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WASP-4b: A 12TH MAGNITUDE TRANSITING HOT JUPITER IN THE SOUTHERN HEMISPHERE

D. M. Wilson,[1] M. Gillon,[2,3] C. Hellier,[1] P. F. L. Maxted,[1] F. Pepe,[2] D. Queloz,[2] D. R. Anderson,[1] A. Collier Cameron,[4] B. Smalley,[1] T. A. Lister,[1,5] S. J. Bentley,[1] A. Blecha,[2] D. J. Christian,[6] B. Enoch,[7] C. A. Haswell,[7] L. Hebb,[4] K. Horne,[4] J. Irwin,[8,9] Y. C. Joshi,[6] S. R. Kane,[10] M. Marmier,[2] M. Mayor,[2] N. Parley,[7] D. Pollacco,[6] F. Pont,[2] R. Ryans,[6] D. Segransan,[2] I. Skillen,[11] R. A. Street,[5,6,12] S. Udry,[2] R. G. West,[13] and P. J. Wheatley[14]

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ABSTRACT

We report the discovery of WASP-4b, a large transiting gas-giant planet with an orbital period of 1.34 days. This is the first planet to be discovered by the SuperWASP-South observatory and CORALIE collaboration and the first planet orbiting a star brighter than 16th magnitude to be discovered in the southern hemisphere. A simultaneous fit to high-quality light curves and precision radial velocity measurements leads to a planetary mass of $1.22^{+0.09}_{-0.08}$ $M_{\rm Jup}$ and a planetary radius of $1.42^{+0.07}_{-0.04}$ $R_{\rm Jup}$. The host star is USNO-B1.0 0479−0948995, a G7 V star of visual magnitude 12.5. As a result of the short orbital period, the predicted surface temperature of the planet is 1761 K, making it an ideal candidate for detections of the secondary eclipse at infrared wavelengths.

Subject headings: planetary systems — stars: individual (WASP-4)

Online material: machine-readable table

1. INTRODUCTION

Transiting extrasolar planets offer our best opportunity for measuring fundamental parameters of extrasolar planets, such as radius and mass, allowing us to test our models for planetary formation and evolution. To date the only transiting planets known in the southern sky are those discovered by surveys targeting the Galactic plane (e.g., Udalski et al. 2002; Pont et al. 2007; Weldrake et al. 2008) and find planets around stars with typical visual magnitudes of 16–17.

The SuperWASP-South (WASP-S) instrument looks for transiting planets around stars of visual magnitude 8–13, and will eventually cover the entire southern sky, excluding the Galactic plane. We report here the discovery of WASP-4b, a transiting hot Jupiter orbiting a star of magnitude 12.5.

This is the first discovery by WASP-S, made in collaboration with radial velocity measurements from the CORALIE spectrograph on the 1.2 m Euler telescope. The discovery marks the beginning of a campaign to discover brighter transiting extrasolar planets in the southern hemisphere, to complement those discovered in the north by projects including HAT (Bakos et al. 2002), TrES (O'Donovan et al. 2006), XO (McCullough et al. 2005), and WASP (Pollacco et al. 2006).

Transit searches are most sensitive to large planets with short orbital periods, and have now found nine Jupiter-mass planets in orbits of less than 2 days.[15] This has led to suggestions of a class of very hot Jupiters (Melo et al. 2006), with highly irradiated atmospheres (e.g., Fortney et al. 2007), to which WASP-4b likely belongs.

2. PHOTOMETRIC OBSERVATIONS

The WASP (Wide Angle Search for Planets) consortium operates two identical robotic observatories: SuperWASP-North on La Palma, in the northern hemisphere, and SuperWASP-South, in the southern hemisphere, hosted by the South African Astronomical Observatory (SAAO). Each consists of eight wide-field cameras consisting of an 11.1 cm aperture Canon 200 mm f/1.8 lens backed by a 2K × 2K e2v CCD. The eight cameras cover 490 deg^2 per pointing. WASP-S started operating in 2006 May, with a strategy of tiling six to eight fields with a cadence of 5–10 minutes and exposure times of 30 s. These fields rotate with the seasons, accumulating to a strip centered on a declination of −32°, resulting in light curves for over one million stars brighter than 13th magnitude. For details of the WASP project, hardware, and data processing see Pollacco et al. (2006). Further details of our data analysis procedures are given in Collier Cameron et al. (2007a), reporting the discovery of WASP-1b and WASP-2b from SuperWASP-North, and in Pollacco et al. (2007), reporting the discovery of WASP-3b.

From the WASP-S data collected between 2006 May–November we identified 1SWASP J233415.06−420341.1 (USNO-B1.0 0479−0948995) as a high-priority planetary transit candidate; over 4000 measurements revealed a possible transit recurring every 1.3 days (see Collier Cameron et al. [2006] for a description of our transit-search methods and Collier Cam-

[1] Astrophysics Group, Keele University, Staffordshire ST5 5BG, UK.
[2] Observatoire de Genève, 51 ch. des Maillettes, 1290 Sauverny, Switzerland.
[3] Institut d'Astrophysique et de Géophysique, Université de Liège, 4000 Liège, Belgium.
[4] School of Physics and Astronomy, University of St. Andrews, North Haugh, Fife KY16 9SS, UK.
[5] Las Cumbres Observatory, 6740 Cortona Drive, Suite 102, Santa Barbara, CA 93117.
[6] Astrophysics Research Centre, School of Mathematics and Physics, Queen's University, University Road, Belfast BT7 1NN, UK.
[7] Department of Physics and Astronomy, Open University, Milton Keynes MK7 6AA, UK.
[8] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK.
[9] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS-16, Cambridge, MA 02138-1516.
[10] Michelson Science Center, California Institute of Technology, MS 100-22, 770 South Wilson Avenue, Pasadena, CA 91125.
[11] Isaac Newton Group of Telescopes, Apartado de Correos 321, E-38700 Santa Cruz de la Palma, Tenerife, Spain.
[12] Department of Physics, Broida Hall, University of California, Santa Barbara, CA 93106-9530.
[13] Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK.
[14] Department of Physics, University of Warwick, Coventry CV4 7AL, UK.

[15] See http://exoplanet.eu.

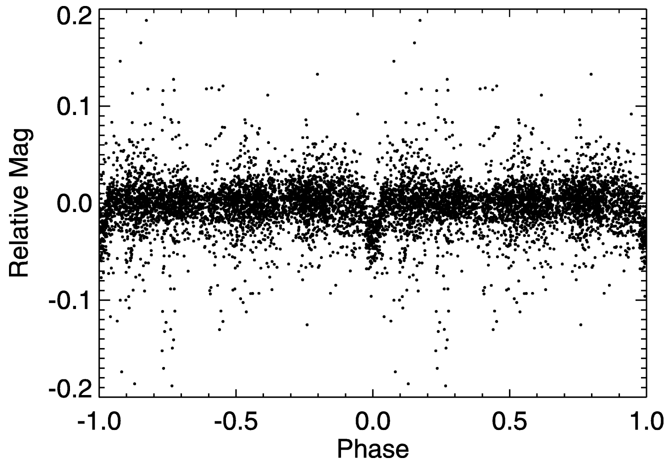

FIG. 1.—SuperWASP-South discovery light curve of WASP-4 folded on the 1.3 day orbital period.

eron et al. [2007b] for an account of our selection of high-priority candidates). A catalog search within the 48″ photometric aperture of 1SWASP J233415.06−420341.1 revealed no bright blending companions or known variable/active stars, which could mimic the photometric signature of a transiting planet. The WASP-S discovery light curve is shown in Figure 1.

A full transit of WASP-4b was observed by EulerCAM on the 1.2 m Euler telescope on 2007 September 25. Observations were performed in *R* band and were heavily defocused to allow exposure times of ∼2 minutes, achieving an rms scatter of 1.8 mmag despite poor transparency conditions. Part of a transit was also observed in SDSS i' band by the 2.0 m Faulkes Telescope South (FTS) on 2007 September 27. The WASP-S, EulerCAM, and FTS light curves are shown in Figure 2 and the EulerCam photometric measurements are listed in Table 1.

3. SPECTROSCOPIC OBSERVATIONS WITH CORALIE

Spectroscopic measurements were obtained using the CORALIE spectrograph installed on the Euler telescope. CORALIE was originally a twin copy of the ELODIE spectrograph (Baranne et al. 1996). However, triggered by the interest to carry out spectroscopic follow-up on transit candidates with this instrument, in 2007 June we carried out major changes to CORALIE to increase its performance on fainter stars. The fiber link and the cross-disperser optics have been removed and replaced by a new design (D. Queloz et al., in preparation). The double scrambler has also been removed and the grism and prism cross-disperser component replaced by a series of 4 Schott F2 prisms of 32° angle each. The net outcome of this new design is to maintain the spectral range from 381 to 681 nm but with a large efficiency gain of about a factor of 6 (8 below 420 nm) and a spectroscopic resolution of 55,000–60,000 (increased by 10%–20%). The overall instrumental precision is also improved. All exposures are reduced by the automated pipeline adapted to the new optical configuration. WASP-4 was observed from 2007 September to November and the radial velocity and the $v \sin i$ computed using a G2-spectral template. Exposures were 30 minutes in length, achieving a signal-to-noise ratio of ∼15. Radial velocity variations of semiamplitude 251 m s^{-1} were detected consistent with a planetary-mass companion whose orbital period closely matches that from the WASP-S transit detections. The RV measurements are listed in Table 2 and are shown phase folded and overplotted with the best-fitting orbital model in Figure 3. The rms of the RV measurements to the model fit is 15.3 m s^{-1}.

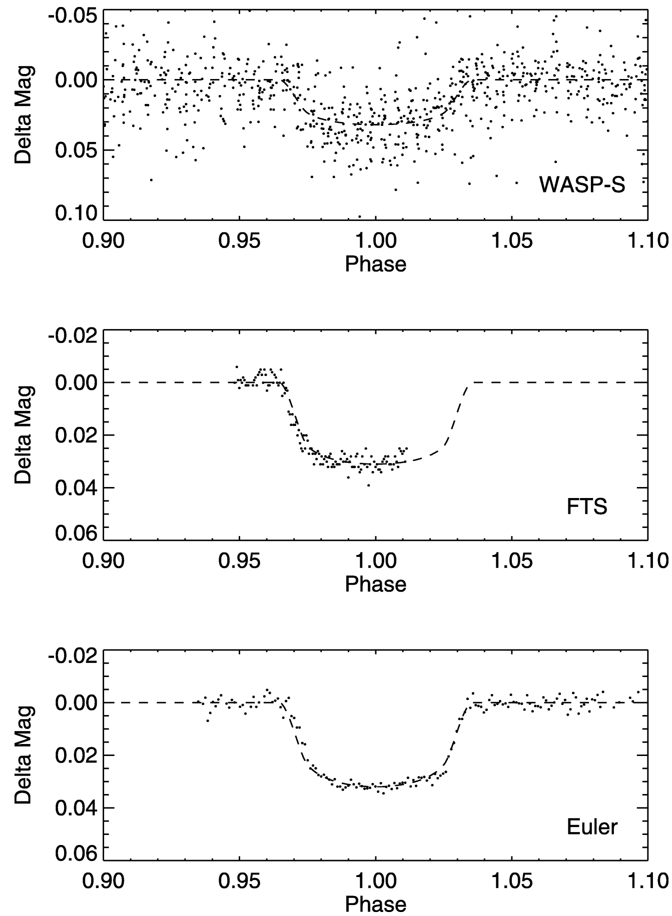

FIG. 2.—WASP-S, FTS, and EulerCam light curves showing the transit of WASP-4b. The data are shown folded on the orbital period together with the best-fitting model determined from a simultaneous MCMC fit of the photometric and radial velocity data. The rms scatter to the model fit of the WASP-S, FTS, and EulerCam light curves is 15.3, 2.7, and 1.8 mmag, respectively. Phase 1 for the EulerCam light curve occurred at HJD = 2,454,368.59121 UT and for the FTS light curve at HJD = 2,454,371.26766 UT.

3.1. *Line-Bisector Analysis*

Although the amplitude of the RV variation of this system is consistent with a planetary companion, the signal could be

TABLE 1
EulerCam OBSERVATIONS OF THE TRANSIT OF WASP-4b CENTERED AT HJD = 2,454,368.59121 UT

HJD	Delta Mag	Mag Error
2454368.50400	1.000557	0.000967
2454368.50632	0.999778	0.000939
2454368.50748	1.001936	0.000903
2454368.50863	0.993879	0.001131
2454368.50988	0.996599	0.001248
2454368.51120	1.000440	0.000949
2454368.51254	0.998934	0.000959
2454368.51387	1.001310	0.000945
2454368.51520	1.002759	0.000910
2454368.51788	0.999890	0.001004

NOTE.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

TABLE 2
CORALIE RV Measurements for WASP-4b

BJD − 2,450,000	RV (km s^{-1})	σ_{RV} (km s^{-1})
4359.71082	57.56557	0.01864
4362.63121	57.79551	0.01883
4364.65260	57.67271	0.02223
4365.73690	57.95703	0.01613
4372.75799	57.58619	0.01496
4376.68882	57.64642	0.01451
4378.66887	57.79207	0.01325
4379.73630	57.50846	0.01470
4380.61034	57.77411	0.01303
4382.79025	57.86396	0.01823
4383.55277	57.51000	0.01434
4387.61904	57.49524	0.01457
4408.66110	57.77556	0.01682
4409.51932	57.82666	0.02156

mimicked by spectral line distortions caused by a blended eclipsing binary (e.g., Santos et al. 2002). To confirm the presence of a transiting planet it is necessary to exclude this scenario. Blended eclipsing binaries can be identified from multicolor photometry or through light curve modeling (Torres et al. 2004); however, the simplest and most reliable method is to search for variations in the spectral line profiles themselves. This has the added advantage of highlighting atmospheric distortion effects which can also affect the measured radial velocities. If the detected radial velocity variations are the result of contamination of the spectrum by an eclipsing binary, we would expect to see distortions in the line profiles in phase with the photometric period. The CORALIE cross-correlation functions were analyzed using the line-bisector technique (Queloz et al. 2001) and no evidence for variation in the bisector spans was found, confirming the planetary nature of this system. A plot of the bisector spans is shown in Figure 4.

4. STELLAR PARAMETERS

The individual CORALIE spectra have a low signal-to-noise ratio, but when co-added (and rebinned) give a S/N of around 30–40 which is suitable for a preliminary photospheric analysis of WASP-4. The analysis was performed using the UCLSYN spectral synthesis package and ATLAS9 models without con-

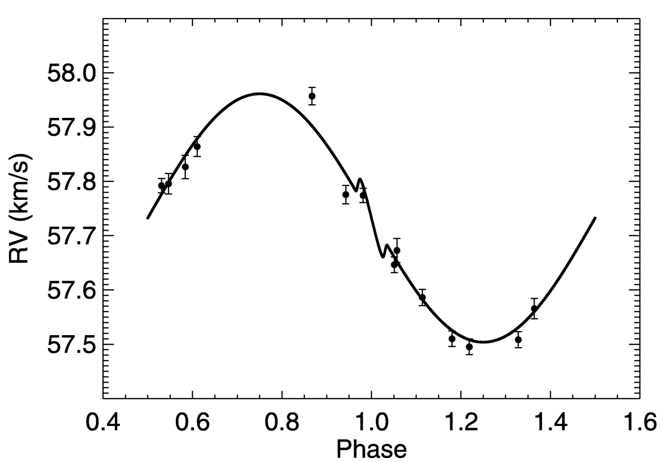

Fig. 3.—CORALIE radial velocity measurements folded on the orbital period together with a radial velocity model which includes the expected Rossiter-McLaughlin effect for a star with $v \sin i = 2$ km s^{-1}. The rms of the RV measurements to the model fit is 15.3 m s^{-1}.

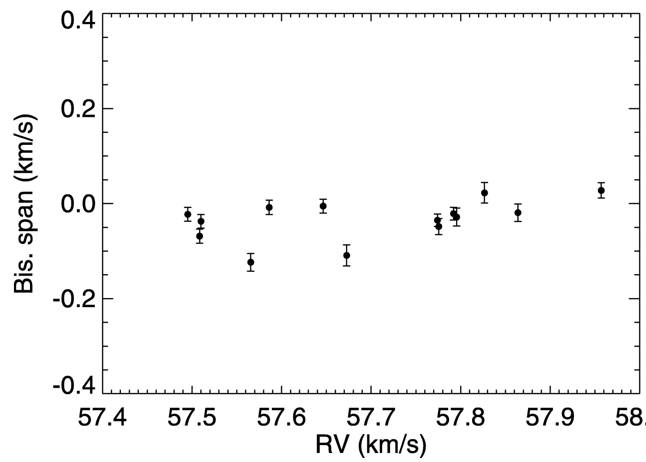

Fig. 4.—Line bisector spans for the CORALIE radial velocity measurements showing no significant variation.

vective overshooting (Castelli et al. 1997). The Hα, Na I D, and Mg I b lines were used as diagnostics of both $T_{\rm eff}$ and $\log g$. The metallicity was estimated using the photospheric lines in the 6000–6200 Å region. However, the co-added spectrum is not of sufficient quality to perform a detailed abundance analysis. The parameters obtained from this analysis are listed in Table 3. In addition to the spectral analysis, we have also used Tycho B, V, and 2MASS magnitudes to estimate the effective temperature using the infrared flux method (Blackwell & Shallis 1977). This gives $T_{\rm eff} = 5410 \pm 240$ K, which is in close agreement with that obtained from the spectroscopic analysis. These results imply a spectral type of around G7.

In our spectra the Li I 6708 Å line is not detected, allowing us to derive an upper limit on the lithium abundance of $\log n(\rm Li/H) + 12 < 1.0$, which is slightly less than the solar photospheric value. This implies a minimum age of around 2 Gyr (Sestito & Randich 2005). Comparison of the temperature and $\log g$ with the stellar evolution models of Girardi et al. (2000) gives maximum likelihood values $M_* = 0.90 \pm 0.07\ M_\odot$ and $R_* = 1.15 \pm 0.28\ R_\odot$. The distance of WASP-4 was calculated as 300 ± 50 pc using the angular diameter from the infrared flux method and the value of the radius of the star from Table 4.

5. PLANETARY PARAMETERS

The photometric and orbital parameters for WASP-4b were determined from a simultaneous Markov Chain Monte Carlo fit of both the photometric and spectroscopic data. The MCMC method is described in detail in Collier Cameron et al. (2007b)

TABLE 3
Stellar Parameters of WASP-4 Derived from a Spectral Analysis of the CORALIE Data

Parameter	Value
R.A. (J2000.0)	23^{h}34^{m}15.06^s
Decl. (J2000.0)	−42°03′41.1″
$T_{\rm eff}$ (K)	5500 ± 150
$\log g$	4.3 ± 0.2
[M/H]	0.0 ± 0.2
$\log n$(Li)	<1.0
$v \sin i$ (km s^{-1})	$2.2^{+0.6}_{-1.0}$
Mass ($M_\odot$)	0.90 ± 0.07
Radius ($R_\odot$)	1.15 ± 0.28
Spectral type	G7 V
Distance (pc)	300 ± 50

TABLE 4
FITTED SYSTEM PARAMETERS OF WASP-4b

Parameter	Value
Period (days)	$1.3382282^{+0.000003}_{-0.000003}$
Epoch (HJD)	$2454365.91464^{+0.00025}_{-0.00023}$
Duration (days)	$0.0928^{+0.0009}_{-0.0007}$
$(R_P/R_*)^2$	$0.0241^{+0.0005}_{-0.0002}$
b	$0.13^{+0.13}_{-0.12}$
i (deg)	$88.59^{+1.36}_{-1.50}$
K_1 (km s^{-1})	$0.24^{+0.01}_{-0.01}$
γ (km s^{-1})	$57.7326^{+0.002}_{-0.001}$
a (AU)	$0.0230^{+0.001}_{-0.001}$
log g (cgs)	$4.45^{+0.016}_{-0.029}$
R_* ($R_\odot$)	$0.9370^{+0.04}_{-0.03}$
M_* ($M_\odot$)	$0.8997^{+0.077}_{-0.072}$
ρ_* ($\rho_\odot$)	$1.094^{+0.038}_{-0.085}$
$R_P/R_{\rm Jup}$	$1.416^{+0.068}_{-0.043}$
$M_P/M_{\rm Jup}$	$1.215^{+0.087}_{-0.079}$
ρ_P ($\rho_{\rm Jup}$)	$0.428^{+0.032}_{-0.044}$
log g_P (cgs)	$3.142^{+0.023}_{-0.034}$
T_P ($A = 0$) (K)	1761^{+24}_{-9}

NOTE.—Fitted system parameters of WASP-4b from a simultaneous MCMC analysis of the WASP-S, FTS, and EulerCam light curves together with the CORALIE RV data, assuming a circular orbit.

and is the same used for the fitting of the parameters of WASP-3b (Pollacco et al. 2007).

The transit light curve was modeled using the small-planet approximation of Mandel & Agol (2002). An initial fit of the radial velocity measurements showed no evidence for significant orbital eccentricity, as expected for such a short-period system. Accordingly the eccentricity was set to zero. This leaves seven parameters defining the system: epoch (T_0), orbital period (P), duration of the transit (t_T) from first to last contact, the squared ratio of the planet to stellar radius [$\Delta F = (R_P/R_*)^2$], the impact parameter ($b = a\cos i/R_*$), the radial velocity amplitude (K_1) and the stellar mass M_*. Gaussian priors were imposed, as determined from the spectroscopic analysis, such that $M_* = 0.90 \pm 0.07$ and $\log g = 4.3 \pm 0.2$. To balance the weight of the radial velocities with the photometry in the MCMC analysis we added 7 m s^{-1} of systematic error to the errors listed in Table 2, thus obtaining a reduced χ^2 value of 1.

The resulting fitted parameters are listed, together with their 1 σ uncertainties, in Table 4. The parameters derived for the host star are consistent with the spectral analysis from the CORALIE data. The precision of the transit photometry is sufficient to constrain the stellar radius and impact parameter such that the uncertainties in the resultant planetary parameters are dominated by the uncertainty in the stellar mass.

6. DISCUSSION

A simultaneous fit of precision photometry and radial velocity measurements result in a planetary radius of 1.42 $R_{\rm Jup}$ and mass of 1.22 $M_{\rm Jup}$ for WASP-4b. This is the second largest transiting planet discovered to date, second only to TrES-4b (Mandushev et al. 2007; for plots comparing WASP-4b with other transiting extrasolar planets see Pollacco et al. 2007).

WASP-4b, with an orbital period of 1.3 days, can be compared to other very short period planets such as OGLE-TR-56b (Konacki et al. 2003), TrES-3b (O'Donovan et al. 2007), and WASP-3b (Pollacco et al. 2007). The low rotation velocity of the host star WASP-4 is comparable with that of TrES-3; in contrast, OGLE-TR-56 and WASP-3 have much higher rotation velocities, which is thought to be due to the young age of these stars. The stars WASP-4 and TrES-3 are thought to be older; however, the synchronization time for WASP-4 would be longer still at 8 Gyr (using the method of Marcy et al. 1997), so their low rotational velocity is consistent with their not having been spun up by their planets.

A preliminary estimate of the stellar parameters indicates that the parent star is spectral type G7 V with solar metallicity. Together with the short orbital period of 1.34 days, this results in a blackbody planetary surface temperature, assuming zero albedo and isotropic reradiation, of 1760 K. The orbital distance of 0.023 AU places WASP-4b well within the criterion ($a <$ 0.04 AU) for the proposed new class of pM planets (Fortney et al. 2007). These planets display a temperature inversion due to low-pressure stellar absorption by gaseous TiO and VO. As a result they exhibit an unusually hot stratosphere which emits strongly in the mid-infrared. The WASP-4b system has a larger flux ratio than the very hot Jupiters WASP-3b and TrES-3b, and so is an ideal target for secondary eclipse studies by *Spitzer*. The study of more of these systems, including WASP-4b, should help constrain models for atmospheric dynamics and heat distribution.

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