

TrES-4: A TRANSITING HOT JUPITER OF VERY LOW DENSITY

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ABSTRACT

We report the discovery of TrES-4, a hot Jupiter that transits the star GSC 02620-00648 every 3.55 days. From high-resolution spectroscopy of the star, we estimate a stellar effective temperature of $T_{\text{eff}} = 6100 \pm 150$ K, and from high-precision z and B photometry of the transit we constrain the ratio of the semimajor axis a and the stellar radius R_* to be $a/R_* = 6.03 \pm 0.13$. We compare these values to model stellar isochrones to constrain the stellar mass to be $M_* = 1.22 \pm 0.17 M_\odot$. Based on this estimate and the photometric time series, we constrain the stellar radius to be $R_* = 1.738 \pm 0.092 R_\odot$ and the planet radius to be $R_p = 1.674 \pm 0.094 R_{\text{Jup}}$. We model our radial velocity data assuming a circular orbit and find a planetary mass of $0.84 \pm 0.10 M_{\text{Jup}}$. Our radial velocity observations rule out line-bisector variations that would indicate a spurious detection resulting from a blend of an eclipsing binary system. TrES-4 has the largest radius and lowest density of any of the known transiting planets. It presents a challenge to current models of the physical structure of hot Jupiters and indicates that the diversity of physical properties among the members of this class of exoplanets has yet to be fully explored.

Subject headings: planetary systems — techniques: photometric — techniques: radial velocities — techniques: spectroscopic

1. INTRODUCTION

Despite the ever increasing number of discovered transiting exoplanets (18 at the time of writing), our understanding of the relationships between host star properties and the planets' physical and orbital parameters is still incomplete. While the mass-radius relation for most transiting planets agrees with the models (Charbonneau et al. 2007a), several planets have either too high or too low densities. In particular, HD 209458b (Knutson et al. 2007), HAT-P-1b (Bakos et al. 2007), and WASP-1b (Collier Cameron et al. 2007) all have much larger radii and lower densities than expected for planets of their mass and distance from the host star. Several mechanisms for explaining this discrepancy have been proposed, among them different internal heat sources (Guillot & Showman 2002; Bodenheimer et al. 2003), increased planetary atmospheric opacities (Burrows et al. 2007), and less efficient heat transport as a result of interior composition gradients (Chabrier & Baraffe 2007). Our Trans-atlantic Exoplanet Survey (TrES) has previously announced the discovery of three transiting planets (Alonso et al. 2004; O'Donovan et al. 2006, 2007), each with distinctive properties. We describe here the newly discovered transiting planet TrES-4, whose mean density of $\rho = 0.222 \pm 0.045 \text{ g cm}^{-3}$ is the lowest of all known exoplanets with measured radii and masses.

2. PHOTOMETRY AND SPECTROSCOPY

We monitored a $5\text{'8} \times 5\text{'8}$ field in Hercules with the Lowell Observatory Planet Search Survey Telescope (PSST; Dunham

et al. 2004) and the Sleuth telescope at Palomar Observatory between UT 2006 May 6 and 2006 August 2. All images were processed and the photometry and transit search carried out as described in Dunham et al. (2004). Both telescopes detected transits of the host star GSC 02620-00648: PSST observed two full and one partial transits, and Sleuth observed three full and four partial transits. The shape of the events was consistent with the transit of a Jupiter-sized planet across an F dwarf, and we undertook a program of follow-up observations to confirm the planetary nature of the object.

We observed the candidate with the CfA Digital Speedometer (Latham 1992) from 2006 September to 2007 April. We obtained seven spectra covering 45 Å centered at 5187 Å, with a resolving power of $\lambda/\Delta\lambda \approx 35,000$ and signal-to-noise ratio (S/N) between 11 and 13 per resolution element. This spectral region includes the gravity-sensitive Mg b triplet, and the host star properties derived from an analysis of this region will depend on the star's metallicity. We obtained the radial velocities (RVs) by cross-correlation against a synthetic template chosen from a large library of calculated spectra based on Kurucz model atmospheres (see Nordström et al. 1994; Latham et al. 2002). These velocities have a typical precision of 0.5 km s^{-1} , and they show no significant variation within the errors. We derived the effective temperature (T_{eff}) and projected rotational velocity ($v \sin i$) by comparing our observed spectra against synthetic spectra with a wide range of parameters (see Torres et al. 2002). The values of T_{eff} and $v \sin i$ are listed in Table 1 and assume $[\text{Fe}/\text{H}] = 0.0$. We also estimate the surface gravity to be $\log g = 3.8 \pm 0.2$. We combined the Johnson-Cousins photometry that we obtained (see below) with archive Two Micron All Sky Survey (2MASS) data and used the color-temperature calibrations for dwarfs by Ramírez & Meléndez (2005) and Casagrande et al. (2006) to estimate T_{eff} . The average result, $T_{\text{eff}} = 6130 \pm 80$ K, is consistent with the spectroscopic value.

The mass and radius of the star were determined on the basis of the spectroscopic T_{eff} , the value of a/R_* derived from the light-curve fit described below, and an assumed metallicity of

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TABLE 1
TrES-4 HOST STAR

Parameter	Value	Reference
R.A. (J2000.0)	17 ^h 53 ^m 13.05 ^s	1
Decl. (J2000.0)	+37°12'42.6"	1
GSC	02620-00648	
$[\mu_\alpha, \mu_\delta]$	$[-6.5, -23.5]$ mas yr ⁻¹	1
V	11.592 ± 0.004	2
$B-V$	0.520 ± 0.007	2
$V-R_c$	0.312 ± 0.008	2
$V-I_c$	0.601 ± 0.008	2
J	10.583 ± 0.018	3
$J-H$	0.233 ± 0.024	3
$J-K_s$	0.253 ± 0.026	3
M_*	$1.22 \pm 0.17 M_\odot$	2
R_* ^a	$1.738 \pm 0.092 R_\odot$	2
L_*	$3.74 \pm 0.86 L_\odot$	2
T_{eff}	6100 ± 150 K	2
$\log g$	4.045 ± 0.034 cm s ⁻²	2
$v \sin i$	9.5 ± 1.0 km s ⁻¹	2
Age	4.7 ± 2.0 Gyr	2
Distance	440 ± 60 pc	2

^a This value of R_* is derived from fitting the entire light curve and is better constrained than the value obtained solely from the stellar evolution models (§ 2). The uncertainty in R_* includes both the statistical uncertainty of $0.044 R_\odot$ and the 14% uncertainty in M_* .

REFERENCES.—(1) UCAC2 (Zacharias et al. 2004); (2) this Letter; (3) 2MASS (Skrutskie et al. 2006).

$[\text{Fe}/\text{H}] = 0.0 \pm 0.2$. The quantity a/R_* is closely related to the stellar density and is determined in this case with much higher relative precision than $\log g$. It is therefore a better proxy for luminosity (see Sozzetti et al. 2007). We searched for the best match between stellar evolution models interpolated to a fine grid in age and metallicity and the three observables, within the stated errors. Uncertainties were derived from the full range in M_* and R_* allowed by the isochrones within observational errors. A comparison with the models from the series by Yi et al. (2001) yielded $M_* = 1.22 \pm 0.17 M_\odot$, $R_* = 1.738 \pm 0.092 R_\odot$, and $\log g = 4.045 \pm 0.034$. This value of $\log g$ is consistent with, but better constrained than, the spectroscopic estimate. The age we derive is 4.7 ± 2.0 Gyr, and the predicted absolute visual magnitude ($M_V = 3.36 \pm 0.27$) implies a distance of 440 ± 60 pc, ignoring extinction. The error estimates above do not include possible systematic errors in the stellar evolution models. The gravity, radius, and age estimates for the host star indicate that this is an evolved star at the base of the subgiant branch.

In order to characterize the host star, we obtained off-transit $BV(RI)_C$ photometry of TrES-4 on UT 2007 April 14 with the 1.05 m Hall telescope at Lowell Observatory in combination with a 2 K × 2 K SITe CCD. We calibrated the photometry using seven standard fields from Landolt (1992). The results are listed in Table 1 together with other relevant data for the host star of TrES-4.

We carried out high-precision in-transit z -band photometry of TrES-4 on UT 2007 May 3 and UT 2007 May 10 with KeplerCam (Holman et al. 2006) at the Fred L. Whipple Observatory 1.2 m telescope and B -band photometry on UT 2007 May 10 using NASACam at the Lowell Observatory 0.8 m telescope. With KeplerCam, we gathered 373 and 540 z -band 30 s exposures on UT 2007 May 3 and UT 2007 May 10, respectively. With NASACam, we obtained 192 60 s B -band exposures. For both data sets, we derived differential fluxes relative to an ensemble of local comparison stars. The photometry is shown in Figure 1.

We obtained high-precision RV measurements of TrES-4 on UT 2007 March 27–29, using the High Resolution Echelle Spec-

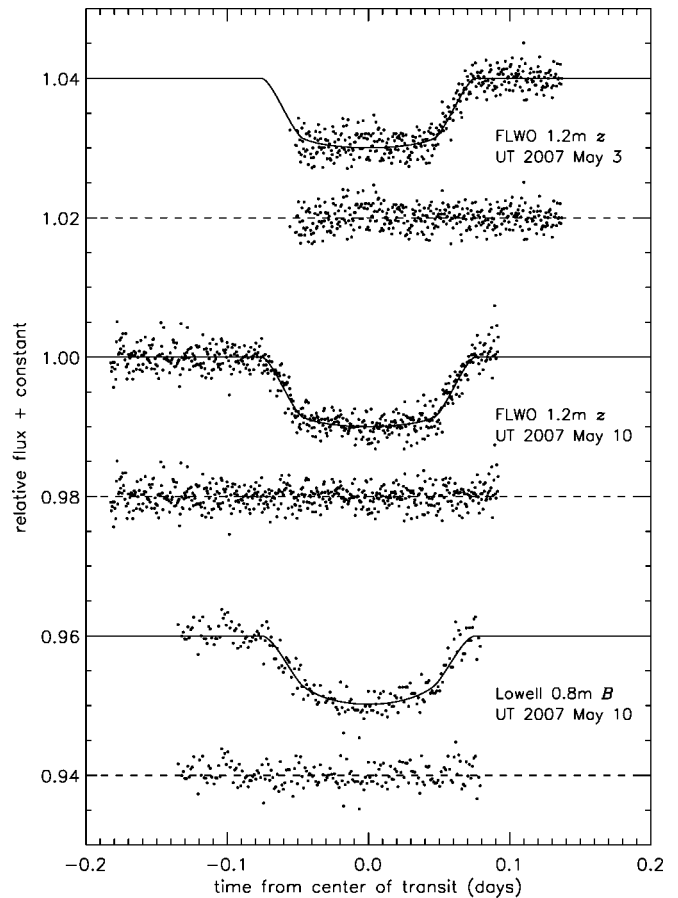


FIG. 1.—High-precision follow-up z -band and B -band photometry of TrES-4. The plot shows the relative flux (including the color-dependent extinction correction) of the TrES-4 system as a function of time relative to the center of transit, adopting the ephemeris in Table 3. Each light curve is labeled with the telescope and date of observation. The residuals from the simultaneous fits (solid lines) are shown below each light curve.

trometer (HIRES) and its I_2 absorption cell (Vogt et al. 1994) on the Keck I telescope. Our spectra have a nominal resolving power $\lambda/\Delta\lambda \approx 55,000$ and a typical S/N ~ 120 pixel⁻¹. We used nine echelle orders in the wavelength range 3200–8800 Å to derive the velocities for TrES-4. The four star-plus- I_2 spectra (plus one I_2 -free template exposure) provide good coverage of the critical phases. As the ephemeris of the system is fixed, RV data are needed only to determine the amplitude and systemic velocity of the orbit. In these cases (see Konacki et al. 2003), a few measurements are enough. We extracted and reduced all raw spectra using the MAKEE software written by T. Barlow (see Sozzetti et al. 2006). The final RV values are listed in Table 2. The typical precision of the RVs $\langle\sigma_{\text{RV}}\rangle \approx 10$ m s⁻¹ is slightly degraded by the modest stellar rotation. The high-resolution, high-S/N Keck spectra were then used to rule out blend scenarios (see below), and they are presently being analyzed for improved characterization of the host star.

We fit a Keplerian orbit to these data assuming zero eccen-

TABLE 2
RADIAL VELOCITY MEASUREMENTS OF TrES-4

HJD	Radial Velocity (m s ⁻¹)
2,454,187.07793	97.5 ± 11.8
2,454,188.11122	58.9 ± 9.4
2,454,189.02631	-76.5 ± 11.6
2,454,189.14920	-73.9 ± 10.3

TABLE 3
TrES-4 PLANET PARAMETERS

Parameter	Value
P	3.553945 ± 0.000075 days
T_c	HJD $2,454,230.9053 \pm 0.0005$
a	0.0488 ± 0.0022 AU
i	$82.81^\circ \pm 0.33^\circ$
a/R_*	6.026 ± 0.131
$b = a \cos i/R_*$	0.755 ± 0.015
K	97.4 ± 7.2 m s $^{-1}$
γ_{HIRES}	23.7 ± 5.8 m s $^{-1}$
M_p	$0.84 \pm 0.10 M_{\text{Jup}}$
R_p^a	$1.674 \pm 0.094 R_{\text{Jup}}$
ρ	0.222 ± 0.045 g cm $^{-3}$
$\log g$	2.871 ± 0.038 cm s $^{-2}$
R_p/R_*	0.09903 ± 0.00088

^a The uncertainty in R_p includes both the statistical uncertainty of $0.053 R_{\text{Jup}}$ and the 14% uncertainty in M_* from Table 1.

tricity as a good first approximation, as expected from theoretical arguments for a period as short as 3.55 days. The period and epoch of transit were held fixed. The rms of this fit is 11 m s^{-1} , which is similar to the internal errors of the velocities. The parameters of this orbital solution are listed in Table 3. We find $M_p \sin i = 0.731 \pm 0.057 [(M_* + M_p)/M_\odot]^{2/3} M_{\text{Jup}}$. The orbit is displayed in Figure 2 (*top panel*) along with the observations, and residuals are shown in the middle panel.

We investigated the possibility that the RV variations are the result of distortions in the line profiles caused by contamination from an unresolved eclipsing binary (Santos et al. 2002; Torres et al. 2005), instead of being caused by a planetary companion. We cross-correlated each Keck spectrum against a synthetic template matching the properties of the star and averaged the correlation functions over all orders blueward of the region affected by the I_2 lines. From this representation of the average spectral line profile, we computed the mean bisectors, and as a measure of the line asymmetry we calculated the “bisector spans” as the velocity difference between points selected near the top and bottom of the mean bisectors (Torres et al. 2005). If the RV variations were the result of a blend with an eclipsing binary, we would expect the line bisectors to vary in phase with the photometric period with an amplitude similar to that of the velocities (Queloz et al. 2001; Mandushev et al. 2005). Instead, we detect no variation in excess of the measurement uncertainties (see Fig. 2, *bottom panel*), and we conclude that the RV variations are real and that the star is orbited by a Jovian planet.

3. PROPERTIES OF TrES-4 AND DISCUSSION

We analyzed the two z -band and one B -band photometric time series using the analytic light curves of Mandel & Agol (2002). We assumed a circular orbit and a quadratic stellar limb-darkening law, fixing the coefficients at the color-dependent values tabulated in Claret (2000, 2004) for the spectroscopic T_{eff} and $\log g$ and assuming solar metallicity. We first estimated the time of center of transit T_c by fitting a model light curve to the z data gathered on UT 2007 May 10. We then determined the orbital period P by combining these data with the TrES discovery data (which affords a baseline of 1.0 yr). We then fixed the values of T_c and P (listed in Table 3) in the subsequent analysis.

Our model has six free parameters: the planet radius R_p , the stellar radius R_* , the orbital inclination i , and the color-dependent extinction for each of the three photometric data sets— k_{z1} , k_{z2} , and k_B . We assume that the observed flux is proportional to e^{-km} , where m denotes the air mass. The values of R_p and R_* as

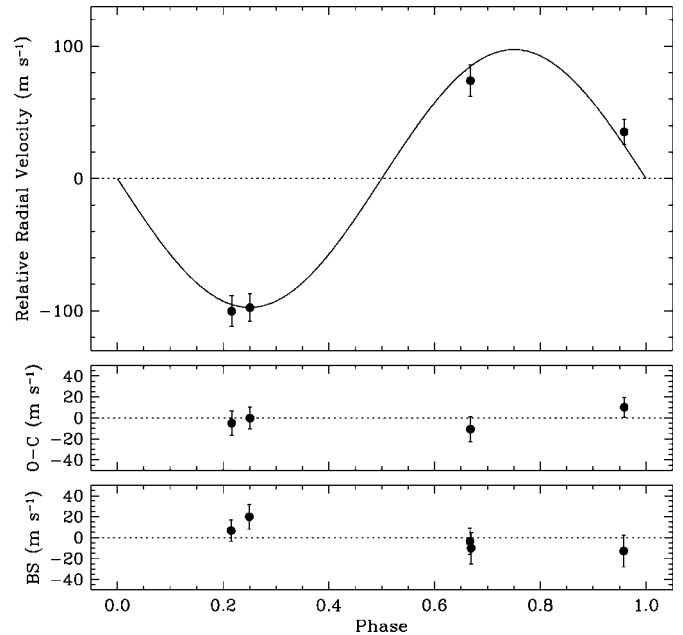


FIG. 2.—*Top*: Radial velocity observations of TrES-4 obtained with the Keck HIRES using the I_2 cell, shown relative to the center of mass and adopting the ephemeris in Table 3. The best-fit orbit (*solid line*) is overplotted. *Middle*: Residuals from the best-fit model to the radial velocities. *Bottom*: Bisector spans shifted to a median of zero, for each of the iodine exposures as well as for the template (which is shown as an additional point at phase 0.669).

constrained by the light curves alone are covariant with M_* . In our analysis, we first estimated the quantity a/R_* , which is independent of the assumed value of M_* , and then used this estimate to constrain the value of M_* from stellar isochrones (Sozzetti et al. 2007; Holman et al. 2007). We then fixed $M_* = 1.22 M_\odot$ and estimated the systematic error in the radii using the scaling relations $R_p \propto R_* \propto M_*^{1/3}$ (see footnote to Table 1).

We found first the values of R_p , R_* , i , k_{z1} , k_{z2} , and k_B that minimized the χ^2 using the AMOEBA algorithm (Press et al. 1992). This model is shown as the solid curves in Figure 1. We then conducted a Markov Chain Monte Carlo (MCMC) analysis similar to that described in Holman et al. (2006), Charbonneau et al. (2007b), and Winn et al. (2007). We created two MCMC chains with 400,000 points each, one starting from the best-fit values and one starting from a random perturbation to those values. We then rejected the first 23% of the points to minimize the impact of the initial conditions and found the results from the two chains to be indistinguishable. We examined the histograms of the six parameters as well as the histograms for several combinations of parameters relevant to anticipated follow-up studies. We assigned the optimal value to the median and the 1σ errors to the symmetric range about the median that encompassed 68.3% of the values. We list these estimates in Table 3.

TrES-4 has the largest radius and the lowest density of all exoplanets whose mass and radius are known, and as such presents new challenges for the theory of irradiated gas giants. Burrows et al. (2007) suggested that increased planetary atmospheric opacities and the inclusion of a transit radius correction (Baraffe et al. 2003; Burrows et al. 2003) can explain the radii of all large planets. It appears, however, that TrES-4’s radius is still too large for its mass, age, and insolation. In terms of mass and distance to the host star, TrES-4 is similar to HD 209458b but has nearly 30% larger radius ($R_p = 1.67$ vs. $R_p = 1.32$). Because of the higher host star luminosity, TrES-4 receives about twice the stellar flux, but it is unlikely that the radius difference can be

explained solely by the higher stellar irradiation. For example, HAT-P-1b, which has about the same radius as HD 209458b and is the only other planet with $\rho < 0.3 \text{ g cm}^{-3}$, receives only 60% of the flux that HD 209458b does. None of the recent models of hot Jupiters (e.g., Fortney et al. 2007; Burrows et al. 2007) can predict a radius as large as that of TrES-4 at its orbital separation for the estimated age and for any mass, even when higher atmospheric opacities are considered and allowance for the transit radius correction is made.

The properties of TrES-4 and its host star allow for many interesting follow-up studies, some of which are already underway. The large radius of TrES-4 in the visual suggests that it may have an extended outer atmosphere, similar to that detected around HD 209458b in Ly α by Vidal-Madjar et al. (2003). If such an extended envelope is caused by mass loss through the planet's Roche lobe boundary, TrES-4 may have an even bigger envelope because of its smaller Roche limit: $R_{\text{Roche}} \approx 3.5R_p$ versus $R_{\text{Roche}} \approx 4.4R_p$ for HD 209458b (Erkaev et al. 2007). Moreover, TrES-4 might be in a strong hydrodynamic "blow-off" regime, where the outer atmospheric layers are detached from the planet's gravitational field and escape in a comet-like tail (Vidal-Madjar et al. 2003; Lecavelier des Etangs et al. 2004).

The relatively fast rotation ($v \sin i = 9.5 \text{ km s}^{-1}$) and brightness of TrES-4's host star, as well as the planet's size, are favorable for measuring the Rossiter-McLaughlin effect (RME) (e.g., Gaudi & Winn 2007). Of particular interest is the angle between the star's spin axis and the planet's orbital plane, as it can provide information about the possible mechanisms of the planet migration and interaction with the protoplanetary disk. The semiamplitude of the RME is proportional to $v \sin i$ and to $(R_p/R_*)^2$, and we estimate that for TrES-4 the RME can reach about 90 m s^{-1} , roughly equal to the semiamplitude of its orbital velocity.

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