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WASP-39b: a highly inflated Saturn-mass planet orbiting a late G-type star

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ABSTRACT

We present the discovery of WASP-39b, a highly inflated transiting Saturn-mass planet orbiting a late G-type dwarf star with a period of 4.055259 ± 0.000008 d. Transit Epoch \( T_0 = 2455342.9688 ± 0.0002 \) (HJD), of duration 0.1168 ± 0.0008 d. A combined analysis of the WASP photometry, high-precision follow-up transit photometry, and radial velocities yield a planetary mass of \( M_\text{pl} = 0.28 \pm 0.03 M_\oplus \) and a radius of \( R_\text{pl} = 1.27 \pm 0.04 R_\oplus \), resulting in a mean density of 0.14 ± 0.02 \( \rho_\oplus \). The stellar parameters are mass \( M_\star = 0.93 \pm 0.03 M_\odot \), radius \( R_\star = 0.895 \pm 0.023 R_\odot \), and age 9 ± 2 Gyr. Only WASP-17b and WASP-31b have lower densities than WASP-39b, although they are slightly more massive and highly irradiated planets. From our spectral analysis, the metallicity of WASP-39 is measured to be [Fe/H] = −0.12 ± 0.1 dex, and we find the planet to have an equilibrium temperature of 1116 ± 53 K. Both values strengthen the observed empirical correlation between these parameters and the planetary radius for the known transiting Saturn-mass planets.

Key words. stars: individual: WASP-39 – techniques: photometric – techniques: radial velocities – planetary systems

1. Introduction

The importance of transiting exoplanets is based on their geometrical configuration (Sackett 1999). Transit geometry severely constrains the orbital inclination of the planet, allowing accurate measurements of its mass and radius to be derived. The inferred planet’s density provides information on the system’s bulk physical properties, and thus is a fundamental parameter for constraining theoretical models of planetary formation, structure, and evolution (e.g. Guillot 2005; Fortney et al. 2007; Liu et al. 2008).

To date, more than 100 transiting planets have been discovered, which show a huge range of diversity in their physical and dynamical properties. For example, their mass ranges from \( \sim 5 M_\oplus \) (Kepler-10b, Batalha et al. 2011) to about 12 M\(_\oplus\) (XO-3b, Johns-Krull et al. 2008; Hébrard et al. 2008). Some planets have radii that agree with models of irradiated planets (Burrows et al. 2007; Fortney et al. 2007), while others are found to be anomalously large (e.g. WASP-12b, Hebber et al. 2009, and TrES-4b, Southworth 2010; Torres et al. 2008; Mandushev et al. 2007). The diversity in exoplanet densities, hence in their internal compositions, is particularly noticeable at sub-Jupiter masses. For example, some exoplanets have very high densities and are thought to have a rocky/ice core (e.g. HD 149026b, \( \rho_\oplus = 1 \rho_\oplus \), Sato et al. 2005), while systems such as TrES-4b (\( \rho_\oplus = 0.17 \rho_\oplus \), Mandushev et al. 2007), WASP-17b (\( \rho_\oplus = 0.06 \rho_\oplus \), Anderson et al. 2010a, 2011b), WASP-31b (\( \rho_\oplus = 0.132 \rho_\oplus \), Anderson et al. 2010a), and Kepler-7b (\( \rho_\oplus = 0.13 \rho_\oplus \), Latham et al. 2010) are examples of planets with puzzlingly low densities that challenge standard evolutionary theories in reproducing their radii (Fortney et al. 2007; Burrows et al. 2007). To assess the inflation status of a system, generally planetary radii are compared to...
tabulated values from models (e.g. Fortney et al. 2007; Burrows et al. 2008). However, the radius depends on multiple physical properties, such as the stellar age, the irradiation flux, the planet’s mass and age, the atmospheric composition, the presence of heavy elements in the envelope or in the core, the atmospheric circulation, and also on any source generating extra heating in the planetary interior. Different mechanisms have been proposed to explain the anomalously large radii, such as tidal heating due to unseen companions pushing up the eccentricity (Bodenheimer et al. 2001, 2003), kinetic heating due to the breaking of atmospheric waves (Guillot & Showman 2002), enhanced atmospheric opacity (Burrows et al. 2007) and semi-conviction (Chabrier & Baraffe 2007). While each individual mechanism would presumably affect all hot Jupiters to some degree, they cannot explain the entirety of the observed radii (Fortney & Nettelmann 2010; Baraffe et al. 2010). More complex thermal evolution models are necessary to fully understand their cooling history. For these planets, the dominant source of energy is a function of the orbital separation and the spectral type of the host star, while its dependency on the planetary mass and age is negligible (with the exception of very young planets). More recently, Batygin et al. (2011) performed calculations of the thermal evolution of gas giants and suggest that the extra energy needed to explain the radius inflation comes from stellar irradiation (see also Laughlin et al. 2011). The proposed mechanism (Ohmic heating), based on the interaction of ionised alkali metals in the planetary atmosphere with the planet’s magnetic field, along with the atmospheric heavy element content, could provide a universal explanation of the currently measured radius anomalies.

Although the majority of the known exoplanets are short-period, Jupiter-mass planets, more recently an increasing number of Saturn-like planets have been discovered (e.g. Enoch et al. 2011), and have encouraged studies of planetary properties and their statistical analysis, searching for possible correlations between planetary parameters (e.g. Enoch et al. 2011; Anderson et al. 2010a; Hartman et al. 2011). To date, 27 transiting planets have been discovered with masses in the range 0.15 < M_J < 0.6M_J, similar to Saturn (M_Saturn = 0.229 M_J, Standish 1995). The detection and characterisation of significantly more bright short-period transiting systems is one of the keys to improving our understanding of planetary structure and evolution.

Here we describe the properties of WASP-39b, a new transiting Saturn-mass planet discovered by the SuperWASP survey. The planet host star WASP-39 belongs to the constellation of Virgo and thus resides in an equatorial region of sky, which is monitored by the SuperWASP-North and Super-WASP-South telescopes simultaneously. WASP-39 is the third least dense planet (ρ_pl = 0.14 ± 0.02 ρ_J) discovered from a ground-based transit survey, and belongs to the sample of highly inflated gas giant planets. It provides observational evidence for the mass-radius relation of planetary systems in a poorly sampled region of the parameter space.

We present follow-up observations of the new system which establish the planetary nature of the transiting object detected by SuperWASP. High precision, high signal-to-noise light-curves have been obtained using both the Faulkes Telescope North (FTN), and the Euler telescope, and radial velocity measurements using the SOPHIE (1.93-m OHP) and CORALIE (Swiss 1.2-m) spectrographs.

### Table 1. Photometric properties of WASP-39.

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<thead>
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<th>Parameter</th>
<th>WASP-39</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA(J2000)</td>
<td>14:29:18.42</td>
</tr>
<tr>
<td>Dec(J2000)</td>
<td>−03:26:40.1</td>
</tr>
<tr>
<td>B</td>
<td>12.93 ± 0.25</td>
</tr>
<tr>
<td>V</td>
<td>12.11 ± 0.13</td>
</tr>
<tr>
<td>I</td>
<td>11.34 ± 0.08</td>
</tr>
<tr>
<td>J</td>
<td>10.663 ± 0.024</td>
</tr>
<tr>
<td>H</td>
<td>10.307 ± 0.023</td>
</tr>
<tr>
<td>K</td>
<td>10.202 ± 0.023</td>
</tr>
<tr>
<td>μx,(mas/yr)</td>
<td>−12.2 ± 3.3</td>
</tr>
<tr>
<td>μy,(mas/yr)</td>
<td>2.8 ± 3.5</td>
</tr>
</tbody>
</table>

Notes. The broad band magnitudes and proper motion are obtained from the NOMAD 1.0 catalogue.

The paper is structured as follows: in Sect. 2 we describe the observations, including the WASP discovery data and the photometric and spectroscopic follow-up. In Sect. 3 we present our results for the derived systems parameters, and the stellar and planetary properties. Finally, we discuss the implication of the discovery of WASP-39b in Sect. 4.

### 2. Observations

1SWASP J142918.42-032640.1 (2MASS 14291840-0326403), hereafter WASP-39, has been identified in several northern sky catalogues which provide broad-band optical (Zacharias et al. 2005) and infra-red 2MASS magnitudes (Skrutskie et al. 2006) as well as proper motion information. Coordinates, broad-band magnitudes, and proper motion of the star are from the NOMAD catalogue and are given in Table 1.

#### 2.1. SuperWASP observations

The WASP North and South telescopes are located in La Palma (ING – Canaries Islands) and Sutherland (SAAO – South Africa), respectively. Each telescope consists of 8 Canon 200 mm f/1.8 focal lenses coupled to e2v 2048 × 2048 pixel CCDs, yielding a field-of-view of 7.8 × 7.8 square degrees with a pixel scale of 13.7″ (Pollacco et al. 2006).

WASP-39 is a V = 12.11 star located in an equatorial region of sky monitored by both WASP instruments, significantly increasing the observing coverage on the target. In January 2009, the SuperWASP-N telescope underwent a system upgrade that improved our control over the main sources of red noise, such as temperature-dependent focus changes (Barros et al. 2011). This upgrade yielded data of unprecedented high quality, and increased the number of planet candidates, flagged in the archive, in particular those with longer period and lower mass (e.g. WASP-38b, Barros et al. 2011; and WASP-39b).

WASP-39 was routinely observed between 2006 July 1 to 2010 July 26, with a total of 11 WASP fields and 40531 photometric points. Over the five WASP seasons only three points were taken in 2006 and none during 2007. However, the same field was observed again in 2008, 2009 and 2010 after both WASP telescopes began observing an overlapping equatorial region.

All data were processed with a custom-built reduction pipeline described in Pollacco et al. (2006). The resulting light curves were analysed using our implementation of the Box Least-Squares and SysRem detrending algorithms (see Collier Cameron et al. 2006; Kovács et al. 2002; Tamuz et al. 2005),

1 http://exoplanet.eu/


2.2. Spectroscopic follow-up

WASP-39 was first observed during our follow-up campaign in April 2010 at Observatoire de Haute-Provence (OHP). During our program we have obtained follow-up spectroscopy and established the planetary nature of WASP-39b together with three additional systems: WASP-37b (Simpson et al. 2011), WASP-38b (Barros et al. 2011) and WASP-40b (Anderson et al. 2011a). Between 2010 April 8 and June 11, we observed eight radial velocity measurements for WASP-39 using SOPHIE, the fiber-fed echelle spectrograph mounted on the 1.93-m telescope at the OHP (Perruchot et al. 2008; Bouchy et al. 2009). We used SOPHIE in high efficiency mode ($R = 40000$) and obtained observations with very similar signal-to-noise ratio ($\sim 30$), to minimise systematic errors arising from the known Charge Transfer Inefficiency effect of the CCD (Bouchy et al. 2009), although this is now corrected by the data reduction software. Wavelength calibration with a Thorium-Argon lamp were performed every $\sim 2$ h, allowing the interpolation of the spectral drift of SOPHIE ($< 3$ m s$^{-1}$ per hour; see Boisse et al. 2010). Two 3" diameter optical fibres were used, the first centred on the target and the second on the sky to simultaneously measure the background to remove contamination from scattered moonlight. During our observations the contribution from scattered moonlight was negligible as it was well shifted from the target’s radial velocity. Nine additional radial velocity measurements were obtained using the CORALIE spectrograph mounted on the 1.2-m Euler Swiss telescope at La Silla, Chile (Baranne et al. 1996; Queloz et al. 2000; Pepe et al. 2002). Observations were obtained with a signal-to-noise of $\sim 30$, during grey/dark time to minimise moonlight contamination. The data were processed with the SOPHIE and CORALIE standard data reduction pipelines, respectively. Radial velocity uncertainties were evaluated, including known systematics such as guiding and centring errors (Boisse et al. 2010), and wavelength calibration uncertainties. All spectra were single-lined.

We computed the radial velocities from a weighted cross-correlation of each spectrum with a numerical mask of spectral type G2, as described in Baranne et al. (1996) and Pepe et al. (2002). The cross-correlation with masks of different spectral types (F0, K5 and M5) produced similar radial velocity variations, rejecting a blended eclipsing system of stars with unequal masses as a possible cause of the variation. Radial velocity measurements and line bisector ($V_{\text{span}}$) are given in Table 2, and plotted with the best-fit Keplerian model in Fig. 2. SOPHIE data are plotted as filled circles and CORALIE data as open squares, and both data sets are offset with respect to the radial velocity zero point, $y_{\text{SOPHIE}}$ and $y_{\text{CORALIE}}$, respectively (see Table 4). No significant correlation is observed between the radial velocity and the line bisector, suggesting the signal’s origin as planetary rather than due to a blended eclipsing binary system or to stellar activity (see Queloz et al. 2001). The rms for SOPHIE and CORALIE radial velocity residuals to the best-fit model are $\text{rms}_{\text{SOPHIE}} = 26$ m s$^{-1}$ and $\text{rms}_{\text{CORALIE}} = 16$ m s$^{-1}$, with the higher rms value of the SOPHIE measurements dominating by two discrepant measurements, $RV_1 = 48$ m s$^{-1}$ and $RV_2 = 43$ m s$^{-1}$. Eliminating the most discrepant of these, the $\text{rms}_{\text{SOPHIE}}$ becomes $19$ m s$^{-1}$, comparable to that of CORALIE. We also plot in Fig. 3 the bisector span measurements as a function of time; and lower panel, the residuals from the RV orbital fit against time. The bisector span values are shifted to a zero mean ($\langle V_{\text{span}} \rangle_{\text{SOPHIE}} = -0.032$ km s$^{-1}$, $\langle V_{\text{span}} \rangle_{\text{CORALIE}} = -0.051$ km s$^{-1}$), to better compare the two data sets.

2.3. Photometric follow-up

To allow more accurate light curve modelling and thus refine the photometric parameters, we obtained two high signal-to-noise transit light curves of WASP-39b. All photometric data...
Fig. 2. Upper panel: phase folded radial velocity measurements of WASP-39 obtained combining data from SOPHIE (filled-circles) and CORALIE (open-squares) spectrographs. Superimposed is the best-fit model RV curve with parameters from Table 4. The centre-of-mass velocity for each data set was subtracted from the RVs ($\gamma_{\text{SOPHIE}} = -58.4826$ km s$^{-1}$ and $\gamma_{\text{CORALIE}} = -58.4708$ km s$^{-1}$). Lower panel: we show the bisector span measurements as a function of radial velocity, values are shifted to a zero-mean ($\langle V_{\text{span}} \rangle_{\text{SOPHIE}} = -0.032$ km s$^{-1}$, $\langle V_{\text{span}} \rangle_{\text{CORALIE}} = -0.051$ km s$^{-1}$). The bisector span shows no significant variation nor correlation with the RVs, suggesting that the signal is mainly due to Doppler shifts of the stellar lines rather than stellar profile variations due to stellar activity or a blended eclipsing binary.

Fig. 3. Upper panel: the bisector span measurements as a function of time (BJD–2450000.0), $V_{\text{span}}$ values are shifted to a zero-mean as in Fig. 2. Lower panel: residuals from the RV orbital fit plotted against time.

3. Results

3.1. Stellar parameters

A total of nine individual CORALIE spectra of WASP-39 were co-added to produce a single spectrum with a typical $S/N$ ratio of around 50. The standard pipeline reduction products were used in the analysis. To improve the line profile fitting for equivalent width measurements, the spectrum was smoothed using a 2

http://nsted.ipac.caltech.edu

http://lcogt.net

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Fig. 4. FTN $z$-band and Euler $r$-band follow-up high signal-to-noise photometry of WASP-39b during the transit. The Euler light curve has been offsetted from zero by an arbitrary amount for clarity. The data are phase-folded on the ephemeris from Table 4. Superposed (black-solid line) is the best-fit transit model estimated using the formalism from Mandel & Agol (2002). Residuals from the fit are displayed underneath.

Table 3. Stellar parameters of WASP-39 from spectroscopic analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{eff}}$</td>
<td>5400 ± 150 K</td>
</tr>
<tr>
<td>log $g$</td>
<td>4.4 ± 0.2</td>
</tr>
<tr>
<td>$\xi$</td>
<td>0.9 ± 0.2 km s$^{-1}$</td>
</tr>
<tr>
<td>$v \sin i^*$</td>
<td>1.4 ± 0.6 km s$^{-1}$</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>-0.12 ± 0.10</td>
</tr>
<tr>
<td>[Na/H]</td>
<td>-0.04 ± 0.10</td>
</tr>
<tr>
<td>[Mg/H]</td>
<td>0.06 ± 0.11</td>
</tr>
<tr>
<td>[Al/H]</td>
<td>0.01 ± 0.08</td>
</tr>
<tr>
<td>[Si/H]</td>
<td>0.04 ± 0.08</td>
</tr>
<tr>
<td>[Ca/H]</td>
<td>0.01 ± 0.14</td>
</tr>
<tr>
<td>[Sc/H]</td>
<td>0.02 ± 0.19</td>
</tr>
<tr>
<td>[Ti/H]</td>
<td>-0.03 ± 0.10</td>
</tr>
<tr>
<td>[V/H]</td>
<td>-0.08 ± 0.17</td>
</tr>
<tr>
<td>[Cr/H]</td>
<td>-0.07 ± 0.10</td>
</tr>
<tr>
<td>[Mn/H]</td>
<td>-0.03 ± 0.20</td>
</tr>
<tr>
<td>[Ni/H]</td>
<td>-0.10 ± 0.12</td>
</tr>
<tr>
<td>log A(Li)</td>
<td>&lt;0.9</td>
</tr>
<tr>
<td>Mass</td>
<td>0.93 ± 0.09 $M_\odot$</td>
</tr>
<tr>
<td>Radius</td>
<td>1.00 ± 0.25 $R_\odot$</td>
</tr>
<tr>
<td>Sp. Type</td>
<td>G8</td>
</tr>
<tr>
<td>Distance</td>
<td>230 ± 80 pc</td>
</tr>
</tbody>
</table>


Gaussian width $\sigma = 0.05$ Å. For the $v \sin i^*$ determination the unsmoothed spectrum was used.

Our analysis was performed using the methods given in Gillon et al. (2009). The H$_\alpha$ line was used to determine the effective temperature ($T_{\text{eff}}$), while the Na i D and Mg i b lines were used as surface gravity (log $g$) diagnostics. The atmospheric parameters obtained from the analysis are listed in Table 3. The elemental abundances were determined from equivalent width measurements of several clean and unblended lines. A value for microturbulence ($\xi$) was determined from the Fe i lines using the method of Magain (1984). Quoted error estimates include those given by the uncertainties in $T_{\text{eff}}$, log $g$ and $\xi$, as well as the scatter due to measurement and atomic data uncertainties.

The projected stellar rotation velocity ($v \sin i^*$) was determined by fitting the profiles of several unblended Fe i lines. A value for macroturbulence ($v_{\text{mac}}$) of 2.1 ± 0.3 km s$^{-1}$ was assumed, based on the tabulation by Gray (2008) and an instrumental FWHM of 0.11 ± 0.01 Å, determined from the telluric lines around 6300 Å. A best-fitting value of $v \sin i^* = 1.4 ± 0.6$ km s$^{-1}$ was obtained. The stellar mass $M_\star$ and radius $R_\star$ were estimated using the calibration of Torres et al. (2010).

The non-detection of lithium in the spectrum, the low rotation rate implied by the $v \sin i^*$ and lack of stellar activity (shown by the absence of Ca ii H and K emission) all indicate that the star is relatively old. Unfortunately, the gyrochronological age estimate from the Barnes (2007) relation ($\sim 5 \pm 2$ Gyr) can only provide a weak constraint on the age of WASP-39.

The stellar density of $\rho_\star = 1.297^{+0.080}_{-0.054} \rho_\odot$ obtained from the MCMC analysis was used together with the stellar temperature and metallicity values, derived from spectroscopy, in an interpolation of the Yonsei-Yale stellar evolution tracks (Demarque et al. 2004), as shown in Fig. 5. Using the best-fit metallicity of [Fe/H] = −0.12, we obtain a mass for WASP-39 of 0.86 ± 0.05 $M_\odot$ and a stellar age of 9±3 Gyr, in agreement with the gyrochronological age and a more accurate estimate. The mass obtained from the YY-isochrone fit is somewhat less than the value from the Torres et al. (2010) calibration (as was also found in the analysis of WASP-37 stellar parameters; Simpson et al. 2011), but their 1-$\sigma$ errors overlap.
3.2. Planetary parameters

The planetary properties were determined using a simultaneous Markov-Chain Monte Carlo (MCMC) analysis including the WASP photometry, the follow-up FTN and Euler photometry, together with SOPHIE and CORALIE radial velocity measurements. A detailed description of the method is given in Collier Cameron et al. (2007) and Pollacco et al. (2008). The parameters we used in the fit are: the epoch of mid-transit $T_0$, the orbital period $P$, the fractional change of flow proportional to the ratio of stellar to planet surface areas $\Delta F = R_\text{pl}^2/R_\star^2$, the transit duration $T_{14}$, the impact parameter $b$, the radial velocity semi-amplitude $K_1$, the stellar effective temperature $T_{\text{eff}}$, metallicity [Fe/H], the Lagrangian elements $\sqrt{e} \cos \omega$ and $\sqrt{e} \sin \omega$ (where $e$ is the eccentricity and $\omega$ the longitude of periastron), and the systematic offset velocity $\gamma$. In this particular case we fitted the 2 systematic velocities $\gamma_{\text{SOPHIE}}$ and $\gamma_{\text{CORALIE}}$ to allow for instrumental offsets between the two datasets.

Four different sets of solutions were considered: with and without the main-sequence mass-radius constraint in the case of circular orbits and orbits with floating eccentricity. For each solution we have included a linear trend in the systemic velocity, as without the main-sequence mass-radius constraint in the case of circular orbits and orbits with floating eccentricity. For each so-

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>Value</th>
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<tbody>
<tr>
<td>$P$ (d)</td>
<td>4.055259 ± 0.000009</td>
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<tr>
<td>$T_0$ (HJD)</td>
<td>2455 342.9688 ± 0.0002</td>
</tr>
<tr>
<td>$T_{14}$ (d$^+$)</td>
<td>0.1168 ± 0.0008</td>
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<tr>
<td>$T_{12} = T_{14}$ (d)</td>
<td>0.0179 ± 0.0009</td>
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<tr>
<td>$\Delta F = R_\text{pl}^2/R_\star^2$</td>
<td>0.0211 ± 0.0003</td>
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<tr>
<td>$b$</td>
<td>0.441 ± 0.036</td>
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<tr>
<td>$i$ (°)</td>
<td>87.83 ± 0.25</td>
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<tr>
<td>$K_1$ (m.s$^{-1}$)</td>
<td>38 ± 4</td>
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<tr>
<td>$\gamma_{\text{SOPHIE}}$ (km s$^{-1}$)</td>
<td>−58.4826 ± 0.0004</td>
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<tr>
<td>$\gamma_{\text{CORALIE}}$ (km s$^{-1}$)</td>
<td>−58.4708 ± 0.0004</td>
</tr>
<tr>
<td>$e$</td>
<td>0 (fixed)</td>
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<tr>
<td>$M_\star$ ($M_\odot$)</td>
<td>0.93 ± 0.03</td>
</tr>
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<td>$R_\star$ ($R_\odot$)</td>
<td>0.895 ± 0.023</td>
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</tr>
<tr>
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<tr>
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<tr>
<td>$\log q_\text{pl}$ (cgs)</td>
<td>2.610 ± 0.047</td>
</tr>
<tr>
<td>$\rho_\text{pl}$ ($\rho_\oplus$)</td>
<td>0.14 ± 0.02</td>
</tr>
<tr>
<td>$a$ (AU)</td>
<td>0.0486 ± 0.0005</td>
</tr>
<tr>
<td>$T_{\text{pl},A=0}$ (K)</td>
<td>1116 ± 2</td>
</tr>
</tbody>
</table>

Notes. $\Delta F$ is the eccentricity and $\omega$ the longitude of periastron. $a$ is the semi-major axis of the orbit. $P$ is the orbital period. $M_\text{pl}$ is the planetary mass. $R_\star$ is the stellar radius. $R_\text{pl}$ is the planetary radius. $\rho_\star$ and $\rho_\text{pl}$ are the stellar and planetary densities, respectively. $g_\star$ is the stellar gravity. $q_\text{pl}$ is the mass ratio of the planet to the star. $e$ is the eccentricity of the orbit. $i$ is the inclination of the orbit. $K_1$ is the radial velocity semi-amplitude. $\gamma$ is the offset velocity. $T_{\text{eff}}$ is the effective temperature. $T_{\text{pl}}$ is the planetary temperature.

4. Discussion

We report the discovery of a new transiting extrasolar planet, WASP-39b. A simultaneous fit to transit photometry and radial velocity measurements gives a planetary mass of 0.28 ± 0.03 $M_\oplus$ and a radius of 1.27 ± 0.040 $R_\oplus$ which yields a planetary density of 0.141 ± 0.02 $\rho_\oplus$. Thus, WASP-39b is the third least dense planet identified by a ground-based transit survey. Only WASP-17b (Anderson et al. 2010b, $\rho_{\text{W17}} = 0.06 \rho_\oplus$), and WASP-31b ($\rho_{\text{W31}} = 0.13 \rho_\oplus$, Anderson et al. 2010a) have lower densities. However, they are slightly more massive planets ($M_{\text{W17}} = 0.49 M_\oplus$ and $M_{\text{W31}} = 0.48 M_\oplus$), but highly irradiated, with larger and hotter host stars (Anderson et al. 2010b,a). This implies higher planet equilibrium temperatures for WASP-17b and WASP-31b compared to WASP-39b. We find WASP-39b to have a highly inflated radius ($R_\text{pl} = 1.27 R_\oplus$), more than 20% larger than the $R_\text{pl}$ obtained by comparison with the Fortney et al. (2007) and the Baraffe et al. (2008) models for a coreless planet of a similar mass, orbital distance and stellar age. For example, tables presented in Fortney et al. (2007) predict a maximum radius of ~1.05 $R_\oplus$ for a 0.24 $M_\odot$ planet orbiting at 0.045 AU from a 4.5 Gyr solar-type star. In addition, WASP-39 is smaller, cooler and probably older than the Sun. Thus, a radius of 1.27 $R_\oplus$ is clearly too large for these models. The fact that we do not detect any eccentricity, and that the age of WASP-39b’s host star is ~9 Gyr, suggests that it is unlikely that recent tidal circularisation and dissipation could be a cause of the large radius of WASP-39b (Leconte et al. 2010; Hansen 2010). The low metallicity ([Fe/H] = −0.12 ± 0.1) of the WASP-39b host star supports the expected low planetary core-mass. However, this will only marginally explain the highly inflated radius of WASP-39b. Hence, this leads to the hypothesis that some additional physics is at play (Fortney et al. 2010). An interior heat source, replacing the radiated heat from gravitational contraction, is needed for the planet to reach thermal equilibrium with a larger radius than theoretically expected. The Ohmic heating mechanism (Batygin et al. 2011), based on the electro-magnetic interaction between atmospheric winds and the planet’s magnetic field, is able to explain the anomalous sizes of close-in transiting planets. WASP-39b has a low equilibrium temperature ($T_{\text{pl},A=0} = 1116$ K) and thus appears to belong to the “pL” class of planets from Fortney et al. (2008). We note that, with the measured planetary parameters (mass, radius, $T_{\text{eq}}$), WASP-39b agrees with the coreless models in Fig. 4 of Batygin et al. (2011).

Of the known transiting systems, WASP-39b joins an increasing number of recently discovered exoplanets with Saturn-like masses. With an increasingly large sample of well-characterised systems, we can begin to make statistical inferences as to the physical reasons behind their diverse nature. Enoch et al. (2011) and Anderson et al. (in prep.), show that the radii of known low-mass (0.15–0.6 $M_\odot$) giant planets strongly...
correlate with equilibrium temperature and host-star metallicity. We have investigated how WASP-39b relates to the rest of the sample of Saturn-mass planets. We calculated the radius anomaly $R = R_{\text{obs}} - R_{\text{eq}}$ versus equilibrium temperature for the known Saturn-mass planets. Lower panel: $R$ as function of the stellar metallicity $[\text{Fe/H}]$ in dex. WASP-39b is indicated with a filled circle.

References

Collier Cameron, A., Pollacco, D., Street, R. A., et al. 2006, MNras, 373, 799

Fig. 6. Upper panel: the radius anomaly $R = R_{\text{obs}} - R_{\text{eq}}$ versus equilibrium temperature for the known Saturn-mass planets. Lower panel: $R$ as function of the stellar metallicity $[\text{Fe/H}]$ in dex. WASP-39b is indicated with a filled circle.
Standish, E. M. 1995, Highlights of Astronomy, 10, 180
Torres, G., Andersen, J., & Giménez, A. 2010, A&ARv, 18, 67
Zacharias, N., Monet, D. G., Levine, S. E., et al. 2005, VizieR Online Data Catalog, 1297, 0