THERMAL EMISSION AND TIDAL HEATING OF THE HEAVY AND ECCENTRIC PLANET XO-3b

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ABSTRACT

We determined the flux ratios of the heavy and eccentric planet XO-3b to its parent star in the four Infrared Array Camera bands of the Spitzer Space Telescope: 0.101% ± 0.004% at 3.6 μm; 0.143% ± 0.006% at 4.5 μm; 0.134% ± 0.049% at 5.8 μm; and 0.150% ± 0.036% at 8.0 μm. The flux ratios are within [−2.2, 0.3, −0.8, and −1.7]σ of the model of XO-3b with a thermally inverted stratosphere in the 3.6 μm, 4.5 μm, 5.8 μm, and 8.0 μm channels, respectively. XO-3b has a high illumination from its parent star ($F_p \sim (1.9–4.2) \times 10^6$ erg cm$^{-2}$ s$^{-1}$) and is thus expected to have a thermal inversion, which we indeed observe. When combined with existing data for other planets, the correlation between the presence of an atmospheric temperature inversion and the substellar flux is insufficient to explain why some high insolation planets like TrES-3 do not have stratospheric inversions and some low insolation planets like XO-1b do have inversions. Secondary factors such as sulfur chemistry, atmospheric metallicity, amounts of macroscopic mixing in the stratosphere, or even dynamical weather effects likely play a role. Using the secondary eclipse timing centroids, we determined the orbital eccentricity of XO-3b as $e = 0.277 \pm 0.009$. The model radius–age trajectories for XO-3b imply that at least some amount of tidal heating is required to inflate the radius of XO-3b, and the tidal heating parameter of the planet is constrained to $Q_p \lesssim 10^6$.

Key words: binaries: eclipsing – infrared: stars – planetary systems – stars: individual (XO-3)

1. INTRODUCTION

The study of hot Jupiter atmospheres is maturing. In particular, low resolution spectra and broadband spectral energy distributions have been assembled from high precision photometry of hot Jupiter’s day and night sides using the Spitzer Space Telescope’s Infrared Array Camera (IRAC; Knutson et al. 2008, 2009a; Tinetti et al. 2007; Charbonneau et al. 2008; Machalek et al. 2008, 2009; O’Donovan et al. 2009; Désert et al. 2009; Todorov et al. 2010; Frassin et al. 2009; Christiansen et al. 2010), Infrared Spectrograph (IRS; Grillmair et al. 2008) and Multiband Imaging Spectrometer (MIPS; Knutson et al. 2009c) as well as the Hubble Space Telescope (Swain et al. 2008, 2009a, 2009b).

Upper atmospheres of hot Jupiters are currently thought to be split into two classes depending on the stellar insolation at their substellar points: planets with substellar flux higher than $F_p \gtrsim 10^9$ erg cm$^{-2}$ s$^{-1}$ should possess temperature inversions in their stratosphere as the intense stellar radiation is absorbed by upper atmospheric gaseous absorbing species (Hubeny et al. 2003; Burrows et al. 2008; Fortney et al. 2006, 2008; Spiegel et al. 2009). Planets with insolation fluxes $F_p \sim (0.5–1.0) \times 10^9$ erg cm$^{-2}$ s$^{-1}$ such as XO-2b, HAT-P-1, OGLE-TR-113, and WASP-2 are in a transition zone between atmospheres with or without a stratosphere. Secondary effects like sulfur chemistry and atmospheric metallicity (Zahnle et al. 2009), amounts of macroscopic mixing in the stratosphere (Spiegel et al. 2009), or even dynamical weather effects (Showman et al. 2009; Rauscher & Menou 2009) could determine the stratospheric temperature profiles of these transition planets.

XO-3b is a hot Jupiter with a high mass $M_p = 11.79 \pm 0.59$ $M_{\text{Jup}}$ (Winn et al. 2008; Johns-Krull et al. 2008), which is close to the deuterium burning limit and has one of the highest observed surface gravities, $g = 209$ m s$^{-2}$ amongst the known transiting planets. Its 3.1915239 day long orbit around the parent star XO-3 (spectral type F5V, $d = 260 \pm 23$ pc; Johns-Krull et al. 2008) has significant eccentricity $e = 0.287 \pm 0.005$ (Hébrard et al. 2008), which causes stellar irradiance to vary three-fold over the entire orbit and causes the secondary eclipse to shift in time from half-phase.

Furthermore, Liu et al. (2008) estimated the amount of tidal energy dissipation rate contributing to the inflated radius of XO-3b ($R_p = 1.217 \pm 0.073$ $R_{\text{Jup}}$; Winn et al. 2008) assuming the age of XO-3b $t = 2.82^{+0.58}_{-0.82}$ Gyr (Winn et al. 2008). Liu et al. (2008) concluded that the radius–age relationship for XO-3b is consistent to within 1σ with no internal heat source (i.e., no tidal heating) or tidal heating dissipation with dimensionless tidal heating parameter $Q_p \gtrsim 10^6$ as defined by Goldreich & Soter (1966). By determining the exact timing of the secondary eclipse in our four infrared light curves obtained with Spitzer Space Telescope IRAC, we will refine the orbital eccentricity of XO-3b and constrain the amount of tidal heating (if any) responsible for inflating the planetary radius. In addition to its high mass and significant orbital eccentricity, XO-3b was also the first planet with detected and confirmed non-zero sky projection angle $\lambda = 37.3 \pm 3.7$ between the orbital axis and stellar rotation axis obtained from the Rositzer–McLaughlin effect (Hébrard et al. 2008; Winn et al. 2009), currently thought to be a result of planet–planet scattering (Nagasawa et al. 2008; Jurić & Tremaine 2008).
The substellar point flux at XO-3b is $F_p \sim (1.9-4.2) \times 10^9$ erg cm$^{-2}$ s$^{-1}$. The exact value depends on the adopted stellar and planetary mass and radius, which are still uncertain (Liu et al. 2008), as well as the changing distance from the star due to an eccentric orbit. However, this range of substellar point flux is clearly consistent with a prominent thermal inversion in the stratosphere. Figure 1 shows the temperature–pressure models of Burrows et al. (2007b, 2008), Spiegel et al. (2009), and the predicted thermal inversion in the stratosphere and the negative temperature gradient in the upper atmosphere of XO-3b.

By obtaining the light curve of XO-3b in the four IRAC (4–8 $\mu$m) channels on the Spitzer Space Telescope and determining the depth and timing of the secondary eclipse in multiple wavelengths, we will be able to constrain the upper atmospheric temperature structure of XO-3b, refine the orbital eccentricity of the planet from the secondary eclipse timing centroids and hence its tidal heating rate, which could be responsible for inflating the radius of XO-3b. The cold Spitzer IRAC observations in this work will provide a firm observational and theoretical foothold on the properties of the XO-3b atmosphere during the secondary eclipse and serve as comparison for future full orbit observation of XO-3b with warm Spitzer similar to previous extended duration phase curves of hot Jupiters (Knutson et al. 2007, 2009c, 2009b; Laughlin et al. 2009). Since there is a strong water band near IRAC 5.8 $\mu$m, coverage in all four IRAC bands will test for transitions between water in emission and in absorption, which cannot be observed with warm Spitzer. Furthermore, as Figure 1 illustrates, there is a steep temperature gradient between depths corresponding to emission in the IRAC 5.8/8.0 $\mu$m channels, which can be uniquely studied with cold Spitzer or otherwise with the James Webb Space Telescope (JWST) in the future. The 5.8 $\mu$m and 8.0 $\mu$m channel planet/star flux ratios will further be correlated with the 3.6/4.5 $\mu$m flux ratio to test the two signatures of stratospheres.

2. OBSERVATIONS AND DATA ANALYSIS

The IRAC (Fazio et al. 2004) has a field of view of $5'/2 \times 5'/2$ in each of its four bands. Two adjacent fields are imaged in pairs (3.6 and 5.8 $\mu$m; 4.5 and 8.0 $\mu$m). The detector arrays each measure $256 \times 256$ pixels, with a pixel size of approximately $1''/22 \times 1''/22$. We closely repeat the data analysis of Machalek et al. (2008, 2009) with modifications and improvements mentioned in the text.

We have observed XO-3 system in all four channels in two separate Astronomical Observing Requests (AORs) in two different sessions: the 3.6 $\mu$m and 5.8 $\mu$m channels for 6.9 hr (with 2.9 hr long secondary eclipse) on UT 2009 March 17 (AOR 31618560) and the 4.5 $\mu$m and 8.0 $\mu$m channels for 6.9 hr on UT 2009 April 21 (AOR 31618816) with a thirty-minute preflash on a bright uniform part of NGC1569. We used the full array 2 s+2 s/12 s frame time in the stellar mode in which the 3.6 $\mu$m and 4.5 $\mu$m bands are exposed for two consecutive 2 s exposures while the 5.8 $\mu$m and 8.0 $\mu$m bands are integrating for 12 s to prevent detector saturation.

The 4.5 $\mu$m and 8.0 $\mu$m time series has been preflashed with a bright uniform extended target to prevent the initial “ramp-up” effect (Charbonneau et al. 2005; Deming et al. 2005; Knutson et al. 2008; Machalek et al. 2008, 2009); consequently, no data points were removed from the beginning of the time series. The 3.6 $\mu$m and 5.8 $\mu$m time series, however, were obtained with no preflashing and hence exhibit an initial charge build up, which is consistently removed during our detector effect removal.

2.1. InSb Detectors

We have repeated our methodology from Machalek et al. (2009) by performing aperture photometry on the 3.6 $\mu$m and 4.5 $\mu$m time series with radii between 2.5 and 6.0 pixels. In order to test whether our secondary eclipse depths and centroid timings depend on aperture radius, we have repeated the entire data reduction for aperture radii between 2.5 and 6.0 pixels in 0.5 pixel increments and obtained consistent results for different apertures. We have improved our photometry pipeline by obtaining the stellar centroids from a flux-weighted position of a $5 \times 5$ pixel square centered on the peak stellar pixel (method suggested by S. Carrey 2009, private communication). Since our starting point was the BCD images produced by the pipeline version 18.7, cosmic rays were already rejected. The heliocentric modified Julian date at Spitzer spacecraft position recorded in the header keyword “HMJD_OBS” did
not necessitate our previous calculations of spacecraft positions (Machalek et al. 2008, 2009).

We have chosen the aperture radii based on the rms of residuals after detector effects and the secondary eclipse were removed. We used an aperture of radius 3.0 pixels for the 3.6 μm time series of XO-3, which had an rms 0.0034 for out of transit points after decorrelation. This is essentially Poisson noise limited, being only 1.01 higher than the predicted noise based on source brightness, detector read noise, and gain. Similarly, the 4.5 μm time series of XO-3 was obtained from 3.0 pixel radius aperture photometry which had the lowest rms of 0.0049, which is 1.08 times higher than the predicted noise. The appropriate aperture corrections were applied to the photometry as specified by the Spitzer Data Handbook.

As is evident from Figure 3, the 3.6 μm time series exhibits a prominent flux variation with a magnitude of ~0.8%, which is a well-studied instrumental effect (Charbonneau et al. 2005; Morales-Calderón et al. 2006; Machalek et al. 2008; Knutson et al. 2009a; Machalek et al. 2009; Désert et al. 2009) due to subpixel sensitivity variations caused by a spacecraft position drift of 0.1–0.3 arcsec over a period of ~3000 s, which makes the star move on the pixel. The 4.5 μm time series, however, has negligible flux variations, probably due to a chance positioning on a pixel phase with a flat response curve (pixel reference: 126.46; 128.78). This pixel could be useful in planning for extended duration observations with warm Spitzer. Désert et al. (2009) have noted a similar pixel with a flat response function at pixel coordinates [147.20; 198.25].

Our removal of the systematic effects and eclipse curve fitting closely follows the methodology of Machalek et al. (2009). The subpixel intensity variations in the 3.6 μm and 4.5 μm time series are detrended as a linear function of subpixel positions of the stellar centroid x, y, x^2, y^2, a linear function of time t, plus a constant for each of the two InSb channels:

\[ I_{3.6 \mu m} = 1.0 + b_1x + b_2y + b_3x^2 + b_4y^2 + b_5t, \] (1)

\[ I_{4.5 \mu m} = 1.0 + b_1x + b_2y. \] (2)

We tried adding higher order terms of x and y, a cross term of x × y, and a linear term linear in t to the 4.5 μm time series decorrelation. However, adding terms did not decrease the \( \chi^2 \) or change the secondary eclipse depth or centroid timing in the 4.5 μm time series, so we chose only two degrees of freedom (Equation (2)) for the 4.5 μm time series decorrelation. Furthermore, as can be seen from Figure 2, the binned residuals in the decorrelated and fitted 4.5 μm light curve of XO-3 scale as \( N^{-1/2} \), where N is the number of points per bin. Since the binning of the residuals scales as \( N^{-1/2} \), we can conclude that negligible systematic errors remain in the decorrelated light curve.

We fit the secondary eclipse with the formalism of Mandel & Agol (2002) with no stellar limb darkening and adopt the stellar and planetary parameters of Winn et al. (2008): \( R_* = 1.38_{-0.08}^{+0.08} R_{\odot} \), \( M_p = 11.79_{-0.59}^{+0.59} M_{\text{Jup}} \), \( R_p = 1.22_{-0.07}^{+0.07} R_{\text{Jup}} \), \( a = 8.42_{-0.54}^{+0.54} \) AU, and \( i = 84.20_{-0.54}^{+0.54} \) degrees, and \( \alpha = 0.0454 \pm 0.0008 \) AU with ephemeris:

\[ T_c(E) = 2, 454, 449.86816 \text{ (HJD)} + E(3.1915239 \text{ days}). \] (3)

We fit the five baseline parameters of Equation (1) and the two baseline fitting parameters of Equation (2) concurrently with the secondary eclipse depth \( \Delta F \) and the phase of the eclipse centroid \( \Phi \) for a total of seven and four fitting parameters, respectively. This was done to properly account for the way in which systematic effects removal affects the secondary eclipse fitting. The best parameter solutions were obtained by using a Monte Carlo Markov chain (MCMC) with 10^5 iterations (Gregory 2005; Markwardt 2009) with ratio of jumps between 20%–40%. The best-fit parameter values were obtained by discarding...
the first 20% of the iterations to prevent initial conditions from influencing the results and adopting the median of the distribution of each parameter as the best-fit value. These values are reported in Table 1 with errors obtained from symmetric 66.8% contours around the median of the posterior probability distribution of the MCMC runs. The decorrelated best-fit light curves are depicted in Figure 4 binned in 3.5 minute intervals.

We find that the XO-3 3.6 \(\mu m\) time series shows a linear flux increase with a slope of \(b_4 = 0.015% \pm 0.002% \text{ hr}^{-1}\), which is consistently removed from our photometry, but inconsistent with the slope of XO-2 at 3.6 \(\mu m\) of \(b_4 = -0.011% \pm 0.005% \text{ hr}^{-1}\) (Machalek et al. 2009). This flux decrease has been attributed by Machalek et al. (2009) and Knutson et al. (2009a) to an instrumental effect on the InSb detectors. When we added a linear time term \(b_4 t\) to the decorrelation of the 4.5 \(\mu m\) time series of XO-3 in Equation (2), its value was consistent with zero. Thus, we omitted a linear time term \(b_4 t\) from the final analysis.

### 2.2. Si:As Detectors

The 5.8 \(\mu m\) and 8.0 \(\mu m\) time series is recorded with Si:As detectors, which have a different set of systematic effects from the 3.6 \(\mu m\) and 4.5 \(\mu m\) InSb detectors. We have performed aperture photometry on the 5.8 \(\mu m\) and 8.0 \(\mu m\) images with aperture radii ranging from 3.0 to 6.0 pixels, choosing the aperture radius with the lowest rms of the residuals after systematic effects and the secondary eclipse were removed. This resulted in an aperture of radius 3.5 pixels for the 5.8 \(\mu m\) time series with a detrended rms of 0.0055 (42% higher than Poisson noise) and an aperture radius of 4.5 pixels for the 8.0 \(\mu m\) time series with a detrended rms of 0.0049 (60% higher than Poisson noise). No points were removed from the beginning of either the 5.8 \(\mu m\) or 8.0 \(\mu m\) time series.

A well-studied instrumental effect of the Si:As arrays is the gain variations of individual pixels over time, which result in flux decrease/increase in the light curve (e.g., Deming et al. 2005; Knutson et al. 2007, 2008; Machalek et al. 2008; Désert, Laughlin et al. 2009) have reported that the gain variations in the 5.8 \(\mu m\) and 8.0 \(\mu m\) channels and resultant flux trends in the light curves differ for the two components of a binary star, which have the same brightness and similar colors, suggesting that relative placement of the stellar centroid with respect to the edges of the pixels determines the Si:As detector pixel response. The gain variations can be clearly seen in the 5.8 \(\mu m\) and 8.0 \(\mu m\) light series in Figure 3: a nonlinear decrease in brightness in the 5.8 \(\mu m\) light series and a nonlinear flux increase in the 8.0 \(\mu m\) time series.

To remove the nonlinear flux variation inherent to the Si:As detector, we fit the secondary eclipse depth \(\Delta F\) along with the eclipse centroid phase \(\Phi\) concurrently with the three “ramp” decorrelation coefficients as follows:

\[
I_{model} = a_1 + a_2 \times \ln(\Delta t + 0.05) + a_3 \times \ln(\Delta t + 0.05)^2, \tag{4}
\]

where \(I_{model}\) is the normalized model flux and \(\Delta t\) is the time in days since the beginning of the integration (constant of +0.05 inserted to avoid singularity at \(\Delta t = 0\)). We fit the five parameters (two for the eclipse and three for the “ramp” in Equation (4)) for the 5.8 \(\mu m\) and 8.0 \(\mu m\) time series concurrently using 10^5 MCMC runs with errors adopted as the 66.8% contours around the median of the posterior distribution of the MCMC runs for each parameter. To ensure that our results are not dependent on the aperture radius, we have repeated the MCMC runs for all aperture radii between 3.0 and 6.0 pixels in 0.5 pixel increments and found the timing centroids to be consistent. The secondary eclipse depths were, however, found to vary by about 1\(\sigma\) for photometry with aperture radii...
between 3.0 and 6.0 pixels. Hence, to be conservative, as stated above, we have adopted the secondary eclipse depths from the aperture photometry with the lowest rms of residuals after eclipse removal. These aperture radii were 3.5 pixels for the 5.8 $\mu$m time series and 4.5 pixels for the 8.0 $\mu$m time series. We adopted uncertainties as the upper and lower envelope of the eclipse depths with their uncertainties for photometry with aperture radii between 3.0 and 6.0 pixels. Note, however, that these large, conservative uncertainties of the 5.8 $\mu$m and 8.0 $\mu$m eclipse depths ($\Delta F_{5.8\mu m} = 0.134\% \pm 0.049\%$ and $\Delta F_{8.0\mu m} = 0.150\% \pm 0.036\%$) still allow us to distinguish between the two models for the upper atmospheric temperature structure of XO-3b (see Figure 5). The final results are reported in Table 1, and the decorrelated time series was binned in 3.5 minute bins for viewing clarity in Figure 4.

3. DISCUSSION

The IR light curves presented in this work allow for the determination of the exact timing of the secondary eclipse centroid such that the orbital eccentricity can be refined more accurately than from the radial velocity (RV) curve. The temperature structure of the upper atmosphere of XO-3b (see Figure 5). The final results are reported such that the orbital eccentricity can be refined more accurately than from the radial velocity (RV) curve. The temperature structure of the upper atmosphere of XO-3b can also be determined from the light curves by comparing the secondary eclipse depths (i.e., the planet/star contrast ratios) to atmospheric models. A refined eccentricity determines the rate of tidal heating of the planet and can help explain the inflated radius of XO-3b.

3.1. Tidal Heating Rate and the Radius of the Planet

A subset of transiting extrasolar giant planets (EGPs) has radii larger than standard models can accommodate (Guillot et al. 1999; Bodenheimer et al. 2001, 2003; Chabrier et al. 2004; Ibgui & Burrows 2009). Numerous explanations have been suggested as sources of the inflated radii of EGP (see Fortney & Nettelmann 2009 for a review). Working in opposition to any inflation mechanism, heavy-element inner cores lead to smaller planetary radii compared to pure H/He objects (Burrows et al. 2007a; Fortney et al. 2007; Baraffe et al. 2008). Tidal inflation has been a popular explanation, as the dissipation of orbital energy into the inner regions of a planet can lead to inflated radii (Bodenheimer et al. 2001, 2003; Liu et al. 2008; Jackson et al. 2008). Radius–age trajectories for EGP are presented by Liu et al. (2008) to explain the inflated radius of several planets, including XO-3b, which is larger than theoretical predictions.

Liu et al. (2008) have investigated the radius of XO-3b as a function of planetary age $t$, planetary radius $R_p$, planetary mass $M_p$, orbital eccentricity $e$, planetary metallicity [Fe/H], and tidal heating parameter $Q_P$. They conclude that for the parameters adopted from the photometric follow-up of XO-3b by Winn et al. (2008), which are used in our study (see Section 2.1), the radius $R_P = 1.22^{+0.07}_{-0.07} R_{\text{Jup}}$ adopted by Winn et al. (2008) is consistent within 1$\sigma$ to either no internal heat source or tidal energy dissipation with tidal heating parameter $Q_P \gtrsim 10^{6.0}$. This is the heating parameter for the adopted eccentricity based upon RV measurements from Winn et al. (2008), $e = 0.260 \pm 0.017$. We have also adopted these parameters of Winn et al. (2008) up to this point in this study (see Section 2.1).

We refine the eccentricity $e$ of XO-3b using the weighted average of the secondary eclipse timing centroids from Table 1 using the displacement from half-orbital phase as a measurement of eccentricity (e.g., Kopal 1959, Equation (9.23)):

$$2\pi \Phi = \pi + 2e \times (\cos \omega)(1 + \csc^2(i)) + \ldots,$$

where $e$ is the eccentricity, $\Phi$ is the orbital phase of the time centroid of the secondary eclipse, $\omega$ is the longitude of periastron, and $i$ is the planetary orbit inclination. Using argument of pericenter $\omega = 345.8^\circ \pm 7.3^\circ$ and inclination $i = 84.20 \pm 0.54$ from Winn et al. (2008), we derive a refined eccentricity of the XO-3b system from our secondary eclipse timings:

$$e = 0.277 \pm 0.009,$$

with uncertainties formally propagated through Equation (5). Taken individually the 2009 March secondary eclipse phase centroids from Table 1 imply an eccentricity of 0.278 $\pm$ 0.010 and the 2009 April secondary eclipse phase centroids imply an eccentricity of 0.276 $\pm$ 0.009, which are consistent with each other. The intriguing possibility of eccentricity changing on a timescale of months will be further studied during the warm Spitzer mission phase observations of XO-3b in Spring 2010, when both the transit and secondary eclipse will be observed.

The refined value of XO-3b eccentricity $e = 0.277 \pm 0.009$ is 1.0$\sigma$ higher than the Winn et al. (2008) and Johns-Krull et al. (2008) eccentricity $e = 0.260 \pm 0.017$. It is also 2$\sigma$ lower than the RV derived eccentricity $e = 0.287 \pm 0.005$ (Hébrard et al. 2008). The tidal heating of XO-3b, which is a strong function of eccentricity, can inflate the radius of the planet. To estimate the relevance of tidal heating to the energy budget of XO-3b, we evaluate the ratio of the tidal energy dissipation rate to the insolation rate from the parent star (Liu et al. 2008):

$$\frac{\dot{E}_{\text{tide}}}{E_{\text{insolation}}} = \frac{GM_* \mu f(e)}{\pi F_p R_p^2 \alpha_{\text{circ}}^2} \sim 6.9 \times 10^{-5} \left(\frac{e}{0.01}\right)^2 \left[\frac{f(e)}{e^2}\right] \times \left(\frac{Q_p}{10^5}\right)^{-1} \frac{M_*}{M_\odot} \left(\frac{R_p}{R_\odot}\right)^3 \left(\frac{a}{0.05\text{ AU}}\right)^{-15/2} \times \left(\frac{F_p}{10^9\text{ erg cm}^{-2} \text{ s}^{-1}}\right)^{-1},$$

where $\dot{E}_{\text{tide}}$ is the tidal energy dissipation within the planet’s rest frame; $E_{\text{insolation}}$ is the insolation rate of the planet $E_{\text{insolation}} = \pi R_p^2 F_p$, where $R_p$ is the radius of the planet; $F_p$ is the stellar flux at the planet's substellar point; $\mu$ is the reduced mass $\mu = \frac{M_* M_p}{M_* + M_p}$; $\tau$ is the circularization timescale as defined by Liu et al. (2008); $e$ is the orbital eccentricity; and $f(e)$ is a function of eccentricity $f(e) \equiv \frac{2}{5}(h_3(e) - 2h_4(e) + h_5(e))$. The terms of $f(e)$ follow from the expansion of the expression of the tidal energy dissipation within the planet’s rest frame in terms of the Runge–Lenz vector (see Gu et al. (2003) for more details) with $h_3(e) = (1 + 3e^2 + \frac{3}{5}e^4)(1 - e^2)^{-9/2}$, $h_4(e) = (1 + \frac{3}{5}e^2 + \frac{3}{7}e^4 + \frac{3}{10}e^6)(1 - e^2)^{-10}$, and $h_5(e) = (1 + \frac{3}{5}e^2 + \frac{25}{8}e^4 + \frac{185}{56}e^6 + \frac{25}{14}(1 - e^2)^{-4})$. $Q_p$ is the dimensionless tidal dissipation parameter of the planet (Goldreich & Soter 1966); $M_\odot$ is the mass of the star in solar units; and $R_\odot$ is the radius of the planet and $a$ is the semimajor axis.

Using Equation (7) we estimate the ratio of tidal heating dissipation rate to the insolation rate of XO-3b to be $\frac{\dot{E}_{\text{tide}}}{E_{\text{insolation}}} \sim e = 0.260 \pm 0.043$ given the Winn et al. (2008) planetary and stellar parameters: $M_* = 1.213 \pm 0.066 M_\odot$, $M_p = 11.79^{+0.59}_{-0.39} M_{\text{Jup}}$, $R_p = 1.22^{+0.07}_{-0.07} R_{\text{Jup}}$, $a = 0.0454 \pm 0.0008$ AU, $F_p = 1.93 \times 10^9$ erg cm$^{-2}$ s$^{-1}$, planetary tidal dissipation parameter $Q_p = 10^5$, and an RV derived eccentricity of $e = 0.260 \pm 0.017$.

Our study refines the eccentricity of XO-3b $e = 0.277 \pm 0.009$, which yields a ratio $\frac{\dot{E}_{\text{tide}}}{E_{\text{insolation}}} \sim 0.56$, i.e., a 29%
increase in the tidal dissipation rate over the lower eccentricity when all other parameters are unchanged. Figure 2 of Liu et al. (2008) would suggest that if the age of XO-3b is currently estimated to be $t = 2.82^{+0.58}_{-0.82}$ Gyr (Winn et al. 2008) and for solar metallicity, the increased tidal heating rate from our work would require a lowered tidal dissipation parameter $Q_P \geq 10^6$. Furthermore, the radius–age trajectory for XO-3b with $M_p = 11.79^{+0.59}_{-0.59} M_{\text{Jup}}$, $R_p = 1.22^{+0.07}_{-0.07} R_{\text{Jup}}$, and the refined eccentricity $e = 0.277 \pm 0.009$ is inconsistent with no tidal heating depicted by infinite tidal heating parameter $Q = \infty$. An important caveat to our radius interpretations for XO-3b is that we assume that tidal heating is the only radius inflation mechanism. Furthermore, the distance to XO-3b is still very uncertain ($d = 260 \pm 23$ pc). Also, the discovery paper by Johns-Krull et al. (2008) and the photometric follow-up by Winn et al. (2008) disagree on the mass of XO-3b by 10% and more than 50% on the radius. Detailed radius–age determinations for XO-3b and its tidal heating history will thus need a parallax determination, which is in progress (Johns-Krull 2008). Furthermore, given the rudimentary nature of the $Q$ model of tides, the assumption that dissipation is all in the convective core, and without detailed knowledge of the real physics of tidal dissipation, our conclusions about tidal heating rates and inferred radii of XO-3b are preliminary.

In short, we have refined the orbital eccentricity of XO-3b using the secondary eclipse timings in the four IRAC channels to $e = 0.277 \pm 0.009$, which increases the rate of tidal heating of the planet by 29% over previous eccentricity estimates. Even in the absence of an accurate parallax measurement, the radius–age trajectory of XO-3b (Figure 2 of Liu et al. 2008) seems to imply that at least some amount of tidal heating must be responsible for the inflated radius of XO-3b.

### 3.2. Stratospheric Temperature Profile

The eclipse depths reported in Table 1 and depicted as filled squares in Figure 5 show the spectral energy distribution of the upper atmosphere of XO-3b as a function of the flux ratio between XO-3b and its parent star XO-3. The flux ratio increases from the 3.6 $\mu$m to the 4.5 $\mu$m channels and stays constant within errors in the 5.8 $\mu$m and 8.0 $\mu$m channels. We compare the flux ratios (filled squares) to atmospheric models based on the methodology of Burrows et al. (2007b, 2008) and Spiegel et al. (2009), which are depicted in Figure 5 as a black solid line (and open squares as IRAC band averages) and a dot-dashed line with open circles as IRAC band averages.

The black solid line with open squares presents an atmospheric model with upper atmospheric temperature inversion induced by an extra absorber of uniform opacity of $k_{\text{ext}} = 0.2$ cm$^2$ g$^{-1}$ placed at optical wavelengths and placed high up in altitude at pressures below $P_0 = 30$ mbar in XO-3b’s atmosphere. The model incorporates a heat re-distribution parameter of $P_n = 0.2$, which corresponds to an atmosphere between the two extremes of no heat re-distribution ($P_n = 0$) and full re-distribution ($P_n = 0.5$; see Burrows et al. 2008 for more details). The dot-dashed line with open circles as IRAC band averages corresponds to an atmospheric model with no extra upper atmospheric absorber and a heat re-distribution parameter of $P_n = 0.3$.

Both atmospheric models are calculated for XO-3b’s orbital distance $a = 0.0454$ AU (Winn et al. 2008) and stellar insolation $F_p \sim 2.01 \times 10^9$ erg cm$^{-2}$ s$^{-1}$, which ignores the dynamical atmospheric effects due to variable stellar insolation caused by XO-3b orbital eccentricity $e = 0.277 \pm 0.009$. A full dynamical model for the atmosphere of XO-3b, which incorporates the time variable stellar insolation and the temporal adjustment of the atmosphere to the instantaneous irradiation (i.e., the radiative time constant), is beyond the scope of this paper. Full dynamical treatment of XO-3b’s atmosphere is planned for the dynamic weather observations of XO-3b during the warm Spitzer mission in the spring of 2010 in the 3.6 $\mu$m and 4.5 $\mu$m IRAC channels.

The planet/star contrast ratios of XO-3b are within $[-2.2, 0.3, -0.8, -1.7]\sigma$ of the thermal inversion in the upper stratosphere model of XO-3b in the 3.6 $\mu$m, 4.5 $\mu$m, 5.8 $\mu$m, and 8.0 $\mu$m channels, respectively. The measured planet/star contrast ratios are inconsistent at more than $3\sigma$ in the 3.6 $\mu$m, 4.5 $\mu$m, 5.8 $\mu$m, and 8.0 $\mu$m channels with the thermally non-inverted upper atmosphere model (dot-dashed line and open circles as band averages in Figure 5). The flux contrast ratios of XO-3b in the four IRAC channels thus represent a detection of an upper atmospheric temperature inversion similar to the temperature–pressure profile depicted as a solid line in Figure 1. We further note that the XO-3b flux ratios can be reproduced in the 3.6 $\mu$m, 4.5 $\mu$m, and 5.8 $\mu$m channels by a blackbody with an effective temperature $T_{\text{eff}} = 1550$ K as well.

A correlation between minimum insolation at the planet’s substellar point and the presence of stratospheric temperature inversions has been recently emerging (Burrows et al. 2008; Fortney et al. 2008) from numerous hot Jupiter spectral energy distribution measurements (Harrington et al. 2007; Charbonneau et al. 2008; Knutson et al. 2008, 2009a; Machalek et al. 2008, 2009; O’Donovan et al. 2009; Fressin et al. 2009; Todorov et al. 2010; Christiansen et al. 2010; Gillon et al. 2009). Currently $F_p \sim 1.0 \times 10^9$ erg cm$^{-2}$ s$^{-1}$ of flux at the planetary substellar point is thought to be necessary for the extra optical absorber to drive a stratospheric temperature inversion, although significant outliers exist: XO-1b with...
a substellar point flux of $F_p \sim 0.49 \times 10^9$ erg cm$^{-2}$ s$^{-1}$ has a stratospheric temperature inversion (Machalek et al. 2008); while TrES-3 is strongly irradiated and yet possesses no thermal inversion according to Fressin et al. (2009). The planet HAT-P-1b has intermediate subsolar flux between XO-1b and TrES-3 and presents evidence for a weak thermal inversion (Todorov et al. 2010). Also, the flux ratios of the planet CoRoT-2b ($F_p \sim 1.3 \times 10^9$ erg cm$^{-2}$ s$^{-1}$) in 4.5 $\mu$m and 8.0 $\mu$m IRAC channels provide a tentative non-detection of thermal inversion (Gillon et al. 2009).

The distance to XO-3 is currently uncertain, so are the estimates for the stellar mass and radius. Therefore, the substellar point flux at the XO-3b is estimated to be in the range $F_p \sim (1.9-4.2) \times 10^9$ erg cm$^{-2}$ s$^{-1}$, Liu et al. (2008). This entire flux range is well above the threshold value and therefore strongly predictive of a temperature inversion in the stratosphere of XO-3b, which is detected in our data set.

The diagnosis of temperature inversions in hot Jupiter atmospheres is still somewhat model dependent as exemplified by the color–color diagram of Gillon et al. (2009). This figure shows that although TrES-3b (Fressin et al. 2009) and TrES-2b (O’Donovan et al. 2009) have almost identical colors, an inversion is claimed for TrES-2b but not for TrES-3b. Alternative determinants for the cause of temperature inversions in stratospheres of hot Jupiters have been suggested by Zahnle et al. (2009) in the form of sulfur photochemistry. Furthermore, three-dimensional global circulation models (3D GCMs) by Showman et al. (2009) and Rauscher & Menou (2009) suggest that dynamic weather patterns can induce temperature inversions even without extra stratospheric optical absorbers. Obtaining flux ratios of hot Jupiters with varying degrees of stellar insolation, planetary metallicity, and eccentricity at multiple IR wavelengths with Spitzer IRAC or JWST in the future will help to constrain the cause of stratospheric thermal inversions in hot Jupiters.

4. CONCLUSION

We determined the flux ratios of the planet heavy and eccentric planet XO-3b to its parent star in the four IRAC bands: 0.101% ± 0.004% at 3.6 $\mu$m; 0.143% ± 0.006% at 4.5 $\mu$m; 0.134% ± 0.049% at 5.8 $\mu$m; and 0.150% ± 0.036% at 8.0 $\mu$m. The flux ratios point toward a stratospheric temperature inversion best fitted with atmospheric models with a uniform stratospheric absorber of $k_e = 0.2$ cm$^2$ g$^{-1}$.

XO-3b is strongly irradiated with a subsolar point flux $F_p \sim (1.9-4.2) \times 10^9$ erg cm$^{-2}$ s$^{-1}$, depending on uncertain parent star parameters and eccentric orbit. This high flux is expected to cause a thermal inversion in the planet’s stratosphere, which is indeed observed. Obtaining the parallax distance Johns-Krull (2008) to the parent star XO-3 would refine both the stellar and planetary masses and radii and hence constrain better the subsolar point flux $F_p$. The correlation between the presence of a temperature inversion in a hot Jupiter atmosphere and the subsolar point flux from the parent star is insufficient to explain why high insolation planets like TrES-3 do not have stratospheric inversions and some low insolation planets like XO-1b do have inversions. Secondary factors such as sulfur chemistry, atmospheric metallicity, amounts of macroscopic mixing in the stratosphere, or even dynamical weather effects likely play a role.

Using the secondary eclipse timing centroids, we refined the orbital eccentricity of XO-3b to be $e = 0.277 \pm 0.009$, which is 1.0$\sigma$ higher than the RV derived eccentricity $e = 0.260 \pm 0.017$ (Winn et al. 2008; Johns-Krull et al. 2008). The refined eccentricity increases the amount of tidal energy dissipation rate by 29%, and the radius–age trajectories for XO-3b thus imply that at least some amount of tidal heating must be responsible for the inflated radius of XO-3b. The tidal heating parameter is constrained to $Q_p \lesssim 10^6$. A more accurate radius measurement of XO-3b is needed from a parallax distance to the parent star XO-3 either from the Hubble Space Telescope or the future Global Astrometric Interferometer for Astrophysics (GAIA) mission to further refine its tidal heating rate and the allowable range for the tidal heating parameter $Q_p$.

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