WASP-34b: a near-grazing transiting sub-Jupiter-mass exoplanet in a hierarchical triple system*

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ABSTRACT

We report the discovery of WASP-34b, a sub-Jupiter-mass exoplanet transiting its 10.4-magnitude solar-type host star (1SWASP J110135.89-235138.4; TYC 6636-540-1) every 4.3177 days in a slightly eccentric orbit (e = 0.038 ± 0.012). We find a planetary mass of 0.59 ± 0.01 M_Jup and radius of 1.22±0.18 R_Jup. There is a linear trend in the radial velocities of 55±4 m s^{-1} y^{-1} indicating the presence of a long-period third body in the system with a mass ≳ 0.45 M_\odot at a distance of ≳ 1.2 AU from the host star. This third-body is either a low-mass star, white dwarf, or another planet. The transit depth ((R_p/R_\star)^2 = 0.0126) and high impact parameter (b = 0.90) suggest that this could be the first known transiting exoplanet expected to undergo grazing transits, but with a confidence of only ~ 80%.

Key words. planets and satellites: general – stars: individual: WASP-34 – techniques: photometry – techniques: spectroscopy – techniques: radial velocities

1. Introduction

The majority of the known exoplanets have been discovered using the radial velocity technique (Mayor & Queloz 1995). In recent years, however, an ever increasing number have been discovered as a result of group-based and space-based transit search projects. Transiting exoplanets allow parameters such as the mass, radius, and density to be accurately determined, as well as their atmospheric properties to be studied during their transits and occultations (Charbonneau et al. 2005; Southworth 2005; Winn 2009).

The SuperWASP project has robotic observatories in the Canary Islands and South Africa. The wide angle survey is designed to find exoplanets around relatively bright stars in the V-magnitude range 9 ~ 13. A detailed description of the SuperWASP project is given in Pollacco et al. (2006).

In this paper we report the discovery of WASP-34b, an exoplanet in orbit around its V = 10.4 mag. host star 1SWASP J110135.89-235138.4 in the constellation Crater. We present the WASP-South discovery photometry, together with Euler Telescope photometry and CORALIE radial velocity measurements.

2. Observations

2.1. WASP-South photometry

The host star WASP-34 (1SWASP J110135.89-235138.4; CD-23 9677; TYC 6636-540-1; GSC 06636-00540) was observed within two WASP-South camera fields during the periods 2006 May 4 to June 20 and 2007 January 4 to June 1, and in 3 fields during the period 2008 January 1 to May 28. A total of 35 351 data points were obtained. The pipeline-processed data were detrended and searched for transits using the methods described in Collier Cameron et al. (2006), yielding a detection of a periodic, transit-like signature with a period of 4.3177 days and a depth of 0.011 magnitudes (Fig. [1]).

2.2. Spectroscopic observations with CORALIE

Spectroscopic observations were obtained with the CORALIE spectrograph on the Swiss 1.2m telescope. The data were processed using the standard pipeline (Baranne et al. 1996; Queloz et al. 2000; Pepe et al. 2002). A total of 24 radial velocity (RV) and line bisector span (V_{span}) measurements were made between 2009 December 1 and August 1 (Table [1]). The bisector spans are a measure of the asymmetry of the cross-correlation function and, based on our experience, have standard errors of ≈ 2\sigma_{rv}.

The RV measurements show velocity variations with the same period as the transit light curve, but with a relatively
large scatter in the residuals (16.1 m s\(^{-1}\)) to a circular orbit fit. Analysis of these residuals shows a trend as a function of time of 55±4 m s\(^{-1}\) y\(^{-1}\), with an F-test revealing that this is significant at >99.9% level (Fig. 2). The amplitude of the RV variations indicates that it is highly improbable that the RV variations are due to an unresolved eclipsing binary or chromospheric activity (Queloz et al. 2001).

2.3. Euler Telescope photometry

We observed two transits (March 3 and April 12, 2010) of WASP-34b with the 1.2m Euler Telescope. All data were taken in the \(R\) band and, owing to the brightness of the target (mag. \(R=9.81\)), with slight defocus. While for the first transit there was no guiding available at the telescope, we made use of a new absolute tracking (ABTR) mode for the second observation. The ABTR performs tracking by computing the location of light sources on each science frame and matching them with a catalogue. This way, the exact position of each image is found and drifts from the nominal position are corrected by adjusting the telescope pointing between the exposures. As a result the target is kept on the same pixel during the whole transit.

The reduction was the same for both transits. After correcting the images for bias, overscan and flatfield, we performed aperture photometry on the data. The flux was extracted for all stars in the field and the final light curve was obtained from differential photometry of the target and a reference source obtained by combining the 3 brightest reference stars. We reached a r.m.s. photometric precision of 4.2 m mag. min\(^{-1}\) for the transit of March 3 and 1.4 m mag. min\(^{-1}\) for the transit of April 12 (Fig. 4). This improvement can mainly be attributed to the use of the ABTR. As the stars were kept on the same pixels, flat field effects were greatly reduced.
produce a single spectrum with an average S/N of around 100:1. The standard pipeline reduction products were used in the analysis.

The analysis was performed using the methods given in Gillon et al. (2009) and Smalley (2005). The Hα line was used to determine the effective temperature ($T_{\text{eff}}$), while the Na i D and Mg i b lines were used as surface gravity (log g) diagnostics. The parameters obtained from the analysis are listed in Table 2. The elemental abundances were determined from equivalent width measurements of several unblended lines. A value for microturbulence ($\xi_t$) was determined from Fe i using the method of Magain (1984). The quoted error estimates include that given by measurement and atomic data uncertainties.

The projected stellar rotation velocity ($v \sin i$) was determined by fitting the profiles of several unblended Fe i lines. A value for macroturbulence ($v_{\text{mac}}$) of $2.3 \pm 0.3$ km s$^{-1}$ was assumed, based on the recent calibration of Bruntt et al. (2010), and an instrumental FWHM of $0.11 \pm 0.01$ Å, determined from the telluric lines around 6300Å. A best-fitting value of $v \sin i = 1.4 \pm 0.6$ km s$^{-1}$ was obtained.

The lack of any measurable lithium in the CORALIE spectra implies that WASP-34 is a relatively old star, with an age of $\gtrsim 5$ Gyr (Sestito & Randich 2005). The measured $v \sin i$ of WASP-34 implies a rotational period of $P_{\text{rot}} \approx 34 \pm 15$ days, which yields a gyrochronological age of $\sim 6.7_{-4.9}^{+6.5}$ Gyr using the relation of Barnes (2007), which is consistent with the lithium age. In many respects WASP-34 is very similar to the Sun.

### 3. Spectral Analysis

To determine the planetary and orbital parameters the CORALIE radial velocity measurements were combined with the photometry from the WASP and Euler Telescopes in a simultaneous fit using the Markov Chain Monte Carlo (MCMC) technique. The details of this process are described in Collier Cameron et al. (2007) and Pollacco et al. (2008). Four sets of solutions were used: with and without the main-sequence mass-radius constraint for both circular and floating eccentricity orbits. In all cases we have included a linear trend in the systemic velocity, $dy/dt$, as a free parameter. Limb-darkening uses the four-coefficient model of Claret (2000) for the r-band, for both WASP and Euler photometry.

With the main-sequence constraint imposed but the eccentricity floating, a value of $e = 0.038 \pm 0.012$ is found, which is significant at the 99.3% level (Lucy & Sweeney 1971, Eq. 21). The radial velocity measurements are well fitted by this orbital parameters for WASP-34b.

#### Table 3. System parameters for WASP-34b.

| Parameter | Value |
|-----------|-------|
| Transit epoch (HJD), $T_0$ | 2454647.55358 ± 0.00064 |
| Orbital period, $P$ | 4.3176782 ± 0.0000045 d |
| Transit duration, $T_{14}$ | 0.0876 ±0.0016 d |
| Transit depth, $(R_p/R_\star)^2$ | 0.01261 ± 0.00026 |
| Impact parameter, $b$ | 0.904 ±0.014 |
| Stellar reflex velocity, $K_1$ | 0.0721 ± 0.0012 km s$^{-1}$ |
| Centre-of-mass velocity at time $T_0$, $\gamma$ | 49.9395 ± 0.0064 km s$^{-1}$ |
| Drift in centre-of-mass velocity, $dy/dt$ | $-54.8 \pm 4.0$ m s$^{-1}$ y$^{-1}$ |
| Orbital separation, $a$ | 0.0524 ± 0.0004 AU |
| Orbital inclination, $i$ | 85.2 ± 0.2 $^\circ$ |
| Orbital eccentricity, $e$ | 0.038 ± 0.012 |
| Argument of periastron, $\omega$ | $-40.2_{-14.6}^{+12.2} $ $^\circ$ |
| $e \cos(\omega)$ | $0.028 \pm 0.009$ |
| $e \sin(\omega)$ | $-0.024 \pm 0.016$ |
| Planet mass, $M_p$ | 0.59 ± 0.01 $M_{\text{Jup}}$ |
| Planet radius, $R_p$ | 1.22 ±0.11 $R_{\text{Jup}}$ |
| Planet surface gravity, log $g_p$ | 2.96 ±0.05 |
| Planet density, $\rho_p$ | 0.34 ± 0.08 $\rho_{\text{Jup}}$ |
| Planet equilibrium temperature, $T_p$ | 1250 ± 30 K |

Notes. The planet equilibrium temperature, $T_p$, assumes a Bond albedo of $A = 0$ and even redistribution of heat around the planet.
Hence, given there is some evidence for a non-circular detection of eccentricity, it does not confirm that the orbit is truly circular but recognises that an eccentric fit to noisy and unevenly sampled data will always lead to a spurious improvement in the eccentricity (Lucy & Sweeney 1971, Eq. 27). The eccentric orbit fit has $\chi^2 = 57.4$, compared to $\chi^2 = 68.5$ for a circular orbit. We adopt the null hypothesis that the underlying orbit is truly circular but recognise that an eccentric fit to noisy and unevenly sampled data will always lead to a spurious improvement in $\chi^2$. The probability that an improvement in the fit could have arisen by chance with the addition of 2 fitting parameters, $e \cos(\omega)$ and $e \sin(\omega)$, is 17.1%. While this is too high to confidently claim detection of eccentricity, it does not confirm that the orbit is truly circular. Hence, given there is some evidence for a non-circular orbit, we present the system parameters for the eccentric solution (Table 3). The impact parameter and transit depth suggest that the planet could be in a grazing transit.

Relaxing the main-sequence constraint yields a larger stellar radius $(1.20\pm0.09 \, R_\odot)$ and lower surface gravity $(\log g = 4.3)$, which is marginally inconsistent with the spectroscopic log g. The planetary radius increases to $1.82^{+0.82}_{-0.48} \, R_{\text{Jup}}$ and the impact parameter also rises to $0.98^{+0.08}_{-0.06} \, R_{\text{Jup}}$. The planetary density now drops to $1.11^{+0.15}_{-0.17} \, \rho_{\text{Jup}}$, which would be similar to that found for WASP-17b (Anderson et al. 2010). While the fit to the transit lightcurves is only slightly different (Fig. 4), the uncertainties in the planetary parameters are now rather large, indicating that the near-grazing nature of the transit is poorly constrained by the available photometry. Consequently, we adopt the main-sequence-constrained eccentric solution.

5. Discussion

WASP-34b is a sub-Jupiter mass exoplanet transiting a G5 host star every 4.3177 days. A simultaneous fit to transit photometry and radial-velocity measurements gave a planetary mass of $0.59 \pm 0.01 \, M_{\text{Jup}}$ and radius of $1.22^{+0.11}_{-0.08} \, R_{\text{Jup}}$.

In many respects the WASP-34b system looks like transiting version of 51 Peg (Mayor & Queloz 1995) with similar periods, separations, masses and host stars. Of the known transiting system, WASP-34b joins an increasing number of exoplanets with masses $\sim 0.5 M_{\text{Jup}}$ and radii $\sim 1.0 R_{\text{Jup}}$, such as WASP-22b (Maxted et al. 2010), WASP-25b (Enoch et al. 2010), HAT-P-24b (Kipping et al. 2010) and HAT-P-25b (Quinn et al. 2010).

Of these systems, the similarity to WASP-22b is striking considering that it too has a linear trend in radial velocities due to a third-body in the system.

5.1. Properties of the third body

The significant linear trend in the radial velocities of 55 $\pm 4 \, \text{m s}^{-1} \, \text{y}^{-1}$, noted in Sect. 2.2, indicates the presence of a third body in the system with a long period. Using the constant acceleration method of Winn et al. (2009) the third body satisfies

$$M_3 \sin i_c = 0.307 \pm 0.022,$$

(1)

where $M_3$ and $a_c$ are the mass (in $M_{\text{Jup}}$) and orbital separation (in AU) of the third body. Given that the period of this outer body must be greater than at least twice the RV data baseline, $P_f > 490$ days and, using Kepler’s third law, $a_c > 1.2 \, \text{AU}$. Hence $M_3 > 0.45 \, M_{\text{Jup}}$. Using literature photometry we estimated the bolometric flux at the Earth to be $f_{\odot} = 1.97 \pm 0.10 \times 10^{-5} \, \text{erg s}^{-1} \, \text{cm}^{-2}$, which gives $T_{\text{eff}} = 5740 \pm 140 \, \text{K}$ using the Infrared Flux Method (IRFM) (Blackwell & Shallis 1977), which is in excellent agreement with the spectroscopic temperature determination. The modified IRFM method of Smalley (1993) suggests that a main-sequence companion would be cooler than $\sim 4000 \, \text{K}$ (M-type or later). There is a GALEX (Morrissey et al. 2007) near-UV flux measurement for WASP-34, and this is in agreement with that predicted for a star of this temperature. This is no significant UV excess that could be attributed to a hot compact stellar companion, but this does not exclude the possibility of a cool white dwarf companion. Thus, we expect that the companion object is either a low mass star (M-type or cooler), cool white dwarf or another planet in a wide long-period orbit. Further radial velocity measurements are required to constrain the orbit.

5.2. Grazing nature of the system

The transit depth $(R_p/R_\star)^2 = 0.0126$ and high impact parameter $(b = 0.90)$ suggest that WASP-34b could be the first transiting exoplanet known to undergo grazing transits. For a transit to be truly grazing, we require

$$b + R_p/R_\star > 1$$

(2)

and that this grazing criterion is significant compared to the observational uncertainties. For WASP-34b we find a value of $0.016^{+0.017}_{-0.014}$ for the grazing criterion. Hence, we might expect grazing transits, unlike the near-grazing transits of TrES-2 (O'Donovan 2006) and HAT-P-14b (Torres et al. 2010), which have grazing criteria of $0.972 \pm 0.007$ and $0.968 \pm 0.022$, respectively. Figure 5 shows the 10 000 MCMC posteriors for $R_p/R_\star$ and $b$. A total of 89.6% of these satisfy the grazing criterion. If the grazing criterion were equal to unity, then we would expect 50% of the points to be higher and 50% to be lower than one. Using the odds ratio test (Kipping et al. 2010), we find a 82.8% probability that the system is truly grazing. However, this is lower than a 3-$\sigma$ value which would be a reasonable limit for detection of a truly grazing system. Hence, we conclude that WASP-34b has near-grazing transits.

The eccentricity ($e$) and argument of periastron ($\omega$) are such that the occultation impact parameter will be

$$b_{\text{occ}} = (0.953 \pm 0.031) \, b_{\text{tra}} = 0.862 \pm 0.035.$$

(3)
extremely correlated to both MCMC posteriors greater than 1. Therefore, the occultations of uncertainties in the orbital elements are such that it is a possibility the planet behind the star are expected to be total. However, the occultations could be partial.

Fig. 6. Plot of the MCMC posteriors $b$ and $R_p/R_\star$. The solid-line indicates the position of the stellar limb, i.e. $b + R_p/R_\star = 1$. A total of 89.6% of the points lie above the line and are grazing solutions.

Table 4. Effect of limb-darkening on the derived impact parameter, $b$, and transit depth, $(R_p/R_\star)^2$, for various filter bands. The grazing criterion, $b + R_p/R_\star$, is given along with the percentage of MCMC posteriors that are grazing, $\% (>1)$, and the confidence values, $P(>1)$.

| band | $b$ | $(R_p/R_\star)^2$ | $b + R_p/R_\star$ | $\% (>1)$ | $P(>1)$ |
|------|-----|------------------|-------------------|----------|---------|
| $v$  | 0.898 | 0.01309 | 1.015$^{+0.013}_{-0.013}$ | 83.1 | 74.7 |
| $r$  | 0.904 | 0.01261 | 1.016$^{+0.017}_{-0.014}$ | 89.6 | 82.8 |
| $i$  | 0.905 | 0.01213 | 1.015$^{+0.016}_{-0.012}$ | 91.1 | 84.9 |
| $z$  | 0.907 | 0.01190 | 1.016$^{+0.016}_{-0.003}$ | 90.3 | 83.8 |

Hence, $b_{\text{occ}} + R_p/R_\star = 0.974 \pm 0.035$ with only 19.2% of the MCMC posteriors greater than 1. Therefore, the occultations of the planet behind the star are expected to be total. However, the uncertainties in the orbital elements are such that there is a possibility that the occultations could be partial.

For transits with large $b$, the limb-darkening coefficients are extremely correlated to both $R_p/R_\star$ and $b$ (Kipping & Bakos 2010). In order to investigate the effects of limb-darkening on the inferred grazing nature of the system, we re-ran our MCMC analysis using limb-darkening coefficients for different filter bands (Table 4). Compared to the $r$-band results, there are small but noticeable, differences. Hence, this heuristic demonstrates that there is a 75 \~ 85% probability that the transit is actually grazing.

The near-grazing nature of the system makes it sensitive to additional planets, via changes to transit duration and shape. Given that there is evidence for another object in the WASP-34 system, further monitoring of the transits is required.

Acknowledgments

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