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THE WATER-ICE LINE IN SYSTEMS WITH HOT JUPITERS:  
EVIDENCE AGAINST HIGH-ECCENTRICITY MIGRATION*

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# THE OCCURRENCE OF ADDITIONAL GIANT PLANETS INSIDE THE WATER–ICE LINE IN SYSTEMS WITH HOT JUPITERS: EVIDENCE AGAINST HIGH-ECCENTRICITY MIGRATION

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## ABSTRACT

The origin of Jupiter-mass planets with orbital periods of only a few days is still uncertain. It is widely believed that these planets formed near the water–ice line of the protoplanetary disk, and subsequently migrated into much smaller orbits. Most of the proposed migration mechanisms can be classified either as disk-driven migration, or as excitation of a very high eccentricity followed by tidal circularization. In the latter scenario, the giant planet that is destined to become a hot Jupiter spends billions of years on a highly eccentric orbit, with apastron near the water–ice line. Eventually, tidal dissipation at periastron shrinks and circularizes the orbit. If this is correct, then it should be especially rare for hot Jupiters to be accompanied by another giant planet interior to the water–ice line. Using the current sample of giant planets discovered with the Doppler technique, we find that hot Jupiters with  $P_{\text{orb}} < 10$  days are no more or less likely to have exterior Jupiter-mass companions than longer-period giant planets with  $P_{\text{orb}} \geq 10$  days. This result holds for exterior companions both inside and outside of the approximate location of the water–ice line. These results are difficult to reconcile with the high-eccentricity migration scenario for hot Jupiter formation.

**Key words:** planetary systems – planets and satellites: detection – planets and satellites: formation – stars: statistics

**Supporting material:** machine-readable table

## 1. INTRODUCTION

Explaining the existence of hot Jupiters—Jupiter-mass planets on circular orbits with periods of only a few days—is one of the oldest problems in exoplanetary science. Theoretical models suggested that while it is formally possible for core accretion to produce a giant planet at  $a \lesssim 0.1$  au around a Sun-like star, it is more likely that they form beyond the location of the water–ice line in the protoplanetary disk at  $a \gtrsim 1$  au and subsequently migrate into the close proximity of the host star (Bodenheimer et al. 2000). Several mechanisms for this migration have been proposed. In disk-driven migration, interactions between a planet and the protoplanetary disk move a giant planet from the water–ice line to the inner edge of the disk within the few Myr of the disk’s lifetime (e.g., Lin et al. 1996). In high-eccentricity migration, a giant planet initially forms on a circular orbit near the water–ice line. The orbital eccentricity is then excited to  $e \gtrsim 0.9$  in one of several possible ways: close encounters with other planets, secular interactions with another massive body in the system, or a combination of scattering and secular interactions. Thereafter, the strong tidal interactions between the planet and its host star at periastron extract energy from the planetary orbit, leaving behind a giant planet on a circular orbit with  $P_{\text{orb}} \lesssim 10$  days (e.g., Rasio & Ford 1996; Weidenschilling & Marzari 1996; Holman et al. 1997; Mazeh et al. 1997; Kiseleva et al. 1998; Wu & Lithwick 2011; Petrovich 2015).

Several of the observed properties of the giant exoplanet population support the high-eccentricity scenario. Cumming

et al. (1999) and Udry et al. (2003) identified a “three-day pile-up” of hot Jupiters—an enhancement in the occurrence rate  $dN/d \log P_{\text{orb}}$  at  $P_{\text{orb}} \approx 3$  days—which is compatible with the action of tidal circularization. Dawson & Murray-Clay (2013) showed that this pile-up is also apparent in the sample of metal-rich *Kepler* giant-planet-candidate host stars, although not among the more metal-poor giant-planet-candidate hosts. They argued that this is a natural outcome of planet–planet scattering. The reason is that metal-rich stars likely had protoplanetary disks with more solid material and therefore a better chance of forming a multiple-giant-planet system that could undergo planet–planet scattering. Protoplanetary disk around more metal-poor stars likely had less solid material and therefore rarely produced multiple-giant-planet systems capable of strong scattering. In addition, the discovery of hot Jupiters for which the orbit is significantly misaligned with the rotation of the host star is seemingly at odds with disk migration, and naturally explained by high-eccentricity migration (e.g., Fabrycky & Tremaine 2007; Chatterjee et al. 2008; Jurić & Tremaine 2008; Naoz et al. 2011, 2012; Wu & Lithwick 2011).

Also widely cited as support for high-eccentricity migration is the idea that hot Jupiters seem to be less likely than other types of planets to be found with additional planetary companions. In other words, hot Jupiters have a reputation as “lonely” planets. This inference relies on a generic prediction of the high-eccentricity migration scenario: in systems with a hot Jupiter, there should be few if any planets exterior to the hot Jupiter and interior to the water–ice line. The body that gained the angular momentum lost by the hot-Jupiter progenitor must be exterior to the water–ice line. At the same time, any pre-existing planets interior to the water–ice line would have been destabilized during

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the high-eccentricity phase of the migration process, leading to the ejection of that planet from that region or the interference with the tidal circularization process. Furthermore, some variants of high-eccentricity migration rely on Kozai–Lidov oscillations excited by a stellar companion, which are incapable of exciting high eccentricities in the presence of companion planets (e.g., Kozai 1962; Lidov 1962; Wu & Murray 2003).

In contrast to hot Jupiters, the population of “warm Jupiters” with  $P_{\text{orb}} \geq 10$  days probably did not form through high-eccentricity migration, as star–planet tidal interactions at their more distant periastron distances are not strong enough to shrink their orbits. Moreover, the possibility that warm Jupiters are actively circularizing and are being observed in a low-eccentricity phase of long-timescale Kozai–Lidov oscillations been investigated and found to be in tension with results from Doppler surveys and the *Kepler* survey (Dong et al. 2014; Dawson et al. 2015).

The high-eccentricity scenario singles out hot Jupiters and predicts they will have different companion statistics than warm Jupiters. The frequency of long-period companions to hot Jupiters therefore provides an observational test. If the occurrence rate of long-period companions to hot Jupiters inside the water–ice line were systematically lower than the equivalent occurrence rate for cooler giant planets, it would support the high-eccentricity migration scenario. On the other hand, if the occurrence rates were comparable, it would disfavor the high-eccentricity migration scenario. This work was motivated by the fact that we were aware of the widely cited statement that hot Jupiters are lonely, but could not find in the literature any quantitative results for the conditional probability for a hot Jupiter to have a companion inside the water–ice line.

Previous studies of the “loneliness” phenomenon have generally used different metrics or had other features that prevented us from performing the exact tests mentioned above. Wright et al. (2009) found the distribution of orbital distances of all the planets in multiple-planet systems to be different from that of all the single-planet systems. In particular, the three-day pile-up discovered by Cumming et al. (1999) was absent from the multiple-planet systems. The sample analyzed by Wright et al. (2009) included systems discovered by both the Doppler and transit techniques. Because the transit technique is especially biased toward short-period planets, many of the apparently single systems analyzed by Wright et al. (2009) may have long-period giant planet companions.

Latham et al. (2011) and Steffen et al. (2012) found that short-period *Kepler* giant planet candidates are less likely to have small-planet candidate companions than close-in Neptune-sized planet candidates or more distant giant-planet candidates. More than 50% of the giant planet candidates discovered by *Kepler* have now been shown to be astrophysical false positives (Santerne et al. 2012, 2016). The false-positive rate for small-planet candidates appears to be much smaller (Fressin et al. 2013). An astrophysical false positive would be much less likely to present evidence of additional planets than a genuine exoplanet system.

A direct approach to measuring the companion probability for close-in giant planets is to undertake long-term Doppler observations of stars known to have such planets. Several groups have embarked on such efforts. Knutson et al. (2014) searched 48 systems with close-in Jupiter mass planets for long-period companions, finding 14 systems likely to have an external companion. Assuming a double-power law for the companion mass–semimajor axis distribution, they found that

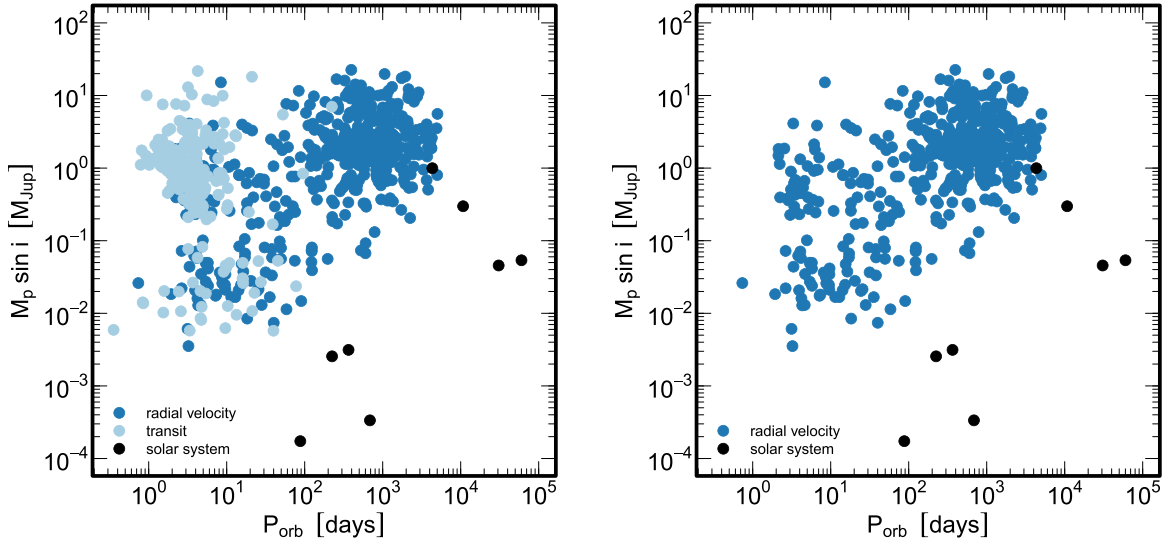
approximately 50% of their targets have a companion in the range  $1 \text{ au} \lesssim a \lesssim 20 \text{ au}$  and  $1 M_{\text{Jup}} \lesssim M_p \sin i \lesssim 13 M_{\text{Jup}}$ . The same group has expanded their search for companions using direct imaging to find distant companions and infrared spectroscopy to find close companions (Ngo et al. 2015; Piskorz et al. 2015). Most recently, Bryan et al. (2016) expanded their sample beyond hot Jupiter hosts to include giant planets over a broader range of orbital distances. They found that the occurrence of companions in the range  $1 M_{\text{Jup}} \lesssim M_p \sin i \lesssim 20 M_{\text{Jup}}$  and  $5 \text{ au} \lesssim a \lesssim 20 \text{ au}$  may be higher for hot Jupiters than for cooler giant planets. That result is subject to the caveat that the companion statistics may be systematically affected by stellar jitter (poorly understood, time-correlated radial-velocity noise), the effect of which is magnified in their hot Jupiter sample because of a relative lack of radial velocity measurements. They also did not make the specific comparison between hot and cool Jupiters in the occurrence of companions within the water–ice line.

In this paper, we compare the occurrence of long-period giant-planet companions to both hot Jupiters and more distant giant planets. We consider exterior companions both inside the water–ice line and out to the completeness limit of our input sample. We find that contrary to the expectation from the high-eccentricity migration scenario, there is no significant difference in the companion fraction for hot Jupiters and more distant giant planets. The same result applies to companions both inside the water–ice line and out to the completeness limit of our input data. We describe our sample definition in Section 2, we detail our analysis procedures in Section 3, we discuss the results and implications in Section 4, and we summarize our findings in Section 5.

## 2. SAMPLE DEFINITION

We would like to calculate  $P(\text{LongPerJup}|\text{HotJup})$ , the conditional probability that a long-period Jupiter-mass planet exists in a system given that it has a hot Jupiter. Rather than directly measuring this quantity with long-term Doppler observations and high-contrast imaging, we calculate it using Bayes’ Theorem and publicly available data. In particular, we use (i) the occurrence rates for giant planets as a function of mass and orbital distance reported by Cumming et al. (2008); (ii) the occurrence rate for hot Jupiters reported by Wright et al. (2012); and (iii) a sample of giant planets discovered by the Doppler technique. We will refer to these data as the “Doppler sample” and describe its construction below.

The planets discovered by the Doppler technique typically orbit bright host stars that have been subject to long-term high-precision radial-velocity measurements, in some cases for more than 20 years. This sample therefore provides the sensitivity to  $M_p \sin i = 0.1 M_{\text{Jup}}$  planets at  $P_{\text{orb}} \lesssim 100$  days and to  $M_p \sin i = 1 M_{\text{Jup}}$  planets at  $P_{\text{orb}} \lesssim 4080$  days (Cumming et al. 2008). We use *exoplanets.org* to identify all giant exoplanets with  $M_p \sin i > 0.1 M_{\text{Jup}}$  discovered by the Doppler technique (Wright et al. 2011; Han et al. 2014). We exclude systems that were first discovered using the transit technique, because of the extreme bias of the transit technique toward short-period planets (Figure 1). We also wish to exclude evolved stars, because they have markedly different giant-planet population statistics that may be due to tidal evolution or other effects (e.g., Schlaufman & Winn 2013). To identify and exclude evolved stars, we obtain for each star the *Hipparcos* parallaxes and Tycho  $B - V$  colors from van Leeuwen (2007) and apparent Tycho-2  $V$ -band magnitudes from Høg et al. (2000). We then select for main-



**Figure 1.** Orbital period vs. minimum planet mass for exoplanets and solar system planets. Left: including exoplanets discovered by both the Doppler and transit techniques. Right: only exoplanets discovered by the Doppler technique. We plot transit discoveries in light blue, Doppler discoveries in dark blue, and solar system planets in black. Because transit surveys are extremely biased toward short-period planets, the sample plotted on the left over-emphasizes the frequency of hot Jupiters.

**Table 1**  
Exoplanet Systems in Our Doppler Sample

System	$N^a$
HD 142	1
HD 1237	1
HD 1666	1
HD 2039	1
HIP 2247	1

**Note.**

<sup>a</sup> Number of planets with  $M_p \sin i > 0.1 M_{\text{Jup}}$ .

(This table is available in its entirety in machine-readable form.)

sequence FGK stars showing little or no evolution, using the criteria  $\Delta M_V < 2.5$  and  $B - V < 1.2$ . Here

$$\Delta M_V = M_{V,\text{MS}}(B - V) - M_V, \quad (1)$$

and

$$M_{V,\text{MS}}(B - V) = \sum_{i=0}^9 a_i (B - V)^i, \quad (2)$$

where the coefficients  $a_i$  are taken from Wright (2005) and represent the average *Hipparcos* main sequence in the Tycho-2 system.<sup>8</sup> Because of this criterion we are forced to reject all planets orbiting stars without *Hipparcos* parallaxes. We are left with 266 giant planets orbiting 225 different stars and 35 multiple-giant-planet systems. We list these systems in Table 1. The multiple-giant-planet systems are the focus of this study,

and we plot them in Figure 2. We only use the Doppler sample to count interior giant-planet companions to announced long-period giant planets. Since the radial velocity signal of interior giant planets always has a shorter period and usually a larger amplitude than more distant giant planets, the Doppler sample should be complete to such planets.

We plot the giant planet occurrence from Cumming et al. (2008) and Wright et al. (2012) as a function of  $P_{\text{orb}}$  and  $M_p \sin i$  in Figure 3. We assume that there is not a significant undiscovered population of short-period giant planets in systems with at least one long-period giant planet. Given the biases of the Doppler technique and the search strategy of existing Doppler surveys, this should be a safe assumption. In addition, we assume that the long-period giant planet occurrence rate observed by Cumming et al. (2008) applies to the unobserved long-period giant planet population in the larger sample of stars analyzed by Wright et al. (2012).

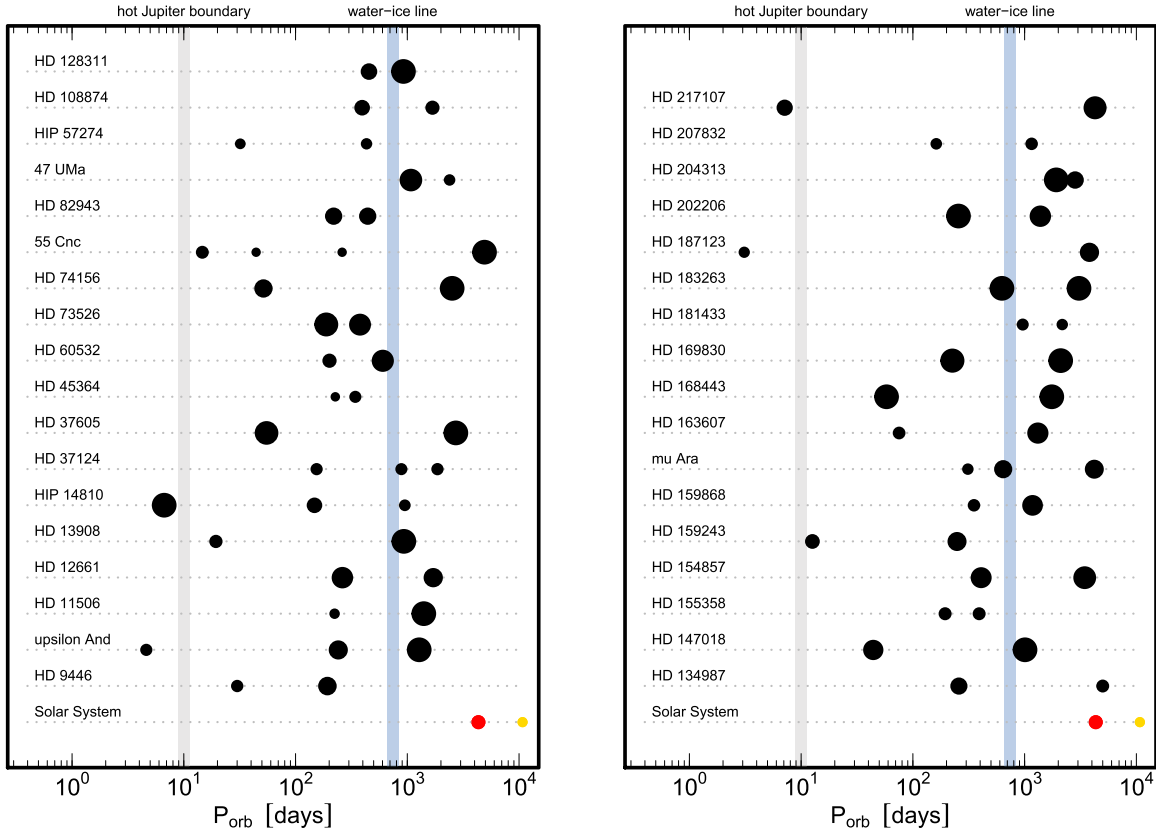
### 3. ANALYSIS

Let  $P(\text{HotJup})$  denote the probability that a star hosts a hot Jupiter, as defined by Wright et al. (2012): a planet with  $M_p \sin i > 0.1 M_{\text{Jup}}$  and  $P_{\text{orb}} < 10$  days. Let  $P(\text{LongPerJup})$  denote the probability that an FGK star hosts a long-period Jovian planet, defined here as a planet with  $M_p \sin i > 1 M_{\text{Jup}}$  and  $10 \text{ days} \lesssim P_{\text{orb}} \lesssim 4080 \text{ days}$ . The outer limit of 4080 days is adopted to match that of Cumming et al. (2008), whose results are necessary for our analysis. Then by Bayes' Theorem, the conditional probability  $P(\text{LongPerJup}|\text{HotJup})$  that a system has a long-period giant planet given that it has a hot Jupiter is

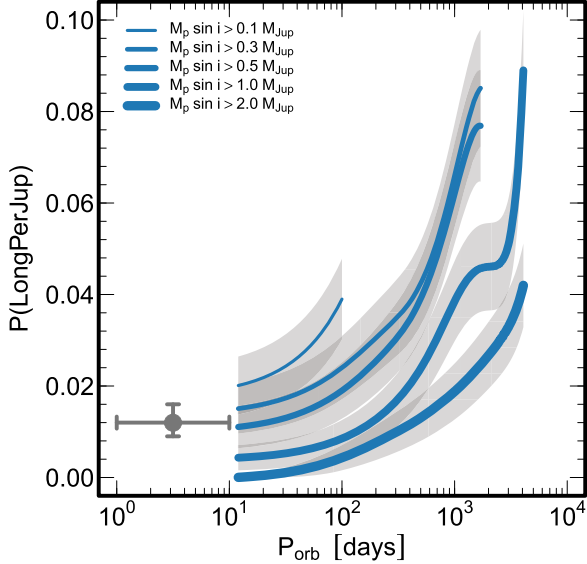
$$P(\text{LongPerJup}|\text{HotJup}) = \frac{P(\text{HotJup}|\text{LongPerJup})P(\text{LongPerJup})}{P(\text{HotJup}|\text{LongPerJup})P(\text{LongPerJup}) + P(\text{HotJup}|\text{LongPerJup}')P(\text{LongPerJup}')}, \quad (3)$$

where  $P(\text{HotJup}|\text{LongPerJup})$  is the conditional probability that a system with a long-period giant planet has a hot Jupiter,  $P(\text{HotJup}|\text{LongPerJup}')$  is the probability that a system with no

<sup>8</sup> The numerical values of the coefficients are  $a_i = (1.11255, 5.79062, -16.76829, 76.47777, -140.08488, 127.38044, -49.71805, -8.24265, 14.07945, -3.43155)$ .



**Figure 2.** Systems of multiple giant planets discovered with the radial velocity technique around slightly evolved main-sequence FGK stars. The size of a plotted point is proportional to  $\log_{10}(M_p \sin i)$ . Four of the 35 multiple-giant-planet systems have a hot Jupiter.



**Figure 3.** Cumulative fraction of stars with a giant planet as a function of period and  $M_p \sin i$ . The hot Jupiter data point at  $P < 10$  days is from Wright et al. (2012), while the colored lines are from natural cubic spline interpolation of the data in Table 1 of Cumming et al. (2008) accounting for completeness and including both announced and unannounced detections. The gray regions are the  $1\text{-}\sigma$  uncertainties.

long-period giant planet has a hot Jupiter, and  $P(\text{LongPerJup}')$  is the probability that a system has no long-period giant planet.

First we will compute  $P(\text{HotJup}|\text{LongPerJup})$ . The Doppler sample contains 136 systems with at least one long-period giant planet, according the definition given above. The Doppler

sample also includes four systems with both a hot Jupiter and at least one long-period companion:  $\nu$  And, HIP 14810, HD 187123, and HD 217107. However, HD 217107c has an orbital period  $P_{\text{orb}} = 4270$  days, which is outside of the period range defined in Table 1 of Cumming et al. (2008) and cannot be used in this analysis. Therefore,  $P(\text{HJ}|\text{GP}) = 3/136 = 0.020^{+0.014}_{-0.010}$ . We calculate our uncertainties using a binomial distribution and an uninformative Beta( $\alpha, \beta$ ) prior (see Section 3.3 of Schlaufman 2014).

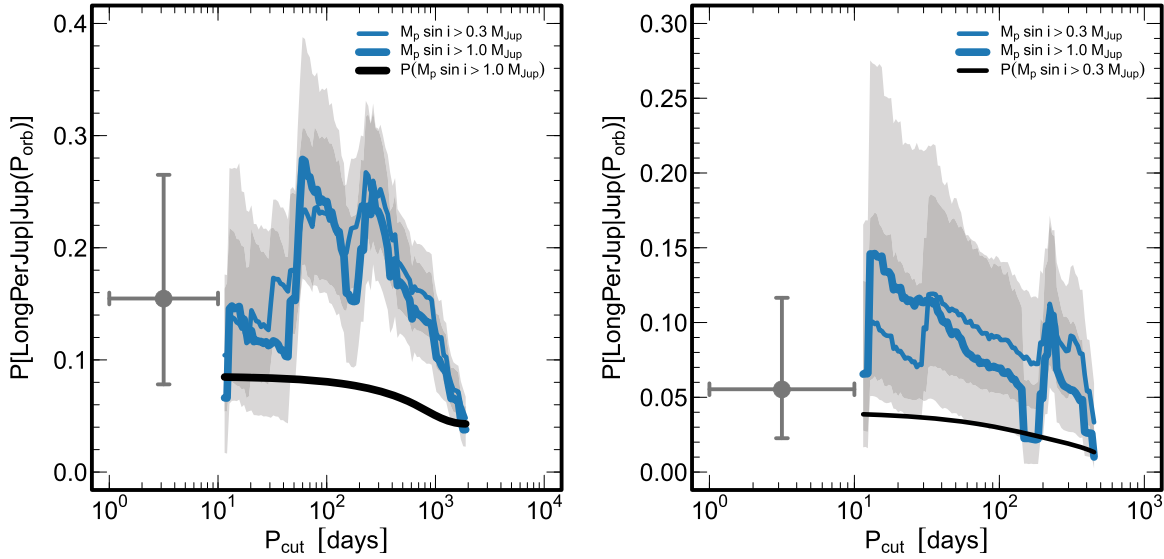
The hot Jupiter probability  $P(\text{HotJup})$  has already been the subject of a careful study by Wright et al. (2012). They found 10 hot Jupiters in their sample of 836 stars, using the criteria defined above, giving  $P(\text{HotJup}) = 0.012^{+0.004}_{-0.003}$ .

For  $P(\text{LongPerJup})$  we rely on the work by Cumming et al. (2008). They found that 8.5% of FGK stars have a  $M_p \sin i = 1 M_{\text{Jup}}$  planet in the range  $11.5 \text{ days} < P_{\text{orb}} < 4080$  days (or  $0.1 \text{ au} < a < 5 \text{ au}$ ), giving  $P(\text{LongPerJup}) = 0.085^{+0.013}_{-0.012}$  and  $P(\text{LongPerJup}') = 1 - P(\text{LongPerJup}) = 0.915^{+0.013}_{-0.012}$ .

To determine  $P(\text{HotJup}|\text{LongPerJup}')$ , we note that two of the 10 hot Jupiters in the sample of Wright et al. (2012) have longer-period companions. None of the other eight hot Jupiters have longer-period companions. Although the sample of 836 stars from which they are drawn has not been searched completely, we know from the occurrence rates of Cumming et al. (2008) that 8.5% of them (on average) have longer-period companions. Therefore  $P(\text{HotJup}|\text{LongPerJup}') = (10 - 2)/[836(1 - 0.085)] = 0.010^{+0.004}_{-0.003}$ .

We now have measurements and uncertainties for all the quantities on the right side of Equation (3). Plugging in the





**Figure 4.** Left: conditional probability of the presence of an exterior, long-period giant planet with  $M_p \sin i > 1 M_{\text{Jup}}$  and  $P_{\text{orb}} < 4080$  days given the presence of an interior giant planet with period and minimum mass as indicated. The gray regions are the  $1\text{-}\sigma$  uncertainties and the solid black curve is the probability  $P(\text{LongPerJup})$ . Right: conditional probability of the presence of an exterior, long-period giant planet inside the water–ice line with  $M_p \sin i > 0.3 M_{\text{Jup}}$  and  $P_{\text{orb}} < 739$  days given the presence of an interior giant planet with period and minimum mass as indicated. We assume a water–ice line at  $a = 1.6$  au, or  $P_{\text{orb}} = 739$  days for a one solar mass star (Mulders et al. 2015). The gray regions are the  $1\text{-}\sigma$  uncertainties and the solid black curve is the probability  $P(\text{LongPerJup})$ . The apparent scatter at short orbital period is smaller than the measurement uncertainty, so there is no evidence for a dependence of  $P[\text{LongPerJup}|\text{Jup}(P_{\text{orb}})]$  on minimum mass. The trend toward smaller  $P[\text{LongPerJup}|\text{Jup}(P_{\text{orb}})]$  as  $P_{\text{cut}}$  increases is statistically real, but best explained by the decreasing range in orbital period available to external companions between the interior giant planet and the completeness limit as the period of the inner planet increases. The fact that hot Jupiters are just as likely as more distant giant planets to have long-period companions inside the water–ice line is contrary to the expectation from simple models of high-eccentricity migration.

numbers reveals that  $P(\text{LongPerJup}|\text{HotJup}) = 0.155^{+0.110}_{-0.077}$ . It is interesting to compare this result to  $P(\text{LongPerJup}) = 0.085^{+0.013}_{-0.012}$ . Evidently, the fact that a hot Jupiter has been observed in a system increases the probability that another giant planet will be found within 5 au in the same system, by nearly a factor of two (with a large statistical uncertainty).

To test the prediction of the high-eccentricity migration scenario, we need to calculate  $P(\text{LongPerJup}|\text{HotJup})$  for the specific case of companions that are inside the water–ice line. Mulders et al. (2015) determined that the water–ice line in a solar-composition protoplanetary disk around a Sun-like star during the planet formation epoch is at  $a \approx 1.6$  au, or  $P_{\text{orb}} \approx 739$  days. Hence we define a long-period Jovian planet inside the water–ice line (InsideIceJup) as a planet with  $M_p \sin i > 0.3 M_{\text{Jup}}$  and  $10 \text{ days} < P < 739$  days, and repeat the calculation from the preceding paragraph. Using this revised definition, only the  $\nu$  And and HIP 14810 systems have both a hot Jupiter and at least one long-period companion, and there are 105 systems with at least one long-period giant planet. Therefore,  $P(\text{HotJup}|\text{InsideIceJup}) = 2/105 = 0.016^{+0.016}_{-0.009}$ . The value of  $P(\text{HotJup}) = 0.012^{+0.004}_{-0.003}$  is the same as before. The overall giant-planet occurrence rate from Cumming et al. (2008) is now 3.9% for FGK stars in the range  $11.5 \text{ days} < P_{\text{orb}} < 739$  days (or  $0.1 \text{ au} < a < 1.6 \text{ au}$ ), giving  $P(\text{InsideIceJup}) = 0.039^{+0.009}_{-0.008}$  and  $P(\text{InsideIceJup}') = 1 - P(\text{InsideIceJup}) = 0.961^{+0.009}_{-0.008}$ . Only  $\nu$  And b is in the sample of Wright et al. (2012), so  $P(\text{HotJup}|\text{InsideIceJup}) = (10 - 1)/[836(1 - 0.039)] = 0.011^{+0.004}_{-0.004}$ . Once again using Equation (3) with InsideIceJup in place of LongPerJup, we find that  $P(\text{InsideIceJup}|\text{HotJup}) = 0.055^{+0.061}_{-0.033}$ .

To complete the test of the high-eccentricity migration scenario, we need to compare  $P(\text{LongPerJup}|\text{HotJup})$  for hot Jupiters to  $P[\text{LongPerJup}|\text{Jup}(P_{\text{orb}})]$ , where

$P[\text{LongPerJup}|\text{Jup}(P_{\text{orb}})]$  is the occurrence of long-period Jovian companions to Jovian planets at an arbitrary period  $P_{\text{orb}}$ . In this way we can evaluate  $P[\text{LongPerJup}|\text{Jup}(P_{\text{orb}})]$  for warm Jupiters and compare it to the corresponding conditional probability for hot Jupiters. Because the sample in Wright et al. (2012) is specific to hot Jupiters, in the general calculation we only use the sample of multiple-giant-planet systems described in Section 2 and the data in Table 1 of Cumming et al. (2008). We define an arbitrary period  $P_{\text{cut}}$  that separates warm giant planets from their longer-period companions. We also define a minimum mass  $M_{\text{in}}$  for giant planets inside of  $P_{\text{cut}}$  and a minimum mass  $M_{\text{out}}$  for giant planets outside of  $P_{\text{cut}}$ .

Using the exoplanet sample from `exoplanets.org`, first we calculate  $N_{\text{comp}}$ , the number of multiple-planet systems with at least one component with  $M > M_{\text{in}}$  and  $P_{\text{orb}} < P_{\text{cut}}$  as well as a long-period companion at  $P_{\text{cut}} < P_{\text{orb}} < P_{\text{out}}$ , where  $P_{\text{out}}$  is the  $M_{\text{out}}$ -dependent completeness limit from Cumming et al. (2008). We next calculate  $N_{\text{in}}$ , the number of systems with at least one component with  $M > M_{\text{in}}$  and  $P_{\text{orb}} < P_{\text{cut}}$ . Finally, we calculate  $N_{\text{out}}$ , the number of systems with at least one component with  $M > M_{\text{out}}$  and  $P_{\text{cut}} < P_{\text{orb}} < P_{\text{out}}$ . We calculate  $P[\text{Jup}(P_{\text{orb}})]$  and  $P(\text{LongPerJup})$ —the giant planet occurrence rates inside and outside of  $P_{\text{cut}}$ —by two-dimensional interpolation of Table 1 from Cumming et al. (2008). By the axioms of probability,  $P(\text{LongPerJup}') = 1 - P(\text{LongPerJup})$  and  $P[\text{Jup}(P_{\text{orb}})|\text{LongPerJup}] = N_{\text{comp}}/N_{\text{out}}$ . The effective size of our multiple-giant-planet sample is  $N_{\text{out}}/P(\text{LongPerJup})$ , implying

$$P(\text{LongPerJup}') = \frac{N_{\text{in}} - N_{\text{comp}}}{N_{\text{out}} [1/P(\text{LongPerJup}) - 1]}. \quad (4)$$

The probability that a warm Jupiter has a long-period companion  $P[\text{LongPerJup}|\text{Jup}(P_{\text{orb}})]$  is then

**Table 2**Occurrence of Long-period Companions with  $a < 5$  au to Short-period Giant Planets

Probability	Hot Jupiter <sup>a</sup>	Warm Jupiter <sup>b</sup>	Mild Jupiter <sup>c</sup>
$P[\text{Jup}(P_{\text{orb}})]$	$0.012^{+0.004}_{-0.003}$	$0.038^{+0.010}_{-0.008}$	$0.036^{+0.009}_{-0.008}$
$P(\text{LongPerJup})$	$0.085^{+0.013}_{-0.012}$	$0.080^{+0.013}_{-0.012}$	$0.070^{+0.012}_{-0.011}$
$P(\text{LongPerJup}')'$	$0.915^{+0.013}_{-0.012}$	$0.920^{+0.012}_{-0.013}$	$0.930^{+0.011}_{-0.012}$
$P[\text{Jup}(P_{\text{orb}}) \text{LongPerJup}]$	$0.020^{+0.014}_{-0.010}$	$0.100^{+0.029}_{-0.024}$	$0.213^{+0.043}_{-0.038}$
$P[\text{Jup}(P_{\text{orb}}) \text{LongPerJup}']$	$0.010^{+0.004}_{-0.003}$	$0.036^{+0.005}_{-0.005}$	$0.053^{+0.006}_{-0.006}$
$P[\text{LongPerJup} \text{Jup}(P_{\text{orb}})]$	$0.155^{+0.110}_{-0.077}$	$0.195^{+0.057}_{-0.049}$	$0.231^{+0.054}_{-0.048}$

**Notes.**<sup>a</sup> Defined as a planet with  $M_p \sin i > 0.1 M_{\text{Jup}}$  and  $P_{\text{orb}} < 10$  days.<sup>b</sup> Defined as a planet with  $M_p \sin i > 0.1 M_{\text{Jup}}$  and  $10 \text{ days} < P_{\text{orb}} < 100 \text{ days}$ .<sup>c</sup> Defined as a planet with  $M_p \sin i > 0.3 M_{\text{Jup}}$  and  $10 < P_{\text{orb}} < 365 \text{ days}$ .**Table 3**Occurrence of Long-period Companions with  $a < 1.6$  au to Short-period Giant Planets

Probability	Hot Jupiter <sup>a</sup>	Warm Jupiter <sup>b</sup>	Mild Jupiter <sup>c</sup>
$P[\text{Jup}(P_{\text{orb}})]$	$0.012^{+0.004}_{-0.003}$	$0.039^{+0.009}_{-0.008}$	$0.036^{+0.009}_{-0.008}$
$P(\text{LongPerJup})$	$0.039^{+0.009}_{-0.008}$	$0.029^{+0.008}_{-0.007}$	$0.016^{+0.007}_{-0.005}$
$P(\text{LongPerJup}')'$	$0.961^{+0.009}_{-0.008}$	$0.971^{+0.007}_{-0.007}$	$0.984^{+0.005}_{-0.007}$
$P[\text{Jup}(P_{\text{orb}}) \text{LongPerJup}]$	$0.016^{+0.016}_{-0.009}$	$0.070^{+0.032}_{-0.025}$	$0.195^{+0.069}_{-0.058}$
$P[\text{Jup}(P_{\text{orb}}) \text{LongPerJup}']$	$0.011^{+0.004}_{-0.004}$	$0.022^{+0.003}_{-0.003}$	$0.037^{+0.004}_{-0.004}$
$P[\text{LongPerJup} \text{Jup}(P_{\text{orb}})]$	$0.055^{+0.061}_{-0.033}$	$0.086^{+0.046}_{-0.034}$	$0.078^{+0.042}_{-0.031}$

**Notes.**<sup>a</sup> Defined as a planet with  $M_p \sin i > 0.1 M_{\text{Jup}}$  and  $P_{\text{orb}} < 10$  days.<sup>b</sup> Defined as a planet with  $M_p \sin i > 0.1 M_{\text{Jup}}$  and  $10 \text{ days} < P_{\text{orb}} < 100 \text{ days}$ .<sup>c</sup> Defined as a planet with  $M_p \sin i > 0.3 M_{\text{Jup}}$  and  $10 < P_{\text{orb}} < 365 \text{ days}$ .

$$P[\text{LongPerJup}|\text{Jup}(P_{\text{orb}})] = \frac{P[\text{Jup}(P_{\text{orb}})|\text{LongPerJup}]P(\text{LongPerJup})}{P[\text{Jup}(P_{\text{orb}})|\text{LongPerJup}]P(\text{LongPerJup}) + P[\text{Jup}(P_{\text{orb}})|\text{LongPerJup}']P(\text{LongPerJup}')}. \quad (5)$$

Figure 4 shows a comparison between the hot Jupiter and warm Jupiter companion probabilities as a function of  $M_{\text{in}}$  and  $P_{\text{cut}}$ . There is no evidence that hot Jupiters are less likely to have long-period giant-planet companions than cooler Jupiters, either inside the water–ice line or out to 5 au. We give sample values in Tables 2 and 3.

## 4. DISCUSSION

We have shown that hot Jupiters are just as likely as cooler Jupiters to have long-period Jupiter-mass companions. This observation applies both for companions inside the water–ice line and out to the completeness limit of long-term Doppler surveys. Our estimate of the fraction of warm Jupiters that have long-period giant-planet companions  $P[\text{LongPerJup}|\text{Jup}(P_{\text{orb}})] \approx 0.2$  is consistent with the multiplicity rate determined by previous studies (e.g., Wright et al. 2007, 2009). These results are inconsistent with the expectation from the simplest models of high-eccentricity migration that suggest that most giant planets form beyond the water–ice line, lose angular momentum to another body in the system, have their eccentricities excited to  $e \gtrsim 0.9$ , lose orbital energy to tidal decay, and circularize in the close proximity of their host stars.

How can one reconcile these findings with the previous work by Latham et al. (2011) and Steffen et al. (2012), which found that giant-planet sized *Kepler* planet candidates are less likely to have additional transiting planets in the system or measurable transit-timing variations (TTVs) than smaller or more distant *Kepler* planet candidates? One possibility is that many of the giant-planet sized *Kepler* planet candidates considered by Latham et al. (2011) and Steffen et al. (2012) may have been false positives. Santerne et al. (2012, 2016) have shown that more than 50% of the giant-planet sized *Kepler* planet candidates are false positives of some kind, and false positives are not likely to show evidence for additional transiting planets or TTVs. More generally, those previous studies were based on samples of transiting planets that are more strongly biased toward close-in planets and companions.

Many of the other observations usually cited in support of high-eccentricity migration are also being reexamined. The reality of the three-day pile-up of hot Jupiters, first identified in Cumming et al. (1999), seemed questionable in light of the

*Kepler* giant planet candidate discoveries (e.g., Youdin 2011; Howard et al. 2012; Fressin et al. 2013). More recently, the existence of a peak in the period distribution was identified in a sample of confirmed *Kepler* giant planets through the groundbreaking work of Santerne et al. (2012, 2016). However the observations are compatible with a rather broad peak, over the range  $1 \text{ day} \lesssim P_{\text{orb}} \lesssim 10 \text{ days}$ , and a narrower period valley than had been previously thought. A broad pile-up and a narrow period valley would be difficult to reconcile with high-eccentricity migration and tidal circularization, as those models predict a sharp peak at twice the tidal radius  $r_t = R_p (M_*/M_p)^{1/3}$  followed by a broad period valley. The broader three-day pile-up can be accommodated in the disk migration scenario (e.g., Ida & Lin 2004).

The existence of significant spin–orbit misalignment can also be explained without high-eccentricity migration. Some candidates mechanisms are star formation itself, hydrodynamic disk–planet or magnetic star–disk interactions, torques from distant stellar companions, or even stochastic rearrangement of angular momentum mediated by gravity waves within hot stars (e.g., Tremaine 1991; Innanen et al. 1997; Thommes & Lissauer 2003; Bate et al. 2010; Foucart & Lai 2011; Lai et al. 2011; Thies et al. 2011; Batygin 2012; Rogers et al. 2012; Storch et al. 2014; Fielding et al. 2015).

While we have argued that our measurement is inconsistent with the expectation from simple models of high-eccentricity migration, our result is consistent with models such as those proposed by Guillochon et al. (2011) that require significant disk migration before eccentricity excitation. It is also consistent with both the classical disk migration scenario and the current generation of in situ formation models (e.g., Lin et al. 1996; Batygin et al. 2015; Boley et al. 2016).

## 5. CONCLUSIONS

We found that hot Jupiters are just as likely as cooler giant planets to have long-period Jupiter-mass companions. This results applies to long-period giant-planet companions both inside and outside the water–ice line. This observation is not expected if hot Jupiters are produced by high-eccentricity migration and therefore emphasizes the importance of either

disk-driven migration or in situ formation for the existence of short-period giant planets.

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