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SPITZER IRAC SECONDARY ECLIPSE PHOTOMETRY OF THE TRANSITING EXTRASOLAR PLANET HAT-P-1b

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ABSTRACT

We report *Spitzer*/IRAC photometry of the transiting giant exoplanet HAT-P-1b during its secondary eclipse. This planet lies near the postulated boundary between the pM and pL-class of hot Jupiters, and is important as a test of models for temperature inversions in hot Jupiter atmospheres. We derive eclipse depths for HAT-P-1b, in units of the stellar flux, that are: $0.080\% \pm 0.008\%$ [$3.6 \mu\text{m}$], $0.135\% \pm 0.022\%$ [$4.5 \mu\text{m}$], $0.203\% \pm 0.031\%$ [$5.8 \mu\text{m}$], and $0.238\% \pm 0.040\%$ [$8.0 \mu\text{m}$]. These values are best fit using an atmosphere with a modest temperature inversion, intermediate between the archetype inverted atmosphere (HD 209458b) and a model without an inversion. The observations also suggest that this planet is radiating a large fraction of the available stellar irradiance on its dayside, with little available for redistribution by circulation. This planet has sometimes been speculated to be inflated by tidal dissipation, based on its large radius in discovery observations, and on a non-zero orbital eccentricity allowed by the radial velocity data. The timing of the secondary eclipse is very sensitive to orbital eccentricity, and we find that the central phase of the eclipse is 0.4999 ± 0.0005 . The difference between the expected and observed phase indicates that the orbit is close to circular, with a 3σ limit of $|e \cos \omega| < 0.002$.

Key words: eclipses – planetary systems – techniques: photometric

1. INTRODUCTION

Infrared light from transiting extrasolar planets can be measured using high precision photometry when the planets pass behind their stars. Most of these secondary eclipse measurements to date have used the *Spitzer Space Telescope* (Charbonneau et al. 2005; Deming et al. 2005, 2006, 2007; Demory et al. 2007; Harrington et al. 2007; Charbonneau et al. 2008; Machalek et al. 2008, 2009; Knutson et al. 2008, 2009). *Spitzer* data in the four bands of the IRAC instrument (Fazio et al. 2004) define the planet’s spectral energy distribution over the $3.6\text{--}8.0 \mu\text{m}$ wavelength region, where water vapor plays a principal role in shaping the spectrum. *Spitzer* studies have shown that there are at least two classes of close in extrasolar giant planets, differentiated by the temperature gradient with height in their atmosphere (Hubeny et al. 2003; Fortney et al. 2006, 2008; Burrows et al. 2007, 2008). One class (pM) exhibits a temperature inversion at high altitude in their atmosphere (Knutson et al. 2008, 2009; Machalek et al. 2008). The inversion affects the emergent spectral energy distribution by causing the water bands to appear in emission. The cause of the inversion is believed to be absorption of strong stellar irradiation in the visible, possibly by TiO/VO (Hubeny et al. 2003; Fortney et al. 2006, 2008), but other absorbers remain possible (Burrows et al. 2007; Zahnle et al. 2009).

Machalek et al. (2008) found that XO-1b exhibits an inverted atmospheric structure, in spite of being nominally below the stellar irradiance level projected to define the transition between the pM and the (non-inverted) pL classes. The pM/pL transition corresponds to the condensation of TiO (Fortney et al. 2008).

Recently, Machalek et al. (2009) found that XO-2b exhibits a weak temperature inversion, consistent with being near the pM/pL transition. Like XO-1b and XO-2b, HAT-P-1b (Bakos et al. 2007) lies at the lower edge of that predicted boundary, so it provides an important additional test of the propensity toward inversion at that level of irradiation. HAT-P-1b may also exhibit a non-zero eccentricity to its orbit (Johnson et al. 2008), that may cause internal energy generation via the dissipation of tidal stress.

In this paper, we report *Spitzer* photometry of HAT-P-1b’s secondary eclipse in the four IRAC bands. We use these data to investigate the atmospheric temperature structure and energy balance of this planet, and to place more stringent limits on the eccentricity of its orbit via the timing of the secondary eclipse (Charbonneau et al. 2005).

2. OBSERVATIONS

We observed HAT-P-1b during two secondary eclipses using *Spitzer*/IRAC. On 2006 December 28, we observed an eclipse at 4.5 and $8.0 \mu\text{m}$ for 356 minutes. To avoid saturation for this relatively bright star, each frame comprised two 2 s exposures in stellar mode at $4.5 \mu\text{m}$ (3212 exposures total), simultaneously with one 12 s exposure at $8 \mu\text{m}$ (1606 exposures total). On 2007 December 29, we observed an eclipse at 3.6 and $5.8 \mu\text{m}$ for 333 minutes (1510 total exposures at each wavelength). For that eclipse, we elected to increase the efficiency at $3.6 \mu\text{m}$ and avoid saturation by placing the star at the corner of a pixel, thus spreading the light over 4 pixels. We used 12 s exposures at both wavelengths, in full array mode. For both eclipses, we centered the star on a portion of the array chosen to avoid known bad pixels and scattered light from bright stars imaged onto other regions of the focal plane.

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3. PHOTOMETRY

All of our photometry used version S18.5.0 of the Basic Calibrated Data from the *Spitzer* pipeline. We applied the recommended factors to correct for the variation in flat-field response to point sources versus extended sources, and the variation in pixel solid angles, as described in Sections 5.3 and 5.6.2, respectively, of the IRAC Data Handbook V3.0. We ran our analysis both with and without these corrections, and we find that they change our final results by less than the 1σ error in the eclipse depth at all wavelengths. Their largest effect is at $4.5\ \mu\text{m}$, where they increase the eclipse depth by 6×10^{-5} in units of the stellar flux. All of the results quoted in this paper include these corrections.

To facilitate the error analysis, we converted the intensities in the images to electron numbers, using the calibration information in the FITS headers. We corrected energetic particle hits by comparing each pixel to a median-filtered time series of that pixel's intensity, using a five-frame resolution. We replaced individual values exceeding the median by more than 4σ with the median value. Some energetic particle hits that overlie the stellar image were not well corrected, and resulted in outlying intensities in the photometric time series; those values were omitted when fitting eclipse curves to the data.

All of our results are based on aperture photometry, but the details differ with wavelength, as described below. At all wavelengths, we centered the aperture on each stellar image by fitting a parabola to the brightest three points in the stellar profile. The image was summed in X to define the profile as a function of Y , and vice versa. We also found the center of each image by fitting a two-dimensional Gaussian to the core of the image point-spread function, but this did not improve the results over the parabolic fit. We varied the size of the photometry aperture, and used the value that minimized the scatter in the time series.

At each wavelength, we subtracted the background due to solar system zodiacal thermal emission. Since HAT-P-1 has a brighter companion star 11 arcsec distant, there was also a contribution due to diffracted light from the companion. Based on model point response functions (PRFs) provided by the Spitzer Science Center, we expect a diffracted contribution of $\sim 0.3\ \text{MJy sr}^{-1}$ at the position of HAT-P-1. This contribution is only weakly dependent on wavelength, because the decreasing brightness of the star at longer wavelength works in the opposite direction to the effect of diffraction. However, the zodiacal background is significantly wavelength dependent, so diffracted light from the companion star can dominate at 3.6 and $4.5\ \mu\text{m}$, decreasing to $\sim 15\%$ of the zodiacal background at $8\ \mu\text{m}$. We, therefore, measured the background at a symmetric position on the opposite side of the companion star from HAT-P-1, using an aperture of the same size and shape. Since this relatively small aperture (typically about 3 pixels in radius) encompasses relatively few electrons from the background, we increase the precision of the background measurement by fitting a parabola to the background time series, and using the value of that fit for each frame. Apart from random error, the background variation was quite gradual and was well represented by the parabolic fit.

3.1. 3.6 and 4.5 μm

Spitzer photometry at 3.6 and $4.5\ \mu\text{m}$ is known to be affected by pixel position, wherein the value from aperture photometry is a function of the location of the stellar centroid within the pixel (Morales-Calderon et al. 2006; Charbonneau et al. 2005). While this is true for our photometry at these wavelengths,

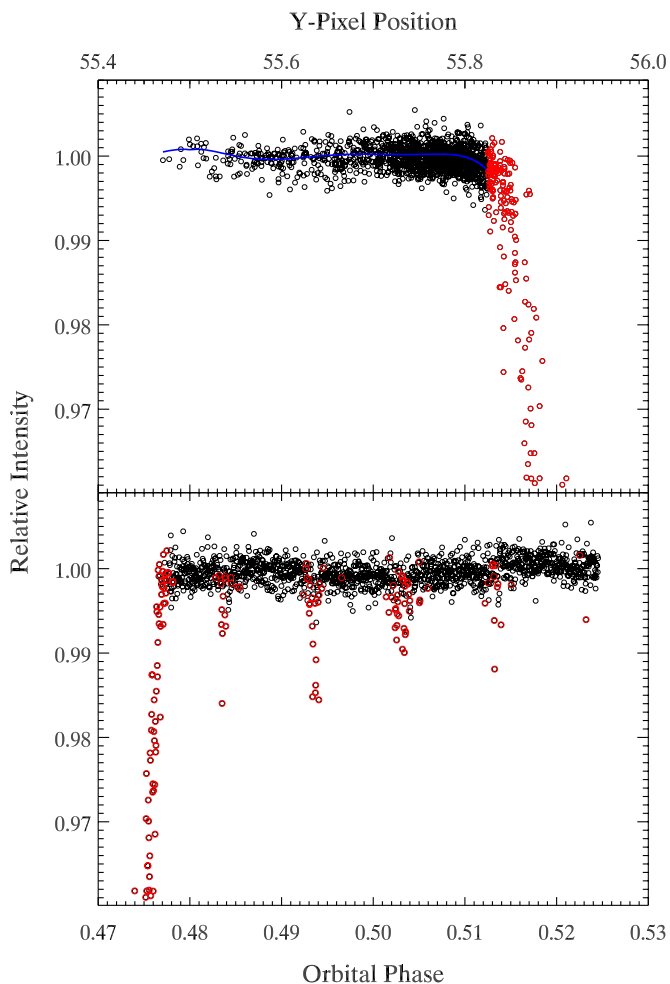


Figure 1. Upper panel: photometric intensity vs. Y -pixel position for $3.6\ \mu\text{m}$ photometry, before correction. Pixel centers are at integer coordinate values. The red points represent lower intensities due to approaching saturation for this bright star as it moves closer to pixel center in the Y -coordinate, and those points were not used in our analysis. The blue line is the fitted correction function. The X -position of the star (not illustrated) was approximately 79 pixel. (Both X - and Y -pixel coordinates are 1-based.) Lower panel: intensity vs. orbital phase for the $3.6\ \mu\text{m}$ photometry, before the correction. The red points are not used in the analysis. Note that the eclipse is visible in this plot, but see Figures 2 and 3 for a clearer view.

an additional factor is important for our $3.6\ \mu\text{m}$ observations. The upper panel of Figure 1 shows the photometric intensity of the star at $3.6\ \mu\text{m}$, as a function of the Y -position of the image. The bulk of the data were collected with the star displaced significantly from pixel center, as was our intention when planning the observations. The median value for the maximum per-pixel intensity in these images is about 130,000 electrons, approximately equal to the 1% non-linearity point for this detector (see the *Spitzer* Observing Manual, Section 6.1.3). However, due to pointing jitter the star sometimes wanders closer to pixel center, and the intensity drops as saturation begins to affect the data (red points on Figure 1). Those points were not included in our analysis. The remaining data still exhibit variations in intensity that are dependent on pixel position, but the variation is complex because of the location of the star near pixel boundaries. We required a sixth-order polynomial in Y -position to fit this relation; incorporating the X -position in the fit did not improve it. We subtracted the fit (blue line on Figure 1) from the unsaturated photometric points, to decorrelate the variation due to pixel position.

The lower panel of Figure 1 plots the uncorrected intensity versus orbital phase, showing that the eclipse is visible even without the correction for pixel position. This panel also shows that the omitted points (in red) occur periodically as the oscillation in telescope pointing moves the stellar centroid toward the center of the pixel. Since most of the correlation between intensity and pixel position depends on the Y -coordinate of the star, we used a square photometric aperture at both 3.6 and 4.5 μm , including fractional pixels at the edge. We reasoned that a square aperture would provide the cleanest isolation of pixel-position effects that are predominately dependent on the Y -coordinate. We found that the photometric scatter at 3.6 μm was minimized using an aperture 5 pixels on a side (2.5 pixels in “radius”).

Our photometry at 4.5 μm shows a much weaker pixel position effect (not illustrated) than at 3.6 μm , but does not involve saturation. The 4.5 μm data show a normal dependence on distance from pixel center (Morales-Calderon et al. 2006), but again with a stronger dependence on the Y - than the X -coordinate. The correlation coefficient between the image δY -position and intensity is -0.3 , indicating a weak correlation, but statistically significant considering the 1604 degrees of freedom. We removed this correlation with a linear relation between intensity and radial distance, and the minimum scatter was achieved using a box 7 pixels on a side (3.5 pixels “radius”). We explored other methods to achieve this decorrelation, such as using a function of Y only, and both X and Y separately, but the minimum χ^2 was achieved using radial distance. Figure 2 shows the 3.6 and 4.5 μm photometry plotted as a function of orbital phase, with the decorrelation functions overplotted. Note that the decorrelation functions are smooth when plotted versus pixel position, but they become more jagged when plotted versus orbital phase as in Figure 2.

Both the 3.6 and 4.5 μm photometry achieve a precision near the photon limit after the decorrelations. Specifically, the scatter at 3.6 μm is 0.00131, which is merely 6% greater than the photon-limited value. At 4.5 μm , the scatter of 0.00533 exceeds the photon limit by 11%. The eclipse fitting procedure at every wavelength always used the unbinned data, but some plots show binned data for clarity. Figure 3 shows binned photometry for both 3.6 and 4.5 μm , with the best-fit eclipse curves and $\pm 1\sigma$ error limits.

3.2. 5.8 and 8.0 μm

Photometry at 5.8 and 8.0 μm did not exhibit a detectable pixel position effect, there being no significant correlation between intensity and either the X - or Y -coordinate of the image. We performed the photometry using both square and circular apertures. Although our results do not depend significantly on the adopted shape of the photometric aperture, we elected to use a circular aperture at both 5.8 and 8.0 μm . We found a minimum scatter in the photometry using aperture radii of 2.4 and 2.8 pixels at 5.8 and 8.0 μm , respectively.

3.3. Eclipse Amplitudes

Following the background subtraction and aperture photometry, we divide the time series at each wavelength by its average value. This places the results in contrast units, i.e., relative to the stellar flux.

We generated an eclipse curve numerically, using the stellar and planetary parameters from Winn et al. (2007) and Johnson et al. (2008). The numerical code was tested for transit curves by comparing to the analytic formulae given by Mandel &

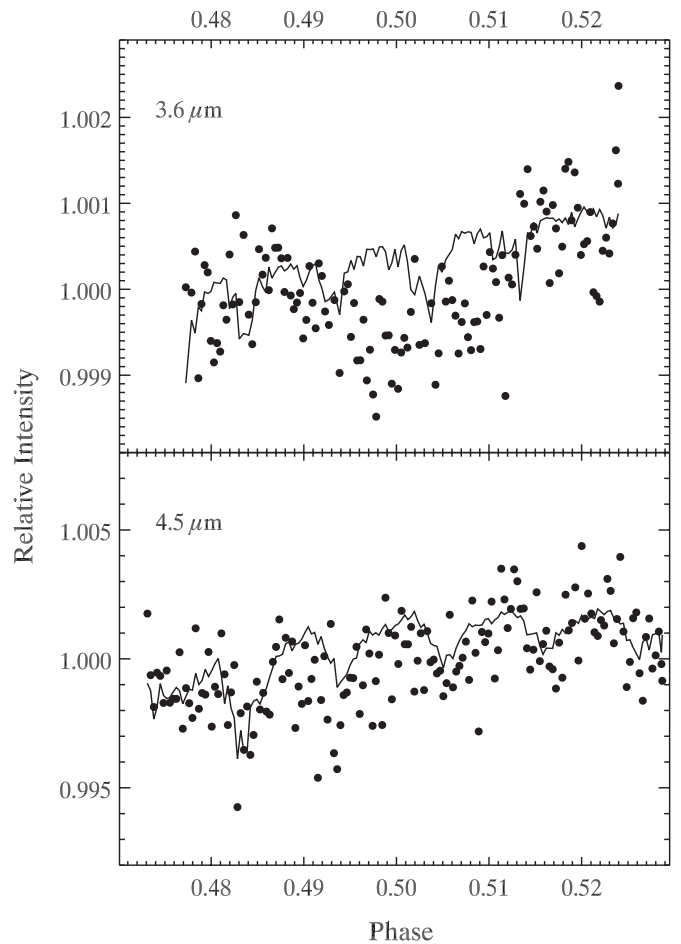


Figure 2. Photometry at 3.6 μm (upper panel) and 4.5 μm (lower panel), before decorrelation with image position. For clarity, each plotted point represents the binned average of the original photometry. In the upper panel, each bin represents 10 exposures (about 2.4 minutes per bin). In the lower panel, each bin represents 20 exposures (about 2.2 minutes per bin). The lines show the decorrelation functions. Note that these functions are smooth when plotted as a function of pixel phase, but because of pointing jitter they exhibit fluctuations when plotted here as a function of orbital phase. The eclipses are clearly visible near orbital phase 0.5, as differences between the points and lines. The decorrelation function at 3.6 μm includes a linear drift as a function of time (see the text), but all of the variations at 4.5 μm can be attributed to changes in pixel position.

Agol (2002), and it attains an accuracy of 10^{-6} , more than sufficient for our purpose (an eclipse curve has the same shape as a transit curve in the limit of zero limb darkening). In fitting to each set of photometry, we scale the depth of the eclipse curve and vary its central phase, but leave its shape (duration, limb-crossing time) unchanged. At all wavelengths, we fit a baseline curve plus the eclipse curve simultaneously via multi-variable linear regression, but the nature of the baseline curve varies with wavelength (see below). Since the linear regressions cannot fit a variable central phase, we perform the regressions separately for each of a series of central phase values, and we pick the solution having the minimum χ^2 .

We found that a linear baseline was adequate for the eclipse fits at all wavelengths except 8.0 μm where the well-known detector ramp (Charbonneau et al. 2005; Deming et al. 2006; Harrington et al. 2007; Knutson et al. 2008, 2009; Desert et al. 2009) exhibits a quasi-logarithmic shape. We model the 8 μm ramp, $R(\phi)$, as a sum of a linear and logarithmic term in phase (ϕ):

$$R(\phi) = a_0 + a_1\phi + a_2 \ln(\phi - \phi_0). \quad (1)$$

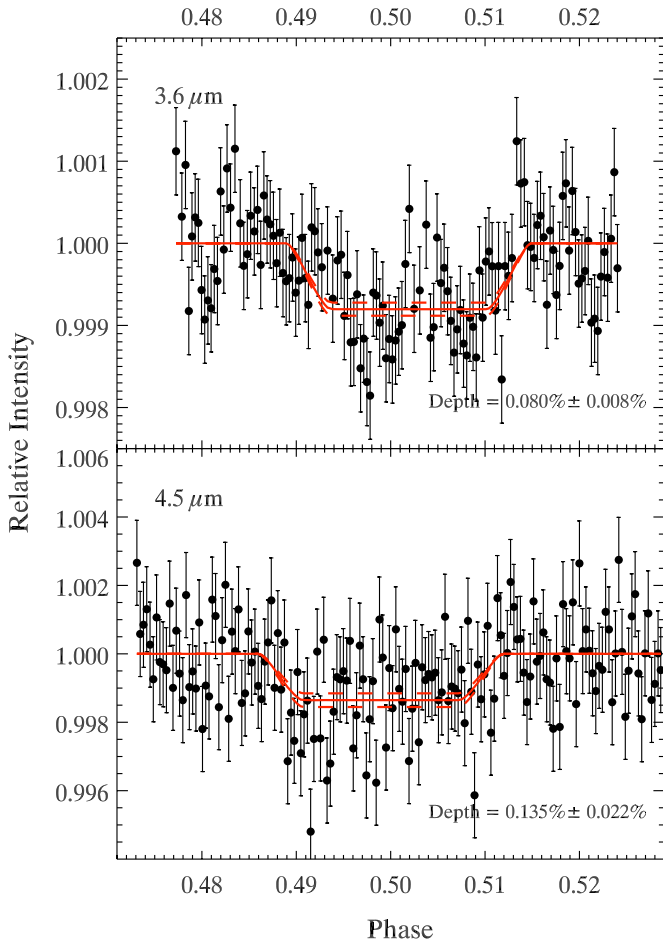


Figure 3. Binned photometry at $3.6 \mu\text{m}$ (upper panel, 10 exposures per bin) and $4.5 \mu\text{m}$ (lower panel, 20 exposures per bin), corrected for the pixel phase effect (see Figures 1 and 2, and the text). The solid red line shows the fitted secondary eclipse, and the dashed red lines show the $\pm 1\sigma$ range on the eclipse depth, from the bootstrap Monte Carlo trials (see Table 1, and the text). The error bars give the standard deviation of the mean, based on the internal scatter within each bin.

We adopt multiple values for ϕ_0 , and solve for a_0 , a_1 , and a_2 by linear regression at each adopted value for ϕ_0 . Note that ϕ_0 is a phase offset used to facilitate the ramp fit, and is not related to the orbit of the planet. We choose the best fit from the two-dimensional grid of ϕ_0 and eclipse central phase values based on the minimum χ^2 . We found that this model of the ramp provides consistently excellent fits, but the best-fit a_i and ϕ_0 can be degenerate in the sense that different combinations can produce indistinguishable ramps. Fortunately, we did not find the eclipse depth and central phase to exhibit significant degeneracies with the ramp parameters. Figure 4 shows the 5.8 and $8 \mu\text{m}$ data before ramp removals, with the best-fit ramps and eclipses overlaid. Figure 5 shows the eclipse fits at 5.8 and $8 \mu\text{m}$, in comparison to binned data with the baseline and ramp effects removed.

Note that a possible temporal drift in intensity at 3.6 and $4.5 \mu\text{m}$ is a phenomenon physically distinct from the pixel position effect. After correcting intensity for pixel position, we include a linear baseline when fitting the eclipse curves. We have added these linear baselines to the total decorrelation function illustrated in Figure 2. The slope of the baseline at $3.6 \mu\text{m}$ is $0.018\% \pm 0.003\%$ per hour. Knutson et al. (2009) found a linear increase at $3.6 \mu\text{m}$ of similar magnitude. We found that

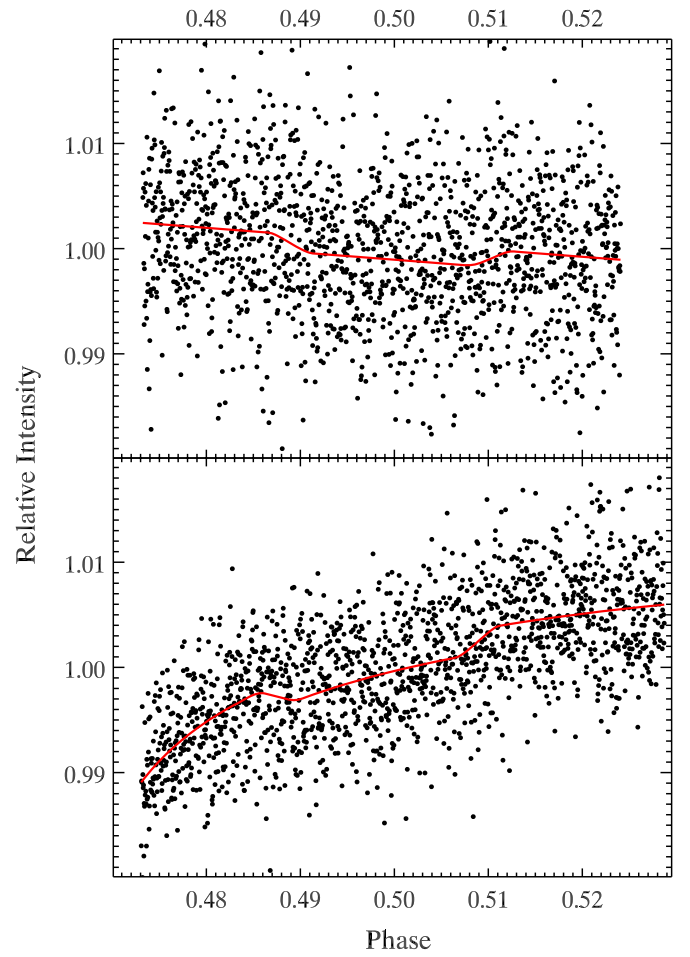


Figure 4. Photometry at 5.8 (upper panel) and $8.0 \mu\text{m}$ (lower panel) before removal of the detector ramp. The points are unbinned. The solid red lines are the best-fit baseline ramps and eclipse curves, obtained via linear regression (see the text). A linear ramp was used at $5.8 \mu\text{m}$, whereas at $8.0 \mu\text{m}$ the ramp is comprised of a linear and logarithmic term, and the best fit (see the text) is $1.005 \times 10^{-2} \ln(\phi - 0.465) - 0.07\phi + 1.07063$, where ϕ is phase.

Table 1
Fitted Eclipse Depth, Central Phase and Heliocentric Julian Date (HJD) of Mid-eclipse

Wavelength	Eclipse Depth	Central Phase	HJD-2454000
$3.6 \mu\text{m}$	$0.080\% \pm 0.008\%$	0.5016 ± 0.0008	464.4228 ± 0.0036
$4.5 \mu\text{m}$	$0.135\% \pm 0.022\%$	0.4991 ± 0.0010	102.7229 ± 0.0045
$5.8 \mu\text{m}$	$0.203\% \pm 0.031\%$	0.4992 ± 0.0012	464.4121 ± 0.0054
$8.0 \mu\text{m}$	$0.238\% \pm 0.040\%$	0.4986 ± 0.0010	102.7206 ± 0.0038

all of the intensity variations at $4.5 \mu\text{m}$ were fully accounted for by changes in pixel position, and the temporal term was not significant.

Best-fit eclipse depths and errors, in units of the stellar flux (contrast units) are given in Table 1.

3.4. Error Estimation

We estimate the errors using the bootstrap Monte Carlo technique (Press et al. 1992). The bootstrap technique generates synthetic data sets using the residuals from the best-fit model, and permutes them to make new data. Each new bootstrap data set is constructed as follows. To construct N new data points, we

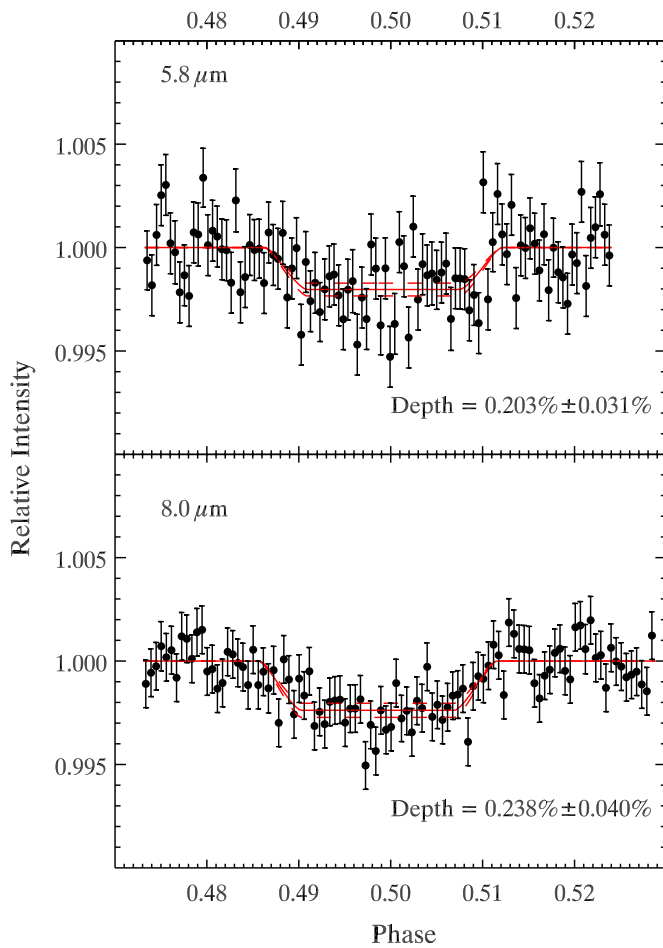


Figure 5. Binned photometry at $5.8 \mu\text{m}$ (upper panel) and $8 \mu\text{m}$ (lower panel), with the baselines removed. The bin size is 16 points at both wavelengths, about 3.6 minutes per bin, but the eclipse fit used the unbinned data (see Figure 4). The solid red lines show the fitted secondary eclipse, and the dashed red lines show the $\pm 1\sigma$ range on the eclipse depth, from the bootstrap Monte Carlo trials (see Table 1, and the text). The error bars give the standard deviation of the mean, based on the internal scatter within each bin.

start with the $i = 1, N$ points from the best-fit curve. We draw a residual randomly from the pool of original residuals, add it to the i^{th} best-fit curve point, return that residual to the pool, and draw again until we have created a data set of N new points. We make 50,000 data sets using this procedure.

For each new bootstrap data set, we repeated the entire fitting procedure, with the exception of the pixel position fits. We did this for the 50,000 bootstrap data sets at each wavelength, and tabulated histograms of the eclipse depth, baseline parameters, and central phase. These histograms are very close to Gaussian distributions, and their standard deviations give estimates of the error in the fit parameters.

We also estimated errors using the residual permutation method described by Southworth (2008). This method—sometimes called the “prayer bead” method—is similar to the bootstrap technique, except that it preserves the order of the residuals, and is therefore more sensitive to the presence of red noise. In most cases the error from the permutation method was very close to the bootstrap error. The adopted error for a given parameter was taken to be the greater of the values from the bootstrap and residual permutation method, and Table 1 includes these errors for the eclipse depth and central phase.

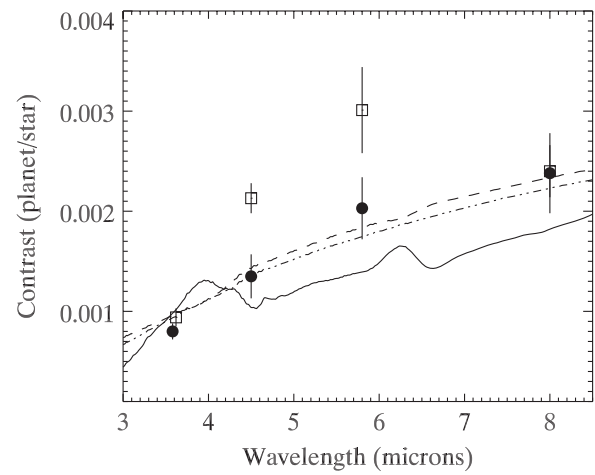


Figure 6. Contrast values for HAT-P-1b (solid circles) vs. wavelength. The open squares are for HD 209458b, from Knutson et al. (2008). The two observed points at $3.6 \mu\text{m}$ have been offset slightly in wavelength to prevent overlap of their error bars. The solid line is a model for the planet (Fortney et al. 2008) with no temperature inversion, and with re-distribution of stellar irradiance over the dayside only—with none to the nightside. The dashed line is for a model with a modest temperature inversion (see the text). In the inverted model, very modest decreases in contrast can be seen at the wavelengths of contrast peaks in the non-inverted model. The dot-dashed line is the contrast for a 1500 K blackbody having the same radius as HAT-P-1b (Winn et al. 2007; Torres et al. 2008).

4. RESULTS AND DISCUSSION

4.1. Atmospheric Temperature Structure

Figure 6 shows our contrast values plotted versus wavelength, and also the results from Knutson et al. (2008) for HD 209458b, the archetype of an inverted atmosphere. We include the contrast predicted by two one-dimensional models of the HAT-P-1b planetary atmosphere (Fortney et al. 2005, 2008), both invoking re-emission of stellar irradiance on the dayside only. The solid line is the nominal model, without a temperature inversion. This nominal model is self-consistent and non-gray, with solar metallicity, and was calculated as in Fortney et al. (2008). It has a Bond albedo of 0.067 and a dayside effective temperature of 1512 K. This model has no inversion because we find that it is too cool to allow gas-phase TiO.

The dashed line is a weakly inverted model, also of solar metallicity. It is *not* self-consistent; it has a constant, ad hoc temperature inversion of $dT/d \log P = -30 \text{ K}$. However, this model is constrained to have the same effective temperature (1512 K) as the non-inverted model. Since the temperature gradient of the inverted model is shallow, the emission features are weak, and it falls close to the contrast expected from a 1500 K blackbody (dot-dashed line). In all instances, we used the planetary and stellar radii from Winn et al. (2007), and a Kurucz 6000/4.5/0.0 model to represent the stellar spectrum (Torres et al. 2008).

The rotation of HAT-P-1b should be tidally locked to its orbit, even though its orbital period is longer than for many planets in the hot Jupiter class. Using Equation (1) of Guillot et al. (1996), we calculate a spin-down time of 8×10^6 years, starting with Jupiter’s rotation rate and adopting a very conservative Q-value (10^6). Since this spin-down time is much less than the age of the system (Torres et al. 2008), we expect tidal locking of the planet’s rotation.

Based on tidally locked rotation, the maximum dayside temperature of HAT-P-1b is 1550 K, assuming zero albedo, a uniform temperature over the dayside hemisphere, and no

transport to the nightside. This is too cool to produce an inversion using TiO/VO absorption, so we first investigate the non-inverted model. Emission at the three longest IRAC wavelengths can arise from levels higher in the atmosphere than does the 3.6 μm radiation (Burrows et al. 2007), and these three channels exhibit a contrast that is moderately higher than the non-inverted model. Comparing to the HD 209458b results (Knutson et al. 2008) shows good agreement at 3.6 and 8.0 μm , but HAT-P-1b exhibits a contrast at 4.5 and 5.8 μm that is intermediate between HD 209458b and the non-inverted model. This seems qualitatively consistent with a moderate inversion, perhaps produced by an absorber other than TiO/VO.

We integrated the flux from each planetary atmospheric model and the stellar model atmosphere over the IRAC bandpass functions. Dividing these integrated fluxes at each wavelength produces expectation values for the observations. (These are not illustrated on Figure 6, but they fall very close to the contrast values at the band center wavelengths.) We used these expectation values to calculate the χ^2 value for the observations compared to each model. For the inverted model (dashed line), χ^2 is 3.9, whereas it is 11.0 for the non-inverted model. A value as high as 11.0 will occur only 2.6% of the time if the non-inverted model is an accurate description of HAT-P-1b's atmosphere. This level of confidence is not sufficient to rigorously eliminate the non-inverted model, but it does indicate that the inverted model is preferable.

Within the errors, our results for HAT-P-1b can also be reproduced using a blackbody spectrum for the planet (dot-dashed line on Figure 6, $\chi^2 = 3.5$).

The luminosity of HAT-P-1A is 1.48 times solar (Torres et al. 2008), and it receives a stellar flux $\sim 2/3$ of the HD 209458b case. If HAT-P-1b absorbs with zero albedo and re-emits uniformly but only on the dayside hemisphere, then we expect a maximum temperature of 1550 K. If the planet's emission is uniform over both hemispheres, we expect an observed temperature of 1300 K. Our observations at secondary eclipse are best described by a blackbody having a temperature of 1500 ± 100 K, where we have factored in the random error of our observations as well as uncertainty in the stellar and planetary parameters. However, most of the flux is probably emitted at shorter wavelengths (Barman 2008; Seager et al. 2005), not directly observable using *Spitzer*. At face value our results suggest that redistribution of the stellar irradiation by dynamics may be inefficient for this planet.

4.2. Orbital Eccentricity

HAT-P-1b orbits a star in a wide visual binary, and this circumstance can have significant consequences for the orbital dynamics of the planet. The inclination and eccentricity (e) of the planet's orbit can in principle undergo oscillations and long-term evolution due to the Kozai mechanism (Fabrycky & Tremaine 2007). Misalignments between the planet's orbital inclination and the rotation axis of the star can result, and can be observed using the Rossiter–McLaughlin effect. Johnson et al. (2008) find that the angle between the sky projections of stellar spin axis and the orbit normal for HAT-P-1b is $3^\circ.7 \pm 2^\circ.1$. They also put an upper limit on the eccentricity of 0.067 with 99% confidence. These values suggest that any Kozai oscillations of HAT-P-1b have largely damped out. Our results for the secondary eclipse timing will further strengthen that conclusion, as discussed below.

The timing of the secondary eclipse is exquisitely sensitive to the eccentricity of the orbit, with one ambiguity being the value

of ω , the argument of periastron. When our line of sight aligns with the minor axis of the planet's orbit ($\omega = 0$ or π), then the secondary eclipse will not be centered on phase 0.5 unless the orbit is circular. When our line of sight aligns with the major axis of the orbit ($\omega = \pi/2$ or $3\pi/2$), departures from circularity will affect the duration of the eclipse, but not the central phase. The phase of secondary eclipse therefore constrains the value of $e \cos \omega$ (Charbonneau et al. 2005).

We observed two eclipses, each at two wavelengths simultaneously. The difference in best-fit phases for the same eclipse observed at different wavelengths is approximately consistent with our errors (Table 1). The larger difference occurs at 3.6 and 5.8 μm , where the central phase difference is $0.5016 - 0.4992 = 0.0027$. Because the noise at each wavelength is independent, the error on the difference in the two phases is the quadrature sum ($= 0.0014$) of the phase errors at the two wavelengths. Hence the phase difference is less than a 2σ variation.

Weighting the central phase of the eclipse at each wavelength (Table 1) by the inverse of its variance, we find a mean value of 0.4999 ± 0.0005 . Considering the 55 s of light-travel time across the orbit, we expect to find the eclipse at phase 0.500014. Accounting for the light-travel time and the error in the observed eclipse phase, we derive a 3σ upper limit of $|e \cos \omega| < 0.002$. If this planet's orbital eccentricity was affected by Kozai oscillations in the past, they have damped to the point where the orbit is closely circular.

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