TRANSIT OBSERVATIONS OF THE WASP-10 SYSTEM

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ABSTRACT

We present here observations of the transit of WASP-10b on 2009 October 14 UT taken from the University of Arizona’s 1.55 m Kuiper telescope on Mount Bigelow. Conditions were photometric and accuracies of 2.0 mmag rms were obtained throughout the transit. We have found that the ratio of the planet to host star radii is in agreement with the measurements of Christian et al. instead of the refinements of Johnson et al., suggesting that WASP-10b is indeed inflated beyond what is expected from theoretical modeling. We find no evidence for large (>20 s) transit timing variations in WASP-10b’s orbit from the ephemeris of Christian et al. and Johnson et al.

Key words: planetary systems – stars: individual (WASP-10)

Online-only material: color figures

1. INTRODUCTION

Transiting extrasolar planets are relatively rare among all known planet discoveries (69 transiting planets out of 429 known planetary systems). However, transits are unique in that they allow for the direct measurement of the radius of the transiting planet relative to the host star. Combined with radial velocity data, it is possible to determine the density of the transiting planet as well. Knowledge of the heating of the star can allow models of the bulk properties of these planets to be formulated and then compared to observation (for example, Baraffe et al. 2008; Fortney et al. 2007; Burrows et al. 2007).

Since the depth of the transit is directly related to its radius, the size of a transiting planet is one of the easiest parameters to measure. This makes transiting planets especially interesting to discover and study in detail; however, this method becomes increasingly difficult when trying to probe to lower mass planets, although the Kepler Space Telescope (Borucki et al. 2008) is expected to detect many planets as small as, or smaller than, the Earth.

While most transiting planets are in nearly circular orbits, there are a small number of planets that maintain eccentric orbits despite being older than the circularization time scale for the system. The most notable of these systems are the transiting Neptunes GJ 436b (Butler et al. 2004) and HAT-P-11b (Bakos et al. 2010). GJ 436b has a significantly nonzero eccentricity of 0.15 ± 0.012 (Deming et al. 2007), despite being older than its circularization time scale (Maness et al. 2007), which has led to speculation about possible additional (possibly resonant) planets in the system gravitationally “pumping” the eccentricity. Gravitational interaction with a third body would also lead to transit timing variations (TTVs) as the line of nodes precesses, but searches for this effect have found no evidence for TTVs in this system (Pont et al. 2009; Ballard et al. 2010). A search in the similar HAT-P-11 exo-Neptune system has yielded no positive indication for large TTVs (Dittmann et al. 2009b).

WASP-10b is a recently discovered 2.96 MJ, 1.28 RJ hot Jupiter in orbit around a K5 dwarf star (Christian et al. 2008). Due to the small size of the star (0.775±0.043R⊙), the transit depth is relatively deep, at 29 mmag (Christian et al. 2008). WASP-10b is in a 3.0927636±0.0000094 day, 0.059±0.014 eccentr-
Figure 1. Plot of the reference stars used to normalize the transit as a function of time. rms scatter of these stars is approximately 2.0 mmag, which is typical for this instrumental setup and reduction. The flux of each reference star was normalized by the average fluxes of the other five reference stars. The two small (≈2 minutes) gaps in the data are due to our instrument script stopping and then restarting, and not due to weather.

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

from 1′1 to 1′5, which is typical for this site. Due to excellent autoguiding, there was less than 5 pixels (2′′15) of image wander over the course of the night. The airmass of our observations ranged between 1.30 at the start of our observations and 1.02 four hours later at the end of our observations. The on-board clock is synched to GPS every few seconds in order to ensure accurate absolute time keeping.

Each of the 579 images was bias-subtracted, flat-fielded, and bad pixel-cleaned in the usual manner. Aperture photometry was performed using the aperture photometry task PHOT in the IRAF3 DAOPHOT package. A 4′3 aperture radius (corresponding to 10.0 pixels—see light curve shown in Figure 1) was adopted because it produced the lowest scatter in the resultant light curve. Several combinations of reference stars were considered, but six were selected for the final reduction because of the low rms (~2.0 mmag) scatter. These reference stars were all distributed a few arcminutes east of the target, but scattered both slightly north and slightly south of WASP-10. We were unable to find sufficiently bright reference stars to the west of WASP-10 without increasing our rms scatter. We show the time series light curve for each reference star (normalized to the average flux of the other reference stars) in Figure 1.

We applied no sigma clipping rejection to the reference stars or WASP-10; all data points were used in the analysis. The final light curve for WASP-10 was normalized by division of the weighted average of the six reference stars. The unbinned residual time series in Figure 2 has a photometric rms of 2.0 mmag, which is typical for the Mont4k on the 61 inch (Kuiper) telescope for our high signal-to-noise ratio transit photometry pipeline (Dittmann et al. 2009a, 2009b; Scuderi et al. 2010).

3 ANALYSIS

We fit the transit light curve with the method prescribed by Mandel & Agol (2002), fitting for the impact parameter ($b = a \cos i / R_*$), central time of transit, and planet to star radius ratio. The fit and residuals from the fit are shown in Figure 2. Linear and quadratic limb darkening coefficients in the $I$ band were taken from Claret (2000) as 0.3678 and 0.2531, respectively. In order to estimate the errors for our fits, we generated and fit 1000 fake data sets by taking our measured data points and adding white noise with a standard deviation equal to the instrumental standard deviation (≈0.002 mag) of our data points. The results of our fit, and those of Christian et al. (2008) and Johnson et al. (2009), are shown in Table 1.

The radius measurements of Christian et al. (2008) and Johnson et al. (2009) are in significant (5σ) disagreement. We

\[ r = \frac{R_p}{R_*} = \frac{R_p}{R_\odot} \]

where $R_p$ is the radius of the planet and $R_\odot$ is the radius of the star.

3 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
find that our measurement, while between these previous results, is significantly closer to the result of Christian et al. (2008) than to that of Johnson et al. (2009). We show a comparison between the different models in Figure 3. We find a planet to star radius ratio of $0.16754 \pm 0.00060$, consistent with the result of Christian et al. (2008) of $0.17029 \pm 0.002$ but not with Johnson et al.’s (2009) of $0.15918^{+0.00050}_{-0.00115}$. However, we note that both our data and Christian et al.’s (2008) data have higher rms scatter than Johnson et al.’s (2009) 0.5 mmag scatter data set. Furthermore, we find it unlikely that Johnson et al.’s (2009) data are contaminated by nearby stars as the brightest star within 40′′ of WASP-10 is over 100× fainter than WASP-10. However, if our result and those of Christian et al. (2008) are correct, then it is clear that WASP-10b is significantly inflated beyond expectations from theoretical modeling. This, combined with its nonzero eccentricity, makes the WASP-10 system an interesting system and in need of further follow-up observations.

4. DISCUSSION

While we do not know the difference between the discrepancy between measurements of the planet to star radius ratio, we can speculate about the possible causes for the different measurements. One possibility for this discrepancy is the presence of starspots on the surface of the star during the transit of Johnson et al. (2009) but not the transits of Christian et al. (2008) or our transit. If a significant amount of the stellar surface area not occulted by the planet were populated with darker starspots, then the disk of the planet would block a larger percentage of luminous area than a strictly geometrical model. This effect, in turn, can lead to differing measurements of the planet size depending on the location and number of starspots on the surface at any individual time. This effect has been observed in the case of WASP-4 by Southworth et al. (2009) and in several other systems using previous data by Southworth (2008).

However, the observed difference in the planet to star radius ratio between Johnson et al. (2009) and Christian et al. (2008) is very large (16%), which requires that the part of the stellar disk not occulted by WASP-10 must also vary its brightness with respect to the occulted portion by this amount. We consider it to be unlikely that WASP-10 would be so heavily spotted, but that no spots would be in the transit path, especially considering that WASP-10b crosses close to the stellar equator, where starspots would be more likely to occur. We see no evidence in our light curve for starspots in the transit path (for an example of such a signal, see Rabus et al. 2009; Dittmann et al. 2009a). Therefore, we suggest that starspots are not the cause of the discrepancy in planet radius measurements.

Another possibility for the different radii measurements could be the different values for the impact parameter ($b = a \cos i/R_*$) adopted for each fit. The larger the impact parameter, the further from the center of the stellar disk the planet transits, which means that due to limb darkening, the planet is effectively crossing a dimmer portion of the star, which can affect the transit depth. However, as the impact parameter increases, the chord length of the transit is shorter, and the transit is therefore shortened. Furthermore, as the impact parameter increases, the shape of the ingress portion changes detectably. For small values of the impact parameter, the precise value of the impact parameter becomes harder to fit, as the curvature of the stellar disk is minimal at this point. We note that while the values for the impact parameter are different for each study, all are relatively small, meaning that WASP-10b is not fully immersed in the severely limb darkened portion of the star. Indeed, we have found that in order to recreate the observed transit depth of Johnson et al. (2009), using our larger radius, we must increase the impact parameter until WASP-10b is nearly grazing, significantly reducing the length of transit. We were unable to leave the planet to star radius ratio unchanged while only altering the impact parameter and be consistent with all data. Therefore, we consider it more likely that the measurement differences are due to systematic effects associated with the OPTIC instrument used by Johnson et al. (2009) rather than the measurements of Christian et al. (2008) and our own measurements.

Since WASP-10b has a significantly nonzero eccentricity orbit despite being older than its circularization time scale (Jackson et al. 2008), then it is possible that a third body is present in the system acting as an eccentricity pump. This body would perturb the orbit of WASP-10b, and could lead to measurable TTVs, as theoretically investigated by Haghighipour et al. (2008). By using the transit times of Christian et al. (2008), Johnson et al. (2010), and our data point, we are able to investigate a time scale of 246 orbits, or ≈760 days. We fit a line to the available transit times, and find a refined best-fit period of $3.092717 \pm 0.000007$ days, only $2\sigma$ lower than that found by

![Figure 3. Overplot of our best-fit model (red) with the model of Christian et al. (2008) in blue and Johnson et al. (2009) in green. Our model, while falling between those of Christian et al. (2008) and Johnson et al. (2009), is significantly closer to Christian et al. (2008).](image1)

![Figure 4. $O-C$ plot of the transit times of Christian et al. (2008), Johnson et al. (2010), and our transit point. We use our best-fit ephemeris of $T_e = 2454357.858089 + E \times 3.092717$. We find no evidence for significant deviations from a linear ephemeris over long (246 orbit) time scales.](image2)
Christian et al. (2008). Figure 4 shows an observed–calculated (%O−C) plot for all currently published transit points, using our linear model. We find no large-scale deviations (>20 s) from a linear ephemeris and therefore conclude that there are unlikely to be large-scale TTVs in the WASP-10 system and there is also unlikely to be a large perturber acting as an eccentricity pump. However, we note that TTVs require many observations to be definitively ruled out, as individual variations can periodically be small.

5. CONCLUSIONS

We have investigated one follow-up transit of WASP-10b in order to investigate the (5σ) discrepancy between the planet radii measurements of Christian et al. (2008) and Johnson et al. (2009). We have found that, while Johnson et al. (2009) apparently collected more precise data, our radii measurement agrees with that of Christian et al. (2008) and that WASP-10b does appear to be inflated beyond the level expected from theoretical models. Furthermore, we have no evidence that WASP-10b’s eccentricity is due to perturbation by a third body. If there was a third body in the system, then we would expect successive transits of WASP-10b to exhibit signs of TTVs. However, we have found that our ephemeris is consistent to within 2σ of Christian et al.’s (2008) and Johnson et al.’s (2009) ephemerides, and therefore large TTVs are unlikely in this system.

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REFERENCES

Bakos, G. Á., et al. 2010, ApJ, 710, 1724
Ballard, S., et al. 2010, BAAS, 42, 425
Baraffe, I., Chabrier, G., & Barman, T. 2008, A&A, 482, 315
Borucki, W., et al. 2008, in IAU Sym. 249, Exoplanets: Detection, Formation and Dynamics, ed. Y.-S. Sun, S. Ferraz-Mello, & J.-L. Zhou (Cambridge: Cambridge Univ. Press), 17
Burrows, A., Hubeny, I., Budaj, J., & Hubbard, W. B. 2007, ApJ, 661, 502
Butler, R. P., et al. 2004, ApJ, 617, 580
Christian, D. J., et al. 2008, MNRAS, 392, 1585
Claret, A. 2000, A&A, 363, 1081
Deming, D., et al. 2007, ApJ, 667, L199
Dittmann, J. A., Close, L. M., Green, E. M., & Fenwick, M. 2009a, ApJ, 701, 756
Dittmann, J. A., Close, L. M., Green, E. M., Scuderi, L. J., & Males, J. R. 2009b, ApJ, 699, L48
Fortney, J. J., Marley, M. S., & Barnes, J. W. 2007, ApJ, 659, 1661
Haghighipour, N., Steffen, J., & Agol, E. 2008, AGU Fall Meeting, abstract #P14B-04
Jackson, B., Greenberg, R., & Barnes, R. 2008, ApJ, 678, 1396
Johnson, J. A., et al. 2009, ApJ, 692, L100
Johnson, J. A., et al. 2010, ApJ, 712, L122
Mandel, K., & Agol, E. 2002, ApJ, 580, L171
Maness, H. L., et al. 2007, PASP, 119, 90
Pont, F., Gilliland, R. L., Knutson, H., Holman, M., & Charbonneau, D. 2009, MNRAS, 393, L6
Rabus, M., et al. 2009, A&A, 494, 391
Scuderi, L. J., et al. 2010, ApJ, 714, 462
Southworth, J. 2008, MNRAS, 386, 1644
Southworth, J., et al. 2009, MNRAS, 399, 287