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THE LOW DENSITY TRANSITING EXOPLANET WASP-15b

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ABSTRACT

We report the discovery of a low-density exoplanet transiting an 11th magnitude star in the Southern hemisphere. WASP-15b, which orbits its host star with a period $P = 3.7520656 \pm 0.0000028$ d, has a mass $M_\mathrm{p} = 0.542 \pm 0.050\,M_\mathrm{J}$ and radius $R_\mathrm{p} = 1.428 \pm 0.077\,R_\mathrm{J}$, and is therefore one of the least dense transiting exoplanets so far discovered ($\rho_\mathrm{p} = 0.247 \pm 0.035$ g cm^{-3}). An analysis of the spectrum of the host star shows it to be of spectral type around F5, with an effective temperature $T_\mathrm{eff} = 6300 \pm 100$ K and [Fe/H] $= -0.17 \pm 0.11$.

Key words: binaries: eclipsing – planetary systems – stars: individual (WASP-15) – techniques: photometric – techniques: radial velocities – techniques: spectroscopic

1. INTRODUCTION

Transiting exoplanets represent the best current opportunity to test theoretical models of the internal structure of such planets, and the formation and evolution of planetary systems. At the time of this writing the discovery of approaching 60 transiting systems had been announced in the literature by numerous well-established survey projects, such as HATnet (Bakos et al. 2004), XO (McCullough et al. 2005), TrES (O'Donovan et al. 2006), and WASP (Pollacco et al. 2006).

The WASP project operates two identical observatories, one at La Palma in the Canary Islands, and the other at Sutherland in South Africa. Each telescope has a field of view of approximately 500 square degrees. The WASP survey is capable of detecting planetary transit signatures in the light curves of hosts in the magnitude range $V \sim 9$–13. A full description of the telescope hardware, observing strategy and pipeline data analysis is given in Pollacco et al. (2006).

2. OBSERVATIONS

The host star WASP-15 (= 1SWASP J135542.70-320934.6 = 2MASS 13554269-3209347 = USNO-B1.0 0578-0402627 = NOMAD1 0578-0409366 = TYCH2 7283-01162-1) is cataloged as a star of magnitude $V = 11.0$ and coordinates $\alpha = 13^\mathrm{h}55^\mathrm{m}42\overset{\mathrm{s}}{.}71$, $\delta = -32^\circ09'34\overset{''}{.}6$. WASP-15 was observed by the WASP-South observatory in a single camera field from 2006 May 4 to 2006 July 17, and in two overlapping camera fields from 2007 January 31 to 2007 July 17 and from 2008 January 31 to 2008 May 29.

The data were processed using the project's routine analysis pipeline, de-trending, and transit-detection tools as described in Pollacco et al. (2006) and Collier Cameron et al. (2006, 2007). A total of 24,943 data points were acquired, in which a recurrent transit signature with a period of 3.7520 days and a depth of 0.011 ± 0.001 mag was detected (Figure 1, top panel). In total, some 11 full or partial transits were observed by WASP-South.

Follow-up photometric observations were made using the EulerCAM photometer on the 1.2 m Euler telescope in the *I*-band on 2008 March 29 and the *R*-band on 2008 May 13 (Figure 1, middle and lower panel), which confirmed the presence of a flat-bottomed dip expected from the transit of an exoplanet. Both transit light-curves from EulerCAM exhibit excess variability likely due to systematic noise.

Subsequent observations using the CORALIE spectrograph on the Euler telescope between 2008 March 6 and 2008 July 17 yielded 21 radial velocity measurements (Table 1; Figure 2, upper panel) which show a sinusoidal variation with a semi-amplitude of around 65 m s^{-1} on the same period as the transit signature. An analysis of the bisector spans (Figure 2, lower panel) shows no correlation with the measured radial velocity, which rules out the possibility that the RV variations were due to a blended eclipsing binary system.

3. EVOLUTIONARY STATUS OF THE HOST STAR

The individual CORALIE spectra have a relatively low signal-to-noise ratio (S/N), but when co-added into 0.01 Å steps they give an S/N of around 80:1 which is suitable for a photospheric analysis of WASP-15. In addition, a single HARPS spectrum was used to complement the CORALIE analysis, but this spectrum had a relatively modest S/N of around 50:1.

An analysis of the available spectral data was performed using the UCLSYN spectral synthesis package (Smith 1992; Smalley et al. 2001) and ATLAS9 models without convective overshooting (Castelli et al. 1997). The Hα and Hβ lines were used to determine the effective temperature (T_eff), while the Na I D and Mg I b lines were used as surface gravity (log g) diagnostics. Additionally, the Ca H and K lines provide a further check on the derived T_eff and log g. This fit yielded a $T_\mathrm{eff} = 6300 \pm 100$ K and log $g = 4.35 \pm 0.15$ (Table 2).

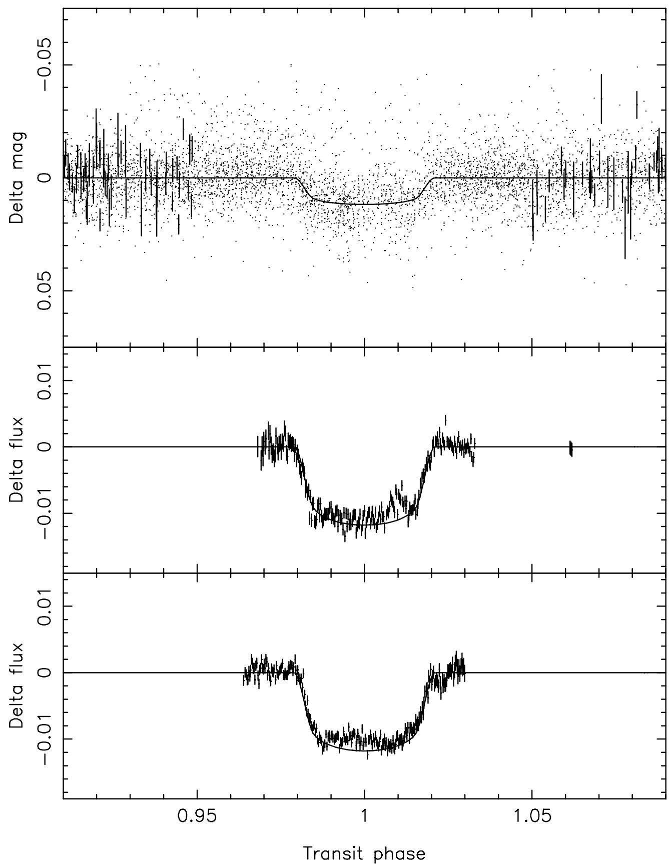

Figure 1. WASP photometry folded on the best-fit period (top panel) with representative error bars for a randomly selected subset of data points. EULER *I* band (middle) and *R* band (lower). The curve shows the best-fit transit model from the MCMC fitting.

Table 1
Radial Velocity Measurements of WASP-15

BJD −2,400,000	RV (km s^{-1})	σ_{RV} (km s^{-1})	BS (km s^{-1})
54531.8146	−2.3020	0.0148	0.0042
54532.7221	−2.3914	0.0180	0.0392
54533.7468	−2.3747	0.0151	0.0209
54534.8778	−2.2799	0.0150	0.0100
54535.7341	−2.3090	0.0137	−0.0494
54536.6666	−2.4124	0.0126	0.0156
54537.7805	−2.3671	0.0099	0.0107
54538.7459	−2.2886	0.0108	0.0009
54556.7948	−2.3156	0.0112	0.0011
54557.7488	−2.2825	0.0133	0.0010
54558.7334	−2.3925	0.0105	0.0055
54559.7479	−2.3923	0.0109	0.0120
54560.6158	−2.3144	0.0118	−0.0067
54589.6590	−2.4257	0.0126	−0.0108
54591.6355	−2.2959	0.0118	0.0046
54655.4689	−2.2933	0.0110	0.0316
54656.5165	−2.3761	0.0106	0.0489
54657.6134	−2.3190	0.0157	0.0171
54662.5205	−2.2760	0.0095	0.0538
54663.5879	−2.3634	0.0132	0.0451
54664.5932	−2.3879	0.0146	0.0126

In order to determine the elemental abundances the equivalent widths of several clean and unblended lines were measured. Atomic line data were mainly taken from the Kurucz & Bell (1995) compilation, but with updated van der Waals broadening coefficients for lines in Barklem et al. (2000) and log *gf* values from Gonzalez & Laws (2000), Gonzalez et al. (2001), or Santos et al. (2004). A value for microturbulence (ξ_t) was determined from Fe I using the method of Magain (1984). The ionization balance between Fe I and Fe II and the null-dependence of abundance on excitation potential were used in addition to the T_{eff} and $\log g$ diagnostics (Smalley 2005). The abundances are given in Table 2. The quoted error estimates include those given by the uncertainties in T_{eff}, $\log g$, and ξ_t, as well as the scatter due to measurement and atomic data uncertainties. The Li I 6708 Å line is not detected (EW < 2 m Å), allowing us to derive an upper limit on the lithium abundance of $\log n(\mathrm{Li/H}) + 12 < 1.2$. The T_{eff} of this star implies it is in the lithium gap (Böhm-Vitense 2004), so the lithium abundance does not provide an age constraint.

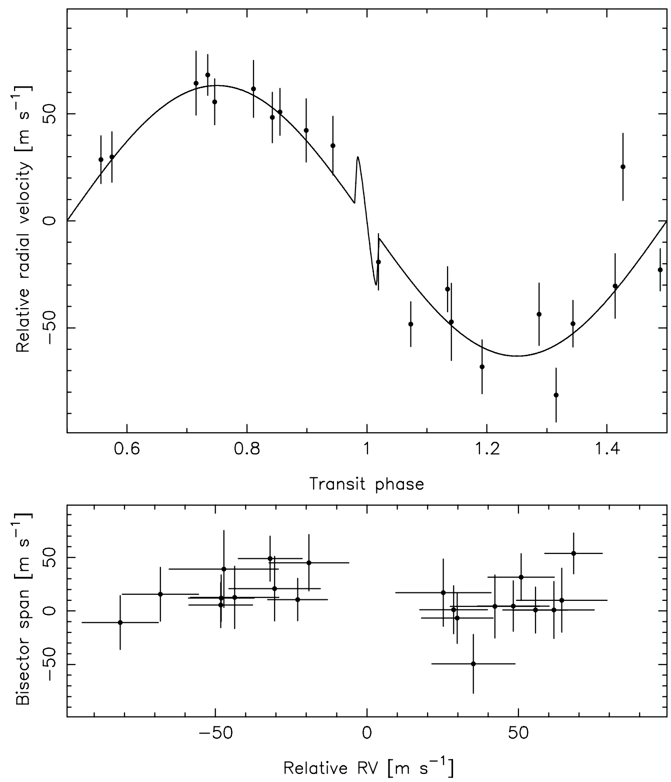

Figure 2. CORALIE radial velocity measurements. The curve shows best-fit MCMC model. The lower panel shows the bisector span plotted against RV.

Stellar rotation velocity ($v \sin i$) was determined by fitting the profiles of several unblended Fe I lines in the HARPS spectrum. A value for macroturbulence (v_{mac}) of 4.8 km s^{-1} was adopted, from the Valenti & Fischer (2005) relationship, and an instrumental FWHM of 0.060 ± 0.005 Å, determined from the telluric lines around 6300 Å. A best fitting value of $v \sin i = 4 \pm 2$ km s^{-1} was obtained.

To estimate the age of WASP-15 we compared the stellar density and temperature measured from the photometric and spectroscopic analysis against the evolutionary models of Girardi et al. (2000) interpolated to a metallicity [M/H] = −0.17 (Figure 3). This procedure yields a best-fit age of $3.9^{+2.8}_{-1.3}$ Gyr and a best-fit mass $M_* = 1.19 \pm 0.10\ M_\odot$.

4. SYSTEM PARAMETERS AND DISCUSSION

The available WASP-South and EulerCAM photometric data were combined with the CORALIE radial velocity

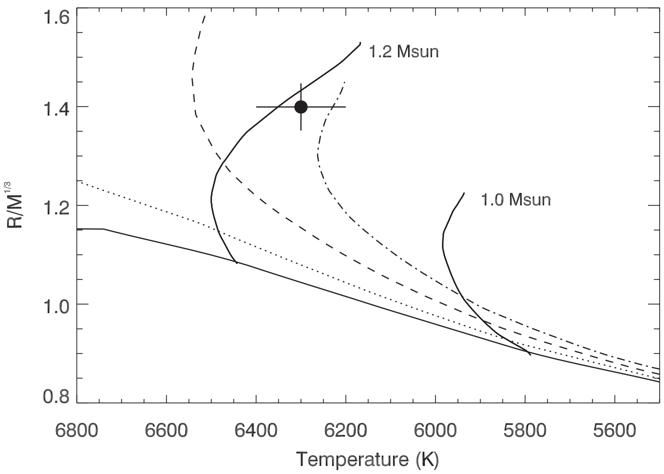

Figure 3. Position of WASP-15 in the $R/M^{1/3}-T_{\rm eff}$ plane. Evolutionary tracks for a star of metallicity [M/H] = −0.17 from Girardi et al. (2000) are plotted along with isochrones for ages 100 Myr (solid), 1 Gyr (dotted), 2.5 Gyr (dashed), and 4 Gyr (dot-dashed). Evolutionary mass tracks are shown for 1.0 and 1.2 $M_\odot$.

Table 2
Parameters of the Host Star

Parameter	Value
Stellar mass, M_* ($M_\odot$)	1.18 ± 0.12
Stellar radius, R_* ($R_\odot$)	1.477 ± 0.072
Stellar surface gravity, $\log g^{\rm a}$ (cgs)	4.169 ± 0.033
Stellar density, ρ_* ($\rho_\odot$)	0.365 ± 0.037
Stellar luminosity, $L_\star$ ($L_\odot$)	3.09 ± 0.34
Age (Gyr)	$3.9^{+2.8}_{-1.3}$
$T_{\rm eff}$ (K)	6300 ± 100
$\log g^{\rm b}$	4.35 ± 0.15
$\xi_{\rm t}$ (km s^{-1})	1.4 ± 0.1
$v \sin i$ (km s^{-1})	4 ± 2
[Fe/H]	-0.17 ± 0.11
[Na/H]	-0.25 ± 0.05
[Mg/H]	-0.13 ± 0.12
[Si/H]	-0.15 ± 0.10
[Ca/H]	-0.06 ± 0.13
[Sc/H]	-0.07 ± 0.12
[Ti/H]	-0.14 ± 0.06
[V/H]	-0.20 ± 0.11
[Cr/H]	-0.11 ± 0.12
[Co/H]	-0.16 ± 0.08
[Ni/H]	-0.25 ± 0.08
$\log N$(Li)	< 1.2

Notes.
[a] Derived from MCMC analysis.
[b] Derived from spectral analysis.

measurements in a simultaneous Markov-Chain Monte Carlo (MCMC) analysis, as described in Collier Cameron et al. (2007). An initial run yielded a best-fit value for the orbital eccentricity nearly consistent with zero ($e = 0.052^{+0.029}_{-0.040}$), so a further fit was made with the eccentricity fixed to zero. We chose not to excise from the fit any data points in the EulerCAM light curves affected by systematics; nevertheless the fitted model light curves (Figure 1) globally do not appear to have been adversely perturbed by these features.

The best-fit system parameters are listed in Tables 2 and 3 and reveal WASP-15b to be a planet with one of the lowest densities

Table 3
Parameters of the Planet and Orbit

Parameter	Value
Transit epoch (BJD), $T_{\rm C}$	$2454584.69823 \pm 0.00029$
Orbital period, P (d)	3.7520656 ± 0.0000028
Transit duration, T_{14} (d)	0.1548 ± 0.0014
Planet/star area ratio, $R_{\rm P}^2/R_*^2$	0.0099 ± 0.0002
Impact parameter, b (R_*)	$0.568^{+0.038}_{-0.046}$
Stellar reflex velocity, K_1 (km s^{-1})	0.0634 ± 0.0038
Center-of-mass velocity, γ (km s^{-1})	-2.3439 ± 0.0005
Orbital separation, a (AU)	0.0499 ± 0.0018
Orbital inclination, i (deg)	85.5 ± 0.5
Orbital eccentricity, e	$\equiv 0$ (adopted)
Planet mass, $M_{\rm p}$ ($M_{\rm J}$)	0.542 ± 0.050
Planet radius, $R_{\rm p}$ ($R_{\rm J}$)	1.428 ± 0.077
Planet surface gravity, $\log g_{\rm p}$ (cgs)	2.784 ± 0.044
Planet density, $\rho_{\rm p}$ ($\rho_{\rm J}$)	0.186 ± 0.026
Planet density, $\rho_{\rm p}$ (cgs)	0.247 ± 0.035
Planet equil. temp. ($A = 0$), $T_{\rm p}$ (K)	1652 ± 28

yet measured, comparable to TrES-4 (Mandushev et al. 2007; Sozzetti et al. 2008). The planetary radius measured here lies above that predicted by the models of Fortney et al. (2007) and Burrows et al. (2007) for a coreless planet of the mass, age, and insolation of WASP-15b. An additional internal heat source such as tidal dissipation (Jackson et al. 2008) may be required in order to account for this anomalously large radius. Indeed, Liu et al. (2008) have recently shown that only moderate tidal heating would be required to explain the radius anomalies of planets such as TrES-4, and that the degree of heating is plausible if it is assumed that the orbital eccentricities of such systems are nonzero yet still consistent with the observational limits.

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