.07}$	0	Kepler-419b (Da12)
	675.47	n/a	$7.3^{+0.4}_{-0.4}$		0	Kepler-419c (Da12)
7898352	127.2824031	$9.32^{+3.76}_{-0.77}$	n/a	$0.883^{+0.356}_{-0.073}$	7.2e-2	Kepler-302c (Ro14)
	30.1836854	$2.88^{+1.15}_{-0.24}$	n/a		3.4e-5	Kepler-302b (Ro14)

- Gandolfi, D., Parviainen, H., Fridlund, M., et al. 2013, *A&A*, 557, A74
- Gibson, N. P., Pollacco, D., Simpson, E. K., et al. 2009, *ApJ*, 700, 1078
- Hadden, S., & Lithwick, Y. 2014, *ApJ*, 787, 80
- Hébrard, G., Santerne, A., Montagnier, G., et al. 2014, *A&A*, 572, A93
- Hellier, C., Anderson, D. R., Collier Cameron, A., et al. 2012, *MNRAS*, 426, 739
- Howard, A. W., Marcy, G. W., Bryson, S. T., et al. 2012, *ApJS*, 201, 15
- Huang, X., Bakos, G. Á., & Hartman, J. D. 2013, *MNRAS*, 429, 2001
- Jenkins, J. M., Borucki, W. J., Koch, D. G., et al. 2010, *ApJ*, 724, 1108
- Koch, D. G., Borucki, W. J., Rowe, J. F., et al. 2010, *ApJ*, 713, L131
- Kovács, G., Bakos, G. Á., Hartman, J. D., et al. 2010, *ApJ*, 724, 866
- Latham, D. W., Borucki, W. J., Koch, D. G., et al. 2010, *ApJ*, 713, L140
- Latham, D. W., Rowe, J. F., Quinn, S. N., et al. 2011, *ApJ*, 732, L24
- Lee, E. J., Chiang, E., & Ormel, C. W. 2014, *ApJ*, 797, 95
- Lillo-Box, J., Barrado, D., & Bouy, H. 2014, *A&A*, 566, A103
- Lissauer, J. J., Marcy, G. W., Bryson, S. T., et al. 2014, *ApJ*, 784, 44
- Lissauer, J. J., Ragozzine, D., Fabrycky, D. C., et al. 2011, *ApJS*, 197, 8
- Lithwick, Y., Xie, J., & Wu, Y. 2012, *ApJ*, 761, 122
- Mayor, M., Marmier, M., Lovis, C., et al. 2011, *arXiv:1109.2497*
- Morton, T. D. 2012, *ApJ*, 761, 6
- Mustill, A. J., Davies, M. B., & Johansen, A. 2015, *ApJ*, 808, 14
- Nesvorný, D., Kipping, D. M., Buchhave, L. A., et al. 2012, *Science*, 336, 1133
- Neveu-VanMalle, M., Queloz, D., Anderson, D. R., et al. 2016, *A&A*, 586, A93
- O'Donovan, F. T., Charbonneau, D., Mandushev, G., et al. 2006, *ApJ*, 651, L61
- Ofir, A., & Dreizler, S. 2013, *A&A*, 555, A58
- Pál, A., Bakos, G. Á., Torres, G., et al. 2008, *ApJ*, 680, 1450
- Petigura, E. A., Howard, A. W., & Marcy, G. W. 2013, *PNAS*, 110, 19273
- Petigura, E. A., Marcy, G. W., & Howard, A. W. 2013, *ApJ*, 770, 69
- Rafikov, R. R. 2006, *ApJ*, 648, 666
- Rivera, E. J., Laughlin, G., Butler, R. P., et al. 2010, *ApJ*, 719, 890
- Rowe, J. F., Bryson, S. T., Marcy, G. W., et al. 2014, *ApJ*, 784, 45
- Sanchis-Ojeda, R., Fabrycky, D. C., Winn, J. N., et al. 2012, *Nature*, 487, 449
- Santerne, A., Díaz, R. F., Moutou, C., et al. 2012, *A&A*, 545, A76
- Santerne, A., Moutou, C., Tsantaki, M., et al. 2016, *A&A*, 587, A64
- Schmitt, J. R., Agol, E., Deck, K. M., et al. 2014a, *ApJ*, 795, 167
- Schmitt, J. R., Wang, J., Fischer, D. A., et al. 2014b, *AJ*, 148, 28
- Schneider, J. 2011, EPSC-DPS Joint Meeting, 2011, 3
- Seager, S., & Mallén-Ornelas, G. 2003, *ApJ*, 585, 1038
- Shporer, A., Jenkins, J. M., Rowe, J. F., et al. 2011, *AJ*, 142, 195
- Silburt, A., Gaidos, E., & Wu, Y. 2015, *ApJ*, 799, 180
- Southworth, J. 2011, *MNRAS*, 417, 2166
- Steffen, J. H., & Agol, E. 2005, *MNRAS*, 364, L96
- Steffen, J. H., Batalha, N. M., Borucki, W. J., et al. 2010, *ApJ*, 725, 1226
- Steffen, J. H., Ragozzine, D., Fabrycky, D. C., et al. 2012, *PNAS*, 109, 7982
- Tremaine, S., & Dong, S. 2012, *AJ*, 143, 94
- Van Eylen, V., Kjeldsen, H., Christensen-Dalsgaard, J., & Aerts, C. 2012, *AN*, 333, 1088
- Wang, J., Fischer, D. A., Barclay, T., et al. 2013, *ApJ*, 776, 10
- Weiss, L. M., Marcy, G. W., Rowe, J. F., et al. 2013, *ApJ*, 768, 14
- Wright, J. T., Fakhouri, O., Marcy, G. W., et al. 2011, *PASP*, 123, 412
- Wright, J. T., Marcy, G. W., Howard, A. W., et al. 2012, *ApJ*, 753, 160
- Wright, J. T., Upadhyay, S., Marcy, G. W., et al. 2009, *ApJ*, 693, 1084
- Xie, J.-W. 2013, *ApJS*, 208, 22