High-precision photometry by telescope defocussing. VIII. WASP-22, WASP-41, WASP-42 and WASP-55


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ABSTRACT

We present 13 high-precision and four additional light curves of four bright southern-hemisphere transiting planetary systems: WASP-22, WASP-41, WASP-42, and WASP-55. In the cases of WASP-42 and WASP-55, these are the first follow-up observations since their discovery papers. We present refined measurements of the physical properties and orbital ephemerides of all four systems. No indications of transit timing variations were seen. All four planets have radii inflated above those expected from theoretical models of gas-giant planets; WASP-55 b is the most discrepant with a mass of 0.63 M\textsubscript{Jup} and a radius of 1.34 R\textsubscript{Jup}. WASP-41 shows brightness anomalies during transit due to the planet occulting spots on the stellar surface. Two anomalies observed 3.1 d apart are very likely due to the same spot. We measure its change in position and determine a rotation period for the host star of 18.6 ± 1.5 d, in good agreement with a published measurement from spot-induced brightness modulation, and a sky-projected orbital obliquity of $\lambda = 6 \pm 11^\circ$. We conclude with a compilation of obliquity measurements from spot-tracking analyses and a discussion of this technique in the study of the orbital configurations of hot Jupiters.

Key words: stars: planetary systems — stars: fundamental parameters — stars: individual: WASP-22, WASP-41, WASP-42, WASP-55

1 INTRODUCTION

Of the over 1200 transiting extrasolar planets (TEPs) now known\(^1\), the short-period gas-giant planets are of particular interest. These ‘hot Jupiters’ are the easiest to find due to their deep transits and high orbital frequency, are the most amenable to detailed characterisation due to their large masses and radii, and have highly irradiated and often rarefied atmospheres in which many physical phenomena are observable.

Most of the transiting hot Jupiters have been discovered by ground-based surveys studying bright stars. The brightness of the host stars is also extremely helpful in further characterisation of these objects via transmission spectroscopy and orbital obliquity studies. We are therefore undertaking a project to study TEPs orbiting bright host stars visible from the Southern hemisphere. Here we present transit light curves of four targets discovered by the SuperWASP project (Pollacco et al. 2006) and measure their physical properties and orbital ephemerides to high precision.

WASP-22 was discovered by Maxted et al. (2010), who found it to be a low-density planet (mass 0.56 M\textsubscript{Jup}, radius 1.12 R\textsubscript{Jup}) orbiting a $V = 11.7$ solar-type star every 3.53 d. A linear trend in the radial velocities (RVs) was noticed and attributed to the presence of a third body in the system, which could be an M-dwarf, white dwarf or second planet. The trend in the RVs has been confirmed by Knutson et al. (2014), who measured the change in the systemic velocity of the system to be $\gamma = 21.3^{+2.9}_{-2.6}$ m s\(^{-1}\) yr\(^{-1}\). Anderson et al. (2011) measured the projected orbital obliquity of the system to be $\lambda = 22^\circ \pm 16^\circ$ via the Rossiter-McLaughlin effect.

WASP-41 was announced by Maxted et al. (2011b) to be a hot Jupiter of mass 0.94 M\textsubscript{Jup}, radius 1.06 R\textsubscript{Jup}, and orbital period $P_{\text{orb}} = 3.05$ d. Its host is a $V = 11.6$ G8 V star showing magnetic activity indicative of a young age, and rotational modulation on a period of 18.41 ± 0.05 d. Neveu-VanMalle et al. (2015) obtained further spectroscopic RV measurements from which they measured $\lambda = 29^{+10}_{-14}^\circ$ and detected a third object in the system with $P_{\text{orb}} = 421 \pm 2$ d and a minimum mass of 3.18 ± 0.20 M\textsubscript{Jup}.

WASP-42 was discovered by Lendl et al. (2012) and is a low-density planet (mass 0.50 M\textsubscript{Jup}, radius 1.12 R\textsubscript{Jup}) orbiting a $V = 12.6$ star of spectral type K1 V every 4.98 d. An orbital eccentricity of $e = 0.060 \pm 0.0013$ was found by these authors, which is small but significant (Lucy & Sweeney 1971). No other study of the WASP-42 system has been published.

WASP-55 was one of a batch of new TEPs announced by Hellier et al. (2012) and is the lowest-density of the four planets considered here, with a mass of 0.50 M\textsubscript{Jup} and radius of 1.30 R\textsubscript{Jup}. Its host is a G1 V star with a slightly sub-solar metallicity, and the $P_{\text{orb}}$ of the system is 4.47 d. No other study of the WASP-55 system has been published, but it was a target in Field 6 of the K2 mission (Howell et al. 2014) and these observations will soon be available.

2 OBSERVATIONS AND DATA REDUCTION

We observed a total of 13 transits with the DFOSC (Danish Faint Object Spectrograph and Camera) instrument installed on the 1.54 m Danish Telescope at ESO La Silla, Chile. DFOSC has a field of view of 13.7′ × 13.7′ at a plate scale of 0.39″ pixel\(^{-1}\). We defocussed the telescope in order to improve the precision and efficiency of our observations (Southworth et al. 2009). The CCD was windowed during some observing sequences in order to shorten the readout time, and no binning was used. In most cases the night was photometric; observations taken through thin cloud were carefully checked and rejected if their reliability was questionable. The data were taken through either a Bessell $R$ or Bessell $I$ filter. An observing log is given in Table 1 and the final light curves are plotted in Fig. 1. All observations were taken after the upgrade of the telescope and CCD controller in 2011 (Southworth et al. 2014).

We reduced the data using the DEFOT pipeline (see Southworth et al. 2014, and references therein), which in turn uses the IDL\(^2\) implementation of the APFIR routine from DAOphot (Stetson 1987) contained in the NASA ASTROLIB library\(^3\). For each

\(^{1}\) Based on data collected by MINDSTEp with the Danish 1.54 m telescope at the ESO La Silla Observatory.

\(^{2}\) http://www.exelisvis.co.uk/ProductsServices/IDL.aspx

\(^{3}\) http://idlastro.gsfc.nasa.gov/
Figure 1. DFOSC light curves presented in this work, in the order they are given in Table 1. Times are given relative to the midpoint of each transit, and the filter used is indicated. Blue and red filled circles represent observations through the Bessell R and I filters, respectively.

Table 1. Log of the observations presented in this work. \(N_{\text{obs}}\) is the number of observations, \(T_{\text{exp}}\) is the exposure time, \(T_{\text{dead}}\) is the dead time between exposures. 'Moon illum.' is the fractional illumination of the Moon at the midpoint of the transit, given in italics if the Moon was down at that time, and \(N_{\text{poly}}\) is the order of the polynomial fitted to the out-of-transit data. The aperture radii refer to the target aperture, inner sky and outer sky, respectively.

<table>
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<th>Target</th>
<th>Telescope</th>
<th>Date of first obs</th>
<th>Start time (UT)</th>
<th>End time (UT)</th>
<th>(N_{\text{obs}})</th>
<th>(T_{\text{exp}}) (s)</th>
<th>(T_{\text{dead}}) (s)</th>
<th>Filter</th>
<th>Airmass</th>
<th>Moon illum.</th>
<th>Aperture radii</th>
<th>(N_{\text{poly}})</th>
<th>Scatter (mmag)</th>
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<td>05:56</td>
<td>353</td>
<td>45</td>
<td>none</td>
<td>R</td>
<td>1.38 → 1.00 → 1.19</td>
<td>0.365</td>
<td>17 65 100</td>
<td>2</td>
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</tr>
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<td>00:54</td>
<td>04:53</td>
<td>228</td>
<td>45</td>
<td>none</td>
<td>R</td>
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<td>0.002</td>
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</tr>
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<td>05:34</td>
<td>09:43</td>
<td>133</td>
<td>100</td>
<td>13 I</td>
<td>I</td>
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<td>18 32 50</td>
<td>1</td>
<td>0.703</td>
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<td>03:10</td>
<td>09:08</td>
<td>172</td>
<td>100</td>
<td>25 I</td>
<td>I</td>
<td>2.21 → 1.00 → 1.05</td>
<td>0.680</td>
<td>18 25 55</td>
<td>1</td>
<td>0.913</td>
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<td>10:08</td>
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<td>35–45</td>
<td>12 I</td>
<td>I</td>
<td>2.11 → 1.00 → 1.03</td>
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<td>09:44</td>
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<td>50</td>
<td>none</td>
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<td>09:40</td>
<td>102</td>
<td>90</td>
<td>7 none</td>
<td>R</td>
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<td>27 54 108</td>
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<td>05:03</td>
<td>155</td>
<td>80–100</td>
<td>13 I</td>
<td>I</td>
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<td>148</td>
<td>100</td>
<td>13 I</td>
<td>I</td>
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<td>2</td>
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<td>23:25</td>
<td>04:30</td>
<td>159</td>
<td>100</td>
<td>13 I</td>
<td>I</td>
<td>1.19 → 1.00 → 1.19</td>
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<td>05:30</td>
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<td>100</td>
<td>13 I</td>
<td>I</td>
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<td>0.015</td>
<td>22 28 50</td>
<td>1</td>
<td>0.646</td>
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<td>Danish</td>
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<td>00:51</td>
<td>06:28</td>
<td>164</td>
<td>100</td>
<td>20 R</td>
<td>R</td>
<td>1.04 → 1.03 → 2.10</td>
<td>1.000</td>
<td>20 28 45</td>
<td>2</td>
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<td>23:11</td>
<td>04:33</td>
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<td>100</td>
<td>16 R</td>
<td>R</td>
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<td>2013 06 28</td>
<td>23:00</td>
<td>03:43</td>
<td>143</td>
<td>100</td>
<td>15 R</td>
<td>R</td>
<td>1.04 → 1.03 → 1.82</td>
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<td>22 30 55</td>
<td>1</td>
<td>0.924</td>
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<td>02:26</td>
<td>07:42</td>
<td>152</td>
<td>90–98</td>
<td>25 R</td>
<td>R</td>
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<td>0.344</td>
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<td>2014 06 18</td>
<td>22:56</td>
<td>03:26</td>
<td>206</td>
<td>50–110</td>
<td>11 I</td>
<td>I</td>
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<td>13 42 80</td>
<td>1</td>
<td>1.144</td>
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<td>2015 04 23</td>
<td>01:06</td>
<td>07:29</td>
<td>184</td>
<td>100</td>
<td>25 I</td>
<td>I</td>
<td>1.41 → 1.02 → 1.45</td>
<td>0.231</td>
<td>16 26 50</td>
<td>1</td>
<td>0.899</td>
</tr>
</tbody>
</table>

dataset, the apertures were placed by hand and the radii of the object aperture and sky annulus were chosen to minimise the scatter in the final light curve (see Table 1). The science images were not calibrated using bias or flat-field frames as these tend to have little effect on the final light curves beyond a slight increase in the scatter of the datapoints.

We observed two transits of WASP-22 and two transits of WASP-41 using the 84 cm telescope at Observatorio Cerro Armazones in Antofagasta, Chile (currently decommissioned). Three transits were observed using an SBIG ST-10 CCD camera, giving a field of view of 15.6′ × 10.5′ at a plate scale of 0.43″/pixel⁻¹, and the first transit of WASP-41 was monitored using an SBIG STL CCD camera with a field of view of 29.3′ × 19.5′ at a plate scale of 0.57″/pixel⁻¹. We defocussed the telescope and windowed the
CCDs, and observed unfiltered except for the first transit of WASP-41 which was seen through an \( R \) filter. Data reduction was performed using a custom pipeline based on Starlink routines, including calibration with dark frames but not flat-fields. The PHOTOM package (Eaton et al. 1999) was used to perform aperture photometry with dark frames but not flat-fields. The data are plotted in Fig. 2.

For all datasets, differential-magnitude light curves were generated for each target star versus an ensemble comparison star containing the weighted flux sum of all good comparison stars. A polynomial was also fitted to the observations outside transit and subtracted to rectify the final light curve to zero differential magnitude. In most cases a first-order polynomial was an adequate match to the slow brightness variations seen throughout the observing sequences, but in some cases a quadratic was required (see Table 1). The coefficients of the polynomial and the weights of the comparison stars were simultaneously optimised to minimise the scatter in the datapoints outside eclipse.

Manual time checks were obtained for several frames and the FITS file timestamps were confirmed to be on the UTC system to account for the uncertainties of the rectification to zero differential magnitude. Times are given relative to the midpoint of each transit, and the filter used is indicated. Blue and green filled circles represent observations through the \( R \) filter and without filter, respectively.

### Table 2. The first line of each of the light curves presented in this work. The full dataset will be made available at the CDS.

<table>
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<th>Target</th>
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<th>Filter</th>
<th>BJD(TDB)</th>
<th>Diff. mag.</th>
<th>Uncertainty</th>
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<td>55949.539861</td>
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</tr>
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</tr>
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</tr>
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<tr>
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</tr>
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</table>

### 3 LIGHT CURVE ANALYSIS

We modelled the light curves of the four targets using the Homogeneous Studies methodology (see Southworth 2012 and references therein), which utilises the JKTEBOP\(^5\) code (Southworth 2013, and references therein). JKTEBOP represents the star and planet as spheres for the calculation of eclipse shapes and as biaxial spheroids for proximity effects.

The fitted parameters in our analysis were the fractional radii of the star and planet \( r_A \) and \( r_1 \), the orbital inclination \( i \), limb darkening coefficients, and a reference time of mid-transit. The fractional radii are the ratio between the true radii and the semi-major axis \( r_A, b \) and \( r_1 \), and were expressed as their sum and ratio \( r_A + r_1 \) and \( k = \frac{r_1}{r_A} \), as these quantities are less strongly correlated. The orbital periods were fixed at the values found in Section 6. A polynomial of brightness versus time was applied to each transit light curve, with a polynomial order as given in Table 1, to account for the uncertainties of the rectification to zero differential magnitude at the data reduction stage (see Southworth et al. 2014).

Limb darkening (LD) was incorporated into the photometric model using each of five LD laws (see Southworth 2008), with the linear coefficients either fixed at theoretically predicted values\(^6\) or included as fitted parameters. We did not calculate fits for both LD coefficients in the four two-parameter laws as they are strongly correlated (Southworth 2008; Carter et al. 2008). The nonlinear coefficients were instead perturbed by \( \pm 0.1 \) on a flat distribution during the error analysis simulations, in order to account for uncertainties in the theoretical coefficients.

All four targets have been observed in the HITEP high-resolution imaging campaign by Evans et al. (2015) using the Two Colour Imager (TCI) (Skottfelt et al. 2015) to perform Lucky Imaging. No stars were found close enough to WASP-22, WASP-41 or WASP-42 to affect our photometry. However, one star was found

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\(^5\) JKTEBOP is written in FORTRAN77 and the source code is available at http://www.astro.keele.ac.uk/jkt/codes/jktebop.html

\(^6\) Theoretical LD coefficients were obtained by bilinear interpolation to the host star's \( T_{\text{eff}} \) and \( \log g \) using the JKTLD code available from: http://www.astro.keele.ac.uk/jkt/codes/jktld.html

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\(^4\) http://vizier.u-strasbg.fr/

---

\(^2\) For all four targets, differential-magnitude light curves were generated for each target star versus an ensemble comparison star containing the weighted flux sum of all good comparison stars. A polynomial was also fitted to the observations outside transit and subtracted to rectify the final light curve to zero differential magnitude. In most cases a first-order polynomial was an adequate match to the slow brightness variations seen throughout the observing sequences, but in some cases a quadratic was required (see Table 1). The coefficients of the polynomial and the weights of the comparison stars were simultaneously optimised to minimise the scatter in the datapoints outside eclipse.

---

\(^3\) Manual time checks were obtained for several frames and the FITS file timestamps were confirmed to be on the UTC system to account for the uncertainties of the rectification to zero differential magnitude. Times are given relative to the midpoint of each transit, and the filter used is indicated. Blue and green filled circles represent observations through the \( R \) filter and without filter, respectively.

---

\(^4\) JKTEBOP is written in FORTRAN77 and the source code is available at http://www.astro.keele.ac.uk/jkt/codes/jktebop.html

---

\(^6\) Theoretical LD coefficients were obtained by bilinear interpolation to the host star's \( T_{\text{eff}} \) and \( \log g \) using the JKTLD code available from: http://www.astro.keele.ac.uk/jkt/codes/jktld.html
Figure 3. The phased light curves of WASP-22 analysed in this work, compared to the JKTEBOP best fits. The residuals of the fits are plotted at the base of the figure, offset from unity. Labels give the source and passband for each dataset. The polynomial baseline functions have been subtracted from the data before plotting.

WASP-22, WASP-41, WASP-42 and WASP-55

Figure 4. As Fig. 3, but for WASP-41.

The final values are consistent with, and an improvement on, previously published values.

3.2 WASP-41

WASP-41 is a trickier beast because there are anomalies due to starspot-crossing events in at least two of our high-precision light curves. In the current part of the analysis these were ignored, in order to maintain homogeneity of approach, so were therefore basically treated as red noise. A detailed analysis of the spot anomalies will be presented below. Our four DFOSC light curves of WASP-41 were fitted simultaneously (Table 3 and Fig. 4), for which the best fit returns $\chi^2_\nu = 1.05$ despite the presence of the spot anomalies. A circular orbit was assumed as Neveu-VanMalle et al. (2015) found $e < 0.026$ at the 2σ confidence level.

As with WASP-22, the discovery paper of WASP-41 included only one high-precision light curve, which does not cover the full transit. This dataset was not analysed here due to the weak constraints on system properties from light curves missing coverage of the third and fourth contact points in the eclipse. However, Neveu-VanMalle et al. (2015) presented eight new light curves of WASP-41 obtained from three telescopes. The single complete transit from the Danish Telescope, labelled ‘DFOSC R’ in Fig. 4, and the transit from Faulkes Telescope South (FTS) were each modelled in isolation. The five datasets from TRAPPIST were modelled together, with an extra polynomial to account for the meridian flip at JD 2456402.653 (L. Delrez, 2015, priv. comm.). The final results are shown in Table 3 and agree with, but improve on, published values.

3.3 WASP-42

Of the four systems studied in this work, WASP-42 is the only one with an eccentric orbit. Lendl et al. (2012) found that their measurement of a small eccentricity was significant at the 99.5% level.
We accounted for this in the JKT EOB modelling by constraining the eccentricity and argument of periastron to be $e = 0.060 \pm 0.013$ and $\omega = 167 \pm 26\degree$, respectively.

Our three light curves were all obtained within 34 d – the observability of transits in this object has a strong seasonal dependence because its orbital period is close to an integer number of days – and were modelled together (Table 3). The combined fit has $\chi^2 = 1.09$, once again showing good agreement between our three light curves (Fig. 5). We also modelled the light curves from the Euler and TRAPPIST telescopes presented in Lendl et al. (2012), which cover two and four transits respectively. The three light curves are in excellent agreement, with values of $\chi^2$ between 0.30 and 0.57 for the photometric parameters, where $\chi^2$ is for the agreement between the weighted means and the individual values.

### 3.4 WASP-55

From high-resolution imaging Evans et al. (2015) found a faint star close to the WASP-55 system. The star is at an angular distance of $4.345 \pm 0.010$ arcsec and has a magnitude difference of $5.210 \pm 0.018$ in the $\nu TCI$ band, which is similar to a combined Gunn $i+z$ band. No observations were obtained in the $\nu TCI$ band, so the colour and therefore spectral type of the faint companion cannot be constrained. We conservatively find that between 50%
from Table 3. We took spectroscopic values for the host star’s ef-
cuments for each parameter. We find \( \chi^2 \) weighted means of the photometric parameters by multiplying to-
4 PHYSICAL PROPERTIES
light curves are in good agreement.
photometric parameters, indicating that the results for the different

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>WASP-22</th>
<th>WASP-41</th>
<th>WASP-42</th>
<th>WASP-55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellar mass (M_⊙)</td>
<td>( M_A )</td>
<td>1.249 ( ^{+0.073}_{-0.015} )</td>
<td>0.987 ( ^{+0.021}_{-0.026} )</td>
<td>0.951 ( ^{+0.037}_{-0.051} )</td>
<td>1.162 ( ^{+0.029}_{-0.027} )</td>
</tr>
<tr>
<td>Stellar radius (R_⊙)</td>
<td>( R_A )</td>
<td>1.255 ( ^{+0.030}_{-0.005} )</td>
<td>0.886 ( ^{+0.009}_{-0.008} )</td>
<td>0.892 ( ^{+0.021}_{-0.016} )</td>
<td>1.103 ( ^{+0.020}_{-0.007} )</td>
</tr>
<tr>
<td>Stellar surface gravity (c.g.s)</td>
<td>( \log g_A )</td>
<td>4.338 ( ^{+0.020}_{-0.002} )</td>
<td>4.538 ( ^{+0.008}_{-0.004} )</td>
<td>4.515 ( ^{+0.022}_{-0.008} )</td>
<td>4.419 ( ^{+0.015}_{-0.003} )</td>
</tr>
<tr>
<td>Stellar density (( \rho_A ))</td>
<td></td>
<td>0.632 ( ^{+0.043}_{-0.041} )</td>
<td>1.420 ( ^{+0.034}_{-0.034} )</td>
<td>1.338 ( ^{+0.092}_{-0.092} )</td>
<td>0.860 ( ^{+0.026}_{-0.041} )</td>
</tr>
<tr>
<td>Planet mass (M_\text{Jup})</td>
<td>( M_{B} )</td>
<td>0.617 ( ^{+0.017}_{-0.005} )</td>
<td>0.977 ( ^{+0.020}_{-0.017} )</td>
<td>0.527 ( ^{+0.020}_{-0.019} )</td>
<td>0.621 ( ^{+0.038}_{-0.007} )</td>
</tr>
<tr>
<td>Planet radius (R_\text{Jup})</td>
<td>( R_{B} )</td>
<td>1.199 ( ^{+0.027}_{-0.005} )</td>
<td>1.178 ( ^{+0.015}_{-0.010} )</td>
<td>1.122 ( ^{+0.033}_{-0.020} )</td>
<td>1.335 ( ^{+0.020}_{-0.008} )</td>
</tr>
<tr>
<td>Planet surface gravity (m s(^{-2}))</td>
<td>( g_{B} )</td>
<td>10.63 ( ^{+0.71}_{-0.71} )</td>
<td>17.45 ( ^{+0.46}_{-0.46} )</td>
<td>10.38 ( ^{+0.61}_{-0.61} )</td>
<td>8.73 ( ^{+0.62}_{-0.62} )</td>
</tr>
<tr>
<td>Planet density (( \rho_{B} ))</td>
<td></td>
<td>0.334 ( ^{+0.033}_{-0.033} )</td>
<td>0.558 ( ^{+0.020}_{-0.005} )</td>
<td>0.349 ( ^{+0.029}_{-0.006} )</td>
<td>0.247 ( ^{+0.021}_{-0.002} )</td>
</tr>
<tr>
<td>Equilibrium temperature (K)</td>
<td>( T_{\text{eq}} )</td>
<td>1502 ( ^{+20}_{-20} )</td>
<td>1242 ( ^{+12}_{-12} )</td>
<td>1021 ( ^{+19}_{-19} )</td>
<td>1300 ( ^{+15}_{-15} )</td>
</tr>
<tr>
<td>Orbital semimajor axis (au)</td>
<td>( a )</td>
<td>0.0489 ( ^{+0.0002}_{-0.0002} )</td>
<td>0.0410 ( ^{+0.0003}_{-0.0004} )</td>
<td>0.0561 ( ^{+0.0007}_{-0.0010} )</td>
<td>0.0558 ( ^{+0.0005}_{-0.0003} )</td>
</tr>
<tr>
<td>Age (Gyr)</td>
<td>( \tau )</td>
<td>1.3 ( ^{-0.7}_{-0.2} )</td>
<td>1.2 ( ^{-0.6}_{-0.2} )</td>
<td>4.4 ( ^{-0.4}_{-0.2} )</td>
<td>1.1 ( ^{-0.6}_{-0.1} )</td>
</tr>
</tbody>
</table>

Table 5. Derived physical properties of the four systems. Where two sets of errorbars are given, the first is the statistical uncertainty and the second is the systematic uncertainty.

Table 4. Spectroscopic properties of the planet host stars used in the determination of the physical properties of the systems.

References: (1) Mortier et al. (2013); (2) Knutson et al. (2014); (3) Neveu-VanMalle et al. (2015); (4) Lundl et al. (2012); (5) Hellier et al. (2012)

and 90% of the total light from this object is contained in the aperture used for WASP-55 itself, giving a contaminating light fraction of 0.41% to 0.74%. We account for this in the JKTEBOP fits by setting the third light constraint to be \( L_3 = 0.006 \pm 0.003 \), where the errorbar has been increased to account for possible differences between the \( v_{TCE} \) band used for the high-resolution images and the \( R \) and \( I \) bands used in the current work.

We observed three transits of WASP-55, one with an \( R \) filter and two through an \( I \) filter. The two datasets were modelled separately but both with the third light constraint (Fig. 6). The results (Table 3) are in good agreement. The discovery paper (Hellier et al. 2012) presented TRAPPIST light curves of two transits and a Euler light curve of one transit. Both TRAPPIST datasets have only partial coverage of the transit so were not analysed here. The Euler light curve is of decent quality and was modelled with JKTEBOP in the same way as for our own data. As with WASP-22, we obtain weighted means of the photometric parameters by multiplying together the probability density functions of the individual measurements for each parameter. We find \( \chi^2 \) values less than 1.0 for all photometric parameters, indicating that the results for the different light curves are in good agreement.

4 PHYSICAL PROPERTIES

The results of the above photometric analysis were combined with measured spectroscopic quantities in order to determine the physical properties of the four planetary systems. For each object we used the weighted mean of the measured values of \( r_A \), \( \rho_A \) and \( i \) from Table 3. We took spectroscopic values for the host star’s effective temperature, \( T_{\text{eff}} \), metallicity, \( [\text{Fe/H}] \), and velocity amplitude, \( K_A \), from the literature (see Table 4). These quantities alone are insufficient to yield determinate results, so the properties of the host stars were constrained using tabulated predictions from theoretical models (Claret 2004; Demarque et al. 2004; Pietrinferni et al. 2004; VandenBerg et al. 2006; Dotter et al. 2008).

For each object we estimated the value of the velocity amplitude of the planet, \( K_b \), and calculated the physical properties of the system using this and the measured quantities. We then iteratively adjusted \( K_b \) to obtain the best agreement between the \( \Delta \) and the measured \( r_A \), and between the \( T_{\text{eff}} \) and that predicted by the stellar models for the observed \( [\text{Fe/H}] \) and calculated stellar mass (\( M_\star \)). This was done for a range of ages, allowing us to identify the overall best fit and age of the system (see Southworth 2009). This process was performed for each of the five sets of theoretical models, allowing us to quantify the effect of using theoretical predictions on our results.

The measured physical properties of the four systems are given in Table 5. Statistical errors were calculated by propagating the uncertainties in all the input quantities to each of the output quantities. Systematic uncertainties were obtained by taking the maximum deviation between the final value and the five values from using the different stellar models. Our results are in good agreement with literature values for three of the four systems, but differ in that they are based on more extensive observational data and explicitly account for systematic errors due to the use of theoretical stellar models.

In the case of WASP-22, our measured system properties differ moderately from previous values (Maxted et al. 2010; Anderson et al. 2011). Whilst there are some differences in the photometric parameters from our data, which are of significantly higher quality than the existing TRAPPIST and Euler light curves, the main effect is due to our adoption of the higher and more precise \( T_{\text{eff}} \) value obtained by Mortier et al. (2013) for the host star. For comparison, we calculated an alternative set of results using the lower value of \( T_{\text{eff}} \) found from the infrared flux method by Maxted et al. (2011a). The mass and radius of the host star change to 1.194 M_⊙ and 1.236 R_\odot, respectively, and those of the planet to 0.598 M_\text{Jup} and 1.181 R_\text{Jup}. These numbers are all smaller than our adopted values, but in all cases the change is within the errorbars.
by third (left) and fourth (right) transits we observed with DF OSC, produced
visualisations of the surface of WASP-41 A at the times of the
Figure 7.

Table 6. Properties of the spots occulted during two transits of WASP-41 A by WASP-41 b, obtained from modelling the light curves with PRISM+GEMC. Longitude and latitude are defined to be zero at the centre of the stellar disc.

<table>
<thead>
<tr>
<th>Light curve</th>
<th>2015/05/13</th>
<th>2015/05/17</th>
<th>2015/05/17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot number</td>
<td></td>
<td>Spot 1</td>
<td>Spot 2</td>
</tr>
<tr>
<td>Spot longitude (°)</td>
<td></td>
<td>−36.3 ± 4.5</td>
<td>−37.2 ± 2.8</td>
</tr>
<tr>
<td>Spot latitude (°)</td>
<td></td>
<td>15.3 ± 10.3</td>
<td>27.4 ± 6.6</td>
</tr>
<tr>
<td>Spot size (°)</td>
<td></td>
<td>10.4 ± 6.5</td>
<td>15.5 ± 3.5</td>
</tr>
<tr>
<td>Spot contrast</td>
<td></td>
<td>0.80 ± 0.14</td>
<td>0.82 ± 0.07</td>
</tr>
</tbody>
</table>

Figure 7. Visualisations of the surface of WASP-41 A at the times of the third (left) and fourth (right) transits we observed with DFOSC. The boundaries of the path of the planet are shown with black lines and the spots are shown with their measured locations, sizes and contrasts.

5 SPOT MODELLING OF WASP-41

The third and fourth transits of WASP-41 show clear evidence of starspot activity, manifested as short increases in brightness during transit when the planet crosses areas which are of lower surface brightness than the rest of the stellar photosphere (see Fig. 1). The spot crossing events hold information on the size and brightness of the spots, and potentially allow the motion of spots and therefore the rotation of the star to be tracked (Silva-Valio 2008; Nutzman et al. 2011). It was for this reason that we observed three transits of WASP-41 over a six-day period in 2015.

We modelled these two transit light curves using the PRISM and GEMC codes (Tregloan-Reed et al. 2013, 2015). PRISM uses a pixellation approach to calculate the light curve of a planet transiting a spotted star, and GEMC is a hybrid between a Markov chain Monte Carlo and a genetic algorithm to find the best fit to a light curve of a single transit. GEMC is based on the differential evolution Markov chain approach by Ter Braak (2006). The light curve from the night of 2015/05/13 shows clear evidence for one spot crossing – attempts to fit for a postulated second spot crossing did not lead to a determinate solution – and the light curve from the night of 2015/05/17 contains two spot crossing events. These two datasets were fitted individually in order to determine the locations, sizes and contrasts of the spots, where ‘contrast’ refers to the ratio of the brightness of the spot to that of the pristine stellar photosphere in the passband used to obtain the observations (Figs. 7 and 8).

In order to limit the strong correlation between the orbital inclination (or, equivalently, the impact parameter) of the planet and the latitude of the spot, we fixed $i = 88.7^\circ$ in the PRISM+GEMC fits. We also fitted for the linear LD coefficient whilst fixing the quadratic coefficient to 0.3. Exploratory fits used a resolution of 15 pixels for the radius of the planet, for speed, and for final fits we used 50 pixels to obtain higher precision in the results (see Table 6).

We found that the latitude of the spots are not very well determined, as expected for the case where the transit cord of the planet passes close to the centre of the star. Even in the case of a fixed spot contrast, a similar amplitude in flux for the spot crossing event can be obtained for a small spot which is totally occulted by the planet, or a larger spot positioned either above or below the transit cord which is partially eclipsed by the planet. Similarly, a partially-eclipsed spot can have very little effect on the light curve shape if a modest increase in its size is compensated for by moving its latitude further away from the transit cord, and vice versa. As there is also a known degeneracy between spot contrast and size (e.g. Tregloan-Reed et al. 2013), but only for those parts of the spot which are occulted by the planet, it is clear that the parameter space for spot-modelling is inherently complex and degenerate.

However, the spot longitudes are very well determined by our data (see Table 6) because they govern the times at which spot crossings are detected. We now assert that the spot observed on 2015/05/13 is the same as the second spot observed on 2015/05/17. In this case the change in the longitude and latitude of the spot (both defined to be zero at the centre of the stellar disc) are $60.0 \pm 4.8^\circ$ and $−7 \pm 12^\circ$, respectively, and the time difference between the midpoints of the two spot crossings is $3.097 \pm 0.005$ d. If the spot moved directly from the first to the second location, this gives a rotation period of $18.6 \pm 1.5$ d at a latitude of approximately $12^\circ$7, in good agreement with the value of $18.41 \pm 0.05$ d measured from the spot-induced brightness modulation of WASP-41 A by Maxted.

7 Alternative assumptions all yield much shorter rotation periods. For example, if the spot moves from the first to the second location but in a retrograde direction it has to travel $300^\circ$ and the rotation period is $3.7 \pm 0.3$ d. If the rotation is instead prograde but the star rotates once plus the 60° difference in longitude, then the rotation period is $2.4 \pm 0.2$ d. All other possibilities require additional rotations of the star between the two detections of the spot, and thus yield ever-shorter rotation periods.

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et al. (2011b). This equates to a projected rotational velocity of \( v \sin i = 2.4 \pm 0.2 \text{ km s}^{-1} \), again in good agreement with the measurements from Maxted et al. (2011b) and Neveu-VanMalle et al. (2015). We also note that the measured radii and contrasts of the two spot events agree to within the (relatively large) errorbars.

The assumption that we have detected the same spot twice in two different positions on the stellar surface leads directly to a detection of a change of latitude and therefore a measurement of the sky-projected orbital obliquity of the system of \( \lambda = 6 \pm 11^\circ \). Neveu-VanMalle et al. (2015) used spectroscopy during a transit of WASP-41 to measure \( \lambda = 29.14^\circ \) with, and \( \lambda = 48.29^\circ \) without, a Bayesian prior on the projected rotational velocity. Our revised value is consistent with both to within 1.3\( \sigma \), removes the ambiguity due to choice of methodology, and also banishes the previous hints of orbital misalignment. WASP-41 is therefore another example of an aligned system containing a transiting hot Jupiter and a cool star with a precisely measured projected orbital obliquity.

### 6 TRANSIT TIMING ANALYSIS

Each of the transit light curves available for the four systems were fitted with the JKTEBOP code in order to determine the time of midpoint of the transit. We did not apply this analysis to light curves lacking complete coverage of a transit, as these give noisy and possibly biased values (e.g. Gibson et al. 2009). We also obtained the SuperWASP light curves, divided them into individual observing seasons, and fit each season separately to obtain a time of minimum close to the midpoint of the data. In the case of the SuperWASP data, which have a very high scatter compared to the follow-up light curves, we fixed the values of the photometric parameters to the best estimates obtained in Section 3 and thus fitted for only the time of midpoint and the out-of-transit brightness of the system. All measured transit times were moved to the TDB timescale.

We also included times of minimum for WASP-41 and WASP-55 from the Exoplanet Transit Database\(^8\) (Poddany et al. 2010), which provides data and transit times from amateur observers affiliated with TRESCA.\(^9\) We assumed that the times were on the UTC timescale and converted them to TDB.

For each object we fitted the times of mid-transit with straight lines to determine a new linear orbital ephemeris. Table 7 gives all transit times plus their residuals versus the fitted ephemeris. In cases where the \( \chi^2 \) was greater than 1.0 we scaled the uncertainties to give \( \chi^2 = 1.0 \). \( E \) gives the cycle count versus the reference epoch, and the bracketed numbers show the uncertainty in the final digit of the preceding number.

The new ephemeris for WASP-22 is based on eight timing measurements and is:

\[
T_0 = \text{BJD(TDB)} \times 2.455532.72776(22) + 3.53273064(70) \times E
\]

where the fit has \( \chi^2 = 1.46 \). The timebase of the ephemeris was chosen to be close to the weighted mean of the data and coincides with the transit observed simultaneously by the TRAPPIST and Euler telescopes. The most discrepant timing is the measurement from TRAPPIST data at cycle \( -4 \), which differs by 2.4\( \sigma \) from the timing predicted by the ephemeris. This is not sufficient grounds to reject the datapoint, so we did not do so. Instead, the errorbar for the ephemeris were multiplied by \( \sqrt{1.46} \) to account for the excess \( \chi^2 \).

For WASP-41 we have 19 timings and obtain the ephemeris:

\[
T_0 = \text{BJD(TDB)} \times 2.455996.67927(10) + 3.05240154(41) \times E
\]

with \( \chi^2 = 2.67 \). This is the largest \( \chi^2 \) among the four objects in this work, and occurs for the system with the most active host star. The errorbars of the ephemeris have been inflated to account for the excess \( \chi^2 \). The times of midpoint of the final two DFOSC transits were obtained using PRISM+GEMC, which agree with the midpoints obtained using JKTEBOP to within 0.00015 d. This is in line with expectations for the effects of spots (Barros et al. 2013; Oshagh et al. 2013; Ioannidis et al. 2015).

For WASP-42 there are three timings from data in the current work, five from published follow-up light curves and one from SuperWASP observations in the 2008 season. Whilst there are plenty of SuperWASP observations from 2006 and 2007, there is no coverage of transits due to the near-integer orbital period of the system. We find the ephemeris:

\[
T_0 = \text{BJD(TDB)} \times 2.455650.56728(15) + 4.9816819(11) \times E
\]

where \( \chi^2 = 1.35 \) and the errorbars have been inflated to account for this.

For WASP-55 we have 11 timings which yield this ephemeris:

\[
T_0 = \text{BJD(TDB)} \times 2.456416.71565(13) + 4.4656291(11) \times E
\]

with \( \chi^2 = 1.10 \) (accounted for in the errorbars).

Fig. 9 shows the residuals versus the linear ephemeris for each of our four targets. No transit timing variations are apparent, and there are too few timing measurements for a search for such variations to be useful. Our period values for all four systems are consistent with previous measurements but are significantly more precise due to the addition of new high-quality data and a longer temporal baseline.

### 7 SUMMARY AND CONCLUSIONS

WASP-22, WASP-41, WASP-42 and WASP-55 are four systems containing transiting hot Jupiters with large radii. We have presented high-precision photometry of 13 transits of the four systems, and used these data to refine their measured orbital ephemerides and physical properties. We find no evidence for transit timing variations in any of the systems, and our new measurements of the system properties are mostly in good agreement with previous determinations based on fewer and less precise data.

All four planets have inexplicably larger radii than expected from theoretical models (Bodenheimer et al. 2003; Fortney et al. 2007; Baraffe et al. 2008). Fig. 10 compares the positions of the four planets in the mass–radius diagram to the overall sample of planets\(^10\) and to predictions from Bodenheimer et al. (2003) for planetary equilibrium temperatures similar to those for the four planets which are the subject of the current work. Whilst WASP-22 b is well represented by models without a heavy-element core, the other three planets are significantly larger than predicted even for coreless gas giants. For comparison, Fig. 11 shows the same mass–radius diagram but with the predictions of the Baraffe et al.

---

\(^8\) The Exoplanet Transit Database (ETD) can be found at: [http://var2.astro.cz/ETD/credit.php](http://var2.astro.cz/ETD/credit.php)


\(^10\) Data on planetary systems were taken from TEPCat on 2015/11/09. Figs. 10 and 11 show only those planets regarded as “well-studied”, i.e. excluding those planets which have been characterised only as part of a large sample of such systems.
expected, particularly WASP-55, and are therefore good candidates for the characterisation of their atmospheres via transmission spectroscopy and photometry (e.g. Nikolov et al. 2014; Mallonn et al. 2015).

Two of our transit light curves of WASP-41 show clear evidence for spot activity, with one spot crossing event observed on 2015/05/13 and two on 2015/05/17. We make the assumption that the spot observed on 2015/05/13 is the same as the second spot observed on 2015/05/17, as the measured spot radii and contrasts agree, and the resulting stellar rotation period and velocity are highly consistent with previous measurements obtained using different methods. The change in longitude of the spot then gives a

Table 7. Times of minimum light and their residuals versus the ephemerides derived in this work.

<table>
<thead>
<tr>
<th>Target</th>
<th>Time of minimum (BJD/TDB)</th>
<th>Uncertainty (d)</th>
<th>Cycle number</th>
<th>Residual (d)</th>
<th>Reference</th>
</tr>
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<tr>
<td>WASP-22</td>
<td>2454041.91397</td>
<td>0.00122</td>
<td>-422.0</td>
<td>-0.00146</td>
<td>This work (SuperWASP 2006)</td>
</tr>
<tr>
<td>WASP-22</td>
<td>2454409.31798</td>
<td>0.00078</td>
<td>-318.0</td>
<td>-0.00143</td>
<td>This work (SuperWASP 2007)</td>
</tr>
<tr>
<td>WASP-22</td>
<td>2455518.85761</td>
<td>0.00059</td>
<td>-4.0</td>
<td>0.00167</td>
<td>This work (TRAPPIST)</td>
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<td>WASP-22</td>
<td>2455532.72730</td>
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<td>0.0</td>
<td>-0.00046</td>
<td>This work (Euler)</td>
</tr>
<tr>
<td>WASP-22</td>
<td>2455532.72761</td>
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<td>0.0</td>
<td>-0.00015</td>
<td>This work (TRAPPIST)</td>
</tr>
<tr>
<td>WASP-22</td>
<td>2455896.60029</td>
<td>0.00081</td>
<td>103.0</td>
<td>0.00128</td>
<td>This work (84 cm)</td>
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<tr>
<td>WASP-22</td>
<td>2456189.81595</td>
<td>0.00022</td>
<td>186.0</td>
<td>0.00029</td>
<td>This work (Danish)</td>
</tr>
<tr>
<td>WASP-22</td>
<td>2456560.75224</td>
<td>0.00029</td>
<td>291.0</td>
<td>-0.00014</td>
<td>This work (Danish)</td>
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<td>WASP-22</td>
<td>2457270.83104</td>
<td>0.00022</td>
<td>492.0</td>
<td>-0.00020</td>
<td>This work (Danish)</td>
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</tbody>
</table>

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stellar rotation period of $18.6 \pm 1.5$ d and $v \sin i$ of $2.4 \pm 0.2$ km s$^{-1}$, both at a latitude of approximately $12^\circ$. The change in latitude yields a measurement of the sky-projected orbital obliquity of the system of $\lambda = 6 \pm 11^\circ$, which is significantly more precise than a previous measurement obtained via the Rossiter-McLaughlin effect.

Spectroscopic measurements of $\lambda$ are notoriously difficult for cool stars because the amplitude of the Rossiter-McLaughlin effect depends on the $v \sin i$ of the host star, which is typically very low below $T_{\text{eff}}$ values of roughly 5500 K. Starspot tracking is a major contributor in this domain, with a total of nine determinations to date (Table 8 and Fig. 12). The host stars have $T_{\text{eff}}$ values...
Table 8. Published measurements of the sky-projected, $\lambda$, and true, $\psi$, orbital obliquities obtained from spot-tracking analyses.

<table>
<thead>
<tr>
<th>System</th>
<th>Host star $T_{\text{eff}}$ (K)</th>
<th>$\lambda$ ($^\circ$)</th>
<th>$\psi$ ($^\circ$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAT-P-11</td>
<td>4780 ± 50</td>
<td>$105^{+12}<em>{-11}$ or $121^{+24}</em>{-21}$</td>
<td>$97^{+4}_{-4}$</td>
<td>Sanchis-Ojeda &amp; Winn (2011)</td>
</tr>
<tr>
<td>HATS-02</td>
<td>5227 ± 95</td>
<td>8 ± 8</td>
<td></td>
<td>Mohler-Fischer et al. (2013)</td>
</tr>
<tr>
<td>Kepler-30</td>
<td>5498 ± 54</td>
<td>$-1 \pm 10$ or $4 \pm 10$</td>
<td></td>
<td>Sanchis-Ojeda et al. (2012)</td>
</tr>
<tr>
<td>Kepler-63</td>
<td>5576 ± 50</td>
<td>$-110^{+22}_{-14}$</td>
<td>$145^{+9}_{-14}$</td>
<td>Sanchis-Ojeda et al. (2013)</td>
</tr>
<tr>
<td>Qatar-2</td>
<td>4645 ± 50</td>
<td>4.3 ± 4.5</td>
<td></td>
<td>Mancini et al. (2014)</td>
</tr>
<tr>
<td>WASP-4</td>
<td>5540 ± 55</td>
<td>$-1^{+14}_{-14}$</td>
<td></td>
<td>Sanchis-Ojeda et al. (2011)</td>
</tr>
<tr>
<td>WASP-6</td>
<td>5375 ± 65</td>
<td>7.2 ± 3.7</td>
<td></td>
<td>Tregloan-Reed et al. (2015)</td>
</tr>
<tr>
<td>WASP-19</td>
<td>5460 ± 90</td>
<td>1.0 ± 1.2</td>
<td></td>
<td>Tregloan-Reed et al. (2013)</td>
</tr>
<tr>
<td>WASP-41</td>
<td>5546 ± 33</td>
<td>6 ± 11</td>
<td></td>
<td>This work</td>
</tr>
</tbody>
</table>

Figure 10. Plot of planet radii versus their masses. WASP-22b, WASP-41b, WASP-42b and WASP-55b are indicated using black filled circles. The overall population of planets is shown using blue open circles without errorbars, using data taken from TEPcat on 2015/11/09. The lines show the predicted planet radius of gas-giants from Bodenheimer et al. (2003, their table 1) for two different equilibrium temperatures (1000 K and 1500 K) which bracket the four planets, and for with and without a solid 20 M$_\oplus$ core (see key).

Figure 11. As Fig. 10 but with different theoretical predictions. The lines show the predicted planet radii of gas-giants from Baraffe et al. (2008, their table 4) for four different heavy-element mass fractions $Z$, labelled on the plot. The unbroken lines show predictions for a planet of age 0.5 Gyr, the dashed lines for an age of 1 Gyr and the dotted lines for an age of 5 Gyr. The lines are colour-coded for clarity.

http://www.astro.keele.ac.uk/jkt/. We thank Laetitia Delrez and Marion Neveu-VanMalle for providing published light curves of WASP-41. JSouthworth acknowledges financial support from the Leverhulme Trust in the form of a Philip Leverhulme Prize. JTR acknowledges financial support from ORAU (Oak Ridge Associated Universities) and NASA in the form of a NASA Post-Doctoral Programme (NPP) Fellowship. DFE is funded by the UK’s Science and Technology Facilities Council. EU-S acknowledges the support of CONICYT QUIMAL 130004 project. Funding for the Stellar Astrophysics Centre in Aarhus is provided by The Danish National Research Foundation (grant agreement no. DNRF106). The research is supported by the ASTERISK project (ASTERoseismic Investigations with SONG and Kepler) funded by the European Research Council (grant agreement no. 267864). TCH acknowledges KASI research grants #2012-1-410-02, #2013-9-400-00, #2014-1-400-06 and #2015-1-850-04. NP acknowledges funding by the Gemini-Conicyt Fund, allocated to project No. 32120036. GD acknowledges Regione
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