

## ON THE PERIOD DISTRIBUTION OF CLOSE-IN EXTRASOLAR GIANT PLANETS

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### ABSTRACT

Transit (TR) surveys for extrasolar planets have recently uncovered a population of “very hot Jupiters,” planets with orbital periods of  $P \leq 3$  days. At first sight this may seem surprising, given that radial velocity (RV) surveys have found a dearth of such planets, despite the fact that their sensitivity increases with decreasing  $P$ . We examine the confrontation between RV and TR survey results, paying particular attention to selection biases that favor short-period planets in TR surveys. We demonstrate that, when such biases and small-number statistics are properly taken into account, the period distributions of planets found by RV and TR surveys are consistent at better than the  $1\sigma$  level. This consistency holds for a large range of reasonable assumptions. In other words, there are not enough planets detected to robustly conclude that the RV and TR short-period planet results are inconsistent. Assuming a logarithmic distribution of periods, we find that the relative frequency of very hot Jupiters (VHJs;  $P = 1\text{--}3$  days) to hot Jupiters (HJs;  $P = 3\text{--}9$  days) is  $\sim 10\%\text{--}20\%$ . Given an absolute frequency of HJs of  $\sim 1\%$ , this implies that approximately one star in  $\sim 500\text{--}1000$  has a VHJ. We also note that VHJs and HJs appear to be distinct in terms of their upper mass limits. We discuss the implications of our results for planetary migration theories as well as present and future TR and RV surveys.

*Subject heading:* planetary systems: formation

### 1. INTRODUCTION

Radial velocity (RV) surveys have yielded a wealth of information about the ensemble physical properties of extrasolar planets. This information, in turn, provides clues to the nature of planetary formation and evolution. The period distribution of planets is particularly interesting in this regard. The very existence of massive planets at periods of  $P \lesssim 10$  days was initially a surprise. Such planets are found around  $\sim 1\%$  of main-sequence FGK stars (Marcy et al. 2004), and have likely acquired their remarkable real estate via migration through their natal disks after they accumulated the majority of their mass. Figure 1 shows the period distribution of short-period extrasolar planets detected in RV surveys. We have included companions with  $M_p \sin i > 0.2M_J$  and  $P \leq 10$  days, corresponding to velocity semiamplitudes of  $K \gtrsim 20 \text{ m s}^{-1}$  for solar-mass primaries and circular orbits; we expect RV surveys in this region of parameter space to be essentially complete. Significantly, roughly half of the 19 planets in this sample with  $P \leq 10$  days have periods in the range  $P \simeq 3\text{--}3.5$  days. There is a sharp cutoff below this pile-up of planets, and there is only one planet with  $P < 3$  days, the companion to HD 73256 with  $P \simeq 2.5$  days.<sup>3</sup> This planet is  $\sim 3\sigma$  away from the clump of planets in the range of  $P = 3\text{--}3.5$  days, and so may be distinct in terms of its genealogy. Because RV surveys are likely to be substantially incomplete for planets with mass  $M_p \sin i \leq 0.1M_J$ , we do not consider the recent RV discoveries of Neptune-mass planets with periods of  $P = 2.644$  days (GJ 436b; Butler et al. 2004),  $P = 2.808$  days (55 Cnc e; McArthur et al. 2004), and  $P = 9.55$  days ( $\mu$  Arae c; Santos et al. 2004).

RV surveys have so far been the most successful extrasolar planet detection technique. Recently, two other planet detection techniques have finally come to fruition, namely, transit (TR) and

microlensing surveys (Bond et al. 2004). In particular, RV follow-up of low-amplitude transits detected by the Optical Gravitational Lensing Experiment (OGLE) collaboration (Udalski et al. 2002a, 2002b, 2002c, 2003) has yielded four bona fide planet detections (Konacki et al. 2003a; Bouchy et al. 2004; Konacki et al. 2004; Pont et al. 2004), and several strong candidates (Konacki et al. 2003b). Recently, the Trans-Atlantic Exoplanet Survey (TrES) collaboration announced the detection of a transiting planet around a relatively bright K0 V star (Alonso et al. 2004). Figure 1 shows the period distribution of both the confirmed and the candidate TR-detected planets, and Table 1 summarizes their properties. Notably, the first three planets detected via transits all have  $P \simeq 1$  day, considerably smaller than the periods of any planets detected via RV, and well below the pile-up and abrupt cutoff seen in the RV period distribution (see Fig. 1). This is perhaps surprising because the sensitivity of RV surveys increases with decreasing period.

This apparent tension between the results of TR and RV surveys begs the question of whether the results from the two techniques are mutually consistent. In this paper we answer this question by considering a simple model for both the statistics and the selection biases of the TR and RV surveys.

### 2. A SIMPLE ARGUMENT

In this section, we present a simple, straightforward argument for our conclusion that RV and TR surveys are essentially consistent. These arguments are presented in more detail in §§ 3 and 4, and in the appendices.

The primary difference between RV and TR surveys is in how their target stars are chosen. RV surveys are essentially “volume limited” and thus have a fixed number of target stars in their sample. Because RV surveys have a fixed sample size, their relative sensitivity as a function of the mass and period depends only on the intrinsic sensitivity of the RV technique. This scales as  $K \propto M_p \sin i P^{-1/3}$ , where the semiamplitude  $K$  characterizes the signal strength. It is possible to define a complete sample of planets by considering an appropriate limit on  $K$ . RV surveys are expected to be essentially complete for  $K \gtrsim 20 \text{ m s}^{-1}$  (Tabachnik &

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<sup>3</sup> Here and throughout, we will assume for simplicity that the companion to HD 83443, which has a best-fit period of  $P = 2.98565 \pm 0.00003$  days (Mayor et al. 2004), actually has a period of  $P = 3$  days.

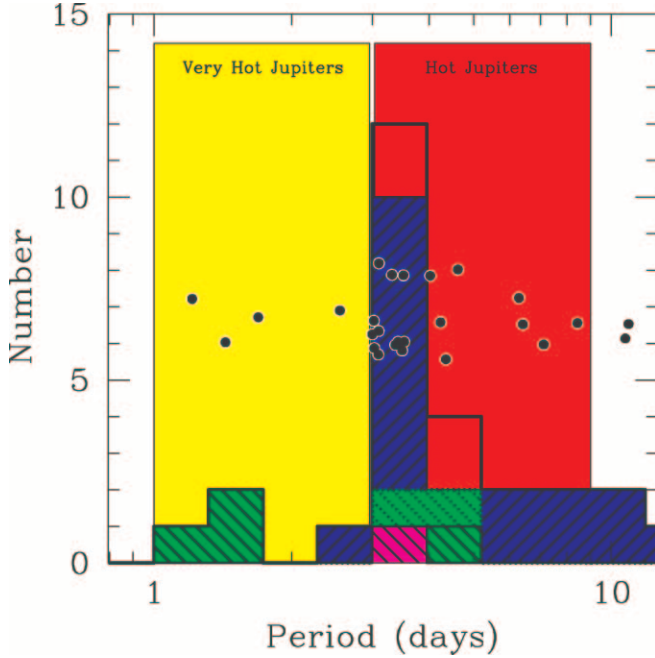


FIG. 1.—Period distribution of short-period extrasolar giant planets. The blue-shaded histogram shows planets with mass  $M_p \sin i > 0.2M_J$  detected via RV surveys, the green-shaded histogram shows planets detected via the OGLE TR surveys, and the magenta-shaded histogram shows the planet detected via the TrES survey. The dotted green-shaded histogram shows the periods of the two unconfirmed candidate transiting planets with  $P \geq 3$  days (Konacki et al. 2003b). The unshaded histogram shows all planets. The yellow and red bands indicate the period ranges for our fiducial division into VHJs and HJs, respectively. The black points show the individual periods of the planets; the ordinate values are arbitrary.

Tremaine 2002), which corresponds to  $M_p \sin i > 0.2M_J$  and  $P \leq 9$  days for solar-mass primaries and circular orbits. RV surveys indicate that the relative frequency of planets with  $P = 1-3$  days to planets with  $P = 3-9$  days in this complete sample is  $\sim 0.07^{+0.09}_{-0.04}$ , where the errors account for Poisson fluctuations (and are calculated in § 4).

Field TR surveys, in contrast to RV surveys, are signal-to-noise ratio (S/N) limited. As a result, the effective volume probed by TR surveys, and therefore the number of target stars, depends on the total S/N of the transits, which in turn depends on the radius and period of the planets. The basic scaling of the sensitivity of TR surveys with period can be understood as follows. The flux  $F$  of a star is  $F \propto d^{-2}$ , where  $d$  is the distance to the star.

The photometric error  $\sigma \propto F^{-1/2} \propto d$ . The number of data points  $N_p$  during transits is proportional to the duty cycle, which is inversely proportional to the semimajor axis  $a$ . Thus  $N_p \propto a^{-1} \propto P^{-2/3}$ . The total S/N of a transiting planet is  $S/N \propto N_p^{1/2} \sigma^{-1}$  and thus, at fixed S/N,  $\sigma \propto N_p^{1/2} \propto P^{-1/3}$ . Therefore,  $d \propto P^{-1/3}$ , i.e., the distance out to which one can detect a transiting planet at fixed S/N scales as  $P^{-1/3}$ . The number of stars in the survey volume is  $\propto d^3 \propto P^{-1}$ . Combined with the TR probability, which scales as  $a^{-1} \propto P^{-2/3}$ , this implies an overall sensitivity  $\propto P^{-5/3}$ .

Thus, TR surveys are, on average,  $\sim (1/3)^{-5/3} \sim 6$  times more sensitive to planets with  $P = 1$  day than for planets with  $P = 3$  days. The observed relative frequency of planets with confirmed  $P = 1-3$  days to planets with confirmed  $P = 3-9$  days discovered in the OGLE-TR surveys is  $\sim 3$ , which corresponds to an intrinsic relative frequency (after accounting for the factor of 6) of  $\sim 0.5^{+1.5}_{-0.3}$ , as compared to  $\sim 0.07^{+0.09}_{-0.04}$  for the RV surveys. Thus, considering the large errors due to small-number statistics, RV and TR surveys are basically consistent (at better than the  $\sim 2\sigma$  level). If at least one of the remaining OGLE  $P \geq 3$  days planet candidates is confirmed in the future, then TR and RV surveys are consistent at better than  $1\sigma$ . In other words, there are not enough planets detected to robustly conclude that the RV and TR short-period planet results are inconsistent.

As we discuss in more detail in the appendices, there are additional effects that favor the confirmation of shorter-period transiting planets. First, shorter-period planets generally tend to exhibit more transits; this makes their period determinations from the TR data more accurate. Accurate periods aid significantly in RV follow-up and confirmation. Second, shorter-period planets generally have larger velocity semi-amplitudes  $K$ , both because of their smaller periods ( $K \propto P^{-1/3}$ ) and because there appears to be a dearth of massive ( $M_p \sin i \gtrsim M_J$ ) planets with  $P = 3-9$  days (see Fig. 2).

### 3. SELECTION EFFECTS IN TRANSIT SURVEYS

In this section, we present a more detailed derivation of the sensitivity of S/N-limited planet TR surveys as a function of the period and radius of the planet.

Field searches for transiting planets are very different from RV searches, as they are uniform surveys in which the target stars are all observed in the same manner (rather than targeted observations of individual stars). Therefore, the noise properties vary from star to star. As a result, the relative number of planets above a given S/N threshold depends not only on the way in which the intrinsic signal scales with planet properties, but also on the number of stars with a given noise level. Since, for TR

TABLE 1  
PARAMETERS OF CONFIRMED AND CANDIDATE TRANSITING PLANETS

Name	$P$ (days)	$a$ (AU)	$M_p$ ( $M_J$ )	$R_p$ ( $R_J$ )	$M_*$ ( $M_\odot$ )	$R_*$ ( $R_\odot$ )	$I$	$(V - I)$	$N_{TR}$	Reference
OGLE-TR-56	1.2119	0.023	$1.45 \pm 0.23$	$1.23 \pm 0.16$	$1.04 \pm 0.05$	$1.10 \pm 0.10$	15.30	1.26	11	1, 2
OGLE-TR-113	1.4325	0.023	$1.08 \pm 0.28$	$1.09 \pm 0.10$	$0.79 \pm 0.06$	$0.78 \pm 0.06$	14.42	...	10	3, 4
OGLE-TR-132	1.6897	0.031	$1.19 \pm 0.13$	$1.13 \pm 0.08$	$1.35 \pm 0.06$	$1.43 \pm 0.10$	15.72	...	11	3, 5
OGLE-TR-111	4.0161	0.047	$0.53 \pm 0.11$	$1.00^{+0.13}_{-0.06}$	$0.82^{+0.15}_{-0.02}$	$0.85^{+0.10}_{-0.03}$	15.55	...	9	6
OGLE-TR-10 <sup>a</sup>	3.1014	...	$0.70 \pm 0.30$	1.3	...	...	14.93	0.85	4	7
OGLE-TR-58 <sup>a</sup>	4.34	...	$1.60 \pm 0.80$	1.6	...	...	14.75	1.20	2	7
HD 209458	3.5248	0.045	$0.69 \pm 0.05$	$1.42^{+0.10}_{-0.13}$	$1.06 \pm 0.13$	$1.18 \pm 0.10$	...	...	...	8, 9
TrES-1	3.0301	0.039	$0.75 \pm 0.05$	$1.08^{+0.18}_{-0.04}$	$0.88 \pm 0.07$	$0.85^{+0.10}_{-0.05}$	10.64 <sup>b</sup>	1.15 <sup>b</sup>	...	10

<sup>a</sup> Candidate (unconfirmed) planets.

<sup>b</sup> Estimated from the observed  $V$  magnitude and  $J-H$  color.

REFERENCES.—(1) Konacki et al. 2003a; (2) Torres et al. 2004; (3) Bouchy et al. 2004; (4) Konacki et al. 2004; (5) Moutou et al. 2004; (6) Pont et al. 2004; (7) Konacki et al. 2003b; (8) Brown et al. 2001; (9) Cody & Sasselov 2002; (10) Alonso et al. 2004.

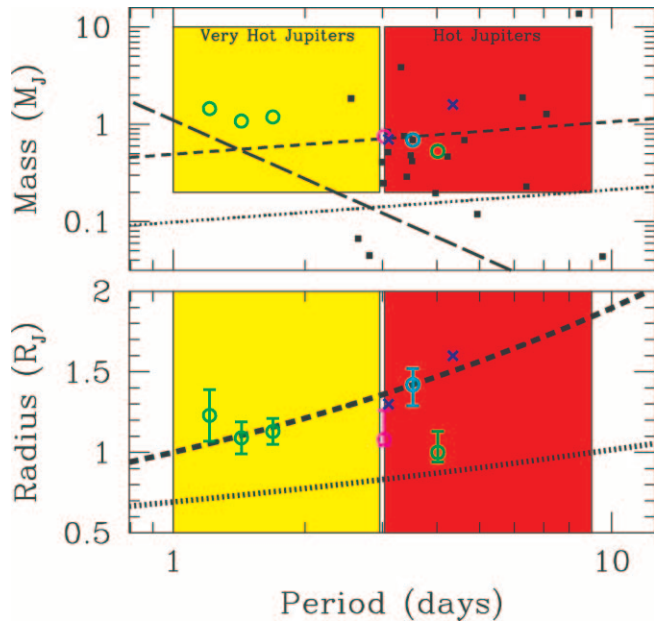


FIG. 2.—Physical properties of short-period extrasolar planets. See Table 1 and references therein. *Top*: The points show the mass  $M_p$  (or  $M_p \sin i$ ) of short-period planets in Jupiter masses ( $M_J$ ) vs. their period  $P$  in days. Black squares are RV-detected planets, green circles are confirmed TR-detected planets, blue crosses are candidate TR-detected planets, the cyan circle is the RV-detected transiting planet HD 209458b, and the magenta circle is the bright transiting planet TrES-1. The dotted line shows  $M_p \sin i$  vs.  $P$  for a RV semi-amplitude of  $K = 20 \text{ m s}^{-1}$  for a planet in a circular orbit and a primary of  $M = M_\odot$ . We assume that RV surveys are complete above this limit, and therefore are complete to masses  $M_p \sin i \geq 0.2M_J$  for  $P \leq 9$  days. The yellow and red bands indicate the period and mass ranges for our division into complete samples of VHJs and HJs, respectively. The short-dashed line corresponds to  $K = 100 \text{ m s}^{-1}$ , roughly appropriate for the follow-up of fainter TR candidate planets. The long-dashed line shows the Roche limit for a planet with radius  $R_p = 2R_J$ . *Bottom*: The circles and crosses show  $R_p$  vs.  $P$  for known transiting planets and candidates. The dashed line shows the contour of the equal number of target stars in the effective TR survey volume, normalized to the number at  $P = 1$  day and  $R_p = R_J$ . The dotted line shows the lower limit on  $R_p$  vs.  $P$  required to achieve a total S/N of 9 for typical light curves from the OGLE surveys. See text for details.

surveys, the noise depends on the flux of the star, which depends on the distance to the star, the effective number of target stars depends on the number of stars in the effective survey volume that is defined by the maximum distance out to which a planet produces a S/N greater than the threshold. This leads to a strong sensitivity of TR surveys on planet period and radius (as well as parent-star mass and luminosity; see Pepper et al. 2003), which we now derive.

The total S/N of a transiting planet can be approximated as

$$S/N = N_p^{1/2} \left( \frac{\delta}{\sigma} \right), \quad (1)$$

where  $N_p$  is the total number of measurements during the transit,  $\delta$  is the depth of the transit, and  $\sigma$  is the fractional flux error for a single measurement. We can approximate  $N_p = N_{\text{tot}}(R_*/\pi a)$  (for a central transit) and  $\delta = (R_p/R_*)^2$ , where  $N_{\text{tot}}$  is the total number of observations,  $a$  is the semimajor axis of the planet, and  $R_*$  is the radius of the parent star. Combining these relations with Kepler’s third law, we have

$$S/N \propto P^{-1/3} R_p^2 \sigma^{-1}. \quad (2)$$

We then estimate the relative sensitivity as follows. Following Pepper et al. (2003), the number of target stars for which a planet of a given  $P$  and  $R_p$  would produce a S/N greater than a given threshold is proportional to

$$\frac{d^2 \mathcal{N}(P, R_p)}{dP dR_p} \propto f(P, R_p) P_T(P) V_{\text{max}}(P, R_p), \quad (3)$$

where  $f(P, R_p) \equiv d^2 n(P, R_p)/dP dR_p$  is the intrinsic frequency of planets as a function of  $P$  and  $R_p$ ,  $P_T(P)$  is the probability that a planet of a given  $P$  will transit its parent star, and  $V_{\text{max}}(P, R_p)$  is the maximum volume within which a planet of a given  $P$  and  $R_p$  can be detected. The geometric transit probability is simply  $P_T \simeq R_*/a \propto P^{-2/3}$ . We assume the form  $V_{\text{max}} \propto F_{\text{min}}^{-3/2}$ , where  $F_{\text{min}}(P, R_p)$  is the minimum flux of a star around which a planet of period  $P$  and radius  $R_p$  can be detected; this form is appropriate for a constant volume density of stars and no extinction. For fixed S/N, we have from equation (2) that  $\sigma \propto P^{-1/3} R_p^2$ . For source-dominated photon noise, we have  $\sigma \propto F_{\text{min}}^{-1/2}$ , and thus  $F_{\text{min}} \propto P^{2/3} R_p^{-4}$  and  $V_{\text{max}} \propto P^{-1} R_p^6$ . Finally, combining this with  $P_T \propto P^{-2/3}$ , we find

$$\frac{d^2 \mathcal{N}}{dP dR_p} \propto f(P, R_p) R_p^6 P^{-5/3}. \quad (4)$$

This strong function of  $P$  implies that the TR surveys are very biased toward detecting short-period planets.

Note that in deriving equation (4), we have made the simplistic assumption that the number of data points during transit is proportional to the duty cycle,  $N_p \propto R_*/\pi a$ . This assumes random sampling and short periods, as compared to the transit campaign. In fact, actual transit campaigns have nonuniform sampling and finite durations. In addition, transit candidates require RV follow-up for confirmation; this introduces additional selection effects. We consider both effects in detail in the appendices.

#### 4. RADIAL VELOCITY VERSUS TRANSITS

We now address the question of whether the period distribution of the planets discovered by RV and TR surveys are consistent, considering both the selection biases discussed in the previous section, as well as the effects of small-number statistics. For our fiducial comparisons, we consider two equal-width logarithmic bins in period with  $(P_{1,\text{min}}, P_{1,\text{max}}) = (1 \text{ day}, 3 \text{ days})$  and  $(P_{2,\text{min}}, P_{2,\text{max}}) = (3 \text{ days}, 9 \text{ days})$ . We argued in § 3 that local RV surveys should be essentially complete for planets with velocity semi-amplitude  $K \gtrsim 20 \text{ m s}^{-1}$ , and therefore if we restrict our analysis to  $M_p \sin i \geq 0.2M_J$ , the observed number of planets detected by RV in these two bins should be an unbiased sample of the true distribution of planets (see Fig. 2). We also restrict our attention to  $M_p \sin i \leq 10M_J$  to avoid possible brown dwarf candidates. The number of RV planets with  $0.2M_J \leq M_p \sin i \leq 10M_J$  in our two fiducial period bins is given in Table 2. There is one planet in the first bin, and 15 in the second. Therefore, the relative frequencies are  $\sim 7\%$ . We denote these two complete samples as “very hot Jupiters” (VHJs) and “hot Jupiters” (HJs), respectively.

For comparison with the RV surveys, we consider the results from the two campaigns by the OGLE collaboration.<sup>4</sup> Pertinent details about the OGLE surveys are summarized in Appendix A. Because the OGLE searches are S/N-limited surveys, as

<sup>4</sup> In this section, we do not consider the recently detected bright transiting planet TrES-1 (Alonso et al. 2004), since the survey details necessary for the statistical analysis are not available.

TABLE 2  
RADIAL VELOCITY VERSUS TRANSITS

Assumption <sup>a</sup>	Range ( $P$ ) (days)	No. RV	No. TR	Range ( $P$ ) (days)	RVs	TRs	$N_1/N_2$ <sup>b</sup>	Probability <sup>c</sup> (%)
Logarithmic .....	1–3	1	3	3–9	15	0	$0.21^{+0.16}_{-0.09}$	12.7
	...	...	...	...	...	1	$0.18^{+0.12}_{-0.08}$	33.1
	...	...	...	...	...	2	$0.15^{+0.10}_{-0.07}$	54.1
	...	...	...	...	...	3	$0.13^{+0.09}_{-0.05}$	70.9
	1–2	0	3	2–4	11	0	$0.25^{+0.21}_{-0.12}$	2.0
	...	...	...	...	...	1	$0.22^{+0.18}_{-0.10}$	6.5
	...	...	...	...	...	2	$0.20^{+0.14}_{-0.09}$	13.3
Linear .....	...	...	...	...	...	3	$0.17^{+0.12}_{-0.08}$	20.7
	1–3	1	3	3–5	12	1	$0.25^{+0.18}_{-0.11}$	22.6

<sup>a</sup> Assumed form for the period distribution.

<sup>b</sup> Inferred intrinsic relative frequency of VHJs and HJs, from the joint RV and TR results.

<sup>c</sup> Probability of observing both RV and TR results at the peak of the distribution of  $N_1/N_2$ .

opposed to the volume-limited RV surveys, it is not possible to define a complete, unbiased sample of observed planets (see the discussion in § 3), and we must take into account the selection biases to infer the true planet frequency. We first assume a frequency distribution  $f(P, R_p)$ . We assume that planets are uniformly distributed in  $\log P$  within each bin, and that all planets in bin  $i$  have radius  $R_{p,i}$ . This gives an intrinsic frequency distribution of

$$f_i(P, R_p) = \frac{d^2 n_i(P, R_p)}{dP dR_p} = \frac{N_i}{\Delta \log P_i} P^{-1} \delta_D(R_p - R_{p,i}), \quad (5)$$

where  $N_i$  is the total number of planets in bin  $i$ ,  $\Delta \log P_i = \log P_{i, \max} - \log P_{i, \min}$  is the logarithmic width of the bin, and  $\delta_D$  is the Dirac delta function. From equation (4), the expected number  $\mathcal{N}_i$  of observed transiting planets in bin  $i$  is

$$\mathcal{N}_i(P, R_p) \propto \int dR_p \int_{P_{i, \min}}^{P_{i, \max}} dP f_i(P, R_p) R_p^6 P^{-5/3}. \quad (6)$$

The constant of proportionality is independent of  $P$  and  $R_p$ , and thus the ratio of the observed number of planets in the two bins is simply

$$\frac{\mathcal{N}_1}{\mathcal{N}_2} = r_{12} \left( \frac{R_{p,1}}{R_{p,2}} \right)^6 \left( \frac{P_{1, \min}}{P_{2, \min}} \right)^{-5/3}, \quad (7)$$

where we have assumed that  $\Delta \log P_1 = \Delta \log P_2$ , and we have defined  $r_{12} = N_1/N_2$ , the ratio of the intrinsic number of planets in the two period bins, i.e., the relative frequency of VHJs and HJs.

For simplicity, we will assume that VHJs and HJs have similar radii on average, and so  $R_{p,1} = R_{p,2}$ . For our period bins, the last factor is  $(1 \text{ day}/3 \text{ days})^{-5/3} \sim 6$ . The number of planets detected by TR surveys in the first bin is  $N_1 = 3$ . There is one confirmed OGLE planet detected by TR in the second bin. This implies an intrinsic relative frequency of VHJs and HJs of  $r_{12} \sim 50\%$ , which is a factor of  $\sim 7$  larger than inferred from RV surveys.

Given the relatively small number of planets in each of our two fiducial period bins, we must account for Poisson fluctuations in order to provide a robust estimate of the relative fre-

quency  $r_{12}$ . In the limit of a large number of trials, the probability  $\mathcal{P}$  of observing  $\mathcal{N}$  planets, given  $\mathcal{M}$  expected planets is

$$\mathcal{P}(\mathcal{N}|\mathcal{M}) = \frac{e^{-\mathcal{M}} \mathcal{M}^{\mathcal{N}}}{\mathcal{N}!}. \quad (8)$$

For large  $\mathcal{M}$ , the probability of observing any particular value of  $\mathcal{N}$  becomes small, simply because of the large number of possible outcomes. We therefore consider relative probabilities  $\tilde{\mathcal{P}}(\mathcal{N}|\mathcal{M}) \equiv \mathcal{P}(\mathcal{N}|\mathcal{M})/\mathcal{P}_{\max}(\mathcal{M})$ , and normalize  $\mathcal{P}(\mathcal{N}|\mathcal{M})$  by the maximum probability  $\mathcal{P}_{\max}(\mathcal{M}) \equiv \max[\mathcal{P}(1|\mathcal{M}), \mathcal{P}(2|\mathcal{M}), \dots, \mathcal{P}(\infty|\mathcal{M})]$  for a given expected number  $\mathcal{M}$ .<sup>5</sup>

We can now construct probability distributions  $\mathcal{P}(r_{12}|\mathcal{N}_1, \mathcal{N}_2)$  of  $r_{12}$ , given the observed numbers  $\mathcal{N}_1$  and  $\mathcal{N}_2$  of VHJs and HJs, and incorporate selection biases and Poisson fluctuations. This probability is

$$\mathcal{P}(r_{12}|\mathcal{N}_1, \mathcal{N}_2) \propto \int d\mathcal{M}_1 \tilde{\mathcal{P}}(\mathcal{N}_1|\mathcal{M}_1) \tilde{\mathcal{P}}(\mathcal{N}_2|\mathcal{M}_2), \quad (9)$$

where  $\mathcal{M}_2$  depends on  $\mathcal{M}_1$  and  $r_{12}$ . For RV, it is simply  $\mathcal{M}_2 = \mathcal{M}_1/r_{12}$ , whereas for TR, it is related via equation (7) (replacing  $\mathcal{N} \rightarrow \mathcal{M}$ ). Note that, up to a constant, equation (9) is equivalent under the transposition  $\mathcal{M}_1 \leftrightarrow \mathcal{M}_2$ , and we could have also integrated over  $\mathcal{M}_2$ .

Figure 3 shows the probability distribution for  $r_{12}$ , normalized to the peak probability, as inferred from RV and TR surveys, assuming that  $\mathcal{N}_2 = 1, 2$ , or 3 of the candidate TR planets with  $P = 3-9$  days are real. The probability distributions peak at the expected value, given the observed numbers of VHJs and HJs. However, owing to Poisson fluctuations, the distributions are quite broad. For example, the RV surveys imply a median and 68% confidence interval of  $r_{12} = 0.07^{+0.09}_{-0.04}$ , whereas the TR surveys with  $\mathcal{N}_{\text{TR},2} = 1$  imply  $r_{12} = 0.5^{+1.5}_{-0.3}$ . Therefore, it is clear that when Poisson fluctuations are taken into account, these two determinations are roughly consistent. Figure 3 also shows the product of the relative probabilities of  $r_{12}$  from the RV and TR surveys. Considering the one confirmed  $P \geq 3$  days OGLE planet ( $\mathcal{N}_{\text{TR},2} = 1$ ), the median and 68% confidence interval for the joint probability distribution is  $r_{12} = 0.18^{+0.12}_{-0.08}$ . The peak

<sup>5</sup> Rather than considering relative probabilities, one might instead consider cumulative probabilities  $\mathcal{P}(<\mathcal{N}|\mathcal{M})$ . We find that these two approaches yield similar results.



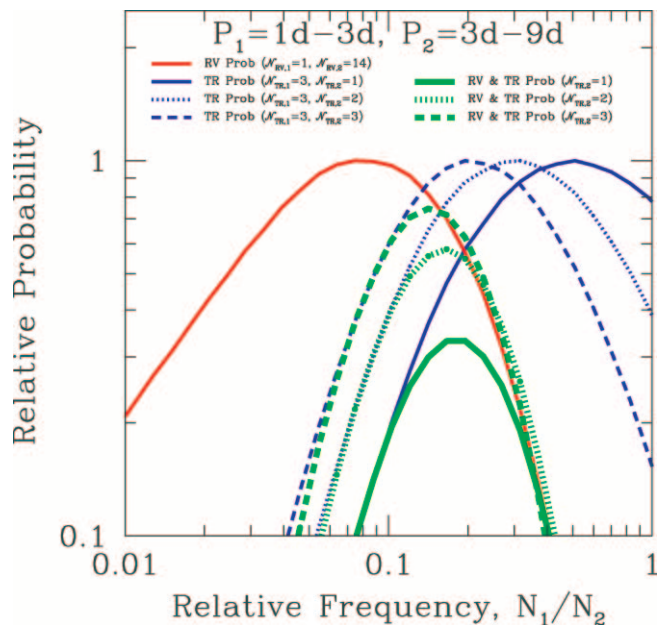


FIG. 3.—Lines showing the relative probability of observing  $\mathcal{N}_1$  planets in the period range  $P_1 = 1-3$  days and  $\mathcal{N}_2$  planets in the period range  $P_2 = 3-9$  days, for an absolute relative frequency of planets in these two period ranges of  $r_{12} \equiv \mathcal{N}_1/\mathcal{N}_2$ , and assuming a uniform logarithmic distribution in  $P$  in each bin. The curves take into account both Poisson fluctuations and period-dependent selection biases. The red curve shows the probability corresponding to the RV surveys, which observe  $\mathcal{N}_{RV,1} = 1$  in the period range  $P_1 = 1-3$  days and  $\mathcal{N}_{RV,2} = 15$  in the period range  $P_2 = 3-9$  days. The blue curves are for the TR surveys for  $\mathcal{N}_{TR,1} = 3$  and  $\mathcal{N}_{TR,2} = 1$  (solid), 2 (dotted), and 3 (dashed). The green curves are joint RV and TR probabilities for  $\mathcal{N}_{RV,1} = 1$ ,  $\mathcal{N}_{RV,2} = 14$ ,  $\mathcal{N}_{TR,1} = 3$ , and  $\mathcal{N}_{TR,2} = 1$  (solid), 2 (dashed), and 3 (dotted).

probability is  $\sim 33\%$ . Table 2 summarizes the inferred values and peak probabilities of  $r_{12}$ , including the cases  $\mathcal{N}_{TR,2} = 0, 1, 2$ , and 3. Even if none of the  $P \geq 3$  days TR planets were real, the TR and RV surveys would still have been compatible at the  $\sim 2\sigma$  level. We therefore conclude that the TR and RV surveys are consistent, and imply a relative frequency of VHJs to HJs of  $\sim 10\%$ – $20\%$ , with the precise number and degree of consistency depending on how many of the  $P \geq 3$  days TR planets turn out to be real.

Two of the HJs in our sample orbit stars that are members of a binary system ( $\tau$  Boo and  $v$  And). There have been various studies that indicate that such planets may have properties that are statistically distinct from those of planets orbiting single stars (e.g., Eggenberger et al. 2004). Since it is unclear whether planets orbiting stars that are members of a binary system could be detected in the OGLE surveys, it is interesting to redo the analysis above, excluding these two planets. We find that doing so leaves our conclusions unchanged. For example, we infer a relative frequency of  $r_{12} = 0.16^{+0.12}_{-0.07}$  for  $\mathcal{N}_{TR,2} = 2$ , with a peak probability of 62%, as compared to  $r_{12} = 0.15^{+0.10}_{-0.07}$  and a peak probability of 54% when we include these two planets.

If we include in our analysis planets with mass  $M_p \sin i \leq 0.2M_J$  (and so the two new Neptune-mass planets with  $P < 3$  days [Butler et al. 2004; McArthur et al. 2004]), as well as the newly discovered bright transiting planet TrES-1 (Alonso et al. 2004) with  $P = 3.0301$  days, RV and TR surveys imply relative frequencies of  $0.16^{+0.15}_{-0.08}$  and  $0.32^{+0.46}_{-0.18}$ , respectively. In other words, the two types of surveys are highly consistent. Combining both surveys, we find a relative frequency of  $0.20^{+0.13}_{-0.08}$ , with a peak probability of  $\sim 87\%$ . We stress that including these planets is probably not valid because (1) RV surveys are very incomplete

for  $M_p \sin i \lesssim 0.1M_J$ , (2) it is not at all clear that TR surveys could detect planets with mass as low as Neptune, (3) even if the TR surveys could detect such planets, they would be extremely difficult to confirm from follow-up RV measurements, and (4) the details of the TrES survey necessary for a proper statistical analysis are unknown. However, the fact that the relative frequency agrees with that inferred when these planets are not included demonstrates that our conclusions are fairly robust.

We have checked that changing the binning or the form of period distribution does not alter our conclusions substantially. For example, if we choose equal logarithmic bins of 1–2 and 2–4 days, the RV surveys imply a  $1\sigma$  upper limit to the relative frequency of planets with  $P = 1-2$  days versus  $P = 2-4$  days of 0.2. This is compared to a relative frequency of  $1.1^{+2.8}_{-0.7}$  implied by TR surveys. In this case, TR and RV surveys are consistent at the  $\sim 2\sigma$  level. Taken together, TR and RV surveys imply a relative frequency of  $0.22^{+0.18}_{-0.10}$  for  $\mathcal{N}_{TR,2} = 1$ , with a peak probability of  $\sim 7\%$ . For planets distributed linearly with period, and period bins of 1–3 and 3–5 days, we find a relative frequency of  $0.25^{+0.18}_{-0.11}$  for  $\mathcal{N}_{TR,2} = 1$ , with a peak probability of  $\sim 23\%$ . We have also checked that aliasing due to uneven sampling does not affect our results substantially. See Appendix B for more details.

## 5. HIDDEN ASSUMPTIONS, CAVEATS, AND COMPLICATIONS

In this section, we briefly mention various caveats and complications that may affect our results in detail. We begin by making a list of some of the more important hidden assumptions we have made. For completeness, we also list assumptions that we have already addressed.

1. *S/N-limited TR surveys.*—We have assumed that the detection of planets in the OGLE surveys is limited only by S/N and not by apparent magnitude. In other words, all stars for which planets (with the periods and radii we consider) would produce TRs with  $S/N > 9$  are considered. We discuss the validity of this assumption in more detail below.

2. *Uniform sampling.*—For the majority of our results, we have assumed uniform sampling.

3. *Logarithmic period distribution and specific binning.*—For the majority of our results, we have assumed a logarithmic intrinsic period distribution and specific choice of bins of  $P = 1-3$  and  $3-9$  days.

4. *All detected planets can be confirmed.*—We have implicitly assumed that all planets detected in TR surveys can be confirmed via follow-up RV observations, regardless of their period. Because of the prevalence of false positives that mimic planetary TR signals, it is not possible to use the observed relative frequency of planet candidates as a function of period to infer the true frequency; one must instead use the observed frequency of true planets, as confirmed by follow-up RV observations.

5. *Homogeneous stellar populations.*—We have assumed that the population of source stars does not vary as a function of distance, and therefore that terms in the TR sensitivity that depend on the mass, radius, and luminosity of the host stars drop out.

6. *Uniform stellar density.*—We adopted  $V_{\max} \propto F_{\min}^{-3/2}$ , which assumes a constant volume density of stars and no dust.

7. *Uniform intrinsic period distribution.*—We have assumed that the period distribution of planets is uniform (in either log or linear period). It is clear, given the “pile-up” of planets at  $P \sim 3$  days, that this assumption cannot be correct in detail.

8. *Photon- and source-limited noise.*—We assumed that the photometric precision is photon-noise limited (i.e., no systematic errors) and furthermore dominated by the source (i.e., sky noise is negligible).

9. *Correspondence between detectable RV and TR planets.*—We have assumed that all planets in the “complete” sample from RV surveys are detectable in TR surveys, i.e., both surveys probe the same population of planets.

10. *Constant radii.*—We have assumed that VHJs and HJs have equal, constant radii.

11. *No correlation between planet and stellar properties.*—We have assumed that the physical properties of short-period planets are not correlated with the physical properties of their parent stars.

The first assumption, namely that the OGLE-TR surveys are S/N limited, is the most crucial, as it provides the crux of our argument, which is that TR surveys are much more sensitive to short-period planets than to long-period planets. In fact, the OGLE surveys are not strictly S/N limited, as several cuts were imposed to preselect light curves to search for transiting planets. Of the cuts made, the most relevant here was the exclusion of light curves whose rms scatter exceeded 1.5%. This is important because it effectively limits the volume that is searched for planets, in a way that depends on the period and radius of the planet. If this volume is smaller than the largest volume for which the S/N is greater than the threshold, then the survey is no longer S/N limited. From the definition of the S/N (eq. [1]), and assuming that the maximum photometric error  $\sigma_{\max}$  is equal to the maximum rms, we find that the TR surveys are S/N limited, provided that the ratio of planet radius to stellar radius satisfies

$$\frac{R_p}{R_*} \leq (S/N)^{1/2} \left( \frac{\sigma_{\max}}{N_{\text{tot}}^{1/2}} \right)^{1/2} \left( \frac{P^2 \pi G M_*}{4R_*^3} \right)^{1/12}. \quad (10)$$

For  $\sigma_{\max} = 1.5\%$  and a threshold of  $S/N = 9$ ,

$$\frac{R_p}{R_*} \leq 0.12 \left( \frac{P}{1 \text{ day}} \right)^{1/6} \left( \frac{M_*}{M_{\odot}} \right)^{1/12} \left( \frac{R_*}{R_{\odot}} \right)^{-1/4} \left( \frac{N_{\text{tot}}}{10^3} \right)^{-1/4}. \quad (11)$$

For the 2002 OGLE campaign,  $N_{\text{tot}} = 1166$ . This gives for  $M_* = M_{\odot}$ ,  $R_* = R_{\odot}$ , and  $P = 1$  day (the smallest period we consider)  $R_p/R_* \lesssim 0.12$ . Therefore, for solar-type primaries, TR surveys are not S/N limited for the largest planets and smallest periods, and the arguments we have presented that are based on this assumption will break down. In practice, the magnitude of the correction will depend on the size distribution of planet radii, as well as the distribution of primary radii. However, if planets with  $R_p/R_* \geq 0.12$  are relatively rare, then the correction will generally be small. We note that the sensitivity of TR surveys to planets around small primaries can be severely reduced by imposing magnitude or rms limits, and thus future transit searches should take care when making such cuts that they are not rejecting otherwise viable candidates.

We have discussed the effects of our second, third, and fourth assumptions in our results in § 4 and the appendices. Although violations of these can and do affect our results in detail, they do not change our basic conclusions substantially.

Violations of the remaining assumptions will have various effects on our conclusions; however, investigation of these in detail is well beyond the scope of this paper. Furthermore, al-

though the importance of many of these assumptions can be determined directly from data, these data are not currently available. In the end, however, our assumptions are approximately valid, and a more careful examination of these issues is not warranted, given the small number of detected planets and resultant poor statistics. Our primary goal is to provide general insight into the biases and selection effects inherent in RV and (especially) TR surveys. We note that when many more planets are detected and the present analysis revisited, the assumptions listed above will likely have to be reconsidered more carefully.

## 6. DISCUSSION

We have demonstrated that the sensitivity of S/N-limited TR surveys scales as  $P^{-5/3}$ . This strong dependence on  $P$  arises from geometric and S/N considerations, and implies that TR surveys are  $\sim 6$  times more sensitive to  $P = 1$  day planets than  $P = 3$  day planets. When these selection biases and small-number statistics are properly taken into account, we find that the populations of close-in massive planets discovered by RV and TR surveys are consistent (at better than the  $2\sigma$  level). In other words, there are not enough planets detected to robustly conclude that the RV and TR short-period planet results are inconsistent. We then used the observed relative frequency of planets as a function of period, as probed by both methods, to show that HJs are approximately 5–10 times more common than VHJs.

RV surveys have demonstrated that the absolute frequency of HJs is  $\sim 1\%$  (Marcy et al. 2004), and thus the frequency of VHJs is  $\sim 0.1\%–0.2\%$ , i.e., 1 in 500–1000 stars have a VHJ. The frequency of VHJs is approximately the same as the frequency of transiting HJs, and therefore future RV surveys that aim to detect short-period planets by monitoring a large number of relatively nearby stars over short time periods (Fischer et al. 2005) should detect VHJs at approximately the same rate as transiting planets. Should such RV surveys not uncover VHJs at the expected rate, this would likely point to a difference in the populations of planetary systems probed by RV and TR surveys.

Roughly 15% of VHJs should transit their parent stars, as opposed to  $\sim 7\%$  of HJs, and approximately one in 3300–6700 single main-sequence FGK stars should have a transiting VHJ, as opposed to one in 1400 for HJs. It has been estimated that there are  $\sim 30$  detectable transiting HJs around stars with  $V \lesssim 10$  in the entire sky (Pepper et al. 2003; Deeg et al. 2004) and thus  $\sim 7–13$  transiting VHJs. The detection of only three VHJs in the OGLE surveys, which contain  $\sim 150,000$  stars, implies that only 5%–10% of the sources are single main-sequence FGK stars useful for detecting transiting planets, which is roughly in accord with, but somewhat smaller than, the fraction estimated for TR surveys of brighter stars (Brown 2003). The fact that other deep surveys such as EXPLORE (Mallén-Ornelas et al. 2003) have not detected any promising VHJ candidates despite searching a similar number of stars may be due to small-number statistics, reduced efficiency due to shorter observational campaigns, or both. Finally, we estimate that *Kepler* should find  $\sim 15–30$  transiting VHJs around the  $\sim 10^5$  main-sequence stars in its field of view.

It is interesting to note that there is some evidence that VHJs and HJs also appear to differ in their mass. Figure 2 shows the distribution of confirmed and candidate planets in the mass-period and radius-period planes. While there is a paucity of high-mass ( $M_p \gtrsim M_J$ ) planets with periods of  $P \sim 3–10$  days (Pätzold & Rauer 2002; Zucker & Mazeh 2002), all of the planets with  $P \lesssim 3$  days have  $M \geq M_J$ . This includes the RV planet HD 73256b with  $P = 2.5$  days, which suggests that this planet is indeed a VHJ and thus that RV surveys have already detected an analog to the OGLE short-period planets. The lack of high-mass

HJs is certainly real, and thus the mere existence of VHJs with  $M \geq M_J$  points toward some differentiation in the upper mass limit of the two populations. Whether or not the lack of lower mass ( $0.5M_J \lesssim M_p \lesssim M_J$ ) VHJs is real is certainly debatable. For TR-selected planets, this could in principle be a selection effect if the radius is a strong decreasing function of decreasing mass in this mass range; however, this is neither seen for the known planets with measured radii, nor expected theoretically. RV follow-up would likely prove more difficult for such lower mass objects, however (see Fig. 2).

As can be seen in Figure 2, there appears to be an “edge” in the distribution of planets in the mass-period plane that is reasonably well described by twice the Roche limit for a planet radius of  $R = R_J$ . This has been interpreted as evidence that short-period planets may have originated from highly eccentric orbits that underwent strong tidal evolution with their parent stars, leading to circularization at twice the Roche limit (Faber et al. 2005). However, this model alone cannot explain the pile-up at 3 days, and paucity of VHJs relative to HJs. Alternatively, it may be that massive  $M \geq M_J$  planets were not subject to whatever mechanism halted the migration of less-massive planets at periods of  $P \simeq 3$  days. Rather, these massive planets migrated on quasi-circular orbits while they were still young (and thus relatively large,  $\sim 2R_J$ ), through periods of 3 days, until they reached their Roche limit, at which point they may have lost mass and angular momentum to their parent star, halting their inward migration (e.g., Trilling et al. 1998).

The recently discovered short-period Neptune-mass planets (Santos et al. 2004; McArthur et al. 2004; Butler et al. 2004) complicate the interpretation of the properties of short-period planets even further. Two of these planets have periods that are less than the 3 day limit observed for planets with mass  $0.2\text{--}1 M_J$ . Both of these planets show marginal ( $\sim 2 \sigma$ ) evidence for non-zero eccentricity. In addition, 55 Cnc has a more distant companion with  $P = 14.653$  days (McArthur et al. 2004), and the RV curve for GJ 436b has marginal evidence for a linear trend, consistent with a more distant companion. Since tidal torques would be expected to circularize the orbits of such close planets on an extremely short timescale, this may be evidence for dynamical interactions with more distant companions, which may affect their migration and explain why they do not obey the 3 day migration limit. However, we stress that the evidence for non-zero eccentricity in these planets is marginal and thus will need to be confirmed with additional observations before any firm conclusions can be drawn. The fact that these planets have orbits that are smaller than the Roche edge observed for higher mass planets is understandable if they are primarily rocky in composition.

It is clear that much remains to be understood about short-period extrasolar planetary companions. In this regard, building

statistics is essential. Future RV surveys that tailor their observations to preferentially discover large numbers of short-period planets are very important, and are currently being undertaken (Fischer et al. 2005). Complementarity is also essential: the success of TR surveys in uncovering a population of heretofore unknown planets demonstrates the benefit of searching for planets with multiple methods, each of which has its own unique set of advantages, drawbacks, and biases. In addition to the success of OGLE and TrES, all-sky shallow TR surveys (Deeg et al. 2004; Pepper et al. 2004; Bakos et al. 2004), wide-angle field surveys (Kane et al. 2004; Brown & Charbonneau 2000), deep ecliptic surveys (Mallén-Ornelas et al. 2003), and surveys in stellar systems (Mochejska et al. 2002; Burke et al. 2003; Street et al. 2003; von Braun et al. 2005) should all uncover a large number of short-period planets, which can be compared and combined with the yield of RV surveys to provide diagnostic ensemble properties of short-period planets.

*Note added in manuscript.*—After the original submission of this paper, and during the refereeing process, we learned of several new results that bear on the discussion here. Bouchy et al. (2005) report on their follow-up of OGLE bulge candidates. They argue that OGLE-TR-58, listed as a possible planet candidate by Konacki et al. (2003b), is more likely a false positive caused by intrinsic stellar photometric variability. They also report radial velocity measurements of OGLE-TR-10 that indicate a possible planetary companion, which is in agreement with sparser RV data from Konacki et al. (2003b). Very recently, Konacki et al. (2005) report additional RV measurements of OGLE-TR-10, confirming the planetary nature of its companion, which has a radius  $R_p = 1.24 \pm 0.09 R_J$ , and a mass  $M_p = 0.57 \pm 0.12 M_J$ . The mass of this planet is consistent with other HJs, and significantly less than that of the known VHJs, reinforcing the case for a difference in the mass of these two populations of planets. With the confirmation of OGLE-TR-10, the number of HJs discovered in the OGLE TR surveys is  $\mathcal{N}_{\text{TR},2} = 2$ . If no other planets are uncovered from the first two OGLE campaigns, this implies a relative frequency of VHJs to HJs of  $r_{12} = 0.15^{+0.10}_{-0.07}$ , with a peak probability of  $\sim 54\%$ . In other words, RV and TR surveys are consistent at better than the  $1 \sigma$  level.

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## APPENDIX A

### PROPERTIES OF THE OGLE CAMPAIGNS

In this paper, we have focused on the OGLE-TR surveys, and we briefly summarize their properties here. OGLE mounted two separate campaigns toward the Galactic bulge and disk. In 2001, OGLE monitored three fields toward the Galactic bulge over a period of 45 days, with 793 epochs per field taken on  $\sim 32$  nights. Approximately 52,000 disk stars with rms  $< 1.5\%$  light curves were searched for low-amplitude transits, yielding a total of 64 candidates (Udalski et al. 2002a, 2002b, 2003). Of these candidates, one planetary companion was confirmed with radial velocity follow-up (OGLE-TR-56; Konacki et al. 2003a), and an additional two are planet candidates with significant spectroscopic follow-up (OGLE-TR-10 and OGLE-TR-58; Konacki et al. 2003b). In 2002, OGLE monitored an additional three fields in the Carina region of the Galactic disk over a period of 95 days, with  $\sim 1166$  epochs per field taken on  $\sim 76$  nights. Approximately 103,000 stars with rms  $< 1.5\%$  light curves were searched for low-amplitude TRs, yielding a total of 73 candidates

(Udalski et al. 2002c, 2003). Of these candidates, three planetary companions have been confirmed with radial velocity follow-up (OGLE-TR-111, OGLE-TR-113, and OGLE-TR-132; Bouchy et al. 2004; Konacki et al. 2004; Pont et al. 2004).

For both the 2001 and 2002 campaigns, candidates were found using the box-fitting least-squares (BLS) algorithm of Kovács et al. (2002). This method works by folding light curves about a trial period, and efficiently searching for dips in the folded curves that have a S/N larger than a given threshold. Udalski et al. (2002b, 2002c, 2003) adopted a threshold of S/N = 9. Figure 2 shows a contour of S/N = 9 in the  $(R_p, P)$  plane, assuming  $N_{\text{tot}} = 1166$  (as appropriate to the 2002 campaign), and  $\sigma = 0.005$ ,  $R_* = R_\odot$ , and  $M_* = M_\odot$ , as is typical of the OGLE target stars.

## APPENDIX B

### UNEVEN SAMPLING AND FINITE CAMPAIGN DURATION

In evaluating the relative sensitivity of TR surveys, we made the simplistic assumption that the number of data points during transit is proportional to the transit duty cycle for a central transit,  $N_p = R_*/\pi a$ . This assumes random sampling and short periods, as compared to the transit campaign. Of course, the OGLE campaigns have sampling that is far from random and in addition have finite durations of 1–3 months. This introduces two effects. First, the true fraction of points in transit for an ensemble of light curves may be biased with respect to the naive estimate of  $N_p/N_{\text{tot}} = R_*/\pi a$ . In addition,  $N_p/N_{\text{tot}}$  will depend strongly on phase, and thus an ensemble of systems at fixed  $P$  will have a large dispersion in  $N_p/N_{\text{tot}}$ .

We illustrate the effects of the nonuniform sampling and finite duration of the OGLE campaigns by analyzing the actual time stream of one light curve from each of the 2001 and 2002 campaigns, namely OGLE-TR-56 and OGLE-TR-113. We fold each of these light curves about a range of trial periods. For each  $P$ , we choose a random phase and determine  $N_p/N_{\text{tot}}$  assuming a primary of  $M = M_\odot$  and  $R = R_\odot$ . We repeat this for many different phases and determine the mean and dispersion of  $N_p/N_{\text{tot}}$ . The result is shown in Figure 4. The mean agrees quite well with the naive estimate of  $N_p/N_{\text{tot}} = R_*/\pi a$ . However, the dispersion is significant, with  $\sigma_{N_p}/N_p$  ranging from  $\sim 20\%$  for  $P \sim 1$  day to  $\sim 70\%$  for  $P \sim 10$  days. Since  $S/N \propto N_p^{1/2}$ , this translates to a dispersion in S/N of  $\sim 0.5(\sigma_{N_p}/N_p) \sim 10\%–35\%$ . This implies that, for a small number of samples (as is the case here), the value of  $N_p$  as a function of  $P$  can have large stochastic variations about the naive analytic estimate. Such variations are largest for near-integer-day periods, as can be seen in Figure 4.

The dispersion in the number of points during TR,  $N_p$ , due to aliasing implies that there is no longer a sharp cutoff in the distance out to which one can detect a planet of a given period. This is illustrated in the middle panel of Figure 4, in which we plot the probability (averaged over phase) that a planet with a fractional depth  $\delta = 0.01$  will yield a S/N > 9 as a function of  $P$  for the 2002 campaign, assuming a photometric precision of  $\sigma = 0.005$  (*green-shaded curve*). Naively, the uniform sampling approximation would imply that for a S/N = 9 threshold, all planets should be detectable out to a period of  $P \sim 9$  days and none with greater periods should be detectable. In fact, because of the dispersion in  $N_p$  for fixed periods caused by aliasing, the transition is more gradual, such that it is possible to detect planets with  $P > 9$  days, and there are sharp dips in the completeness near integer-day periods. Figure 4 also shows the results for  $\sigma = (3)^{-1/3} 0.005 \sim 0.007$  (*gray-shaded curve*). There should be 3 times more stars with  $\sigma = 0.007$  than with  $\sigma = 0.005$ , and the naive expectation is that all planets with periods  $P \lesssim 3$  days should be detectable. Clearly, uneven sampling will affect the estimates of the relative sensitivity of TR surveys as a function of period.

We note that OGLE-TR-111, which has  $\delta \simeq 0.014$ ,  $\sigma \sim 0.005$ , and  $P \simeq 4$  days, would easily have exceeded the S/N > 9 cut, even under the assumption of uniform sampling, which would predict S/N  $\sim 16$ . Therefore, we find that it may not be necessary to invoke aliasing to explain the detection of this planet, as suggested by Pont et al. (2004). However, it is difficult to be definitive because the “by-eye” final selection of OGLE candidates may effectively impose a S/N limit that is significantly greater than the limit of S/N > 9 used for the initial candidate selection. The fact that a larger number of transits ( $N_{\text{TR}} = 9$ ) were detected for OGLE-TR-111 than would be expected based on its period is likely a consequence of its near-integer period.

We can make a rough estimate of the possible error made in adopting the naive estimate in the present case by determining the expected distribution in the total number of points in transit  $N_p$ . We consider our two fiducial period bins,  $P_1 = 1–3$  and  $P_2 = 3–9$  days, with planets distributed uniformly in  $\log P$  within each bin. We then draw three planets from each bin, with a random phase and period for each planet. We evaluate  $N_p$  for each, and then find the mean  $\langle N_p \rangle$  of the three planets. We repeat this for many different realizations. The ratio of the average  $N_p$  for the two bins should be, on average,  $\langle N_p \rangle_1 / \langle N_p \rangle_2 \simeq (1 \text{ day}/3 \text{ days})^{-2/3} \sim 2$ . For the 2001 campaign, we find a median and 95% confidence interval of  $\langle N_p \rangle_1 / \langle N_p \rangle_2 = 2.11^{+3.06}_{-1.06}$ , whereas for the 2002 campaign, we find  $\langle N_p \rangle_1 / \langle N_p \rangle_2 = 2.10^{+1.83}_{-0.89}$ . A significant fraction of the variance arises from the small number of samples; if we assume there is no dispersion of the relation between  $N_p$  and  $P$  (i.e., uniform sampling), we find  $\langle N_p \rangle_1 / \langle N_p \rangle_2 = 2.08^{+0.69}_{-0.52}$ . If we assume the exact periods for the four confirmed planets and two candidates, rather than random periods, we find very similar results, with  $\langle N_p \rangle_1 / \langle N_p \rangle_2 = 1.87^{+1.42}_{-0.67}$  for the 2001 campaign, and  $\langle N_p \rangle_1 / \langle N_p \rangle_2 = 1.92^{+1.09}_{-0.77}$  for the 2002 campaign.

By incorporating these distributions of  $\langle N_p \rangle_1 / \langle N_p \rangle_2$  into the analysis presented in § 4, it is possible to determine the effect of aliasing on the inferred relative frequency of VHJs to HJs. We find that aliasing does not alter our conclusions substantially.

## APPENDIX C

### RV FOLLOW-UP BIASES

One important distinction between TR surveys and RV surveys is that candidate transiting planets must be confirmed by RV measurements. Additional selection effects can be introduced at this stage. We discuss two such effects here.

The first effect is related to the detectability of the RV variations. The detectability depends on the flux of the source and the magnitude of the RV signal. At fixed transit depth, shorter-period planet candidates are, on average, fainter than longer-period candidates, since



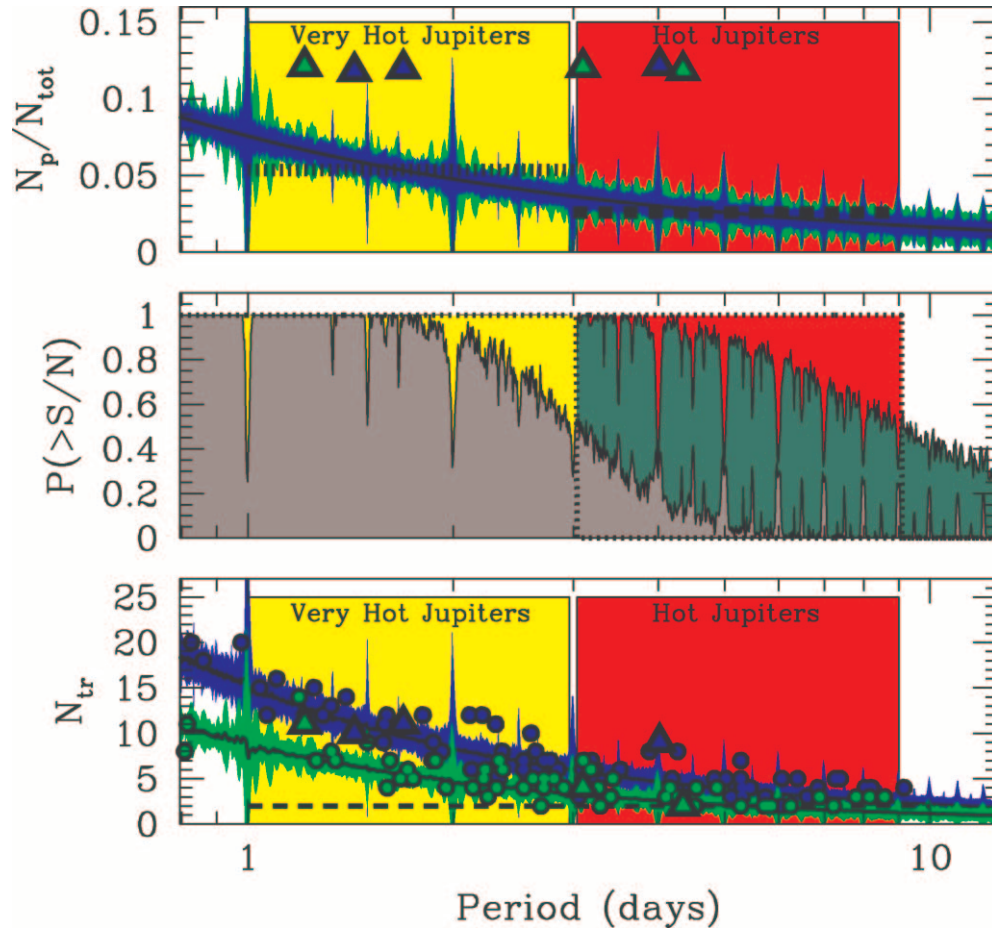


FIG. 4.—*Top*: Solid black lines showing the mean fraction of data points in transit,  $N_p/N_{\text{tot}}$ , as a function of period  $P$  for the OGLE TR surveys, averaged over all phases. The green- and blue-shaded regions show the dispersion around the mean for the 2001 and 2002 OGLE campaigns, respectively. The yellow and red bands indicate the period and mass ranges for our division into VHJs and HJs, respectively. The filled-square and vertical-dashed horizontal lines show the fraction of data points averaged over these two bins, assuming a uniform logarithmic distribution in  $P$ . The triangles show the periods of the OGLE-TR confirmed and candidate planets; the ordinate values are arbitrary. Green and blue triangles are the points found in the 2001 and 2002 campaigns, respectively. *Middle*: The green-shaded curve shows the probability, averaged over phase, for a planet with radius  $R_p = 0.1 R_*$  to have  $S/N > 9$  for a photometric precision  $\sigma_1 = 0.005$ , for the 2002 OGLE campaign. The red box shows the naive expectation under uniform sampling that all planets with  $P \lesssim 9$  days will have  $S/N > 9$  for this  $\sigma < \sigma_1$ . The gray-shaded curve shows the same probability for  $\sigma_1 = 3^{1/3}\sigma_2 \sim 0.007$ ; three times more stars have  $\sigma < \sigma_2$  than  $\sigma < \sigma_1$ . The yellow box shows the naive expectation that all planets with  $P \lesssim 3$  days will have  $S/N > 9$  for  $\sigma < \sigma_2$ . *Bottom*: The black lines show the number of observed transits,  $N_{\text{tr}}$ , with more than three points for the given  $P$  averaged over all phases. The green- and blue-shaded regions show the dispersion around the mean for the 2001 and 2002 OGLE campaigns, respectively. The triangles and circles show the number of observed transits as a function of period for all the OGLE low-luminosity or planetary transit candidates. Green and blue triangles and circles are those found in the 2001 and 2002 campaigns, respectively. Circles show all candidates, triangles are the confirmed planets or strong candidates. The horizontal dashed line shows  $N_{\text{tr}} = 2$ , the minimum number of transits needed to establish a period.

$F_{\text{min}} \propto P^{2/3}$ . For photon-limited measurements, the typical RV error is  $\sigma_{\text{RV}} \propto F_{\text{min}}^{-1/2} \propto P^{-1/3}$ . Thus, shorter-period planets will require longer integration times to achieve a fixed  $\sigma_{\text{RV}}$ . However, the RV signal varies as  $K \propto M_p P^{-1/3}$ , and therefore, for all else equal, the dependence of the relative S/N,  $S/N = K/\sigma_K$ , on period cancels out. Thus, for fixed observing conditions, the relative S/N of RV measurements for VHJs versus HJs depends (on average) only on their masses. As discussed in § 6, it appears that the upper mass thresholds of VHJs and HJs are different; whereas there exists a real paucity of HJs with mass  $\gtrsim M_J$ , the four known VHJs all have masses  $\gtrsim M_J$ . This favors the confirmation of VHJs.

An additional bias arises because two or more transits are needed to establish the period of the planet. Since an accurate period is generally required for follow-up<sup>6</sup> (because prior knowledge of the planet phase is important for efficient targeted RV observations), and longer periods are less likely to exhibit multiple transits, this bias also favors the confirmation of short-period planets. Figure 4 shows the mean and dispersion of the number of transits with more than three data points per transit as a function of period for the 2001 and 2002 OGLE campaigns. The majority of planets with periods of  $P \lesssim 3$  days will exhibit at least two transits, whereas planets with  $P \gtrsim 3$  days are increasingly likely to exhibit only one transit (or no transits at all).

In summary, biases involved in both detection and confirmation of transiting planets generally favor short-period planets. It is important to stress that all of the above arguments are true only on average. For the handful of planets currently detected, stochastic effects associated with the small sample size change the magnitudes or even the signs of the biases.

<sup>6</sup> Indeed, Konacki et al. (2003b) rejected all OGLE candidates with only one transit detection as unsuitable for follow-up.

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