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WASP-29b: A SATURN-SIZED TRANSITING EXOPLANET

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ABSTRACT

We report the discovery of a Saturn-sized planet transiting a $V = 11.3$, K4 dwarf star every 3.9 days. WASP-29b has a mass of $0.24 \pm 0.02\ M_{\rm Jup}$ and a radius of $0.79 \pm 0.05\ R_{\rm Jup}$, making it the smallest planet so far discovered by the WASP survey, and the exoplanet most similar in mass and radius to Saturn. The host star WASP-29 has an above-solar metallicity and fits a possible correlation for Saturn-mass planets such that planets with higher-metallicity host stars have higher core masses and thus smaller radii.

Key words: stars: individual (WASP-29) – planetary systems

Online-only material: color figures

1. INTRODUCTION

Searches for transiting exoplanets have now found more than 50 "hot Jupiters" with masses of ∼0.5–3 Jupiters. At much smaller masses there are several transiting "Neptunes" (GJ 436b, Gillon et al. 2007; HAT-P-11b, Bakos et al. 2010; & Kepler-4b, Borucki et al. 2010) and "super-Earths" (GJ1214b, Charbonneau et al. 2009; CoRoT-7b, Léger et al. 2009).

By 2009 there were only two known transiting planets of Saturn-mass (∼0.3 $M_{\rm Jup}$), namely, HD 149026b (Sato et al. 2005) and HAT-P-12b (Hartman et al. 2009). In 2010 this number is growing fast, with near simultaneous announcements of WASP-29b (this Letter), CoRoT-8b (Bordé et al. 2010), WASP-21b (Bouchy et al. 2010), and HAT-P-18b and HAT-P-19b (Hartman et al. 2010), giving rapidly increasing insight into planets of this mass range.

2. OBSERVATIONS

WASP-South is an array of cameras based on 11.1 cm, $f/1.8$ lenses which cover a total of 450 deg^2 of sky. The typical observing pattern tiles 30 s exposures of several fields with a cadence of 8 minutes, recording stars in the range $V = 8$–15. The WASP-South survey is described in Pollacco et al. (2006) while a discussion of our planet-hunting methods can be found in Collier Cameron et al. (2007a), Pollacco et al. (2008), and references therein.

WASP-29 is a $V = 11.3$, K4V star in the constellation Phoenix. It was observed by WASP-South from May to November in both 2006 and 2007, accumulating 9161 data points. These data show periodic transits with a 3.9 day period (Figure 1). There are no other significant sources within the 48″ extraction aperture (3.5 14″ pixels) to dilute the transit depth.

We used the CORALIE spectrograph on the Euler 1.2 m telescope at La Silla to obtain fourteen radial-velocity measurements over 2009 August–December (Table 1). These show that the transiting body is a Saturn-mass planet. On 2010 September 6, we obtained a transit light curve with Euler's CCD camera, using 20 s, R-band exposures, resulting in a mean error of 1.5 mmag (Figure 1).

The CORALIE radial-velocity measurements were combined with the Euler and WASP-South photometry in a simultaneous Markov chain Monte Carlo (MCMC) analysis to find the parameters of the WASP-29 system (Table 2). For details of our methods see Collier Cameron et al. (2007b) and Pollacco et al. (2008). For limb darkening, we used the four parameter non-linear law of Claret (2000) with parameters fixed to the values noted in Table 2. The eccentricity was a free parameter but the data are compatible with a circular orbit.

One departure from early WASP practice is the way we determine the stellar mass. The stellar effective temperature and metallicity are treated as jump parameters in the Markov chain, and controlled by Gaussian priors derived from their spectroscopically determined values and uncertainties. At each step in the chain the stellar density is determined from the transit duration and impact parameter. The stellar mass is then determined at each step as a polynomial function of $T_{\rm eff}$, [Fe/H], and $\log \rho/\rho_\odot$, as determined by Enoch et al. (2010a). This calibration is derived from the compilation of 40 stars in eclipsing binaries with well-determined masses, radii, effective temperatures, and metallicities, published by Torres et al. (2010).

3. WASP-29 STELLAR PARAMETERS

The 14 CORALIE spectra of WASP-29 were co-added to produce a spectrum with a typical S/N of 80:1, which we analyzed using the methods described in Gillon et al. (2009). We used the Hα line to determine the effective temperature ($T_{\rm eff}$), and the Na I D and Mg I b lines as diagnostics of the surface gravity ($\log g$). The parameters obtained are listed in Table 2. The elemental abundances were determined from equivalent-width measurements of several clean and unblended lines. A value for microturbulence (ξ_t) was determined from Fe I using

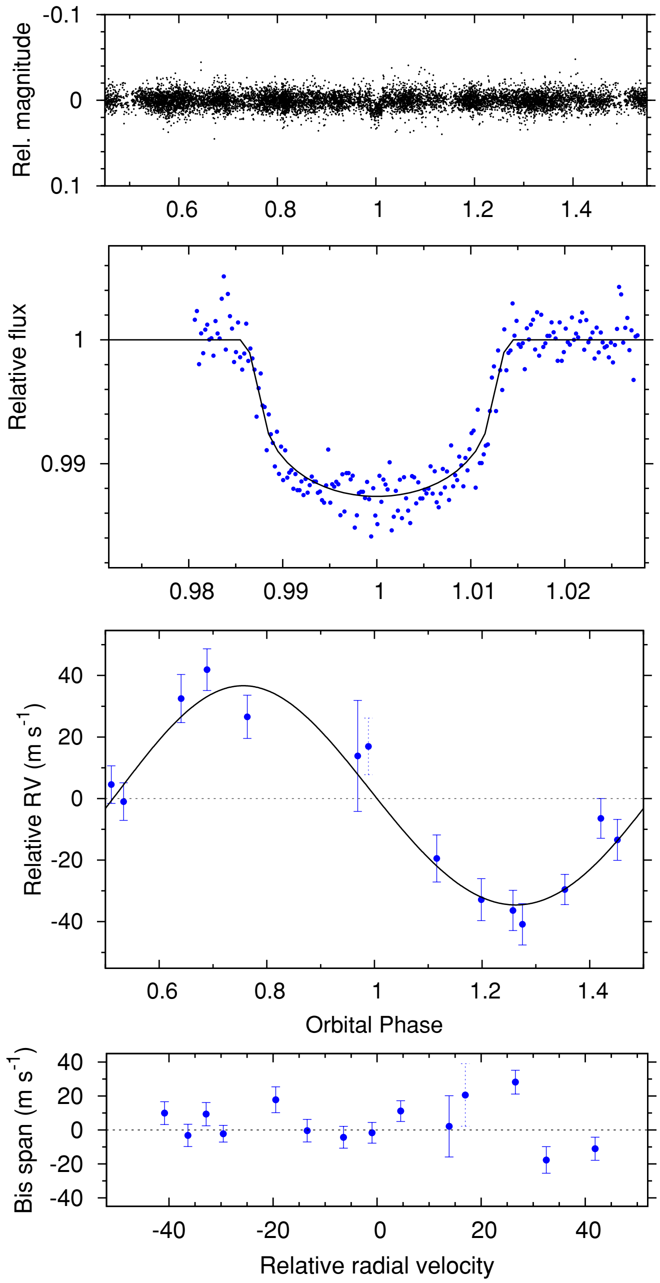

Figure 1. Top panel: the WASP-South light curve folded on the 3.9 day transit period. Second panel: the Euler (Gunn r) transit light curve with the fitted MCMC model (phase 1 is HJD 2,455,445.7614). Third panel: the CORALIE radial velocities with the fitted model (the point with dashed error bars was taken during transit and thus was excluded from the model fit). Bottom panel: the bisector spans; the absence of any correlation with radial velocity is a check against transit mimics (Queloz et al. 2001).

(A color version of this figure is available in the online journal.)

Magain's (1984) method. The quoted error estimates include that given by the uncertainties in $T_{\rm eff}$, $\log g$, and ξ_t, as well as the scatter due to measurement and atomic data uncertainties.

The temperature and $\log g$ values are consistent with a K4 main-sequence star, and this is also consistent with the *BVRIJHK* magnitudes collected by SIMBAD. There is some indication of above-solar metal abundances (Table 2).

The projected stellar rotation velocity ($v \sin i$) was determined by fitting the profiles of several unblended Fe I lines. We assumed a value for macroturbulence (v_{mac}) of 0.5 ± 0.3 km s^{-1}, based on the tabulation by Gray (2008), and an instrumental

Table 1
CORALIE Radial Velocities of WASP-29

BJD −2400 000	RV (km s^{-1})	$\sigma_{\rm RV}$ (km s^{-1})	Bisector (km s^{-1})
55071.8814	24.5671	0.0068	−0.0111
55073.8810	24.4924	0.0068	0.0093
55074.8740	24.5118	0.0066	−0.0004
55076.9032	24.5391	0.0180	0.0022
55092.6724	24.5422	0.0092	0.0206
55093.7263	24.4889	0.0066	−0.0032
55094.7205	24.5298	0.0061	0.0111
55095.7121	24.5518	0.0070	0.0282
55097.7176	24.4844	0.0067	0.0099
55098.7330	24.5243	0.0061	−0.0017
55116.7063	24.5058	0.0076	0.0178
55118.7652	24.5577	0.0078	−0.0177
55129.6706	24.5188	0.0065	−0.0043
55168.6361	24.4957	0.0049	−0.0022

Note. Bisector errors are twice RV errors.

Table 2
System Parameters for WASP-29

Parameter	Value
Stellar Parameters from Spectroscopic Analysis	
R.A. = 23$^{\rm h}$51$^{\rm m}$31$^{\rm s}$.08, Decl. = −39°54′24″.2 (J2000) (TYC 8015-1020-1, 2MASS J23513108–3954241)	
V mag	11.3
Spectral type	K4V
$T_{\rm eff}$ (K)	4800 ± 150
$\log g$	4.5 ± 0.2
ξ_t (km s^{-1})	0.6 ± 0.2
$v \sin i$ (km s^{-1})	1.5 ± 0.6
[Fe/H]	+0.11 ± 0.14
[Si/H]	+0.25 ± 0.08
[Ca/H]	+0.30 ± 0.19
[Ti/H]	+0.38 ± 0.17
[Cr/H]	+0.22 ± 0.16
[Ni/H]	+0.19 ± 0.10
$\log A$(Li)	<0.3
Parameters from MCMC Analysis	
P (days)	3.922727 ± 0.000004
T_c (HJD)	2455320.2341 ± 0.004
T_{14} (days)	0.1108 ± 0.0015
$T_{12} = T_{34}$ (days)	0.0108 ± 0.0016
Rel. depth (*R* band)	0.0126 ± 0.0002
R_P^2/R_*^2	0.0102 ± 0.0004
b	0.26 ± 0.15
i (°)	88.8 ± 0.7
K_1 (m s^{-1})	35.6 ± 2.7
a (AU)	0.0457 ± 0.0006
γ (km s^{-1})	24.5252 ± 0.0009
e	$0.03^{+0.05}_{-0.03}$
M_* ($M_\odot$)	0.825 ± 0.033
R_* ($R_\odot$)	0.808 ± 0.044
$\log g_*$ (cgs)	4.54 ± 0.04
ρ_* ($\rho_\odot$)	$1.56^{+0.20}_{-0.23}$
M_P ($M_{\rm Jup}$)	0.244 ± 0.020
R_P ($R_{\rm Jup}$)	$0.792^{+0.056}_{-0.035}$
$\log g_P$ (cgs)	2.95 ± 0.05
ρ_P (ρ_J)	0.49 ± 0.08
ρ_P (cgs)	0.65 ± 0.10
$T_{\rm P,A=0}$ (K)	980 ± 40

Errors are 1σ; Limb-darkening coefficients were:
a1 = 0.7291, a2 = −0.8130, a3 = 1.5386, a4 = −0.6296

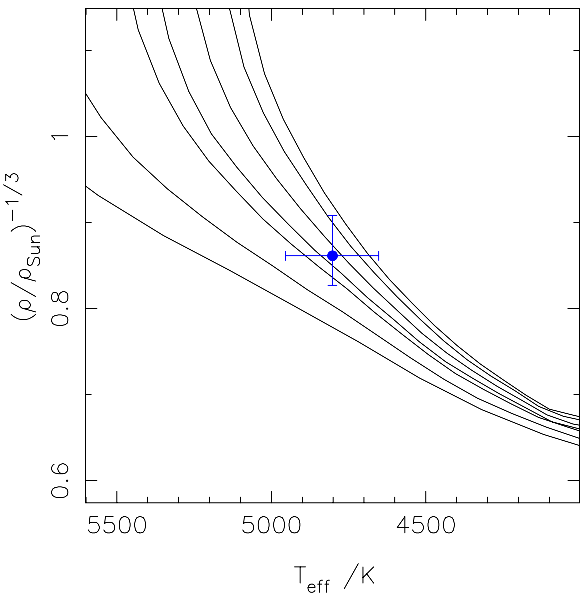

Figure 2. Evolutionary tracks on a modified H-R diagram ($\rho_*^{-1/3}$ vs. $T_{\rm eff}$). The isochrones are (in order from the left) 1, 5, 10, 12, 15, 18, and 20 Gyr, for a metallicity of [M/H] = +0.25 (from Demarque et al. 2004).

(A color version of this figure is available in the online journal.)

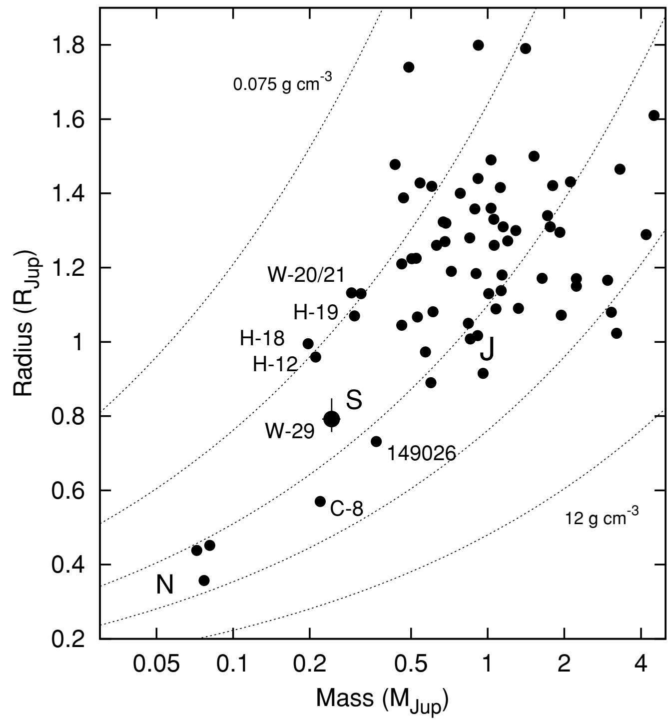

Figure 3. Mass–radius plot for transiting exoplanets. W = WASP, H = HAT, C = CoRoT, 149026 = HD 149026b, and the symbols J, S, and N mark the location of Jupiter, Saturn, and Neptune. Dotted lines are density contours (at 12, 3, 1, 0.3, and 0.075 g cm^{-3}). Data from Schneider (2010, as of August).

FWHM of 0.11 ± 0.01 Å, determined from the telluric lines around 6300 Å. The best-fitting value of $v \sin i$ was 1.5 ± 0.6 km s^{-1}.

3.1. *Evolutionary Status of WASP-29*

The temperature and density of the host star WASP-29 are shown on a modified H-R diagram in Figure 2. The best-fit values place it above the zero-age main sequence (ZAMS), which would indicate either a pre- or post-main-sequence star, while the absence of lithium and the low value of $v \sin i$ of 1.5 ± 0.6 km s^{-1} argue for the latter. Plotting against evolutionary tracks from Demarque et al. (2004), and using a metallicity of [M/H] = 0.2, near the mean of the values in Table 2, indicates an age of 15 Gyr with a 1σ lower limit of 7 Gyr (and an upper limit beyond the 20 Gyr oldest isochrone). For this metallicity, track fitting results in a stellar mass of 0.78 ± 0.05 $M_\odot$, compatible with the 0.83 ± 0.03 $M_\odot$ derived in Section 2.

Increasing the metallicity to [M/H] = 0.3 reduces the age to 12 Gyr, with a 1σ lower limit of 5 Gyr, while reducing the metallicity would increase the age, with [M/H] = 0 giving an age of 20 Gyr.

For a K4V star, $V = 11.3$ would indicate a distance of ∼70 pc. The proper motion of 0$''$.1 yr^{-1} (Zacharias et al. 2004) then indicates a transverse velocity of 33 km s^{-1}, which, with our measured radial velocity of 24.5 km s^{-1}, gives a space velocity of 40 km s^{-1} relative to us, which is typical of a local thin-disk star (e.g., Navarro et al. 2010).

Thus, the properties of WASP-29 are compatible with a local thin-disk star, provided that its metallicity is above solar and that its age is toward the younger end of the current error range, thus bringing it within the ∼9 Gyr age of the thin disk. For this reason it will be worthwhile to obtain better parameterizations of WASP-29's metallicity and effective temperature.

4. DISCUSSION

We show in Figure 3 the mass–radius distribution for transiting exoplanets. WASP-29b is now the planet closest in mass and radius to Saturn itself, and among the Saturn-mass planets is midway between the dense CoRoT-8b (Bordé et al. 2010) and the more bloated systems WASP-21b (Bouchy et al. 2010) and HAT-P-12b, HAT-P-18b, and HAT-P-19b (Hartman et al. 2009, 2010).

The smaller radius of WASP-29b among Saturn-mass exoplanets is unlikely to be caused primarily by irradiation, since the three HAT planets and WASP-29b all orbit stars of K1V to K4V, while WASP-29b has the shortest orbital period and so will be the most irradiated. Further, the irradiation for HD 149026b is greater, yet it is denser. In addition, all of the above planets have eccentricities compatible with zero, suggesting that tidal heating is not currently important.

It has been suggested that metallicity is a major factor in determining the radii of Saturn-mass planets (Hartman et al. 2009; Bouchy et al. 2010), with higher-metallicity systems having larger cores and thus smaller radii. WASP-29 is in line with this pattern, with indications of an elevated abundance of iron, [Fe/H] = +0.11 ± 0.14, and other metals (Table 2). From the theoretical models of Fortney et al. (2007) and Baraffe et al. (2008), WASP-29b could have a heavy-element core of approximately 25 $M_\oplus$ compared to ∼50 $M_\oplus$ for the denser HD 149026b (Carter et al. 2009), and contrasting with <10 $M_\oplus$ for the less-dense HAT-P-12b (Hartman et al. 2009) and WASP-21b (Bouchy et al. 2010). However, the recently announced planets HAT-P-18b and HAT-P-19b break the pattern by being underdense while having above-solar metallicities (Hartman et al. 2010). Thus, although there does appear to be an overall correlation between metallicity, irradiation, and planet radii (Enoch et al. 2010b; D. R. Anderson et al. 2010, in preparation), these factors cannot be the full explanation.

It is worth remarking that the known transiting Saturns mostly orbit K dwarves, with all the stars except HD 149026 being G7 or later. This is likely a selection effect, since transits of smaller planets are easier to detect against smaller stars (the exception, HD 149026b, was first found by radial velocities; Sato et al. 2005). Similarly, while radial-velocity surveys find more planets around higher-metallicity stars (Santos et al. 2004), a correlation of lower metallicity with larger planet radius would bias transit-survey detections to lower-metallicity systems.

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