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Period variations in extrasolar transiting planet OGLE-TR-111b

Rodrigo F. Díaz[1], Patricio Rojo[2], Mario Melita[1], Sergio Hoyer[2], Dante Minniti[3,4], Pablo J. D. Mauas[1], and María Teresa Ruíz[2]

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

[2]Department of Astronomy, Universidad de Chile,
Santiago, Chile

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

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

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.

1. Motivation and Observations

Transits on OGLE-TR-111 were first reported by Udalski *et al.* (2002), and Pont *et al.* (2004) confirmed the planetary nature of the companion through radial velocity (RV) data. A few years later, Winn *et al.* (2007) obtained precise photometry of the system during two transits, and improved the orbital and planetary parameters. They also produced a refined ephemeris for the transits using the complete OGLE data set, as well as their two transits.

In a previous work (Minniti *et al.* 2007) we reported a single transit observed in the V band which occurred around 5 minutes before the expected time obtained using the ephemeris of Winn *et al.* (2007). Since the presence of variations in the timing of transits (TTVs) can be attributed to otherwise undetectable planets or satellites in the system, and as current techniques should be able to detect perturbations due to planets as small as the Earth, we decided to follow-up this system.

We observed two consecutive transits of planetary companion OGLE-TR-111b in the I band with the FORS1 instrument at the European Southern Observatory (ESO) Very Large Telescope (VLT). The observations were acquired on a Director's Discretionary Time run during the nights of December 19 and December 23, 2006. 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 May 2008.

We used the ISIS package (Alard & Lupton 1998; Alard 2000) to compute precise differential photometry with respect to a reference image, which was obtained combining the 10 images with best seeing, producing an image with FWHM $\approx 0.46''$. Aperture

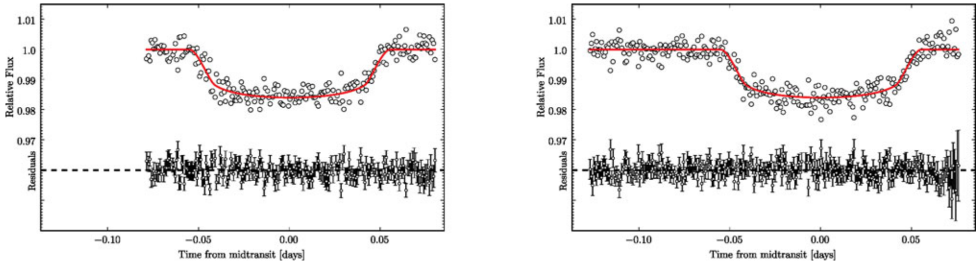

Figure 1. Relative flux during two consecutive transits of planetary companion OGLE-TR-111b. In the left (right) panel we present data taken on the night of December 19 (23) 2006. The residuals with the error bars are also shown. The dashed line represents the displaced zero for the residuals, and the solid line is the best fit model.

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_{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 - 2450000)	4088.79145	±0.00045
T_{c2} (HJD - 2450000)	4092.80493	±0.00045
$T_{c,VIMOS}$ (HJD - 2450000)	3470.56389	±0.00055

photometry was performed on the difference images using IRAF DAOPHOT package (Stetson 1987), which was found to give better results than the ISIS photometry routine phot.csh. To remove possible systematic effects from the light curves we employed the signal reconstruction method of the Trend Filtering Algorithm (Kovács *et al.* 2005).

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. A detailed description of the observations, the reduction method and the estimation of the uncertainties is given in Díaz *et al.* (2008).

2. Measurements

Planetary and orbital parameters, including the central times of transits, were fitted to the OGLE-TR-111 light curve. We used the model by Mandel & Agol (2002), considering a quadratic model for the limb-darkening, with coefficients taken from Claret (2000) for a star with $T_{eff} = 5000$ K, $\log g = 4.5$ cm s^{-2} and $[Fe/H] = 0.2$ and microturbulent velocity $\xi = 2$ km/s. The mass of the planet and the star were fixed to the values reported by Santos *et al.* (2006), $M_s = 0.81\,M_\odot$ and $M_p = 0.52\,M_{Jup}$. 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 obtained by minimizing the χ^2 statistic using the downhill simplex algorithm (Nelder & Mead 1965) and the uncertainties were estimated using the Markov Chain Monte Carlo method. Again, for further details as well as an analysis of possible sources of systematic errors not considered by the Markov Chain method, we refer the reader to Díaz *et al.* (2008).

We present the parameters in Table 1, and the best-fit model and the residuals in Figure 1. Except for the planetary radius and the time between first and last contact, the parameters reported in Table 1 are in agreement with previously published values.

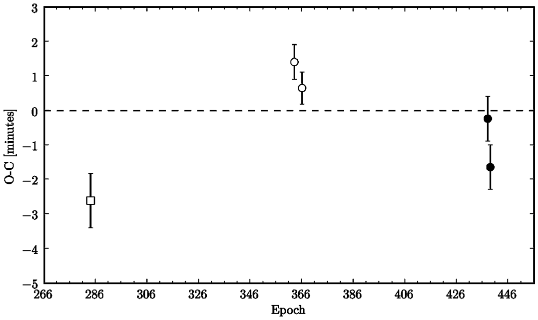

Figure 2. Observed-minus-calculated times (in minutes) for the transits of planet OGLE-TR-111b in front of its host star. The filled circles are the new transits presented in this work, the empty circles are from Winn *et al.* (2007) and the empty square is the transit presented by Minniti *et al.* (2007), which has been reprocessed for this work.

We also reanalysed the RV data from Pont *et al.* (2004), without a constrain to the eccentricity and found that an eccentric orbit with $e = 0.3$ fits the data slightly better than a circular orbit. Unfourtunately, the uncertainty for the eccentricity is large, and $e = 0$ lies within 1 σ from $e = 0.3$. A value of the eccentricity different from zero is meaningful only if the age of the system is larger than the circularization time due to tidal forces. Using the expression from Goldreich & Soter (1966) we obtained a circularization time of ≈ 0.9 Gyr, for the largest value of the tidal quality factor ($Q = 2 \times 10^6$). This time is shorter than the age of OGLE-TR-111 estimated by Melo *et al.* (2006). Therefore, any planetary companion should be on a circular orbit.

3. Results and implications

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 ($T_{c,VIMOS}$) 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:

$$T_c = 2454092.80607 \pm 0.00029 \text{ (HJD)} \tag{3.1}$$

$$P = 4.0144540 \pm 0.0000038 \text{ days} \;, \tag{3.2}$$

with correlation coefficient $\rho = 0.785$. The reduced χ^2 is 9.04, indicating that the hypothesis of a constant period can be discarded with confidence level above 99.999% if the errors on the central times are gaussian. In Fig. 2 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. 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.

First, the hypothesis of an exomoon seems unlikely. Assuming the satellite is in a circular orbit, in order to produce the observed O-C amplitude, $d/v_{orb} \approx 2$ min, where d is the distance from the center of the planet to the center of mass of the system and v_{orb} is the orbital velocity of the center of mass around the central star. We computed the needed mass as a function of orbital radius, and found that at a Hill radius, the needed mass is 1/26 of the planet mass (Figure 3). Compare with Solar System values, where the satellite-planet mass ratio never exceeds 2.5×10^{-4}.

On the other hand, the fact that the eccentricity is different from zero suggests that the timing variations can be produced by an additional planet in the system. The

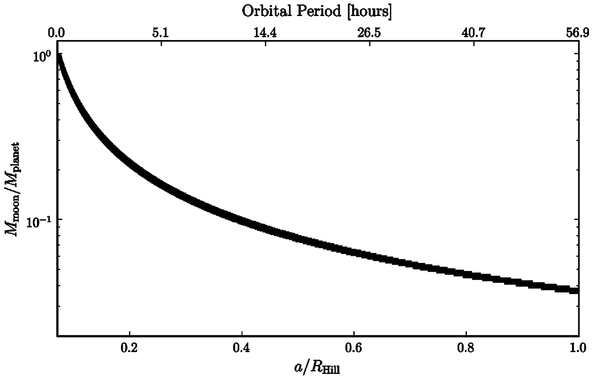

Figure 3. Satellite mass producing the observed O-C amplitude as a function of distance from the planet.

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 TR111b is eccentric ($e = 0.3$). On the other hand, the mass of the perturber planet must be at least around 4 M_{Jup} if the orbit of the interior planet is nearly circular. However, no meaningful fit can be obtained due to the few number of data points. Further observations are warranted in order to pinpoint the origin of the variation in the period of this interesting planet.

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