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The sub-Jupiter mass transiting exoplanet WASP-11b

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ABSTRACT

We report the discovery of a sub-Jupiter mass exoplanet transiting a magnitude V = 11.7 host star 1SWASP J030928.54+304024.7. A simultaneous fit to the transit photometry and radial-velocity measurements yield a planet mass \( M_p = 0.53 \pm 0.07 \, M_J \), radius \( R_p = 0.91^{+0.03}_{-0.02} \, R_J \), and an orbital period of 3.722 days. The host star is of spectral type K3V, with a spectral analysis yielding an effective temperature of 4800 \( \pm 100 \, K \) and \( \log g = 4.45 \pm 0.2 \). It is amongst the smallest, least massive and lowest luminosity stars known to harbour a transiting exoplanet. WASP-11b is the third least strongly irradiated transiting exoplanet discovered to date, experiencing an incident flux \( F_\nu = 1.9 \times 10^8 \, \text{erg s}^{-1} \text{cm}^{-2} \) and having an equilibrium temperature \( T_{eq} = 960 \pm 70 \, K \).

1. Introduction

Observations of planets that transit their host star represent the current best opportunity to test models of the internal structure of exoplanets and of their formation and evolution. Since the first detection of an exoplanetary transit signature (Charbonneau et al. 2000, Henry et al. 2000) over fiftytransiting planetary systems have been identified. A number of wide-field surveys are in progress with the goal of detecting transiting exoplanets, for example OGLE (Udalski et al. 2002), XO (McCullough et al. 2005), HAT (Bakos et al. 2004), TRES (O’Donovan et al. 2006) and WASP (Pollacco et al. 2006).

The WASP project operates two identical instruments, at La Palma in the Northern hemisphere, and at Sutherland in South Africa in the Southern hemisphere. Each telescope has a field of view of just under 500 square degrees. The WASP survey is sensitive to planetary transit signatures in the light-curves of hosts in the magnitude range V ~9–13. A detailed description of the telescope hardware, observing strategy and pipeline data analysis is given in Pollacco et al. (2006).

In this paper we report the discovery of WASP-11b, a sub-Jupiter mass gas giant planet in orbit about the host star 1SWASP J030928.54+304024.7. We present the WASP discovery photometry plus higher precision optical follow-up and radial velocity measurements which taken together confirm the planetary nature of WASP-11b.

2. Observations

2.1. WASP photometry

The host star 1SWASP J030928.54+304024.7 (= USNO-B1.0 1206-0003989 = 2MASS 03092855+3040249; hereafter labelled WASP-11) was observed by SuperWASP-N during the 2004, 2006 and 2007 observing seasons, covering the intervals 2004 July 08 to 2004 September 29, 2006 September 09 to 2007 January 20 and 2007 September 04 to 2007 December 12 respectively. 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 3.722 days. A total of ten transits are observed in data from all three observing seasons (Table I; Figure I).

2.2. Photometric follow-up

WASP-11 was followed-up with the 2-m Liverpool telescope on La Palma as part of the Canarian Observatories’ International Time Programme for 2007-08. We used the 2048 x 2048 pixel EEV CCD42-40 imaging camera giving a scale of 0.27 arcseconds/pixel in 2x2 bin mode and a total field of view of ~ 4.6 x 4.6 arcminutes². Observations were taken during the transit of 2008 January 14, and consist of 656 images of 10 seconds exposure in the Sloan z’ band. The night was non-photometric and with
Table 1. WASP-N survey coverage of WASP-11

| Season | Camera | N_{pix} | N_{tr} | T_0  | P   | BJD-2400000.0 |
|--------|--------|---------|--------|------|-----|----------------|
| 2004   | 103    | 1756    | 4      | 53240.921696 | 3.7220
| 2006   | 144    | 2679    | 3      | 54056.140758 | 3.7223
| 2007   | 146    | 2750    | 2      | 54346.4883  | 3.7226
| 2007   | 147    | 729     | 1      | -    | -   | -              |

![Fig. 1. SuperWASP-N photometry of WASP-11 from the 2004, 2006 and 2007 seasons. The data have been de-trended using the system scheme described in [Collier Cameron et al. 2006] and are plotted here phase-folded on the best-fit period from the MCMC analysis (section 3).](image)

Table 2. Radial velocity measurements of WASP-11

| BJD (UT) | RV (km s\(^{-1}\)) | \(\sigma_{RV}\) (km s\(^{-1}\)) | \(v_{\text{span}}\) | Inst |
|----------|---------------------|-------------------------------|----------------------|------|
| 2454462.395 | 4.8689            | 0.0185                        | NOT      |      |
| 2454463.456 | 4.8725             | 0.0203                        | NOT      |      |
| 2454465.404 | 4.9208             | 0.0258                        | NOT      |      |
| 2454466.440 | 4.8262             | 0.0244                        | NOT      |      |
| 2454466.443 | 4.9486             | 0.0246                        | NOT      |      |
| 2454491.424 | 4.9339             | 0.0220                        | NOT      |      |
| 2454508.3700 | 4.8910            | 0.0103                        | 0.011    | SOPHIE|
| 2454509.3534 | 5.0104             | 0.0084                        | 0.000    | SOPHIE|
| 2454510.3813 | 4.8989             | 0.0120                        | 0.025    | SOPHIE|
| 2454511.3092 | 4.8515             | 0.0076                        | -0.002   | SOPHIE|
| 2454511.3800 | 4.8330             | 0.0106                        | -0.002   | SOPHIE|
| 2454511.4206 | 4.8235             | 0.0143                        | -0.035   | SOPHIE|
| 2454512.3848 | 4.9482             | 0.0096                        | 0.022    | SOPHIE|

2.3. Radial velocity follow-up

Initial spectroscopic observations were obtained using the Fiber-fed Echelle Spectrograph (FIES) mounted on the 2.5-m Nordic Optical Telescope. A total of five radial velocity points were obtained during 2007 December 27–31 and 2008 January 25. WASP-11 was observed with an exposure time of 1800s giving a signal-to-noise ratio of around 70–80 at 5500Å. FIES was used in medium resolution mode with R=46000 with simultaneous ThAr calibration. We used the bespoke data reduction package FIESStool to extract the spectra and a specially developed IDL line-fitting code to obtain radial velocities with a precision of 20–25 m s\(^{-1}\).

Radial velocity measurements of WASP-11 were also made with the Observatoire de Haute-Provence’s 1.93 m telescope and the SOPHIE spectrograph ([Bouchy & The Sophie Team 2006]), over the 8 nights 2008 February 11 – 15; a total of 7 usable spectra were acquired. SOPHIE is an environmentally stabilized spectrograph designed to give long-term stability at the level of a few m s\(^{-1}\). We used the instrument in its medium resolution mode, acquiring simultaneous star and sky spectra through separate fibres with a resolution of R=48000. Thorium-Argon calibration images were taken at the start and end of each night, and at 2- to 3-hourly intervals throughout the night. The radial velocity drift never exceeded 2–3 m s\(^{-1}\), even on a night-to-night basis.

Conditions during the SOPHIE observing run were photometric throughout, though all nights were affected by strong moonlight. Integrations of 1080 s yielded a peak signal-to-noise per resolution element of around ~30–40. The spectra were cross-correlated against a KSV template provided by the SOPHIE control and reduction software.

In all SOPHIE spectra the cross-correlation functions (CCF) were contaminated by the strong moonlight. We corrected them by using the CCF from the background light’s spectrum (mostly the Moon) in the sky fibre. We then scaled both CCFs using the difference of efficiency between the two fibres. Finally we subtracted the corresponding CCF of the background light from the star fibre, and fitted the resulting function by a Gaussian. The parameters obtained allow us to compute the photon-noise uncertainty of the corrected radial velocity measurement (\(\sigma_{RV}\)), using the relation

\[
\sigma_{RV} = 3.4 \sqrt{\frac{\text{FWHM}}{(S/N) \times \text{Contrast}}}
\]

Overall our SOPHIE RV measurements have an average photon-noise uncertainty of 10.3 m s\(^{-1}\). The measured barycentric radial
velocity (Table 2, Figure 2, lower panel) show a sinusoidal variation of half-amplitude $\sim 90$ m s$^{-1}$ about a centre-of-mass RV of $\sim 4.9$ km s$^{-1}$, consistent with the presence a companion of planetary mass. The period and ephemeris of the RV variation are consistent with those of found by the transit search.

An analysis of the line-bisector spans shows no significant correlation with radial velocity (Figure 3), as would be expected if the observed radial velocity variations were due to a diluted eclipsing binary or chromospheric activity (Queloz et al. 2001).

3. System parameters

3.1. Stellar parameters

In order to perform a detailed spectroscopic analysis of the stellar atmospheric properties of WASP-11, we merged the available FIES spectra into one high-quality spectrum, carefully removing any radial velocity signature during the process. This merged spectrum was then continuum-normalized with a very high signal-to-noise ratio of around 200 per resolution element. We were not able to include the SOPHIE spectra in this analysis, because these spectra were obtained with the HE (high-efficiency) mode which is known to suffer from problems with removal of the blaze function.

For our analysis we followed the same procedure as for the spectroscopic characterization of WASP-1 (Stempels et al. 2007) and WASP-3 (Pollacco et al. 2008). We used the package Spectroscopy Made Easy (SME, Valenti & Piskunov 1996), which combines spectral synthesis with multidimensional minimization to determine which atmospheric parameters best reproduce the observed spectrum of WASP-11 (effective temperature $T_{\text{eff}}$, surface gravity log $g$, metallicity [M/H], projected radial velocity $v \sin i$, systemic radial velocity $v_{\text{rad}}$, microturbulence $v_{\text{mic}}$ and the macroturbulence $v_{\text{mac}}$). For a more detailed description of the spectral synthesis and our assumptions we refer to Stempels et al. (2007).

The four spectral regions we used in our analysis are (1) 5160–5190Å, covering the gravity-sensitive Mg b triplet (2)
Fig. 4. A comparison between the observed FIES spectrum of WASP-11 and the calculated spectrum obtained from spectral synthesis with SME. The white regions are excluded from the spectral analysis, mainly because of the presence of telluric absorption. Light shaded regions were used to determine the continuum level, and the remaining dark shaded regions to determine the stellar atmospheric parameters.

5850–5950Å, with the temperature and gravity-sensitive Na D doublet (3) 6000-6210Å, containing a wealth of different metal lines, providing leverage on the metallicity, and (4) 6520–6600Å, covering the strongly temperature-sensitive H-alpha line. A comparison between the observed FIES spectrum and the synthetic spectrum is shown in Figure 4. The spectral analysis yields an effective temperature \( T_{\text{eff}} = 4800 \pm 100 \) K, \( \log g = 4.45 \pm 0.2 \), \([M/H] = 0.0 \pm 0.2 \) and \( v \sin i < 6.0 \) km s\(^{-1}\). These parameters correspond to spectral type of K3V. A close examination of the region around the Li i 6708 shows no evidence of such a feature, suggesting that the lithium abundance is very low.

3.2. Planet parameters

To determine the planetary and orbital parameters the SOPHIE and NOT FIES radial velocity measurements were combined with the photometry from WASP and the Liverpool Telescope in a simultaneous fit using the Markov Chain Monte Carlo (MCMC) technique. The details of this process are described in Pollacco et al. (2008). An initial fit showed that the orbital eccentricity \( (e = 0.086^{+0.076}_{-0.062}) \) was poorly constrained by the available data and nearly consistent with zero. We therefore fixed the eccentricity parameter at zero in a further fits. Figure 2 shows the best-fitting models. The best-fit parameters (Table 3) show WASP-11b to have a mass \( M = 0.53 \pm 0.07 \) M\(_J\) and a radius of \( R = 0.91^{+0.06}_{-0.03} \) R\(_J\).

4. Discussion

The system parameters derived here place WASP-11b towards the lower end of the mass range of known transiting planets, falling approximately mid-way between the masses of Jupiter and Saturn. The host star WASP-11 is also amongst the smallest and lowest luminosity stars known to host a transiting planet, however it is relatively nearby and thus quite bright \( (V = 11.7) \). WASP-11b is irradiated by a stellar flux \( F_p = 1.9 \times 10^8 \) erg cm\(^{-2}\) s\(^{-1}\) at the sub-stellar point making it the third least heavily irradiated transiting planet after GJ436b and HD17156b. We compute an equilibrium temperature for WASP-11b of \( T_{\text{eq}}(A = 0; f = 1) = 960 \pm 70 \) K, which makes it more typical of the bulk of known exoplanets than of the “hot Jupiter” class most commonly found by the transit method.

Theoretical models of the atmospheres of hot giant exoplanets (Fortney et al. 2006; Burrows et al. 2007) have shown that heavy irradiation can lead to the development of a temperature inversion and a hot stratosphere. This is due to the absorption of stellar flux by an atmospheric absorber, possibly TiO and...
VO. In both sets of models the magnitude of the incident stellar flux is the key controlling variable determining whether a given extra-solar giant planet (EGP) will possess a hot stratosphere. Recent observations by Machalek et al. (2008) of secondary transits of XO-1b using the Spitzer Space Telescope suggest the presence of a temperature inversion in the atmosphere of that exoplanet. On the other hand analogous observations of HD189733b (Charbonneau et al. 2008) show no evidence for an inversion, despite the irradiating fluxes of XO-1b and HD189733b being almost identical ($F_p = 0.49 \times 10^9$ and $F_p = 0.47 \times 10^9$ erg cm$^{-2}$ s$^{-1}$ respectively). This strongly suggests that the incident stellar flux is not the sole controlling parameter determining the presence of the inversion, a likelihood which the authors of the atmosphere models readily point out themselves. Further observations of planets particularly in the low-irradiation regime are required to help parameterise the thermal inversion. WASP-11b is amongst the nearest and brightest low-irradiation transiting exoplanets, GJ436b and HD17156b ($e = 0.15$ and $e = 0.67$ respectively). As a consequence the secular variation in irradiation around the orbit will be correspondingly lower in WASP-11b, removing a potentially complicating factor when comparing follow-up observations with predictions from atmospheric models developed assuming steady-state irradiation.

To estimate the age of the WASP-11 we compared the observed stellar density and temperature against the evolutionary models of low- and intermediate-mass stars of Girardi et al. (2000) and Baraffe et al. (1998). In Figure 5 we plot the position of WASP-11 in the $R/M^{1/3}$ versus $T_{\text{eff}}$ plane atop isochrones of different ages from the two models. For such a cool star, the isochrones are closely spaced in this parameter plane due to the slow post-main-sequence evolution of late-type stars. The sets of isochrones from the two models overlap in this regime, and both models suggest the same mass and age for the host star. WASP-11 falls above the 10 Gyr isochrone for both models, though it is consistent with this age within the errors. The very low lithium abundance also points toward WASP-11 being $\gtrsim 1$–2 Gyr old (Sestito & Randich 2005). We investigated using gyrochronology to age the host star, following Barnes (2007), however we were unable to measure a definite rotational period. No rotation modulation was detected in the lightcurve to an amplitude limit of a few milli-magnitudes. The spectral analysis furnishes only an upper-limit to $v \sin i$, so no rotational period can be determined in that way. Taken together these factors are all consistent with WASP-11 being an old star, older than maybe 1 Gyr, however it is not possible to be more definite than that with the available data.

Fortney et al. (2007) present models of the evolution of planetary radius over a range of planetary masses and orbital dis-
tances, and under the assumption of the presence of a dense core of various masses up to 100 M\textsubscript{\textoplus}. To compare our results with the Fortney et al. models we plotted the modelled mass-radius relation as a function of core mass in Figure 6. To account for the lower-than-Solar luminosity of the host star WASP-11 we calculated the orbital distance \( a_0 = a(M_*/M_\odot)^{-3.5/2} \) at which a planet in orbit about the Sun would receive the same incident stellar flux as WASP-11b does from its host. We then interpolated the models of Fortney et al. to this effective orbital distance (\( a_0 = 0.068 \) for WASP-11b). As the age of the WASP-11 system is poorly constrained we compare our results with the modelled mass-radius relation at 300 Myr, 1 Gyr and 4.5 Gyr. We find that the radius of WASP-11b is consistent with the presence of a dense core with a mass in the range \( M_{\text{core}} \sim 42–77 \) M\textsubscript{\textoplus} for a system age of 300 Myr, \( M_{\text{core}} \sim 33–67 \) M\textsubscript{\textoplus} at 1 Gyr, and \( M_{\text{core}} \sim 22–56 \) M\textsubscript{\textoplus} at 4.5 Gyr.

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