Two Transiting Hot Jupiters from the WASP Survey: WASP-150b and WASP-176b

Benjamin F. Cooke1,2, Don Pollacco1,2, Y. Almleaky3,4, K. Barkaoui5,6, Z. Benkhaldoun6, James A. Blake1,2, François Bouchy7, Panos Boumis8, D. J. A. Brown1,2, Ivan Bruni9, A. Burdanov5, Andrew Collier Cameron10, Paul Chote1,2, A. Daassou6, Giuseppe D’agostino11, Shweta Dalal12, Mario Damasso13, L. Delrez14, A. P. Doyle1, E. Ducrot5, M. Gillon5, G. Hébrard7, C. Hellier15, Thomas Henning16, E. Jehin16, Flavien Kiefer12, George W. King1,2, Alexios Liakos16, Théo Lopez12, Luigi Mancini15,18,19, Rosemary Mardling7,20, P. F. L. Maxted21, S. Velasco23,24, Richard West1,2, Pete Wheatley1,2, Y. Almleaky3,4, K. Barkaoui5,6, Z. Benkhaldoun6, James A. Blake1,2, James McCormac1,2, C. Murray14, John Southworth21, S. Thompson14, Oliver Turner7, respectively. WASP-150b has a mass and radius of 8.5 and 1.4, leading to a large planetary bulk density of 6.4. WASP-176b has a mass and radius of 0.86 and 1.7, leading to a large planetary bulk density of 1.7. WASP-150b is found to be ~3 Gyr old, well below its circularization timescale, supporting the eccentric nature of the planet. WASP-176b is a hot Jupiter planet on a 3.9 day orbit around a V = 12.01, F9 sub-giant host. The host star has a mass and radius of 1.3 M ☉ and 1.9 R ☉, respectively, leading to a planetary bulk density of 0.23 ρ j. 

Unified Astronomy Thesaurus concepts: Exoplanet systems (484); Radial velocity (1332); Exoplanet detection methods (489); Photometry (1234)

Supporting material: data behind figures

1. Introduction

As of 2019 October, over 4000 exoplanets have been discovered using the transit method. These results have shown that exoplanet populations are both very common and very diverse (Batalha 2014), with a wide range of system parameters found thus far. The transit discoveries have been made using both space-based surveys, for example Kepler/K2 (Borucki et al. 2010; Howell et al. 2014), and ground-based surveys, including the Wide Angle Search for Planets (WASP; Pollacco et al. 2006), HATNet/HATSouth (Bakos 2018), Kilodegree Extremely Little Telescope (KELT; Pepper et al. 2007), TRAnstiting Planets and PlanetesImals Small Telescope (TRAPPIST; Jehin et al. 2011), and Next-Generation Transit Survey (NGTS; Wheatley et al. 2018). This field is expected to be expanded upon even further in the coming years with the yield of the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) and other future planned missions such as the James Webb Space Telescope (Garner et al. 2006), Planetary Transits and Oscillations of stars (PLATO; Rauer et al. 2016), and Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL; Pascale et al. 2018).

Within this sample of exoplanets lies the region corresponding to hot Jupiters. A type of planet noticeably absent from

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Abstract

We report the discovery of two transiting exoplanets from the WASP survey, WASP-150b and WASP-176b. WASP-150b is an eccentric (e = 0.38) hot Jupiter on a 5.6 day orbit around a V = 12.03, F8 main-sequence host. The host star has a mass and radius of 1.4 M ☉ and 1.7 R ☉, respectively. WASP-150b has a mass and radius of 8.5 M J and 1.1 R J, leading to a large planetary bulk density of 6.4 ρ j. WASP-150b is found to be ~3 Gyr old, well below its circularization timescale, supporting the eccentric nature of the planet. WASP-176b is a hot Jupiter planet on a 3.9 day orbit around a V = 12.01, F9 sub-giant host. The host star has a mass and radius of 1.3 M ☉ and 1.9 R ☉, respectively, leading to a planetary bulk density of 0.23 ρ j.
our own solar system, hot Jupiters are planets with masses comparable to Jupiter but with orbital periods on the order of days. Current estimates put the occurrence rate of giant planets within 5–10 au around FGK stars at 10%–20% (Cumming et al. 2008; Mayor et al. 2011). Further detections and precise characterizations of hot Jupiter exoplanets will improve our ability to study this population using statistical methods, and hence allow for a better understanding of this unique type of planet.

Exoplanets are broadly characterized using a combination of the transit method (Charbonneau et al. 2000; Henry et al. 2000; Winn 2010) and radial velocity (RV) measurements. When combined these methods allow for the measurement of radius, mass, and density, which can lead to inferences of composition.

This paper discusses the discovery and characterization of the transiting hot Jupiters WASP-150b and WASP-176b. Sections 2–4 detail the WASP discovery, spectroscopic follow-up, and photometric follow-up, respectively. Section 5 discusses the high spatial resolution follow-up of WASP-150. Section 6 outlines the analysis and derived parameters. Finally, Section 7 summarizes the discovery findings.

2. SuperWASP Discovery Photometry

The WASP project (now decommissioned) was split into north and south facilities with telescopes located at the Isaac Newton Group at the Observatorio del Roque de los Muchachos, La Palma, Spain and at the South African Astronomical Observatory, Sutherland, Republic of South Africa respectively. Both facilities consisted of 8 Canon 200 mm f/1.8 lenses, each linked to an Andor e2v 2048 × 2048 pixel CCD. Each camera had a total field of view of 7°8 × 7°8 with a pixel scale of 13"/7 (Pollacco et al. 2006).

For WASP-150, a total of 99,892 photometric data points were taken between 2004 May 14 and 2011 August 4. These data ranged across 38 transits. WASP-150b was flagged as a high priority candidate on 2014 February 17 and confirmed as a planet on 2015 June 25. Figure 1 shows the WASP discovery curve folded by the best-fit period and binned to 10 minutes. Additionally we show the best-fit transit model from our Markov Chain Monte Carlo (MCMC).

For WASP-176, a total of 23,082 photometric data points were taken between 2004 May 26 and 2010 October 6. These data ranged across 30 transits. WASP-176b was flagged as a high priority candidate on 2014 February 12 and confirmed as a planet on 2018 January 23. Figure 2 shows the WASP discovery curve folded by the best-fit period and binned to 10 minutes. Additionally we show the best-fit transit model from our MCMC.

The SuperWASP data were reduced using the standard SuperWASP pipeline as described in Pollacco et al. (2006). Analysis of the light curve was then carried out using the box least-squares (BLS) fit method, as in Kovács et al. (2002), and the SysRem detrending algorithm, described in Tamuz et al. (2005). The results of BLS searches on the detrended data are shown in Figures 1 and 2. The data were searched with a transit-search algorithm (Collier Cameron et al. 2007b) and flagged as belonging to a planetary candidate. System parameters were then estimated from catalog data and a Monte Carlo simulation (Collier Cameron et al. 2006). These initial estimates produced a period of 5.644 days, a depth of 3.2 mmag, and a width of 2.4106 hr for WASP-150b and a period of 3.899 days, a depth of 3.4 mmag, and a width of 4.5292 hr for WASP-176b. Additional follow-up spectroscopy and photometry were then obtained to confirm and characterize the planets. Basic photometric properties of the two hosts are shown in Table 1.
3. Spectroscopic Follow-up

3.1. WASP-150b

WASP-150 was observed with the SOPHIE spectrograph, first to establish the planetary nature of the transiting candidate, then to characterize the secured planet by measuring in particular its mass and orbital eccentricity. SOPHIE is dedicated to high-precision RV measurements at the 1.93 m telescope of the Haute-Provence Observatory (Perruchot et al. 2008; Bouchy et al. 2009) and is widely used for WASP follow-up (e.g., Collier Cameron et al. 2007a; Hébrard et al. 2013; Schanche et al. 2019). We used its high-efficiency mode with a resolving power of $R = 40,000$ and slow readout mode. We obtained 22 observations between 2014 May and 2015 April. Depending on weather conditions, exposure times ranged between 8 and 33 minutes in order to maintain a signal-to-noise ratio as constant as possible among observations.

The spectra were extracted using the SOPHIE pipeline (Bouchy et al. 2009), and the RVs were measured through weighted cross-correlation with a numerical mask (Baranne et al. 1996; Pepe et al. 2002). They were corrected for the CCD charge transfer inefficiency (Bouchy et al. 2009), and their error bars were computed from the cross-correlation function (CCF) using the method presented by Boisse et al. (2010). The monitoring of constant stars revealed no significant instrumental drifts during the epochs of observation, and none of the spectra were significantly affected by any moonlight or other sky background pollution.

The resulting CCFs have FWHM of $14.1 \pm 0.1 \text{ km s}^{-1}$, and contrast that represents $\sim 14\%$ of the continuum. The lines are slightly broader than what is usually measured in the high-efficiency mode due to the stellar rotation of WASP-150 (we measured a projected rotational velocity $v \sin i = 8.3 \pm 1.0 \text{ km s}^{-1}$ from the parameters of the CCF using the calibration of Boisse et al. 2010).

The RVs have uncertainties around $19 \text{ m s}^{-1}$. They show large variations in phase with the SuperWASP transit ephemeris for an eccentric orbit, and a semi-amplitude of the order of $800 \text{ m s}^{-1}$. This would correspond to a companion in the massive-planet regime. The SOPHIE RVs are shown in Figure 3 with the best-fit model and residuals from our MCMC analysis (see Section 6.1.2). Data files can be found at https://github.com/BenCooke95/W150-W176.

Radial velocities measured using different stellar masks (F0, G2, K0, or K5) produce variations with similar amplitudes, so it is unlikely that these variations are produced by blend scenarios composed of stars of different spectral types. Similarly, the measured CCF bisector spans quantify possible shape variations of the spectral lines. They show a low dispersion of $27 \text{ m s}^{-1}$, which agrees with their expected accuracy and is tiny in comparison to the large RV variations. We can thus conclude that the RV variations are not due to spectral-line profile changes attributable to blends or stellar activity, but rather to Doppler shifts due to a massive, eccentric planetary companion. Figure 4 shows the bisector spans.

3.2. WASP-176b

High resolution spectroscopy for WASP-176 was performed with the CORALIE spectrograph (Queloz et al. 2000;
Pepe et al. 2017 on the Swiss 1.2 m telescope at La Silla Observatory (Chile). In total we obtained 26 measurements between 2014 and 2018 July. RVs were computed with the standard CORALIE data reduction pipeline by cross-correlating the spectra with a binary G2 mask (Pepe et al. 2002).

The reduced CORALIE data are displayed in Figure 5 along with the best-fit model and residuals from our MCMC analysis (see Section 6.2.2). Data files can be found at https://github.com/BenCooke95/W150-W176.

Additionally, the line bisector was analyzed to ensure that the observed signal was indeed from an orbiting body and not a blended binary (Queloz et al. 2001). Figure 6 shows the results of this analysis using the bisector velocity span as a function of RV. No significant correlation is seen (evidenced by the best-fit linear slope). Thus, this analysis supports the detection of a planetary companion. The aspect ratio of the two axes is unity.

4. Photometric Follow-up

4.1. WASP-150b

A number of telescopes were used to gather the necessary follow-up photometry for WASP-150b. These are summarized in Table 2 along with observation dates, photometric filters, and transit notes. The following sections detail the follow-up. The light curves are shown in Figures 7 and 8. Data files can be found at https://github.com/BenCooke95/W150-W176.

Figure 3. Upper panel: phase-folded SOPHIE RV observations of WASP-150. Data are shown in blue with the best-fit model derived from the MCMC analysis shown in red. Lower panel: residuals from the RV fit. (The data used to create this figure are available.)

Figure 4. SOPHIE RV bisector span as a function of RV for WASP-150. The solid black line shows the best weighted linear fit to the data. The lack of any significant gradient supports the assumption that the RV signal is produced by a planetary companion. The aspect ratio of the two axes is unity.

Figure 5. Upper panel: phase-folded CORALIE RV observations of WASP-176. Data are shown in blue with the best-fit model derived from the MCMC analysis shown in red. Lower panel: residuals from the RV fit. (The data used to create this figure are available.)

Figure 6. CORALIE RV bisector span as a function of RV for WASP-176. The solid black line shows the best weighted linear fit to the data. The lack of any significant gradient supports the assumption that the RV signal is produced by a planetary companion. The aspect ratio of the two axes is unity.

4.1.1. IAC80

A full transit of WASP-150b was observed on 2015 July 7 using the CAmera MEjorada Ligera del Observatorio del Teide (CAMELOT) camera installed on the IAC80 telescope at the Observatorio del Teide, Tenerife, Spain. CAMELOT contains a 2048 × 2048 back-illuminated e2v CCD, providing a field of view of 10'4 × 10'4, with a pixel scale of 0'304.

Data were reduced using standard routines of IRAF (Tody 1986, 1993). All images were bias and flat subtracted and differential photometry was carried out using IDL DAOPHOT-Type Photometry Procedures (Stetson 1987). Among the several stars appearing on the field of view of the camera, those showing less dispersion were selected to produce...
an average reference star and obtain the final light curve. We used a fixed aperture radius of 13 pixels, which minimized the rms scatter in the out-of-transit data.

4.1.2. CAHA 1.23 m

The transit on 2015 August 27 was observed with the DLR-MKIII camera fed by the Zeiss 1.23 m Centro Astronómico Hispano-Alemán telescope. During the observations the sky was clear besides a couple of intervals when some thin clouds passed in front of the target. The observations were carried out using the defocussing technique, which allowed the use of longer exposures compared to in-focus observations, without the risk of saturation (Southworth et al. 2009).

The data reduction was performed using standard methods making use of the DEFOT pipeline (Southworth et al. 2009, 2014). In brief, each scientific image was calibrated using a master bias and a master flat. The fluxes detected from the target and comparison stars were then obtained via aperture photometry, selecting the aperture sizes that minimized the scatter of the light curves. A relative-flux light curve was then obtained for the target star relative to an optimally weighted composite comparison star constructed from the light curves of comparison stars present in the same field of view, to account for atmospheric and instrumental changes occurring during the observations.

4.1.3. Cassini 1.52 m

On 2015 August 27 WASP-150b was simultaneously observed with the Cassini 1.52 m telescope at the Astronomical Observatory of Bologna in Loiano (Italy), thus performing the two-site observational strategy (Ciceri et al. 2013). The Cassini has a focal ratio of f/8, a focal length of 12 m, and is equipped with a back-illuminated CCD with 1300 × 1340 pixels and a pixel size of 20 μm. A focal reducer makes the telescope an f/5, so that its plate scale is 0.58 pixel−1 and the field of view is 13′ × 12′6. The autoguided observations were performed with the defocussing technique (to improve the photometric precision), though the level of defocussing was limited in order to avoid blending from a fainter star a few arcsec away. The data were reduced using the DEFOT code, as described in the preceding section.

Table 2

| Instrument | Date (Night of) | Filter | No. Points | Average Cadence (s) | Comment |
|------------|----------------|--------|------------|-------------------|---------|
| NITES      | 2014 Sep 11    | None   | 805        | 26                | Noisy egress |
| RISE       | 2015 May 23    | V + R  | 14600      | 1                 | No pre-transit OOT |
| IAC80      | 2015 Jul 7     | Johnson-Bessel B | 230 | 75 | Full transit observed |
| TCS        | 2015 Jul 24    | Johnson-Cousins R | 13500 | 1 | Full transit observed |
| RISE       | 2015 Jul 24    | V + R  | 12140      | 1                 | Missed egress |
| Cassini    | 2015 Aug 27    | Johnson I | 482 | 47 | Full transit observed |
| CAHA       | 2015 Aug 27    | Cousins I | 421 | 46 | Full transit observed |

Figure 7. Upper panel: individual WASP-150 light curves binned to 10 minutes (TESS data are left unbinned). From the top down the light curves are from NITES, RISE, RISE, TESS, TCS, Cassini, CAHA, and IAC80. The red curves show the best fit from the MCMC. Lower panel: best-fit residuals colored as in the upper panel. (The data used to create this figure are available.)

Figure 8. Upper panel: combined photometry data for WASP-150 binned to 10 minutes and including the best fit from the MCMC. Lower panel: the MCMC fit residuals.
4.1.4. RISE

Two partial transits of WASP-150b were observed on 2015 May 23 and July 24 with the Rapid Imaging Search for Exoplanets (RISE) optical camera, installed on the 2 m robotic Liverpool Telescope (Gibson et al. 2008; Steele et al. 2008) at the Observatorio del Roque de los Muchachos, La Palma, Spain. The camera is a frame transfer e2v CCD of 1024 × 1024 pixels, which has a field of view of 9/2 × 9/2.

Bias and flat reduced images were provided by the telescope pipeline. The light curves were extracted following the standard procedures described in Section 4.1.1, using a fixed aperture radii of 5.5 and 7 pixels, for the first and second night respectively.

4.1.5. TCS

On 2015 July 24, WASP-150b was simultaneously observed with the Telescopio Carlos Sánchez (TCS), a 1.52 m telescope installed at the Observatorio del Teide, once again performing the two-site observational strategy (Ciceri et al. 2013). We used the WIDE FASTCAM camera, a 1024 × 1024 pixels EMCCD detector, coupled to an optical design (Murga et al. 2014) that is able to provide a field of view of ∼8′ × 8′. This camera provides small readout times and low electronic noise, which allow us to precisely measure exoplanet transit timings.

All images were bias and flat subtracted, and light curves were extracted using similar procedures to those described in Section 4.1.1. In this case, a fixed radius aperture of 11.5 pixels was selected.

4.1.6. NITES

A transit of WASP-150b was obtained on 2014 September 11 using the Near Infra-red Transiting ExoplanetS telescope (NITES; McCormac et al. 2014) on La Palma. The data were reduced in PYTHON using CCDPROC (Craig et al. 2015). Master, dark, and flat biases were created using the standard process. Non-variable nearby comparison stars were selected by hand, and aperture photometry was extracted using SEP (Bertin & Arnouts 1996; Barbary 2016).

4.1.7. TESS

The TESS (Ricker et al. 2015) observed WASP-150b during its northern hemisphere campaign. WASP-150b was observed in the full frame images of sectors 14 and 20. To account for the blending in the TESS light curve (TESS pixels are 21′′ square) this data was included with a variable dilution term in the MCMC modeling for WASP-150b. This light curve was extracted from the full frame images using the Eleanor extraction pipeline (Feinstein et al. 2019) utilizing the background subtraction and systematics removal packages.

4.2. WASP-176b

To gather the necessary follow-up photometry for WASP-176b, a number of telescopes were used. These are summarized in Table 3 along with observation dates, photometric filters, and transit notes. The following sections detail the follow-up.

The light curves are shown in Figures 9 and 10. Data files can be found at https://github.com/BenCooke95/W150-W176.

4.2.1. Cassini 1.52 m

A partial transit of WASP-176b was recorded with the Cassini 1.52 m telescope on 2018 June 30. Unfortunately, cloud prevented observing the start of the transit. The observations were performed by defocussing the telescope for improving the photometric precision and using autoguiding. The data were reduced as discussed in Section 4.1.3. We detrended the light curve to remove slow instrumental and astrophysical trends, by fitting a straight line to the out-of-transit data.

4.2.2. NITES

A total of two transits were obtained using NITES (McCormac et al. 2014) on La Palma. The data were reduced in PYTHON using CCDPROC (Craig et al. 2015). Master, dark, and flat biases were created using the standard process on each night. Twenty-one images of each type were used for the master calibration frames. Non-variable nearby comparison stars were selected by hand, and aperture photometry was extracted using SEP (Bertin & Arnouts 1996; Barbary 2016). The aperture photometry radii were chosen to minimize the dispersion in the data points out of transit.

4.2.3. RISE-2

WASP-176 was observed with RISE-2 mounted on the 2.3 m telescope situated at Helmos observatory in Greece. RISE-2 has a CCD size of 1K × 1K with a pixel scale of 0′′51 and a field of view of 9′ × 9′ (Boumis et al. 2010). The data were reduced using master bias and flat frames, created using the standard process on each night. Non-variable nearby comparison stars were selected by hand and aperture photometry was extracted using SEP (Bertin & Arnouts 1996; Barbary 2016). The aperture photometry radii were chosen to minimize the dispersion in the data points out of transit.

4.2.4. TRAPPIST

TRAPPIST-North (Gillon et al. 2017; Barkaoui et al. 2019) observed one full transit of WASP-176b on 2018 June 26. TRAPPIST-North is a 60 cm robotic telescope installed in spring 2016 at Oukaimeden Observatory in Morocco. TRAPPIST-North is a northern twin of TRAPPIST-South (Gillon et al. 2011; Jehin et al. 2011). TRAPPIST-North has an f/8 Ritchey–Chretien optical design. It is equipped with a thermoelectrically cooled 2048 × 2048 deep-depletion Andor iKon-L CCD camera that has a pixel size of 13.5 µm, which translates into a 0′′60 pixel−1 image scale and a field of view of 19′8 × 19′8. Data reduction consisted of standard calibration steps (bias, dark, and flat-field corrections) and subsequent aperture photometry using IRAF/DAOPHOT (Tody 1986). Extraction of fluxes of selected stars using aperture photometry was performed with IRAF/DAOPHOT (as described in Gillon et al. 2013).

During the TRAPPIST-North observations of WASP-176 the telescope underwent a meridian flip at JD 2458296.6355. To counter this problem the pre- and post-meridian flip data are treated separately.

https://telescope.livjm.ac.uk/TelInst/Inst/RISE/
http://www.iac.es/OOCC/instrumentation/telescopio-carlos-sanchez/
4.2.5. SPECULOOS

One partial transit of WASP-176b was observed with SPECULOOS-Io, one of the four telescopes of the Search for habitable Planets ECLipsing ULtra-cOOl Stars (SPECULOOS)-South facility (Burdanov et al. 2018; Delrez et al. 2018; Gillon 2018; Jehin et al. 2018), which is located at ESO Paranal Observatory (Chile). Each telescope is a robotic Ritchey–Chretien (f/8) telescope of 1 m diameter. They are equipped with Andor iKon-L Peltier-cooled deeply depleted 2K × 2K CCD cameras, with good sensitivities in the very near-infrared up to 1 μm. The field of view of each telescope is 12′ × 12′ and the pixel scale is 0.35 pixel⁻¹. The calibration and photometric reduction of the data were performed as described in Gillon et al. (2013).

5. High Spatial Resolution Follow-up

WASP-150 was observed on four occasions, 2015 November 15, 2016 March 9 and 10, and 2016 May 6, using the FASTCAM camera (Oscoz et al. 2008) installed on the 1.52 m Telescopio Carlos Sánchez (TCS) located at the Observatorio del Teide, Tenerife, Spain. FASTCAM is an EMCCD camera with 512 × 512 pixels, with a physical pixel size of 16 μm, which makes a field of view of 21.52 × 21.52. Thanks to the very low noise and fast readout speed of the EMCCD array, this camera is appropriate for Lucky Imaging (LI) observations.

During each of the four observing nights, 10,000 individual frames of WASP-150 were collected in the Johnson-Cousins I filter, except on the 2015 November 15 night, for which a clear filter was used due to the dusty weather conditions (calima). Each individual frame had an exposure time of 50 ms. In total, 500 s and 1500 s of data were gathered of WASP-150, with the clear and I-band filters, respectively.

Using the FASTCAM dedicated software developed at the Universidad Politécnica de Cartagena (Labadie et al. 2010; Jódar et al. 2013), each individual frame was bias-subtracted, aligned and co-added, and then processed in order to construct a high resolution long-exposure image. For each night’s data set, we took a high resolution image constructed by co-addition of the best 30% of images, thus making a 150 s total exposure time. No close companion was detected, only a ΔmI = 2.17 ± 0.03 mag fainter star at a distance of 1058 ± 005. Figure 11 shows the contrast light curve that was computed based on the scatter within the annulus as a

![Figure 9](images/figure9.png)

**Figure 9.** Upper panel: individual WASP-176 light curves binned to 10 minutes. From the top down the light curves are from NITES, TRAPPIST, NITES, SPECULOOS, Cassini, and RISE-2. The red curves show the best fit from the MCMC. Lower panel: best-fit residuals colored as in the upper panel. (The data used to create this figure are available.)

![Figure 10](images/figure10.png)

**Figure 10.** Upper panel: combined photometry data for WASP-176 binned to 10 minutes and including the best fit from the MCMC. Lower panel: MCMC fit residuals.

### Table 3

| Instrument   | Date (Night of) | Filter | No. Points | Average Cadence (s) | Comment |
|--------------|-----------------|--------|------------|---------------------|---------|
| SPECULOOS-Io | 2018 Jun 14     | Sloan z' | 1127       | 21                  | Missed egress |
| TRAPPIST-North | 2018 Jun 26   | I + z  | 708        | 28                  | Full but no out of transit (meridian flip) |
| Cassini      | 2018 Jun 30     | Johnson V | 123      | 119                 | Missed ingress (cloud) |
| NITES        | 2018 Aug 4      | Johnson-Bessel R | 345     | 32                  | Missed ingress (cloud) |
| NITES        | 2018 Aug 8      | Johnson-Bessel I | 676     | 32                  | Missed egress |
| RISE-2       | 2018 Sep 24     | V + R  | 1929       | 11                  | Missed ingress |
function of angular separation from the target centroid (see, e.g., Gauza et al. 2015).

6. Results

6.1. WASP-150b

6.1.1. Stellar Parameters

To determine the stellar parameters of WASP-150 a spectral analysis of the SOPHIE spectra was carried out. The results of this analysis are shown in Table 4. Additionally, the second data release of Gaia (Gaia Collaboration et al. 2016, 2018) provided some of the stellar parameters presented in Table 5. Gaia was also searched for close companions of WASP-150. No significant companion was found.

The open-source stellar modeling code BAGEMASS31 (Maxted et al. 2015) was then used to estimate the age and mass of WASP-150. BAGEMASS uses the GARSTEC stellar evolution code (Weiss & Schlattl 2008) to calculate model grids of individual stars. A Bayesian method then samples the posterior distributions on mass and age. The results of this analysis are presented in Table 6.

The best-fit evolutionary track and isochrone produced from the BAGEMASS analysis are shown in Figure 12 along with the $1\sigma$ uncertainties. This plot also includes the posterior distribution produced by the EXOFASTv2 analysis (see Section 6.1.2).

Figure 12 includes a small collection of points above the main area of convergence. These data are not affected by the burn-in period, thus we do not believe them to be an artifact of unfinished fitting. However, since the significance of this region is $\lesssim10$ times lower than the peak we do not find it impactful.

6.1.2. EXOFASTv2 Analysis

To perform simultaneous fitting of the SuperWASP detection, the SOPHIE RVs, and the follow-up photometry we used the fitting code EXOFASTv2 (Eastman 2017; Eastman et al. 2019). This tool is designed to fit all the available data and ensure consistency between derived stellar and planetary parameters. EXOFASTv2 explores the given parameter space through a differential evolution Markov chain method using 30,000 steps. We use the Gelman–Rubin statistic (Gelman et al. 2003) to check the mixing of the chains as proposed by Ford (2006). We fit a total of 50 free parameters, these are the parameters presented in Table 7 as well as the limb-darkening

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31 https://sourceforge.net/projects/bagemass/

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Table 4

| Parameter (unit) | WASP-150 | WASP-176 |
|------------------|----------|----------|
| Spectral type    | F8       | F9       |
| $T_{\text{eff}}$ (K) | 6250 ± 80 | 6100 ± 100 |
| log g            | 4.23 ± 0.13 | 4.0 ± 0.2 |
| [Fe/H]           | 0.18 ± 0.11 | 0.15 ± 0.08 |
| $v \sin i$ (km s$^{-1}$) | 8.82 ± 0.95$^a$ | 3.8 ± 1.0$^a$ |

Notes.

$^a$ Assuming a microturbulence of 0.78 ± 0.05 km s$^{-1}$ from the Doyle et al. (2013) calibration.

$^b$ Assuming a macroturbulence of 5.1 ± 0.7 km s$^{-1}$ from the Doyle et al. (2013) calibration.

Table 5

| Parameter (unit) | WASP-150 | WASP-176 |
|------------------|----------|----------|
| Parallax (mas)   | 1.865 ± 0.020 | 1.731 ± 0.036 |
| Distance (pc)    | 536 ± 6       | 578 ± 12  |
| PM R.A. (mas yr$^{-1}$) | −4.289 ± 0.041 | −6.192 ± 0.064 |
| PM Decl. (mas yr$^{-1}$) | 7.000 ± 0.040  | −4.954 ± 0.062 |
| $T_{\text{eff}}$ (K) | 6093$^{+108}_{-106}$ | 5902$^{+20}_{-10}$ |
| $R_*$ ($R_\odot$) | 1.706$^{+0.040}_{-0.041}$ | 1.945$^{+0.024}_{-0.013}$ |
| $L_*$ ($L_\odot$) | 3.616 ± 0.073  | 4.136 ± 0.130 |

Table 6

| Parameter (Unit) | WASP-150 | WASP-176 |
|------------------|----------|----------|
| Mass ($M_*$)     | 1.346 ± 0.029 | 1.270 ± 0.025 |
| $\tau_{\text{iso}}$ (Gyr) | 2.950 ± 0.229 | 4.810 ± 0.191 |
| [Fe/H]$_{\text{last}}$ | 0.204 ± 0.079 | 0.215 ± 0.069 |
parameters for each band used and the offset baselines and variances to account for any errors in normalization.

For the EXOFASTv2 input parameters we take period and epoch from the initial SuperWASP discovery photometry. The metallicity and effective temperature are taken from the results of the spectroscopic analysis. Additionally, we use stellar radius and luminosity as well as parallax and distance from Gaia DR2. Finally we impose a prior on the radius and luminosity as well as parallax and distance from metallicity and effective temperature are taken from the results (Collaboration et al. 2016, 2018) and Schlauf & Finkbeiner (2011), which are used to model the stellar properties through SED fitting. Within EXOFASTv2 we use the MESA Isochrones and Stellar Tracks (MIST; Choi et al. 2016; Dotter 2016) to model the star. This produces an age of 2.18\pm0.05 Gyr, which is in reasonable agreement with the BAGEMASS age in Table 6. The best-fit values, along with uncertainties, are presented in Table 7.

6.2. WASP-176b

6.2.1. Stellar Parameters

Similar to WASP-150, the stellar parameters of WASP-176 are calculated via a spectral analysis of the CORALIE spectra. The results of this analysis are shown in Table 4.

Once again, the second data release of Gaia (Gaia Collaboration et al. 2016, 2018) provided some additional stellar parameters presented in Table 5. Gaia was also searched for close companions of WASP-176.

To determine the age of WASP-176 we again ran BAGEMASS and show the results in Table 6.

The best-fit evolutionary track and isochrone produced from the BAGEMASS analysis are shown in Figure 13 along with the 1σ uncertainties. This plot also includes the posterior distribution produced by the MCMC analysis (see Section 6.2.2).

Once again we see that Figure 13 includes a few points above the main peak. As before we find that these data are not affected by increasing the run time of the MCMC analysis or by increasing the burn-in period so, again, we do not believe them to be an artifact of un converged fitting. Since the significance of this region is ~10 times lower than the peak we do not find it impactful.

6.2.2. EXOFASTv2 Analysis

As for WASP-150b we once again use EXOFASTv2 to derive the quoted parameters for WASP-176b. We use the same number of steps, 30,000, and utilize the Gelman–Rubin statistic to check the mixing of the chains. We fit 43 free parameters, these are the parameters presented in Table 7 as well as limb-darkening parameters for each band used and offset baselines and variances to account for any errors in normalization. In the same way as for WASP-150b we take the EXOFASTv2 input parameters from a combination of the WASP discovery photometry (period and epoch), spectroscopic analysis (metallicity and effective temperature), and Gaia DR2 (stellar radius, luminosity, parallax, and distance). Additionally we impose a V-band extinction prior from Schlegel et al. (1998) and Schlafly & Finkbeiner (2011). We use MIST (Choi et al. 2016; Dotter 2016) to model the star. This produces an age of 3.69\pm0.53 Gyr, which is in good agreement with the BAGEMASS age in Table 6. The best-fit values, along with uncertainties, are presented in Table 7.

The WASP-176b analysis was first conducted allowing for an eccentric orbit. This resulted in \( \chi^2_{\text{ec}} = 11.423 \). Repeating the analysis, this time forcing a circular orbit gives \( \chi^2_{\text{ec}} = 11.358 \). Since the discrepancy between these values is negligible it was decided there was insufficient evidence to support eccentricity and thus a circular orbit was assumed.

7. Discussion and Conclusions

7.1. WASP-150b

WASP-150b is a high-density hot Jupiter on a 5.6442\pm0.0 day orbit around its F8 host. With a mass of 8.46\pm0.2 M\(_J\) and a radius of 1.07\pm0.025 R\(_J\), WASP-150b has a density of 6.44\pm0.47 \( \rho_i \) placing it among the highest density planets known. Figure 14 shows a plot of all the confirmed exoplanets from the NASA

Table 7

| Parameter (unit) | WASP-150b | WASP-176b |
|------------------|-----------|-----------|
| \( T_\text{o} \) (HJD) | 7217.2614\pm0.0004 | 8234.1771\pm0.0027 |
| \( P \) (days) | 5.6442\pm0.0001 | 3.8991\pm0.0 |
| \( \Delta t \) | 0.0044\pm0.0001 | 0.0064\pm0.0002 |
| \( t_\text{ini} \) (days) | 0.1299\pm0.015 | 0.2147\pm0.0021 |
| \( \rho \) | 0.758\pm0.011 | 0.347\pm0.012 |
| \( i \) (°) | 84.01\pm0.25 | 86.7\pm1.1 |
| \( e \) | 0.3775\pm0.0029 | 0.0 (Fixed) |
| \( M_s \) (M\(_J\)) | 1.394\pm0.049 | 1.345\pm0.13 |
| \( R_s \) (R\(_J\)) | 1.651\pm0.024 | 1.92\pm0.047 |
| \( \rho_\text{sc} \) (ρi) | 0.439\pm0.032 | 0.263\pm0.03 |
| \( \log g_s \) (cgs) | 4.147\pm0.027 | 3.995\pm0.037 |
| \( T_\text{eff} \) (K) | 6218.0\pm49.6 | 5941.0\pm79.0 |
| [Fe/H] | 0.156\pm0.089 | 0.164\pm0.082 |
| \( M_d \) (M\(_J\)) | 8.46\pm0.28 | 8.55\pm0.69 |
| \( R_d \) (R\(_J\)) | 1.07\pm0.024 | 1.50\pm0.05 |
| \( \rho_d \) (ρi) | 6.44\pm0.50 | 2.34\pm0.032 |
| \( \log g_d \) (cgs) | 4.263\pm0.024 | 2.97\pm0.047 |
| \( \rho_\text{sc} \) (ρi) | 0.439\pm0.032 | 0.263\pm0.03 |
| \( \log g_d \) (cgs) | 4.263\pm0.024 | 2.97\pm0.047 |
| \( \rho_\text{sc} \) (ρi) | 0.439\pm0.032 | 0.263\pm0.03 |
| \( \log g_d \) (cgs) | 4.263\pm0.024 | 2.97\pm0.047 |
| \( \rho_\text{sc} \) (ρi) | 0.439\pm0.032 | 0.263\pm0.03 |
| \( \log g_d \) (cgs) | 4.263\pm0.024 | 2.97\pm0.047 |
| \( \rho_\text{sc} \) (ρi) | 0.439\pm0.032 | 0.263\pm0.03 |
| \( \log g_d \) (cgs) | 4.263\pm0.024 | 2.97\pm0.047 |
| \( \rho_\text{sc} \) (ρi) | 0.439\pm0.032 | 0.263\pm0.03 |
| \( \log g_d \) (cgs) | 4.263\pm0.024 | 2.97\pm0.047 |
| \( \rho_\text{sc} \) (ρi) | 0.439\pm0.032 | 0.263\pm0.03 |
| \( \log g_d \) (cgs) | 4.263\pm0.024 | 2.97\pm0.047 |
| \( \rho_\text{sc} \) (ρi) | 0.439\pm0.032 | 0.263\pm0.03 |
| \( \log g_d \) (cgs) | 4.263\pm0.024 | 2.97\±.047 |
| \( \rho_\text{sc} \) (ρi) | 0.439\±0.032 | 0.263\±0.03 |
| \( \log g_d \) (cgs) | 4.263\±0.024 | 2.97\±.047 |
WASP-176b is a slightly inflated hot Jupiter orbiting an F9 host star on a 3.8991\textsuperscript{+0.00}{-0.00} day orbit. The MCMC best-fit results presented here give a planetary mass of 0.855\textsuperscript{+0.072}{-0.065} M\textsubscript{J} and a planetary radius of 1.505\textsuperscript{+0.045}{-0.045} R\textsubscript{J}, leading to a density of 0.234\textsuperscript{+0.032}{-0.032} ρ\textsubscript{J}. Using the same scaling relation as above predicts the main-sequence lifetime of WASP-176 as ∼4.77 Gyr. Using the isochronal age estimated in Section 6.2.1 indicates that the star has evolved past the end of its main-sequence life. This comparison, combined with the stellar surface gravity and density given in Table 7, indicates that the host is a sub-giant. This is further supported by its location on the HR diagram as seen in Figure 13. The planetary radius found here is approximately 25% larger than expected for a coreless planet, when predicted using the planetary evolution models from Fortney et al. (2007).

WASP-176b is similar to other hot Jupiters (WASP-54b, Faedi et al. 2013; WASP-78b and WASP-79b, Smalley et al. 2012; WASP-142b, Hellier et al. 2016; WASP-136b, Lam et al. 2016) in that it receives stronger irradiation from its F-type host than it would from a G-type star, thus leading to inflation. Based on this increased radiation we suggest that the inflation mechanism behind WASP-176b may be due to the deposit of stellar irradiation into the planetary core, consistent with the Class I model presented in Lopez & Fortney (2016). If so, then this planet may have experienced increasing inflation as its host moved off the main sequence. However this is only a possible solution, additional characterization may give more information to this end.

WASP-176b is a potential target for atmospheric characterization via transmission spectroscopy due to its low density and high equilibrium temperature. If we assume an atmosphere similar in composition to Jupiter (μ = 2.2 u, where u = 1.66 × 10\textsuperscript{-27} kg is the atomic mass units) then the scale height is found to be H = k\textsubscript{p}T/μg ∼ 500 km which is smaller, but comparable, to values seen in recent successful atmospheric retrievals (Kirk et al. 2019). However, with a magnitude of only V = 12.01, the follow-up would be a significant challenge.

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**Figure 14.** Scatter plot of all confirmed exoplanets from the NASA exoplanet archive with radius and mass known to an accuracy of ≤10% and periods of ≤10 days. The points are then colored by density in cgs units. WASP-150b is shown as a red diamond and Jupiter is shown as a black diamond for reference (WASP-162b is shown as an orange diamond). The plot also includes lines of constant density to guide the eye.
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**ORCID iDs**

Benjamin F. Cooke https://orcid.org/0000-0002-8824-9956
Don Pollacco https://orcid.org/0000-0001-9850-9697
D. J. A. Brown https://orcid.org/0000-0003-1098-2442
Andrew Collier Cameron https://orcid.org/0000-0002-8863-7828
Giuseppe D’agro https://orcid.org/0000-0001-9697-7331
C. Hellier https://orcid.org/0000-0002-3439-1439
Alexios Liakos https://orcid.org/0000-0002-0490-1469
Luigi Mancini https://orcid.org/0000-0002-9428-8732
P. F. L. Maxted https://orcid.org/0000-0003-3794-1317
F. J. Pozuelos https://orcid.org/0000-0003-1572-7707
D. Queloz https://orcid.org/0000-0002-3012-0316
Nicole Schanche https://orcid.org/0000-0002-9526-3780
Barry Smalley https://orcid.org/0000-0002-3456-087X
Stéphane Udry https://orcid.org/0000-0001-7576-6236
Petre Wheatley https://orcid.org/0000-0003-1452-2240

**References**

Adams, F. C., & Laughlin, G. 2006, ApJ, 649, 1004
Bakos, G. Á 2018, in Handbook of Exoplanets, ed. H. Deeg & J. Belmonte (Cham: Springer), 957
Baranne, A., Queloz, D., Mayor, M., et al. 1996, A&AS, 119, 373
Barbary, K. 2016, JOSS, 1, 58
Barkaoui, K., Burdanov, A., Hellier, C., et al. 2019, AJ, 157, 43
Batalha, N. M. 2014, PNAS, 111, 12647
Barbary, K. 2016, JOSS, 1, 58
Bakos, G. Á 2018, in Handbook of Exoplanets, ed. H. Deeg & J. Belmonte (Cham: Springer), 957

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**References**

Adams, F. C., & Laughlin, G. 2006, ApJ, 649, 1004
Bakos, G. Á 2018, in Handbook of Exoplanets, ed. H. Deeg & J. Belmonte (Cham: Springer), 957
Baranne, A., Queloz, D., Mayor, M., et al. 1996, A&AS, 119, 373
Barbary, K. 2016, JOSS, 1, 58
Barkaoui, K., Burdanov, A., Hellier, C., et al. 2019, AJ, 157, 43
Batalha, N. M. 2014, PNAS, 111, 12647
Barbary, K. 2016, JOSS, 1, 58
Bakos, G. Á 2018, in Handbook of Exoplanets, ed. H. Deeg & J. Belmonte (Cham: Springer), 957

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