The Astrophysical Journal, 682: L49–L52, 2008 July 20

DETECTION OF PERIOD VARIATIONS IN EXTRASOLAR TRANSITING PLANET OGLE-TR-111b[1]

Rodrigo F. Díaz,[2] Patricio Rojo,[3] Mario Melita,[2] Sergio Hoyer,[3] Dante Minniti,[4,5] Pablo J. D. Mauas,[2] and María Teresa Ruíz[3]

Received 2008 April 25; accepted 2008 June 6; published 2008 July 3

ABSTRACT

Two consecutive transits of planetary companion OGLE-TR-111b were observed in the *I* band. Combining these observations with data from the literature, we find that the timing of the transits cannot be explained by a constant period and that the observed variations cannot be originated by the presence of a satellite. However, a perturbing planet with the mass of the Earth in an exterior orbit could explain the observations if the orbit of OGLE-TR-111b is eccentric. We also show that the eccentricity needed to explain the observations is not ruled out by the radial velocity data found in the literature.

Subject headings: planetary systems — stars: individual (OGLE-TR-111)

Online material: color figures

1. INTRODUCTION

The observations of transiting extrasolar planets have produced some of the most interesting results in the study of other planetary systems. Their orbital configurations have permitted the first direct measurements of radius, temperature, and composition (Swain et al. 2008; Harrington et al. 2007 and references therein), all of which are critical to constraining the interior and evolution models of extrasolar planets (e.g., Fortney 2008).

It has been further realized that the presence of variations in the timing of transits can be attributed to otherwise undetectable planets in the system (see, for example, Miralda-Escudé 2002; Holman & Murray 2005; Agol et al. 2005; Heyl & Gladman 2007; Ford & Holman 2007; Simon et al. 2007). Deeg et al. (2008) and Ribas et al. (2008) reported indirect detections of unseen companions by monitoring eclipse timing of the binary stellar system CM Draconis (1.5 M_J to 0.1 $M_\odot$ candidate) and variations in the orbital parameters of the planetary system around GJ 436 (5 $M_\oplus$ companion), respectively. However, this last case has been recently argued against by Alonso et al. (2008). Besides, recently discovered transiting planets (Pont et al. 2008; Udalski et al. 2008) exhibiting shifts in their radial velocities are promising new candidates to search for variations in the timing of their transits. On the other hand, Steffen & Agol (2005) found no evidence of variations in the timing of transits of the TrES-1 system, after analyzing data for 12 transits. Also, after monitoring 15 transits of the star HD 209458, Miller-Ricci et al. (2008) were able to set tight limits to a second planet in the system.

Here we report a significant detection of variability in the timing of the transits of extrasolar planet OGLE-TR-111b (Udalski et al. 2002; Pont et al. 2004) and discuss its possible causes, including a second unseen planet OGLE-TR-111c.

In a previous work (Minniti et al. 2007) we reported a single transit observed in the *V* band that occurred around 5 minutes before the expected time obtained using the ephemeris of Winn et al. (2007), but the result was inconclusive since it had a 2.6 σ significance. In the present work we analyze data of two consecutive follow-up transits of the same planet.

Section 2 presents the new data and the reduction procedures, in § 3 we describe the technique used to measure the central times of the transits. Finally, in § 4 we present our results and discuss their implications.

2. OBSERVATIONS AND DATA REDUCTION

We observed two consecutive transits of planetary companion OGLE-TR-111b in the *I* band with the FORS1 instrument (Appenzeller et al. 1998) at the European Southern Observatory (ESO) Very Large Telescope (VLT). The observations were acquired during a Director's Discretionary Time run during the nights of 2006 December 19 and December 23. Since the orbital period of OGLE-TR-111b ($P = 4.01444$ days) is almost an exact multiple of Earth's rotational period, those were the last events visible from the ESO facilities in Chile until 2008 May.

FORS1 is a visual focal-reducer imager who had a 2048×2048 Tektronik CCD detector and a pixel scale of 0.2 arcsec pixel^{-1}. For the observations, a nearby bright star was moved outside the field of view, leaving OGLE-TR-111 near the center of the northeastern quadrant. The chosen integration time of 6 s was the maximum possible to avoid saturation of the star in case of excellent seeing. A total of over 9 hr of observations were obtained during the second half of both nights. During the first night the seeing remained stable below 0.6″, but it oscillated between 0.6″ and 1.4″ during the second night. Observations finished near local sunrise, producing a noncentered bracketing of the events and an additional source of scatter as the sky background increased near sunrise.

We used the ISIS package (Alard & Lupton 1998; Alard 2000) to compute precise differential photometry with respect to a reference image in a 400×400 pixel subframe. The reference image was obtained combining the 10 images with best seeing, which produced an image with FWHM $\approx 0.46''$. The resulting subtracted images were checked for abnormally large deviations or means significantly different from zero; an image from the first night and three images from the end of the second night were discarded in this way, leaving a total of 488 images.

Aperture photometry was performed on the difference images using IRAF DAOPHOT package (Stetson 1987), which was found to give better results than the ISIS photometry rou-

[1] Based on observations collected with the Very Large Telescope at Paranal Observatory (ESO Programme 278.C-5022).

[2] Instituto de Astronomía y Física del Espacio (CONICET-UBA), Buenos Aires, Argentina; rodrigo@iafe.uba.ar.

[3] Department of Astronomy, Universidad de Chile, Santiago, Chile.

[4] Department of Astronomy, Pontificia Universidad Católica, Casilla 306, Santiago 22, Chile.

[5] Specola Vaticana, V-00120 Citta del Vaticano, Italy.

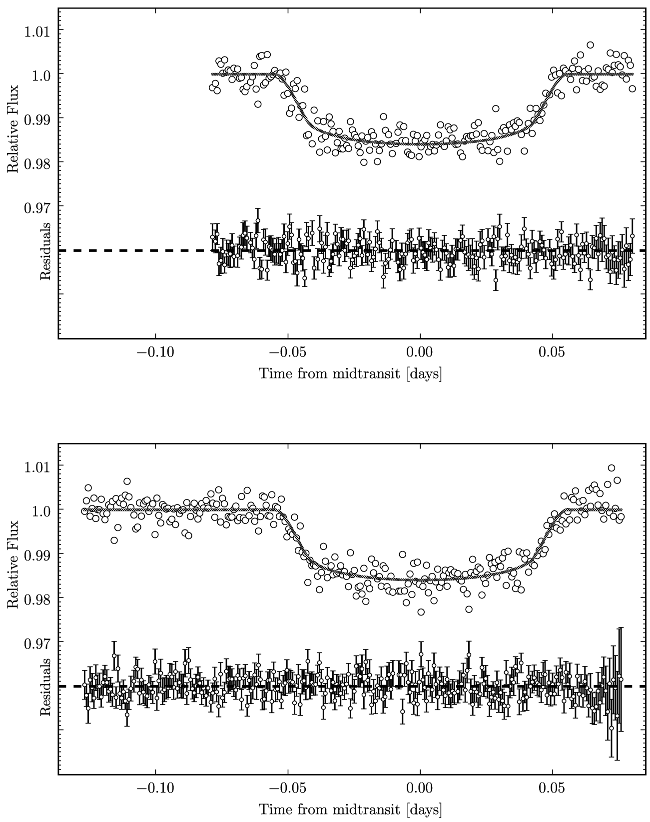

FIG. 1.—Relative flux during two consecutive transits of planetary companion OGLE-TR-111b. Except for those mentioned in the text, no points were discarded. In the upper (lower) panel we present data taken on the night of 2006 December 19 (23). The residuals with the error bars are also shown. The dashed line represents the displaced zero for the residuals, and the (*red*) solid line is the best-fit model. Note how the errors increase at the end of the second night due to the increase of the background noise caused by dawn. [*See the electronic edition of the Journal for a color version of this figure.*]

tine phot.csh (see Hartman et al. 2004). In agreement with Gillon et al. (2007) we found that the scatter increased rapidly with aperture size, although in our case the transit amplitude remained constant (within a 0.1% level). We therefore choose a 5 pixel aperture since our goal is to obtain precise measurements of the central times of transits, and thus the relevance of obtaining the correct amplitude is diminished.

The uncertainty in the difference flux was estimated from the magnitude error obtained from DAOPHOT/APPHOT, which uses Poisson statistics and considers the deviation in the sky background. The flux in the reference image was measured using PSF-fitting photometry with DAOPHOT/ALLSTARS. The systematic error introduced by this measurement is studied further in § 3.

To remove possible systematic effects from the light curves we employed the signal reconstruction method of the trend-filtering algorithm (Kovács et al. 2005). We refer readers to this paper for a description of the method as well as for an illuminating discussion of the possible causes of systematic effects. We chose light curves of 19 stars distributed as uniformly as possible around OGLE-TR-111 as template light curves and checked them for obvious variability or uncommonly large scatter. The algorithm was iterated until the relative difference in the curves obtained in two successive steps was less than 10^{-5}. The resulting science light curves for both nights are shown in Figure 1. The standard deviation before the transit of the second night is 2.65 mmag, almost reaching the photon noise limit of 2.55 mmag.

TABLE 1
ORBITAL AND PHYSICAL PARAMETERS FOR SYSTEM OGLE-TR-111

Parameter	Value	Confidence Limits
R_s ($R_\odot$)	0.811	$^{+0.041}_{-0.048}$
R_p ($R_{\rm Jup}$)	0.922	$^{+0.057}_{-0.067}$
i (deg)	88.2	$^{+0.65}_{-0.85}$
$t_{IV} - t_I$ (hr)	2.670	± 0.014
T_{c1} (HJD − 2,450,000)	4088.79145	± 0.00045
T_{c2} (HJD − 2,450,000)	4092.80493	± 0.00045
$T_{c,\rm VIMOS}$ (HJD − 2,450,000)	3470.56389	± 0.00055

3. MEASUREMENTS

Planetary and orbital parameters, including the central times of transits, were fitted to the OGLE-TR-111 light curve. The model used consisted on a perfectly opaque spherical planet of radius R_p and mass M_p, orbiting a limb-darkened star of radius R_s and mass M_s (Mandel & Agol 2002) in a circular orbit of period P and inclination i. We considered a quadratic model for the limb darkening, with coefficients taken from Claret (2000) for a star with $T_{\rm eff} = 5000$ K, $\log g = 4.5$ cm s^{-2}, and [Fe/H] = 0.2 and microturbulent velocity $\xi = 2$ km s^{-1}. The masses of the planet and the star were fixed to the values reported by Santos et al. (2006): $M_s = 0.81\ M_\odot$ and $M_p = 0.52\ M_{\rm Jup}$. The remaining five parameters for the model—R_p, R_s, i, and the central time of each transit (T_{c1} and T_{c2})—were adjusted using the 488 data points of the light curve.

The parameters were obtained by minimizing the χ^2 statistic using the downhill simplex algorithm (Nelder & Mead 1965) implemented in the SciPy library.[6] We present the parameters in Table 1 and the best-fit model and the residuals in Figure 1. Note that, except for the planetary radius and the time between first and last contacts, the parameters reported in Table 1 are in agreement with previously published values (see § 4).

The uncertainties in the parameters were estimated using the Markov chain Monte Carlo (MCMC) method, which is described in detail by Tegmark et al. (2004), Ford (2005), and Holman et al. (2006). We constructed chains with 500,000 points each and discarded the first 100,000 to guarantee convergence. The jump function employed was the addition of a Gaussian random number to each parameter, and a global scaling of the sigma of the random Gaussian perturbations was adjusted after convergence was reached so that between 20% and 30% of the jumps were executed.

In this manner, we built five independent chains and found that the mean values and the confidence intervals of the parameters (computed as described below) are in excellent agreement for all chains, a sign of good convergence. Besides, the correlation length, defined as the number of steps over which the correlation function (see Tegmark et al. 2004, Appendix A) drops to 0.5, was about 80 for the central times of the transits and around 800 for the highly covariant parameters R_p, R_s, and i, in agreement with Winn et al. (2007). This produces an effective length of about 5000 for T_{c1} and T_{c2}, a sign of good mixing.

For each chain we took a random subset of 5000 values (the effective length) of the central times and tested the hypothesis that the sets were drawn from identical populations using the Wilcoxon's rank-sum test (see Frodesen et al. 1979, § 14.6.9). For all cases the test statistic (which is approximately Gaussian) falls within 2.5 σ of the expected value, and therefore the hypothesis cannot be discarded for significance levels below ≈1.2%.

[6] See the SciPy Web site at http://www.scipy.org.

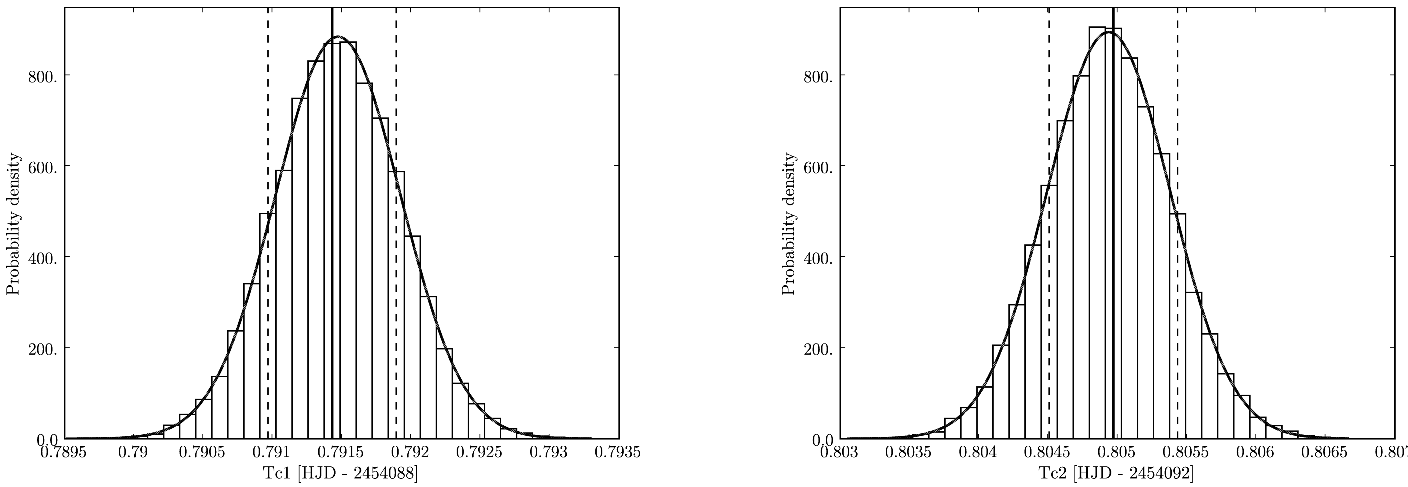

FIG. 2.—Probability density distributions for the central times of the transits obtained from the MCMC simulations. The thick vertical solid line indicates the median of the distribution, and the dotted lines mark the upper and lower 68% confidence limits. The solid (*blue*) curve is a Gaussian distribution with the same mean and standard deviation as the data. [*See the electronic edition of the Journal for a color version of this figure.*]

Figure 2 shows two representative probability density distributions corresponding to the two central transit times, and Table 1 reports the median and the upper and lower 68% confidence limits, defined in such a way that the cumulative probability below (above) the lower (upper) confidence limit is 16%. As a solid curve we plot the Gaussian probability density having the same mean and standard deviation as the data.

To test the robustness of our results, the fit was repeated by fixing the values of R_p, R_s, and i to those reported by Winn et al. (2007) ($R_p = 1.067\ R_{\rm Jup}$, $R_s = 0.831\ R_\odot$, $i = 88.1°$) and including the out-of-transit flux as an adjustable parameter. The obtained times for the centers of the transits are in agreement with those reported above. The same results are obtained if only R_s is fixed to the value of Winn et al. (2007).

Additionally, to check that the systematic effects removal procedure does not modify the shape of the light curves, we also measured the central times in the original curves obtained with aperture photometry. Again, the obtained values are in excellent agreement with the ones presented above, and the errors computed with MCMC are larger by a factor between 1.04 and 1.99, depending on the parameter, as expected.

Possible systematic errors may be introduced by the choice of the stellar mass, the orbital period—which affects the determination of the orbital radius—the model for the limb darkening, and the flux in the reference image. To study these effects we obtained new fits to the data by varying the fixed parameters and the function for the limb darkening. The stellar mass was varied by $\pm 10\%$, the photometry in the reference image was varied by ± 0.1 mag, and the orbital period by $\pm 10\ \sigma$ (see eq. [2]). The coefficients for the quadratic limb-darkening model were adjusted from the data instead of fixed to the values of Claret (2000), and additionally, a linear limb-darkening model was considered, both fixing the linear coefficient to the value computed by Claret (2000) and adjusting it as part of the fit. In all cases, the variation in the central times of transit was smaller than the uncertainties reported in Table 1. We therefore conclude that the values obtained for the central transit times are robust.

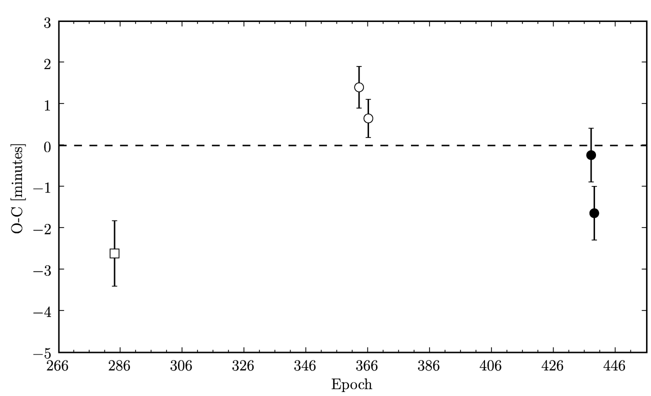

FIG. 3.—Observed minus calculated times (in minutes) for the transits of planet OGLE-TR-111b in front of its host star. The filled circles are the new transits presented in this work, the empty circles are from Winn et al. (2007), and the empty square is the transit presented by Minniti et al. (2007), which has been reprocessed for this work.

4. RESULTS AND DISCUSSION

We fitted a straight line to the central times of the two transits together with those from Winn et al. (2007) and Minniti et al. (2007). The central time of this last transit ($T_{c,\rm VIMOS}$) has been remeasured using the procedure described above, and the result is shown in Table 1. In this way we obtained a new ephemeris for the transit times:

$$T_c = 2{,}454{,}092.80607 \pm 0.00029\ \text{(HJD)} \qquad (1)$$

$$P = 4.0144540 \pm 0.0000038\ \text{days}, \qquad (2)$$

with correlation coefficient $\rho = 0.785$. The reduced χ^2 is 9.04, indicating a poor fit. Note that the value of the period is consistent with the value reported by Winn et al. (2007). The fit was repeated including a point for the OGLE data, and we also obtained the period from a simultaneous fit to all the available photometry (OGLE; Winn et al. 2007; Minniti et al. 2007; and this work). In both cases the obtained value is in excellent agreement with the one reported above.

In Figure 3 we plot the residuals of the fit. It is clear that the observed minus computed ($O-C$) values are not consistent with a constant period since the VIMOS transit, one of the transits from Winn et al. (2007), and one of the FORS transits lie $-3.29\ \sigma$, $2.79\ \sigma$, and $-2.52\ \sigma$ away from zero, respectively. However, the data available to date are not enough to determine the nature of these variations. Nevertheless, we have been able to discard a few possibilities and study some others. We present

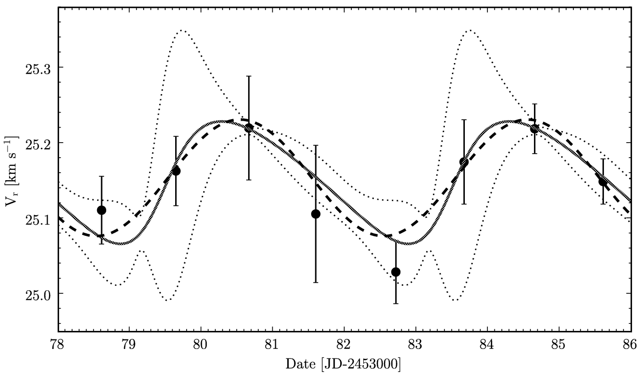

FIG. 4.—Radial velocity measurements from Pont et al. (2004) together with the best fit (*solid line*) and the corresponding $\pm 1\ \sigma$ curves (*dotted lines*). Also shown is the fit for $e = 0$ (*dashed line*). [*See the electronic edition of the Journal for a color version of this figure.*]

some preliminary results here and defer a more detailed study for a future work.

First, the hypothesis of an exomoon seems unlikely, since the mass needed to produce the observed $O-C$ amplitude is at least 1/26 of the planetary mass if the moon is at a Hill radius from the planet. However, at this distance the orbit of the moon is expected to be unstable. For moons closer to the planet, the needed mass increases. These are extreme values when compared with the solar system, where this ratio never exceeds 2.5×10^{-4} (Cox 2000).

On the other hand, several planetary system configurations reproduce the observed trend. The equations of motion for the three-body problem were solved with the Bulirsch-Stoer algorithm implemented in the Mercury package (Chambers 1999) using different sets of orbital parameters for the perturbing planet, and the results were compared with the observations. A particularly interesting solution is that an exterior Earth-mass planet near the 4 : 1 resonance produces the observed amplitude and periodicity in the $O-C$ times, if the orbit of TR 111b is eccentric ($e = 0.3$). On the other hand, the mass of the perturber planet must be at least around 4 $M_{\rm Jup}$ if the orbit of the interior planet is nearly circular. This shows the importance of accurately measuring the eccentricity of the interior planet through radial velocity data or measurements of the planet occultation (see Deming et al. 2007).

In the discovery paper by Pont et al. (2004) the orbital solution was obtained by fixing the eccentricity of TR 111b to zero. Although this is reasonable for a single planet in a close orbit to the star, since circularization is very effective in those conditions (see, for example, Zahn 1977), a second planet can perturb the orbit of the first one, increasing its eccentricity. Therefore, we reanalyzed the radial velocity data from Pont et al. (2004) in order to constrain the possible eccentricity of the system. We found that the data are compatible with an eccentricity of 0.3, with a reduced χ^2 of about 0.4 (for 5 degrees of freedom; see Fig. 4) compared to the value of 0.7 for a circular orbit, as reported in the original paper.

Additionally, note that the 1.55 σ difference between the transit length presented in Table 1 and that reported by Winn et al. (2007) might indicate a change in the inclination angle of OGLE-TR-111b (see Ribas et al. 2008; Miralda-Escudé 2002), which could in principle help constrain the parameters of the perturber planet. Future observations are warranted in order to pinpoint the origin of the variation in the period of this interesting planet.

D. M., P. R., and S. H. are supported by the CATA and FONDAP Center for Astrophysics 15010003.

Facilities: VLT:Kueyen(FORS1)

REFERENCES

Agol, E., Steffen, J., Sari, R., & Clarkson, W. 2005, MNRAS, 359, 567
Alard, C. 2000, A&AS, 144, 363
Alard, C., & Lupton, R. H. 1998, ApJ, 503, 325
Alonso, R., Barbieri, M., Rabus, M., Deeg, H. J., Belmonte, J. A., & Almenara, J. M. 2008, A&A, in press (arXiv:0804.3030)
Appenzeller, I., et al. 1998, Messenger, 94, 1
Chambers, J. E. 1999, MNRAS, 304, 793
Claret, A. 2000, A&A, 363, 1081
Cox, A. N., ed. 2000, Allen's Astrophysical Quantities (4th ed.; New York: AIP)
Deeg, H. J., Ocaña, B., Kozhevnikov, V. P., Charbonneau, D., O'Donovan, F. T., & Doyle, L. R. 2008, A&A, 480, 563
Deming, D., Harrington, J., Laughlin, G., Seager, S., Navarro, S. B., Bowman, W. C., & Horning, K. 2007, ApJ, 667, L199
Ford, E. B. 2005, AJ, 129, 1706
Ford, E. B., & Holman, M. J. 2007, ApJ, 664, L51
Fortney, J. J. 2008, in ASP Conf. Ser., Proc. Extreme Solar Systems, ed. D. Fischer et al. (San Francisco: ASP), in press (arXiv:0801.4943)
Frodesen, A. G., Skjeggestad, O., & Tøfte, H. 1979, Probability and Statistics in Particle Physics (Oxford: Oxford Univ. Press)
Gillon, M., et al. 2007, A&A, 466, 743
Harrington, J., Luszcz, S., Seager, S., Deming, D., & Richardson, L. J. 2007, Nature, 447, 691
Hartman, J. D., Bakos, G., Stanek, K. Z., & Noyes, R. W. 2004, AJ, 128, 1761
Heyl, J. S., & Gladman, B. J. 2007, MNRAS, 377, 1511
Holman, M. J., & Murray, N. W. 2005, Science, 307, 1288
Holman, M. J., et al. 2006, ApJ, 652, 1715
Kovács, G., Bakos, G., & Noyes, R. W. 2005, MNRAS, 356, 557
Mandel, K., & Agol, E. 2002, ApJ, 580, L171
Miller-Ricci, E., et al. 2008, ApJ, in press (arXiv:0802.0718)
Minniti, D., Fernández, J. M., Díaz, R. F., Udalski, A., Pietrzynski, G., Gieren, W., Rojo, P., Ruíz, M. T., & Zoccali, M. 2007, ApJ, 660, 858
Miralda-Escudé, J. 2002, ApJ, 564, 1019
Nelder, J., & Mead, R. 1965, Comput. J., 7, 308
Pont, F., Bouchy, F., Queloz, D., Santos, N. C., Melo, C., Mayor, M., & Udry, S. 2004, A&A, 426, L15
Pont, F., et al. 2008, A&A, in press (arXiv:0710.5278)
Ribas, I., Font-Ribera, A., & Beaulieu, J.-P. 2008, ApJ, 677, L59
Santos, N. C., et al. 2006, A&A, 450, 825
Simon, A., Szatmáry, K., & Szabó, G. M. 2007, A&A, 470, 727
Steffen, J. H., & Agol, E. 2005, MNRAS, 364, L96
Stetson, P. B. 1987, PASP, 99, 191
Swain, M. R., Vasisht, G., & Tinetti, G. 2008, Nature, 452, 329
Tegmark, M., et al. 2004, Phys. Rev. D, 69, 103501
Udalski, A., Szewczyk, O., Zebrun, K., Pietrzynski, G., Szymanski, M., Kubiak, M., Soszynski, I., & Wyrzykowski, L. 2002, Acta Astron., 52, 317
Udalski, A., et al. 2008, A&A, 482, 299
Winn, J. N., Holman, M. J., & Fuentes, C. I. 2007, AJ, 133, 11
Zahn, J.-P. 1977, A&A, 57, 383