

WASP-5b: a dense, very hot Jupiter transiting a 12th-mag Southern-hemisphere star

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ABSTRACT

We report the discovery of WASP-5b, a Jupiter-mass planet orbiting a 12th-mag G-type star in the Southern hemisphere. The 1.6-d orbital period places WASP-5b in the class of very hot Jupiters and leads to a predicted equilibrium temperature of 1750 K. WASP-5b is the densest of any known Jovian-mass planet, being a factor of 7 denser than TrES-4, which is subject to similar stellar insolation, and a factor of 3 denser than WASP-4b, which has a similar orbital period. We present transit photometry and radial velocity measurements of WASP-5 (= USNO-B1 0487–0799749), from which we derive the mass, radius and density of the planet: $M_P = 1.58^{+0.13}_{-0.08} M_J$, $R_P = 1.090^{+0.094}_{-0.058} R_J$ and $\rho_P = 1.22^{+0.19}_{-0.24} \rho_J$. The orbital period is $P = 1.6284296^{+0.0000048}_{-0.0000037}$ d and the mid-transit epoch is T_C (HJD) = 245 4375.62466^{+0.00026}_{-0.00025}.

Key words: stars: individual: WASP-5 – planetary systems.

1 INTRODUCTION

Several wide-angle, ground-based surveys for transiting extrasolar planets have now been successful, including HAT (Bakos et al. 2002), TrES (O'Donovan et al. 2006), WASP (Pollacco et al. 2006) and XO (McCullough et al. 2005). In the Southern hemisphere relatively faint ($V = 16$ – 17) transiting systems have been found by OGLE (Udalski et al. 1992; Pont et al. 2007) and by Welldrake et al. (2008). The WASP-South survey is the first to find much brighter transiting systems in the south (Wilson et al. 2008). We report here

the second planet found by the WASP-South and CORALIE collaboration, a dense, very hot Jupiter transiting a $V = 12.3$ star with an orbital period of 1.6 d.

Transit searches are most sensitive to large, Jupiter-sized planets in very short orbits. WASP-5b, like the recently announced WASP-3b and WASP-4b, has an ultrashort period below 2 d (Pollacco et al. 2008; Wilson et al. 2008). We discuss the characteristics of these ultraclose, highly irradiated planets.

2 OBSERVATIONS

The WASP-South observatory is sited at the Sutherland station of the South African Astronomical Observatory. It consists of an array

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of eight cameras, each with a Canon 200-mm $f/1.8$ lens backed by an $e2v$ $2k \times 2k$ CCD, covering $7.8^\circ \times 7.8^\circ$. WASP-South started operating in 2006 May with a strategy of tiling up to eight pointings with a cadence of 5–10 min, taking two 30-s exposures at each pointing. The WASP hardware, observing strategy, data reduction pipeline and archive are described in detail by Pollacco et al. (2006). The data were detrended and transit searched as described in Collier Cameron et al. (2006), and candidates were selected as described in Collier Cameron et al. (2007).

WASP-5 (=1SWASP J235723.74–411637.5 = USNO-B1 0487–0799749 = 2MASS 23572375–4116377 = NOMAD10487–0881175) is listed in the NOMAD (Naval Observatory Merged Astrometric Dataset) catalogue as a $V = 12.3$ star, and was observed by WASP-South from 2006 May 13 to 2006 November 14. Transits of WASP-5b were detected by two WASP-South cameras, where they overlap at the field edges. A total of 4642 data points were obtained with camera 7 and 4108 data points with camera 8 (Fig. 1).

During follow-up, a transit was observed in the R band using EulerCam on the 1.2-m telescope at La Silla on 2007 October 10 (Fig. 2). The telescope was heavily defocused to allow long exposure times (2 min) resulting in an rms scatter of 1-mmag. A further transit was observed in the Sloan Digital Sky Survey (SDSS) i' band on 2007 October 13 using HawkCam2 on the 2.0-m Faulkes Telescope South (FTS) at Siding Spring Observatory (Fig. 2).

Radial velocity data were obtained with the CORALIE spectrograph on the Euler 1.2-m telescope. CORALIE had recently been upgraded, as described in Wilson et al. (2008). 11 radial velocity measurements were taken over the course of one month (Table 1; Fig. 3), establishing WASP-5b as a planetary-mass companion.

We used a line-bisector analysis to look for asymmetries in the spectral line profiles, as could be caused by contamination from an unresolved eclipsing binary (Queloz et al. 2001; Mandushev et al. 2005). Such a binary would produce bisector spans that vary in phase with the photometric period with an amplitude comparable to the

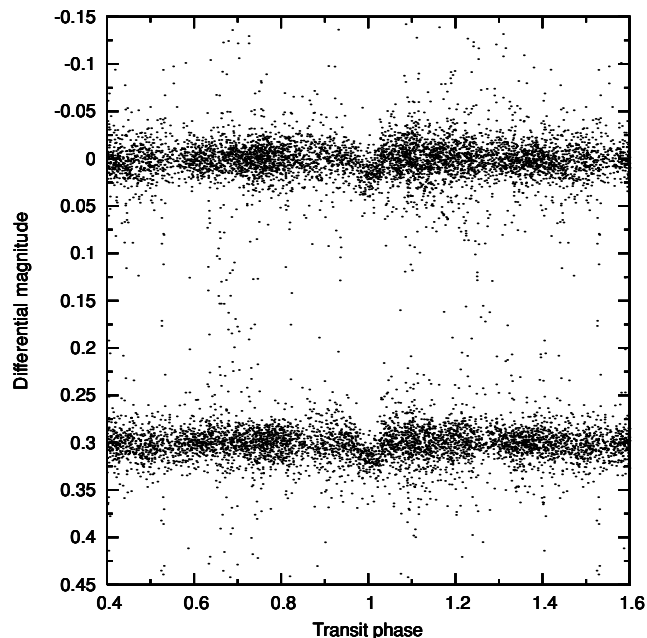


Figure 1. Discovery light curves for WASP-5 obtained with WASP-South camera 7 (top) and WASP-South camera 8 (bottom, offset by 0.3 mag for clarity).

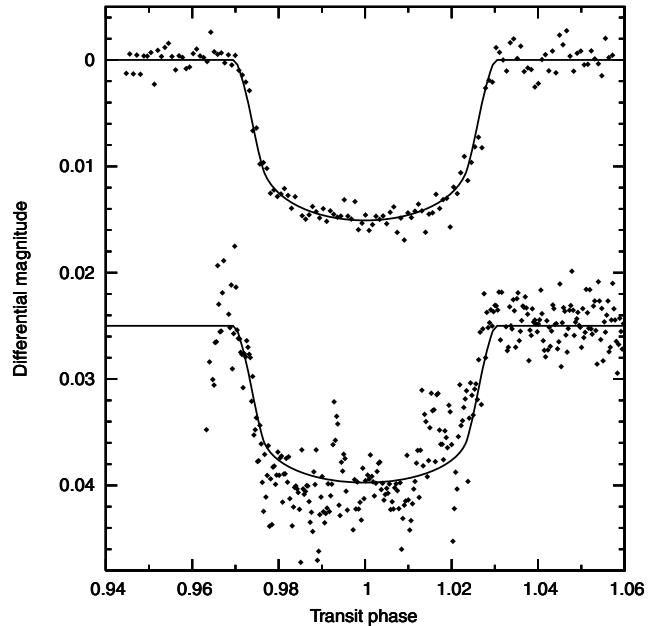


Figure 2. The R -band light curve obtained with the Euler telescope (top) and the SDSS i' -band light curve obtained with Faulkes Telescope South (bottom, offset by 0.025 mag for clarity). In each case the solid line is the optimal MCMC solution (see Section 4).

Table 1. Radial velocity measurements of WASP-5.

BJD 2 400 000 (d)	RV (km s^{-1})	σ_{RV} (km s^{-1})	BS ^a (km s^{-1})
54359.614570	19.785	0.016	−0.023
54362.654785	19.942	0.015	0.033
54364.676219	19.753	0.021	0.026
54365.682733	20.203	0.013	0.015
54372.781658	19.750	0.013	−0.047
54374.817984	20.016	0.040	0.091
54376.714797	20.248	0.014	−0.024
54377.762440	19.747	0.013	−0.002
54379.627523	19.907	0.014	−0.060
54380.682557	19.830	0.010	−0.024
54387.644986	19.818	0.015	0.027

^aBisector spans; $\sigma_{\text{BS}} \approx 2\sigma_{\text{RV}}$.

radial velocity amplitude. This is not seen in our data (Fig. 3, bottom panel), supporting the conclusion that the radial velocity variations are due to a planet.

3 STELLAR PARAMETERS

The CORALIE spectra, when co-added, give a signal-to-noise ratio (S/N) of ~ 40 , which is suitable for a preliminary photospheric analysis of WASP-5. The analysis was performed using the UCLSYN spectral synthesis package and ATLAS9 models without convective overshooting (Castelli, Gratton & Kurucz 1997). The $H\alpha$, Na I D and Mg I b lines were used as diagnostics of both T_{eff} and $\log g$. The metallicity was estimated using the photospheric lines in the 6000–6200 Å region. The parameters obtained from this analysis are listed in Table 2.

We also used the Galaxy Evolution Explorer (GALEX) near-ultraviolet (NUV) flux and magnitudes from the NOMAD, DENIS (Deep Near Infrared Survey) and 2MASS (Two Micron

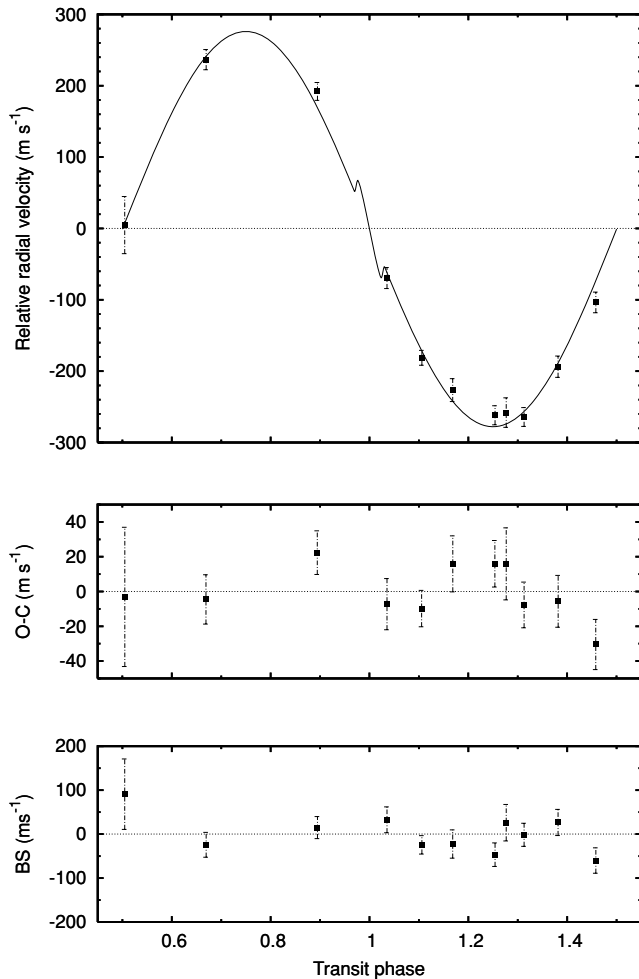


Figure 3. Top: the radial velocity measurements of WASP-5 obtained with CORALIE. The centre-of-mass velocity has been subtracted. The solid line is the MCMC solution (Section 4); it includes the Rossiter–McLaughlin effect resulting from a $v \sin i$ of 3.4 km s^{-1} , as obtained from the CORALIE spectra. Middle: the radial velocity residuals about the MCMC fit. Bottom: bisector spans for the 11 CORALIE spectra.

Table 2. Stellar parameters for WASP-5.

Parameter	Value
RA (J2000)	$23^{\text{h}} 57^{\text{m}} 23^{\text{s}}.74$
Dec. (J2000)	$-41^{\circ} 16' 37''.5$
T_{eff} (K)	5700 ± 150
$\log g_*$ (cgs)	4.3 ± 0.2
[M/H]	0.0 ± 0.2
$v \sin i$ (km s^{-1})	3.4 ± 0.7
$\log A(\text{Li})$	< 1.0
M_* (M_{\odot})	0.99 ± 0.08
R_* (R_{\odot})	0.97 ± 0.06
Spec. type	G4V ± 2 subtypes
Age (Gyr)	1.7–4.4
Distance (pc)	300 ± 50

All Sky Survey) catalogues to estimate the effective temperature using the infrared flux method (IRFM; Blackwell & Shallis 1977). This gives $T_{\text{eff}} = 5610 \pm 250 \text{ K}$, which is in close agreement with the spectroscopic analysis. These results imply a spectral type in

the range G2V–G6V. The Li I 6708 Å line is not present in the co-added spectrum, giving an upper limit on the lithium abundance of $\log A(\text{Li}) \lesssim 1.2$. This implies an age of $\gtrsim 2 \text{ Gyr}$ for a star of this effective temperature (Sestito & Randich 2005). The value of $v \sin i = 3.4 \text{ km s}^{-1}$ obtained from the CORALIE spectra indicates an age of 1.7–4.4 Gyr (Bouvier 1997). Comparison of the temperature and $\log g_*$ with the stellar evolution models of Girardi et al. (2000) gives maximum likelihood values of $M_* = 0.99 \pm 0.08 M_{\odot}$ and $R_* = 0.97 \pm 0.06 R_{\odot}$. The distance of WASP-5 ($d = 300 \pm 50 \text{ pc}$) was calculated using the distance modulus, the NOMAD apparent visual magnitude ($V = 12.3$) and the absolute visual magnitude of a G4V star ($V = 4.9$; Gray 1992). We assumed $E(B - V) = 0$, which is reasonable at such a distance and in a direction out of the galactic plane.

4 SPECTROSCOPIC ORBITAL SOLUTION AND PLANETARY PARAMETERS

The CORALIE radial velocity measurements were combined with the WASP-South and EulerCAM photometry in a simultaneous Markov chain Monte Carlo (MCMC) analysis to find the system parameters. This process is described in detail in Collier Cameron et al. (2007) and Pollacco et al. (2008). The FTS data were not used owing to their higher red noise. The best-fitting solution to the radial velocity data gave an eccentricity of $e = 0.03 \pm 0.03$. Our adopted MCMC solution fixes the eccentricity at $e = 0$, which is expected for such a short-period planet.

In optimizing the MCMC solution we used constraints (Gaussian priors) on the stellar parameters, setting $M_* = 0.99 \pm 0.08 M_{\odot}$ and $\log g_* = 4.30 \pm 0.20$. In order to balance the weights of the photometry and radial velocities in the MCMC analysis, we added a systematic error of 7 m s^{-1} to the radial velocities (as might arise,

Table 3. System parameters for WASP-5.

Parameter	Value	
P (d)	1.6284296	$+0.0000048$ -0.0000037
T_C (HJD)	2454375.62466	$+0.00026$ -0.00025
T_{14} (d) ^a	0.0979	$+0.0011$ -0.0009
R_P^2/R_*^2	0.01192	$+0.00038$ -0.00027
$b \equiv a \cos i/R_*$ (R_{\odot}) ^b	< 0.46	(0.14)
i ($^{\circ}$) ^b	> 85.0	(1.7)
e	0 (adopted)	
K_1 (km s^{-1})	0.2778	$+0.0085$ -0.0078
γ (km s^{-1})	20.0105	$+0.0031$ -0.0034
M_* (M_{\odot})	0.972	$+0.099$ -0.079
R_* (R_{\odot})	1.026	$+0.073$ -0.044
T_{eff} (K)	5880	$+150$ -150
$\log g_*$ (cgs)	4.403	$+0.039$ -0.048
M_P (M_J)	1.58	$+0.13$ -0.08
R_P (R_J)	1.090	$+0.094$ -0.058
ρ_P (ρ_J)	1.22	$+0.19$ -0.24
a (au)	0.02683	$+0.00088$ -0.00075
$\log g_P$ (cgs)	3.484	$+0.043$ -0.062
T_P (K)	1753	$+66$ -56

^a T_{14} : transit duration, the time between first and fourth contact.

^b The limits on b and i are 1σ . The error bar is given in parentheses.

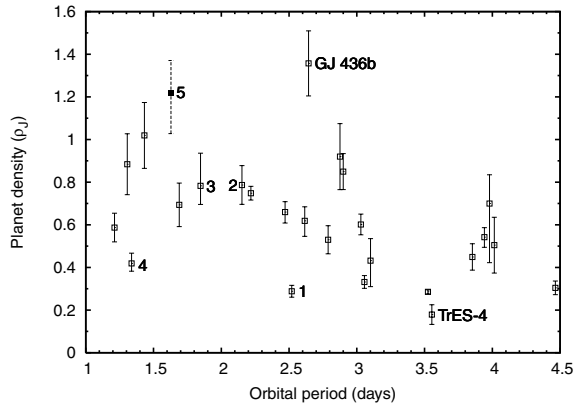


Figure 4. Planet density versus orbital period for planets with periods less than 5 d. The dense, hot Neptune, GJ 436b, and underdense TrES-4 are labelled; the five WASP planets are labelled numerically. The error bars on the densities were calculated from the uncertainties on the masses and radii, which were assumed to be uncorrelated. Data taken from <http://www.inscience.ch/transits/>

for example, from stellar activity) to reconcile χ^2 with the number of degrees of freedom; the error bars in Fig. 3 do not incorporate this error. The optimal MCMC parameters are shown in Table 3.

5 DISCUSSION

The discovery of WASP-3b (Pollacco et al. 2008), WASP-4b (Wilson et al. 2008) and WASP-5b, all transiting, Jupiter-mass planets with orbital periods of less than 2 d, increases the number of such systems known from four to seven.¹ It is notable that they show a large disparity in density (Fig. 4). WASP-5b is the densest of these systems, whereas WASP-4b is the least dense, with a density a third that of WASP-5b. This illustrates that planets with a similar orbital period and radiation environment must still have different compositions or past histories.

For example, WASP-5b will receive the same insolation and thus has a similar estimated equilibrium temperature (1753 K) to TrES-4 (1720 K), which has a longer orbit about a more luminous star (Mandushev et al. 2007). Despite this, WASP-5b is denser by a factor of 7 ($1.22 \rho_J$ compared with $0.167 \rho_J$ for TrES-4). Burrows et al. (2007) postulate that the bloating of the underdense planets could be due to an enhanced atmospheric opacity, which could be absent in WASP-5b.

Although it is denser than other planets with a similar orbital period, WASP-5b is still within the expected theoretical range (Fortney, Marley & Barnes 2007); depending on the age of the system, a core mass of $\sim 50\text{--}100 M_{\oplus}$ is expected, with a younger planet requiring a more massive core. However, if the bloating of some planets were due to an extra energy source that is common to all hot Jupiters, then the core of a dense planet such as WASP-5b would have to be more massive to compensate (Fortney et al. 2006; Guillot et al. 2006). If the core mass is toward the higher end of the estimate and the metallicity is no more than solar then there could be a discrepancy with the relationship between core mass and stellar metallicity postulated by Burrows et al. (2007). High-resolution spectra with better S/N are required to reduce the uncertainties in the metallicity and age.

¹ <http://www.inscience.ch/transits/>

WASP-5b ($\log g_* = 3.48$) has the highest surface gravity of planets with orbital periods less than 5 d. Thus it could be a good system for studying evaporation as a function of surface gravity. In comparison HD 209458b is heavily bloated ($\log g_* = 2.97$) and appears to be undergoing evaporation (Vidal-Madjar et al. 2003, 2008; Ben-Jaffel 2007). Given its high equilibrium temperature, WASP-5b is also expected to have a prominent secondary transit, which should be detectable with *Spitzer* (e.g. Harrington et al. 2007). Further, with the moderately bright host star having a moderate rotation rate of $v \sin i = 3.4 \text{ km s}^{-1}$, the Rossiter–McLaughlin effect ($40 \pm 8 \text{ m s}^{-1}$) should be detectable (Gaudi & Winn 2007), allowing us to check the alignment between the planetary orbit and the stellar spin axis.

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REFERENCES

- Bakos G. Á., Lázár J., Papp I., Sári P., Green E. M., 2002, *PASP*, 114, 974
 Ben-Jaffel L., 2007, *ApJ*, 671, L61
 Blackwell D. E., Shallis M. J., 1977, *MNRAS*, 180, 177
 Bouvier J., 1997, *Mem. Soc. Astron. Ital.*, 68, 881
 Burrows A., Hubeny I., Budaj J., Hubbard W. B., 1997, *A&A*, 318, 841
 Castelli F., Gratton R. G., Kurucz R. L., 1997, *A&A*, 318, 841
 Collier Cameron A. et al., 2006, *MNRAS*, 373, 799
 Collier Cameron A. et al., 2007, *MNRAS*, 380, 1230
 Fortney J. J., Saumon D., Marley M. S., Lodders K., Freedman R. S., 2006, *ApJ*, 642, 495
 Fortney J. J., Marley M. S., Barnes J. W., 2007, *ApJ*, 659, 1661
 Gaudi B. S., Winn J. N., 2007, *ApJ*, 655, 550
 Girardi L., Bressan A., Bertelli G., Chiosi C., 2000, *A&AS*, 141, 371
 Gray D. F., 1992, *The Observation and Analysis of Stellar Photospheres*. Cambridge Univ. Press, Cambridge
 Guillot T., Santos N. C., Pont F., Iro N., Melo C., Ribas I., 2006, *A&A*, 453, L21
 Harrington J., Luszcz S., Seager S., Deming D., Richardson L. J., 2007, *Nat*, 447, 691
 McCullough P. R., Stys J. E., Valenti J. A., Fleming S. W., Janes K. A., Heasley J. N., 2005, *PASP*, 117, 783
 Mandushev G. et al., 2005, *ApJ*, 621, 1061
 Mandushev G. et al., 2007, *ApJ*, 667, L195
 O’Donovan F. T. et al., 2006, *ApJ*, 651, L61
 Pollacco D. L. et al., 2006, *PASP*, 118, 1407
 Pollacco D. L. et al., 2008, *MNRAS*, in press (doi:10.1111/j.1365-2966.2008.12939.x)
 Pont F. et al. 2007, *A&A*, submitted (arXiv:0710.5278)
 Queloz D. et al., 2001, *A&A*, 379, 279
 Sestito P., Randich S., 2005, *A&A*, 442, 615
 Udalski A., Szymanski M., Kaluzny J., Kubiak M., Mateo M., 1992, *Acta Astron.*, 42, 253
 Vidal-Madjar A., Lecavelier des Etangs A., Désert J.-M., Ballester G. E., Ferlet R., Hébrard G., Mayor M., 2003, *Nat*, 422, 143
 Vidal-Madjar A., Lecavelier des Etangs A., Désert J.-M., Ballester G. E., Ferlet R., Hébrard G., Mayor M. 2008, *ApJ*, 676, 57
 Weldrake D. T. F., Bayliss D. D. R., Sackett P. D., Tingley B. W., Gillon M., Setiawan J., 2008, *ApJ*, 675, L37
 Wilson D. M. et al., 2008, *ApJ*, 675, L113

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