THERMAL EMISSION FROM TRANSITING VERY HOT JUPITERS: PROSPECTS FOR
GROUND-BASED DETECTION AT OPTICAL WAVELENGTHS

MERCEDES LÓPEZ-MORALES¹ AND SARA SEAGER²

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ABSTRACT

Very hot Jupiters (VHJs) are defined as Jupiter-mass extrasolar planets with orbital periods shorter than 3 days. For low albedos the effective temperatures of irradiated VHJs can reach 2500–3000 K. Thermal emission from VHJs is therefore potentially strong at optical wavelengths. We explore the prospects of detecting optical-wavelength thermal emission during secondary eclipse with existing ground-based telescopes. We show that OGLE-TR-56b and OGLE-TR-132b are the best-suited candidates for detection and that the prospects are highest around $\nu1$ band ($\sim0.9$ $\mu$m). We also speculate that any newly discovered VHJs with the right combination of orbital separation and host star parameters could be thermally detected in the optical. The lack of detections would still provide constraints on the planetary albedos and reradiation factors.

Subject headings: binaries: eclipsing — planetary systems — stars: individual (OGLE-TR-56, OGLE-TR-132) — techniques: photometric

1. INTRODUCTION

Five hot Jupiters have published lower atmosphere measurements (Charbonneau et al. 2002, 2005; Deming et al. 2005, 2006; Harrington et al. 2006; Knutson et al. 2007; Grillmair et al. 2007; Richardson et al. 2007; Tinetti et al. 2007). Several upper atmosphere detections have also been reported (Vidal-Madjar et al. 2003, 2004; Ballester et al. 2007). All these measurements have been made from space, with Spitzer and the Hubble Space Telescope. Exoplanet atmosphere detection from the ground has so far been elusive, despite many tries (e.g., Deming et al. 2007; Snellen & Covino 2007; Snellen 2005). Yet ground-based detection capability would greatly facilitate studies of hot Jupiter atmospheres.

Hot Jupiters are Jupiter-mass planets in 3–9 day period orbits. Very hot Jupiters (VHJs) are those in 1–3 day period orbits. These planets are heated primarily by incident radiation from their parent stars. The closer the planet is to the star, the hotter the planet will be. VHJs orbiting solar-type stars may have their parent stars. The closer the planet is to the star, the hotter it will be. If the radiative timescale is shorter than the advective timescale, the incident radiation will be reradiated back to space, in which case the planet has no net energy gain. In the opposite case, atmospheric circulation redistributes the energy around the planet, or a combination of both. If the radiative timescale is short compared to the advective timescale, the incident radiation will be reradiated back to space, in which case the planet remains in equilibrium.

2. THERMAL EMISSION VERSUS REFLECTED LIGHT

For VHJs at optical wavelengths one usually thinks of the reflected light without considering that, depending on the VHJ effective temperature, thermal emission could dominate reflected light.

The effective temperatures of externally heated extrasolar planets can be estimated from energy balance as

$$T_p = T_e \left[\frac{R_p}{a}\right]^{1/2} \left[f(1 - A_n)\right]^{1/4},$$

where $T_e$ is the temperature of the planet, $T_p$ and $R_p$ are the effective temperature and the radius of the star, $a$ is the star-planet orbital separation, and $f$ and $A_n$ are the reradiation factor and the Bond albedo of the planet.

Given the planets effective temperatures, their thermal and reflected fluxes can be computed using

$$F_{plan} = \frac{2h}{e^2} \frac{\pi R_p^2}{e^{nokT_p} - 1} \frac{1}{D^2},$$

for the thermal flux and

$$F_{ref} = F_s A_s \frac{R_p^2}{a^2},$$

for the reflected flux, where $F_s$ is the stellar surface flux divided by $D^2$, $A_s = \frac{2}{3}A_n$, assuming Lambert’s law (e.g., Rowe et al. 2006), and $R_p$ is the radius of the planet. $D$ is the distance from the planet to Earth.

2.1. Effective Temperatures

We computed temperatures for each known VHJ from equation (1), adopting published masses, radii, and effective temperatures for the host stars (see Table 1). The orbital separations were derived from the mass of the stars and the planets, and the published orbital periods.

The parameter $f$ describes how the stellar radiation absorbed by a planet is redistributed in its atmosphere. The absorbed radiation can be reradiated back to space, advected around the planet, or a combination of both. If the radiative timescale is shorter than the advective timescale, the incident radiation will be reradiated back to space, in which case $f = \frac{2}{3}$. In the opposite case, atmospheric circulation redistributes the energy around...
the planetary atmosphere before it can get reradiated, and \( f = \frac{1}{4} \). Recent studies of the day-to-night side brightness variations of \( \nu \) Andromedae b (Harrington et al. 2006) and HD189733b (Knutson et al. 2007) indicate that both scenarios are possible. We consider values of \( f = \frac{1}{4} \) and \( \frac{1}{2} \) to bracket the possible range.

The Bond albedo \( A_b \) is the fraction of incident stellar radiation reflected by the planets atmosphere. \( A_b \) depends on a planet’s chemical composition, which in turn depends partly on temperature. We consider the cases \( A_b = 0, 0.3, \) and 0.5. Observations indicate that the albedos of hot Jupiters are, in fact, very low (\( A_b < 0.15 \); Rowe et al. 2006; J. Harrington 2007, private communication). Model atmospheres also suggest these planets are dark (e.g., Marley et al. 2007). Even so, we include \( A_b = 0.3 \) and 0.5 to illustrate possible unexpectedly reflective cases. VHJs may be as bright as \( A_b = 0.3 \) if covered by homogeneous pure silicate clouds at 1 mbar level or higher altitudes (Marley et al. 1999; Seager et al. 2000; Sudarsky et al. 2000). If they have patchy silicate or iron clouds, then \( A_b \) will be <0.3, as the stellar radiation can penetrate below the clouds and be absorbed by gas-phase molecules (Hood et al. 2007). Of most relevance to this work is that VHJ atmospheres are too hot on the substellar side for silicate or iron clouds to form.

Table 1 gives the expected \( T_p \) for each known transiting VHJ, for the \( f \) and \( A_b \) values above. The table includes formal errors derived from equation (1) and published parameters of each system. The maximum expected temperatures in the table reveal two groups of VHJs: one with \( T_{\text{max}} > 2600 \) K, which includes OGLE-TR-56b and OGLE-TR-132b, and a second group with \( T_{\text{max}} < 2200 \) K, which includes the other nine planets. OGLE-TR-56b and OGLE-TR-132b are therefore the most likely candidates for detection.

### 2.2. Thermal Emission and Reflected Light Fluxes

A successful detection of radiation from transiting extrasolar planets depends on the ratio of fluxes emitted by the planet and the star at a given wavelength. Figure 1 shows the computed model stellar fluxes for OGLE-TR-56 and OGLE-TR-132, between 0.5 and 2.5 \( \mu \)m, and the planets’ expected thermal emission and reflected light fluxes, based on the \( T_p \) and \( A_b \) values from § 2.1.

The stellar fluxes are derived using grids of Kurucz (1993) models, interpolated for the specific \( T_{\text{eff}} \), [Fe/H], and log \( g \) values of OGLE-TR-56 and OGLE-TR-132. Stellar parameters for OGLE-TR-56 have been measured by Santos et al. (2006), who obtain \( T_{\text{eff}} \) = 6119 ± 62 K, [Fe/H] = +0.25 ± 0.08 dex, and \( g = 4.21 ± 0.19 \) cgs. For OGLE-TR-132, the stellar parameters derived by Bouchy et al. (2004) are \( T_{\text{eff}} = 6411 ± 179 \) K, [Fe/H] = +0.43 ± 0.18 dex, and \( g = 4.86 ± 0.14 \) cgs.

For the planets, we derive thermal emission and reflected light fluxes from equations (2) and (3), assuming that the planets and the stars emit as blackbodies. We consider two temperature scenarios: (1) \( f = \frac{1}{4} \) and \( A_b = 0.5 \), where the planetary fluxes in the optical are dominated by reflected light (such high albedos are unlikely for VHJs; see § 2.1) and (2) \( f = \frac{1}{2} \) and \( A_b = 0.05 \), close to the \( f = \frac{1}{2} \); \( A_b = 0.0 \) scenario, to illustrate the significantly lower contribution of reflected light versus thermal emission for very low albedos. The expected temperatures of OGLE-TR-56b and OGLE-TR-132b in scenario 2 are 2852 ± 24 and 2581 ± 35 K.

We go beyond blackbody models by including in Figure 1 the Hubeny et al. (2003) models for irradiated planets at \( T_p = 2600 \) K, with and without TiO/VO molecules in their atmospheres. In the latter case, TiO and VO have condensed into solids, no longer contributing to the opacity. TiO and VO are such strong absorbers that the incident stellar radiation is absorbed at an altitude where reradiation dominates over advection, potentially leading to very hot planetary atmospheres on the substellar side. The presence of TiO and VO is furthermore expected to create a temperature inversion in the lower atmosphere in some cases (e.g., metal-rich; see also Fortney et al. 2006), leading to emission lines and making the planet flux at some wavelengths brighter than blackbodies of the same temperature.

### 3. Detectability of Secondary Transits at Optical Wavelengths

Secondary transits can be detected at any given wavelength if the planet-to-star flux ratios, \( F_p/F_\star \), are high enough. In terms of magnitudes, the transits are detectable if the difference in magnitude during transit, \( \Delta \text{mag} \), is larger than the photometric precision of the observational light curves, \( \sigma_{\text{mag}} \). Here \( \Delta \text{mag} \) is derived as

\[
\Delta \text{mag} = 2.5 \log \left( 1 + \frac{F_p}{F_\star} \right).
\]

where \( F_p \) is either the thermal emission flux, \( F_p^{\text{th}} \), or the reflected light flux, \( F_p^{\text{ref}} \). Detectability can be further increased by binning the transit data, as done, for example, by Deming et al. (2005)
for HD 209458b. The photometric precision of the light curves is then $\sigma_{\text{mag}}/\sqrt{t}$, where $t$ is the time duration of the bins.

Figure 2 shows the expected $|\Delta \text{mag}|$ during secondary transits of OGLE-TR-56b and OGLE-TR-132b, for the thermal emission and reflected light cases in Figure 1. A detailed description is given in the figure’s caption. The stellar and planetary fluxes have been integrated over two model filter passbands with FWHMs of 0.1 $\mu$m, centered at 0.76 and 0.91 $\mu$m. Those passbands resemble the $i'$- and $z'$-band filters of the Sloan Digital Sky Survey (SDSS; Fukugita et al. 1996).

We also show the achievable $\sigma_{\text{mag}}$ for OGLE transit light curves at optical wavelengths (Fig. 2, horizontal dashed lines) for integration times of $t = 1$, 120 (3 $\sigma$), and 120 (1 $\sigma$) minutes. The transits of both planets last about 120 minutes, so the two bottom lines represent the 1 and 3 $\sigma$ level photometric precision that would be achieved by binning $\sigma_{\text{mag}} = 1.0$ mmags minute$^{-1}$ light-curve data over the entire duration of the transits (see below and § 4).

To compare our estimates with $\sigma_{\text{mag}}$ from OGLE primary transit light curves, we give the average $\sigma_{\text{mag}}$ and exposure times per data point in Table 2. Assuming no correlation between photometric precision and filter passbands, $\sigma_{\text{mag}}$ varies between 0.83 and 1.18 mmags minute$^{-1}$, depending on the instrument and the target. Here we have excluded the Magellan/IMACS values because its low photometric precision results from instrumental effects (Winn et al. 2007a). We therefore reasonably assume an average $\sigma_{\text{mag}}$ of 1.0 mmags minute$^{-1}$.

4. DISCUSSION

Secondary transits of extrasolar planets are normally pursued in the infrared, where $F_{\text{IR}}/F_{\text{opt}}$ is higher than in the optical. We argue that, for the right combination of stellar and planetary parameters, the thermal emission from some VHJs could be detected at optical wavelengths during secondary transits.

Our investigation of all known transiting VHJs concludes that only two of them, OGLE-TR-56b and OGLE-TR-132b, have the right combination of stellar and planetary parameters to be hotter than 2600 K. At those temperatures thermal emission dominates over reflected light emission. Therefore, thermal
emission could be detected during secondary transits in the optical. OGLE-TR-56b is the most promising candidate for detection, in either \(i\) or \(z\) band. OGLE-TR-132b could also be detected in \(z\) band, but the prospects are lower. Reflected light emission is similar in both filters, and a factor of 10–20 less than the thermal emission if the planets are very hot.

Observations in \(z\) band are better suited for detecting thermal emission from these two planets than ground-based observations at other optical or near-IR passbands. The better performance of \(z\) band versus \(i\) band is clearly illustrated in Fig. 2. At shorter wavelengths, for example, 0.50–0.65 μm, \(F_p/F_0\) decreases considerably (see Fig. 1). At near-IR wavelengths, the expected \(F_p/F_0\) are higher, but the effect of the atmosphere on ground-based observations produce lower quality light curves (Snellen & Covino 2007; Díaz et al. 2007).

The transits of OGLE-TR-56b and OGLE-TR-132b last for ~2 hr. By binning \(z\)-band light curves with \(0.21\) mag minute⁻¹ over the duration of the transits (in-transit and out-of-transit bins of the same duration), thermal emission from OGLE-TR-56b could be detected with \(>5\)σ significance after three secondaries, if the planet emits as a blackbody with \(T_p > 2500\) K. If the planet emits as predicted by the Hubeny et al. (2003) models with TiO/VO, the expected transit depth is 0.04% (Fig. 2, filled magenta squares). The transit could be then detected with \(>6\)σ significance after three transits. In the case of OGLE-TR-132b, four secondary transits are needed for a 5σ significance detection.

One might expect that cooler VHJs around brighter stars would be as promising or more so than the more distant and fainter (yet hotter) OGLE-TR-56b and OGLE-TR-132b. In principle, slightly cooler planets around brighter stars should be just as favorable, because the brighter stars have lower Poisson photon noise. In practice, \(\sigma_{\text{mag}}\) is limited for bright stars in two ways. On small telescopes atmospheric scintillation limits \(\sigma_{\text{mag}}\) from reaching the photon noise limit (\(\sigma_{\text{mag}}\) from scintillation is typically several millimag). On large telescopes the limit is usually imposed by the absence of suitable nearby comparison stars within their small fields of view.

Any newly discovered transiting VHJs should be examined for the possibility of detecting their thermal emission at optical wavelengths. In particular, hot VHJs orbiting bright stars with a binary star companion would be ideal. Such detections will provide important clues about the energy processing mechanisms undergoing in the atmospheres of those planets.

### REFERENCES

Ballester, G. E., Sing, D. K., & Herbert, F. 2007, Nature, 445, 511
Bouchy, F., et al. 2004, A&A, 421, L13
———. 2005, A&A, 444, L15
Burke, C. J., et al. 2007, preprint (arXiv:0705.0003)
Charbonneau, D., Brown, T. M., Noyes, R. W., & Gilliland, R. L. 2002, ApJ, 568, 377
Charbonneau, D., et al. 2005, ApJ, 626, 523
———. 2007, ApJ, 658, 1322
Deming, D., Harrington, J., Seager, S., & Richardson, L. J. 2006, ApJ, 644, 560
Deming, D., Richardson, L. J., & Harrington, J. 2007, MNRAS, in press
Deming, D., Seager, S., Richardson, L. J., & Harrington, J. 2005, Nature, 434, 740
Díaz, R. F., et al. 2007, ApJ, 660, 850
Fortney, J. J., et al. 2006, ApJ, 642, 495
Fukugita, M., et al. 1996, AJ, 111, 1748
Gillon, M., et al. 2006, A&A, 459, 249
Grillmair, C. J., et al. 2007, ApJ, 658, L115
Harrington, J. et al. 2006, Science, 314, 623
Holman, M. J., et al. 2007, ApJ, 655, 1103
Hood, B., et al. 2007, MNRAS, submitted
Hubeny, I., Burrows, A., & Sudarsky, D. 2003, ApJ, 594, 1011
Knutson, H. A., et al. 2007, preprint (arXiv:0705.0993)
Kurucz, R. 1993, CD-ROM 13, ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid (Cambridge: SAO)
Marley, M. S., et al. 1999, ApJ, 513, 879
———. 2007, ApJ, 655, 541
Moutou, C., Pont, F., Bouchy, F., & Mayor, M. 2004, A&A, 424, 31
O’Donovan, F. T., et al. 2007, preprint (arXiv:0705.2938)
Pond, F., et al. 2007, A&A, 465, 1096
Richardson, L. J., et al. 2007, Nature, 445, 892
Rowe, J. F., et al. 2006, ApJ, 646, 1241
Santos, N. C., et al. 2006, A&A, 450, 825
Sato, B., et al. 2005, ApJ, 633, 465
Seager, S., Whitney, B. A., & Sasselov, D. D. 2000, ApJ, 540, 504
Snellen, I. A. G. 2005, MNRAS, 363, 211
Snellen, I. A. G., & Covino, E. 2007, MNRAS, 375, 307
Soffizetti, A., et al. 2007, preprint (arXiv:0704.2938)
 Sudarsky, D., Burrows, A., & Pinto, P. 2000, ApJ, 538, 885
Tinetti, G., et al. 2007, Nature, 448, 169
Vidal-Madjar, A., et al. 2003, Nature, 422, 143
———. 2004, ApJ, 604, L69
Winn, J. N., Holman, M. J., & Fuentes, C. I. 2007a, AJ, 133, 11
Winn, J. N., et al. 2007b, AJ, 133, 1828