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WASP-10b: a 3$M_J$, gas-giant planet transiting a late-type K star

D. J. Christian,1,2⋆ N. P. Gibson,1 E. K. Simpson,1 R. A. Street,1,3 I. Skillen,4 D. Pollacco,1 A. Collier Cameron,5 Y. C. Joshi,1 F. P. Keenan,1 H. C. Stempels,5 C. A. Haswell,6 K. Horne,5 D. R. Anderson,7 S. Bentley,7 F. Bouchy,8,9 W. I. Clarkson,6,10 B. Enoch,6 L. Hebb,5 G. Hébrard,8 C. Hellier,7 J. Irwin,11 S. R. Kane,12 T. A. Lister,3,5,7 B. Loeillet,13 P. Maxted,7 M. Mayor,14 I. McDonald,7 C. Moutou,13 A. J. Norton,6 N. Parley,6 F. Pont,14,15 D. Queloz,14 R. Ryans,1 B. Smalley,7 A. M. S. Smith,5 I. Todd,1 S. Udry,14 R. G. West,16 P. J. Wheatley17 and D. M. Wilson7

1 Astrophysics Research Centre, School of Mathematics and Physics, Queen’s University, University Road, Belfast, BT7 1NN
2 Department of Physics and Astronomy, California State University Northridge, 18111 Nordhoff Street, Northridge, CA 91330-8268, USA
3 Las Cumbres Observatory, 6740 Cortona Dr Suite 102, Santa Barbara, CA 93117, USA
4 Isaac Newton Group of Telescopes, Apartado de Correos 321, E-38700 Santa Cruz, de la Palma, Tenerife, Spain
5 School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS
6 Department of Physics and Astronomy, The Open University, Milton Keynes, MK7 6AA
7 Astrophysics Group, Keele University, Staffordshire, ST5 5BG
8 Institut d’Astrophysique de Paris, CNRS (UMR 7095) – Université Pierre and Marie Curie, 98bis bvd. Arago, 75014 Paris, France
9 Observatoire de Haute-Provence, 04870 St Michel l’Observatoire, France
10 STScI, 3700 San Martin Drive, Baltimore, MD 21218, USA
11 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
12 Michelson Science Center, Caltech, MS 100-22, 770 South Wilson Avenue Pasadena, CA 91125, USA
13 Laboratoire d’Astrophysique de Marseille, BP 8, 13376 Marseille Cedex 12, France
14 Observatoire de Genève, Université de Genève, 51 Ch. des Maillettes, 1290 Sauron, Switzerland
15 School of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL
16 Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH
17 Department of Physics, University of Warwick, Coventry, CV4 7AL

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ABSTRACT

We report the discovery of WASP-10b, a new transiting extrasolar planet (ESP) discovered by the Wide Angle Search for Planets (WASP) Consortium and confirmed using Nordic Optical Telescope Fibre-fed Echelle Spectrograph and SOPHIE radial velocity data. A 3.09-d period, 29 mmag transit depth and 2.36 h duration are derived for WASP-10b using WASP and high-precision photometric observations. Simultaneous fitting to the photometric and radial velocity data using a Markov Chain Monte Carlo procedure leads to a planet radius of 1.28 $R_J$, a mass of 2.96 $M_J$ and eccentricity of ≈0.06. WASP-10b is one of the more massive transiting ESPs, and we compare its characteristics to the current sample of transiting ESP, where there is currently little information for masses greater than ≈2$M_J$ and non-zero eccentricities. WASP-10’s host star, GSC 2752−00114 (USNO-B1.0 1214−0586164) is among the fainter stars in the WASP sample, with $V = 12.7$ and a spectral type of K5. This result shows promise for future late-type dwarf star surveys.

Key words: methods: data analysis – techniques: photometric – techniques: radial velocities – stars: planetary systems.

1 INTRODUCTION

Photometric transit observations of extrasolar planets (ESP) are important because the transit strongly constrains their orbital inclination and allows accurate physical parameters for the planet to be
We obtained photometry of WASP-10 with the MEROPE instrument to routine automated observing. We show the WASP-10b transiting ESP in Fig. 1. The data were phased using the ephemeris, $T_0 = 2454357.85808_{-0.00041}^{+0.00041}$, $P = 3.09276$ d.

derived. Their mass–radius relation allows us to probe their internal structure and is vital to our understanding of orbital migration and planetary formation. The radial velocity (RV) measurements which are used to confirm a candidate transiting ESP also provide more complete information on the orbital eccentricity.

As wide-field photometric transit surveys have collected additional sky and temporal coverage, and understood their noise components (Collier Cameron et al. 2007a; Smith et al. 2007), the number of transiting ESP has grown to over 50 in line with earlier predictions (Horne 2003). Recently, one such survey SuperWASP (Pollacco et al. 2006) published its first five confirmed ESP, all of which have periods of less than 3 d (Anderson et al. 2008; Collier Cameron et al. 2007b; Pollacco et al. 2008; Wilson et al. 2008), and reported an additional 10 (Hellier et al. 2008; Hebb et al. 2008; Cameron et al. 2007b; Pollacco et al. 2006). We present a summary of the FIES and SOPHIE RV data in Table 1.

In this paper, we present the WASP photometry of 1SWASP J231558.30+312746.4 (GSC 2752−00114), higher precision photometric follow-up observations with the MERCATOR and Tenagra telescopes and high-precision RV observations with the Nordic Optical Telescope new Fibre-fed Echelle Spectrograph (FIES) and the Observatoire de Haute-Provence (OHP) SOPHIE collaboration. These observations lead to the discovery and confirmation of a new, relatively high-mass, gas-giant exoplanet, WASP-10b.

![Figure 1](image_url)

**Figure 1.** Shown is the un-binned SuperWASP folded light curve for WASP-100b (1SWASP J231558.30+312746.4). The data were phased using the ephemeris, $T_0 = 2454357.85808_{-0.00041}^{+0.00041}$, $P = 3.09276$ d.

2.2 Spectroscopic follow-up

We obtained high-precision RV follow-up observations of WASP-10 with the 2.5 m Nordic Optical Telescope (NOT) new FIES, supplemented with observations from the Observatoire de Haute-Provence’s 1.93 m telescope and the SOPHIE spectrograph (Bouchy et al. 2006). We present a summary of the FIES and SOPHIE RV data in Table 1.

2.2.1 NOT and FIES

Spectroscopic observations were obtained using the new FIES spectrograph mounted on the NOT Telescope. A total of seven RV points were obtained during 2007 December 2, 28–31 and 2008 January 24–25. WASP-10 required observations with an exposure time of 2400 s due its relative faintness ($V = 12.7$) yielding a peak signal-to-noise ratio per resolution element of $\approx 60–70$ in the Hα region. FIES was used in medium resolution mode with $R = 46000$ with simultaneous ThAr calibration. We used the bespoke data reduction package FIEStool, to extract the spectra and a specially developed IDL line-fitting code to obtain RVs with a precision of 15–25 m s$^{-1}$ (except for the poor night of 2008 January 24, JD 2454490).

2.2.2 OHP 1.9 m and SOPHIE

Additional RV measurements were taken for WASP-10 on 29 and 30 August 2007, and again between 2008 Feb 11 and 15 with

1 http://www.inscience.ch/transits/

2 http://www.lcogt.net

3 http://www.not.iac.es/instruments/fies/fiestool/FIEStool.html
the OHP 1.93 m telescope and the SOPHIE spectrograph (Bouchy et al. 2006), a total of seven usable spectra were acquired. We used SOPHIE in its high-efficiency mode, acquiring simultaneous star and sky spectra through separate fibers with a resolution of $R = 40,000$. Thorium–Argon calibration images were taken at the start and end of each night, and at 2- to 3-h intervals throughout the night. The RV drift never exceeded 2 to 3 m s$^{-1}$, even on a night-to-night basis. Although errors for each RV measurement are limited by the photon noise. Thus, the average RV error is $\approx 14$ m s$^{-1}$ and includes the 2 to 3 m s$^{-1}$ systematic error and the contribution from the photon noise. Typical signal-to-noise ratio estimates for each spectra were $\approx 30$ (near 5500 Å). The SOPHIE WASP-10 spectra were cross-correlated against a K5V template provided by the SOPHIE control and reduction software. Typical full width at half-maximum (FWHM) and contrasts for these spectra were $\approx 10.2$–10.4 km s$^{-1}$ and 30–31 per cent, respectively. The cross-correlation techniques and derivation of errors in the RV measurements are presented in Pollacco et al. (2008).

### 3 RESULTS AND ANALYSIS

#### 3.1 Stellar parameters

We merged all available WASP-10 FIES spectra into one high-quality spectrum in order to perform a detailed spectroscopic analysis of the stellar atmospheric properties. Radial velocity signatures were carefully removed during the process. This merged spectrum was then continuum normalized with a low-order polynomial to retain the shape of the broadest spectral features. The total signal-to-noise ratio of the combined spectrum was $\approx 180$ per pixel. We were not able to include the SOPHIE spectra in this analysis, because these spectra were obtained in the high-efficiency (HE) mode, which is known to suffer from problems with removal of the blaze function.

### Table 1. Journal of RV measurements for WASP-10 (1SWASP J231558.30+312746.4, USNO-B1.0 1214–0586164). Stellar coordinates are for the photometric apertures; the USNO-B1.0 number denotes the star for which the RV measurements were secured. The quoted uncertainties in the RV errors include components due to photon noise (Section 2.2) and 10 m s$^{-1}$ of jitter (Section 3.2) added in quadrature.

<table>
<thead>
<tr>
<th>BJD</th>
<th>$t_{\text{exp}}$ (s)</th>
<th>$V_r$ km s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2454437.540</td>
<td>2400</td>
<td>$-11.028 \pm 0.026$</td>
</tr>
<tr>
<td>2454463.377</td>
<td>2400</td>
<td>$-11.941 \pm 0.030$</td>
</tr>
<tr>
<td>2454465.342</td>
<td>2400</td>
<td>$-11.003 \pm 0.018$</td>
</tr>
<tr>
<td>2454466.335</td>
<td>2400</td>
<td>$-11.804 \pm 0.021$</td>
</tr>
<tr>
<td>2454490.329</td>
<td>2400</td>
<td>$-11.013 \pm 0.143$</td>
</tr>
<tr>
<td>2454490.358</td>
<td>2400</td>
<td>$-10.990 \pm 0.120$</td>
</tr>
<tr>
<td>2454491.340</td>
<td>2400</td>
<td>$-11.955 \pm 0.024$</td>
</tr>
<tr>
<td>SOPHIE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2454340.569</td>
<td>3300</td>
<td>$-11.657 \pm 0.008$</td>
</tr>
<tr>
<td>2454342.505</td>
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<td>$-11.575 \pm 0.011$</td>
</tr>
<tr>
<td>2454508.268</td>
<td>1680</td>
<td>$-11.027 \pm 0.014$</td>
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<tr>
<td>2454509.268</td>
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<td>$-11.336 \pm 0.017$</td>
</tr>
<tr>
<td>2454510.276</td>
<td>1680</td>
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</tr>
<tr>
<td>2454511.262</td>
<td>1680</td>
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</tr>
<tr>
<td>2454512.262</td>
<td>1680</td>
<td>$-11.244 \pm 0.016$</td>
</tr>
</tbody>
</table>

As previously undertaken for our analysis of WASP-1 (Stempels et al. 2007) and WASP-3 (Pollacco et al. 2008), we employed the methodology of Valenti & Fischer (2005), using the same tools, techniques and model atmosphere grid. We used the package Spectroscopy Made Easy (SME) (Valenti & Piskunov 1996), which combines spectral synthesis with multidimensional $\chi^2$ minimization to determine which atmospheric parameters best reproduce the observed spectrum of WASP-10 (effective temperature $T_{\text{eff}}$, surface gravity $\log g$, metallicity $[\text{M/H}]$, projected RV $v \sin i$, systemic RV $v_{\text{rad}}$, microturbulence $v_{\text{mic}}$ and the macroturbulence $v_{\text{mac}}$).

The four spectral regions we used in our analysis are:

1. $5160$–$5190$ Å, covering the gravity-sensitive Mg b triplet;
2. $5850$–$5950$ Å, with the temperature and gravity-sensitive Na I D doublet;
3. $6000$–$6210$ Å, containing a wealth of different metal lines, providing leverage on the metallicity, and
4. $6520$–$6600$ Å, covering the strongly temperature-sensitive Hα line.

In addition, we analysed a small region around the Li i 6708 line to possibly derive a lithium abundance, but no Li i 6708 was detected for WASP-10. The parameters we obtained from this analysis are listed in Table 2. In addition to the spectral analysis, we also use available photometry [from The Amateur Sky Survey (NOMAD), Naval Observatory Merged Astrometric Dataset (TASS4) and Carlsberg Meridian Catalogue 14 (CMC14) catalogues] plus Two-Micron All-Sky Survey to estimate the effective temperature using the infrared flux method (Blackwell & Shallis 1977). This yields $T_{\text{eff}} \approx 4650 \pm 120$ K, which is in agreement with the spectroscopic analysis and a spectral type of K5. The characteristics of WASP-10 are also given in Table 2.

#### 3.2 Markov Chain Monte Carlo analysis

Transit timing and the RV measurements provide detailed information about the orbit. We modelled WASP-10’s transit photometry and the reflex motion of the host star simultaneously using the Markov Chain Monte Carlo (MCMC) algorithm described in detail by Collier Cameron et al. (2007a), and the same techniques that were applied to WASP-3 by Pollacco et al. (2008) to which we refer the reader for more details.

We find WASP-10b has a radius $1.28_{-0.03}^{+0.09}$ $R_J$, mass of $2.96_{-0.17}^{+0.22}$ $M_J$ and a significant non-zero eccentricity of 0.059$_{-0.004}^{+0.014}$. The best-fitting solution for the MCMC model for a circular orbit ($e = 0$) has a $\chi^2$ 55 higher than the solution with a non-zero eccentricity, and thus, the eccentricity is significant at $> 99.6$ per cent confidence level using the $F$ test. The values of the parameters of the optimal solution are given, together with their associated 1σ confidence intervals, in Table 3. The FIES + SOPHIE RV data measurements are plotted in Fig. 2 together with the best-fitting global fit to the SuperWASP-N, MERCATOR and Tenagra transit photometry.

The value of the scaling factor $\hat{\sigma}$ is determined with a signal-to-noise ratio

$$\text{SNR} = \frac{\hat{\sigma}}{\sqrt{\text{Var} (\hat{\sigma})}}.$$
studied to rule out a putative outer plane that may be driving its eccentricity. Thus, the $\approx 6$ per cent eccentricity of WASP-10b makes it an attractive target for future transit-timing variation studies, and for longer term RV monitoring to establish the mass and period of the putative outer planet.

The majority of transiting ESP found have masses below $1.5M_J$, although there are a few more massive ESP. HD 17156 and COROT-Exo-2 have similar masses to WASP-10b and although there are two more massive ESP, the nearly $9M_J$ HAT P-2 (HD 147506b) (Bakos et al. 2007) and $7.3M_J$ WASP-14b (Joshi et al. 2008), this higher mass region has been poorly explored. Additional transiting objects in the mass range are important for completing the current ESP mass-radius relations and constraining their compositions. The current sample of transiting ESP reveals a large range of densities. We derive a mean density for WASP-10b of $\approx 1.89$ g cm$^{-3}$ ($1.42\rho_j$) and it would lie along the higher density contour in a mass–radius plot (Pollacco et al. 2008; Sozzetti et al. 2007).

One ultimate goal of our transit-search programme is to provide the observational grist that will stimulate and advance refined models for the formation and evolution of the hot and very hot Jupiters (e.g. Burrows et al. 1997; Fortney, Marley & Barnes 2007; Seager et al. 2007). By thus constraining the underlying physics, we will have a richer context for the interpretation of the lower mass planets expected from missions such as COROT and Kepler.

4 DISCUSSION

Photometric surveys have now provided a large sample of transiting ESP that can be used to determine their mass–radius relation and provide constraints on their compositions. Here, we presented the discovery of a new ESP with a mass of $2.96M_J$, $1.28R_J$ radius and a significant eccentricity of $0.059^{+0.014}_{-0.004}$. We now discuss the properties of WASP-10b in relation to the current sample of transiting ESP, starting with its non-zero eccentricity.

Most of the current sample of published transiting ESP have orbits consistent with being circular and are fit with models using zero eccentricity as is expected for short-period planets in orbits with semimajor axes $<0.2$ au. Recent work (Jackson, Greenberg & Barnes 2008; Mardling 2007, and references therein) have investigated the effects of tidal dissipation on the orbits of short-period ESP. The evolution of the orbital eccentricity appears to be driven primarily by tidal dissipation within the planet, giving a circularization time-scale substantially less than 1 Gyr for typical tidal dissipation parameter, $Q_p = 10^5$ to $10^6$. WASP-10 is a K dwarf with a spin period of 12 d and $J - K = 0.62$ and is rotating more slowly than stars of comparable colour in the Hyades (Ternudrap et al. 2000). This suggests a rotational age between 600 Myr and 1 Gyr. Thus, the persistence of substantial orbital eccentricity in WASP-10b is therefore surprising.

One plausible mechanism for maintaining the high eccentricity is secular interaction with an additional planet in the system. Adams & Laughlin (2006) explore the effects of dynamical interactions among planets in extrasolar planetary systems and conclude that the outer planets can cause the inner planet to move through a range of eccentricities over time-scales that are short when compared to the lifetime of the system, but very long when compared to the current observational baseline. However, recently Matsumura, Takeda & Rasio (2008) have argued that an unseen companion driving short-period systems is unlikely. They present an upper limit of $1M_{Neptune}$ for a possible unseen companion in the GI 436 system and exclude this based on the current RV upper limits of $\lesssim 5$ m s$^{-1}$. Matsumura et al. (2008) also present a range of tidal quality $Q_p$ time-scales that could be as large as $10^6$ yr, and argue that this new class of eccentric, short-period ESP is simply still in the process of circularizing. WASP-10b has not been extensively

REFERENCES


Figure 3. Line bisectors as a function of RV for WASP-10. Plot symbols are the same as for Fig. 2. Analysis of these line bisectors for WASP-10 does not show a correlation between the bisector velocity ($V_{span}$) and stellar RV (see the text).

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