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Lessons from detections of the near-infrared thermal emission of hot Jupiters

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Abstract. There have recently been a flood of ground-based detections of the near-infrared thermal emission of a number of hot Jupiters. Although these near-infrared detections have revealed a great deal about the atmospheric characteristics of individual hot Jupiters, the question is: what information does this ensemble of near-infrared detections reveal about the atmospheric dynamics and reradiation of all hot Jupiters? I explore whether there is any correlation between how brightly these planets shine in the near-infrared compared to their incident stellar flux, as was theoretically predicted to be the case. Secondly, I look for whether there is any correlation between the host star's activity and the planet's near-infrared emission, like there is in the mid-infrared, where Spitzer observations have revealed a correlation between the host star activity with the presence, or lack thereof, of a temperature inversion and a hot stratosphere.

Keywords. eclipses, infrared: planetary systems, planetary systems, techniques: photometric

1. Introduction

Near-infrared observations of the thermal emission of hot Jupiters are crucial to our understanding of these exotic worlds. The blackbodies of the hottest of the hot Jupiters peak in the near-infrared, and it is thus in this wavelength regime that we will obtain the best constraints on the properties of their atmospheres. Near-infrared detections will help to constrain their bolometric luminosities, their temperature-pressure profiles at depth, and the efficiency of day/night redistribution of heat deep in their atmospheres. The desire to achieve such goals led to the program that I have been involved in using the Wide-field Infrared Camera on the Canada-France-Hawaii Telescope to detect the thermal emission of several hot Jupiters in the near-infrared (Croll *et al.* 2010a; Croll *et al.* 2010b; Croll *et al.* 2011). Truly understanding even the reradiation of hot Jupiters, however, will require multiple-band detections in the near- and mid-infrared of the thermal emission of a great number of hot Jupiters. There have been a series of multiple band detections of the thermal emission of hot Jupiters to date, mostly in the mid-infrared from observations obtained with the Spitzer Space Telescope. These multiple-band detections have revealed a wealth of information about these worlds, including that the most highly irradiated hot Jupiters orbiting inactive hosts seem to harbor hot stratospheres and temperature inversions (e.g. Knutson *et al.* 2008a; Charbonneau *et al.* 2008; Machalek *et al.* 2008; Knutson *et al.* 2008b; Knutson *et al.* 2010). One could imagine that near-infrared constraints, where the majority of the flux of these planets emerges, would be equally informative - especially if we are able to achieve multiple-band near-infrared detections. Here we attempt to determine what lessons, if any, can be taken away from all the ground-based near-infrared detections of the thermal emission of hot Jupiters that have been achieved to date, including two multiple-band detections.

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2. Comparison of near-infrared detection of the thermal emission of hot Jupiters to date

There have been a wealth of recent detections from the ground of the thermal emission of hot Jupiters in the near-infrared. Detections with greater than 3σ confidence include†: TrES-3b in Ks-band (de Mooij & Snellen 2009; Croll *et al.* 2010b), OGLE-TR-56b in z'-band (Sing & Lopez-Morales 2009), WASP-12b in z'-band (Lopez-Morales *et al.* 2010) and in J, H & Ks (Croll *et al.* 2011), CoRoT-1b at ∼2.1 μm (Gillon *et al.* 2009) and in Ks (Rogers *et al.* 2009), TrES-2 in Ks (Croll *et al.* 2010a), WASP-19 in H (Anderson *et al.* 2010) and Ks (Gibson *et al.* 2010), HAT-P-1 in Ks (de Mooij *et al.* 2010), as well as our own WASP-3 detection in Ks-band (Croll *et al.* in prep.). Given this recent flurry of detections it is high-time to search for possible trends revealed by these observations.

One such possible correlation is between the incident stellar flux and the efficiency of redistribution of heat from the day to the nightside, which we parameterize with a joint constraint on the Bond albedo and the reradiation factor, $f \times (1 - A_B)$. As, the geometric and Bond albedoes of many hot Jupiters have been measured (Rowe *et al.* 2008; Snellen *et al.* 2009; Alonso *et al.* 2009; Alonso *et al.* 2009b; Snellen *et al.* 2010) or inferred to be close to zero (Cowan & Agol 2011), this joint constraint should be in most cases largely identical to a constraint on the reradiation factor, f. Fortney *et al.* 2008 predicted that more highly irradiated hot Jupiters would have temperature inversions and feature more inefficient redistribution of heat to their nightsides than their less highly irradiated cousins, which were predicted to lack such inversions; although, Spitzer observations have not universally supported this theory (i.e. Machalek *et al.* 2008; Fressin *et al.* 2010), it is worth investigating if at least the redistribution of heat is supported at near-infrared wavelengths. We thus plot the correlation between the inferred equilibrium temperatures of these planets, a proxy for incident stellar flux, and their observed near-infrared brightness temperatures, and joint constraints on $f \times (1 - A_B)$ (Figure 1, top and middle panel). HAT-P-1b's Ks-band thermal emission is an obvious outlier; we note that de Mooij *et al.* (2011) highlighted the possibility that unaccounted for systematic errors may have affected their measurement of the Ks-band thermal emission of this planet. Even ignoring the HAT-P-1b measurement, the efficiency of day-to-nightside redistribution in the atmospheric layers probed by the near-infrared does not decrease monotonically with increasing effective temperature. With still so few near-infrared measurements it is unclear whether there is, or is not, a trend with increasing equilibrium temperature.

Recently, Knutson *et al.* 2010 suggested that there was a trend between the activity of the hot Jupiter host stars (as measured by the Ca II H & K activity index, $log[R'_{HK}]$), and the depths of the Spitzer/IRAC secondary eclipses. Specifically, Knutson *et al.* 2010 suggested that hot Jupiters orbiting active stars (higher $log[R'_{HK}]$ values) lacked temperature inversions, while those orbiting less active stars (lower $log[R'_{HK}]$ values) displayed signs of temperature inversions. One possible explanation for this phenomenon is that active stars should have increased UV flux, which may destroy the high altitude absorber that would otherwise cause the hot stratosphere and the temperature inversion. It is predicted that planets with and without temperature inversions, should have

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† We note that we do not include detections from space using the NICMOS instrument on the Hubble Space Telescope (of HD 189733b [Swain *et al.* 2009a], and HD 209458b [Swain *et al.* 2009b]), as the analysis of this data has recently been called into question (Gibson *et al.* 2011). Also, we do not include the spectroscopic detection of the dayside spectrum of HD 189733b in the near-infrared using the SPEX instrument on the NASA Infrared Telescope Facility (Swain *et al.* 2010), as some of the features in this spectrum have likely been ruled out with another data-set with high confidence (Mandell *et al.* 2011).

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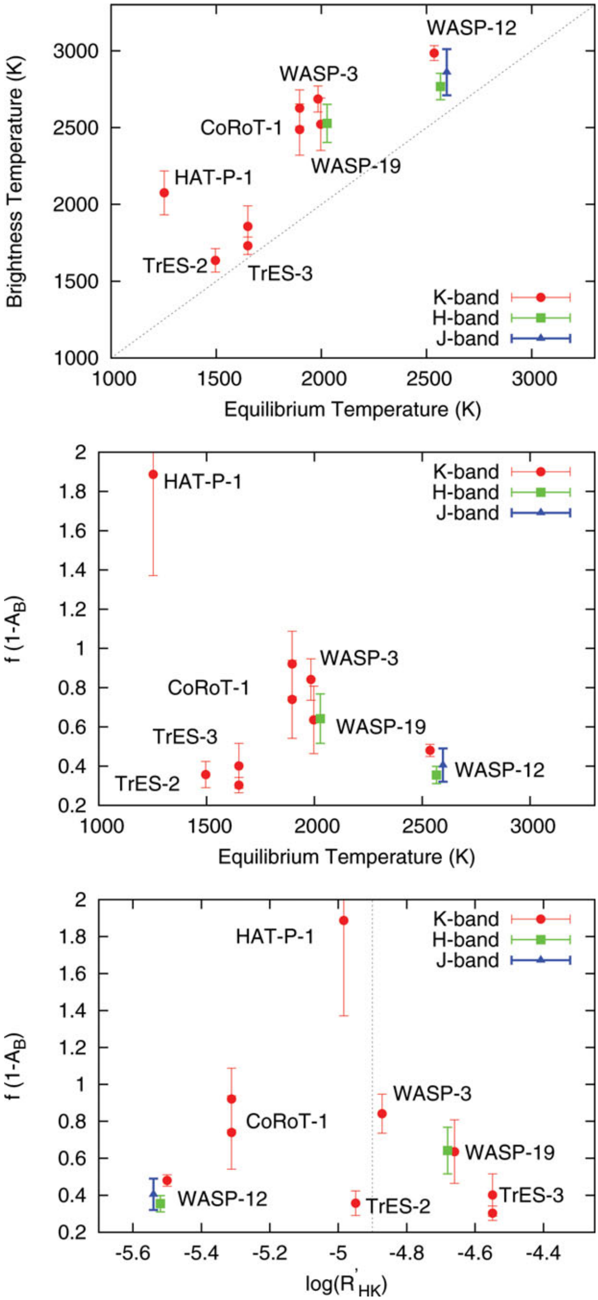

Figure 1. Various thermal emission detections from broadband, ground-based photometry in the JHK-bands (or at wavelengths that overlap with those filters). Top: The observed brightness temperatures compared to the equilibrium temperatures of the planets. The dashed line indicates a one-to-one correlation between brightness and equilibrium temperatures. Middle: The joint Bond albedo reradiation factors, $f \times (1 - A_B)$, compared to the equilibrium temperatures. Bottom: $f \times (1 - A_B)$ compared to the Ca II H & K activity index obtained from Knutson *et al.* 2010. The dotted vertical line indicates the dichotomy between hot Jupiters that Knutson *et al.* 2010 (and references therein) observed to have temperature inversions ($log(R'_{HK})$ <-4.9; to the left of the line) and those that did not ($log(R'_{HK})$ >-4.9; to the right of the line). In all plots we marginally offset the thermal emission measurements of the same planet in different near-infrared bands (JHK) along the x-axis for clarity.

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observable differences in the near-infrared as well; as already mentioned, planets with a hot stratosphere, should have increased thermal emission in the mid-infrared, and are therefore expected to reradiate less at shorter wavelengths in the near-infrared (Hubeny *et al.* 2003). We note that all those planets orbiting less active stars with ground-based near-infrared detections have been reported to have temperature inversions: CoRoT-1b (Deming *et al.* 2011), HAT-P-1b (Todorov *et al.* 2010 report a modest temperature inversion), WASP-12b (Madhusudhan *et al.* 2010 report a weak inversion) and TrES-2b (O'Donovan *et al.* 2010, although see Madhusudhan & Seager 2010). Of the sample orbiting active stars with near-infrared thermal emission detections, TrES-3b (Fressin *et al.* 2010) has been reported to lack an inversion as expected, while the Spitzer/IRAC eclipse depths of WASP-19b and WASP-3b have yet to be reported. However, as Figure 1 (bottom panel) shows there is no clear trend between more active hot Jupiter hosts and increased near-infrared thermal emission.

A greater number of near-infrared thermal emission detections of hot Jupiters, along with confirmation of the current detections, will be required to elucidate whether any of the predicted trends have been observed or can be confidently ruled out.

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