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NEW DATA AND IMPROVED PARAMETERS FOR THE EXTRASOLAR TRANSITING PLANET OGLE-TR-56b

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ABSTRACT

We report new spectroscopic observations with the Keck HIRES instrument of the recently discovered transiting planet OGLE-TR-56b. Our radial velocity measurements with errors of $\sim$100 m s^{-1} show clear variations that are in excellent agreement with the phasing (period and epoch) derived from the OGLE transit photometry. Careful analysis of the spectral line bisectors, along with numerical simulations of blend scenarios, supports the argument for the planetary nature of the companion. The new data, combined with measurements from the previous season, allow an improved determination of the mass of the planet, $M_p = (1.45 \pm 0.23)M_{\rm Jup}$. All available OGLE photometry, including new measurements made during the 2003 season, have also been analyzed to derive an improved value for the planetary radius of $R_p = (1.23 \pm 0.16)R_{\rm Jup}$. We discuss the implications of these results for the theory of extrasolar planets.

Subject headings: binaries: eclipsing — planetary systems — stars: low-mass, brown dwarfs — techniques: radial velocities

1. INTRODUCTION

Most extrasolar planets to date have been discovered with the high-precision radial velocity technique, which provides only a lower limit to the mass of the companion, because the inclination angle cannot be determined from spectroscopy alone. Systems for which the orbit happens to be nearly edge-on, so that the planet transits across the disk of the star once every orbital period, show a photometric signature and allow the absolute mass of the planet to be determined. Transiting systems are valuable in many other ways, providing the planet's absolute radius, as well as allowing a variety of follow-up studies (see, e.g., Brown et al. 2002; Charbonneau et al. 2002; Vidal-Madjar et al. 2003, 2004; Fortney et al. 2003; Richardson et al. 2003; Moutou et al. 2003). Transits are also a viable planet discovery technique: our recent follow-up in 2002 of candidates from the OGLE-III sample toward the bulge of the Galaxy (Udalski et al. 2002a, 2002b) resulted in the spectroscopic confirmation of a planet around the star OGLE-TR-56 ($V = 16.6$) with a period of 1.2 days. This is the first case originally discovered from its photometric signature rather than its Doppler signature (Konacki et al. 2003a).

The limited amount of spectroscopic data we collected during our 2002 season allowed for only a relatively uncertain estimate of the mass of OGLE-TR-56b. A combined orbital solution using our velocities and the OGLE-III light curve yielded $M_p = (0.9 \pm 0.3)M_{\rm Jup}$ (Konacki et al. 2003a). In this paper we report new radial velocity measurements that allow us to improve the accuracy of the mass determination and to better characterize its uncertainty, as well as to strengthen the case against false-positive scenarios. In addition, we present an updated transit light curve solution based on improvements in the OGLE photometry.

2. OBSERVATIONS AND REDUCTIONS

OGLE-TR-56 was observed spectroscopically on five nights in 2003 August with the Keck I Telescope and the HIRES instrument (Vogt et al. 1994). We obtained a total of eight new spectra of the object, with exposure times ranging from 30 to 50 minutes. The setup allowed us to record 35 usable echelle orders covering the spectral range from 3850 to 6200 Å at a resolving power of $R \simeq 65,000$. Typical signal-to-noise ratios per pixel are in the range of 10–20 for a single exposure. Our main wavelength reference was provided by a hollow-cathode thorium-argon lamp, of which we obtained short exposures immediately preceding and following each stellar exposure.

In addition to our program star, two brighter stars were observed (HD 209458 and HD 179949) that have known low-amplitude velocity variations at the level of about 200 m s^{-1} (peak to peak) due to orbiting substellar companions (Henry et al. 2000; Charbonneau et al. 2000; Mazeh et al. 2000; Tinney et al. 2001), which we used as "standards." These stars were observed with the iodine gas absorption cell (Marcy & Butler 1992). All HIRES spectra were bias-subtracted, flat-fielded, cleaned of cosmic rays, and extracted using the MAKEE reduction package written by Barlow (2002). Compared to the procedures followed in Konacki et al. (2003a), a number of details in the reductions were fine-tuned for the new observations and led to slightly improved noise levels and better velocities. We therefore re-reduced the original 2002 spectra in the same way as the new spectra for uniformity. Wavelength solutions based on the Th-Ar exposures were carried out with standard tasks in IRAF.[5]

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TABLE 1
Radial Velocities Measurements for OGLE-TR-56, in the Barycentric Frame

HJD (2,400,000+)	Phase	Velocity[a] (km s^{-1})	Error[b] (km s^{-1})
52,480.9239	0.8570	−48.062	0.278
52,481.9095	0.6702	−48.177	0.067
52,483.9068	0.3182	−48.506	0.082
52,853.7474	0.4866	−48.408	0.087
52,853.8960	0.6092	−48.133	0.085
52,854.8062	0.3602	−48.287	0.163
52,855.7863	0.1689	−48.548	0.091
52,855.8772	0.2439	−48.654	0.074
52,863.7802	0.7650	−48.053	0.093
52,864.7497	0.5649	−48.188	0.074
52,864.8389	0.6386	−47.863	0.114

[a] Includes a correction of -192 m s^{-1} to place the 2003 velocities on the same scale as the 2002 measurements (see text).

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

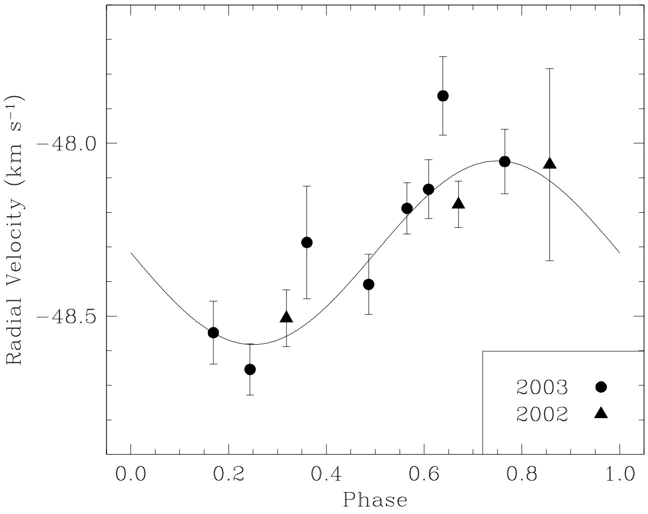

Fig. 1.—Radial velocity observations and fitted velocity curve for OGLE-TR-56, as a function of orbital phase (ephemeris from § 5).

Radial velocities for OGLE-TR-56 and for the standard stars were derived by cross-correlation against a synthetic template computed specifically for the parameters of each object, as detailed by Konacki et al. (2003b). For the cross-correlations we used the IRAF task *xcsao* (Kurtz & Mink 1998). The final velocities are the weighted average of all echelle orders in each spectrum (only orders not affected by the iodine were used for the standards). Formal errors were derived from the scatter of the velocities determined from the different orders. These are typically well under $\sim$100 m s^{-1} and do not include systematic components, which we have previously estimated to be no larger than about 100 m s^{-1} for this instrumentation (see Konacki et al. 2003b). The radial velocities in the frame of the solar system barycenter from all of the spectra (2002 and 2003), along with their final errors, are listed in Table 1.

3. SPECTROSCOPIC ORBITAL SOLUTION

The new radial velocities for OGLE-TR-56 show clear changes with orbital phase. The phasing is well known from the photometric observations that yield a very accurate period and transit epoch (see below). However, there is also a systematic shift, compared to the 2002 velocity measurements, of about 200 m s^{-1}. A similar shift is observed in the two standards, indicating that it is a real effect. Such offsets from run to run are common in radial velocity work and can be due to a number of reasons, including temperature changes and other instrumental effects beyond the control of the observer. In order to optimally remove this shift using all of the available information, we developed a procedure by which we fit for the orbits of the three stars simultaneously. We solve for the shift at same time as the rest of the orbital elements and assume that the offset is identical for the three stars. The phase and velocity amplitudes of the circular orbits for HD 209458 and HD 179949 are known from high-precision velocity work (Mazeh et al. 2000; Tinney et al. 2001) and were held fixed. Therefore, the five free parameters in the least-squares adjustment are the semiamplitude of the velocity curve of OGLE-TR-56, the center-of-mass velocity for each star, and the common offset between the 2002 and 2003 seasons. The ephemeris for OGLE-TR-56 is also fixed, as mentioned above, to the value determined in our light curve analysis, described in § 5.

The solution, based on a total of 28 observations (11 of our target, nine of HD 179949, and eight of HD 209458), gives a velocity semiamplitude for OGLE-TR-56 of $K = 265 \pm 38$ m s^{-1}. The offset between the two observing seasons is determined to be $\Delta_{2003-2002} = +192 \pm 47$ m s^{-1}, and the overall rms residual from the fit for OGLE-TR-56 is 114 m s^{-1}. The minimum mass for the planet in orbit around our target is $M_p \sin i = (1.33 \pm 0.21) \times 10^{-3}(M_s + M_p)^{2/3}\, M_\odot$, where M_s is the mass of the primary star. The observations for OGLE-TR-56, along with the orbital fit, are shown in Figure 1. The measurements listed in Table 1 include the offset $\Delta_{2003-2002}$, so that all measurements are referred to the 2002 frame.

The center-of-mass velocities derived for the three stars are -24.579 ± 0.045 (HD 179949), -14.577 ± 0.048 (HD 209458), and -48.317 ± 0.045 km s^{-1} (OGLE-TR-56). For the latter object the difference compared to the value of -49.49 km s^{-1} from Konacki et al. (2003a) is due to differences in the reduction of the spectra (§ 2) and the increased number of observations in the present solution. The above center-of-mass velocities are on the reference frame of the templates used for the cross-correlations, which are calculated spectra. The errors given are strictly internal and do not include contributions from uncertainties in the instrumental zero point (of the kind that lead to $\Delta_{2003-2002}$) or in the wavelength scale or other details of the model atmospheres that go into the calculation of the templates. The absolute accuracy of these velocities is likely to be limited to several hundred m s^{-1}. Nevertheless, it may be of interest for future studies to refer the center-of-mass velocity of OGLE-TR-56 to some well-defined frame of reference. A comparison of our values for the two standards against the results by Nidever et al. (2002) gives systematic differences of 0.083 (HD 179949) and 0.182 km s^{-1} (HD 209458), in the sense that our velocities are larger in both cases. The average offset is 0.132 km s^{-1}. Applying this correction to OGLE-TR-56 gives the value -48.449 km s^{-1} for its center-of-mass velocity, on the same scale as Nidever et al. (2002), with an estimated total uncertainty of approximately 100 m s^{-1}.

4. RULING OUT BLEND SCENARIOS

Following Konacki et al. (2003b), we used our new spectroscopic observations to reexamine the possibility that the

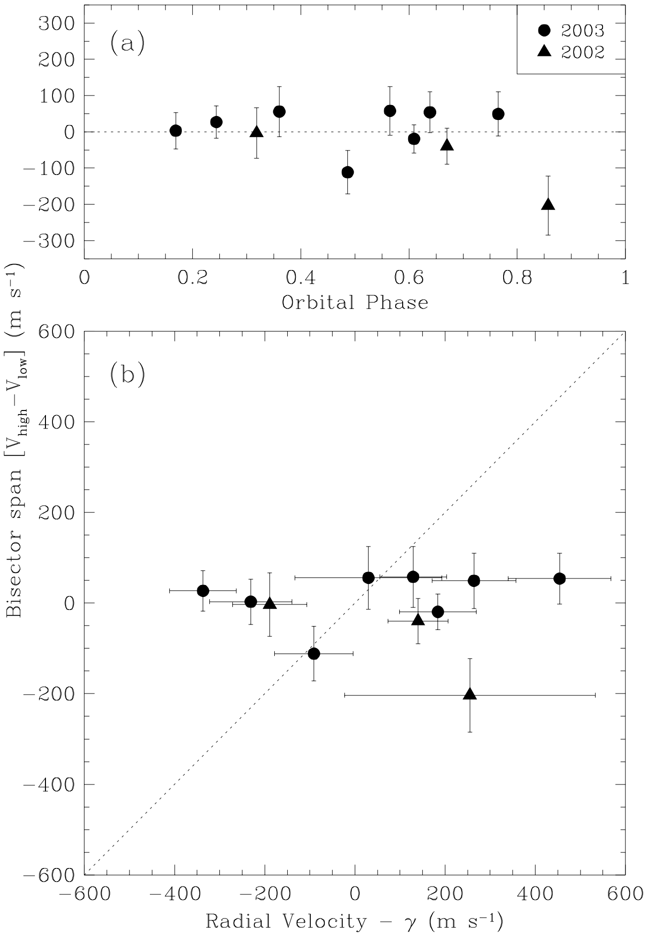

FIG. 2.—(*a*) Bisector span used as a proxy for line asymmetry for each of our spectra of OGLE-TR-56, as a function of orbital phase (see text). The error bars are determined from the agreement between different echelle orders. The asymmetries are very small, and there is no obvious correlation with phase. (*b*) Bisector span as a function of measured radial velocity (with the center-of-mass velocity γ subtracted). Once again, there is no obvious correlation. The dotted line represents the one-to-one relation, for reference.

velocity variations we measured for OGLE-TR-56 are not produced by a planet orbiting the star but are instead the result of a blend configuration. In this case, small asymmetries in the spectral lines due to the presence of another star (e.g., the primary of an eclipsing binary along the same line of sight, as in a triple system) can lead to spurious velocities as the second set of lines moves back and forth with the photometric period. A good illustration of this effect is given by the example of HD 41004AB, a close visual binary studied by Santos et al. (2002). Those authors found that the small velocity changes, originally suggestive of a planetary companion around the primary star, were accompanied by changes in the "bisector span" (which quantifies the line asymmetries) that are of the same order. Furthermore, the asymmetries correlated with phase and velocity and agreed with predictions based on numerical simulations of such a blend scenario. Thus, they were able to rule out the presence of a planet around HD 41004A, arguing instead for a brown dwarf companion around the secondary HD 41004B (see also Zucker et al. 2003).

To see whether a similar situation might hold for OGLE-TR-56, we computed the line bisectors for each of our spectra directly from the correlation functions (co-added over all orders), which are representative of the average line profile for the star. We then calculated the bisector span as the velocity difference between the bisectors at two different correlation levels. The results are displayed in Figure 2. There is no significant change in the line bisectors within the errors, at least not at the level of the velocity changes we measure.

To further investigate this we performed extensive numerical simulations (similar to those of Santos et al. 2002) of blend scenarios that satisfy the strong observational constraints on the brightness of the eclipsing binary relative to OGLE-TR-56 ($\leq$3%; Konacki et al. 2003b), as well as on the depth and duration of the transits. The upper limit on the brightness, further supported by examination of our present spectra, is the strongest of these constraints. These tests show that while the expected line bisector variations are small ($\sim$30 m s^{-1}), as we indeed observe, the predicted radial velocity variations induced by the asymmetries are *also* very small. Their semiamplitude of about 20 m s^{-1} or less differs from the velocity semiamplitude we measure, by a large factor. This is essentially due to the rather restrictive upper limit we can place on the brightness of any additional stars that might be present in our spectra, which strongly attenuates their perturbing effect on the line profiles. We conclude that the observations are inconsistent with a blend scenario, and therefore that the velocity variations are real and imply a planetary mass for the occulting body.

5. ANALYSIS OF THE LIGHT CURVE

Photometric observations of OGLE-TR-56 by the OGLE team have continued after its discovery in 2001 and now include three observing seasons (1113 measurements covering more than 600 cycles of the orbit). A total of 13 transits have been recorded. Additionally, small corrections for systematic errors in the photometry have recently been applied that slightly improve the errors.[6] We have used these new data to update the ephemeris and the light curve solution.

The reanalysis of the transit light curve was carried out with the tools developed by Mandel & Agol (2002). The stellar parameters (mass and radius) and the limb-darkening coefficient in the *I* band, u_I, were adopted from Konacki et al. (2003a) and Sasselov (2003): $M_s = 1.04 \pm 0.05\ M_\odot$, $R_s = 1.10 \pm 0.10\ R_\odot$, and $u_I = 0.56 \pm 0.06$. We solved for five parameters: the orbital period, transit epoch, inclination angle, planet radius, and mean magnitude level. Figure 3 shows a section of the χ^2 surface in the vicinity of the minimum, in the plane of planet radius versus inclination angle. The best-fit values are given in Table 2, and the rms residual of the fit is 0.005 mag. Final errors in the derived parameters include the contribution from uncertainties in the adopted quantities for the star, as well as the mass of the planet. These were estimated from Monte Carlo simulations and added quadratically to the statistical errors. The new ephemeris we derive, $T = 2{,}452{,}075.1046(17) + 1.2119189(59)n$ (where n is the number of cycles since the transit epoch and T is in HJD), is consistent with that given in footnote 6. The fit to the OGLE-III photometry is shown in Figure 4.

6. DISCUSSION AND CONCLUSIONS

Our new radial velocity measurements for OGLE-TR-56 confirm the variations reported by Konacki et al. (2003a) and are consistent with the photometric ephemeris that was held

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[6] See http://bulge.princeton.edu/~ogle/ogle3/transits/ogle56.html and Kruszewski & Semeniuk (2003).

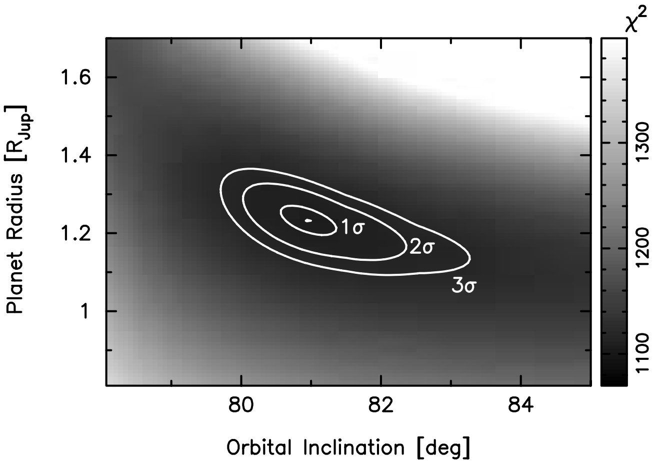

FIG. 3.—χ^2 surface corresponding to the light curve solution for OGLE-TR-56, in the plane of planet radius vs. orbital inclination. The number of degrees of freedom in the fit is 1108.

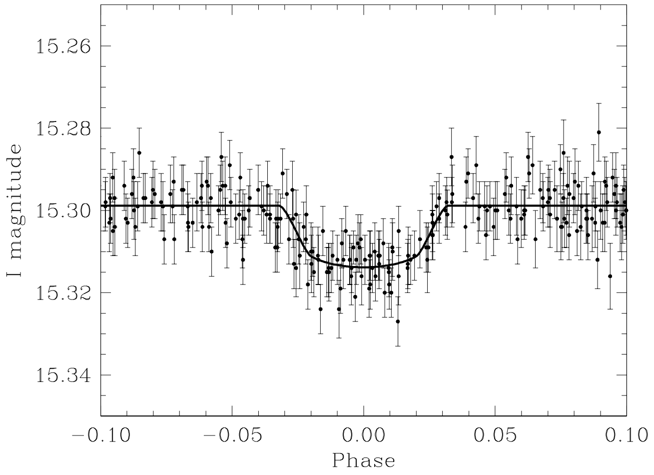

FIG. 4.—OGLE-III photometry for OGLE-TR-56 and our best-fit transit light curve.

fixed in the orbital solution. The semiamplitude we derive using all the data available, $K = 265$ m s^{-1}, is approximately 60% larger than the original discovery estimate ($K = 167$ m s^{-1}), which was based on only three observations (with two free parameters). The significance of the determination is now much greater, as can be seen visually in Figure 1, and the errors are better characterized because of the increased number of observations. Consequently, the mass we derive is also larger: $M_p = (1.45 \pm 0.23)M_{\rm Jup}$. The radius, $R_p = (1.23 \pm 0.16)R_{\rm Jup}$, is similar to the initial determination. The reality of the velocity variations is supported by the lack of any significant spectral line asymmetries (as quantified by the bisector spans) and by numerical simulations of blend configurations that are unable to reproduce the measured velocity amplitude while still satisfying all other observational constraints, in particular the upper limit on the presence of other stars in our spectra.

OGLE-TR-56b is roughly twice as massive as HD 209458b and marginally smaller [$M_p = (0.69 \pm 0.02)M_{\rm Jup}$, $R_p = 1.42^{+0.12}_{-0.13}R_{\rm Jup}$; Cody & Sasselov 2002]. As shown in Figure 5, both planets appear to have radii that are larger than expected from theoretical cooling models that include a consistent treatment of irradiation by the parent star (see, e.g., Baraffe et al. 2003; Burrows et al. 2003). The possible need for additional sources of internal heating is actively being debated in the literature (Showman & Guillot 2002; Bodenheimer et al. 2003; Chabrier et al. 2004), although the observational errors are still rather large and OGLE-TR-56b may yet be consistent with the models. The radius of HD 209458b, on the other hand, does appear significantly larger than expected. More precise radius determinations for both planets are needed to resolve this issue. In fact, despite the difference in quality between the OGLE-III light curve for OGLE-TR-56 and the remarkable *HST* light curve for HD 209458 (Brown et al. 2001), the error in our radius determination is not much worse than that of Cody & Sasselov (2002). The reason for this is that the dominant contribution in both cases is the uncertainty in the stellar parameters, which are at the same level for the two stars. Multicolor *HST* photometry for both HD 209458 and OGLE-TR-56 should improve the situation considerably.

TABLE 2
PARAMETERS FOR OGLE-TR-56b

Parameter	Value
Orbital period (days)	1.2119189 ± 0.0000059
Transit epoch (HJD−2,400,000)	$52{,}075.1046 \pm 0.0017$
Center-of-mass velocity (km s^{-1})	-48.317 ± 0.045
Eccentricity (fixed)	0
Velocity semiamplitude (m s^{-1})	265 ± 38
Inclination angle (deg)	81.0 ± 2.2
Stellar mass ($M_\odot$) (adopted)	1.04 ± 0.05
Stellar radius ($R_\odot$) (adopted)	1.10 ± 0.10
Limb-darkening coefficient (*I* band)	0.56 ± 0.06
Planet mass ($M_{\rm Jup}$)	1.45 ± 0.23
Planet radius ($R_{\rm Jup}$)	1.23 ± 0.16
Planet density (g cm^{-3})	1.0 ± 0.3
Semimajor axis (AU)	0.0225 ± 0.0004

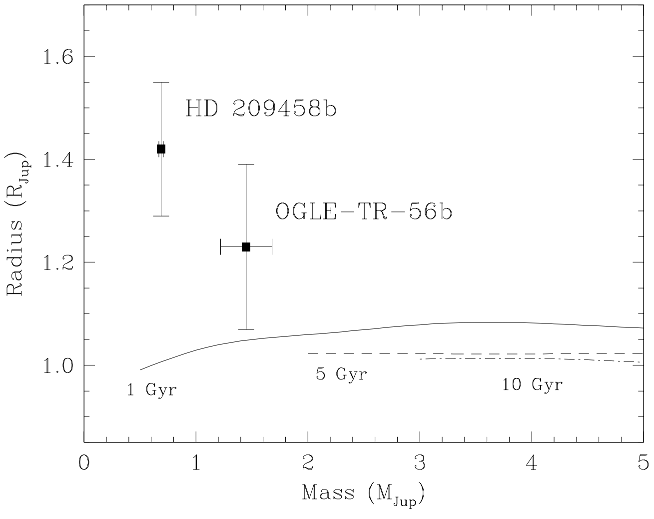

FIG. 5.—Mass-radius relation by Baraffe et al. (2003) for close-in giant planets, including the effect of heating by irradiation from the central star. The observed values for HD 209458b (Cody & Sasselov 2002) and OGLE-TR-56b (this paper) would appear to be inconsistent with these models at the 3–5 Gyr ages inferred for the two planets. However, given the uncertainties, OGLE-TR-56 is only moderately inconsistent. Note also that the models shown (computed specifically for HD 209458b) have less irradiation than needed for OGLE-TR-56b, which is twice as close to its parent star.

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