NEAR-INFRARED THERMAL EMISSION FROM WASP-12b: DETECTIONS OF THE SECONDARY ECLIPSE IN Ks, H, AND J*

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ABSTRACT

We present Ks, H, & J-band photometry of the very highly irradiated hot Jupiter WASP-12b using the Wide-field Infrared Camera on the Canada–France–Hawaii telescope. Our photometry brackets the secondary eclipse of WASP-12b in the Ks and H bands, and in J band starts in mid-eclipse and continues until well after the end of the eclipse. We detect its thermal emission in all three near-infrared bands. Our secondary eclipse depths are 0.309±0.013% in Ks band (24σ), 0.176±0.021% in H band (9σ), and 0.131±0.025% in J band (4σ). All three secondary eclipses are best fit with a consistent phase, φ, that is compatible with a circular orbit: φ = 0.4998±0.0008. The limits on the eccentricity, e, and argument of periastron, ω, of this planet from our photometry alone are thus |ecosω| < 0.0040. By combining our secondary eclipse times with others published in the literature, as well as the radial-velocity and transit-timing data for this system, we show that there is no evidence that WASP-12b is precessing at a detectable rate and that its orbital eccentricity is likely zero. Our thermal-emission measurements also allow us to constrain the characteristics of the planet’s atmosphere; our Ks-band eclipse depth argues strongly in favor of inefficient day to nightside redistribution of heat and a low Bond albedo for this very highly irradiated hot Jupiter. The J- and H-band brightness temperatures are slightly cooler than the Ks-band brightness temperature, and thus hint at the possibility of a modest temperature inversion deep in the atmosphere of WASP-12b; the high-pressure, deep atmospheric layers probed by our J- and H-band observations are likely more homogenized than the higher altitude layer probed by our Ks-band observations. Lastly, our best-fit Ks-band eclipse has a marginally longer duration than would otherwise be expected; this may be tentative evidence for material being tidally stripped from the planet—as was predicted for this system by Li and collaborators, and for which observational confirmation was recently arguably provided by Fossati and collaborators.

Key words: eclipses – infrared: planetary systems – planetary systems – stars: individual (WASP-12) – techniques: photometric

Online-only material: color figures

1. INTRODUCTION

Multi-wavelength constraints on the thermal emission of hot Jupiters are crucial to precisely defining the spectral energy distributions of these planets and understanding their energy budgets. Interestingly, most hot Jupiter thermal-emission detections to date have not been at the blackbody peaks of these planets, but at longer wavelengths with the Spitzer Space Telescope (λ > 3 μm; e.g., Charbonneau et al. 2005; Deming et al. 2005). Probing shorter near-infrared wavelengths at the blackbody peaks of these planets has only recently been proven feasible first through space-based observations with the Hubble Space Telescope (HST; Swain et al. 2009a), and then from the ground (e.g., de Mooij & Snellen 2009; Sing & Lopez-Morales 2009; Gillon et al. 2009). Our program to detect near-infrared thermal emission from the hottest of the hot Jupiters has also been successful using the Wide-field Infrared Camera (WIRCam) on the Canada–France–Hawaii Telescope (CFHT) to detect the Ks-band thermal emission of: TrES-2b (Croll et al. 2010a), TrES-3b including an H-band upper limit (Croll et al. 2010b), and two eclipses of WASP-3b, including a limit on its temporal variability (B. Croll et al. 2011, in preparation).

In the near-infrared, multiple-band detections have only been performed on a handful of occasions; such multiple-band detections were performed in narrow-wavelength regimes from space via spectroscopy with HST for HD 209458 and HD 189733 (Swain et al. 2009a, 2009b), and arguably recently from the ground for HD 189733 using the Infrared Telescope Facility (Swain et al. 2010), as well as from the ground using the Very Large Telescope in the H & K bands for the highly irradiated hot Jupiter WASP-19b (Anderson et al. 2010; Gibson et al. 2010). Multiple-band detections in the near-infrared are therefore rare compared to the frequent multiple-band detections at longer wavelengths using the IRAC (Fazio et al. 2004), IRS (Houck et al. 2004), or MIPS (Rieke et al. 2004) instruments on the Spitzer Space Telescope. Multi-wavelength thermal-emission measurements with Spitzer have revealed a wealth of information, including that the most highly irradiated exoplanets seem to harbor hot stratospheres and temperature inversions (Knutson et al. 2008a; Charbonneau et al. 2005; Machalek et al. 2008; Knutson et al. 2008b). One could imagine that obtaining multi-wavelength constraints on a planet’s thermal

Based on observations obtained with WIRCam, a joint project of CFHT, Taiwan, Korea, Canada, France, at the Canada–France–Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institute National des Sciences de l’Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

Canada Research Chair in Astrophysics.
emission in the near-infrared could be equally informative. Furthermore, the near-infrared is also an ideal place to directly constrain these planets’ pressure–temperature profiles at depth, dayside bolometric luminosities, and the fraction of the incident stellar radiation that is transported from the tidally locked day to nightsides deep in these planets’ atmospheres (Barman 2008).

Here we continue our program using WIRCam on CFHT to detect thermal emission from some of the hottest of the hot Jupiters. Our target was the highly irradiated hot Jupiter WASP-12b. The discovery of the inflated, transiting exoplanet WASP-12b was of immediate interest to those attempting to measure the loss in flux during the secondary eclipses of hot Jupiters in the near-infrared—this was because WASP-12b circles a late F-type star with a period of only ~26 hr (Hebb et al. 2009). It is thus exposed to extremely high stellar insolation, with an incident flux of ~9 × 10^9 erg s^{-1} cm^{-2}. The planet is also one of the most inflated hot Jupiters, with a radius of R_p ~ 1.8 R_J and a favorable planet-to-star radius ratio (R_p/R_∗ ~ 0.12; Hebb et al. 2009). It should be heated to an equilibrium temperature of over ~2500K assuming isotropic reradiation and a zero Bond albedo.\(^5\)

For these reasons, it was predicted to display near-infrared thermal emission on the order of 0.1%–0.3% of the stellar flux in the J, H, and Ks near-infrared bands, assuming isotropic reradiation and a zero Bond albedo. Lopez-Morales et al. (2010) have already reported a detection of the secondary eclipse of WASP-12b in \(\text{\textit{z}}\) band (0.9 μm), and more recently Campo et al. (2010) have presented detections of two eclipses in the four IRAC channels for WASP-12b. Campo et al. (2010), however, did not report the eclipse depths for WASP-12b, and for reasons discussed below the Lopez-Morales et al. (2010) detection has recently been called into question. Thus the atmospheric characteristics of WASP-12b remain largely unconstrained.

In addition to receiving extremely high stellar insolation, WASP-12b is intriguing because the combination of its close proximity to its star and its putative original eccentricity (\(e = 0.049 \pm 0.015\); Hebb et al. 2009) suggests that it could be precessing at a rate that is detectable with current instruments. Such a putative precession signal was recently claimed by Campo et al. (2010). Although the IRAC eclipses reported by Campo et al. (2010) suggest an \(\text{\textit{e}} \cos \omega\) constraint similar to that expected for a circular orbit (\(\text{\textit{e}} \cos \omega = -0.0054 \pm 0.0030\)), Lopez-Morales et al. (2010) had earlier reported an eclipse detection that was offset from a circular orbit (\(\text{\textit{e}} \cos \omega = 0.016^{+0.011}_{-0.009}\)). While at first glance the two measurements are inconsistent, if the planet precesses this is not the case. By combining their secondary eclipses with those of Lopez-Morales et al. (2010), together with the original radial-velocity data for the system (Hebb et al. 2009), as well as a series of transit-time measurements from the original detection paper and ground-based amateurs (from the Exoplanet Transit Database; Poddany et al., 2010), Campo et al. (2010) show that a precessing orbital model best fits the data with a 2σ confidence. The authors caution that this detection is heavily dependent on the secondary eclipse offset reported by Lopez-Morales et al. (2010). Even more recently, radial-velocity observations of WASP-12b have suggested that the eccentricity of WASP-12b is small (\(e = 0.017^{+0.015}_{-0.010}\); Husnoo et al. 2010) and likely zero, constraining the Campo et al. (2010) precession signal and calling into question the Lopez-Morales et al. (2010) eclipse detection. Nevertheless, the best-fit eccentricity of WASP-12b remains non-zero, and thus this planet could be precessing at a much slower rate than Campo et al. (2010) claim. The definitive nail in the coffin on the claim that WASP-12b is precessing at a detectable rate will thus only result from further detections of this planet’s secondary eclipse well separated in time from the original eclipse detections.

Also recently, preliminary evidence was presented that material from WASP-12b may be tidally stripped from the planet and may possibly form a circumstellar disk in this system. Li et al. (2010) predicted that this system may have such a disk from material overfilling the Roche lobe of WASP-12b, because WASP-12b’s observed radius in the optical (\(R_p \sim 1.79 R_J\); Hebb et al. 2009) is already close to its 2.36 \(R_J\) Roche lobe radius (as quoted in Fossati et al. 2010a). That WASP-12b may exhibit material overfilling its Roche lobe and forming a circumstellar disk from this material has recently received possible confirmation from \textit{HST} Cosmic Origins Spectrograph (COS) observations of this system. From these observations, Fossati et al. (2010a) find increased transit depths in the ultraviolet when compared to the optical, indicative of material surrounding WASP-12b overfilling its Roche lobe and blocking out a larger fraction of the stellar flux at these wavelengths. In addition they observe an early ingress of the transit of WASP-12b in their near-ultraviolet data; Fossati et al. (2010a) interpret this early ingress as a putative sign of previously stripped material from WASP-12b forming a circumstellar disk. These putative signs of a disk are interesting to observers in the near-infrared, specifically the \(K\) band, as Li et al. (2010) predicted that such a disk in this system may exhibit CO emission as bright as 10 mJy at 2.292 μm. WASP-12 does not, however, display a significant near-infrared excess (Fossati et al. 2010b).

Here we present detections of WASP-12b’s thermal emission in the \(Ks\) (24σ), \(H\) (9σ), and \(J\) bands (4σ). Our \(J\)-band detection is the first thermal-emission measurement in this band. Our photometry favors a circular orbit for WASP-12b (\(\text{\textit{e}} \cos \omega = -0.0007^{+0.0013}_{-0.0011}\)). By combining our secondary eclipse times with those of Lopez-Morales et al. (2010) and Campo et al. (2010), as well as the radial-velocity data of Hebb et al. (2009) and Husnoo et al. (2010), and all the transit-time data for the system, we are able to show that not only is there no evidence to date that WASP-12b is precessing at a detectable rate, but also that the orbit of WASP-12b is likely circular. Our analysis also allows us to constrain the characteristics of the atmosphere of WASP-12b; our \(Ks\)-band eclipse depth argues in favor of inefficient redistribution of heat from the day to nightside, while our \(J\)- and \(H\)-band observations seem to be probing deeper, higher pressure atmospheric layers that are slightly more homogenized. We also show that our \(Ks\)-band photometry may feature a longer than expected eclipse duration that could arguably be interpreted as evidence for material streaming from the planet or a circumstellar disk in this system.

2. OBSERVATIONS AND DATA REDUCTION

We obtained observations with WIRCam on CFHT of WASP-12 (\(J \sim 10.48, H \sim 10.23, K \sim 10.19\)) on 2009 December 26–28 in the \(J, H,\) and \(Ks\) bands, respectively. Our \(J\)-band observations on December 26 lasted for 3.9 hr and started in mid-eclipse and persisted for 2.2 hr after the end of eclipse. Our observations on December 27 and 28 lasted for 6.0 hr in \(H\) band and 6.2 hr in \(Ks\) band, respectively, evenly bracketing the predicted secondary eclipse of WASP-12b. Numerous reference stars were also observed in the 21 × 21 arcmin field of view of WIRCam.
The telescope was defocused for our various observations to approximately 1.5 mm (J band), 1.8 mm (H band), and 2.0 mm (Ks band), resulting in the flux of our target star being spread over a ring ∼19, ∼23, and ∼26 pixels in diameter (6–8′′) on our array. For each observation, as the telescope temperature changed over the course of the night, we used the focus stage model, kept the defocus amount constant, thus achieved a stable PSF over the entire observation set. We used “Staring mode” for our J- and Ks-band observations where we do not dither for the duration of our observations; for the H-band eclipse, the queue observations mistakenly used micro-dithering which featured small 0.5 pixel shifts between consecutive exposures. The exposure times for our J, H, and Ks-band observations were 5-s. The effective duty cycle after accounting for readout and for saving exposures was 34%.

For both observations the data were reduced and aperture photometry was performed on our target star and our reference stars as discussed in Croll et al. (2010b) (with the details provided in Croll et al. 2010a). We used an aperture with a radius of 17 pixels for our Ks-band photometry, and 16.5 pixels for our H- and J-band photometry. We used an annulus to define the sky with an inner radius of 22, and an outer radius of 34 pixels for all our photometry. We ensured that these choices of aperture were optimal by testing smaller and larger aperture sizes in increments of 0.5 pixels and ensuring these choices displayed the smallest root mean square (rms) outside of occultation and the least time-correlated red noise.
Following our aperture photometry we correct the flux of our target star with a number of nearby reference stars as discussed in Croll et al. (2010a). We used 22, 7, and 17 reference stars to correct our \( J \)-, \( H \)-, and \( K_s \)-band eclipse photometry, respectively. The normalized flux of WASP-12 and the various reference stars that are used to correct the flux of our target star are displayed in Figure 1. For our \( K_s \)-band photometry we corrected our photometry for a small trend with the \( x \) and \( y \) pixel position of the target star on the chip.\(^8\) We did not notice such trends in our \( H \)- and \( J \)-band photometry.

For our \( H \)-band photometry the air mass, \( X \), was high at the start of the observations (\( X \sim 1.9 \)), and fell to \( X \sim 1.2 \) by mid-eclipse. We noticed a downward trend in our \( H \)-band photometry following the correction with nearby reference stars that appeared to be correlated with air mass. We found that this effect was reduced, but not removed, for our \( H \)-band photometry by correcting the flux of WASP-12 with reference stars solely on the same WIRCam chip as WASP-12; this downward trend in flux of our target star compared to the reference stars is still apparent at the start of our \( H \)-band photometry. To reduce the impact of these systematic data we scale-up the errors of the apparent at the start of our

\[ R_{\text{rms}} = \frac{1}{\sqrt{N}} \]

\( R_{\text{rms}} \) is the interval from the beginning of the observations and \( c_1 \) and \( c_2 \) are fit parameters. We use Markov Chain Monte Carlo (MCMC) fitting to fit for our background as well as a secondary eclipse model calculated from the Mandel & Agol (2002) algorithm without limb darkening. We fit for the background, the depth of the secondary eclipse (\( \Delta F \)), and the offset that the eclipse occurs later than the expected eclipse center (\( t_{\text{offset}} \)). Our MCMC method is discussed in Croll (2006) and Croll et al. (2010a). We obtain our stellar and planetary parameters for WASP-12 from Hebb et al. (2009), while the planetary period and ephemeris are obtained from Campo et al. (2010) from their non-precessing best fit.

The best-fit secondary eclipses from our individual MCMC analyses with a fixed eclipse duration are presented in Figures 3–5 and the best-fit eclipse parameters are presented in Table 1 along with associated parameters, such as the best-fit phase, \( \phi \), and the barycentric julian date of the eclipse center in the terrestrial time format.\(^9\) \( t_{\text{eclipse}} \). The phase dependence of these fits are presented in Figure 6. We also perform a joint analysis of the three secondary eclipses with a common offset from the eclipse center (\( t_{\text{offset}} \)); the fit parameters are thus \( \Delta F_{K_s} \), \( \Delta F_H \), \( \Delta F_J \), \( t_{\text{offset}} \), and \( c_1 \) and \( c_2 \) in each band. The resulting best-fit parameters of this joint fit are listed in Table 1.

We also repeat our fit for our \( K_s \)-band photometry, our highest signal-to-noise photometry, and for the joint analysis while fitting for an additional parameter—the duration of the secondary eclipse, \( \Phi_{II} \). We parameterize this by the duration of the eclipse divided by the duration of the transit, \( \Phi_{II} \sim 2.93 \ h \) reported by Hebb et al. (2009). The results from this fit are presented in

\[ \Phi_{II} = \Phi - \Delta \phi \]

\( \Phi_{II} \) is the duration of the secondary eclipse in our observations.\(^9\)

\[ B_f = 1 + c_1 + c_2 dt \]

\( B_f \) is the predicted photometric flux in a given band.

\( B_f \) is the predicted photometric flux in a given band.\(^8\) The correction is described in Croll et al. (2010a).

\( B_f \) is the predicted photometric flux in a given band.\(^9\) As calculated using the routines of Eastman et al. (2010).
Figure 3. CFHT/WIRCam photometry of the secondary eclipse of WASP-12b observed in the Ks band on 2009 December 28. The top panel shows the unbinned light curve with the best-fit secondary eclipse and background from our MCMC analysis of the Ks-band data with the fixed eclipse duration (red line). The second panel shows the light curve with the data binned every ∼7.0 minutes and again our best-fit eclipse and background. The third panel shows the binned data after the subtraction of the best-fit background, $B_f$, along with the best-fit eclipse model. The bottom panel shows the binned residuals from the best-fit model. (A color version of this figure is available in the online journal.)

Figure 4. Same as Figure 3 except that the data are our H-band photometry obtained on 2009 December 27. (A color version of this figure is available in the online journal.)
Table 1. We do not fit our $J$-band or $H$-band data individually with this additional parameter, $\Phi_{II}$, as the $J$-band data are of a partial eclipse, and thus the duration of the secondary eclipse is degenerate with an offset of the eclipse center, and the $H$-band data suffer from additional time-correlated systematics that could lead to erroneous conclusions.

4. DISCUSSION

We strongly detect all three secondary eclipses in the three near-infrared bands that we observed. The individual analyses of our three eclipses confirm that all three secondary eclipses are fit with a consistent phase (Table 1); thus the best-fit parameters from our joint analysis are similar to the parameters returned by the analyses of the individual eclipses. We therefore quote the results of the joint analysis below. The best-fit eclipse depth from our joint analysis is $0.309^{+0.013}_{-0.012}\%$ in $Ks$ band, $0.176^{+0.016}_{-0.021}\%$ in $H$ band, and $0.131^{+0.027}_{-0.029}\%$ in $J$ band.

4.1. Eccentricity and Precession of WASP-12b

The best-fit phase of the joint analysis is $\phi = 0.4998^{+0.0008}_{-0.0007}$. The resulting limit on the eccentricity, $e$, and argument of periastron, $\omega$, is $e \cos \omega = -0.0007^{+0.0013}_{-0.0013}$, a result that is consistent with a circular orbit and the Campo et al. (2010) results. This value is inconsistent, however, with the Lopez-Morales et al. (2010) $e \cos \omega$ result. The discrepancy between the Lopez-Morales et al. (2010) result and that of Campo et al. (2010) and our own could be due to WASP-12b precessing—we explore this possibility below.

Campo et al. (2010) performed an analysis of the reported transit times and secondary eclipse times and presented tentative
evidence that WASP-12b may be precessing at an observable rate, $\dot{\omega} = 0.02 \pm 0.01$ d$^{-1}$, with a period as short as 40 years. The primary evidence for the precession was the ground-based secondary eclipse detection of Lopez-Morales et al. (2010), which occurred late by approximately $\sim$15 minutes (at a phase of $\phi = 0.5100^{+0.0072}_{-0.0061}$ using the Hebb et al. 2009 ephemeris and period).

We repeat the Campo et al. (2010) precession analysis adding in our three-secondary eclipse detections. We summarize the Campo et al. (2010) precession model that we employ here. The mid-transit time of the $N$th transit, $T_N$, in our precessing model is predicted to occur at

$$T_N = t_0 + P_s N - \frac{e P_a}{\pi} (\cos \omega_N - \cos \omega_0).$$

(2)

$T_0$ and $\omega_0$ are the transit time and argument of periastron at the reference epoch, $\omega_N$ is the argument of periastron of the $N$th transit, $P_s$ is the sidereal period, $P_a$ is the period between successive periastron passages, and $e$ has already been defined as the eccentricity. $P_s$ is not an independent variable, but is related to the sidereal period, $P_a$, and the constant precession rate, $\dot{\omega}$: $P_s = \frac{1}{1 - P_a \frac{e}{\pi}} P_a$. The argument of periastron of the $N$th transit is simply $\omega_N = \omega_0 (T_N - T_0) + \omega_0$. Equation (2) is solved iteratively for $T_N$ after it is expanded to the fifth order in $e$ (as shown in Equation (22) of Ragozzine & Wolf 2009). We fit the radial-velocity data from Hebb et al. (2009) and Husnoo et al. (2010), and the transits listed in Table 2 of Campo et al. (2010) as well as four additional, recent transits$^{11}$ from the Exoplanet Transit Database (Poddany et al. 2010) and our own secondary eclipse data along with those of Lopez-Morales et al. (2010) and Campo et al. (2010). We exclude the in-transit radial-velocity data as we do not model for the Rossiter–McLaughlin effect (Gaudi & Winn 2007). We follow Campo et al. (2010), and quote the Lopez-Morales et al. (2010) eclipse point that results from the combined photometry from 1.5 eclipses, at a single epoch halfway between their observations (HJD ~ 2455002.8560 ± 0.0073). $T_N$ of course gives the transit time to compare to the data, we use $e$, $\omega_N$, $T_N$, and $P_a$ to calculate the eclipse times, and $\omega(t)$ to calculate the radial-velocity values. We use the MCMC techniques explained above to calculate the best-fit precessing model, and non-precessing models, except that we fit for $e \cos $...

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### Table 1

| Parameter | $K$-band MCMC | $H$-band MCMC | $J$-band MCMC | Joint MCMC | $K$-band MCMC Duration | $H$-band MCMC Variable | Joint MCMC Duration |
|-----------|----------------|----------------|---------------|------------|------------------------|------------------------|------------------------|
| Reduced $\chi^2$ | 0.73$^{+0.03}_{-0.00}$ | 0.43$^{+0.02}_{-0.00}$ | 0.35$^{+0.03}_{-0.02}$ | 0.53$^{+0.02}_{-0.01}$ | 0.72$^{+0.03}_{-0.01}$ | 0.53$^{+0.01}_{-0.00}$ |
| $\Delta F_K$ | 0.310$^{+0.014}_{-0.013}$ | ... | ... | ... | ... | ... |
| $\Delta F_H$ | ... | 0.180$^{+0.015}_{-0.018}$ | ... | ... | ... | ... |
| $\Delta F_J$ | ... | ... | ... | ... | ... | ... |
| $\omega_{0}$ (min)$^a$ | $-1.3^{+0.7}_{-1.2}$ | $2.0^{+0.2}_{-1.6}$ | $-2.4^{+0.5}_{-1.5}$ | $-0.7^{+1.3}_{-1.1}$ | $-0.9^{+1.4}_{-1.4}$ | $-0.6^{+1.9}_{-1.4}$ |
| $\varepsilon_{eclipse}$ (KBJD-2450000) | 5194.9351$^{+0.0001}_{-0.0008}$ | ... | ... | ... | ... | ... |
| $\varepsilon_{eclipse}$ (BJD-2450000) | ... | ... | ... | ... | ... | ... |
| $c_{1K}$ ($d^{-1}$) | ... | ... | ... | ... | ... | ... |
| $c_{2K}$ ($d^{-1}$) | ... | ... | ... | ... | ... | ... |
| $c_{3H}$ ($d^{-1}$) | ... | ... | ... | ... | ... | ... |
| $c_{4H}$ ($d^{-1}$) | ... | ... | ... | ... | ... | ... |
| $\Phi_{11/1}$ | ... | ... | ... | ... | ... | ... |
| $\Phi_{12/1}$ (hours) | 2.93 | 2.93 | 2.93 | 2.93 | 3.2$^{+0.1}_{-0.1}$ | 3.1$^{+0.1}_{-0.1}$ |
| $T_{BRI}$ (K) | 2985$^{+45}_{-46}$ | ... | ... | ... | ... | ... |
| $T_{BRI}$ (K) | 2765$^{+70}_{-70}$ | ... | ... | ... | ... | ... |
| $e \cos (\omega_0)^{b}$ | $-0.003^{+0.0015}_{-0.0015}$ | ... | ... | ... | ... | ... |
| $e \sin (\omega_0)$ | ... | ... | ... | ... | ... | ... |
| $f_{K}$ | 0.48$^{+0.030}_{-0.029}$ | ... | ... | ... | ... | ... |
| $f_{H}$ | 0.35$^{+0.037}_{-0.036}$ | ... | ... | ... | ... | ... |
| $f_{J}$ | ... | ... | ... | ... | ... | ... |

Note. $^a$ We account for the increased light travel time in the system (Loeb 2005), and use the best-fit period for the non-precessing case reported by Campo et al. (2010).

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$^{10}$ Husnoo et al. (2010) argue that there may be correlated red noise in the Hebb et al. (2009) radial-velocity data, possibly due to a systematic offset in the RV zero point from night to night. As a result we scale-up the errors for the Hebb et al. (2009) data by a factor of 8 and those of Husnoo et al. (2010) by a factor of 2 to account for possible offsets between these two data sets. We refer the reader to Husnoo et al. (2010) for further discussion.

$^{11}$ The additional transits have mid-transit times (HJD) of 2455246.7764 ± 0.00217 (A. Gibson, TRESCA), 2455253.3214 ± 0.00287 (F. Lomoz, TRESCA), 2455257.6913 (G. Haagen, TRESCA), and 2455265.3327 ± 0.00129 (H. Kucakova, TRESCA).
Given that the timing offset of the Lopez-Morales et al. (2010) eclipse detection may be suspect, we also refit the non-precessing case with this eclipse excluded, and present the MCMC results in Table 2. The distribution of eccentricity values from our MCMC chain without the Lopez-Morales et al. (2010) eclipse is non-Gaussian (the bottom left panel of Figure 8) and favors a near-zero eccentricity with a tail to higher eccentricity values; this limit is $e = 0.00101^{+0.00245}_{-0.00063}$. This is due to the fact that although the $ecosinω_o$ values for WASP-12b are well constrained from the radial-velocity data and the combination of the timing of the eclipses and transits (the top-left panel of Figure 8), the $esinω_o$ values are not well constrained and thus higher eccentricity values are allowed (the top-right panel of Figure 8) for an argument of periastron where $cosω_o \sim 0$ at $ω_o \sim 90^\circ$ and $-90^\circ$ (as can be seen in the contour plot in the bottom right panel of Figure 8). Although we are not able to rule out higher eccentricity values for WASP-12b with high confidence, the orbit of WASP-12b is likely circular; thus WASP-12b is no longer an outlier from the expectation of the timescale of tidal circularization for close-in giant exoplanets. The above analysis would be improved by including an a priori constraint on $esinω_o$ using the eclipse duration values from our own eclipses and the Campo et al. (2010) Spitzer/IRAC eclipses. Unfortunately, although Campo et al. (2010) indicate that their best-fit eclipse durations are similar to that of the transits and should thus place a tight constraint on $esinω_o$ near zero, Campo et al. (2010) do not formally fit for the duration of the eclipse and do not include the associated uncertainties. We discuss the implications of fitting our own eclipse durations below.

### 4.2. A Longer Duration Secondary Eclipse; Possible Signs of Material Stripped From the Planet

We also fit our $K_s$-band photometry and our joint $J$, $H$- and $K_s$-band photometry with an eclipse model with the eclipse duration as a free parameter. Our best-fit $K_s$-band variable eclipse duration fit is presented in Figure 9. Our variable eclipse duration fit does argue for a marginally wider secondary eclipse than transit; $Φ_{II} = 1.109^{+0.046}_{-0.035}$, although this result is only significant at the 2.8σ-level, the associated eclipse duration is $Φ_{II} = 3.25^{+0.14}_{-0.03}$ hours, longer than the $∼2.93$ hour optical transit found by Hebb et al. (2009), and longer than the similar duration IRAC eclipses found by Campo et al. (2010). That the data suggests a wider secondary eclipse than our best-fit model can be seen in the ingress and egress of our $K_s$-band photometry (Figure 3).
Figure 8. Top-left, top-right, and bottom-left panels: marginalized likelihood for WASP-12b’s $e_{cos}$, $esin$ and its eccentricity from the non-precessing MCMC chain with the Lopez-Morales et al. (2010) point excluded. The best-fit value for each panel is given with the solid vertical line (for the bottom-left panel this value is nearly indistinguishable from zero), while the 68% credible region is indicated by the dotted vertical line. Bottom-right panel: contour parameter showing the eccentricity, $e$, and the argument or periastron, $\omega$, of WASP-12b again from the same MCMC chain. The 68.3% (1$\sigma$; solid-line), 95.5% (2$\sigma$; dashed-line), and 99.7% (3$\sigma$; dotted-line) credible regions are indicated.

Figure 9. Same as Figure 3 except that the best-fit model is our variable eclipse duration model for our $Ks$-band photometry. (A color version of this figure is available in the online journal.)

Our joint analysis of our $J$-, $H$- and $Ks$-band data also argues for a marginally wider secondary eclipse than transit: $\Phi_{II/I} = 1.080^{+0.034}_{-0.034}$, or that the duration of the eclipse is $\Phi_{II} = 3.16^{+0.10}_{-0.10}$ hours. As our $J$-band data is a partial eclipse, it has no ability to constrain the eclipse duration on its own. Similarly, as our $H$-band data suffers from significant systematics prior to and
during ingress, its ability to constrain the eclipse duration is compromised; in fact, the systematics at the beginning of the \( H \)-band photometry that manifest themselves as a sharp decrease in flux, can be well-fit by a significantly wider, and deeper secondary eclipse that is unlikely to be physical. These facts, combined with a visual inspection of Figures 3–5, suggests that \( H \)-compromised; in fact, the systematics at the beginning of the transit was predicted by Li et al. (2010), while the former was argued to be the longer duration secondary eclipse. Also, although the \( \varepsilon \) value necessary to explain our longer duration eclipse can be ruled out at several sigma and thus we find this possibility unconvincing.

Another possibility—perhaps the most intriguing possibility—is that if this apparently wider secondary eclipse is not due to systematic effects or due to a small \( \varepsilon \) for WASP-12b, then it could be due to radiation from gas that is escaping from the planet and possibly forming a circumstellar disk. The latter was predicted by Li et al. (2010), while the former was argued to be the longer duration secondary eclipse. Also, although the \( \varepsilon \) value necessary to explain our longer duration eclipse can be ruled out at several sigma and thus we find this possibility unconvincing.

4.3. The Properties of WASP-12b’s Atmosphere

Our measurements of the thermal emission of WASP-12b allow us to constrain the characteristics of its atmosphere, including: its Bond albedo, the level of redistribution of heat from the day to the nightside at various depths, and the planet’s timescale bolometric luminosity. We parameterize the level of redistribution by the reradiation factor, \( f \), following the Lopez-Morales & Seager (2007) definition (i.e., \( f = \frac{1}{3} \) denotes isotropic reradiation, while \( f = \frac{2}{3} \) denotes redistribution and reradiation from the dayside only). Our eclipse depths are consistent with a range of Bond albedos, \( A_B \), and overall day to nightside redistribution of heat, \( f_{\text{tot}} \) (Figure 10). If we assume a Bond albedo near zero, consistent with observations of other hot Jupiters (Charbonneau et al. 1999; Rowe et al. 2008) and with model predictions (Burrows et al. 2008), the best-fit reradiation factor, \( f_{\text{tot}} \), that results from our three near-infrared eclipse measurements is \( f_{\text{tot}} = 0.441_{-0.024}^{+0.024} \). This suggests that the dayside of WASP-12b reradiates most of the incident stellar flux without redistributing it to the nightside.

As the atmospheres of hot Jupiters may be highly vertically stratified, different atmospheric layers may redistribute heat much more or much less efficiently than other layers. The best-fit brightness temperatures and reradiation factors of the individual atmospheric layers probed by our various wavelengths of observations are: \( T_{\text{BKs}} = 2988_{-46}^{+45} \) K and \( f_{\text{BKs}} = 0.482_{-0.030}^{+0.030} \) for our \( K_{\text{s}} \)-band observations, and \( T_{\text{BH}} = 2765_{-70}^{+70} \) K and \( f_{\text{BH}} = 0.353_{-0.036}^{+0.037} \) for our \( H \)-band observations, and \( T_{\text{BJ}} = 2833_{-152}^{+152} \) K and \( f_{\text{BJ}} = 0.389_{-0.087}^{+0.091} \) for our \( J \)-band observations. Our three different bands should be probing high-pressure regions, deep into the atmosphere of WASP-12b. Specifically, if the near-infrared opacity is dominated by water vapour opacity, the \( J \)-, \( H \)-, and \( K \)-bands should be windows in water opacity (Fortney et al. 2008), and the \( K_{\text{s}} \), \( H \), and \( J \)-bands should be seeing progressively deeper into WASP-12b’s atmosphere. Within the errors the brightness temperatures displayed in our three near-infrared bands are similar. However, the \( J \)- and \( H \)-band brightness temperatures are marginally lower, and taken at face value compared to the \( K_{\text{s}} \)-band brightness temperature they suggest a modest
temperature inversion at very high pressures of \(~100–500\) mbar, deep in the atmosphere of WASP-12b. One explanation for why WASP-12b might display decreased flux at these shorter wavelengths as compared to the \(K_s\) band, is that the atmospheric depths and pressures probed by these shorter wavelength observations may be more homogenized than higher altitude layers. The efficiency of redistribution of the incident stellar flux from the dayside to the nightside may be more homogenized than higher altitude layers. The efficiency of redistribution of the incident stellar flux from the dayside to the nightside should be proportional to the ratio of the reradiative timescale \(\tau_{\text{rad}}\) to advective timescales \(\tau_{\text{adv}}\). It is thought that the reradiative timescale should increase with pressure and depth.\(^{13}\) The advective timescale\(^{13}\) is also thought to increase in pressure, although it is generally thought that advection should win out over reradiation as one descends through the atmosphere of a typical hot Jupiter (Seager et al. 2005; Fortney et al. 2008). Thus, one might expect more efficient redistribution of heat at the layers probed by our shorter wavelength observations compared to the layers probed by our \(K_s\)-band observations. Other explanations for the relatively higher \(K_s\)-band emission than the \(H\)- and \(J\)-band emission are certainly possible, including: extra flux from a circumstellar disk or material streaming from the planet in the \(K_s\) band, an atmospheric emission feature at \(K_s\) band, or absorption features over the \(H\) and \(J\) bands. The eclipse depths from the Campo et al. (2010) Spitzer/IRAC measurements will not shed much additional light on this matter, as, if water dominates, the Spitzer/IRAC bands do not probe as deeply as the \(JHK\) near-infrared bands.

We compare the depths of our near-infrared eclipses to a series of planetary atmosphere models in Figure 11. This comparison is made qualitatively as well as quantitatively by integrating the models over the WIRCam \(J\), \(H\), and \(K_s\) bandpasses and calculating the \(\chi^2\) of the thermal-emission data compared to the models. We include the Lopez-Morales et al. (2010) eclipse depth in Figure 11, but do not include it in our \(\chi^2\) calculation due to the aforementioned uncertainty with the timing and depth of this eclipse. The Spitzer/IRAC eclipse depths (Campo et al. 2010) are also not included, as of the time of writing only the central eclipse times have been reported. We first plot two blackbody models, the first one displaying modestly efficient heat redistribution \(f=0.35\); blue dotted line; \(T_{\text{eq}} \sim 2735\) K), while the latter features emission from the dayside only \(f=0.50\); gray dotted line; \(T_{\text{eq}} \sim 2990\) K). The \(f = \frac{1}{2}\) blackbody model provides an excellent fit to the longer wavelength \(K_s\)-band emission, and does a reasonable job of fitting our \(H\) - and \(J\)-band emission \(f=0.35; \chi^2 = 34\), which generally underpredicts the observed emission.

In Figure 11, we also compare our measurements to a series of one-dimensional, radiative transfer, spectral models (Fortney et al. 2005, 2006, 2008) with different reradiation factors that specifically include or exclude gaseous TiO/VO into the chemical equilibrium and opacity calculations. In these models, when TiO/VO are present in gaseous form in the upper atmosphere, the TiO/VO display temperature inversions. The models on the top panel are divided by a stellar atmosphere model (Hauschildt et al. 1999) of WASP-12 using the parameters from Hebb et al. (2009). \((M_*=1.35 M_\odot, R_*=1.57 R_\odot, T_{\text{eff}} = 6300\) K, and \(g = 4.38\)). We also plot one-dimensional, radiative transfer spectral models (Fortney et al. 2006, 2008) for various reradiation factors and with and without TiO/VO. We plot models with modest redistribution \(f=0.35\) with and without TiO/VO (magenta-dotted and green-dashed lines, respectively), and for dayside only emission \(f=\frac{1}{2}\) with and without TiO/VO (orange dotted and cyan dot-dashed lines, respectively). The models with TiO/VO display temperature inversions. The models on the top panel are divided by a stellar atmosphere model (Hauschildt et al. 1999) of WASP-12 using the parameters from Hebb et al. (2009). \((M_*=1.35 M_\odot, R_*=1.57 R_\odot, T_{\text{eff}} = 6300\) K, and \(g = 4.38\)). We also plot one-dimensional, radiative transfer spectral models (Fortney et al. 2005, 2006, 2008) with different reradiation factors that specifically include or exclude gaseous TiO/VO into the chemical equilibrium and opacity calculations. In these models, when TiO/VO are present in gaseous form in the upper atmosphere, the TiO/VO display temperature inversions.

\(^{13}\) The reradiative timescale \(\tau_{\text{rad}}\) is thought to be proportional to \(\tau_{\text{rad}} \sim \frac{c_T}{\sigma T^4}\) \(\text{erg cm}^2\) \(\text{g}^{-1}\) \(\text{s}^{-1}\) (Showman & Guillot 2002), where \(c_T\) is the specific heat capacity, \(\sigma\) is the Stefan–Boltzmann constant, \(T\) is the temperature of the atmospheric layer, and \(g\) is the gravitational acceleration of the planet.

\(^{14}\) It is thought that the advective timescale \(\tau_{\text{adv}}\) is approximately equal to the radius of the planet \(R_P\) divided by the horizontal wind speed \(U\): \(\tau_{\text{adv}} \sim \frac{R_P}{U}\) (Showman & Guillot 2002).
atmosphere they act as absorbers at high altitudes and lead to hot stratospheres and temperature inversions (Hubeny et al. 2003). We present models with modest redistribution \((f = 0.35)\) and dayside only emission \((f = \frac{1}{2})\) with and without TiO/VO. The associated \(\chi^2\) for the \(f = \frac{1}{2}\) models with and without TiO/VO are \(\chi^2 = 20\) and \(\chi^2 = 20\), while the \(f = 0.35\) models with and without TiO/VO are \(\chi^2 = 72\) and \(\chi^2 = 83\). None of these models provide quantitative improvements over the \(f = \frac{1}{2}\) blackbody model, as they do not do as good of a job of matching the longer wavelength \(K\)-band thermal emission, nor do they feature reduced emission in \(H\) and \(J\) band.

Our near-infrared measurements also allow us to estimate the bolometric dayside luminosity of WASP-12b, \(L_{\text{day}}\). We use a blackbody model with a total reradiation factor equal to the best-fit value we calculate from our three near-infrared bands \((f_{\text{tot}} = 0.441)\); by integrating over this model we can estimate \(L_{\text{day}}\) as \(1.12 \times 10^{-3} L_\odot\). Another way of parameterizing the efficiency of the day-to-nightside heat redistribution rather than the reradiation factor is comparing the bolometric dayside luminosity, \(L_{\text{day}}\), to the nightside luminosity, \(L_{\text{night}}\). By following elementary thermal equilibrium calculations one can deduce that WASP-12b should display a total bolometric luminosity of \(L_{\text{tot}} = 1.25 \times 10^{-3} L_\odot\). This suggests that 89% of the incident stellar irradiation is reradiated by the dayside, leaving a mere 11% to be advected to the nightside and reradiated. However, caution is encouraged with this conclusion as shorter and longer wavelength emission for this planet may deviate significantly from that of a blackbody.

4.4. Future Prospects

We lastly note that the combination of thermal emission as prominent as that displayed here with near-infrared photometry this precise suggests the possibility that thermal phase curve measurements may be possible from the ground. For the shortest period exoplanets \((P \sim 1 d\) or less) even in a single night of observing \((8-9\) hr) one could conceivably view the flux maximum of the phase curve where hot gas is advected downwind on the planet, the decrement in flux during the secondary eclipse, and then view a significant fraction of the near-sinusoidal decrease as the cool nightside face of the exoplanet rotates into sight. WASP-12b is an ideal target for such observations with its short \(\sim 1.09\) d period, and its bright dayside emission suggests that thermal phase curve observations for this planet should reveal a large asymmetry over the course of the orbit as WASP-12b’s nightside should be cold. Thermal phase curve observations from the ground in the near-infrared would require one to control the background systematic trends that are present in our near-infrared photometry even after we correct the flux of our target star with a great many reference stars; the feasibility of this task is, as of yet, unproven. Nevertheless, we will be investigating the possibility of obtaining such near-infrared phase curve information in this photometry as well as with future observations of WASP-12b. These near-infrared phase curve observations will be accompanied by near-simultaneous, 3.6 and 4.5 \(\mu\)m Spitzer/IRAC thermal phase curve observations of a full orbit of WASP-12b (Pi.-P. Machalek) that will allow for an unprecedented understanding of the characteristics of the day and nightside deep atmosphere of this planet.

We also plan to reobserve a full, rather than partial, eclipse of WASP-12b in \(J\) band so as to better define its thermal emission at that wavelength. Lastly, we plan to observe the transit of WASP-12b in the near-infrared \(K\) and \(H\) bands, combined with our aforementioned planned reobservations of the eclipse of WASP-12b in these bands. These combined transit and eclipse observations will allow us to confirm if the \(K\)-band eclipse is indeed longer in duration than the optical transit, and if so whether this is due to material tidally stripped from the planet that may or may not form a circumstellar disk in this system.

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