

WTS1 b: The first planet detected in the WFCAM Transit Survey

An inflated hot-Jupiter in a 3.35 day orbit around a late F-star*

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Abstract. We report the discovery of WTS1 b, the first extrasolar planet found by the WFCAM Transit Survey. For one of the most promising transiting candidates, high-resolution spectra taken at the Hobby-Eberly Telescope (HET) allowed us to estimate the spectroscopic parameters of the host star, a late-F main sequence dwarf ($V = 16.13$), and to measure its radial velocity variations. The combined analysis of the light curves and spectroscopic data resulted in an orbital period of the companion of 3.35 days, a planetary mass of $4.01 \pm 0.35 M_J$, and a planetary radius of $1.49^{+0.16}_{-0.18} R_J$. WTS1 b has one of the largest radius anomalies among the known hot Jupiters in the mass range $3\text{--}5 M_J$.

1. INTRODUCTION

The existence of highly-irradiated, gas-giants planets orbiting within <0.1 AU of their host stars, and the unexpected large radii of many of them, is an unresolved problem in the theory of planet formation and evolution [2]. Their prominence amongst the ~ 850 confirmed exoplanets is unsurprising; their large radii, large masses, and short orbital periods make them accessible to ground-based transit and radial velocity (RV) surveys. Exoplanet searches often focus on the detection of small Earth-like exoplanets, but understanding the formation mechanism and evolution of the giant planets is a key question in astrophysics. We report on WTS1 b [1], the first planet discovery in the WFCAM Transit Survey (WTS, [3]), an infrared photometric monitoring program operating as back-up program at the UKIRT telescope at Mauna Kea, Hawaii. Since the WTS was primarily designed to find planets transiting M-dwarf stars, the observations are obtained in the J-band ($\sim 1.25 \mu\text{m}$).

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*Based on Cappetta et al. (2012), [1].

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Theoretical models of isolated giant planets predict an almost constant radius for pure H+He objects in the mass range $0.5\text{--}10 M_J$ as a result of the equilibrium between the electron degeneracy in the core and the pressure support in the external gas layers [4]. Hence the larger radii of many HJs must arise from other factors. Due to the proximity of these planets to their host star, the irradiation of the surface of the planet play a major role in the so-called radius anomaly [5]. However, this cannot be the only explanation for the radius anomaly [6]. Several physical mechanisms can be responsible for radius inflation, including: tidal heating [7], enhanced opacities of the planetary atmosphere [6] and increased heating via Ohmic dissipation [8]. Studying the radius anomaly in higher mass HJs ($>3 M_J$) is useful as they are perhaps more resilient to atmospheric loss due to their larger Roche lobe radius.

2. OBSERVATIONS

The final normalized J -band light curve for WTS1 is characterized by an out-of-transit rms of 0.0064 (equivalent to 6.92 mmag). In addition, we observed one half transit in the i' -band using the Wide Field Camera on the 2.5-m Isaac Newton Telescope [9]. A total of 82 images sample the ingress of the transit. The final out-of-transit rms in the i' -band light curve is 0.0026 (equivalent to 2.87 mmag) and is used to refine the transit model fitting procedure.

WTS1 was observed at the beginning of WTS also in the $ZYHK$ bands provided by the WFCAM [10]. Five more optical photometric data points ($ugriz$ bands) are available from the Sloan Digitized Sky Survey archive (SDSS 7th release, [11]). Other single epoch observations in the Johnson BVR bands, were observed at the University of Hertfordshire's Bayfordbury Observatory. The Two Micron All Sky Survey (2MASS, [12]) and the Wide-field Infrared Survey Explorer (WISE, [13]) provide further near-infrared data points ($JHKs$ bands and $W1 W2$ bands respectively).

In 2010 and 2011, WTS1 was observed with the High Resolution Spectrograph (HRS) at the Hobby-Eberly Telescope (HET, [14]). A total of 40 orders (18 from the red CCD and 22 from the blue one) cover the wavelength range 4400-6300 Å. The spectra have a SNR ~ 8 . Intermediate-resolution spectroscopy was carried out using the ISIS spectrograph and the William Herschel Telescope and the spectrograph CAFOS at the 2.2-m telescope at the Calar Alto Observatory.

3. THE WTS1 SYSTEM

The parent star was first characterized comparing the SED, constructed from the broad band photometric data, with a grid of synthetic Kurucz ATLAS9 theoretical spectra. The data were analysed with the application VOSA (Virtual Observatory SED Analyser, [15]). For our purpose, only the effective temperature, surface gravity, metallicity and extinction A_V were assumed as free parameters. Spectral type determination was done by comparing the CAFOS spectra with a set of template observed spectra and synthetic stellar spectra. Moreover, the high-resolution HET spectra were employed to attempt a more detailed spectroscopic analysis of the host star. The stellar atmosphere parameters and the metal abundances were determined. In particular, the measure of the Lithium abundance ($\log N(\text{Li}) = 2.5 \pm 0.4$) allowed to constrain the age of the host star. All the properties of WTS1, a slightly metal poor late F-star, are collected in Table 1. In order to investigate the planetary properties, the J - and i' -band light curves were fitted simultaneously with analytic models of transit shape [16]. We used quadratic limb-darkening coefficients for a star with the same properties of WTS1. The J -band data and the related best fitting model are shown in Figure 1 while the quantities estimated from the fit (period P , time of the central transit t_0 , etc.) are reported in Table 1. In particular, the fit of the photometric data allowed to estimate the R_p/R_* ratio and thus to compute the radius of the sub-stellar companion, which results to be $1.49^{+0.16}_{-0.18} R_J$. The noise in the data did not allow a secondary transit detection. Afterwards, we analysed the high-resolution HET spectra to accurately estimate the RV curve of the parent star. The spectra related to each single night were cross-correlated with the synthetic spectrum of a star with the same properties of WTS1.

Hot Planets and Cool Stars

Table 1. Properties of the WTS1 host star and the new discovered planet WTS1 b.

Star parameter	Value	Planet parameter	Value
Spectral type	F6-8v	M_p	$4.01 \pm 0.35 M_J$
T_{eff}	6250 ± 200 K	R_p	$1.49^{+0.16}_{-0.18} R_J$
$\log g$	4.4 ± 0.1	P_{rot}	$3.352057^{+1.3 \times 10^{-5}}_{-1.5 \times 10^{-5}}$ d
[Fe/H]	[-0.5, 0] dex	a	0.047 ± 0.001 AU
M_s	$1.2 \pm 0.1 M_{\odot}$	e	< 0.1 (C.L. = 95%)
R_s	$1.15^{+0.10}_{-0.12} R_{\odot}$	inc	$85.5^{+1.0}_{-0.7}$ deg
m_V	16.13 ± 0.04	β_{impact}	$0.69^{+0.05}_{-0.09}$
Age	[0.6, 4.5] Gyr	t_0	$2454318.7472^{+0.0043}_{-0.0036}$ HJD
RA _a	19 h 35 m 58.37 s	ρ_p	$1.61 \pm 0.56 \text{ g cm}^{-3}, 1.21 \pm 0.42 \rho_J$
Dec _a	+36 d 17 m 25.17 s	T_{eq}	1500 ± 100 K

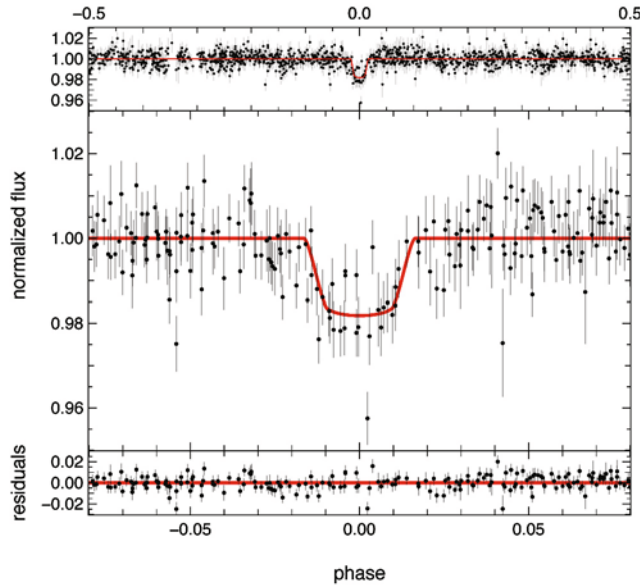


Figure 1. *Upper panel:* folded J -band curve of WTS1. *Middle panel:* folded photometric data centred in the transit and best-fit model (red line). *Lower panel:* residuals of the best fit.

Figure 2 shows the RV data and the best-fitting sinusoidal curve. We imposed the orbit to be circular as the eccentricity was compatible with zero when a Keplerian orbit fit was performed. The fitted RV semi-amplitude implies a planet mass of $4.01 \pm 0.35 M_J$, assuming a host star mass of $1.2 \pm 0.1 M_{\odot}$. The phase values ϕ were computed from the epochs of the observations, expressed in Julian date, and using the extremely well determined P and t_0 values obtained from the fit of the J and i' light curves. Further details on the analysis of the properties of the WTS1 system can be found in [1].

4. DISCUSSION

We announce the discovery of a new transiting extrasolar planet, WTS1 b, the first detected by the WFCAM Transit Survey. The parameters of the planet are collected in Table 1. WTS1 b is a $\sim 4 M_J$ planet orbiting in 3.35 days a late F-star with possibly slightly subsolar metallicity. With a radius of

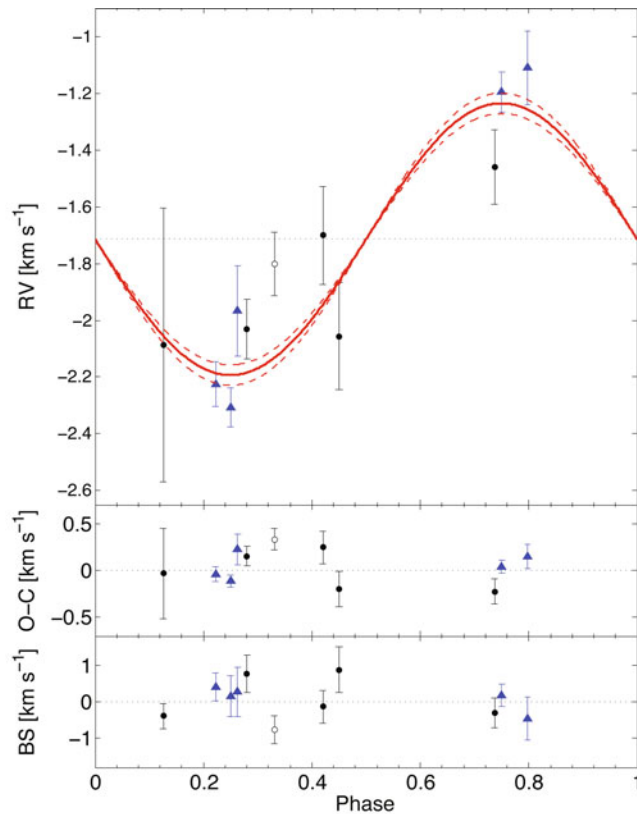


Figure 2. *Top panel:* phase folded RVs of WTS1. Black dots and blue triangles refers to observations performed in 2010 and 2011 respectively. Best-fit circular orbit model (red solid) and 1σ uncertainty of the semi-amplitude (red dashed) are shown. *Middle panel:* residuals from the best-fit. *Bottom panel:* bisector spans.

$1.49^{+0.16}_{-0.18} R_J$, it is located in the upper part of the mass – radius diagram of the known extrasolar planets in the mass range $3\text{--}5 M_J$ (see Figure 3). The properties of WTS1 b, as well as those of the other two planets present in the upper part of the diagram, CoRoT-2b and OGLE2-TR-L9b, are not explained within standard formation and evolution models of isolated gas giant planets [4].

The radius anomaly is at the $\sim 2\sigma$ level even considering the stellar irradiation that retards the contraction of the planets, the distance of the planet from the host star and the age of the planet [17]. The models of Fortney and collaborators predict indeed a radius of $1.2 R_J$ for a 600 Myr-old planet. This radius estimate is an upper limit as 600 Myr is the lower limit on the age of the WTS1 system due to the Li abundance. The radius trend shown in the figure (green dashed) would suggest an age for WTS1 less than 10 Myr. Surface day/night temperature gradients due to the strong incident irradiation, are likely to generate strong wind activity through the planet atmosphere. Recently, [18] showed how the Ohmic heating can effectively bring energy in the interior of the planet and slow down the cooling contraction of a HJ even on timescales of several Gyr: a surface wind blowing across the planetary magnetic field acts as a battery that rises Ohmic dissipation in the deeper layers.

To conclude, the discovery of WTS1 b demonstrates the capability of WTS to find planets, even if it operates in a back-up mode during dead time on a queue-schedule telescope and despite of the somewhat randomised observing strategy. Moreover, WTS1 b is an inflated HJ orbiting a late F-star even if the project is designed to search for extrasolar planets hosted by M-dwarfs.

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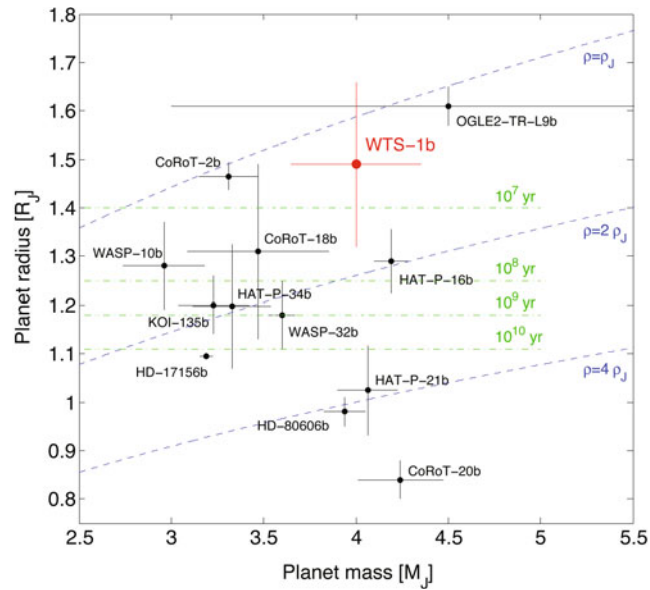


Figure 3. Mass – Radius diagram of the known planets with a mass in the range 3–5 M_J . Labels with the related planet name are shown for an easier identification. Planets with only an upper limit on mass and/or radius are not shown. The blue dashed lines represent the iso-density curves. The green dot-dashed lines indicate the planetary radii at different ages [17]. WTS1 b is shown in red.

References

- [1] Cappetta M., Saglia R.P., Birkby J.L., Koppenhoefer J., et al., 2012, MNRAS, **427**, 1877C
- [2] Baraffe I., Chabrier G., Barman T., 2010, arXiv, 1001, 3577
- [3] Kovács B., Hodgkin S., Sipőcz B., Pinfield D., et al., 2012, MNRAS submitted
- [4] Guillot T., 2005, Ann Rev EPS, **33**, 493G
- [5] Showman A.P., Guillot T., 2002, A&A, **385**, 166
- [6] Burrows A., Hubeny I., Budaj J., Hubbard W.B., 2007, ApJ, **661**, 502B
- [7] Jackson B., Greenberg R., Barnes R., 2008, ApJ, **678**, 1396J
- [8] Batygin K., Stevenson D.J., 2010, ApJ, **714**, 238B
- [9] McMahon R.G., Walton N.A., Irwin M.J., et al., 2001, New Astronomy Reviews, **45**, 97
- [10] Hodgkin S.T., Irwin M.J., Hewett P.C., Warren S.J., 2009, MNRAS, **394**, 675H
- [11] Nash T., 1996, sube.conf, 477N
- [12] Skrutskie M.F., Cutri R.M., Stiening R., Weinberg M.D., et al., 2006, AJ, **131**, 1163
- [13] Wright E.L., Eisenhardt P.R.M., Mainzer A.K., Ressler M.E., et al., 2010, AJ, **140**, 1868
- [14] Ramsey L.W., Adams. M.T., Barnes T.G., Booth J. A., et al., 1998, SPIE, **3352**, 34
- [15] Bayo A., Rodrigo C., Barrado y Navascués D., Solano E., et al., 2008, A&A, **492**, 277B
- [16] Mandel K., Agol E., 2002, ApJ, **580L**, 171M
- [17] Fortney J.J., Marley M.S., Barnes J.W., 2007, ApJ, **659**, 1661
- [18] Wu Y., Lithwick Y., 2012, arXiv, 1202, 0026