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TrES-2: THE FIRST TRANSITING PLANET IN THE *KEPLER* FIELD[1]

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ABSTRACT

We announce the discovery of the second transiting hot Jupiter discovered by the Trans-atlantic Exoplanet Survey. The planet, which we dub TrES-2, orbits the nearby star GSC 03549-02811 every 2.47063 days. From high-resolution spectra, we determine that the star has $T_{\rm eff} = 5960 \pm 100$ K and $\log g = 4.4 \pm 0.2$, implying a spectral type of G0 V and a mass of $1.08^{+0.11}_{-0.05}\,M_{\odot}$. High-precision radial velocity measurements confirm a sinusoidal variation with the period and phase predicted by the photometry, and rule out the presence of line bisector variations that would indicate that the spectroscopic orbit is spurious. We estimate a planetary mass of $1.28^{+0.09}_{-0.04}M_{\rm Jup}$. We model B, r, R, and I photometric time series of the 1.4% deep transits and find a planetary radius of $1.24^{+0.09}_{-0.06}R_{\rm Jup}$. This planet lies within the field of view of the NASA *Kepler* mission, ensuring that hundreds of upcoming transits will be monitored with exquisite precision and permitting a host of unprecedented investigations.

Subject headings: planetary systems — stars: individual (GSC 03549-02811) — techniques: photometric — techniques: radial velocities

1. INTRODUCTION

Observations of the 10 known transiting hot Jupiters have provided precise planetary radii and masses, and tested formation and structure models for extrasolar planets (see Laughlin et al. 2005 and Charbonneau et al. 2006). More detailed studies of the nearby planets have probed their atmospheres and led to the direct detection of their thermal emission (e.g., Charbonneau et al. 2002, 2005; Deming et al. 2005a, 2005b).

Three of these planets were known from radial velocity (RV) surveys of the solar neighborhood and were subsequently observed to transit. The remaining seven were discovered from photometric observations. The RV confirmation of transiting planet candidates involves extensive use of large-aperture telescopes. With the goal of maximizing the yield of transiting planets around bright stars and minimizing the time required of large observatories, several teams are undertaking wide-field photometric surveys using small telescopes (for a review, see Charbonneau et al. 2006). Our collaboration is conducting the Trans-atlantic Exoplanet Survey (TrES): TrES-1 was the first nearby transiting planet to be discovered photometrically (Alonso et al. 2004).

Such photometric surveys yield numerous transit candidates, of which the majority are astrophysical false positives that are discarded by follow-up photometric and spectroscopic observations (e.g., O'Donovan et al. 2006b). However, eliminating a blend, wherein a bright star forms a chance superposition or a hierarchical triple with a faint eclipsing binary, can require a careful analysis (Torres et al. 2004; Mandushev et al. 2005; O'Donovan et al. 2006a). We present here the discovery of the planet TrES-2 and describe the process by which we confirmed its planetary nature and deduced its bulk properties.

2. OBSERVATIONS AND ANALYSIS

Transits of the parent star TrES-2 were first observed by Sleuth (Palomar Observatory, California) and the Planet Search Survey Telescope (PSST; Lowell Observatory, Arizona; Dunham et al. 2004), part of the TrES network of 10 cm telescopes. The two telescopes monitored a $5\overset{\circ}{.}7 \times 5\overset{\circ}{.}7$ field of view (FOV) centered on the star 16 Lyr from UT 2005 June 16 to September 3. The analysis of TrES images has been described in detail in Dunham et al. (2004) and O'Donovan et al. (2006a, 2006b). In summary, we analyzed the Sleuth and PSST images separately. After calibration, we obtained a list of the field stars in each image and determined their equatorial coordinates. We applied our image spatial interpolation and subtraction routines based in part on Alard (2000) to obtain the differential magnitude of each star in each image. We decorrelated and binned the stellar light curves, before applying the transit search algorithm of Kovács et al. (2002) to identify stars showing statistically significant, periodic transit-like events.

We quickly selected TrES-2 as a prime candidate. The Sleuth r and PSST R photometric time series obtained near-transit and folded with a period $P = 2.47063$ days are shown in Figure 1. Five full transits and three partial transits were observed by Sleuth. PSST observed two full transits and one partial event, events that were also observed by Sleuth. We were therefore confident that the events were not the result of instrumental error.

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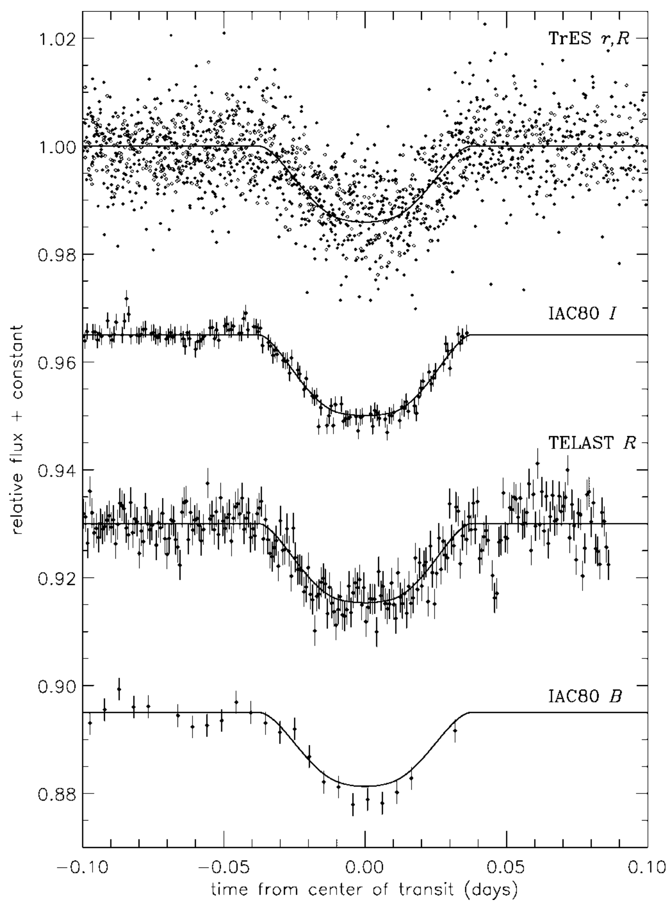

FIG. 1.—Relative flux of the TrES-2 system as a function of time from the center of transit, assuming the ephemeris in Table 2. The top light curve shows the unbinned discovery data, consisting of points from Sleuth *r* (*filled diamonds*) and PSST *R* (*open diamonds*). Each of the follow-up light curves is labeled with the telescope and filter employed. We have overplotted the simultaneous best-fit solution, assuming the appropriate quadratic limb-darkening parameters for each bandpass.

The depth of 1.4% was consistent with the transit of a Jupiter-sized object across a solar-type star, and the duration of only 1.5 hr implied a near-grazing eclipse.

We searched for the counterpart of TrES-2 in publicly available catalogs and identified the star as GSC 03549-02811. The 2MASS $J-K=0.386$ is consistent with a Sun-like star. The UCAC2 proper motion (5.60 mas yr^{-1}) is also consistent with, but slightly less than, the expectation for a nearby dwarf. We examined the DSS images and found no nearby bright companions within the 30″ radius of the Sleuth photometric aperture. In order to obtain absolute photometry and colors of TrES-2, we observed it in Johnson *UBV* and Cousins *R* on the nights of UT 2006 August 29 and 30 with the 105 cm Hall telescope at Lowell Observatory. We calibrated the data using six standard fields (Landolt 1992), and the results are given in Table 1.

We observed TrES-2 using the CfA Digital Speedometers (Latham 1992) on UT 2005 October 18, 20, and 23, November 13, and 2006 June 13. These spectra are centered on 5187 Å and cover 45 Å with a resolving power of $\lambda/\Delta\lambda \approx 35{,}000$. By cross-correlating these spectra with synthetic spectra created by J. Morse using Kurucz model stellar atmospheres (J. Morse & R. L. Kurucz 2004, private communication), we computed the RV at each epoch. Within the measurement error (~0.5 km s^{-1}), the RVs are constant with a mean velocity of −0.56 km s^{-1} and a scatter of 0.55 km s^{-1}. This limits the mass of the companion to be less than $8M_{Jup}$. From a similar cross-correlation analysis, we estimate (assuming a solar metallicity) the stellar effective temperature T_{eff}, surface gravity $\log g$, and the projected rotational velocity $v \sin i$ (Table 1). These estimates are consistent with the G0 V spectral type implied by the photometry.

TABLE 1
PARENT STAR

Parameter	Value	Reference
R.A. (J2000.0)	$19^h07^m14.^s03$	
Decl. (J2000.0)	+49°18′59.″3	
GSC	03549-02811	
V (mag)	11.411 ± 0.005	1
$B-V$ (mag)	0.619 ± 0.009	1
$U-B$ (mag)	0.112 ± 0.012	1
$V-R_C$ (mag)	0.361 ± 0.008	1
J (mag)	10.232 ± 0.020	2
$J-H$ (mag)	0.312 ± 0.033	2
$J-K_s$ (mag)	0.386 ± 0.030	2
$[\mu_\alpha, \mu_\delta]$ (mas yr^{-1})	[4.45, −3.40]	3
Spectral type	G0 V	1
$M_\star$ ($M_\odot$)	$1.08^{+0.11}_{-0.05}$	1
$R_\star$ ($R_\odot$)	$1.00^{+0.06}_{-0.04}$	1
T_{eff} (K)	5960 ± 100	1
$\log g$ (dex)	4.4 ± 0.2	1
$v \sin i$ (km s^{-1})	2.0 ± 1.5	1

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

We gathered rapid cadence, high-precision photometric observations in *I* and *B* on UT 2006 August 10 with the CCD camera on the IAC80 telescope of the Observatorio del Teide, Tenerife, Spain. The CCD camera has a FOV of 10′ × 10′, corresponding to 0.″33 $pixel^{-1}$. After calibrating the images, we carried out aperture photometry with `vaphot` (Deeg & Doyle 2001) on the target and several reference stars of similar brightness in the FOV. We constructed an ensemble average of the calibrators, divided the target by the resulting time series, and renormalized the resulting light curve by the median of its value prior to the transit event. Simultaneous *R* observations were gathered with the TELAST 0.35 m telescope, also located at the Teide Observatory, and were analyzed in a similar fashion. This telescope is able to follow the target to larger air mass permitting greater time coverage, but the resulting light curve showed a residual trend that was likely due to an imperfect extinction correction. To correct for this, we fit a cubic polynomial in time to the out-of-transit data, extended the fit across the complete data set, and divided the data by this function. For each data set, we estimated the measurement errors from the rms variation of the data preceding first contact. The light curves are presented in Figure 1.

In order to confirm the planetary nature of the companion and measure its mass, we carried out RV observations using Keck/HIRES (Vogt et al. 1994) with its I_2 absorption cell (Marcy & Butler 1992). Eleven star + iodine spectra and one template spectrum were collected on UT 2006 August 2–4, permitting good sampling of critical orbital phases. We reduced the data using the MAKEE package written by T. Barlow. Our spectra were gathered with a resolving power of $\lambda/\Delta\lambda \simeq 71{,}000$ and with exposure times of 15 minutes, permitting a typical signal-to-noise ratio of 120 $pixel^{-1}$. Our analysis procedure to derive relative RVs incorporates the full modeling of temporal and spatial variations of the HIRES instrumental profile (Valenti et al. 1995; see also Butler et al. 1996; Korzennik et al. 2000; Cochran et al. 2002). We model each echelle order containing I_2 lines independently and then calculate the internal uncertainties for this star) for each observation as the

TABLE 2
TrES-2 Planet

Parameter	Value
P (days)	2.47063 ± 0.00001
T_c (HJD)	$2{,}453{,}957.6358 \pm 0.0010$
a (AU)	$0.0367^{+0.0012}_{-0.0005}$
i (deg)	83.90 ± 0.22
K (m s^{-1})	181.3 ± 2.6
M_p ($M_{\rm Jup}$)	$1.28^{+0.09}_{-0.04}$
R_p ($R_{\rm Jup}$)[a]	$1.24^{+0.09}_{-0.06}$

[a] Here $R_{\rm Jup} = 71{,}492$ km.

RV scatter about the mean divided by the square root of the number of spectral orders. The RV precision achieved by our code is described in Alonso et al. (2004) and Sozzetti et al. (2006a, 2006b). The RV measurements are listed in Table 3.

The best-fit orbital solution, constrained to have zero eccentricity (as expected from theoretical arguments for a short-period planet), and with the P and transit epoch T_c determined from the photometric data, yields a velocity semiamplitude $K = 181.3 \pm 2.6$ m s^{-1} and an instrumental γ-velocity of $\gamma = -29.8 \pm 2.2$ m s^{-1}. The fit has a $\chi^2_\nu = 0.89$ ($\nu = 9$), and the rms of the residuals is 6.9 m s^{-1}, in excellent agreement with the internal errors. Figure 2 shows the RV data overplotted with the best-fit model, as well as the residuals to the fit. The parameters of the orbital solution are listed in Table 2. We find a minimum mass for the planet of $M_p \sin i = 1.206 \pm 0.016\ [(M_p + M_\star)/M_\odot]^{2/3}\ M_{\rm Jup}$, where i is the orbital inclination and $M_\star$ is the stellar mass. In § 3 we estimate these two quantities to obtain M_p. As a further check on the consistency between the photometric and RV data sets, we fix P, set $e = 0$, and solve for T_c (as well as K and γ). We find $T_c = 2{,}453{,}957.6283 \pm 0.0084$, which is consistent with, but less precisely determined than, the value predicted from the photometry (Table 2).

To investigate the possibility that the RV variations are due not to a planetary companion but rather to distortions in the spectral line profiles arising from contamination of the spectrum by an unresolved eclipsing binary (Santos et al. 2002; Torres et al. 2005), we examined the line bisectors carefully for signs of time-varying asymmetries. We cross-correlated each of our Keck spectra against a synthetic spectrum matching the measured properties of the star. Line bisectors were then computed from the cross-correlation function averaged over spectral orders not affected by the iodine lines, which is representative of the average spectral line profile. Bisector spans were calculated as the velocity difference between points selected near the top and bottom of the bisectors (Torres et al. 2005). If the velocity variations were the result of a stellar blend, we would expect the bisector 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 did not detect any variation exceeding the measurement uncertainties.

As an additional check we carried out detailed modeling of the TrES photometry following Torres et al. (2004) to test the hypothesis that the light curve is the result of blending the main G0 star with an unseen eclipsing binary. The properties of the three stars (parameterized in terms of their mass) were taken from model isochrones subject to the $T_{\rm eff}$ and $\log g$ constraints on the main star. An excellent fit to the TrES r-band light curve was obtained for a triple system composed of a G dwarf primary blended with an eclipsing binary with individual components of spectral type M0 and M4–M5. In this model, the flux ratio between the G dwarf primary and the brightest (M0) component of the blended binary is less than 2%, which would be un-

TABLE 3
Relative Radial Velocity Measurements of TrES-2

Observation Epoch (HJD − 2,400,000)	Radial Velocity (m s^{-1})	$\sigma_{\rm RV}$ (m s^{-1})
53,949.76054	135.5	6.1
53,949.91993	96.8	6.1
53,950.00216	58.9	7.7
53,950.79018	−201.0	8.1
53,950.93491	−204.8	9.0
53,950.98051	−201.7	9.0
53,951.02136	−198.5	7.2
53,951.75032	91.7	6.0
53,951.84863	136.7	7.0
53,951.95209	140.5	7.1
53,952.02736	145.6	8.4

detectable in our spectra. However, the color difference between the G0 and M0 stars is such that we would expect the B data to present an eclipse depth half of that in the TrES bandpass, in contrast to what is observed (Fig. 1). (Although we note in § 3 that a modest color-dependent extinction error may be present in the B data, it is both the opposite sign and of too small an amplitude to permit the blend described here.) More generally, any blend scenario is strongly disfavored by the observed RV orbit and corresponding lack of bisector variability. We conclude from these tests that a blend scenario is strongly inconsistent with the data, and therefore that the star is indeed orbited by a Jovian planet.

3. ESTIMATES OF PLANET PARAMETERS AND CONCLUSIONS

In order to determine $M_\star$ and its uncertainties, we compared our estimates of $T_{\rm eff}$ and $\log g$ with evolutionary models from Yi et al. (2001) assuming solar metallicity. For each isochrone, we identified the range of $M_\star$ for which the $T_{\rm eff}$ and $\log g$ lay within our 1 σ errors. We took the best-fit model as our estimate of $M_\star$ and the span of permitted models (over all ages greater than 500 Myr) to be our uncertainty. We then used the resulting value, $M_\star = 1.08^{+0.11}_{-0.05}\ M_\odot$, and the spectroscopic orbit (§ 2) to estimate $M_p = 1.28^{+0.09}_{-0.04} M_{\rm Jup}$. We also evaluated the stellar radius $R_\star$ in a similar fashion and found results that were consistent with, but less tightly constrained than, that from the light-curve modeling (below). The uncertainty contributed by that in the evolutionary models is less than 0.02 $M_\odot$. Based on the absolute visual mag-

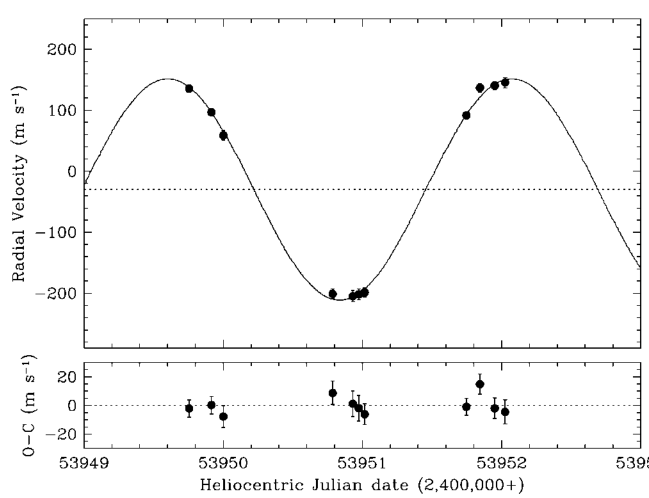

Fig. 2.—*Top*: RV observations of TrES-2 obtained with Keck/HIRES using the I_2 cell. The best-fit orbit (*solid line*) and γ-velocity (*dashed line*) are overplotted. *Bottom*: Residuals from the best-fit model to the RV data.

nitude ($M_V = 4.5$) predicted by the best-fit model, we estimate the distance to be approximately 230 pc. We estimate the reddening in the direction of TrES-2 to be $E(B - V) \sim 0.05$ and the extinction to be ∼0.15 mag from comparison of its observed colors with the intrinsic colors predicted by the model.

To estimate $R_\star$, i, and the planetary radius R_p, we simultaneously fit our light curves using the analytical transit curves of Mandel & Agol (2002) and the color-dependent quadratic limb-darkening parameters from Claret (2000), which were matched to the spectroscopically estimated properties of the star. We identified the best-fit solution by fixing the value of $M_\star$ at its best estimate, 1.08 $M_\odot$, and minimizing the χ^2 to all the photometry. We note that the available time series are well-described by the model, with the exception of the IAC80 B, for which the in -transit data fall below the model. We speculate that those data, which were gathered at high air mass, may have been imperfectly corrected for extinction, which is a larger effect at B than the other bandpasses. The best-fit solution obtains $\chi^2_\nu = 1.15$ ($\nu = 2065$), and its values for $\{R_\star, R_p, i\}$ are listed in Tables 1 and 2. The uncertainties in these quantities are dominated by our uncertainty in $M_\star$. To derive 1 σ errors for each of $\{R_\star, R_p, i\}$, we change the value of that parameter and fix it at a new value, and then allow the other two parameters to float, as well as allow for a value of $M_\star$ within our uncertainty. (The uncertainties in P and T_c are sufficiently small so as not to contribute significantly to the errors in $R_\star$, R_p, and i.) We repeat this procedure until the best-fit solution produces an increase in the χ^2 corresponding to a 1 σ change. Our estimate of the planetary radius, $R_p = 1.24^{+0.09}_{-0.06} R_{\rm Jup}$, implies a mean density of $0.83^{+0.12}_{-0.09}$ g cm^{-3}, indistinguishable from that of TrES-1 (using the values from Sozzetti et al. 2004), despite the fact that TrES-2 is nearly twice as massive. We also note that the impact parameter, $b = a \cos i/R_\star = 0.84 \pm 0.02$, is the largest of any known transiting exoplanet.

We intend to improve our estimates of the planetary and stellar parameters by undertaking a more detailed analysis of the stellar spectrum as we did for TrES-1 (Sozzetti et al. 2004) and by gathering very high-precision z-band photometry (e.g., Holman et al. 2006). Such data will permit us to look for transit timing variations indicative of additional planets in the TrES-2 system (Agol et al. 2005; Holman & Murray 2005; Steffen & Agol 2005). TrES-2 lies within the FOV of the NASA *Kepler* mission. During the 4 year mission, *Kepler* will observe nearly 600 transits of TrES-2. The precision with which *Kepler* will observe these transits will enable an extremely sensitive search for additional planets in the TrES-2 system through their dynamical perturbations. Moreover, the large impact parameter means that very subtle changes in its value could be detected. Such variations are predicted (Miralda-Escudé 2002) to occur as a result of either additional planets, or the stellar quadrupole moment. *Kepler* may also detect the reflected light from TrES-2 (Jenkins & Doyle 2003) and hence determine the long-sought geometric albedo and phase function of a hot Jupiter. The large impact parameter also makes TrES-2 particularly favorable for determining the angle between the stellar spin axis and the orbital axis via the Rossiter-McLaughlin effect (Gaudi & Winn 2006). Williams et al. (2006) discussed the use of *Spitzer* IRAC observations spanning the time of secondary eclipse to resolve the surfaces of extrasolar planets. The large impact parameter of the TrES-2 orbit is ideal for this application, since it grants access to both longitudinal and latitudinal flux variations across the dayside hemisphere of the planet.

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