A THEORETICAL INTERPRETATION OF THE MEASUREMENTS OF THE SECONDARY ECLIPSES OF TrES-1 AND HD 209458b

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ABSTRACT

We calculate the planet-to-star flux density ratios as a function of wavelength from 0.5 to 25 μm for the transiting extrasolar giant planets TrES-1 and HD 209458b and compare them with the recent Spitzer/IRAC-MIPS secondary eclipse data in the 4.5, 8.0, and 24 μm bands. With only three data points and generic calibration issues, detailed conclusions are difficult, but inferences regarding atmospheric composition, temperature, and global circulation can be made. Our models reproduce the observations reasonably well, but not perfectly, and we speculate on the theoretical consequences of variations around our baseline models. One preliminary conclusion is that we may be seeing in the data indications that the day side of a close-in extrasolar giant planet is brighter in the mid-infrared than its night side, unlike Jupiter and Saturn. This correspondence will be further tested when the data anticipated in other Spitzer bands are acquired, and we make predictions for what those data may show.

Subject headings: planetary systems — planets and satellites: general — stars: individual (HD 209458, TrES-1)

1. INTRODUCTION

The detection of a few (currently seven) transiting extrasolar giant planets (EGPs), whose orbits are nearly edge-on, has provided radii, masses, and inclinations for them (Henry et al. 2000; Charbonneau et al. 2000; Brown et al. 2001; Sasselov 2003; Konacki et al. 2003a, 2003b, 2004; Bouchy et al. 2004; Pont et al. 2004; Torres et al. 2005). For HD 209458b, there are in addition indications of its atmospheric composition from the wavelength dependence of the photometric dip of the stellar light during transit (Charbonneau et al. 2002; Vidal-Madjar et al. 2003; § 2).

However, it is only by direct detection of the planets and their photometric and spectroscopic characterization that they can be studied in depth to reveal their atmospheric and physical properties (Sudarsky et al. 2003; Allard et al. 2003; Burrows et al. 2004c; Burrows 2005). While orbital distances (a), periods (P), and eccentricities (e) are reasonably well determined, the investigation of an EGP in physical detail requires at a minimum the actual mass (Mₚ), radius (Rₚ), and composition. Space provides access, but it had generally been thought that high-resolution contrast imaging is necessary to separate out the planet from the bright star. However, Charbonneau et al. (2005) and Deming et al. (2005) have recently shown that variations in the summed light of the planet and star for the close-in transiting EGPs TrES-1 and HD 209458b can be detected with Spitzer during secondary eclipse. Secondary eclipse is ~180° out of phase with the transit and is when the planet is occulted by the star, thereby shutting off the planet’s contribution to the summed light. The approximate magnitude of this diminution varies significantly with wavelength, with the mid- to far-infrared being the most favorable bands. At 10–30 μm and in the Spitzer Infrared Array Camera (IRAC) bands from 3.6 to 8.0 μm, this contrast was predicted to be ~10⁻³ (Burrows et al. 2004b; Burrows 2005). This is near what has now been detected. In this Letter, we customize to the TrES-1 and HD 209458 systems the calculation of the planet-to-star flux density ratio as a function of wavelength and compare the resulting theory with the Spitzer secondary eclipse data to draw conclusions about close-in EGP atmospheres. In § 2, we summarize the new Spitzer data, and in § 3 we briefly describe our numerical techniques. Then, in § 4 we present our results from 1 to 25 μm, and in § 5 we wrap up with a discussion of our conclusions and the outstanding issues concerning irradiated EGPs that such eclipse data might address.

2. SUMMARY OF TrES-1 AND HD 209458b DATA

The parameters of a transiting planetary system determine the inputs to a theoretical calculation of its spectrum and its planet-to-star flux density ratio as a function of wavelength. Incident radiation at the planet’s surface is a function of the stellar flux density and the orbital distance, and the planet’s mass and radius determine the gravity of its atmosphere. For both TrES-1 and HD 209458b, the interior flux (Burrows et al. 2000) is dwarfed by the irradiation effects for any reasonable system ages. Since we are not performing evolutionary calculations (Burrows et al. 2000; Burrows et al. 2003, hereafter BSH; Baraffe et al. 2003) in this Letter, the system ages are not germane to the problem at hand, which is reproducing the observed planet-to-star flux density ratios in the Spitzer bands. These ratios depend only on the stellar spectrum, the orbital distance, and the planet’s mass and radius, but not directly on age.

The K0 V stellar primary of the transiting extrasolar giant planet TrES-1 is 157 ± 6 pc distant, has a T_eff of 5214 ± 23 K, a metallicity near solar ([Fe/H] ~ 0), a radius (R*) of 0.83 ± 0.03 R$_\odot$, a mass (M*) of 0.87 ± 0.05 M$_\odot$, and a bolometric luminosity (L*) near half-solar (Laughlin et al. 2005). The planet’s orbital and physical parameters are a semimajor axis (a) of 0.0393 AU, a period (P) of 3.030 days, a planet mass (M_p) of (0.729 ± 0.036)M_J (Laughlin et al. 2005) or (0.76 ± 0.05)M_J (Sozzetti et al. 2004),2 and a transit radius (BSH; Burrows et al. 2004a) of approximately (1.08 ± 0.05)R_J (Alonso et al. 2004; Sozzetti et al. 2004; Laughlin et al. 2005).3

The corresponding quantities for the F8 V/G0 V star HD 209458 are 47.3 pc (Perryman 1997), T_eff = 6000 ± 50 K (Mazeh et al. 2000), [Fe/H] ~ 0, R* = 1.2 ± 0.1 R$_\odot$, M* = 1.1 ± 0.1 M$_\odot$, and L* = 1.6 L$_\odot$ (Henry et al. 2000; Charbonneau et al. 2000; Brown et al. 2001). The planet’s pa-

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2 M$_J$ is the mass of Jupiter, ~1.89914 x 10$^{20}$ g.

3 R$_J$ = 7.149 x 10$^4$ km, Jupiter’s radius.
The logarithm base 10 of the planet-to-star flux density ratio as a function of wavelength ($\lambda$, in microns) for our baseline models of TrES-1 and HD 209458b is green. Superposed are the secondary eclipse data: the gold circles with corresponding error bars are the TrES-1 IRAC data from Charbonneau et al. (2005), while the green circle with error bars is the HD 209458b MIPS 24 $\mu$m datum from Deming et al. (2005). Also included are the band-averaged detected electron$/$flux ratios for the TrES-1 (yellow circles) and HD 209458b (blue circles) models in the four IRAC bands. Note that coincidently the blue circle at 4.5 $\mu$m overlaps the gold TrES-1 data point. The position of the strong CO absorption feature at $\sim$4.67 $\mu$m is indicated and clearly coincides with the $\sim$4.5 $\mu$m IRAC band flux. See text for a discussion and details.

Prior to the recent measurements of the secondary eclipses that motivate this Letter, Charbonneau et al. (2002) had uncovered evidence for the presence of sodium in the atmosphere of HD 209458b from the different transit radii in and out of the Na D line (see also Fortney et al. 2003). Similarly, Vidal-Madjar et al. (2003) had seen evidence of atomic hydrogen, and perhaps atomic carbon and oxygen (Vidal-Madjar et al. 2004), in a stellar-flux–induced planetary wind from HD 209458b. The transit dip in Ly$\alpha$ is of such a magnitude ($\sim$15%) that the planetary material clearly extends beyond the Roche lobe, indicating planetary mass loss (Burrows & Lunine 1995; Lecavelier des Etangs et al. 2004).

The new secondary eclipse data for TrES-1 (Charbonneau et al. 2005) and HD 209458b (Deming et al. 2005) hint that this situation may be changing. TrES-1 shows eclipse depths (planet-to-star flux density ratios) in the IRAC band centered at 4.5 $\mu$m of 0.00066 $\pm$ 0.00013 and in the IRAC band centered at 8.0 $\mu$m of 0.00225 $\pm$ 0.00036 (Charbonneau et al. 2005). HD 209458b shows a corresponding ratio of 0.0026 $\pm$ 0.00045 in the Multiband Imaging Photometer for Spitzer (MIPS) band centered near 24 $\mu$m (Deming et al. 2005). These numbers are actually the ratios of detected electrons, an approximate substitute for the ratio of average flux densities in a given band. For flux density comparisons, one relies on flux calibrations that may not yet be robust, particularly given the significant differences between the spectra of a close-in EGP and a calibration star (e.g., Vega). Given this, in § 4 we also provide theoretical bandpass-averaged detected electron ratios.

Since the data from Charbonneau et al. (2005) and Deming et al. (2005) are but three of the 10 potential data points (five bands times two nearby transiting planets) we can expect using Spitzer, very low resolution spectra (but “spectra” nevertheless) of EGPs are anticipated soon that will provide compositional and atmospheric information of an unprecedented character.

3. NUMERICAL TECHNIQUES AND ASSUMPTIONS

The numerical tools we employ to derive the close-in planet’s spectrum during secondary eclipse are described in BSH and Burrows et al. (2004c), to which we refer the reader for further details. The incident flux is isotropically spread over the hemisphere of a given planar patch of planetary “surface.” As described in BSH, to account in approximate fashion for the variation in incident flux with latitude when using a planar atmosphere code, as well as the possible day-to-night differences, we introduce the flux parameter $f$. A value of $f = 0.5$ assumes that there is little sharing of heat between the day and night sides of the EGP. A value of $f = 0.25$ assumes in the calculation of the $T / \sin i$ profile that the heat from irradiation is uniformly distributed by efficient winds over the entire sphere and that the infrared emissions are isotropic. For this study of the planet-to-star flux density ratios of close-in EGPs, we use a fiducial value for $f$ of 0.25, but we return to the issue of the proper choice of $f$ in § 5. The spectral models for the stellar primaries (given a specific spectral subtype) come from Kurucz (1994).

4. COMPARISON OF THEORETICAL PLANET-TO-STAR FLUX RATIOS

Figure 1 depicts our theoretical planet-to-star flux density ratios versus wavelength in the near- and mid-infrared for TrES-1 (magenta line) and HD 209458b (green line). To derive these curves we have used the physical data for the planets and their primaries described in § 2. Our baseline planet models have solar metallicity. The phase-averaged (Sudarsky et al. 2003) flux ratios, but for $f = 0.25$ (§ 3; Sudarsky et al. 2003; Burrows et al. 2004c), are given and have not been shifted in any way. Superposed are the new data at 24 $\mu$m for HD 209458b (green circle) and at 4.5 and 8.0 $\mu$m for TrES-1 (gold circles). The vertical error bars are the quoted 1 $\sigma$ ranges, and the horizontal bars indicate the widths of the corresponding IRAC and MIPS bands. Also included are the four theoretical IRAC band-averaged fluxes for the TrES-1 model (yellow circles) and for the HD 209458b model (blue circles). These band averages are derived using the published transmission functions, divided by frequency to obtain the theoretical ratio of detected electrons. Since the close-in EGP (this work) and stellar (Kurucz 1994) spectra are so flat at 24 $\mu$m, a transmission band-averaged point is not shown (or needed) there.

Varying $M_p$, $R_p$, and $R_e$ within the error bars alters the resulting planet-to-star flux density ratios only slightly. Similarly, and perhaps surprisingly, adding Fe and forsterite clouds does not shift the predictions in the Spitzer bands by an appreciable amount. Moreover, despite the more than a factor of 2 difference in the stellar flux at the planet, the predictions for the planet-to-star ratios for two such disparate close-in EGPs as TrES-1 and HD 209458b are not very different. For TrES-1, raising or lowering the metallicity by a factor of 3 changes the flux ratios by less than $\sim$10%. Interestingly, however, changes in $f$ and, by inference, day-to-night atmospheric differences and phase function effects can result in 25%–50% deviations in the flux ratios of which one should take note.

The 24 $\mu$m data point is close to the predicted value, although
for all three data points the theory slightly underestimates the data by a factor of ~1.5–1.8, with the largest discrepancy being for the TrES-1 band at 8.0 μm. For HD 209458b at 24 μm, this deviation is only ~1 σ. The high absolute values of the flux ratios imply that the close-in EGP atmospheres are indeed at high temperature, predicted for TrES-1 and HD 209459b to be ~1500 and ~1600 K, respectively, at a Rosseland depth of ~1. Both atmospheres clearly span the temperature range 1000–2000 K. For TrES-1 at 8 μm, theory yields a brightness temperature (temperature at \( T_\text{B} = \frac{f}{j} \)) near 800–900 K, slightly lower than the ~1100 K crudely inferred from the data. At 4.5 μm, the theoretical brightness temperature of TrES-1 is ~750–900 K (using \( f = 0.25 \)), again slightly lower than the data might imply. However, care must be taken in estimating temperatures of any sort, and we will not, due to the hazards of extracting an “effective” or “equilibrium” temperature from these data, say much more about them.

In Figure 1, there is a hint of the presence of H₂O, since it is expected to suppress flux between 4 and 10 μm. This is shortward of the predicted 10 μm peak in the planet-to-star flux density ratio, which is due to water’s relative abundance and the strength of its absorption bands in that wavelength range. Without H₂O, the fluxes in the IRAC bands would be much higher than the fluxes in the mid-infrared. Hence, a comparison of the TrES-1 and HD 209458b data at 4.5/8.0 and 24 μm suggests, but does not prove, the presence of water. Seeing the expected slope between the 5.8 and 8.0 μm bands and the rise from 4.5 to 3.6 μm would be more revealing in this regard and is a prediction of our theory. Furthermore, the relative strength of the 24 μm MIPS flux ratio in comparison with the 3.6, 4.5, and 5.8 μm IRAC channel ratios is another prediction of the models, as is the closeness of the 8.0 and 24 μm ratios. The latter seems borne out by the data, although these data are for two different objects. If CH₄ is present in abundance in either HD 209458b or TrES-1, then the 3.6 μm IRAC band will test this (although the CH₄ feature at 7.8 μm might then also have affected the 8.0 μm band flux). However, our expectation for these close-in EGPs is that CH₄ will not be in evidence.

Nevertheless, the models have difficulty fitting the depth of the 4.5 μm feature in TrES-1. This feature coincides with the strong CO absorption predicted to be a signature of hot EGP atmospheres (Sudarsky et al. 2003; Burrows et al. 2004c; Burrows 2005) but is shallower than expected and ~2 σ discrepant. The data are in fact the band-averaged flux density ratios of the detected electrons. As such, the larger fluxes on either side of the trough theoretically centered close to 4.5 μm contribute planet flux to the detected band. As a result, the yellow circle that represents this integrated band contribution is a weak function of CO abundance. In fact, a CO abundance 100 times larger than expected in chemical equilibrium lowers this flux ratio at 4.5 μm by only ~25%. Therefore, while the 4.5 μm data point for TrES-1 implies that CO has been detected, the exact fit is problematic. More data and further attention to calibration are called for. However, as we have indicated and will discuss in § 5, the contrast between theory and measurement at all data points may be a signature of day-to-night infrared flux asymmetry. The close-in planets may not be radiating heat energy isotropically (as is assumed when using \( f = 0.25 \)), a not-unexpected result (see, e.g., Guillot & Showman 2002).

5. Discussion

We predict that both the 3.6 and 5.8 μm flux ratios will be higher than the 4.5 μm ratio by at least 50% and that the pattern of the yellow and blue circles on Figure 1 will be realized. We also predict that the 24 μm flux ratio for TrES-1 will be similar to that seen for HD 209458b (Deming et al. 2005). However, while the close correspondence of the measured and theoretical fluxes depicted on Figure 1 is striking, it is not perfect. What could explain the differences? One major uncertainty is the day-to-night atmospheric profile difference. HD 209458b and TrES-1 are close enough to their primaries to be in synchronous rotation. Therefore, they show the same hemisphere to the star at all times. It is the zonal winds, atmospheric circulation currents, and jet streams (Menou et al. 2003; Guillot & Showman 2002; Showman & Guillot 2002; Cho et al. 2003; Burkert et al. 2005) that advect heat from the day side to the night side, thereby affecting the atmospheric temperature structure as a function of longitude. How much of the stellar radiation goes to heating the day side (visible just before and after the secondary eclipse), and how much is transported by mass motion away from the day side to heat the night side? These questions remain unresolved but directly impinge upon the planet-to-star flux density ratios in the infrared measured during secondary eclipses.

The \( f \) factor we use for our fiducial model (0.25) is tailored to distribute heat over the entire planet, on both the day side and the night side. The three data points depicted in Figure 1 are all factors of ~1.5–1.8 above the \( f = 0.25 \) theory curves. This implies that the planet’s radiation is predominantly radiated by the day side and that its emissions are forward-beamed. This is not entirely unexpected in the optical but seems to be the case in the mid-infrared as well. The implication of the new secondary eclipse data at 24 and 8 μm may be that we are seeing indirect signs of an asymmetry in the day-to-night heating and temperature profiles, with the day side hotter than the night side by at least 500 K. This estimate is based on the mid-infrared “excuses” seen in Figure 1, on the possible model variations, and on the measurement errors. However, the confirmation of such a conclusion awaits more detailed multidimensional general circulation models with correct transport, next-generation models of the wavelength-dependent phase functions of close-in EGPs (Sudarsky et al. 2005), and, most importantly, additional data.

It has long been suggested, and recently articulated (Cooper & Showman 2005), that due to winds the substellar point of an irradiated close-in EGP may not be the hottest spot. Advection would introduce a lag even for circular orbits between the planet’s ephemeris and its light curve (the light curve would lead). Cooper & Showman (2005) estimate that the lead could be as much as 60° and could amount to a 20% brightness shift in the value at superior conjunction. A 20% decrement is not enough to close the modest apparent gap between our theory and the 24 μm data for HD 209458b, and is not of the correct sign. However, the concept of a shift in the light curve deserves further scrutiny.

Charbonneau et al. (2005) estimate a Bond albedo (\( A \)) for TrES-1 of 0.31 ± 0.14. However, one should be very cautious using these new data to infer temperatures and reflection coefficients. Not only is the reradiation not expected to be isotropic off the planet, but the atmospheres are not blackbodies. While one can distinguish hot atmospheres (1000–2000 K) from cooler atmospheres (500–1000 K), the data and theory are not yet adequate to allow these TrES-1 data to strongly constrain \( A \). However, if \( A \) were in the 0.31 ± 0.14 range, this would imply that there is a cloud of nontrivial optical depth in the upper layers of TrES-1, putting it into the “class V” category of EGPs rather than the “class IV” category (Sudarsky et al. 2000). The latter, due to strong absorption bands and little Rayleigh scattering, have very low Bond albedos (below 0.05).
Our models for TrES-1 would favor the low-albedo class IV category for TrES-1 and the higher albedo class V category for HD 209458b, but we feel it is premature to conclude anything definitive about albedos at this stage (other than that they cannot be very high and that the close-in EGPs cannot be highly reflective).

In this Letter, we have calculated planet-to-star flux density ratios versus wavelength, focusing on the near- and mid-infrared out to 25 μm and the irradiated close-in extrasolar giant planets TrES-1 and HD 209458b, and we have compared our theory with the recent secondary eclipse data from Charbonneau et al. (2005) and Deming et al. (2005). We have inferred the presence of carbon monoxide, and perhaps water, in the atmosphere of TrES-1 and have determined that both atmospheres are hot (~1000–2000 K). We have explored the effects of varying the metallicity, , and , the latter three within the stated error bars, and find our predictions for the planet-to-star flux density ratios to be robust. However, more work is required to understand the apparent shallowness of the TrES-1 secondary eclipse data. This study was supported in part by NASA grants NNG04GL22G and NAG5-13775. This material is based on work supported by the National Aeronautics and Space Administration through the NASA Astrobiology Institute under Cooperative Agreement CAN-02-OSS-02 issued through the Office of Space Science.

REFERENCES

Allard, F., Baraffe, I., Chabrier, G., Barman, T. S., & Hauschildt, P. H. 2003, in ASP Conf. Ser. 294, Scientific Frontiers in Research on Extrasolar Planets, ed. D. Deming & S. Seager (San Francisco: ASP), 483
Alonso, R., et al. 2004, ApJ, 613, L153
Baraffe, I., Chabrier, G., Barman, T. S., Allard, F., & Hauschildt, P. H. 2003, A&A, 402, 701
Bouchy, F., Pont, F., Santos, N. C., Melo, C., Mayor, M., Queloz, D., & Udry, S. 2004, A&A, 421, L13
Brown, T. M., Charbonneau, D., Gilliland, R. L., Noyes, R. W., & Burrows, A. 2001, ApJ, 552, 699
Burkart, A., Lin, D. N. C., Bodenheimer, P., Jones, C., & Yorke, H. 2005, ApJ, 618, 512
Burrows, A. 2005, Nature, 433, 261
Burrows, A., Guillot, T., Hubbard, W. B., Marley, M. S., Saumon, D., Lunine, J. I., & Sudarsky, D. 2000, ApJ, 534, L97
Burrows, A., Hubeny, I., Hubbard, W. B., Sudarsky, D., & Fortney, J. J. 2004a, ApJ, 610, L53
Burrows, A., & Lunine, J. I. 1995, Nature, 378, 333
Burrows, A., Sudarsky, D., & Hubbard, W. B. 2003, ApJ, 594, 545 (BSH)
Burrows, A., Sudarsky, D., & Hubeny, I. 2004b, in AIP Conf. Proc. 713, The Search for Other Worlds, ed. S. S. Holt & D. Deming (Melville: AIP), 143–147, 2004c, ApJ, 609, 407
Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJ, 529, L45
Charbonneau, D., Brown, T. M., Noyes, R. W., & Gilliland, R. L. 2002, ApJ, 568, 377
Charbonneau, D., et al. 2005, ApJ, in press
Cho, J. Y-K., Menou, K., Hansen, B. M. S., & Seager, S. 2003, ApJ, 587, L117
Cody, A. M., & Sasselov, D. D. 2002, ApJ, 569, 451
Cooper, C. S., & Showman, A. P. 2005, ApJL, submitted (astro-ph/0502476)
Deming, D., Seager, S., Richardson, L. J., & Harrington, J. 2005, Nature, 434, 740
Fortney, J. J., Sudarsky, D., Hubeny, I., Cooper, C. S., Hubbard, W. B., Burrows, A., & Lunine, J. I. 2003, ApJ, 589, 615
Guillot, T., & Showman, A. P. 2002, A&A, 385, 156
Henry, G., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, ApJ, 529, L41
Konacki, M., Torres, G., Jha, S., & Sasselov, D. 2003a, Nature, 421, 507
Konacki, M., Torres, G., Sasselov, D., & Jha, S. 2003b, ApJ, 597, 1076
Konacki, M., et al. 2004, ApJ, 609, L37
Kurucz, R. 1994, CD-ROM 19, Solar Abundance Model Atmospheres for 0, 1, 2, 4, 3 km/s (Cambridge: SAO)
Laughlin, G., Wolf, A., Vanmunster, T., Bodenheimer, P., Fischer, D., Marcy, G., Butler, P., & Vogt, S. 2005, preprint
Lecavelier des Etangs, A., et al. 2004, A&A, 418, L1
Mazeh, T., et al. 2000, ApJ, 532, L55
Menou, K., Cho, J. Y-K., Hansen, B. M. S., & Seager, S. 2003, ApJ, 587, L113
Perryman, M. A. C. 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200; Noordwijk: ESA)
Pont, F., Bouchy, F., Queloz, D., Santos, N. C., Melo, C., Mayor, M., & Udry, S. 2004, A&A, 426, L15
Sasselov, D. D. 2003, ApJ, 596, 1327
Showman, A. P., & Guillot, T. 2002, A&A, 385, 166
Smith, G. R., & Hunt, M. 1990, Rev. Geophys., 28, 117
Sozzetti, A., et al. 2004, ApJ, 616, L167
Sudarsky, D., Burrows, A., & Hubeny, I. 2003, ApJ, 588, 1121
Sudarsky, D., Burrows, A., Hubeny, I., & Li, A. 2005, ApJ, in press
Sudarsky, D., Burrows, A., & Pinto, P. 2000, ApJ, 538, 885
Torres, G., Konacki, M., Sasselov, D. D., & Jha, S. 2005, ApJ, 619, 558
Vidal-Madjar, A., Lecavelier des Etangs, A., Désert, J.-M., Ballester, G. E., Ferlet, R., Hébrard, G., & Mayor, M. 2003, Nature, 422, 143
Vidal-Madjar, A., et al. 2004, ApJ, 604, L69