FOLLOW-UP OBSERVATIONS OF THE NEPTUNE MASS TRANSITING EXTRASOLAR PLANET HAT-P-11b

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Received 2009 May 7; accepted 2009 May 26; published 2009 June 15

ABSTRACT

We have confirmed the existence of the transiting super Neptune extrasolar planet HAT-P-11b. On 2009 May 1 UT, the transit of HAT-P-11b was detected at the University of Arizona’s 1.55 m Kuiper telescope with 1.7 millimag rms accuracy. We find a central transit time of $T_c = 2454952.92534 \pm 0.00060$ BJD; this transit occurred $80 \pm 73$ s sooner than previous measurements (71 orbits in the past) would have predicted. Hence, our transit timing rules out the presence of any large (> 200 s) deviations from the ephemeris of Bakos et al. We obtain a slightly more accurate period of $P = 4.8878045 \pm 0.0000043$ days. We measure a slightly larger planetary radius of $R_p = 0.452 \pm 0.020 R_J$ (5.07 \pm 0.22 $R_{\oplus}$) compared to Bakos and coworkers’ value of $0.422 \pm 0.014 R_J$ (4.73 \pm 0.16 $R_{\oplus}$). Our values confirm that HAT-P-11b is very similar to GJ 436b (the only other known transiting super Neptune) in radius and other bulk properties.

Key words: planetary systems – stars: individual (HAT-P-11)

1. INTRODUCTION

The transit of an extrasolar planet across the face of its host star allows direct measurement of the bulk properties of the planet. In particular, the transit allows accurate determination of the planet’s radius (see, for example, Charbonneau et al. 2006 and references within). When these radii are combined with radial velocity (RV) measurements of masses then densities of the transiting extrasolar planets can be calculated. Knowledge of the heating from the star allows estimates of the temperatures of the irradiated planets. Models of the bulk properties of these planets can be compared to observation (see, for example, Baraffe et al. 2008; Fortney et al. 2007; Burrows et al. 2007; Seager et al. 2007).

While some 591 transiting extrasolar planets are now known, only three have masses less than 10% of Jupiter (closer to Neptune in mass). The first transiting super Neptune was GJ 436b which was discovered during a M2.5 star at 0.028 AU by an RV survey of Butler et al. (2004). They found it had a mass of $\sim 21 M_{\oplus}$. Follow-up photometric observations of GJ 436b then discovered it to be a $\sim 8$ millimag (mmag) ($\sim 0.7\%$) transiting planet (Gillon et al. 2007). Further follow-up measurements find a radius of $\sim 4.2-4.9 R_{\oplus}$ (Torres et al. 2008; Bean et al. 2008, respectively) and a density of $\rho = 1.69^{+0.14}_{-0.12} g cm^{-3}$ (Torres 2007). Through these transit observations and modeling by Baraffe et al. (2008), it has been determined that GJ 436b is mainly composed of metals with only a small H/He envelope.

The second transiting Neptune discovered was HAT-P-11b, in orbit around HAT-P-11 (2MASS 19505021+4804508) a K4 (V = 9.6 mag) metal-rich star. This planet was discovered by the HATNet array of small 0.11 m telescopes on Mt. Hopkins in Arizona (Bakos et al. 2009). At just 4.2 mmag, HAT-P-11b was the smallest planet discovered by the transit method. Moreover, Bakos et al. (2009) argue that compared to recent measurements of the radius of GJ 436b, HAT-P-11b was at the time the smallest transiting extrasolar planet known. However, the CoRoT team has announced the discovery of COROT-7b which is smaller still with just 1.7 $R_{\oplus}$ (Rouan et al. 2009). In any case, transiting objects of less than 0.1 $M_J$ number no more than three today and start to probe densities and masses closer to terrestrial—in contrast to lower density gas giants composed mainly of a large H/He envelope.

In the case of HAT-P-11b, detailed RV measurements by Bakos et al. (2009) show a linear drift ($0.0297 \pm 0.0050 \ m \ s^{-1} \ day^{-1}$) in the RV residual of HAT-P-11. This drift is possibly due to the pull of an additional unseen planet in the system (Bakos et al. 2009). In addition, Bakos et al. (2009) determine a nonzero (0.198 \pm 0.046) eccentricity which might be maintained by interactions with another planet. Both observations hint at the presence of another outer planet “HAT-P-11c” in the system. Indeed, most systems with super Neptunes are multiple planet systems (Bakos et al. 2009 and references within). However, it is worth noting that, to date, no transiting planet is known to be a member of a multiple planet system. Hence, detection of multiple transiting planet system would be very interesting. Continued RV monitoring of this system may directly detect curvature in the RV residuals due to this outer planet. Another way to directly detect the presence of a possible “HAT-P-11c” would be a sensitive search for transit timing variations over a series of HAT-P-11b transits. A search to bound the magnitude of such timing variations motivated this Letter.

2. OBSERVATIONS AND REDUCTIONS

Data were taken at the University of Arizona’s 61 inch (1.55 m) Kuiper telescope on Mt. Bigelow, Arizona on 2009 May 1 UT with the Mont4k CCD, binned 3 \times 3 to 0’043 pixel$^{-1}$. Observing a single transit of HAT-P-11b at high signal-to-noise ratio (S/N) is fairly challenging, since the transit depth is just $\sim 4.3$ mmag, HAT-P-11 itself is a very bright V = 9.6 mag K4 star with a nearby faint (likely background) star, the surrounding “Kepler field” is somewhat crowded, and all of the potential photometric reference stars are several magnitudes fainter than HAT-P-11. Defocusing was not possible, due to the crowded field and the difficulty of maintaining a consistent focus offset with this telescope/instrument combination. In order to take long enough exposures to sufficiently average out atmospheric scintillation noise, while still avoiding saturation of the CCD, we used a medium bandwidth Stromgren b filter ($\Delta \lambda = 18.0 \ nm$). The Mont4k filter holder and filter sensor

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position were specifically modified to accommodate the thicker Stromgren filter for our observations.

The conditions were photometric with light wind and no moon throughout the observational period. In total 448 images were obtained with < 2 pixels of wander, due to excellent autoguiding. Integration times of 20 s were used at the start when the target was still at relatively high air mass. Just prior to the start of the transit (after the 109th image), the exposure times were reset to 17 s, giving a sampling time of 28.3 s for the remainder of the observations. The relatively fast overhead time is achieved mainly by binning 3 × 3 and skipping the flushing of the CCD after each readout and before the subsequent exposure in the sequence, but is also a product of the Mont4k’s design, which includes two amplifiers and preamplifiers.

The images were bias subtracted, flat-fielded, and bad pixel cleaned in the usual manner. Aperture photometry and sky subtraction was performed for the target star and three reference stars using the aperture photometry task PHOT in the IRAF DAOPHOT package. An aperture radius of 4′/3 (10.0 pixels) was adopted, as it produced the smallest scatter in the light curve and also eliminated contamination from HAT-P-11’s nearby companion, which is 5.4 mag fainter in b and 8′/9 to the north-northeast (at a position angle of 9°). The reference stars are 2.3–2.65 mag fainter than HAT-P-11, and were chosen to be distributed as uniformly as possible about the target star on the sky (they formed a triangle around HAT-P-11 at distances of 89, 208, 345″ from HAT-P-11). The reference stars were normalized to unity and then weighted according to their average fluxes.

We applied no sigma clipping rejection to the reference stars or HAT-P-11—all data points were used in the analysis. The final light curve for HAT-P-11 was normalized by division of the weighted average of the three reference stars. The residual light curve in Figure 1 (bottom left) has a photometric rms range of 1.7 mmag rms and a time sampling of 29 s on average. This is very typical of the relative photometric precision achieved with the Mont4k on the 61 inch (Kuiper) telescope for high S/N images (Randall et al. 2007; Dittmann et al. 2009).

### Table 1

| Parameter        | Value                  | Reference               |
|------------------|------------------------|-------------------------|
| \(P\) (days)     | 4.8878162 ± 0.0000071  | Bakos et al. (2009)     |
| \(T_c\) (BJD)    | 2453217.75466 ± 0.00187| Bakos et al. (2009)     |
| \(T_c\) (BJD)    | 2454605.89132 ± 0.00032| Bakos et al. (2009)     |
| \(b\)            | 0.347 ± 0.139          | Bakos et al. (2009)     |
| \(R_p/R_\ast\)   | 0.0621 ± 0.0011         | This work               |
| \(R_p/R_\ast\)   | 0.452 ± 0.020          | This work               |

Note.

* The new period value was calculated by a sigma-weighted least square of all three \(T_c\) values.

The planetary transit light curves were fitted using the \(\chi^2\) method prescribed by Mandel & Agol (2002). The transit HAT-P-11b parameters used in the fit were those in Table 1 measured by Bakos et al. (2009). The correct linear and quadratic limb darkening parameters for our \(b\) filter were taken from Claret (2000). In order to detect any transit timing variations, the only parameter that was allowed to vary in the fit was the central time of the transit, \(T_c\). The time of the center of this transit, \(T_c\), is shown near the bottom of Table 1. We note that the purpose of this section of the Letter was not to re-derive all the parameters of the transit but to understand if our transit is consistent with the period of Bakos et al. (2009).

To measure \(T_c\), we minimized \(\chi^2\) to find a \(T_c = 2454952.92534 ± 0.00060\) BJD value (the flux uncertainty for each data point in the \(\chi^2\) fit was calculated from the propagation of the photometric errors determined with the PHOT task). The ±0.00060 day 1\(\sigma\) uncertainty was estimated by Monte Carlo (MC) simulations of 1000 simulated data sets with the same light curve in Figure 1 (bottom left) has a photometric rms of 89, 208, 345" which includes two amplifiers and preamplifiers.

### 3.2. Determination of a New Planetary Radius Value

To try and understand if our transit data suggest a different planetary radius for HAT-P-11, we repeated the fit in the last section using the \(\chi^2\) method prescribed by Mandel & Agol (2002) but this time allowed the planetary radius \(R_p\) to vary along with \(T_c\). In Figure 1 (right), we plot the result of our fit (solid red line) and the residuals of this fit below.

To measure \(R_p/R_\ast\), we further minimized the reduced \(\chi^2\) to 1.06 with simultaneous fits of \(R_p/R_\ast = 0.0621 ± 0.0011\) and \(T_c = 2454952.92534\). The ±0.0011 1\(\sigma\) uncertainty in \(R_p/R_\ast\) was estimated by MC simulations of 1000 fake data sets with the same 1.7 mmag rms scatter as the original data (see Figure 2, right).

### 4. DISCUSSION

#### 4.1. Is the Timing of the Transits Changing?

A key goal of this Letter is to compare our measured 2009 May 1 UT \(T_c\) to that predicted from the previously measured values. Projecting the \(P = 4.8878162 ± 0.0000071\) day period of Bakos et al. (2009) forward from their most accurate \(T_{c1} = 2454605.89132 ± 0.00032\) transit suggests that our May 1 transit \((n = 71\) periods later\) occurred \(\Delta T = 80 ± 73\) s sooner (where \(\Delta T\) was calculated by \(\sqrt{\sigma^2_{T1} + \sigma^2_{T2}}\)) than our observed \(T_{c2} = 2454952.92534 ± 0.00060\) BJD was predicted to be. However, the significance of this disagreement is small. Indeed there is ~60% probability that our observations are fully consistent with the timing measurements (and uncertainties) of Bakos et al. (2009). Certainly, we can rule out large > 200 s timing errors at the ~ 3\(\sigma\) level.

With the addition of our new \(T_c\) values to the two previous values, we derive a new \(P = 4.8878045 ± 0.000043\) day value for the period of HAT-P-11b (based on a sigma-weighted average; see Table 1). This new value is slightly shorter than the \(P = 4.8878162 ± 0.0000071\) day period of Bakos et al. (2009). However, it will require future observations to determine if this new period will better predict future transit times. It is entirely possible that all of our transit timing values are consistent with predictions from Bakos et al.’s ephemeris within

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2 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Figure 1. Left: the time series of HAT-P-11 during the transit of 2009 May 1 UT. We show our best fit (reduced $\chi^2 = 1.06$) with simultaneous fits of $R_p/R_\ast = 0.0621 \pm 0.0011$ and $T_c = 2454952.92534$ (solid red curve). The 1.7 mmag rms residuals of the fit are shown below. Right: the time series of our three calibrator stars (each normalized by the sum of the remaining two calibrator stars). The excellent conditions of the night allowed for mmag photometry in individual 17 or 20 s exposures even on these fainter reference stars.

Figure 2. Left: one thousand Monte Carlo (MC) simulations of independent simulated data sets following our best-fit transit model each drawn from a population of data with the same 1.7 mmag rms as our data in Figure 1 (left). Based these MC simulations we find with our 1.7 mmag rms uncertainty, we can constrain $T_c$ to an accuracy of $\pm 0.00060$ days (or 51.84 s) at the 1$\sigma$ level. Right: here another 1000 MC realizations imply the uncertainty in the $R_p/R_\ast$ ratio to be $\pm 0.0011$ at the 1$\sigma$ level.

In general, it is difficult with a single additional transit to confidently determine if the discovery period of Bakos et al. (2009) and over the last 71 orbits has only changed by 0.177 $\pm$ 1.009 s. Hence, there is no significant evidence, with the data in hand, that HAT-P-11b’s period has changed over the last 0.95 year compared to the previous 3.79 years.

4.2. What is the Radius of HAT-P-11b?

Our observations of the depth of the transit finds a deeper transit and a $R_p/R_\ast = 0.0621 \pm 0.0011$ compared to 0.0576 $\pm$ 0.0009 of Bakos et al. (2009). We find that $R_p/R_\ast$ is 0.0045 $\pm$ 0.0014 larger than that of Bakos et al. (2009). Hence, there is a significant probability that our transit was deeper than that of Bakos et al. (2009). We derive a slightly larger planetary radius of $R_p = 0.452 \pm 0.020 R_J (5.07 \pm 0.22 R_\oplus)$ compared to Bakos et al.’s values of $0.422 \pm 0.014 R_J (4.73 \pm 0.16 R_\oplus)$. Our values suggest that HAT-P-11b is very similar to GJ 436b in radius.
5. CONCLUSIONS

We confirm the existence of the transiting planet HAT-P-11b. Our main conclusions from our 1.7 mmag rms (unbinned) transit observations (with the University of Arizona’s 1.55 Kuiper telescope) of the 2009 May 1 UT transit are

1. We find a central transit time of \( T_c = 2454952.92534 \pm 0.00060 \) BJD from a best fit to our data. We estimate that the transit occurred 80 ± 73 s sooner than previous (71 orbits in the past) measurements would have predicted (Bakos et al. 2009). Our finding is consistent with the ephemeris of Bakos et al. and rules out the presence of any large timing variation.

2. We derive a slightly larger planetary radius of \( R_p = 0.452 \pm 0.020 \) \( R_J \) \( (5.07 \pm 0.22 \) \( R_\oplus \) \) compared to Bakos et al.’s values of \( 0.422 \pm 0.014 \) \( R_J \) \( (4.73 \pm 0.16 \) \( R_\oplus \) \). Our values suggest that HAT-P-11b is very close to GJ 436b in radius.

We thank the anonymous referee for helpful comments leading to a better final paper. We thank Greg Stafford, Gary Rosenbaum, and the Catalina Mountain staff for modifying the Mont4k filter box and holder so that we could use the Stromgren b filter. We also thank the Arizona NASA Space Grant program for funding this work. L.M.C. is supported by an NSF Career award and the NASA Origins program.

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