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THE FREQUENCY OF HOT JUPITERS ORBITING NEARBY SOLAR-TYPE STARS*

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ABSTRACT

We determine the fraction of F, G, and K dwarfs in the solar neighborhood hosting hot Jupiters as measured by the California Planet Survey from the Lick and Keck planet searches. We find the rate to be 1.2% ± 0.38%, which is consistent with the rate reported by Mayor et al. from the HARPS and CORALIE radial velocity (RV) surveys. These numbers are more than double the rate reported by Howard et al. for *Kepler* stars and the rate of Gould et al. from the OGLE-III transit search; however, due to small number statistics these differences are of only marginal statistical significance. We explore some of the difficulties in estimating this rate from the existing RV data sets and comparing RV rates to rates from other techniques.

Key words: planetary systems – techniques: radial velocities

1. INTRODUCTION

Hot Jupiters are rare objects, a fact obscured by the relative ease with which they seem to be detected today, and the attention they deservedly gather. The first exoplanet discovered orbiting a Sun-like star, 51 Peg *b*, was such a close-in giant planet (Mayor & Queloz 1995), and many of the most interesting and informative members of the exoplanet menagerie are transiting hot Jupiters. As a result of the success of ground-based transit surveys, which are sensitive to almost no other kind of planet, the fraction of hot Jupiters among all known planets is approximately 20% (as determined from the Exoplanet Orbit Database (EOD); Wright et al. 2011). While the overall occurrence rate of planets can be high (with 25% or more of metal-rich or massive stars having detected planets; Santos et al. 2001; Fischer & Valenti 2005; Johnson et al. 2010a), only ∼7% of radial velocity (RV) detected planets are hot Jupiters.

The *Kepler* mission (Borucki et al. 2010) has independently measured the rate of transiting hot Jupiters orbiting 58,041 stars, which Howard et al. (2011) find to be 5 ± 1 per thousand stars. They note that this is only 40% of the rate of 1.2% ± 0.1% (or 12 ± 1 per thousand dwarfs) found by Marcy et al. (2005) from RV searches.

The overall rate of hot Jupiters is an important constraint on theories of their origin, as are any differences in the hot Jupiter rate among various stellar populations. It is therefore interesting and potentially significant that the rate reported by RV surveys appears to be in strong conflict with the rate reported by *Kepler*.

Herein, we perform a new analysis of the hot Jupiter occurrence rate from the Lick and Keck planet searches for comparison with the *Kepler*, and compare this rate to that found in other RV and transit searches.

2. THE CPS SAMPLE (THE DENOMINATOR)

The California Planet Search (CPS) has been operating since 1988 at Lick Observatory and since 1995 at Keck Observatory. The initial target lists comprised stars carefully selected to be bright, single, chromospherically quiet, and to span a range of spectral types. We have added target lists over the years through many programs, including programs to monitor low-mass stars (the Keck M-dwarf survey and M2K; Johnson et al. 2010c; Apps et al. 2010), intermediate-mass stars ("Retired A Stars"; Johnson et al. 2007), high-metallicity stars (N2K; Fischer et al. 2005), active stars, SIM reference stars, Kepler targets, systems discovered by transit (e.g., the HATNet targets; Bakos et al. 2007), planetary systems discovered by RVs by other groups, and many other purposes. Today, this master list of targets has been observed at a variety of cadences, resulting in a range of sensitivities to exoplanets that varies strongly with planetary parameters and from star to star.

Fortunately, the detection of hot Jupiters with precise RVs does not require intense observation. Fischer et al. (2005) showed that hot Jupiters could be reliably identified with only three or four observations spaced over a few days, since their periods are short and amplitudes are high. We can thus crudely, but not inaccurately, identify those stars for which we could detect hot Jupiters, should they exist, simply from the number of observations we have made. This metric is not perfect; stars discovered to be spectroscopic binaries or highly active (and thus having large stochastic RV variations) might be observed only five or six times before being dropped from our program and yet still harbor an undetected hot Jupiter. Based on our extensive familiarity with our program, we judge the number of such systems in the following discussion to be an insignificant contributor to our error budget.

Since most stars in our sample have been observed much more than six times, we are essentially complete to hot Jupiters. In principle, we will have some very small contamination from face-on binaries and miss some number of face-on hot Jupiters. These effects work in opposite directions and are both very small compared to the Poisson noise in our sample; we neglect them here.

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[*] Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the University of California and the California Institute of Technology.

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Table 1
Radial Velocity-detected Hot Jupiters

Planet	$M \sin i (M_{\rm Jup})$	$B - V$	V	P (d)	Distance (pc)	First Reference[a]	Sample[b]
υ And *b*	0.669 ± 0.026	0.536	4.1	4.6	13.492 ± 0.035	Butler et al. (1997)	In primary sample
τ Boo *b*	4.12 ± 0.15	0.508	4.5	3.3	15.618 ± 0.046	Butler et al. (1997)	In primary sample
51 Peg *b*	0.461 ± 0.016	0.666	5.45	4.2	15.608 ± 0.093	Mayor & Queloz (1995)	Included in primary sample
HD 217107 *b*	1.401 ± 0.048	0.744	6.17	7.1	19.86 ± 0.15	Fischer et al. (1999)	In primary sample
HD 185269 *b*	0.954 ± 0.069	0.606	6.67	6.8	50.3 ± 1.4	Johnson et al. (2006a)	In primary sample
HD 209458 *b*	0.689 ± 0.024	0.594	7.65	3.5	49.6 ± 2.0	Henry et al. (2000); Charbonneau et al. (2000)	In primary sample
HD 189733 *b*	1.140 ± 0.056	0.931	7.67	2.2	19.45 ± 0.26	Bouchy et al. (2005)	Included in primary sample
HD 187123 *b*	0.510 ± 0.017	0.661	7.83	3.1	48.3 ± 1.2	Butler et al. (1998)	In primary sample
HD 46375 *b*	0.2272 ± 0.0091	0.860	7.91	3.0	34.8 ± 1.1	Marcy et al. (2000)	In primary sample
HD 149143 *b*	1.328 ± 0.078	0.714	7.89	4.0	62.0 ± 3.2	Fischer et al. (2006); da Silva et al. (2006)	In primary sample
HD 88133 *b*	0.299 ± 0.027	0.810	8.01	3.4	81.4 ± 5.8	Fischer et al. (2005)	In expanded sample
HD 102956 *b*	0.955 ± 0.048	0.971	8.02	6.5	126 ± 13	Johnson et al. (2010b)	In expanded sample
HD 109749 *b*	0.275 ± 0.016	0.680	8.08	5.2	56.3 ± 4.0	Fischer et al. (2006)	In expanded sample
HD 49674 *b*	0.1016 ± 0.0082	0.729	8.1	4.9	44.2 ± 1.7	Butler et al. (2003)	In expanded sample
HD 179949 *b*	0.902 ± 0.033	0.548	6.25	3.1	27.55 ± 0.53	Tinney et al. (2001)	Excluded from primary sample
HD 168746 *b*	0.245 ± 0.017	0.713	7.95	6.4	42.7 ± 1.4	Pepe et al. (2002)	Excluded from primary sample
HD 102195 *b*	0.453 ± 0.021	0.835	8.07	4.1	29.64 ± 0.73	Ge et al. (2006)	Excluded from expanded sample
HD 73256 *b*	1.869 ± 0.083	0.782	8.08	5.2	37.76 ± 0.91	Udry et al. (2003)	Excluded from expanded sample
HD 149026 *b*	0.360 ± 0.016	0.611	8.16	2.9	79.4 ± 4.4	Sato et al. (2005)	Outside sample
HD 68988 *b*	1.80 ± 0.10	0.652	8.2	6.3	54.5 ± 2.3	Vogt et al. (2002)	Outside sample
HD 83443 *b*	0.396 ± 0.018	0.811	8.23	3.0	41.2 ± 1.2	Butler et al. (2002)	Outside sample
HIP 14810 *b*	3.87 ± 0.13	0.777	8.52	6.7	53.4 ± 3.6	Butler et al. (2006); Wright et al. (2009)	Outside sample
HD 86081 *b*	1.496 ± 0.050	0.664	8.73	2.1	95.3 ± 9.0	Johnson et al. (2006b)	Outside sample
BD -10 3166 *b*	0.430 ± 0.017	0.903	10.08	3.5	80.0 ± 8.0	Butler et al. (2000)	Outside sample

Notes.
[a] First refereed source of orbital elements; taken from the Exoplanet Orbit Database (Wright et al. 2011).
[b] See the text for more specific sample definitions.

We cannot construct a target list that is perfectly statistically matched to the *Kepler* targets, not least because those targets have not been perfectly characterized; the Kepler Input Catalog provided crude temperatures and luminosity classes but is not, and was never intended to be, a precise tool (Brown et al. 2011). Nonetheless, we can make a somewhat clean comparison to the *Kepler* sample by mimicking certain aspects of that survey.

We have first performed a magnitude cut at $V < 8$ (we use magnitudes from *Hipparcos* (Perryman & ESA 1997) throughout this work). This cut removes all stars added to our target list as part of follow-up to transit search programs (the brightest transit-discovered planet, WASP-33, has $V = 8.3$ (Christian et al. 2006)). This magnitude cut is near our completeness limit for predominantly old, cool, and single dwarf and subgiant stars easily accessible from Lick and Keck Observatories. This also generates a Malmquist bias (Malmquist 1920) that favors evolved and metal-rich stars at any given color. We discuss the degree to which this bias also exists in the other samples we consider in Section 5.

In order to make a fair comparison with other works, we perform a color cut at $B - V < 1.2$ to exclude very cool stars, which are not well represented in the *Kepler* or CORALIE samples (though the Gould et al. 2006 result does include these lower-mass stars). We note that the giant planet frequency around M dwarfs appears to be lower than that of FGK stars (Johnson et al. 2010a; Bonfils et al. 2011), and so it is appropriate to exclude them here.

Finally, we perform an evolution cut, including only dwarf and subgiant stars (those whose height is above the main sequence $\Delta M_{\rm V} < 2.5$ mag, using the main-sequence fit of Wright 2005).

Of the remaining stars on our target list, 836 have a number of observations at any one telescope $N_{\rm obs} \geqslant 5$. Four observations should be sufficient, in principle, to detect a hot Jupiter; we explore the sensitivity of our results to $N_{\rm obs}$ below.

3. THE HOT JUPITERS (THE NUMERATOR)

We use the EOD at http://exoplanets.org (Wright et al. 2011) to determine the number of planets in our sample. The EOD contains only planets with well-determined orbits described in peer-reviewed journals. We define a planet as being a hot Jupiter in our sample if it orbits one of the stars in our denominator (Section 2), the EOD lists it, and it has $P < 10$ d and $M \sin i > 0.1\ M_{\rm Jup}$. We list all planets meeting these criteria in Table 1.

Because *Kepler* measures planetary radius, and not mass, a perfect comparison of the samples is not possible until all of the *Kepler* planets have masses measured through RV or other studies. We have chosen 0.1 $M_{\rm Jup}$ as a lower mass limit for "hot Jupiter" to most closely match the Cumming et al. (2008) analysis, and because the term "hot Jupiter" has traditionally referred to such massive planets, and not to presumed "ice giants" with $M < 0.1\ M_{\rm Jup}$.

This mass limit corresponds to a radius limit of 8 $R_\oplus$ as adopted by Howard et al. (2011) for densities of 1.4 g cc^{-1}, typical of gas giants with small rocky cores. Clearly, it is impossible to associate a given mass limit with a precise radius limit, as the densities of such planets range from 0.1 to 1.4 g cc^{-1}. But lower densities imply larger radii, and so all such planets will be included in the Howard et al. (2011) sample of hot Jupiters from *Kepler*.

Table 2
Hot Jupiter Rate from Previous Works

Work	Rate (per thousand)	Sample
Gould et al. (2006)	$3.1^{+4.3}_{-1.8}$	OGLE-III Transits (90% confidence limits, $P < 5$ d)
Howard et al. (2011)	5 ± 1	Kepler Transits
Marcy et al. (2005)	12 ± 1	Keck, Lick, and AAT RVs
Cumming et al. (2008)	15 ± 6	Keck RVs (entire target list)
Mayor et al. (2011)	8.9 ± 3.6	HARPS and CORALIE RVs
This work	12.0 ± 3.8	Keck and Lick RVs

To get a sense of how our sample limits affect our statistics, we have divided hot Jupiter hosts into two samples. Stars in our primary sample satisfy our stellar cuts and were in our Keck and Lick samples before the discovery of planets orbiting them. They unambiguously represent hot Jupiters detected in our sample.

Two special cases are 51 Peg and HD 189733. While 51 Peg was not in our original Lick target list, the star is sufficiently bright that it would certainly have eventually been included in the Lick and Keck planet searches, even if its planet had not been discovered by Mayor & Queloz. Similarly, while HD 189733 was not first announced by our team, we were following the target and had detected the planet when Bouchy et al. (2005) announced it. It would be thus inappropriate to ignore these planets from our statistics, and so we include them in our primary sample.

Stars in our expanded sample are those just beyond our cutoff, extending into $8.0 < V \leqslant 8.1$ and $1.2 < B - V < 1.25$. The number of stars in our sample that we would have under this expanded definition is $N_{\rm obs} \geqslant \{4, 5, 6\} = \{965, 906, 843\}$. There are five extended sample hot Jupiters in Table 1.

For completeness, we also include in Table 1 the hot Jupiters orbiting stars that lie outside our sample's various cuts, or that we excluded because their hosts were added to our target list only after a planet was discovered by another team.

4. THE FREQUENCY OF HOT JUPITERS (THE RATIO)

We choose to use only primary sample stars with five or more measurements for our analysis, yielding a hot Jupiter frequency of $10/836$ or 12.0 ± 3.8 per thousand stars.[7]

Our sample cutoffs in color, evolutionary state, and magnitude were chosen to be round numbers. The inclusion of the 906 stars with $N_{\rm obs} \geqslant 5$ from the extended sample (and their planets) gives a sense of how sensitive our numbers are to these limits. Our expanded sample then includes four additional planets, and the implied rate in our expanded sample is thus 15.5 ± 4.1 per thousand. We note that HD 109749 and HD 88133 were added to our sample as part of the N2K program, which targeted metal-rich (and thus planet-rich) stars, and HD 102956 was added as part of the "Retired A Stars" program which, in retrospect, similarly targets planet-rich stars, though they may lack many hot Jupiters. This expanded sample, which shows an additional 3.5 hot Jupiters per thousand stars, is thus probably not representative of field FGK dwarfs, which explains its slightly higher hot Jupiter detection fraction.

Finally, we can vary the minimum number of observations we require of a star in order for our RV survey to be sensitive to hot Jupiters. The number of stars in our sample is $\{890, 836, 785\}$ for $N_{\rm obs} \geqslant \{4, 5, 6\}$, implying a hot Jupiter rate of $\{11.2, 12.0, 12.7\}$ for these values. From the spread in these values we estimate a systematic error of ~0.7 per thousand stars from this consideration.

We thus estimate that the true rate of hot Jupiter detections around FGK dwarfs and subgiants in our sample is 1.20% ± 0.38%, with some small, additional contribution of systematic error of order 0.07% from our choices for $N_{\rm obs}$, and some potentially larger systematic error stemming from our sample cuts. Certainly this rate could be more robustly determined, but we note that the random Poisson errors here are at least as large as these systematic errors, and so the latter probably do not warrant significant further refinement.

5. COMPARISON WITH EARLIER RESULTS AND OTHER SURVEYS

We summarize the hot Jupiter rates implied by various surveys and published analyses in Table 2, and describe them in more detail below.

5.1. Transit Surveys

Transit surveys are not, of course, complete to hot Jupiters because they require edge-on geometry, but the assumption of isotropy of the ensemble of orbital planes makes the calculation a true hot Jupiter rate straightforward (but hardly trivial, see, e.g., Gaudi et al. 2005). The most thorough calculations of the transit-survey hot Jupiter rate are those from OGLE-III and *Kepler*.

Both surveys may probe a significantly different population than the RV surveys. For instance, based on stellar population models of the Milky Way, Gould et al. (2006) calculate that the magnitude limits imposed in transit surveys may produce a sample with a significantly different metallicity distribution than would be seen in an RV survey of nearby stars. They estimate that, compared to the true metallicity distribution in the Galaxy, RV survey samples will be overrepresented by 20% for every 0.1 dex in [Fe/H] from the Malmquist bias if magnitude cuts are made in discrete bins of $B - V$. They predict that the OGLE-III sample should exhibit a similar but smaller overrepresentation of metal-rich stars of 2% per dex in [Fe/H]. If this is correct, then transit surveys like OGLE and *Kepler* probe a lower-metallicity population, on average, than RV surveys.

5.1.1. OGLE-III

Gould et al. (2006) reported the hot Jupiter rate implied by the OGLE-III transit survey to be $3.1^{+4.3}_{-1.8}$ (90% confidence limits) hot Jupiters per thousand stars. In this study, a "hot Jupiter" was any detection with $P = 3$–5 d. OGLE surveyed 52,000 stars toward the Galactic center and 103,000 stars toward Carina, with sensitivity to planets down to $\sim 1\ R_{\rm Jup}$, and rapidly decreasing sensitivity below this level. Like in our analysis, Gould et al. (2006) restricted their calculation to main-sequence stars, but with a cutoff of $V < 17.5$ mag (while many subgiants and giants

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[7] Our analysis is simplified by the fact that there are no systems in our sample with *multiple* hot Jupiters.

were observed in the survey, the larger radii of these stars make planet detection around them impossible and so they were not considered). If we calculate our hot Jupiter rate using a similar cutoff of $P < 5$ d, we find a rate of 9.6 per thousand, still over three times the OGLE rate.

5.1.2. Kepler

Howard et al. (2011) reported that the occurrence rate from *Kepler* is based on an analysis of 58,041 GK dwarfs in the larger 156,000 *Kepler* sample. They find the frequency of giant ($R_P = 8$–$32\ R_\oplus$) planets with periods $P < 10$ d to be 4 ± 1 per thousand stars of magnitude $K_p < 15$, and 5 ± 1 per thousand stars with $K_p < 16$.

The *Kepler* field is centered at $b = +13\overset{\circ}{.}3$, so the distant stars it probes (sitting several hundreds of parsecs from Earth) will have significant heights above the galactic plane, potentially distinguishing that population from that in the RV surveys by age and, possibly, metallicity.

5.2. Radial Velocity Surveys

The RV surveys described here can be roughly divided into two broad collaborations, each encompassing multiple programs and teams: efforts by members of the Keck, Lick, and Anglo-Australian Planet Searches, and the European/Geneva efforts with the ELODIE, CORALIE, SOPHIE, and HARPS spectrographs. The target lists of these searches have some overlap (since they target the brightest stars) but their methodologies and analysis procedures are independent. We describe the most important three prior measurements of the hot Jupiter rate around nearby dwarfs here.

5.2.1. Marcy et al. (2005)

The overall rate of hot Jupiters among FGK dwarfs surveyed by RV was estimated by Marcy et al. (2005) to be $1.2\% \pm 0.1\%$ (12 ± 1 per thousand). This study analyzed 1330 stars from the Lick, Keck, and Anglo-Australian Planet Searches, and counted the number of detections of planets of any minimum mass with semimajor axis $a < 0.1$ AU. The Marcy et al. study is thus similar to our analysis here in that it employs a similar sample of stars and RVs, but has some methodological differences.

Marcy et al. used a well-defined initial sample, but the planets included had no specified cutoff at $M \sin i > 0.1\ M_{\rm Jup}$, and so included a small number of planets with significantly lower masses than those considered here (and presumably significantly smaller than the 8 $R_\oplus$ cutoff used by Howard et al. 2011). Marcy et al. also included the Anglo-Australian Telescope (AAT) planet search, where we do not. Despite those differences, we find an identical result in our analysis, but with more conservative uncertainties.

5.2.2. Cumming et al. (2008)

Cumming et al. (2008) performed a careful analysis of the detectability of target stars in the Keck planet search to determine the distribution of planets in the minimum-mass-period plane, and found that 15 ± 6 stars in a thousand harbor a planet with $M \sin i > 0.3\ M_{\rm Jup}$ and $P < 11.5$ d, and 20 ± 7 stars in a thousand for planets with $M \sin i > 0.1\ M_{\rm Jup}$.

Cumming et al., however, made no attempt to distinguish among stars added blindly and stars added because they were more likely to have planets (metal-rich stars), or specifically because they had some property not representative of the *Kepler* field (i.e., subgiants), or even because they were already known to have planets. In other words, Cumming et al. determined the hot Jupiter frequency in the Keck sample, but that sample is clearly enriched with respect to the field, which explains their higher hot Jupiter rate. We have avoided these effects without various sample cuts (see Sections 2 and 3).

5.2.3. Mayor et al. (2011)

Most recently, Mayor et al. (2011) used the HARPS and CORALIE RV planet survey to estimate the hot Jupiter occurrence rate as a function of minimum mass and period in their sample of dwarf stars. Their occurrence rate for planets with $M \sin i > 50\ M_\oplus$ and $P < 11$ d is 8.9 ± 3.6 per thousand stars, which is consistent with both *Kepler* and the Marcy et al. results. The different minimum $M \sin i$ and maximum period used between the studies of Marcy et al. and Mayor et al. is not significant here because there is only one planet in the EOD with $30\ M_\oplus < M \sin i < 50\ M_\oplus$ and $P < 10$ d (HD 49674*b*) and only one with both 10d $< P < 11$ d and $V < 8$, and neither host star is in our primary sample. Our statistics would thus be identical if we had adopted the cutoffs of Mayor et al. instead of emulating those of Howard et al.

6. DISCUSSION AND CONCLUSION

The analysis presented here fairly represents, within the Poisson noise, the true hot Jupiter frequency among old FGK dwarfs in the solar neighborhood. We note that our result is not enhanced by high-metallicity stars from the N2K sample, since most of those stars are fainter than those in our primary sample, and especially since only one of our primary sample planets was discovered by that survey (HD 149143).

We decline here to attempt a more rigorous comparison of the Keck and Lick stellar sample, with its heterogeneous selection effects and sensitivities, to the *Kepler* sample. *Kepler*, as noted above, doubtless probes a different stellar population than ours, since those stars were selected from different criteria, lie at a different Galactocentric radius and Galactic height, and so have a different distribution of ages, evolutionary states, binary fractions, and dynamical histories. We also note that our binary star rejection predominantly rejects binaries with separations $<2''$ due to concerns of spectral contamination at the slit. Transit surveys will typically have no such rejection criterion, though they may have a more difficult validation or confirmation procedure for binary stars.

Nonetheless, it is interesting to note that there is some indication that the RV surveys, which probe the solar neighborhood, are consistently finding a hot Jupiter rate at least twice that seen with the transit surveys. Given the differences in the stellar populations of these surveys, this is perhaps not surprising.

The most salient difference between the samples may be metallicity. If the difference in metallicity bias between the RV and transit samples is as severe as Gould et al. (2006) estimate, then the difference in the hot Jupiter rate may simply reflect the difference in giant planet occurrence rate among high- and low-metallicity stars. We point out that the Gould et al. (2006) estimate is based on stellar population models of the Milky Way, and not on a comparison of metallicity measurements between transit and RV samples. The stars in the RV samples are generally well known and well characterized because the stars are known to be single, generally have good parallaxes, and have metallicities measured from spectra and color-absolute magnitude information. A thorough spectroscopic metallicity analysis of a statistically appropriate sample of *Kepler* targets should provide a similar sense of the *Kepler* metallicity distribution, which would help confirm or rule out metallicity as a source of the hot Jupiter rate discrepancy.

We close noting that the apparent RV versus transit hot Jupiter rate discrepancy, while apparently large, is of only marginal statistical significance: the hot Jupiter frequency per thousand stars of the Keck and Lick sample (12.0 ± 3.8) and from the Mayor et al. sample (8.9 ± 3.6) is only 1σ–2σ discrepant from the Gould et al. frequency from OGLE-III transits ($3.1^{+4.3}_{-1.8}$, 90% confidence limits) and with the frequency of 5 ± 1 in the *Kepler* sample found by Howard et al.

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This research has made use of the Exoplanet Orbit Database and the Exoplanet Data Explorer at exoplanets.org.

Facility: Keck:I

Note added in proof: After this manuscript was accepted for publication, we were alerted to the hot Jupiter rate analysis of Bayliss & Sackett (2011) from SuperLupus survey data. They find for $1 < P < 10$ d periods a hot Jupiter rate of $1^{+2.7}_{-0.8}$ per thousand for dwarf stars in the galactic disk, consistent at the 2-σ level with the other transit surveys listed in our work. They also compare hot Jupiter rates found in a broader selection of surveys than we mention here. We regret the oversight and thank Everett Schlawin for bringing it to our attention.

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