THREE WASP-SOUTH TRANSITING EXOPLANETS: WASP-74b, WASP-83b, AND WASP-89b

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ABSTRACT

We report the discovery of three new transiting hot Jupiters by WASP-South together with the TRAPPIST photometer and the Euler/CORALIE spectrograph. WASP-74b orbits a star of $V = 9.7$, making it one of the brighter systems accessible to southern telescopes. It is a 0.95$M_{\text{Jup}}$ planet with a moderately bloated radius of 1.5 $R_{\text{Jup}}$ in a 2 day orbit around a slightly evolved F9 star. WASP-83b is a Saturn-mass planet at 0.3 $M_{\text{Jup}}$ with a radius of 1.0 $R_{\text{Jup}}$. It is in a 5 day orbit around a fainter ($V = 12.9$) G8 star. WASP-89b is a 6 $M_{\text{Jup}}$ planet in a 3 day orbit with an eccentricity of $e = 0.2$. It is thus similar to massive, eccentric planets such as XO-3b and HAT-P-2b, except that those planets orbit F stars whereas WASP-89 is a K star. The $V = 13.1$ host star is magnetically active, showing a rotation period of 20.2 days, while star spots are visible in the transit. There are indications that the planet’s orbit is aligned with the stellar spin. WASP-89 is a good target for an extensive study of transits of star spots.

Key words: planetary systems – stars: individual (WASP-74, WASP-83, WASP-89)

1. INTRODUCTION

The combination of the WASP-South survey instrument, the Euler/CORALIE spectrograph, and the robotic TRAPPIST photometer continues to be an efficient team for the discovery of transiting exoplanets around stars of $V = 9–13$ in the Southern Hemisphere (e.g., Hellier et al. 2014; Anderson et al. 2015). Ongoing discoveries are important for expanding our census of the hot-Jupiter population, while exoplanets transiting relatively bright stars are also good targets for follow-up studies. In this paper we report three new discoveries: WASP-74b, which orbits a bright $V = 9.7$ star; WASP-83b, a moderately bloated Saturn-mass planet, which, with a period of 4.97 days, demonstrates the capability of a single-longitude transit search to find planets with integer-day periods; and WASP-89b, a massive planet in a short and eccentric orbit around a magnetically active K star.

2. OBSERVATIONS

The observational and analysis techniques used here are similar to those in recent WASP-South discovery papers (e.g., Hellier et al. 2012; Anderson et al. 2014), and so are reported briefly. WASP-South surveys the southern sky using an array of 200 mm f/1.8 lenses and a cadence of ~10 minutes (see Pollacco et al. 2006). Transit searching of accumulated light curves (Collier Cameron et al. 2007a) leads to tens of thousands of possible candidates, of which the vast majority are false alarms resulting from the limitations of the photometry. The best 1% are selected by eye as candidates and are passed to TRAPPIST (a robotic 0.6 m photometric telescope) and to the 1.2 m Euler/CORALIE spectrograph (for radial-velocity observations). About 1 in 12 of these turns out to be a planet, with most of the others being astrophysical transit mimics (blended or grazing-eclipse binaries). High-quality transit light curves are then obtained with TRAPPIST (Jehin et al. 2011) and with EulerCAM (Lendl et al. 2012). We have also observed a transit of WASP-74b using RISE on the Liverpool Telescope (see Steele et al. 2008).

A list of the observations reported here is given in Table 1 while the CORALIE radial velocities are listed in Table 7.

3. THE HOST STARS

We used the CORALIE spectra to analyze the three host stars, co-adding the standard pipeline reduction products to produce spectra with signal-to-noise ratios (S/N) of 150:1, 100:1, and 30:1 for WASP-74, WASP-83, and WASP-89 respectively. Our analysis methods are described in Doyle et al. (2013). The effective temperature ($T_{\text{eff}}$) estimate comes from the excitation balance of Fe I lines, while the surface gravity ($\log g$) estimate comes from the ionization balance of Fe I and Fe II and the Ca I line at 6439 Å and the Na I D lines. The metallicity was determined from equivalent-width measurements of several unblended lines. The quoted error estimates include that given by the uncertainties in $T_{\text{eff}}$ and $\log g$, as well as the scatter due to measurement and atomic data uncertainties.

The projected stellar rotation velocity ($v \sin i$) was determined by fitting the profiles of several unblended Fe I lines. Values of macroturbulent velocity of $3.9 \pm 0.7$ and $2.9 \pm 0.7 \text{ km s}^{-1}$ were adopted for WASP-74 and WASP-83, using the calibration of Doyle et al. (2014). For WASP-89, however, macroturbulence was assumed to be zero, since for mid-K stars...
it is expected to have a smaller effect than thermal broadening (Gray 2008).

The parameters obtained from the analysis are given in Tables 2–4. The quoted spectral type derives from T_{eff}, using the values in Gray (2008). Abundances are relative to the solar values obtained by Asplund et al. (2009). Gyrochronological age estimates derive from the measured v sin i, assuming that the star’s spin is perpendicular to us, so that this would be the true equatorial speed (but note that this will not be true for misaligned hot-Jupiter systems, which should be borne in mind when interpreting these ages). This is then combined with the stellar radius to give a rotational period, to compare with the values in Barnes (2007). Lithium age estimates come from values in Sestito & Randich (2005). We also list proper motions from the UCAC4 catalog of Zacharias et al. (2013).

We searched the WASP photometry of each star for rotational modulations by using a sine-wave fitting algorithm as described by Maxted et al. (2011). We estimated the significance of periodicities by subtracting the fitted transit lightcurve and then repeatedly and randomly permuting the nights of observation. We found a significant modulation in WASP-89 (see Section 8.1) but not in the other two stars.

### 4. SYSTEM PARAMETERS

The CORALIE radial-velocity measurements were combined with the WASP, Euler-CAM, and TRAPPIST photometry in a simultaneous Markov-chain Monte-Carlo (MCMC) analysis to find the system parameters. For details of our methods see Collier Cameron et al. (2007b). The limb-darkening parameters are noted in each table, and are taken from the four-parameter nonlinear law of Claret (2000).

| Table 1 | Observations |
|---------|--------------|
| **WASP-74:** | | |
| WASP-South | 2010 May–2012 Jun | 10,000 points |
| CORALIE | 2011 Aug–2012 Oct | 20 RVs |
| EulerCAM | 2012 May 07 | Gunn r filter |
| TRAPPIST | 2012 May 07 | z’ band |
| EulerCAM | 2012 May 22 | Gunn r filter |
| TRAPPIST | 2012 May 22 | z’ band |
| TRAPPIST | 2012 Jun 21 | z’ band |
| TRAPPIST | 2012 Jun 23 | z’ band |
| TRAPPIST | 2012 Sep 04 | z’ band |
| TRAPPIST | 2013 Jun 27 | I + z band |
| LT/RISE | 2014 Aug 19 | V + R |

| **WASP-83:** | | |
| WASP-South | 2006 May–2010 Jun | 20,600 points |
| CORALIE | 2011 Mar–2013 Feb | 28 RVs |
| TRAPPIST | 2012 Jan 07 | Blue-block filter |
| TRAPPIST | 2012 Jan 22 | Blue-block filter |
| TRAPPIST | 2012 Feb 06 | Blue-block filter |

| **WASP-89:** | | |
| WASP-South | 2008 Jun–2012 Jun | 18,000 points |
| CORALIE | 2011 May–2013 May | 20 RVs |
| EulerCAM | 2012 Aug 26 | Blue-block filter |
| TRAPPIST | 2012 Sep 12 | Gunn r filter |
| EulerCAM | 2012 Oct 02 | Gunn r filter |
| TRAPPIST | 2013 Jun 14 | Blue-block filter |
| TRAPPIST | 2013 Aug 27 | Blue-block filter |

| Table 2 | System Parameters for WASP-74 |
|---------|-------------------------------|
| 1SWASP J201809.32–010432.6 | | |
| 2MASS 20180931–0104324 | | |
| R.A. = 20°18′09.32, decl. = −01°04′32.6 (J2000) | | |
| V mag = 9.7 | | |
| Rotational modulation <0.7 mmag (95%) | | |
| pm (R.A.) = 1.6 ± 1.0, (decl.) = −64.3 ± 0.7 mas yr^{-1} | | |

**Stellar Parameters from Spectroscopic Analysis.**

| Parameter | Value |
|-----------|-------|
| Spectral type | F9 |
| T_{eff} (K) | 5990 ± 110 |
| log g | 4.39 ± 0.07 |
| v sin i (km s^{-1}) | 4.1 ± 0.8 |
| [Fe/H] | +0.39 ± 0.13 |
| log A(Li) | 2.74 ± 0.09 |
| Age (Gyr) | 0.5 ± 2 |
| Age (Gyr) | 2.0^{+1.6}_{-1.0} |
| Distance (pc) | 120 ± 20 |

**Parameters from MCMC Analysis.**

| Parameter | Value |
|-----------|-------|
| P (days) | 2.137750 ± 0.000001 |
| T_c (HJD) (UTC) | 245 6506.8918 ± 0.0002 |
| T_{14} (days) | 0.0955 ± 0.0008 |
| T_{12} = T_{14} (days) | 0.0288 ± 0.0014 |
| ΔF = R_p^2/R_∗^2 | 0.00961 ± 0.00014 |
| b | 0.860 ± 0.006 |
| i (deg) | 79.81 ± 0.24 |
| K_1 (km s^{-1}) | 0.1141 ± 0.0014 |
| γ (km s^{-1}) | −15.767 ± 0.0011 |
| e | 0 (adopted) (<0.07 at 3σ) |
| M_a (M_⊕) | 1.48 ± 0.12 |
| R_a (R_⊕) | 1.64 ± 0.05 |
| log g_a (cgs) | 4.180 ± 0.018 |
| ρ_a (ρ_⊕) | 0.338 ± 0.018 |
| T_c (K) | 5970 ± 110 |
| M_p (M_{Jup}) | 0.95 ± 0.06 |
| R_p (R_{Jup}) | 1.56 ± 0.06 |
| log g_p (cgs) | 2.95 ± 0.02 |
| ρ_p (ρ_⊕) | 0.25 ± 0.02 |
| a (AU) | 0.037 ± 0.001 |
| T_r, A = 0 (K) | 1910 ± 40 |

**Errors are 1σ; Limb-darkening coefficients were:**

- Trap: a1 = 0.757, a2 = −0.591, a3 = 0.890, a4 = −0.416.
- Euler & RISE: a1 = 0.669, a2 = −0.284, a3 = 0.765, a4 = −0.395.

For WASP-89b the orbital eccentricity is significant and was fitted as a free parameter. For WASP-74b and WASP-83b we imposed a circular orbit during the analysis since for most hot-Jupiter systems the circularization timescale is expected to be less than the age, and thus adopting a circular orbit gives the most likely parameters (see Anderson et al. 2012 for a discussion of this).

The fitted parameters were $T_c$, $P$, $\Delta F$, $T_{14}$, $b$, $K_1$, where $T_c$ is the epoch of mid-transit, $P$ is the orbital period, $\Delta F$ is the fractional flux-deficit that would be observed during transit in the absence of limb-darkening, $T_{14}$ is the total transit duration (from first to fourth contact), $b$ is the impact parameter of the planet’s path across the stellar disc, and $K_1$ is the semi-amplitude of the stellar reflex velocity. The transit light curves
lead directly to stellar density but one additional constraint is required to obtain stellar masses and radii, and hence full parameterization of the system. Here we use the calibrations presented by Southworth (2011), based on masses, radii, and effective temperatures of eclipsing binaries.

For each system we list the resulting parameters in Tables 2–4, and plot the resulting data and models in Figures 1–5. We also refer the reader to Smith et al. (2012), who present an extensive analysis of the effect of red noise in the transit light curves on the resulting system parameters.

5. EVOLUTIONARY STATUS

One area where the methods of this paper differ from those of previous WASP-South discoveries is in the comparison of the stellar parameters to evolutionary models. Here we use the method described in detail in Muxted et al. (2015). This uses an MCMC method to calculate the posterior distribution for the mass and age estimates of the star, by comparing the observed values of \( \rho_\ast \), \( T_{\text{eff}} \), and \([\text{Fe/H}]\) to a grid of stellar models. The stellar models were calculated using the Garstec stellar evolution code (Weiss & Schlattl 2008) and the methods used to calculate the stellar model grid are described in Serenelli et al. (2013). The results of this Bayesian analysis are given in Table 5 and are shown in Figure 6.

6. WASP-74

WASP-74 is a V = 9.7, F9 star with a metallicity of \([\text{Fe/H}] = +0.39 \pm 0.13\). The transit analysis gives a mass and radius of 1.48 ± 0.12 \( M_\odot \) and 1.64 ± 0.05 \( R_\odot \). The transit log \( g_\ast \) of 4.20 ± 0.02 compares to a spectroscopic log \( g_\ast \) of 4.39 ± 0.07. The evolutionary comparison (Figure 6) suggests an evolved star with an age of 3.7 ± 0.9 Gyr and a lower mass of 1.31 ±
The gyrochronological and lithium age estimates are lower at 2.0±1.0 Gyr and ∼2 Gyr respectively. The planet, WASP-74b, is a relatively typical hot Jupiter in a 2 day orbit, having a mass of 0.95 ± 0.06 MJup and a moderately bloated radius of 1.56 ± 0.06 RJup.

7. WASP-83

WASP-83 is a G8 star of V = 12.9 with a metallicity of [Fe/H] = +0.29 ± 0.12. The spectroscopic log g of 4.34 ± 0.08 is compatible with the transit log g of 4.44±0.08. The mass of 1.11 ± 0.06 MJ and from the transit analysis is in line with the evolutionary estimate of 1.00 ± 0.05 MJ. The evolutionary age of 7.1 ± 2.9 Gyr is in line with the lithium age of ≥5 Gyr. The $v \sin i$ of <0.5 km s$^{-1}$ is compatible with an old star, though the gyrochronological age of 12±3 Gyr does not add a useful constraint.

The planet, WASP-83b, has a mass of 0.30 ± 0.03 MJup, matching that of Saturn, and a moderately bloated radius of 1.2 RJup. It is very similar to WASP-21b (Bouchy et al. 2010), which has a similar mass (0.3 MJup), is also bloated (1.2 RJup), and also has a 4 day orbit around a G star.

8. WASP-89

With a magnitude of V = 13.1, WASP-89 is among the faintest planet-hosts found by WASP-South, but is among the more interesting systems. The spectroscopy (with a low S/N owing to the faintness) reports it as a K3 star with log g = 4.31 ± 0.16 and a mass of 0.88 ± 0.08 MJ. The transit analysis gives log g = 4.52 ± 0.02, with a mass of 0.92 ± 0.08 MJ.

The initial Bayesian evolutionary analysis of WASP-89 (Table 5) gave an age of 12.5 ± 3.1 Gyr, which would likely make it older than the Galactic disk. This raises the possibility
that this star is affected by the “radius anomaly” observed in many other late-type stars, particularly those like WASP-89 that show signs of magnetic activity (Hoxie 1973; Popper 1997; López-Morales 2007; Spada et al. 2013). It has been proposed that this is due to the reduction in the efficiency of energy transport by convection, a phenomenon that can be approximated by reducing the mixing length parameter used in the model (Chabrier et al. 2007; Feiden & Chaboyer 2013). The mixing length parameter used to calculate our model grid is \( \alpha_{\text{MLT}} = 1.78 \). With this value of \( \alpha_{\text{MLT}} \) GARSTEC reproduces the observed properties of the present-day Sun, assuming that the composition is that given by Grevesse & Sauval (1998), the overall initial metallicity is \( Z = 0.01876 \), and the initial helium abundance is \( Y = 0.269 \). There is currently no objective way to select the correct value of \( \alpha_{\text{MLT}} \) for a magnetically active star other than to find the range of this parameter that gives plausible results. Accordingly, we also calculated a Markov chain for the observed parameters of WASP-89 using stellar
models with $\alpha_{\text{MLT}} = 1.22$, for which value we find $p(\tau_b < 10 \text{ Gyr}) = 0.91$. By comparing the results for WASP-89 with the two values of $\alpha_{\text{MLT}}$ we arrive at a mass of $0.85 \pm 0.05 M_\odot$ with the age being indeterminate. This is then compatible with the masses from the spectral analysis and the transit analysis.

### 8.1. Magnetic Activity

WASP-89 shows clear evidence of magnetic activity in the form of a rotational modulation and through star spots during transit. Three years of WASP-South data all show a $\sim 1\%$ modulation at a period near 20 days, and the fourth shows a modulation at half that (10 days), presumably the first harmonic of the rotational period caused by a more complex spot pattern (Table 6, Figure 7). The average from four different years of WASP-South data is a rotational period of $P = 20.2 \pm 0.4 \text{ days}$. This, together with our value for the stellar radius, implies a value of $V = 2.2 \pm 0.1 \text{ km s}^{-1}$, which compares to the spectroscopic $V = 2.5 \pm 0.9 \text{ km s}^{-1}$. This is consistent with WASP-89’s spin axis being at 90° to us.

The transit light curves from TRAPPIST and EulerCAM show clear star spots, visible as bumps in the transit profile, most clearly at phase 0.997 in the EulerCAM light curve from 2012 October 2 (Figure 4). This raises the issue of whether we are treating the light curves correctly in our MCMC analysis (see the discussion in, e.g., Oshagh et al. 2013). When a planet transits a spot we see a slight brightening, and including such data will cause the fitted transit to be shallower. However, any spots that are not transited but still present will do the opposite, causing the fitted transit to be deeper. Thus excluding bumps...
caused by transited spots would introduce a bias. Without more information on the extent of spottedness there is no secure way of dealing with this. The rotation modulation suggests that the difference between different faces of the star is of order 1% of the brightness, which is comparable to other uncertainties. We have thus chosen to simply combine all the light curves in the analysis, effectively averaging over any spots present.

In principle one can use transits of star spots to deduce the orbital alignment (e.g., Tregloan-Reed et al. 2013). The TRAPPIST and EulerCAM light curves from 2012 September 12 are of the same transit, as are those from 2012 October 2, the latter being six orbital cycles (20.1 days) later. There appears to be a spot at phase 0.992 in the September 12 lightcurve and a spot at 0.997 in the October 2 lightcurve. This could be the same spot being transited one stellar rotation later, which is unlikely unless the planet’s orbit is aligned (or anti-aligned) with the stellar rotation.

If it is the same spot, the difference in the phase of the spot transit implies that the star had rotated by 1.07 cycles (or 0.93 cycles), which translates to a rotation period of 18.8 ± 0.3 days (or 21.7 ± 0.3 days). This is slightly different from the value of 20.2 ± 0.4 days from the WASP data, but the discrepancy might be accounted for by differential rotation.

Thus, we conclude that WASP-89 rotates with a period of 20 days and is magnetically active, and that there are indications that the planetary orbit is aligned or anti-aligned. However, we need more extensive star-spot observations and observations of the Rossiter–McLaughlin effect to be sure.

8.2. A Massive Planet in an Eccentric Orbit

WASP-89b has a mass of 5.9 ± 0.4 M_{\text{Jup}} and is in a 3.356 day orbit with an eccentricity of 0.19 ± 0.01. It thus joins a small number of massive planets in short-period, eccentric orbits, of which the most similar are XO-3b (12 M_{\text{Jup}}, 3.2 days, \(e = 0.26\); Johns-Krull 2008), HAT-P-2b (8.7 M_{\text{Jup}}, 5.6 days, \(e = 0.52\); Bakos et al. 2007), and HAT-P-21b (4.0 M_{\text{Jup}}, 4.1 days, \(e = 0.23\); Bakos et al. 2011).

It is worth noting, though, that those three planets orbit stars of spectral type F5, F8, and G3, respectively. WASP-89 is the first known K star hosting a massive planet in a short-period eccentric orbit (\(M > 1 M_{\text{Jup}}\); \(P < 6\) days; \(e > 0.1\)). The magnetic activity of WASP-89 could be related to the hosting of a massive, short-period planet, since magnetic activity might be enhanced in hot-Jupiter hosts (e.g., Poppenhaeger & Wolk 2014).

Planets in eccentric, short-period orbits are of particular interest in that their rotation cannot be fully phase-locked to their orbit, and so they must experience large differences in radiative forcing around the orbit. Thus they can tell us about the dynamics of giant-planet atmospheres (e.g., Wong et al. 2014 and references therein).

The usual explanation for the occurrence of such eccentric orbits in short-period hot Jupiters is that they are moved inwards by a process of “high-eccentricity migration,” followed by circularization (e.g., Rasio & Ford 1996; Fabrycky & Tremaine 2007; Naoz et al. 2011; Socrates et al. 2012a).

The circularization timescale can be estimated from (Adams & Laughlin 2006, Equation (3)):

$$
t_{\text{cir}} \approx 1.6 \, \text{Gyr} \times \left( \frac{Q_p}{10^6} \right) \times \left( \frac{M_p}{M_{\text{Jup}}} \right) \times \left( \frac{M_\star}{M_\odot} \right)^{-3/2} \times \left( \frac{R_p}{R_{\text{Jup}}} \right)^5 \times \left( \frac{a}{0.05 \, \text{AU}} \right)^{13/2}.
$$

The value of the quality factor, \(Q_p\), is unclear, but if we take it as \(10^5\) (e.g., Socrates et al. 2012b), then we obtain for WASP-89b a circularization timescale of ~2 Gyr. Here, the

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**Figure 7.** Periodograms of the WASP light curves for WASP-89 obtained in 2008 (top left) and 2009 (bottom left). Horizontal lines indicate false-alarm probability levels of 0.1, 0.01, and 0.001. Top right shows the 2008 data folded on 20.69 days; bottom right the 2009 data folded on 10.46 days.
large mass of the planet prevents circularization in less than 1 Gyr despite the short orbit. This timescale is in line with the gyrochronological age of the host star, and thus the fact that the planet has not circularized is consistent. Tidal damping of eccentricity is expected to occur faster than damping of obliquity or inward orbital decay (Matsumura et al. 2010), and thus we would expect the current values of these properties to be direct products of the high-eccentricity migration.

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