WASP-10b: a 3M(J), gas-giant planet transiting a late-type K star

Christian, D. J., Gibson, N. P., Simpson, E. K., Street, R. A., Skillen, I., Pollacco, D., Collier Cameron, A., Joshi, Y. C., Keenan, F. P., Stempels, H. C., Haswell, C. A., Horne, K., Anderson, D. R., Bentley, S., Bouchy, F., Clarkson, W. I., Enoch, B., Hebb, L., Hebrard, G., ... Wilson, D. M. (2009). WASP-10b: a 3M(J), gas-giant planet transiting a late-type K star. *Monthly Notices of the Royal Astronomical Society*, 392(4), 1585-1590. https://doi.org/10.1111/j.1365-2966.2008.14164.x

Published in:
Monthly Notices of the Royal Astronomical Society

Document Version:
Publisher's PDF, also known as Version of record

Queen's University Belfast - Research Portal:
Link to publication record in Queen's University Belfast Research Portal

Publisher rights
This article has been accepted for publication in Monthly Notices of the Royal Astronomical Society © 2008 The Authors. Published by Oxford University Press on behalf of the Royal Astronomical Society. All rights reserved.

General rights
Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.
WASP-10b: a 3M$_J$, 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, 98 bis 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, 1290 Sauverny, 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

Accepted 2008 October 29. Received 2008 October 28; in original form 2008 September 10

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 $\approx 0.06$. 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 $\approx 2$ 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
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 components (Collier Cameron et al. 2007a; Smith et al. 2007), the transits. Details of the WASP project and observatory infrastructure are described in Pollacco et al. (2006).

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.

2 OBSERVATIONS

1SWASP J231558.30+312746.4 (GSC 2752−00114) was monitored by SuperWASP-N starting in 2004. SuperWASP is a multi-camera telescope system with SuperWASP-North located in La Palma and consisting of 8 Canon 200-mm f/1.8 lenses each coupled to e2v 2048 × 2048 pixel back illuminated CCDs. This combination of lens and camera yields a field of view of 7.8 × 7.8 with an angular size of 14.2 arcsec per pixel. During 2004, SuperWASP was run with four or five cameras as the operations moved from commissioning to routine automated observing. We show the WASP-10b light curve in Fig. 1.

2.1 Higher precision photometry

We obtained photometry of WASP-10 with the MEROPE instrument on the 1.2 m MERCATOR Telescope in V band on 2007 September 1. Only a partial transit was observed due to uncertainties in the period and epoch from the SuperWASP data. Observations were in the V band with 2 × 2 binning over ~2.9 h. Despite clear conditions, exposure times were varied from 25 to 30 s to account for changes in seeing and to keep below the saturation limits of the chip. This allowed 170 images to be taken. There was a drift of only 1 binned pixel in x and y on the chip during the run. The MEROPE images were first de-biased and flat-fielded with combined twilight flats using IRAF and the APPHOT package to obtain aperture photometry of the target and five nearby companion stars using a 10 pixel radius. Finally, the light curve was extracted and normalized to reveal a depth of ~33 mmag.

Further observations of WASP-10 were taken as part of an observing program sponsored by the Las Cumbres Observatory Global Telescope Network2 on the Tenagra II, 0.81 m F7 Ritchey–Chretien telescope sited in the Sonora desert in S. Arizona, USA. The science camera contains a 1 × 1 kSiTe CCD with a pixel scale of 0.87 arcsec pixel−1 and a field of view of 14.8 × 14.8 arcm. The filter set is the standard Johnson/Cousins/Bessel UBVRI set and the data presented here have been taken in V band.

Calibration frames were obtained automatically every twilight, and the data were de-biased and flat-fielded using the calibration section of the SuperWASP pipeline. Object detection and aperture photometry were then performed using DAOPHOT (Stetson 1987) within IRAF. Differential photometry was derived from a selection of typically 5 to 10 comparison stars within the frame.

These confirmed that the object had a sharp egress with an amplitude of 0.033 ± 0.001 mag. The MERCATOR V and Tenagra I light curves show consistent transit depths, confirming that the companion is a transiting ESP.

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 60–70 in the Hα region. FIES was used in medium resolution mode with R = 46 000 with simultaneous ThAr calibration. We used the bespoke data reduction package FIESTOOL3 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 www.lcogt.net
3 http://www.not.iac.es/instruments/fies/fiestool/FIEStool.html

© 2008 The Authors. Journal compilation © 2008 RAS, MNRAS 392, 1585–1590
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 [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: (i) $5160$–$5190$ Å, covering the gravity-sensitive Mg b triplet; (ii) $5850$–$5950$ Å, with the temperature and gravity-sensitive Na I D doublet; (iii) $6000$–$6210$ Å, containing a wealth of different metal lines, providing leverage on the metallicity, and (iv) $6520$–$6600$ 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 $T_{\text{eff}} = 4650 \pm 120$ 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 to have a radius $1.28^{+0.03}_{-0.06}$, mass of $2.96^{+0.22}_{-0.17} M_J$, and a significant non-zero eccentricity of $0.059^{+0.014}_{-0.004}$. 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.

### 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.

| BJD      | $t_{\text{exp}}$ | $v_r$   |
|----------|------------------|---------|
| 2454437.540 | 2400             | $-11.028 \pm 0.026$ |
| 2454463.377 | 2400             | $-11.941 \pm 0.030$ |
| 2454465.342 | 2400             | $-11.003 \pm 0.018$ |
| 2454466.335 | 2400             | $-11.804 \pm 0.021$ |
| 2454490.329 | 2400             | $-11.013 \pm 0.143$ |
| 2454490.358 | 2400             | $-10.990 \pm 0.120$ |
| 2454491.340 | 2400             | $-11.955 \pm 0.024$ |

### Table 2. Stellar parameters for WASP-10. The last five parameters were derived from the SME analysis of the FIES spectroscopy.

| Parameter | WASP-10 |
|----------|---------|
| RA (J2000) | $23\,15\,58.3$ |
| Dec. (J2000) | $+31\,27\,46.4$ |
| $v$ | 12.7 |
| Distance | $90 \pm 20$ pc |
| $T_{\text{eff}}$ | $4675 \pm 100$ K |
| $\log g$ | $4.40 \pm 0.20$ |
| [M/H] | $0.03 \pm 0.20$ |
| $v \sin i$ | $<6$ km s$^{-1}$ |
| $v_{\text{rad}}$ | $-11.44 \pm 0.03$ km s$^{-1}$ |
\[ a = \frac{\text{SNR}}{\text{ratio}} \]

The value of the scaling factor \( \hat{w}_i \) to be 2.5 times the uncertainty on the RV in our data. If we define

\[ \hat{a} = \sum \frac{x_i y_i w_i}{\sum x_i^2 w_i}, \quad \text{Var}(\hat{a}) = \frac{1}{\sum x_i^2 w_i} \]

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

\[ \text{SNR} = \frac{\hat{a}}{\sqrt{\text{Var}(\hat{a})}}. \]

### 3.3 Line-bisector variation

Line bisectors have been shown to be a powerful diagnostic in distinguishing true ESPs from blended and eclipsing stellar systems chromospheric activity (Queloz et al. 2001). Torres et al. (2004) showed that for OGLE-TR-33 line asymmetries which changed with a 1.95-d period, it was a blended system. From the cross-correlation function (CCF), we obtained the line bisectors and these are plotted, as a function of RV, in Fig. 3.

![Figure 2](http://mnras.oxfordjournals.org/)

We quantified the significance of the bisector variation as follows. We determined the inverse-variance-weighted averages of the RV and bisector span as

\[ \hat{a} = \sum \frac{v_i w_i}{\sum w_i}; \quad \hat{b} = \sum \frac{b_i w_i}{\sum w_i}, \]

where the \( v_i \) and \( b_i \) are the RV and span bisector values, respectively, and the weights \( w_i \) are the inverse variances of the individual bisector measurements. The uncertainty in the span bisector is assumed to be 2.5 times the uncertainty on the RV in our data. If we define

\[ x_i = v_i - \hat{v}_i \quad \text{and} \quad y_i = b_i - \hat{b}, \]

then the slope is determined as

\[ \hat{a} = \sum x_i y_i w_i / \sum x_i^2 w_i; \quad \text{Var}(\hat{a}) = 1 / \sum x_i^2 w_i. \]

The model fit to the RV data includes orbital eccentricity (solid line), and the McLaughlin effect, which is small for this system given the low orbital inclination.

We obtain SNR = 1.16 indicating a non-significant correlation between the bisector span and RV variations. This demonstrates that the CCF remains symmetric, and that the RV variations are not likely to be caused by line-of-site binarity or stellar activity and indicate WASP-10b is an exoplanet.
the process of circularizing. WASP-10b has not been extensively studied to rule out a putative outer plane that may be driving its eccentricity. Thus, the ≈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 1.5$M_J$, 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 9 $M_J$ HAT P-2 (HD 147506b) (Bakos et al. 2007) and 7.3 $M_J$ 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 ≈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 data that can 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.

ACKNOWLEDGMENTS

The SuperWASP Consortium consists of astronomers primarily from the Queen’s University of Belfast, St Andrews, Keele, Leicester, The Open University, Isaac Newton Group La Palma and Instituto de Astrofísica de Canarias. The SuperWASP Cameras were constructed and operated with funds made available from Consortium Universities and the UK’s Science and Technology Facilities Council. SOPHIE observations have been funded by the Optical Infrared Coordination Network. The data from the Mercator and NOT telescopes were obtained under the auspices of the International Time Service of the Canary Islands. We extend our thanks to the staff of the ING and OHP for their continued support of SuperWASP-N and SOPHIE instruments. FPK is grateful to AWE Aldermaston for the award of a William Penney Fellowship.

REFERENCES

Adams F. C., Laughlin G., 2006, ApJ, 649, 992
Anderson D. R. et al., 2008, MNRAS, 387, 4
Bakos G. A. et al., 2007, ApJ, 670, 826
Blackwell D. E., Shallis M. J., 1977, MNRAS, 180, 177
Bouchy F., The Sophie Team, 2006, in Arnold L., Bouchy F., Moutou C., eds, Tenth Anniversary of 51 Peg-b: Status of and Prospects for Hot Jupiter Studies. Frontier Group, Paris, p. 319
Burrows A. et al., 1997, ApJ, 491, 856
Collier Cameron A. et al., 2007a, MNRAS, 380, 1230
Collier Cameron A. et al., 2007b, MNRAS, 375, 951
Fortney J. I., Marley M. S., Barnes J. W., 2007, ApJ, 659, 1661
Hedb L. et al. 2008, A&A, submitted
Hellier C. et al. 2008, ApJ, submitted (arXiv:0805.2600)
Horne K. D., 2003, in Deming D. and Seager S., eds, ASP Conf. Ser. Vol. 294, Scientific Frontiers of Exoplanet Research. Astron. Soc. Pac., San Francisco, p. 361
Jackson B., Greenberg R., Barnes R., 2008, ApJ, 678, 1396
Joshi Y. C. et al. 2008, MNRAS, submitted (arXiv:0806.1478)
Mardling R. 2007, MNRAS, 382, 1768
Matsumura S., Takeda G., Rasio F. A., 2008, ApJ, 686, L29

© 2008 The Authors. Journal compilation © 2008 RAS, MNRAS 392, 1585–1590
Pollacco D. et al., 2006, PASP, 106, 1088
Pollacco D. et al., 2008, MNRAS, 385, 1576
Queloz D. et al., 2001, A&A, 379, 279
Seager S., Kuchner M., Hier-Majumder C. A., Militzer B., 2007, ApJ, 669, 1279
Smith A. M. S. et al., 2007, MNRAS, 373, 1151
Sozzetti A., Torres G., Charbonneau D., Latham D. W., Holman M. J., Winn J. N., Laird J. B., O’Donavan F. T., 2007, ApJ, 664, 1190
Stetson P., 1987, PASP, 99, 191
Stempels H. C., Collier Cameron A., Hebb L., Smalley B., Frandsen S., 2007, MNRAS, 379, 773
Terndrup D. M., Stauffer J. R., Pinsonneault M. H., Sills A., Yuan Y., Jones B. F., Fischer D., Krishnamurthi A., 2000, AJ, 119, 1303
Torres G., Konacki M., Sasselov D. D., Jha S., 2004, ApJ, 614, 979
Valenti J. A., Fischer D., 2005, ApJS, 159, 141
Valenti J. A., Piskunov N., 1996, A&AS, 118, 595
West R. et al. 2008, A&A, submitted (arXiv:0809.4597)
Wilson D. et al., 2008, ApJ, 675, 113

This paper has been typeset from a \LaTeX file prepared by the author.