WASP-16b: A NEW JUPITER-LIKE PLANET TRANSITING A SOUTHERN SOLAR ANALOG

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ABSTRACT

We report the discovery from WASP-South of a new Jupiter-like extrasolar planet, WASP-16b, which transits its solar analog host star every 3.12 days. Analysis of the transit photometry and radial velocity spectroscopic data leads to a planet with \( R_p = 1.008 \pm 0.071 \) \( R_{\odot} \) and \( M_p = 0.855 \pm 0.059 \) \( M_{\odot} \), orbiting a host star with \( R_* = 0.946 \pm 0.054 \) \( R_{\odot} \) and \( M_* = 1.022 \pm 0.101 \) \( M_{\odot} \). Comparison of the high resolution stellar spectrum with synthetic spectra and stellar evolution models indicates the host star is a near-solar metallicity (\([\text{Fe/H]} = 0.01 \pm 0.10\) solar analog (\( T_{\text{eff}} = 5700 \pm 150 \) K and \( \log g = 4.5 \pm 0.2 \)) of intermediate age (\( \tau = 2.3^{+5.8}_{-2.2} \) Gyr).

Key words: planetary systems – stars: abundances – stars: individual (WASP-16b)

1. INTRODUCTION

There are currently over 300 known exoplanets15 with the majority of them discovered through the radial velocity (RV) technique. A growing number of exoplanets in recent years have been discovered through the transit method. Transiting exoplanets are particularly valuable as they allow parameters such as the mass, radius, and density to be accurately determined and further studies such as transmission spectroscopy, secondary eclipse measurements, and transit timing variations to be carried out.

There are several wide angle surveys that have been successful in finding transiting exoplanets around bright stars, namely HAT (Bakos et al. 2002), TyES (Alonso et al. 2004), XO (McCullough et al. 2005), and WASP (Pollacco et al. 2006). The WASP Consortium conducts the only exoplanet search currently operating in both hemispheres although HATnet is planning a southern extension and several groups are planning searches from Antarctica (e.g., Strassmeier et al. 2007; Crouzet et al. 2009).

We report the discovery from the WASP-South observatory of a \(~0.86 \) \( M_{\text{Jup}} \) mass companion orbiting a \(~11.3 \) close solar analog WASP-16 (=TYC 6147-229-1, USNO-B1.0 0697-0298329).

2. OBSERVATIONS

2.1. Photometric Observations

WASP-South, located at SAAO, South Africa, is one of two SuperWASP instruments and comprises eight cameras on a robotic mount. Each camera consists of a Canon 200mm f/1.8 lens with an Andor 2048 \( \times \) 2048 e2v CCD camera giving a field of view of \( 7.8 \times 7.8 \) and a pixel scale of 13”/7”. Exposure times were 30 s and the same field is returned to and reimaged every 8–10 minutes. Further details of the instrument, survey, and data reduction pipelines are given in Pollacco et al. (2006); and the candidate selection procedure is described in Collier Cameron et al. (2007), Pollacco et al. (2008), and references therein.

WASP-16 was observed for a partial season in 2006, a full season in 2007, and a further partial season in 2008 with the distribution of data points as 3324 points (2006), 6013 (2007), and 4084 (2008). The 2007 light curve revealed the presence of a \(~1.3\% \) dip with a period of \(~3.11\) days. The transit coverage in the other two seasons was very sparse, particularly in 2006, and there is only evidence for two partial transits in the 2008 data. WASP-16 was a fairly strong candidate for follow up despite the small number of transits, passing the filtering tests of Collier Cameron et al. (2006) with a signal to red noise ratio, \( S_{\text{red}} = 9.38 \) (with \( S_{\text{red}} > 5 \) required for selection), “transit to antitransit ratio” \( \Delta \chi^2 / \Delta \chi^2 \approx 2.5 \) \( (\Delta \chi^2 / \Delta \chi^2 \geq 1.5 \) required for selection) and no measurable ellipsoidal variation.

The SuperWASP light curve showing a zoom of the transit region, along with the model transit fit, is shown in Figure 1. In order to better constrain the transit parameters, follow-up high precision photometric observations with the Swiss 1.2m+EulerCam on La Silla, were obtained in the \( I \) band on the night of 2008 May 4 and are shown in Figure 2.

2.2. Spectroscopic Observations

In order to confirm the planetary nature of the transit signal, we obtained follow-up spectroscopic observation with the
Swiss 1.2m+CORALIE spectrograph. The data were processed through the standard CORALIE reduction pipeline as described by Baranne et al. (1996) with an additional correction for the blaze function. Fourteen RV measurements were made between 2008 March 10 and 2008 August 4 and an additional sixteen between 2009 February 19 and 2009 June 3 (see Table 1) by crosscorrelating with a G2 template mask. The resulting RV curve is shown in Figure 3. The low amplitude RV variation clearly supports the existence of a planetary mass companion. In order to rule out a nonplanetary explanation for the RV variation such as a blended eclipsing binary or starspots, we examined the line-bisector spans. Contamination from an unresolved eclipsing binary will cause asymmetries in the spectral line profiles and line-bisector span variations (Queloz et al. 2001; Torres et al. 2005). As can be seen from the lower panel of Figure 3, there is no sign of variation with phase of the bisector spans and their amplitude is much smaller than the RV variation. This supports the conclusion that the RV variations are due to a planet orbiting the star and not due to some other cause.

3. WASP-16 SYSTEM PARAMETERS

3.1. Stellar Parameters

The individual CORALIE spectra are of relatively low signal-to-noise ratio (S/N), but when coadded into 0.01 Å steps they give a S/N of around 70:1 which is suitable for a photospheric analysis of the host star. In addition, a single HARPS spectrum was used to complement the CORALIE analysis, but this spectrum had relatively modest S/N of around 50:1. The standard CORALIE/HARPS pipeline reduction products were used in the analysis.

The analysis was performed in a very similar fashion to that described by West et al. (2009) using a spectral synthesis package and LTE model atmospheres. The \( H_\alpha \) and \( H_\beta \) lines were 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. In addition, the Ca H and K lines provided a further check on the derived \( T_{\text{eff}} \) and \( \log g \). The elemental abundances of several elements were determined from measurements of several clean and unblended lines. The parameters and the abundances obtained from the analysis are listed in Table 2.

In our spectra, the Li i 6708 Å line is not detected (EW < 2 mÅ), allowing us to derive an upper limit on the Lithium abundance of \( \log n (\text{Li}/H) + 12 < 0.8 \). The lack of lithium would imply an age in excess of 5 Gyr (Sestito & Randich 2005). The stellar rotation velocity \( (v \sin i) \) was determined by fitting the profiles of several Fe i lines using an average value of \( v_{\text{mac}} = 2.0 \text{ km s}^{-1} \) for the macroturbulence \( (v_{\text{mac}}) \).

In addition to the spectral analysis, we have also used available broadband photometry to estimate the total observed bolometric flux. The Infrared Flux Method (Blackwell & Shallis 1977) was then used with Two Micron All Sky Survey
(2MASS) magnitudes to determine $T_{\text{eff}}$ and stellar angular diameter ($\theta$). This gives $T_{\text{eff}} = 5550 \pm 130$ K, which is in close agreement with that obtained from the spectroscopic analysis ($T_{\text{eff}} = 5700 \pm 150$ K).

Comparison with the stellar evolution models of Girardi et al. (2000) for solar metallicity ($Z = 0.02$) gives maximum-likelihood values $M_\star = 1.00^{+0.06}_{-0.07} M_\odot$ as shown in Figure 4. Alternative models from Baraffe et al. (1998) give essentially the same results as the stellar evolution models have close agreement in this mass range. The uncertainties on the stellar density lead to a large uncertainty on the age from the Girardi et al. (2000) isochrones producing an estimated age of $\tau = 2.3^{+5.3}_{-2.2}$ Gyr.

### 3.2. Planet Parameters

The CORALIE spectroscopic RV data were combined with the WASP-South and EULERCAM photometric data in a simultaneous fit to determine the planetary parameters. The method of Markov Chain Monte Carlo (MCMC) as detailed in previous investigations (Pollacco et al. 2008; Collier Cameron et al. 2007) was used. We used the Claret (2000) limb darkening coefficients for the appropriate stellar temperature and photometric passband and a adaptive stepsize mechanism is used during the 5000 step burn-in phase until the chain converges. At the end of this phase, the adaptive stepsize mechanism is switched off for the final 20,000 steps in the chain. The autocorrelation length...
of the chain was $9 \pm 1$ for all the parameters, indicating that no unwanted correlations are present and the chain is “well mixed.”

Initial fits showed that the eccentricity was poorly constrained but consistent with zero and so was fixed at this value in subsequent fits. The prior on the stellar mass was set to $1.0 M_\odot$, as indicated by the evolutionary tracks discussed in the previous section, but no constraint or prior on the stellar radius or density was used in the fit. The transit parameters such as the period, depth, and duration were initially set at the values from the transit search of the WASP-South data and subsequently refined in the MCMC code using all the available data.

The best-fitting system parameters are listed in Table 3 and show that WASP-16b is a reasonably close Jupiter analog albeit somewhat less massive and in a $P \sim 3$ day orbit. The host star has a fitted mass and radius which are slightly smaller than the Sun, leading to a slightly higher density than the solar case; but all the parameters are identical to the Sun within the error bars. The lack of lithium detection, low $v \sin i$ and similar large inferred age also point toward WASP-16 being a solar analog hosting a hot Jupiter planet.

4. TIMES OF TRANSIT

Although WASP-16 was observed with WASP-South for one full and two partial seasons, there are very few complete transits within the timeseries suitable for determining times of transits. This illustrates the need for long timeseries on potential transit fields as shown by Smith et al. (2006). In total, we find four complete and well-measured transits from the SuperWASP data and these are shown in Table 4 as “Fitted $T_0$” along with one time of transit determined from the EULER CAM data. The predicted times of transit from the MCMC ephemeris (given in Table 3) are also shown in Table 4. There are currently an insufficient number of measured transits with adequate precision to suggest anything other than a constant period.

5. CONCLUSIONS

We report the discovery of a new transiting planet with the WASP-South station of the SuperWASP survey. The planet, designated WASP-16b, orbits a star which is a close solar analog, having temperature, mass, radius, metallicity, and gravity the same as the Sun, within the error bounds. The age of the host star, with an admittedly large error bar, is also close to the solar age.

The orbiting planet is a reasonable Jupiter analog although somewhat less massive than Jupiter ($M_p \sim 0.85 M_{\text{Jup}}$), but with a near identical radius ($R_p \sim 1.01 R_{\text{Jup}}$) leading to a density some 80% of Jupiter. This planet falls in the lower left corner of the group of “normal” Jupiter-sized planets in the mass/radius diagram, with the majority of objects in this region being somewhat larger than Jupiter in either mass or radius. Additionally, if we compute the Safronov number $\Theta = \frac{1}{2} \left( \frac{V_{esc}}{V_{orb}} \right)^2$ for this planet, this along with its equilibrium temperature $T_{\text{eq}} = 1280$ K places it in the center of the Class I planets as defined by Hansen & Barman (2007). The “normality” of this planet makes it similar to WASP-2b, TrES-1b, and other “normal” extrasolar planets and stands in contrast to the inflated radii and low densities of planets like TrES-4b (Sozzetti et al. 2009), HD 209458b (Brown et al. 2001), and WASP-1b (Collier Cameron et al. 2007).

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Table 3

| Parameter | Value   | Error   |
|-----------|---------|---------|
| $P$ (days) | 3.1186009 | ±0.000146 |
| $T_0$ (HJD) | 2454584.4278 | ±0.000131 |
| $T_{\text{dur}}$ (days) | 0.0800 | ±0.0018 |
| $R_p^2/R_\star^2$ | 0.01199 | ±0.00052 |
| $b = a \cos i / R_\star$ | 0.798 | ±0.026 |

Table 4

| $T_0$ (HD-2450000) | Predicted $T_0$ (HD-2450000) | Error | $O-C$ |
|-------------------|-------------------------------|-------|-------|
| 4216.43288        | 4216.43417                    | 0.00243 | -0.00129 |
| 4238.26861        | 4238.26436                    | 0.00458 | 0.00425 |
| 4266.31992        | 4266.33175                    | 0.06319 | -0.01183 |
| 4291.27823        | 4291.28054                    | 0.03342 | -0.00231 |
| 4590.66606        | 4590.66602                    | 0.00028 | 0.00004 |

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