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A TRANSITING EXTRASOLAR GIANT PLANET AROUND THE STAR OGLE-TR-10

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ABSTRACT

We report a transiting extrasolar giant planet around the star OGLE-TR-10 (orbital period = 3.1 days), which was uncovered as a candidate by the OGLE team in their photometric survey toward the Galactic center. We observed OGLE-TR-10 spectroscopically over a period of 2 yr (2002–2004), using the HIRES instrument with an iodine cell on the Keck I telescope, and measured small radial velocity variations that are consistent with the presence of a planetary companion. This confirms the earlier identification of OGLE-TR-10b by our team and also recently by Bouchy and coworkers as a possible planet. In addition, in this paper we are able to rule out a blend scenario as an alternative explanation. From an analysis combining all available radial velocity measurements with the OGLE light curve, we find that OGLE-TR-10b has a mass of $0.57 \pm 0.12 M_{\rm J}$ and a radius of $1.24 \pm 0.09 R_{\rm J}$. These parameters bear close resemblance to those of the first known transiting extrasolar planet, HD 209458b.

Subject headings: line: profiles — planetary systems — stars: evolution — stars: individual (OGLE-TR-10) — techniques: radial velocities

Online material: color figures

1. INTRODUCTION

Photometric observations combined with radial velocity measurements of stars harboring transiting giant planets yield the absolute radii, masses, and densities of the planets. The ongoing photometric surveys for transiting planets have now delivered a large number of candidates, but those observations alone cannot distinguish between companions that are Jupiter-size planets, brown dwarfs, or late type M dwarfs, since they all have similar radii (of order 0.1 $R_\odot$). They also cannot distinguish between true transiting planets and so-called "blends," chance alignments or physical triple systems involving an eclipsing binary that can mimic planetary transits (Konacki et al. 2003a; Torres et al. 2004b, 2005). These can be very common, particularly in crowded fields. Hence, follow-up spectroscopic observations are not only necessary to measure the radial velocities and derive the mass of a transiting planet, but they are also vital for weeding out astrophysical false positives.

The first confirmed case of a transiting planet proposed by a photometric survey (Udalski et al. 2002b, 2002c) was that of OGLE-TR-56b (Konacki et al. 2003a; Torres et al. 2004a; Bouchy et al. 2005). Three other examples have also come out of the OGLE survey (Udalski et al. 2002a, 2003): OGLE-TR-113b (Bouchy et al. 2004; Konacki et al. 2004), OGLE-TR-132b (Bouchy et al. 2004; Moutou et al. 2004), and OGLE-TR-111b (Pont et al. 2004). In addition, the first transiting planet from a wide-field bright-star survey has recently been reported (TrES-1; Alonso et al. 2004). This brings the total number to six, including the case of HD 209458b, a planet originally discovered in the course of a radial velocity survey and only later found to undergo transits (Henry et al. 2000; Charbonneau et al. 2000).

OGLE-TR-10 was identified as a promising candidate by the OGLE team during their 2001 campaign in three fields toward the Galactic center (Udalski et al. 2002c). The possible planetary nature of its companion, based on spectroscopic follow-up, was first established by Konacki et al. (2003b). In that paper we reported a tentative radial velocity semiamplitude of $K = 100 \pm 43$ m s^{-1} and a mass for the putative planet of $M_p = 0.7 \pm 0.3 M_{\rm J}$. However, the possibility of a blend could not be categorically ruled out at the time, because of the small number of observations. Recently, Bouchy et al. (2005) also called OGLE-TR-10 a possible planet, with $K = 81 \pm 25$ m s^{-1} and $M_p = 0.66 \pm 0.21 M_{\rm J}$, although these authors were still unable to completely exclude a blend scenario because of the insufficient signal-to-noise ratio (S/N) of their observations.

In this paper we present the results from additional spectroscopic monitoring of OGLE-TR-10 with Keck I/HIRES on two additional runs, for a total of three seasons (2002–2004). We are now able to confirm the planetary nature of OGLE-TR-10b. Our new radial velocities and the parameters of the parent star are presented in §§ 2 and 3. The OGLE light-curve solution and planet parameters are derived in § 4, where we combine our radial velocities with those reported by Bouchy et al. (2005). In § 5 we analyze and rule out a blend as an alternative explanation. The results are discussed in § 6.

2. OBSERVATIONS

OGLE-TR-10 was observed spectroscopically with the Keck I telescope, using the HIRES instrument (Vogt et al. 1994) in 2002 July, 2003 August, and 2004 July. The exposure times ranged from 30 to 50 minutes, and the wavelength coverage was 3850 to 6200 Å (36 echelle orders), at a resolving power of $R \simeq 65{,}000$. We collected 10 spectra, of which 9 were taken with the iodine gas absorption cell (I_2) that superimposes a dense forest of absorption lines directly on the stellar spectrum in the region from approximately 5000 to 6200 Å (some 12 echelle orders). The iodine orders had typical S/N of 15 to 25 pixel^{-1}. One spectrum was taken without the I_2, to serve as the template for the iodine velocity reductions.

For faint stars such as OGLE-TR-10 ($V = 15.8$, $I = 14.9$), light losses due to the iodine cell typically prevent one from using that technique to determine precise radial velocities in the manner done for brighter Doppler targets. However, as described

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TABLE 1
Radial Velocity Measurements for OGLE-TR-10, in the Barycentric Frame

HJD (2,400,000+)	Phase	Velocity (km s^{-1})	Error (km s^{-1})
52481.7946.................	0.706	−6.130	0.058
52483.7578.................	0.330	−6.296	0.057
52853.7813.................	0.648	−6.247	0.048
52855.8454.................	0.314	−6.340	0.059
52864.7786.................	0.194	−6.304	0.054
53206.7856.................	0.470	−6.223	0.097
53207.7794.................	0.790	−6.152	0.056
53208.7772.................	0.112	−6.380	0.070
53209.7727.................	0.433	−6.254	0.056

by Konacki et al. (2003b), precision as good as 50 m s^{-1} can still be achieved with the I_2 cell on faint targets by using a synthetic spectrum instead of an observed spectrum as the template. In addition, in order to monitor changes in the instrumental point-spread function (PSF) that affect the velocities significantly, we obtained observations of a bright star with the I_2 cell on every night we observed OGLE-TR-10. Those observations were used to model the PSF and establish the parameters that we then applied to OGLE-TR-10. In this way we were able to determine radial velocities with typical uncertainties of about 60 m s^{-1}, which are listed in Table 1. Our spectroscopic orbital solution is described below in § 4.

3. PARAMETERS OF THE PARENT STAR

The stellar parameters for OGLE-TR-10 were derived from our high-resolution co-added Keck spectrum (S/N of 44) with fits to synthetic spectra computed from model atmospheres for different compositions based on the ATLAS 9 and ATLAS 12 programs by Kurucz (1995). We use a code, rewritten in FORTRAN 90 (J. Lester 2002, private communication) and incorporating new routines for improved treatment of contributions from various broadening mechanisms, as well as updated and expanded opacities and line lists. This code has been tested extensively and performs very well for solar-type stars (F–K type) such as OGLE-TR-10. The fits between observed and synthetic spectra were made in spectral regions unaffected by the I_2 lines and include a large number of metal absorption lines of different ionization and excitation states as well as the core and wings of the λ4861 Hβ line. Our effective temperature determination, $T_{\rm eff} = 5750$ K, has an estimated accuracy of about 100 K (see below). Our projected rotational velocity, $v \sin i = 3$ km s^{-1}, is good to better than 2 km s^{-1}; we use an approach to the line broadening similar to that described by Fischer & Valenti (2003). Our procedures allow us to derive the metallicity, [Fe/H], and the limb-darkening parameter, $u_I = 0.51 \pm 0.04$, with good confidence. [Fe/H] is estimated to be solar, with a 0.2 dex uncertainty. The surface gravity is much more difficult to determine reliably. We estimate $\log g = 4.4^{+0.4}_{-0.9}$, in which the upper limit is much better constrained than the lower bound, as is common in this type of analysis. Given the morphology of evolutionary tracks for main-sequence stars and the lack of an independent distance estimate for OGLE-TR-10, this uncertainty in $\log g$ allows us to rule out a giant or subgiant status for the star, but provides only a weak constraint on the stellar radius on the main sequence.

The stellar mass and radius were determined by using a stellar evolution code described in detail elsewhere (Cody & Sasselov 2002; Sasselov 2003). As evolutionary tracks are nearly vertical in the $T_{\rm eff}$ versus $\log g$ plane for the range of interest for

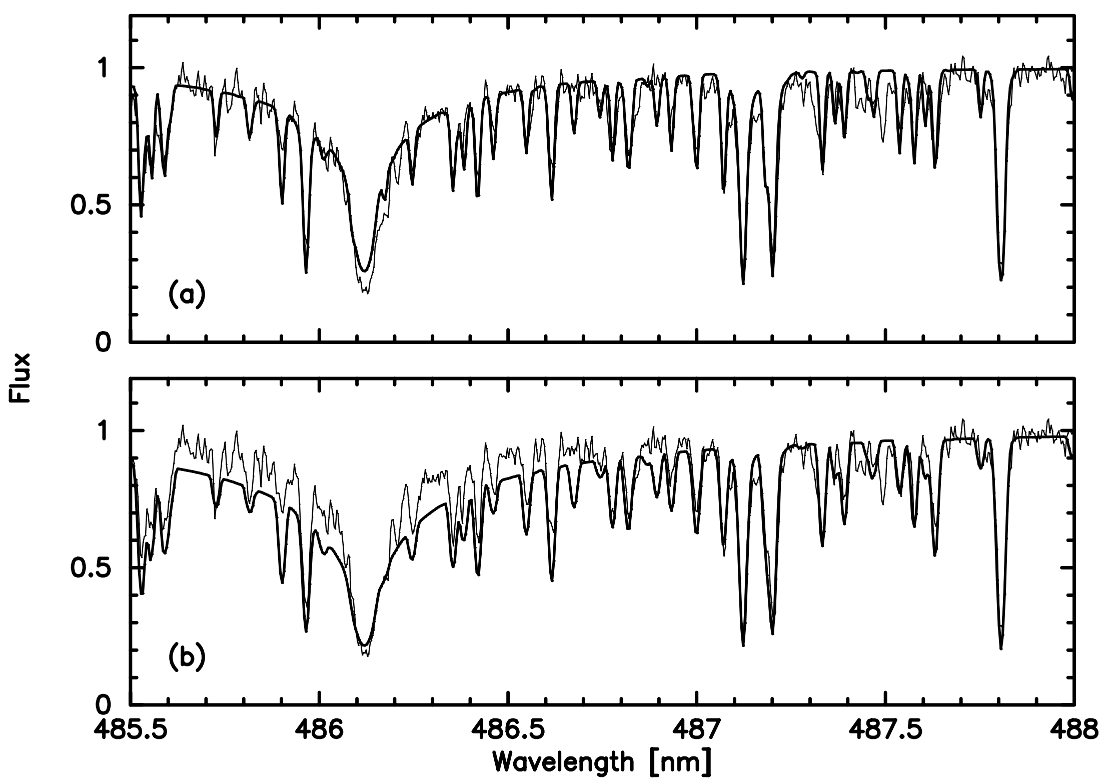

Fig. 1.—Portion of the observed (co-added) spectrum of OGLE-TR-10 around the Hβ line with (*a*) our best-fit synthetic spectrum superimposed (*thick solid line*) and (*b*) a synthetic spectrum for the stellar parameters derived by Bouchy et al. (2005). [*See the electronic edition of the Journal for a color version of this figure.*]

OGLE-TR-10, the largest uncertainty in deriving the radius would be an error in $T_{\rm eff}$. A temperature that is too hot would lead to an overestimate of the stellar mass and also a stellar radius that is too large (given the stricter upper bound on log g). This in turn would lead to a significant overestimate of the derived planet radius (R_p) in the solution of the transit light curve. Figure 1 illustrates our efforts to obtain an accurate value of $T_{\rm eff}$, and in particular the strong sensitivity of Balmer line profiles to the temperature. We point out that LTE radiative equilibrium codes like ATLAS are particularly well suited to fit the wings of such lines. The cores are usually affected by chromospheres and non-LTE effects, and are expected to appear deeper in a solar-type star like OGLE-TR-10. A fit to the wings of the λ4861 Hβ line requires a careful setting of the continuum (for better illustration, only a fraction of the HIRES order is shown in Fig. 1). To guard against problems with continuum setting and line broadening, in deriving $T_{\rm eff}$ we also rely on temperature-sensitive line pairs: moderate-strength metal lines having different (often opposite) sensitivity to temperature and colocated (within 0.1–0.2 nm) in wavelength (see Gray & Johanson 1991 for a general description and some line pairs). We get $T_{\rm eff} = 5800 \pm 100$ K, in good agreement with the Balmer line wings and neutral-to-ionized metal lines comparisons.

Thus, based on the overall fit of the good-quality Keck spectrum, OGLE-TR-10 is confidently identified as a close analog to our Sun. Our estimates of the stellar parameters are significantly different from those reported by Bouchy et al. (2005; $T_{\rm eff} = 6220 \pm 140$ K, log $g = 4.70 \pm 0.34$, [Fe/H] $= 0.39 \pm 0.14$, $M = 1.22 \pm 0.045\ M_\odot$, $R = 1.21 \pm 0.066\ R_\odot$). However, as can be also seen in Figure 1, our determinations lead to a much better match with the overall high S/N spectrum of OGLE-TR-10 from Keck I/HIRES.

4. ANALYSIS AND RESULTS

Our radial velocities from § 2 show clear variations as a function of photometric phase. Adopting the orbital period and epoch reported for OGLE-TR-10 by Udalski et al. (2002c), we fitted for a circular orbit, solving for the center-of-mass velocity and the semiamplitude K (see Fig. 2a). The best-fit value of $K = 77 \pm 23$ m s^{-1} is consistent with the early result from Konacki et al. (2003b) and Bouchy et al. (2005). The rms of our spectroscopic solution is 45 m s^{-1}, and from Monte Carlo simulations we find that the probability of obtaining by chance a K amplitude as large as we measure is only $\sim 4 \times 10^{-4}$.

For our final spectroscopic orbital solution we combined our HIRES measurements with 14 velocity measurements by Bouchy et al. (2005).[4] The latter were obtained with two different configurations of the VLT spectrograph UVES: in the standard slit mode (hereafter UVES), and a setup with a fiber link (FLAMES). We considered these as independent data sets and solved for the corresponding velocity offsets relative to HIRES along with the rest of the orbital elements. The combined fit gives an improved velocity semiamplitude of $K = 80 \pm 17$ m s^{-1}, with an rms residual of 60 m s^{-1} (see Fig. 2b). The corresponding false-alarm probability from Monte Carlo simulations is $\sim 10^{-6}$. We use this combined fit in the rest of our paper. The best-fit parameters are presented in Table 2, along with our light-curve solution based on the OGLE photometry, using the formalism of Mandel & Agol 2002 (Fig. 3). By

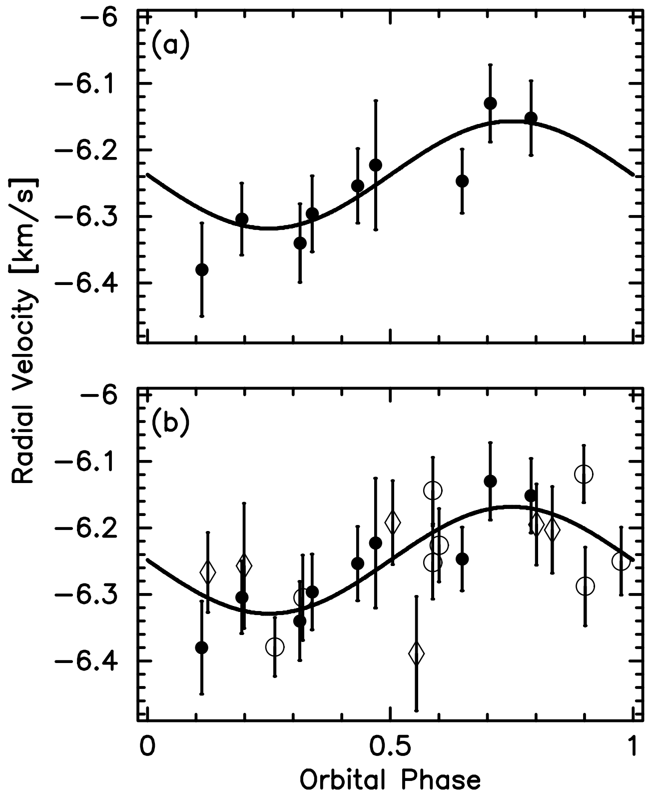

FIG. 2.—Radial velocity measurements and fitted velocity curve for OGLE-TR-10, as a function of orbital phase. The transit ephemeris is adopted from the photometry (see text). Our HIRES velocities are represented with filled circles, and UVES and FLAMES velocities by Bouchy et al. (2005) are shown with diamonds and open circles, respectively. (a) Fit to HIRES velocities only (rms = 45 m s^{-1}). (b) Fit to all available data (rms = 60 m s^{-1}). [*See the electronic edition of the Journal for a color version of this figure.*]

combining this information with the stellar parameters described previously, we derive for the planet in orbit around OGLE-TR-10 an absolute mass of $0.57 \pm 0.12 M_{\rm J}$ and a radius of $1.24 \pm 0.09 R_{\rm J}$. The formal errors include the contribution from uncertainties in the mass and radius of the parent star.

5. FALSE-POSITIVE REJECTION

To test for the possibility that the radial velocities we measured for OGLE-TR-10 are simply caused by blending with an eclipsing binary, we computed the spectral line bisectors from our Keck observations, as described by Torres et al. (2004a). There is no significant variation of the bisector spans as a function of phase (see below), as would be expected if lines from another star were causing asymmetries in the profiles of the main star by moving back and forth with the photometric period. Similar results were reported by Bouchy et al. (2005).

Next, we modeled the OGLE light curve in detail, using the procedures described by Torres et al. (2004b), assuming a configuration consisting of an eclipsing binary blended with the main G star forming a hierarchical triple system. Although we were able to achieve an excellent fit that is essentially indistinguishable from a true transit light curve, this blend model predicts an optical brightness for the primary of the eclipsing binary that is *greater* than the G star itself, which is clearly not observed. We then relaxed the condition that the three stars be at the same distance, and considered models with the eclipsing binary in the background, in order to make it fainter. Here too

[4] Two additional measurements by Bouchy et al. were considered by them to be of lower quality and rejected. We have done the same here.

TABLE 2
Orbital and Physical Parameters for OGLE-TR-10 and Its Planet

Parameter	Value
Orbital period (days)	3.101386 ± 0.000030
Transit epoch (HJD−2,400,000)	52070.2223 ± 0.0028
Center-of-mass velocity (km s^{-1})	−6.250 ± 0.020
Eccentricity (fixed)	0
Velocity semiamplitude (m s^{-1})	80 ± 17
Velocity offset between HIRES and FLAMES (m s^{-1})	−14 ± 27
Velocity offset between HIRES and UVES (m s^{-1})	218 ± 34
Inclination angle (deg)	89.2 ± 2.0
Stellar mass ($M_\odot$; adopted)	1.00 ± 0.05
Stellar radius ($R_\odot$; adopted)	1.00 ± 0.10
Fractional radius (R_{planet}/R_{star})	0.127 ± 0.017
Limb-darkening coefficient (*I* band)	0.51 ± 0.04
Planet mass (M_J)	0.57 ± 0.12
Planet radius (R_J)	1.24 ± 0.09
Planet density (g cm^{-3})	0.38 ± 0.10
Semimajor axis (AU)	0.04162 ± 0.00069

we were able to find a perfectly acceptable fit for an eclipsing binary composed of an F9 V star and a K5 V star located several kpc behind the G star (see Fig. 4*a*). The relative brightness of the eclipsing pair in this model is only about 4.5% compared to the G star, which would be just below our threshold of 5% for detecting lines of another star in the spectra (see Konacki et al. 2003b). The predicted orbital velocity semiamplitude of the F9 star is 65 km s^{-1}, and its spectral lines should show a rotational broadening that corresponds to $v \sin i = 20$ km s^{-1} (assuming the spin is synchronized with the orbital motion).

In order to test this blend scenario further we ran extensive numerical simulations, following Torres et al. (2005), to predict the bisector span and radial velocity variations that would be expected from this configuration. In Figure 4 we compare these predictions with the observations, as a function of orbital phase. The expected bisector-span variations in Figure 4*b* are relatively small (less than about 100 m s^{-1}), and are therefore still consistent with the measurements, which show no significant variation, given typical errors that are also about 100 m s^{-1}. Thus, the fact that bisector spans for a transit candidate show no appreciable change with phase *does not* necessarily rule out a blend scenario. However, Figure 4*c* indicates that the expected radial velocity variations are even smaller and do not show the trend with phase displayed by the velocity measurements for OGLE-TR-10. As discussed in § 4, the latter velocity trend is confirmed and reinforced by independent measurements from two different data sets, as reported by Bouchy et al. (2005). The false-alarm probability, based on Monte Carlo simulations, that a set of velocity measurements resulting from such a blend scenario would have the phase coherence we observe, with a semiamplitude as large as we observe, is 1.3×10^{-3} from our HIRES measurements alone, and 3×10^{-5} using all the radial velocity data. This effectively rules out this blend configuration. Experiments show that it is not possible to make the predictions more consistent with all of the observational constraints by changing the parameters of the blend model. Additional evidence against a blend has been obtained recently by M. Holman et al. (2005, in preparation), based on new high-quality and high-cadence photometric observations of the star. Their accurate light curves in two passbands define the morphology of ingress and egress significantly better than the OGLE measurements and are clearly inconsistent with the light curve from a blend configuration such as we described above, involving a background eclipsing binary. We conclude that the observations

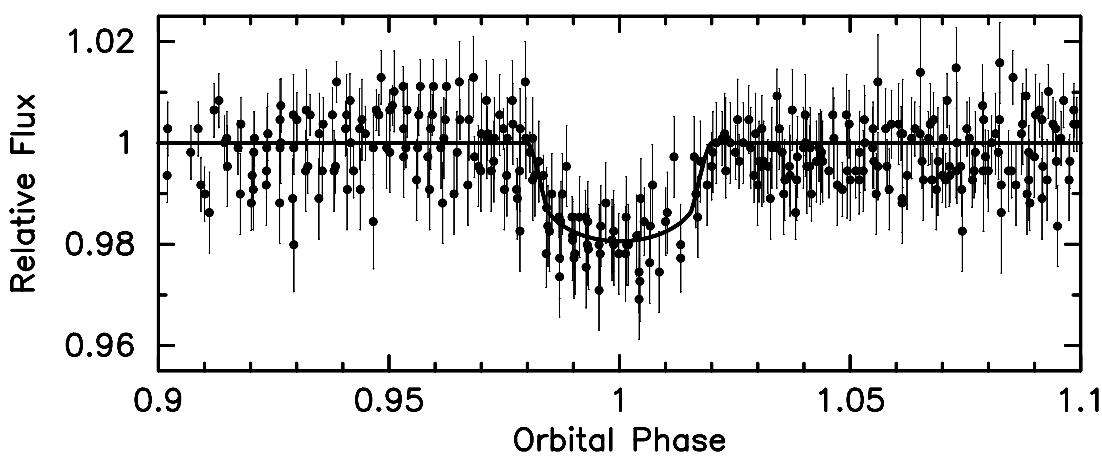

Fig. 3.—OGLE photometry for OGLE-TR-10 in the *I* band, with our best-fit transit light curve. The resulting parameters are listed in Table 2. [*See the electronic edition of the Journal for a color version of this figure.*]

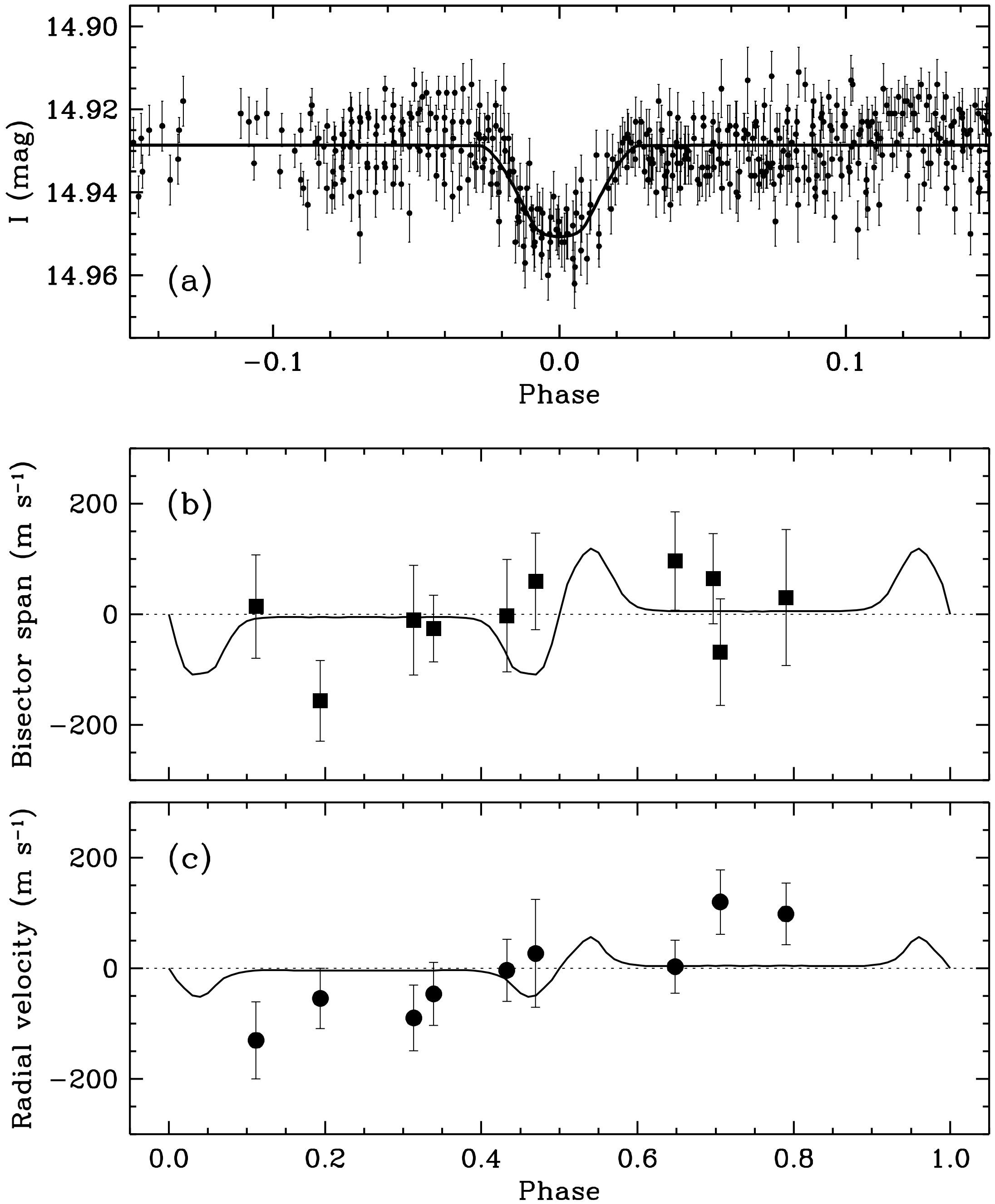

Fig. 4.—Blend model for OGLE-TR-10, in which an eclipsing binary (F9 V + K5 V) is located in the background of the main G star and has a relative brightness (4.5%) that makes it undetectable in our spectra. This particular model assumes a systemic velocity for the binary that is equal to the velocity of the G star, but extensive tests show that this has no effect on the conclusions. (*a*) Fit to the OGLE light curve near the primary eclipse. (*b*) Measured bisector spans as a function of phase, compared to predictions from the blend model. The cusps are the result of the large velocity semiamplitude of the eclipsing binary compared to the width of the lines of the G star (see Torres et al. 2005). (*c*) Our radial velocity measurements shown with the predictions from the blend model. The observed velocity trend is not reproduced by the model. [*See the electronic edition of the Journal for a color version of this figure.*]

do not support a blend scenario, and the planetary nature of the companion to OGLE-TR-10 is confirmed.

6. DISCUSSION

OGLE-TR-10b is the seventh known extrasolar transiting planet and the fifth to come out of the OGLE survey. Admittedly, the faintness of the transiting planet candidates from the OGLE survey requires some of the largest available telescopes merely to confirm their planetary status, and other detailed follow-up studies are very difficult to pursue with current instrumentation. Nevertheless, these discoveries around faint stars have been extremely important in the field of extrasolar planets. They account for most of the points in the current mass-radius diagram for giant planets (see Fig. 5), which relates key properties of these objects for our theoretical understanding of their structure and evolution. In addition, they have led to the discovery of a new class of "very hot Jupiters" (Bouchy et al. 2004; Konacki et al. 2003a, 2004) with remarkably short orbital periods (1–2 days). The importance of faint transit candidates from surveys like OGLE is likely to continue in the near future, especially given that the OGLE team has recently released a new set of 40 candidates that seem very promising (Udalski et al. 2004). The wide-field surveys, on the other

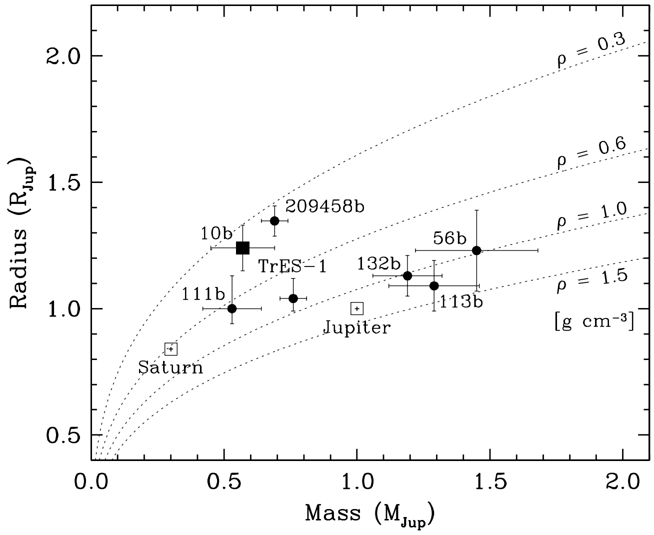

FIG. 5.—Radii of transiting extrasolar planets plotted against their masses. Jupiter and Saturn are included for reference, along with dotted lines of constant density. Data are from Brown et al. (2001) for HD 209458b, Torres et al. (2004a) for OGLE-TR-56b, Moutou et al. (2004) for OGLE-TR-132b, Pont et al. (2004) for OGLE-TR-111b, Sozzetti et al. (2004) for TrES-1, and this paper for OGLE-TR-10b. For OGLE-TR-113b we have combined the original observations reported by Bouchy et al. (2004) and Konacki et al. (2004), and derived an improved planetary mass of $1.29 \pm 0.17 M_J$ and a radius of $1.09 \pm 0.10 R_J$ (see http://www.gps.caltech.edu/~maciej/Planets/OGLE-TR-113b.html). [*See the electronic edition of the Journal for a color version of this figure.*]

hand, have only recently produced their first transiting planet (Alonso et al. 2004) despite having been in operation longer than the OGLE effort. They should provide planets for more detailed follow-up studies in the future.

OGLE-TR-10b is very similar to HD 209458b (Brown et al. 2001) in terms of its orbital and physical parameters. In particular, its orbital period (3.1 days) places it in the "hot Jupiter" category (planets with orbital periods of 3–4 days) already well populated from the radial velocity surveys. OGLE-TR-10b has a low average density and, like HD 209458b, might require an additional heating mechanism to explain it. There are now as many hot Jupiters as there are very hot Jupiters among the transiting planets uncovered photometrically, so the apparent lack of longer-period planets in the transit surveys that initially appeared to cause some concern (Bouchy et al. 2004; Pont et al. 2004) no longer seems to be a problem, as anticipated by Gaudi et al. (2005).

We note, finally, an apparent dichotomy in the mass-radius diagram of Figure 5, in that the four planets with the longer periods (in the hot Jupiter class) all have small masses ($\sim 0.7 M_J$), while all the short-period planets (very hot Jupiters) have masses roughly twice as large. This trend, noted previously by Mazeh et al. (2005), now seems to be reinforced and may perhaps be related to issues of survival of planets in very close proximity to their parent stars.

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