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TrES-3: A NEARBY, MASSIVE, TRANSITING HOT JUPITER IN A 31 HOUR ORBIT[1]

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ABSTRACT

We describe the discovery of a massive transiting hot Jupiter with a very short orbital period (1.30619 days), which we name TrES-3. From spectroscopy of the host star GSC 03089−00929, we measure $T_{\rm eff} = 5720 \pm 150$ K, $\log g = 4.6 \pm 0.3$, and $v \sin i < 2$ km s^{-1} and derive a stellar mass of $0.90 \pm 0.15\ M_\odot$. We estimate a planetary mass of $1.92 \pm 0.23\ M_{\rm Jup}$, based on the sinusoidal variation of our high-precision radial velocity measurements. This variation has a period and phase consistent with our transit photometry. Our spectra show no evidence of line bisector variations that would indicate a blended eclipsing binary star. From detailed modeling of our B and z photometry of the 2.5% deep transits, we determine a stellar radius $0.802 \pm 0.046\ R_\odot$ and a planetary radius $1.295 \pm 0.081\ R_{\rm Jup}$. TrES-3 has one of the shortest orbital periods of the known transiting exoplanets, facilitating studies of orbital decay and mass loss due to evaporation, and making it an excellent target for future studies of infrared emission and reflected starlight.

Subject headings: planetary systems — stars: individual (GSC 03089−00929) — techniques: photometric — techniques: radial velocities

1. INTRODUCTION

The OGLE-III deep-field survey (Udalski et al. 2003 and references therein) has identified three transiting planetary systems with very short orbital periods: OGLE-TR-56b ($P = 29$ hr; Konacki et al. 2003), OGLE-TR-113b ($P = 34$ hr; Bouchy et al. 2004; Konacki et al. 2004), and OGLE-TR-132b ($P = 41$ hr; Bouchy et al. 2004). At the time of discovery, such 1 day period planets were conspicuously absent from radial velocity (RV) surveys. These surveys had not discovered a planet with an orbital period of substantially less than 3 days, despite the sensitivity of such surveys to planets with short orbital periods. Several authors reconciled this apparent discrepancy by determining the respective observational biases and selection effects (Gaudi et al. 2005; Pont et al. 2005; Gould et al. 2006; Fressin et al. 2007). Since then, hot Jupiters with periods just over 2 days have been detected by both RV surveys (HD 189733b; Bouchy et al. 2005) and wide-field transit surveys (WASP-2b; Collier Cameron et al. 2007), indicating a consistent picture for the underlying distribution of orbital periods of hot Jupiters.

With the discovery of these nearby planets, we continue to observe (Sozzetti et al. 2007) the decreasing linear relation between P and the planetary mass (M_p) for transiting planets first noticed by Mazeh et al. (2005) and Gaudi et al. (2005). It appears from this small number of planets that shorter period exoplanets are on average more massive. This may suggest different evolution of these planetary systems than the canonical migration (see, e.g., Trilling et al. 1998) of hot Jupiters from beyond the ice line.

We present here the discovery of TrES-3, a massive planet that has one of the shortest periods of the transiting planets and that was independently identified by two transit surveys.

2. OBSERVATIONS AND ANALYSIS

Transits of the parent star GSC 03089−00929 were detected by two 10 cm telescopes, part of the Trans-atlantic Exoplanet Survey (TrES) network. Sleuth (Palomar Observatory, California) observed seven full transits and three partial transits, of which three full and two partial transits were observed by the Planet Search Survey Telescope (Lowell Observatory, Arizona; Dunham et al. 2004). We obtained these observations between UT 2006 May 6 and 2006 August 2, during which time we monitored a 5.7° × 5.7° field of view (FOV) centered on θ Her. We then processed the data from each telescope separately, as we have described previously (Dunham et al. 2004; O'Donovan et al. 2006b, 2007). We then search our binned light curves using the box-fitting transit search algorithm of Kovács et al. (2002) for periodic events consistent with the passage of a Jupiter-sized planet across a solar-like star. We flagged TrES-3 as a candidate, noting that the transit duration of 1.3 hr implied a high impact parameter b.

Transits of TrES-3 were independently observed by the Hungarian Automated Telescope Network (HATNet; Bakos et al. 2004). We observed the HAT field "G196" between UT 2005 June 8 and December 5, using the HAT-7 telescope at the Fred L. Whipple Observatory (FLWO) and HAT-9 at the Submillimeter Array atop Mauna Kea. We applied standard calibration and aperture photometry procedures to the frames as described earlier in Bakos et al. (2007). We also applied the trend filtering algorithm (Kovács et al. 2005) and identified TrES-3 as a transit candidate using the algorithm of Kovács et al. (2002).

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TABLE 1
TrES-3 Parent Star

Parameter	Value	Reference
R.A. (J2000.0)	$17^h52^m07.03^s$	
Decl. (J2000.0)	$+37°32'46.1''$	
GSC	03089−00929	
$M_\star$ ($M_\odot$)	0.90 ± 0.15	1
$R_\star$[a] ($R_\odot$)	0.802 ± 0.046	1
$T_{\rm eff}$ (K)	5720 ± 150	1
log g (dex)	4.6 ± 0.3	1
$v \sin i$ (km s^{-1})	<2	1
V (mag)	12.402 ± 0.006	1
$B-V$ (mag)	0.712 ± 0.009	1
$V-R_C$ (mag)	0.417 ± 0.010	1
$V-I_C$ (mag)	0.799 ± 0.010	1
J (mag)	11.015 ± 0.022	2
$J-H$ (mag)	0.360 ± 0.030	2
$J-K_s$ (mag)	0.407 ± 0.028	2
[μ_α, μ_δ] (mas yr^{-1})	[−22.5, 32.0]	3

[a] The uncertainty in $R_\star$ includes both the statistical error and the 5.6% uncertainty resulting from uncertainty in $M_\star$.

References.—(1) This work; (2) 2MASS Catalog; (3) UCAC2 Bright Star Supplement.

TABLE 2
Relative Radial Velocity Measurements of TrES-3

Observation Epoch (HJD − 2,400,000)	Radial Velocity (m s^{-1})	$\sigma_{\rm RV}$ (m s^{-1})
54186.99525	229.0	10.8
54187.11354	82.1	8.5
54187.96330	167.5	8.4
54188.04216	286.3	9.7
54188.96503	−336.5	8.6
54189.04672	−234.5	10.9
54189.09622	−183.9	9.3

We observed TrES-3 using the CfA Digital Speedometers (Latham 1992) on 13 occasions from 2006 September 9 to 2007 April 6. These spectra are centered at 5187 Å and cover 45 Å with a resolving power of $\lambda/\Delta\lambda \approx 35{,}000$. We derived RVs at each epoch by cross-correlation against synthetic spectra created by J. Morse using Kurucz model stellar atmospheres (J. Morse & R. L. Kurucz 2004, private communication). There is no significant variation in these measurements, which have a mean of $+9.58$ km s^{-1} and a scatter of 0.73 km s^{-1}. This limits the mass of the companion to be less than $\sim 7\ M_{\rm Jup}$. We estimated the stellar parameters from a cross-correlation analysis similar to that above, assuming a solar metallicity. The effective temperature ($T_{\rm eff}$), surface gravity (log g), and projected rotational velocity ($v \sin i$) we derive are listed in Table 1. On the basis of these values, we estimate the stellar mass to be $M_\star = 0.90 \pm 0.15\ M_\odot$. Further spectroscopic analysis of the parent star (similar to that performed for TrES-1 and TrES-2; Sozzetti et al. 2004, 2007) is in progress and will be presented elsewhere.

The 2MASS $J-K$ color (0.407 mag) and UCAC2 proper motion (39.1 mas yr^{-1}) of GSC 03089-00929 are as expected for a nearby G dwarf. We obtained absolute BVR_CI_C photometry for TrES-3 on the night of UT 2007 April 14 with the 105 cm Hall telescope at Lowell Observatory. The photometry was calibrated using seven standard fields from Landolt (1992). The results are listed in Table 1.

We observed a full transit in the z-band on UT 2007 March 26 using KeplerCam (see, e.g., Holman et al. 2006) at the FLWO 1.2 m telescope. We obtained 150, 90 s exposures of a $23.1' \times 23.1'$ FOV containing TrES-3. We observed another transit in Bessell B on UT 2007 April 8 with the Las Cumbres Observatory Global Telescope 2 m Faulkes Telescope North on Haleakala, Maui, Hawaii. The CCD camera imaged a $4.6'$ square field with an effective pixel size of $0.28''$ (the images were binned 2×2). We obtained 126 images with an exposure time of 60 s and a cadence of 70 s. We defocused the telescope slightly (to an image diameter of $\sim 3''$) to avoid saturation of the brightest comparison star. We analyzed these data sets separately. Using standard IRAF procedures, we corrected the images for bias, dark current, and flat-field response. We determined fluxes of the target star and numerous comparison stars using synthetic aperture photometry. To correct the target star fluxes for time-varying atmospheric extinction, we divided them by a weighted average of the fluxes of all the comparison stars.

We collected high-precision RV measurements on UT 2007 March 27–29 using HIRES (Vogt et al. 1994) and its I_2 absorption cell on the Keck I telescope. We obtained a total of seven star+iodine exposures and one template spectrum. All spectra were gathered with a nominal resolving power $\lambda/\Delta\lambda \simeq 55{,}000$, using the HIRES setup with the $0.86''$ slit. We used an integration time of 15 minutes, which yielded a typical signal-to-noise ratio of 110 pixel^{-1}. We reduced the raw spectra using the MAKEE software written by T. Barlow. We have described the software used to derive relative radial velocities with an iodine cell in earlier works (e.g., O'Donovan et al. 2006a; Sozzetti et al. 2006). We estimate our internal errors from the scatter about the mean for each spectral order divided by the square root of the number of orders containing I_2 lines and find them to be around 10 m s^{-1}. The radial velocity measurements are listed in Table 2.

We constrained the orbital fit to these data to have zero eccentricity (e), as expected from theoretical arguments for such a short period planet, and we also held P and the transit epoch T_c fixed at their values determined from the photometric data. The rms residual from this fit (15.4 m s^{-1}) is larger than the typical internal errors (10 m s^{-1}). Preliminary analysis of the template spectrum suggests that the star shows evidence of activity. For the inferred spectral type, the presence of radial velocity "jitter" of 10–20 m s^{-1} is not unexpected (Saar et al. 1998; Santos et al. 2000; Wright 2005) and would explain the excess scatter we find. Figure 1 displays the RV data overplotted with the best-fit model, along with the residuals from the fit. The parameters of the orbital solution are listed in Table 3. We find a minimum planetary mass of $M_p \sin i = 2.035 \pm 0.090[(M_p + M_\star)/M_\odot]^{2/3}\ M_{\rm Jup}$, where i represents the orbital inclination. As a consistency check we repeated the fit with P fixed and $e = 0$ as before, but solving for T_c. The result is $T_c = $ HJD $2{,}454{,}185.911 \pm 0.045$, which is consistent with, but less precise than, the value determined from the photometry (Table 3).

We investigated the possibility that the velocity variations are due not to a planetary companion but instead to distortions in the line profiles caused by an unresolved eclipsing binary (Santos et al. 2002; Torres et al. 2005). We cross-correlated each 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 iodine 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 velocity variations were the result of a stellar blend, we would expect the bisector

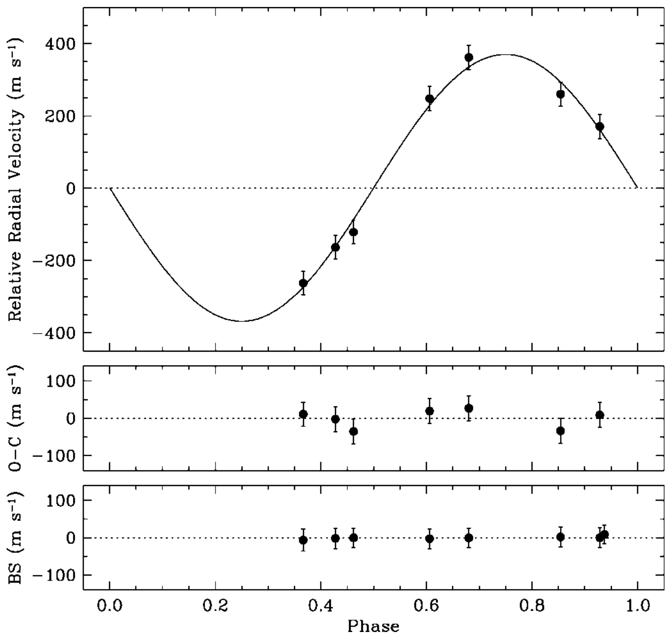

FIG. 1.—*Top*: Radial velocity observations of TrES-3 obtained with Keck/HIRES using the I_2 cell, shown relative to the center of mass and adopting the ephemeris in Table 3. The best-fit orbit (*solid line*) is overplotted. *Middle*: Residuals from the best-fit model to the radial velocities. *Bottom*: Bisector spans shifted to a median of zero, for each of the iodine exposures as well as for the template (which is shown as the additional data point at phase 0.937).

spans to vary in phase with the photometric period with an amplitude similar to that seen in the RVs (Queloz et al. 2001; Mandushev et al. 2005). Instead, we do not detect any variation exceeding the measurement uncertainties (see Fig. 1). We conclude that the RV variations are real, and the star is indeed orbited by a Jovian planet.

3. ESTIMATES OF PLANET PARAMETERS AND CONCLUSIONS

We analyze our photometric time series using the analytic transit curves of Mandel & Agol (2002) and the Markov Chain Monte Carlo (MCMC) techniques described in Holman et al. (2006), Charbonneau et al. (2007), and Winn et al. (2007). We assume a circular orbit of constant P. We first estimate T_c by fitting a model light curve (as described below) to only the z data. We then determine P by phase-folding the z data with the TrES and HAT discovery data (which affords a baseline of 1.8 yr) while varying the trial values for P. We then fix the values for T_c and P (stated in Table 3) in the subsequent analysis.

The values of the planet radius R_p and the stellar radius $R_\star$ as constrained by the light curves are covariant with $M_\star$. In our MCMC analysis, we fix $M_\star = 0.9\,M_\odot$ and then estimate the systematic error in the radii using the scaling relations $R_p \propto R_\star \propto M_\star^{1/3}$ (see Table 1, footnote a). We assume a quadratic limb-darkening law with coefficients fixed at the band-dependent values tabulated in Claret (2000, 2004) for the spectroscopically estimated $T_{\rm eff}$ and $\log g$ and assuming solar metallicity.

The remaining free parameters in our model are R_p, $R_\star$, and i. We require two additional parameters, k_B and k_z, the respective residual color-dependent extinction to the B and z light curves, assuming that the observed flux is proportional to $\exp(-km)$, where m denotes the air mass. We find that the TrES and HAT discovery data are too noisy to meaningfully constrain the parameters, and so we restrict our analysis to the B and z data. We

TABLE 3
TrES-3 Planet

Parameter	Value
P (days)	1.30619 ± 0.00001
T_c (HJD)	2454185.9101 ± 0.0003
$a/R_\star$	6.06 ± 0.10
a (AU)	0.0226 ± 0.0013
$b = a\cos i/R_\star$	0.8277 ± 0.0097
i (deg)	82.15 ± 0.21
K (m s^{-1})	378.4 ± 9.9
γ (m s^{-1})	−70.6 ± 6.2
M_p ($M_{\rm Jup}$)	1.92 ± 0.23
$R_p/R_\star$	0.1660 ± 0.0024
R_p[a] ($R_{\rm Jup}$[b])	1.295 ± 0.081

[a] The uncertainty in R_p includes both the statistical error and the 5.6% uncertainty resulting from uncertainty in $M_\star$ (Table 1).
[b] $R_{\rm Jup} = 71{,}492$ km, the equatorial radius of Jupiter at 1 bar.

first find the values of R_p, $R_\star$, i, k_B, and k_z that minimize χ^2 using the AMOEBA algorithm (Press et al. 1992). This model is shown as the solid curves in Figure 2. We then created two MCMC chains with 428,000 points each, one starting from the best-fit values and one starting a randomly generated perturbation to these values. We subsequently rejected the first 100,000 points to minimize the effect of the initial conditions and found the results of the two chains to be indistinguishable. We then examined the histograms of the five input parameter values, as well as the histograms for several combinations of parameters relevant to anticipated follow-up studies. We assigned the optimal value to be the median and the 1 σ error to be the symmetric range about the median that encompassed 68.3% of the values. We state our estimates of the parameters in Table 3. The estimated values for k_B (0.0029 ± 0.0006) and k_z (−0.0021 ± 0.0004) are small and of opposite sign, which is consistent with a modest difference between the average color of the calibration field stars and the target.

Despite the V-shaped transit, our best-fit values indicate that TrES-3 is not grazing; i.e., the disk of the planet is entirely contained within the disk of the star at midtransit, although grazing solutions are permitted by the data. Importantly, our ability to obtain well-constrained estimates of R_p and $R_\star$ despite

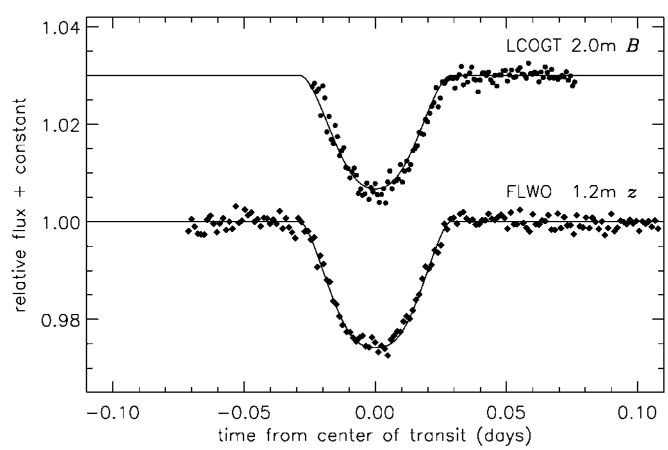

FIG. 2.—Relative flux of the TrES-3 system as a function of time from the center of transit, adopting the ephemeris in Table 3, and including the residual color-dependent extinction correction (§ 3). Each of these follow-up light curves is labeled with the telescope and filter employed. We have overplotted the simultaneous best-fit solution, adopting the appropriate quadratic limb-darkening parameters for each band pass.

the large b hinged on having observations of the transit in both B and z. The large difference in central wavelength and hence stellar limb darkening between these two bands permitted us to rule out a family of degenerate solutions that is allowed by observations in only a single color. We tested this notion by repeating the analysis above for only the z data and found that values of R_p as large as 2.0 $R_{\rm Jup}$ could not be excluded.

TrES-3 presents a useful test bed for theoretical models of gas giants. Its radius places it in the growing family of planets with radii that exceed that predicted for models of irradiated gas giants. It is one of the most massive transiting planets and has one of the shortest periods. We recall that the discovery of OGLE-TR-56b at a distance of only 0.023 AU from its star stimulated investigations into the timescales for orbital decay and thermal evaporation. The comparable orbital separation of TrES-3 implies that many of these estimates are directly applicable to the new planet, but with the important difference that the much brighter apparent magnitude affords the opportunity for more precise study. In particular, we note that direct searches for decay of the orbital period may inform our understanding of dissipation in stellar convective zones (Sasselov 2003), particularly since both the TrES-3 planet and its stellar convective zone are more massive than that of OGLE-TR-56b. Furthermore, the mass and orbital separation of TrES-3 are intriguingly close to the critical values estimated by Baraffe et al. (2004), below which evaporation would become a dominant process. The measurement of the angle between the planetary orbit and stellar spin axis of TrES-3 may detect the substantial misalignment that might be expected for planets that were tidally captured rather than migrating inward (Gaudi & Winn 2007). Assuming isotropic emission, the equilibrium temperature of TrES-3 is $1643(1-A)^{1/4}$ K, where A is the Bond albedo. We intend to obtain *Spitzer* observations of TrES-3, as we have previously done for TrES-1 and TrES-2. Finally, we note that TrES-3 is extremely favorable for attempts to detect reflected starlight (Charbonneau et al. 1999; Leigh et al. 2003; Rowe et al. 2006) and thus determine the geometric albedo, p_λ of the planet. The flux of the planet near opposition relative to that of the star is $p_\lambda \times (R_p/a)^2 = p_\lambda \times 7.5 \times 10^{-4}$, which is more than twice that of any of the other known nearby transiting planets.

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