DETECTION OF $K_S$-BAND THERMAL EMISSION FROM WASP-3b

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ABSTRACT

We report the detection of thermal emission from the hot Jupiter WASP-3b in the $K_S$ band, using a newly developed guiding scheme for the WIRC instrument at the Palomar Hale 200 inch telescope. Our new guiding scheme has improved the telescope guiding precision by a factor of $\sim 5$–7, significantly reducing the correlated systematics in the measured light curves. This results in the detection of a secondary eclipse with depth of $0.181\% \pm 0.020\%$ ($9\sigma$)—a significant improvement in WIRC’s photometric precision and a demonstration of the capability of Palomar/WIRC to produce high-quality measurements of exoplanetary atmospheres. Our measured eclipse depth cannot be explained by model atmospheres with heat redistribution but favors a pure radiative equilibrium case with no redistribution across the surface of the planet. Our measurement also gives an eclipse phase center of 0.5045 ± 0.0020, corresponding to an $e \cos \omega$ of 0.0070 ± 0.0032. This result is consistent with a circular orbit, although it also suggests that the planet’s orbit might be slightly eccentric. The possible non-zero eccentricity provides insight into the tidal circularization process of the star–planet system, but might also have been caused by a second low-mass planet in the system, as suggested by a previous transit timing variation study. More secondary eclipse observations, especially at multiple wavelengths, are necessary to determine the temperature–pressure profile of the planet’s atmosphere and shed light on its orbital eccentricity.

Key words: infrared: planetary systems – planetary systems – stars: individual (WASP-3)

Online-only material: color figures

1. INTRODUCTION

Detections of thermal emission from exoplanetary atmospheres have been widely achieved from ground for about a dozen hot Jupiters since 2009 (e.g., Rogers et al. 2009; Sing & López-Morales 2009; Alonso et al. 2009; Gibson et al. 2010; Croll et al. 2010, 2011; Cáceres et al. 2011; de Mooij et al. 2011; Zhao et al. 2012, etc.). These observations provide important probes of planetary atmospheres at the near-IR where most of the bolometric output of the planet emerges. They also measure deeper and higher-pressure layers of atmospheres than observations at longer wavelengths, highly complementary to the Spitzer IRAC measurements. When combined together, these broadband multi-wavelength measurements can provide constraints to planetary spectral energy distributions, and help to distinguish between differing atmospheric pressure–temperature profiles and chemistries (e.g., Madhusudhan et al. 2011). Detection of secondary eclipses of transiting planets also provide important constraints to their small orbital eccentricities that are usually hard to distinguish from zero by radial velocity measurements. Precise eccentricity measurements can improve estimates of planetary radius (Madhusudhan & Winn 2009), and can provide important information to their tidal circularization process, shedding light on the nature of, in some cases, anomalously inflated radii of some planets (e.g., Miller et al. 2009).

WASP-3b is a massive transiting hot Jupiter (1.76 $M_{Jup}$) orbiting an F7-8V type star at 0.0317AU (Pollacco et al. 2008). Several groups have measured its spin–orbit alignment via the Rossiter–McLaughlin effect, finding a close alignment between the stellar rotation axis and the planet’s orbital axis (Tripathi et al. 2010; Miller et al. 2010; Simpson et al. 2010). Studies have also measured transits of WASP-3b at many epochs to search for possible transit timing variation (TTV) caused by a low-mass body in an outer orbit. Gibson et al. (2008) observed two transits of WASP-3b but did not find significant difference from the original timing of Pollacco et al. (2008). Maciejewski et al. (2010) later combined six new transits with previous data and found a periodic time variation of $\sim 3.7$ days, which could be interpreted as caused by a hypothetical second planet with a mass of $\sim 15 M_{Jup}$ at a semimajor axis of 0.0507AU and a period very close to the 2:1 mean motion resonance. However, they also emphasized that more observations are required to confirm this periodic variation. Meanwhile, Littlefield (2011) observed five transits of WASP-3b and found supportive evidence to the result of Maciejewski et al. (2010). Efforts have also been employed to search for additional transiting planets in the WASP-3 system, but no candidates were found (Ballard et al. 2011).

The close-in orbit and relatively large radius of WASP-3b and the strong radiation from its host star ($T_{eff} \sim 6400$ K) make its atmosphere highly irradiated ($T_{eq} = 1960$ K), making it an ideal target for secondary eclipse detections and studies of its atmospheric properties. Despite its high temperature, WASP-3b’s atmosphere remains one of the least characterized among the most irradiated hot Jupiters, i.e., with only an upper limit of secondary eclipse at 650 nm (Christiansen et al. 2011) and two detections in the $K_S$ band (Croll 2011; B. Croll et al. 2012, in preparation).
Here we report another detection of WASP-3b’s thermal emission in the $K_S$ band using the Palomar Hale 200 inch telescope with an improved guiding scheme. We present our observations, including the guiding improvement, and data reduction procedure in Section 2. We describe our data analysis and results in Section 3. We discuss our measured eclipse phase center and compare the eclipse depth of WASP-3b with existing models in Section 4. We then summarize our results in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

The observation of WASP-3b was conducted in the $K_S$ band with the WIRC instrument (Wilson et al. 2003) on the Palomar 200 inch Hale telescope on UT 2011 June 24 (PI: Hinkley). WIRC has a $2048 \times 2048$ Hawaii-II HgCdTe detector with a scale of $0.2487$ pixel$^{-1}$ and a wide field of view of $8.7 \times 8.7$. The observation started at 04:05:59.012 UTC on 2011 June 24 and ended 358.12 minutes later. To minimize instrument systematics, we stayed on the target without dithering for the entire observation. The telescope was defocused to an FWHM of about 2.5–3." to keep the counts well within the linearity regime and to mitigate intra-pixel variations. Each image was taken with 12 s exposure and single Fowler sampling. A total of 683 images were obtained. The duty cycle of the observation was 44%.

2.1. Improved Guiding for Palomar/WIRC

Because WIRC does not have a dedicated guider, its guiding of targets relies completely on telescope tracking. A previous study has shown that the limited tracking precision of the telescope, especially along the X-axis (i.e., the direction of R.A.), results in highly correlated systematics in the detected light curves (Zhao et al. 2012). These systematics are caused by inter-pixel variations of the detector (due to imperfect flat-fielding) and is a dominant source of “red noise” in high-precision light-curve measurements. Stabilized guiding is necessary to partially mitigate this problem. We therefore designed an active guiding scheme to correct for the telescope tracking errors during observing based on the information obtained from previous images. The algorithm has been integrated into the WIRC control system to offer fast corrections. Figure 1 demonstrates the effectiveness of the new guiding scheme, which has improved the guiding precision of WIRC by a factor of $\sim 5–7$. Currently, the precision is limited to $\sim 2–3$ pixels due to a highly periodic gear oscillation with a frequency of $\sim 0.5$ Hz from the telescope. We have been developing another algorithm to further correct this oscillation, and expect to deliver better guiding precision in future observations.

The observation of WASP-3 was conducted during the development stage of the new guiding scheme. The guiding performance was similar to the middle panel of Figure 1, despite a loss of 45.43 minutes of data due to a software glitch occurred during middle eclipse (also see Figure 2) and a $\sim 0.5$ pixel centroid shift after the observation was recovered.

2.2. Data Reduction

For the data reduction process, we first subtracted all images with corresponding averaged dark frames. Twilight and sky flats were normalized and averaged to get a master flat field. A bad pixel mask was then created with the master flat and dark frames. The bad pixels in each image were interpolated with cubic splines based on adjacent flat-fielded pixels. WASP-3 is the brightest star in its relatively sparse field. To properly correct the highly correlated common-mode systematics in its light curve, six well-separated and evenly distributed stars within the flux range of 0.13–0.71 times that of WASP-3 were selected as references. Other stars in the field were too faint to have sufficient signal to noise and were thus excluded. We calculated the centroids of all stars in each image using a center-of-mass calculation, since it provided the smallest scatters of their relative positions. The time series of WASP-3’s centroid was determined by averaging the relative positions of all reference stars after correcting for their relative distances.

Aperture photometry was performed on WASP-3 and the reference stars following the IDL routines of DAOPHOT. The extracted fluxes of each star were normalized to the median of the time series. We used the median of the six reference time series as the final reference light curve due to the presence of outliers in the light curves of some reference stars and the fact that the median is a more robust estimator. The final reference light curve is then used to normalize the flux of WASP-3 to correct for the common-mode systematics such as variations of atmospheric transmission, change of seeing and airmass, etc. We applied 48 different aperture sizes with a step of 0.5 pixel, and determined that an aperture with a radius of 16 pixels (i.e., a 32 pixel diameter) gives the smallest out-of-eclipse and in-eclipse scatters for the normalized WASP-3 data; this was taken as the final photometry aperture for all stars in every image.
Figure 2. Reduced flux and best-fit light curve of WASP-3b. The first panel shows the reduced and normalized flux of WASP-3b (black dotted line), overplotted with the fluxes of the six reference stars (colored lines). The second panel shows the light curve of WASP-3b after correcting with the reference light curve, along with its best-fit model (solid blue line). The third panel shows the residual of the best fit. The bottom panel shows the averaged light curve together with the best-fit model. Error bars of the points are calculated from the scatter of the data in each bin. A software glitch occurred during middle transit, causing a gap of 45.43 minutes in the light curve. The larger scatter in the data between phases 0.54 and 0.55 was likely due to deteriorated seeing.

A sky annulus with 30 pixel inner radius and 35 pixel width was used for background estimation. The median value of the sky annulus was then used as the final sky background for subtraction. We have also explored different annulus ranges and sizes, and found consistent results. The top two panels of Figure 2 show the reduced fluxes of all seven stars and the final normalized flux of WASP-3, respectively. The UTC mid-exposure time of each image was converted to BJD TDB using the UTC2BJD routine provided by Eastman et al. (2010). The orbital phases were calculated based on the latest ephemeris of Christiansen et al. (2011), since they have taken both the previously published transit times and their new EPOCh transits into account (i.e., period = 1.8468373 ± 0.0000014 days, and transit epoch $T_0(BJDTDB) = 2454686.82069 ± 0.00039$).

3. ANALYSIS AND RESULTS

After normalizing the time series of WASP-3 with the reference light curve, the flux decrease caused by WASP-3b’s eclipse becomes visually identifiable (Figure 2). To measure the eclipse depth and determine the phase center, we fit a light curve simultaneously with a background baseline to the data. Thanks to the improved guiding of WIRC, the drift of the centroid is relatively small and we do not see obvious correlation between the flux and centroid positions (Figure 3). We experimented with both a linear baseline and a quadratic baseline with the data, and a linear baseline with a negligible slope is preferred to a quadratic baseline by the Bayesian Information Criterion (BIC)\(^6\) (Liddle 2007).

The light curve is generated following the prescription of Mandel & Agol (2002), assuming uniform bodies without limb darkening. The stellar and planetary parameters for the light curve ($R_p$, $R_\text{star}$, inclination, and semimajor axis) are adopted from Christiansen et al. (2011). The free parameters in the least-square fit are the eclipse depth, the mid-eclipse phase, the level of the out-of-eclipse baseline $a_1$, and the baseline slope $a_2$. The known durations of ingress and egress are maintained in the fit.

We employed the Levenberg–Marquardt (LM) algorithm (Press et al. 1992) for the least-squares fit. To ensure that we find the global minimum instead of local minima, we searched the parameter space extensively with a fine grid of starting points on top of the least-square fit. The grid has a few hundred steps for each parameter. The fact that most starting values on the grid converge to the same minimum suggests that we indeed

\(^6\) We use a linear baseline of the form: $f = a_1 + a_2 \cdot t$, where $f$ is the flux, $t$ is the time of each datum, and $a_1$, $a_2$ are the linear coefficients of the baseline. The linear baseline gives a BIC value of 710, less than the value of 716 from the quadratic baseline. Thus, the linear baseline model is preferred.
have found the global minimum. The data points are uniformly weighted such that the $\chi^2$ is nearly 1.0. The global best-fit light curve gives an eclipse depth of $0.181\pm0.020\%$, and a phase center of $0.5045\pm0.0014$. The best-fit model is shown in Figure 2, along with the residual of the best fit and the binned light curve. The right panel of Figure 3 compares the noise level of WASP-3b’s light curve with the Gaussian noise expectation. Both the in-eclipse and out-of-eclipse data follow the Gaussian expectations closely, although there are still some uncorrected systematics in the data.

To examine the statistical significance and robustness of the eclipse depth and to estimate its error, we conduct two statistical tests. We first apply the standard bootstrapping technique (Press et al. 1992). In each bootstrapping iteration, we uniformly resample the data with replacement. For each new sample, we re-fit the light curve and baseline model to determine the eclipse depth and phase center, using the aforementioned grid search and LM minimization. This technique is suitable for unknown distributions like our case, and can robustly test the best-fit model and the distribution of the parameters. A total number of 2000 iterations are performed and the resulting distributions of the eclipse depth and phase center are nearly Gaussian, with a median depth of $0.183\%\pm0.019\%$ and an eclipse phase center of $0.5045\pm0.0020$, highly consistent with the previous best fit.

For the second test, we use the “prayer-bead” residual permutation method (Winn et al. 2008 and references therein). The same light curve and baseline model are employed to re-fit the simulated data in each iteration. A total number of 1365 iterations (i.e., $2N-1$, where $N = 683$ is the number of data points) are conducted. This method maintains the time-correlated errors and is therefore another robust way of testing our fit. Thanks to the minimal amount of “red noise” in the data, the resulting distribution is also close to Gaussian. The resulting median depth and 1$\sigma$ error is $0.185\%\pm0.019\%$, and the eclipse phase center is at $0.5044\pm0.0015$, also consistent with the previous results.

Figure 3. Left: flux of WASP-3b as a function of $x$ and $y$ positions of its centroid. The centroid drifts in both directions are relatively small and have no obvious correlations with flux. Right: comparison of WASP-3b’s noise level with Gaussian noise expectation. Both the in-eclipse and out-of-eclipse data follow the Gaussian expectations closely as the data points are binned down.

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

We take the values from the LM best fit and the largest error bars from the three different error analyses as our final results, and summarize them in Table 1. Based on the average flux of the target and the sky background, the expected photon noise precision for the eclipse data is $0.0065\%$. Thus, our precision of $0.020\%$ corresponds to $\sim 3$ times of the photon noise limit.

4. DISCUSSION

We compare our $K_S$-band measurement of WASP-3b in Figure 4 with atmospheric models generated based on Barman et al. (2005) and Barman (2008). Our measured flux ratio agrees with that of Croll (2011), $0.176^{+0.015}_{-0.017}$. However, it is too high to match models with heat redistribution. Instead, the flux ratio is more consistent with a hot atmosphere in pure radiative equilibrium (at the 2$\sigma$ level), with no redistribution across the surface of the planet. Such a model has a nearly isothermal radial temperature profile across the near-IR photosphere over most of the dayside, except near the planet limb. The nightside is very cold. This conclusion is also consistent with that of Croll (2011). Perhaps coincidentally, the observed flux matches very
closely the value predicted by a model for the substellar point (top curve), suggesting that, at the \( K_s \)-band photospheric depth, the temperature is on average close to that at the substellar point (also corresponding to a blackbody temperature of \( \sim 2435 \) K). It is unrealistic for a planet’s entire dayside to be as hot as the substellar point, indicating a large departure from radial temperature profile predicted by traditional one-dimensional atmosphere models. However, with no color information, it is difficult to infer detailed information about the nature of the temperature structure. More observations at other wavelengths are definitely needed.

Our final measurement of the eclipse center, \( \phi = 0.5045 \pm 0.0020 \), corresponds to a delay of 11.97 ± 5.32 minutes from the expected mid-eclipse time based on Christiansen et al. (2011). This gives \( e \cos \omega = 0.0070 \pm 0.0032 \), consistent with the values of Pollacco et al. (2008) (\( e = 0.05 \pm 0.05 \)) and Simpson et al. (2010) (\( e = 0.07 \pm 0.08 \)). However, this result is only consistent with the joint measurement of Croll (2011) at 2.5\( \sigma \) level (\( \phi = 0.4999^{+0.0006}_{-0.0010} \)), although it agrees better with their second and higher-significance measurement of \( \phi = 0.5014^{+0.0009}_{-0.0014} \).

In search for TTV signals, Maciejewski et al. (2010) found a potential periodic time variation with a semi-amplitude of 0.0014 days, which could be interpreted as a hypothetical low-mass body in an outer orbit. They also performed a joint reanalysis of the existing RV data and found an eccentricity of 0.05 ± 0.04, which is also consistent with our slight non-zero result. However, they also pointed out that the possible non-zero eccentricity might be a result of confusion with a two-planet system in an inner 2:1 resonance. Miller et al. (2009) indicated that the observed radius of WASP-3b, 1.385\( R_{\text{Jup}} \), is more consistent with their full tidal evolution model. Thus, if the orbit of WASP-3b is indeed slightly eccentric, it might be able to shed light on its migration and tidal evolution history. However, we also emphasize that the current measurement is still consistent with zero and given the slight difference from Croll (2011), more observations are required to better constrain the eccentricity and shed light on the aforementioned scenarios.

5. CONCLUSIONS

We have developed a new integrated guiding scheme for Palomar/WIRC observations. Our algorithm has improved the guiding precision by a factor of \( \sim 5–7 \), significantly mitigated the centroid drifts of the targets on the detector, and largely reduced the correlated systematics in the light curves seen in our previous study. Using the new guiding scheme, we have detected the \( K_s \)-band thermal emission of the hot Jupiter WASP-3b at 9\( \sigma \) significance. The detected secondary eclipse has a depth of 0.181% ± 0.020%, in agreement with the previous result of Croll (2011). The measured flux ratio of the planet is too high to be explained by models with heat redistribution but favors a pure radiative equilibrium case with a very cold nightside. Further observations at multiple wavelengths are necessary to help determine the temperature–pressure profile of the planetary atmosphere and shed light on the nature of its high eclipse depth in \( K_s \). Our measurement also gives an \( e \cos \omega \) of 0.0070 ± 0.0032, consistent with a circular orbit while also suggesting the planet’s orbit might be slightly eccentric. This result differs slightly from that of Croll et al. (2011) by \( \sim 2.5\sigma \). On the other hand, a previous study has found possible periodic TTV signals in the system, and a small non-zero eccentricity might be caused by a second planet in the system (Maciejewski et al. 2010). More secondary eclipse observations are certainly needed to better constrain the eccentricity.

Despite the 45 minute gap during the eclipse, we still achieved a 9\( \sigma \) detection thanks to the large aperture of the telescope and the substantially reduced systematics. This demonstrates the capability of Palomar/WIRC in providing high-quality secondary eclipse measurements of hot Jupiters, and its potential to expand to other wavelengths such as \( H \) and \( J \). With the large aperture size and additional improvements in guiding, we expect Palomar/WIRC to make significant contributions to the studies of exoplanetary atmospheres.

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Facility: Hale

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5
