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Letter to the Editor

The "missing link": A 4-day period transiting exoplanet around OGLE-TR-111★

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Abstract. We report the discovery of a transiting hot Jupiter around OGLE-TR-111, from our radial velocity follow-up of OGLE transiting candidates in Carina. The planet has a mass of 0.53 ± 0.11 M_J and a radius of $1.0^{+0.13}_{-0.06}$ R_J. Three transiting exoplanets have already been found among OGLE candidates, all with periods near 1.5 days. The planet presented here, with $P = 4.0$ days, is the first exoplanet detected by transits with the characteristics of a "normal" hot Jupiter, as found in abundance by radial velocity surveys. The radius of OGLE-TR-111b and the scarcity of hot Jupiters detected among OGLE transit candidates tend to indicate that the case of HD 209458b, with a radius of 1.4 R_J, is exceptional, with most hot Jupiters being smaller.

Key words. techniques: radial velocities – instrumentation: spectrographs – stars: planetary systems

1. Introduction

Photometric searches for transiting exoplanets are fast emerging as worthy competitors of radial velocity surveys to detect and characterize hot Jupiters. About 120 exoplanet candidates have been discovered by radial velocity surveys since 1995, but because of the nature of the method, only the orbital period and a lower limit on their mass is provided. The observation of planetary transits, together with radial velocity measurements, also yield the exact mass and the planetary radius, providing much tighter constraints for planet models.

The first exoplanet transit observed was that of HD 209458b (Charbonneau et al. 2000; Henry et al. 2000), a planet already known from Doppler surveys (Mazeh et al. 2000).

Within the past year, three exoplanets have been discovered by their photometric transit thanks to the OGLE planetary transit survey (Udalski et al. 2002a,b, 2003) and spectroscopic follow-up (OGLE-TR-56, Konacki et al. 2003; OGLE-TR-113 and OGLE-TR-132, Bouchy et al. 2004a). However, these three planets share a very unusual characteristic compared to those discovered by Doppler surveys: they all have very short periods near 1.5 days, much below the observed pile-up of periods in hot Jupiters at 3–4 days, even much lower than the hot Jupiter with the shortest period known, 2.5 days (Udry et al. 2003a,b).

Here we will call "Pegasids" the hot Jupiters with P = 2.5−10 days and dub "Oglies" those with $P < 2.5$ days, in recognition of the pivotal role of the OGLE survey in their discovery. The phrase "hot Jupiter" is used for all short-period gas giant planets.

The result of the OGLE survey posed two related problems of coherence: why are "Oglies" absent from Doppler surveys, and where are the much more abundant Pegasids in the transit surveys? The radial velocity surveys show that Pegasids in the solar neighbourhood are at least an order of magnitude more abundant than "Oglies", and HD209458, with a radius of $\sim$1.4 R_J, indicates that they can easily cause eclipses deep enough to be detected by the OGLE survey. Even accounting for the fact that the time sampling of the OGLE survey favours the detection of short-period transits, the absence of any Pegasid was difficult to explain.

In this Letter we report the discovery of just such an object around OGLE-TR-111. Its characteristics provide some indication as to why the OGLE survey may have missed most hot Jupiter transits.

2. Observations and reductions

The spectroscopic observations were obtained during a 26-h run spread on 8 nights on FLAMES/VLT in March 2004

★ Based on observations collected with the FLAMES+UVES spectrograph at the VLT/UT2 Kueyen telescope (Paranal Observatory, ESO, Chile).

Table 1. Radial velocity measurements (in the barycentric frame) and CCF parameters for OGLE-TR-111.

BJD [−2 453 000 d]	*RV* [km s^{-1}]	depth [%]	*FWHM* [km s^{-1}]	*S/N*	$\sigma_{\rm RV}$ [km s^{-1}]
78.60419	25.118	31.27	9.2	7.4	0.033
79.64235	25.161	30.75	9.0	7.3	0.033
80.65957	25.224	28.18	9.0	5.5	0.048
81.59492	25.112	25.46	9.4	4.5	0.067
82.71279	25.041	31.09	9.1	8.0	0.030
83.66468	25.184	29.14	9.0	6.2	0.042
84.65149	25.233	33.57	9.0	9.5	0.024
85.60720	25.159	32.84	9.1	8.5	0.027

(program 72.C-0191). FLAMES is a multi-fiber link which feeds into the spectrograph UVES up to 7 targets on a field-of-view of 25 arcmin diameter, in addition to simultaneous ThAr calibration. The fiber link produces a stable illumination at the entrance of the spectrograph, and the ThAr calibration is used to track instrumental drift. Forty-five minutes on a 17 mag star yield a signal-to-noise ratio of about 8 corresponding to a photon noise uncertainty of about 30 m s^{-1} on an unrotating K dwarf star. In our programme, we have observed all the OGLE candidates in the Carina field compatible with a planetary companion (Pont et al., in preparation) as well as 18 candidates in the OGLE Galactic bulge field (Bouchy et al. 2004b).

The spectra from the FLAMES+UVES spectrograph were reduced and the radial velocities were computed following the procedure described in Bouchy et al. (2004a). However, a significant improvement was obtained by using a specific numerical correlation mask tailored to the spectral type of the target. Furthermore, the calculation of the radial velocity from the Cross-Correlation Function (CCF) was improved. We find that our new procedure significantly improves the radial velocity accuracy and pushes the systematics well below the 35 m s^{-1} quoted in Bouchy et al. (2004a).

3. Results

Radial velocities

Our radial velocity measurements and CCF parameters are listed in Table 1. If the radial velocity variations are caused by a transiting object, then the transit phase must correspond to the passage at center-of-mass velocity with decreasing velocity, and the period is fixed by the periodicity of the transit signal. Given the short period, we assume that the orbit is circularized with zero excentricity. We therefore fit on the data a sinusoid of phase and period fixed at the Udalski et al. (2002b) values. There are only two free parameters, the centre-of-mass velocity V_0 and the semi-amplitude K. We find $K = 78 \pm 14$ m s^{-1} and $V_0 = 25.145 \pm 0.010$ km s^{-1}. The radial velocity measurements and best-fit curve are displayed in Fig. 1. The reduced χ^2 is 4.2 for a constant velocity and 0.7 for a circular orbit.

Leaving the period as a free parameters in the velocity fit does not cause any significant change, and no period other than 4 days produces an adequate orbit fit.

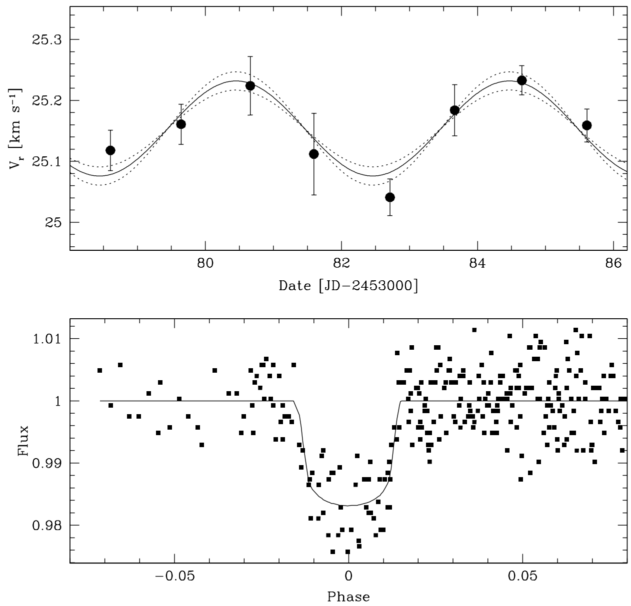

Fig. 1. *Top*: radial velocity measurements for OGLE-TR-111, together with our orbital solution. *Bottom*: phase-folded normalized light curve and best-fit transit curve for OGLE-TR-111 (composed of nine partial individual transits).

Table 2. Parameters for the star OGLE-TR-111 and its planetary companion.

Period [days]	4.01610 [fixed]
Transit epoch [JD − 2 452 000]	330.44867 [fixed]
Radius ratio	0.120 ± 0.006
Impact parameter	0–0.68
Inclination angle [°]	86.5–90
Radial velocity semi-amplitude [m s^{-1}]	78 ± 14
Systemic velocity [km s^{-1}]	25.154 ± 0.010
O–C residuals [m s^{-1}]	24
Temperature [K]	5070 ± 400
[Fe/H]	0.12 ± 0.28
log *g*	4.8 ± 1.0
Star mass [$M_\odot$]	$0.82^{+0.15}_{-0.02}$
Star radius [$R_\odot$]	$0.85^{+0.10}_{-0.03}$
Orbital semi-major axis [AU]	0.047 ± 0.001
Orbital excentricity	0 [fixed]
Planet mass [$M_{\rm J}$]	0.53 ± 0.11
Planet radius [$R_{\rm J}$]	$1.00^{+0.13}_{-0.06}$
Planet density [g cm^{-3}]	$0.61^{+0.39}_{-0.26}$

Spectral classification

On the summed spectra, the intensity and equivalent width of some spectral lines were analyzed to estimate the temperature, gravity and metallicity of the primary in the manner described in Santos et al. (2003). The resulting spectroscopic parameters are given in Table 2. Although the low signal-to-noise ratio of the spectra prevents a very precise determination, the data indicates that OGLE-TR-111 is an early-K dwarf of solar or higher metallicity.

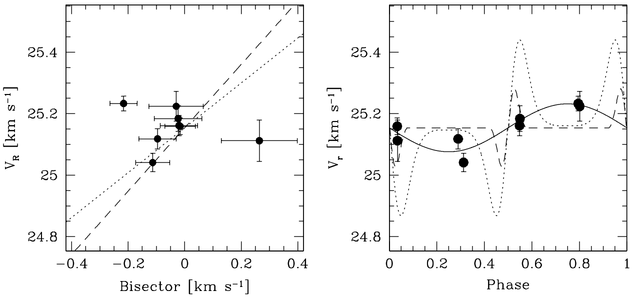

Fig. 2. *Left*: bisector span $[V_{\rm top} - V_{\rm bottom}]$ for OGLE-TR-111 as a function of radial velocity. Uncertainties correspond to twice the radial velocity uncertainties. *Right*: phased radial velocity data with the best-fit planet orbit as a solid line. In both plots, the prediction of two blend scenarios are shown. Dotted: $M_{\rm p} = 0.7\ M_{\odot}$, $M_{\rm s} = 0.2\ M_{\odot}$, dashed: $M_{\rm p} = 0.3\ M_{\odot}$, $M_{\rm s} = 0.2\ M_{\odot}$.

The full width at half-maximum (*FWHM*) of the CCF shows that the rotation velocity is lower than 5 km s^{-1}, indicating that the target star is not tidally locked with its companion.

Light curve analysis and physical parameters

OGLE-TR-111 was measured 1176 times by the OGLE survey during one season in 2002. Nine individual transits were covered, with a depth of 1.9 percent and a periodicity of 4.01610 days (Udalski et al. 2002b).

We fitted an analytical transit light curve to the photometric data by non-linear least-squares in the manner described in Bouchy et al. (2004b), to constrain the radius ratio, the sum of masses, the primary radius and the impact parameter.

These constraints were then combined with the spectroscopic parameters, assuming that OGLE-TR-111 is a normal dwarf star situated within the stellar evolution tracks of Girardi et al. (2002), with the radial velocity orbit and the assumption of a circular Keplerian orbit seen almost edge-on. All the constraints were combined by χ^2 minimisation in the way also described in details in Bouchy et al. (2004b). The resulting values for the mass and radius of the star and planet are given in Table 2. Note that because of the geometry of the problem, the uncertainties on several parameters are not symmetrical. We find a mass of $0.53 \pm 0.11\ M_{\rm J}$ and a radius of $1.00{+}^{+0.13}_{-0.06}\ R_{\rm J}$ for OGLE-TR-111b.

Triple-system blend scenarios

In certain circumstances, a triple system, or a single star with a background unresolved eclipsing binary, can mimic a planet transit and produce phased velocity variations. In such cases, however, the CCF bisector is expected to vary. In order to examine the possibility that the radial velocity variations be due to a blend scenario, we computed the line bisectors as described by Santos et al. (2002). Figure 2 shows that there is no significant correlation of the line asymmetries with phase.

As a further check of blend scenarios, the cross-correlation function was computed with different masks (G2, K0 and K5 spectra) without significant change in the amplitude of the orbital signals. Blends of different spectral types are expected to produce velocity signals varying with the correlation mask.

Contrary to the OGLE Galactic bulge transiting candidates, the probability of chance blending by a background binary is low in the Carina sample, because the field is less crowded. The dominant case of blending is that of triple, gravitationally bound systems. In this case, more contraints can be put on a blend scenario for OGLE-TR-111. Let us call "target", "primary" and "secondary" the components of such a triple system. The target is the star dominating the light and spectrum, the primary and secondary are the components of an associated close binary system. In the case of OGLE-TR-111, the only free parameter in a triple scenario is the mass of the primary. The mass and radius of the target are constrained by the spectroscopy, the masses, radii and luminosity of the three component are linked by main-sequence relations for low-mass stars, and the radius of the secondary is fixed by the transit depth. The radial velocity variation of the primary is governed by Kepler's law, the rotation velocity of the primary and secondary are fixed by tidal synchronisation.

The spectroscopy shows that the target is a low-mass star ($M \sim 0.8 \pm 0.1\ M_{\odot}$). Using approximations of the Baraffe et al. (1998) models for low-mass stars, the primary would have to be lighter than about $0.7\ M_{\odot}$ ($L_{\rm p}/L_{\rm t} < 15\%$), otherwise its spectrum would cause a clearly visible signal in the CCF. It would have to be heavier than $\sim 0.3\ M_{\odot}$ to contribute enough light to cause the transit signal in the combined photometry ($L_{\rm p}/L_{\rm t} > 2\%$). For a triple system the transit depth is $d \simeq (\frac{R_{\rm s}}{R_{\rm p}})^2 \frac{1}{1+L_{\rm t}/L_{\rm p}}$. With $K \sim P^{-1/3}\, m\,(m+M)^{-2/3}$, it turns out that all configurations imply a velocity semi-amplitude of the primary larger than 25 km s^{-1}. Because the target has a narrow CCF, the CCF signal of the primary would be separated from the CCF of the target during most of the phase. Two typical exemples from synthetic CCF simulations are shown in Fig. 2 for illustration. Even if the period is left as a free parameter, no scenario can reproduce the observed velocity variation and the absence of bisector variation.

Other blend scenarios with a background binary or an equal-mass binary of double period all involve heavier stars, and therefore higher radial velocity amplitudes, making it even harder to reproduce the observed signal.

Therefore no simple three-star blend scenario can be made compatible with the spectroscopic data for OGLE-TR-111.

4. Discussion and conclusion

OGLE-TR-111b is a typical Pegasid in terms of both period and mass (see Fig. 3). It corresponds to the pile-up of periods near 3–4 days observed in Doppler exoplanet surveys (Udry et al. 2003), and its small mass is near the median of Pegasid masses, that are found to be much lighter on average than longer-period gas giants (Zucker & Mazeh 2002).

OGLE-TR-111b is only the second normal hot Jupiter for which a secure determination of radius has been obtained, and it has a markedly lower radius than the other case, HD 209458 ($R \sim 1.4\ R_{\rm J}$). OGLE-TR-111b is also clearly different from the three very short-period planets detected earlier in the

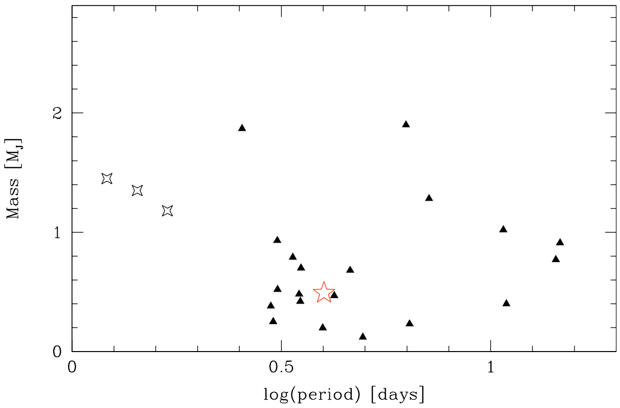

Fig. 3. The period-mass relation for hot Jupiters from radial velocity (triangles) and transit (stars) surveys (in the first case, minimum masses only). The large star symbol is OGLE-TR-111b. Contrarily to the three other OGLE transiting planets, OGLE-TR-111b is a "normal" hot Jupiter in terms of mass and period.

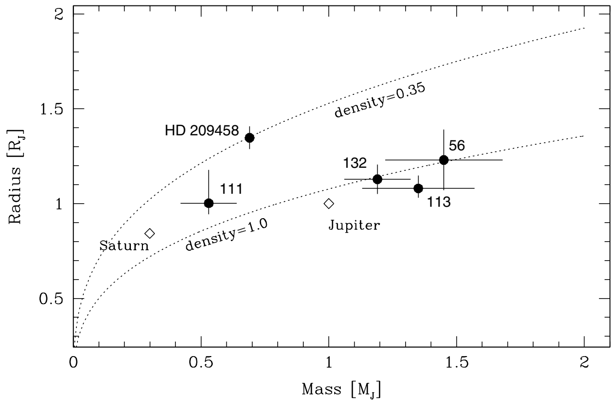

Fig. 4. The mass-radius relation for transiting exoplanets. Jupiter and Saturn are indicated for comparison, as well as the loci of isodensities at 1.0 $\mathrm{g\,cm^{-3}}$ and 0.35 $\mathrm{g\,cm^{-3}}$. Data from Brown et al. 2001 (HD 290458), Konacki et al. (2003) (OGLE-TR-56), Bouchy et al. (2004a) (OGLE-TR-113), Moutou et al. (2004) (OGLE-TR-132) and this letter (OGLE-TR-111).

OGLE survey (see Introduction), all three having masses superior to 1 M_{J}.

In some way, OGLE-TR-111b provides the "missing link" between planets from transit and radial velocity surveys. Both the absence of "normal" hot Jupiters and the abundance of $P \sim 1.5$ days planets in the OGLE survey were difficult to reconcile with the period distribution of the two dozens hot Jupiters known from radial velocity surveys. OGLE-TR-111b offers two crucial elements in the resolution of this mystery: First, its detection shows that Pegasids are present in the OGLE transit survey. Second, its radius shows that HD 209458 cannot be taken as a prototype of Pegasids, therefore that many of them may have smaller radii, making their detection by transit much more difficult (the transit depth depending on the square of the planet radius).

In the context of the statistical interpretation of the detection of OGLE-TR-111b, it is worth noting that its period is very nearly an integer number of days. This is probably no coincidence. Given the time sampling of ground-based transit survey, with a dominant 1-day frequency, resonant periods near multiples of 1-day can be detected even below the nominal detection threshold (the detection of transits in OGLE-TR-111 was indeed made easier by the resonance: 9 individual transits were detected, compared to an expected average of 3 to 4 for a non-resonant period near four days). It is significant that, even with such a small-radius primary, this planet would probably not have been detected without its resonant period, which goes some way to explain the low detection rate of hot Jupiters by the OGLE survey.

Our result thus has sobering implications for the expected output of other ground-based exoplanet transit searches. If hot Jupiters can have radii similar to Jupiter, the accuracy and time coverage of the OGLE survey is sufficient to detect them only for a $R < R_{\odot}$ host star and with a resonant period. This implies that unless surveys have a better time coverage, larger volume coverage and/or better photometric accuracy than the OGLE survey, they cannot be expected to detect Pegasids in significant number.

The comparison of HD 209458b and OGLE-TR-111b is compatible with simple expectations about the effect of stellar illumination on the structure of hot Jupiters: a gas giant close to a warm stars can have a large radius, low density and high evaporation rate, while around a cooler star it may stand nearer to the density of an isolated planet (HD 209458 is ~1000 K hotter than OGLE-TR-111). The discovery of more transiting planets, and age information on the host stars, are obviously needed for a more detailed understanding.

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