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THE TRANSITING EXTRASOLAR GIANT PLANET AROUND THE STAR OGLE-TR-113

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ABSTRACT

We report the independent discovery of a new extrasolar transiting planet around OGLE-TR-113, a candidate star from the Optical Gravitational Lensing Experiment. Small radial velocity variations have been detected based on observations conducted with the MIKE spectrograph on the Magellan I (Baade) telescope at the Las Campanas Observatory (Chile) during 2003. We have also carried out a light-curve analysis incorporating new photometry and realistic physical parameters for the star. OGLE-TR-113b has an orbital period of only 1.43 days, a mass of $(1.08 \pm 0.28)M_{\rm Jup}$, and a radius of $(1.09 \pm 0.10)R_{\rm Jup}$. Similar parameters have been obtained very recently in an independent study by Bouchy et al., from observations taken a year later. The orbital period of OGLE-TR-113b and the previously announced planet OGLE-TR-56b ($P_{\rm orb} = 1.21$ days)—the first two found photometrically—are much shorter than the apparent cutoff of close-in giant planets at 3–4 day periods found in high-precision radial velocity surveys. Along with a third case reported by Bouchy et al. (OGLE-TR-132b, $P_{\rm orb} = 1.69$ days), these objects appear to form a new class of “very hot Jupiters” that pose very interesting questions for theoretical study.

Subject headings: line: profiles — planetary systems — stars: evolution — stars: individual (OGLE-TR-113) — techniques: radial velocities

1. INTRODUCTION

In recent years, the field of extrasolar planet research has seen significant developments in the ability to discover and measure these objects using a variety of techniques. High-precision Doppler searches (e.g., Fischer et al. 2003; Naef et al. 2004) have yielded the vast majority of the discoveries, and measurements in at least one case have even been made astrometrically (Benedict et al. 2002). Transit searches had their first success with HD 209458 (Henry et al. 2000; Charbonneau et al. 2000), a bright star ($V = 7.65$) that was known previously to harbor a planet in a 3.5 day period orbit from its radial velocity signature. Numerous photometric programs are monitoring large samples of stars looking for small dips in the brightness of the central object at the ~1% level (see Horne 2003), which might indicate a planet-size object crossing in front of the star. These studies are very important for the additional information they bring to bear on the nature of the companion, namely, the inclination angle of the orbit (~90°) and the absolute radius of the planet. The inclination angle complements the spectroscopic information and allows us to determine the mass directly.

Dozens of transiting planet candidates among faint stars have already been reported by several teams including OGLE (Udalski et al. 2002a), EXPLORE (Mallén-Ornelas et al. 2003), MACHO (Drake & Cook 2004), and others. Multiple efforts are underway to follow up on these candidates, a necessary step given the high incidence of false positive detections, particularly among fainter stars in crowded fields. The first case to be confirmed was that of OGLE-TR-56, a star with $V = 16.6$ located in the direction of the Galactic center (Udalski et al. 2002c; Konacki et al. 2003a; Torres et al. 2004). The very short orbital period of this planet (only 1.21 days) makes it extremely interesting and has provided theorists with the opportunity to explore the effects of strong irradiation from the central star as well as evaporation (e.g., Burrows et al. 2003; Baraffe et al. 2003, 2004).

In this Letter, we report the detection of a Doppler signature induced by a giant planet orbiting OGLE-TR-113, another faint transit candidate ($I = 14.42$) in the constellation of Carina reported recently by the OGLE project (Udalski et al. 2002b). This star shows periodic dips in brightness of about 3% and has a photometric period of 1.43 days. OGLE-TR-113 was originally identified as a very promising candidate from our low-resolution spectroscopic observations conducted in 2002 (see Konacki et al. 2003b). This reconnaissance showed it to be a star of late spectral type with no obvious velocity variations at the level of a few kilometers per second, which would have otherwise disqualified it for implying a stellar companion. Subsequently it was placed on our program for high-resolution follow-up, and the observations were carried out in early 2003. As this Letter was being prepared, we learned of a very recent independent detection of radial velocity variations in OGLE-TR-113 by Bouchy et al. (2004), based on observations taken in 2004. That study found yet another case of a very short period transiting planet (OGLE-TR-132, $P_{\rm orb} = 1.69$ days), which brings the number of such objects to three. It appears, therefore, that they form a new class of “very hot Jupiters” not previously seen in high-precision radial velocity surveys.

2. OBSERVATIONS AND REDUCTIONS

Our high-resolution spectroscopic observations were carried out with the MIKE spectrograph (Bernstein et al. 2003) on the Magellan I (Baade) telescope at the Las Campanas Observatory in Chile. Seven spectra of OGLE-TR-113 were obtained from

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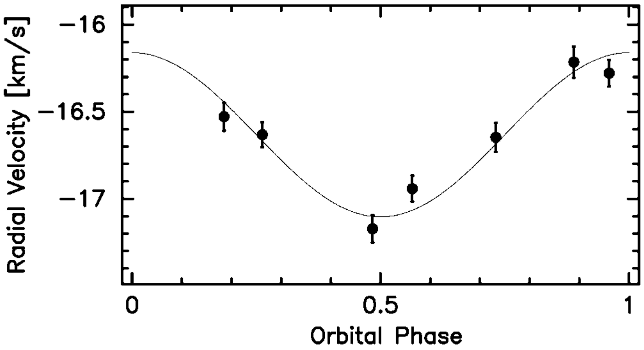

FIG. 1.—Radial velocity measurements for τ Boo as a function of orbital phase, along with the orbit determined by Butler et al. (1997). The only parameter we have adjusted is the velocity of the center of mass.

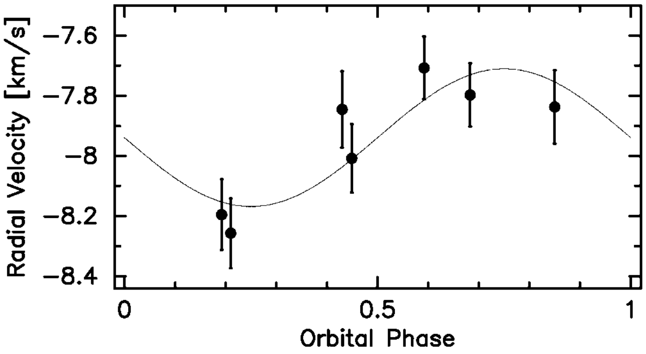

FIG. 2.—Radial velocity measurements and fitted velocity curve for OGLE-TR-113, as a function of orbital phase. Only the semiamplitude and center-of-mass velocity have been adjusted. The transit ephemeris is adopted from the photometry (see text).

February to April of 2003. The resolving power of these observations is $\lambda/\Delta\lambda \approx 54{,}000$, and the wavelength coverage is from 450 to 725 nm. Only 22 of the 29 echelle orders were used, since the others had low signal or were affected by telluric lines. The average signal-to-noise ratios per pixel achieved in our 30–40 minute exposures range from about 15 to 20. In addition to OGLE-TR-113, we observed several brighter stars with known planets each night as radial velocity standards. The wavelength reference for all observations was determined from exposures of a hollow-cathode thorium-argon lamp taken immediately before and after each stellar exposure.

The spectra were reduced using standard tasks in IRAF[8] as well as rectification tools developed by Kelson (2003). Radial velocities were obtained by cross-correlation against a calculated template that was tuned to match the star. For OGLE-TR-113, the stellar parameters we determined are $T_{\rm eff} = 4800 \pm 150$ K, $\log g = 4.5^{+0.5}_{-0.8}$, $[{\rm Fe/H}] = 0.0^{+0.1}_{-0.3}$, a radial-tangential macroturbulent velocity $\zeta_{\rm RT} = 2 \pm 1$ km s^{-1}, and $v \sin i = 9 \pm 3$ km s^{-1}. These were derived by careful comparison of calculated LTE model spectra against features such as the Hα, Hβ, and Na D lines, in addition to numerous other metal lines, which taken together provide strong constraints on the effective temperature and surface gravity of the star. The parameters for the standards were adopted from detailed analyses in the literature. The velocity results from the different orders were combined for each star, and the scatter between orders was used to derive an estimate of the uncertainty. Instrumental shifts during the night were monitored and corrected for by using telluric lines present in the spectrum. Typical corrections average 100–150 m s^{-1} with occasionally larger values, and they are found to improve the accuracy of the velocities significantly.

The results for one of our standards, τ Boo (HD 120136), are shown in Figure 1. The measured radial velocities are in excellent agreement with the known spectroscopic orbit for this star from Butler et al. (1997), which has a semiamplitude of about 470 m s^{-1}. The rms residual from the published orbit is 85 m s^{-1}, and the only parameter adjusted to match the observations is a velocity offset. This demonstrates that the instrumental setup allows us to clearly detect small velocity changes at the level of a few hundred meters per second.

3. SPECTROSCOPIC RESULTS

Our velocity measurements for OGLE-TR-113 are listed in Table 1 and shown in Figure 2. Typical measurement errors are ~100 m s^{-1}. We fitted a Keplerian orbit to these observations by holding the well-determined period and epoch fixed from the photometry (see § 4) and adjusting only the velocity semiamplitude (K) and the center-of-mass velocity (γ). A circular orbit was assumed, based on the extremely short orbital period and the likelihood that tidal forces have reduced the eccentricity to zero. We obtained $K = 229 \pm 58$ m s^{-1} and $\gamma = -7.939 \pm 0.043$ km s^{-1}, with an rms residual from the fit of 108 m s^{-1} (Table 2). The semiamplitude is significantly different from zero, and it is robust. The minimum mass of the companion derived from our best orbital fit is $M_p \sin i = (0.00121 \pm 0.00031)(M_* + M_p)^{2/3}\, M_\odot$, where M_* is the mass of the primary star. Formally our systemic velocity for OGLE-TR-113 agrees very well with the value of $\gamma = -7.944 \pm$

TABLE 1

RADIAL VELOCITY MEASUREMENTS FOR OGLE-TR-113[a]

HJD (2,400,000+)	Phase	Velocity (km s^{-1})	Error[b] (km s^{-1})
52690.6259	0.683	−7.797	0.105
52691.7230	0.449	−8.008	0.114
52692.7873	0.192	−8.195	0.118
52692.8128	0.210	−8.257	0.116
52693.7298	0.850	−7.837	0.122
52694.7927	0.592	−7.707	0.104
52754.7244	0.430	−7.845	0.127

[a] In the barycentric frame.

[b] Internal errors have been scaled to provide a reduced χ^2 of unity in the orbital solution.

TABLE 2

ORBITAL AND PHYSICAL PARAMETERS FOR OGLE-TR-113b

Parameter	Value
Orbital period (days)	1.4324758 ± 0.0000046
Transit epoch (HJD 2,400,000)	52325.79823 ± 0.00082
Center-of-mass velocity (km s^{-1})	−7.939 ± 0.043
Eccentricity (fixed)	0
Velocity semiamplitude (m s^{-1})	229 ± 58
Inclination angle (deg)	88.4 ± 2.2
Stellar mass ($M_\odot$) (adopted)	0.79 ± 0.06
Stellar radius ($R_\odot$) (adopted)	0.78 ± 0.06
Limb-darkening coefficient (I band)	0.586 ± 0.015
Planet mass ($M_{\rm Jup}$)	1.08 ± 0.28
Planet radius ($R_{\rm Jup}$)	1.09 ± 0.10
Planet density (g cm^{-3})	1.0 ± 0.4
Semimajor axis (AU)	0.02299 ± 0.00058

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[8] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

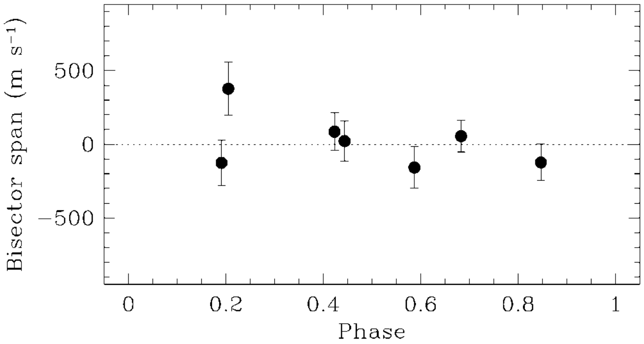

FIG. 3.—Bisector span used to quantify the line asymmetry for each of our spectra of OGLE-TR-113, plotted as a function of orbital phase. The error bars are determined from the agreement between different echelle orders. There is no obvious correlation with phase.

0.027 km s^{-1} by Bouchy et al. (2004). For our standard τ Boo, we obtain $\gamma = -16.632 \pm 0.033$ km s^{-1}, which also compares favorably with the determination by Nidever et al. (2002) of -16.542 km s^{-1}, referred to a well-defined velocity system. However, we do not claim here that the accuracy of our zero point is much better than ~100 m s^{-1}, partly because of the small number of observations. Nevertheless, the similarity of the systemic velocity we derive for OGLE-TR-113 to that of Bouchy et al. (2004) places at least some constraint on the presence of additional massive planets in wider orbits around the star.

Among the phenomena that can mimic the photometric and spectroscopic signatures of transit candidates, the presence of an eclipsing binary along the same line of sight (a “blend”) is one of the most common. Deep eclipses in the binary can be strongly diluted by the main star, and they appear with depths of only a few percent that are very similar to those produced by a Jupiter-size planet around a solar-type star. Furthermore, light from one of the stars in the eclipsing binary can contaminate the spectrum of the main star and can introduce line asymmetries that could lead to spurious velocity variations. To examine this possibility, we quantified the asymmetries by computing the line bisector spans (see, e.g., Gray 1992, p. 417). This was done directly from the cross-correlation function of OGLE-TR-113 co-added over all echelle orders, following Santos et al. (2002) and Torres et al. (2004). The results are shown as a function of phase in Figure 3. Within the errors, we detect no significant variation, indicating that line asymmetries cannot be the source of the velocity variations (~500 m s^{-1}, peak to peak) since these two quantities should be of the same order.

4. LIGHT-CURVE SOLUTION

The discovery of a transit signature in OGLE-TR-113 was reported by (Udalski et al. 2002b) and was based on observations collected during the 2002 observing season in which 10 transit events were recorded. Since then, further measurements spanning two additional seasons have been made (for a total of 1517), and four more transits have been detected. We have incorporated these new measurements into our analysis. The internal errors of 0.003 mag, possibly a bit optimistic, were rescaled to 0.006 mag for consistency with the out-of-eclipse variations and also to provide a reduced χ^2 near unity in the light-curve solution. The best-fit transit model, computed following Mandel & Agol (2002), is shown in Figure 4 together with the observations. The resulting parameters along with the period and transit epoch, which were adjusted simultaneously, are given in Table 2. The improved period and transit epoch are $P_{\rm orb} = 1.4324758 \pm 0.0000046$ days and T(HJD) $= 2{,}452{,}325.79823 \pm 0.00082$. The limb-darkening coefficient in the I band (linear law), $u_I = 0.586 \pm 0.015$, was derived from models consistent with the physical properties of the star.

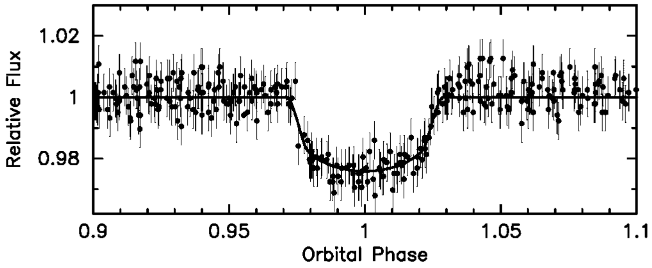

FIG. 4.—OGLE photometry for OGLE-TR-113 in the I band, with our best-fit transit light curve. The resulting parameters are listed in Table 2.

The photometric observations provide strong constraints on the model fit, and the χ^2 surface has a well-defined minimum (Fig. 5). The statistical error on the radius of the planet, R_p, is only $0.02R_{\rm Jup}$. However, the dominant contribution to the total error in R_p is the uncertainty in the stellar radius, R_*. For a fixed stellar mass of $M_* = 0.79\ M_\odot$, the value of R_* (~0.78 $R_\odot$) can be determined to about $\pm 0.02\ R_\odot$ from stellar evolution models. But the stellar mass itself is uncertain by ~0.06 $M_\odot$, and this propagates directly into R_* because the star must presumably conform to a model isochrone. When this increased error for the stellar radius is accounted for, the uncertainty in the planet radius is $R_p = (1.09 \pm 0.10)\ R_{\rm Jup}$. This is larger than the uncertainty reported by Bouchy et al. (2004), but we believe it is much more realistic.

5. DISCUSSION

From the combination of the spectroscopic and photometric solutions, we have derived the key physical parameters of the planet. OGLE-TR-113b has an orbital period of only 1.43 days, a mass of $(1.08 \pm 0.28)\ M_{\rm Jup}$, and a radius of $(1.09 \pm 0.10)\ R_{\rm Jup}$ (Table 2). These values are consistent at the 1 σ level with the determinations by Bouchy et al. (2004). The radius appears to be consistent also with irradiated models for the very

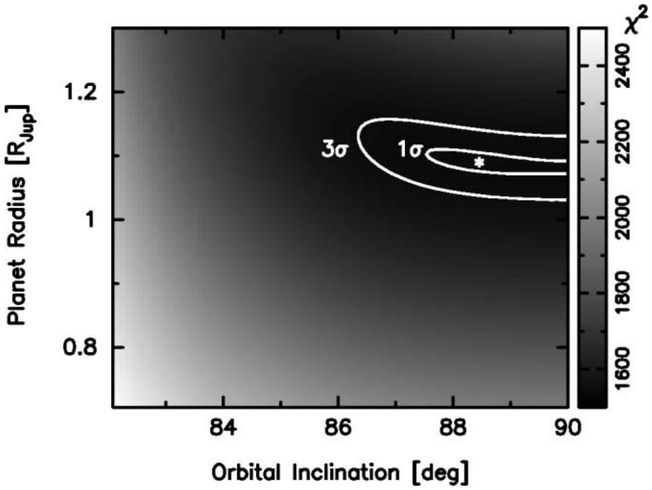

FIG. 5.—The χ^2 surface corresponding to the light-curve solution for OGLE-TR-113, in the plane of orbital inclination vs. planet radius. The number of degrees of freedom in the fit is 1512.

similar case of OGLE-TR-56b (Chabrier et al. 2004; Burrows et al. 2004), which is very reassuring and makes the large size of HD 209458b special. We note also that OGLE-TR-113 is a K dwarf that appears to have excess rotation, as in young or active stars. The issue of its age should be followed up observationally. We estimate the distance to the star to be roughly 600 pc. But perhaps the most interesting parameter in this case is the very short orbital period. OGLE-TR-56b, OGLE-TR-113b, and also the recently announced OGLE-TR-132b (Bouchy et al. 2004, $P_{\rm orb} = 1.69$ days) all have orbital periods much shorter than the apparent cutoff of close-in giant planets at around 3 day periods, determined from the radial velocity surveys. Thus, OGLE-TR-56b (the first of these discoveries) can no longer be considered an oddity among the extrasolar planets, and it appears these new cases point toward an extremely interesting new class of “very hot” Jupiters.

It is worth pointing out that these three short-period planets are the result of just the first two campaigns conducted by the OGLE team, in relatively small fields toward the Galactic center and Carina. If these or similar surveys were to continue producing candidates at the current rate for a period of operation similar to that of the Doppler surveys, it is not unreasonable to expect that the number of very hot Jupiters could increase significantly and even exceed the number of 3–4 day period planets from the radial velocity searches. The *frequency* of occurrence of very hot Jupiters, however, appears to be much lower than that of the shortest period Doppler planets, as discussed by Bouchy et al. (2004). Thus, the apparent inconsistency with the lack of any Doppler discoveries having periods as short as those of the OGLE planets may simply be due to a combination of their lower rate of occurrence and the much higher sensitivity to these objects in the photometric surveys. The latter is the result of the relatively short duration of the OGLE photometric campaigns (a few weeks) and the increased probability of transits from geometry, such that the chance of finding longer period transiting planets actually falls off dramatically beyond $P_{\rm orb}$ of 3–4 days. The extreme conditions of proximity to the parent stars in these very hot Jupiters opens up the possibility of very interesting theoretical studies into their structure and evolution, as well as migration scenarios.

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