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Hot Jupiter secondary eclipses measured by *Kepler*

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Abstract. Hot-Jupiters are known to be dark in visible bandpasses, mainly because of the alkali metal absorption features. The outstanding quality of the *Kepler* mission photometry allows a detection (or non-detection upper limits on) giant planet secondary eclipses at visible wavelengths. We present such measurements on published planets from Kepler Q1 data. We then explore how to disentangle between the planetary thermal emission and the reflected light components that can both contribute to the detected signal in the Kepler bandpass. We finally investigate how different physical processes can lead to a wide variety of hot-Jupiters albedos.

1. Background and motivation

Secondary eclipses of two dozen transiting hot-Jupiters have been observed at infrared wavelengths with the *Spitzer* Space Telescope so far (see, e.g., Seager & Deming 2010). These strongly irradiated planets efficiently absorb visible light from their host stars and exhibit temperatures that largely exceed 1000K. The hot Jupiters consequently produce infrared emission signature of the order of 10^{-3} as compared to the host star flux.

The reflected light component of the hot-Jupiter population is critical to constrain planetary energy budgets and to explore the upper atmosphere properties. While Jupiter has a geometric albedo of 0.5 in the visible, HD209458b's geometric albedo is surprisingly low : <0.08 (3-σ upper limit, Rowe et al. 2008). Establishing a survey of secondary eclipses in the visible is thus highly desirable to better understand the origins of such diversity.

Table 1 summarizes visible band geometric albedo measurements that have been obtained to date. Hot Jupiters are dark, due to the alkali metal (Na and K) line absorption and possibly due to TiO and VO strong molecular absorption bands in the visible (e.g. Seager & Sasselov 2000, Marley et al. 1999, Sudarsky et al. 2000, 2003).

The planetary to stellar flux ratio of hot Jupiters at visible wavelengths is of the order of 10^{-5}, making it very challenging to measure (see Fig.1). After just 1.5 years of operation, *Kepler* has proven to be a facility able to achieve a few parts per million (ppm) photometric precision (e.g. Jenkins et al., 2010). We present an overview of secondary eclipse measurements for published *Kepler* giant planets and explore the possible origins of the signature measured in visible wavelengths.

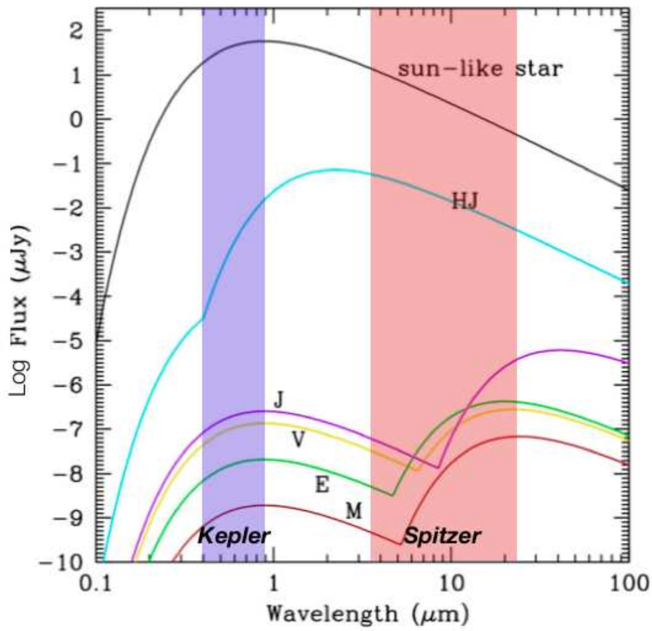

Figure 1: *Approximate spectral energy distribution for the Sun, Jupiter, Venus, Mars, the Earth and a representative hot Jupiter. Both thermal and reflected components are plotted for each planet. Bandpasses of Kepler and Spitzer are indicated, showing which wavelength region of the planetary spectra are probed. Adapted from Seager 2003.*

2. Geometric albedo determination

We performed Markov Chain Monte-Carlo analyses on the 6 hot Jupiters that have been observed by Kepler, including two previously known exoplanets : TrES-2b and HAT-P-7b. Public data from the first quarter were used to derive the systems parameters. Geometric albedos were computed from the secondary eclipse depth, planetary radius, and semi-major axis (eq. 1, Lopez-Morales & Seager 2007). The geometric albedo is wavelength-dependent and measures the ratio of the planet flux at zero phase angle to the flux from a Lambert sphere at the same distance and the same cross-sectional area as the planet (see Seager 2010).

$$\frac{F_p}{F_\star} = A_g \left(\frac{R_p}{a}\right)^2 \tag{1}$$

The photometric precision of *Kepler* is illustrated in Fig. 2, where a single, 80 ppm secondary eclipse of HAT-P-7b is shown and clearly detected. Results from this preliminary study appear in Table 2 and depict a wide variety of geometric albedos, ranging from 0.06 to 0.35. Such analysis has been performed by Kipping &Bakos (2010) and results show good consistency with those presented here.

Before any interpretation regarding scattered light contribution, one should cautiously examine to which extent the measured depth encompasses a thermal component.

Table 1: *Published constraints on hot Jupiters geometric albedos measured in the visible.*

Planet	Geometric Albedo	T_{eq} [K]	Reference
τ Bootis b	0.32±0.13 (R_P=1.2R_{Jup})	$\sim$ 1500K	Leigh et al. 2003a
"	< 0.3 (R_P=1.2R_{Jup})	"	Charbonneau et al. 1999
HD75289	< 0.12 (3-σ upper limit)	1260	Leigh et al. 2003b
HD209458b	< 0.08 (3-σ upper limit)	1550	Rowe et al. 2008
CoRoT-1b	< 0.20 (3-σ upper limit)	2330	Snellen et al. 2010
CoRoT-2	0.06±0.06	1910	Alonso et al. 2010

Table 2: *Geometric albedos and equilibrium temperatures (assuming no redistribution) for Kepler published giant planets from public data (Q1).*

Planet	Geometric Albedo	T_{eq} [K]
Kepler 5b	0.21 ±0.10	1557
Kepler 6b	0.18 ± 0.09	1411
Kepler 7b	0.35 ± 0.11	1370
Kepler 8b	0.21 ± 0.10	1567
TrES-2b	0.06 ± 0.05	1464
HAT-P-7b	0.20 ± 0.03	2085

3. Disentangling thermal emission and reflected light

As illustrated in Fig. 3 with the case of Kepler-5b, hot-Jupiter thermal emission could have a significant contribution to the planetary flux measured in the *Kepler* bandpass. While most of those planets do not benefit from a known effective temperature, one has to rely on an estimate of possible equilibrium temperature domain, through an estimation of both redistribution factor f and Bond albedo A_B (see eq. 2).

$$T_p = T_\star \left(\frac{R_\star}{a}\right)^{\frac{1}{2}} \left[f(1-A_B)\right]^{\frac{1}{4}} \quad (2)$$

Comparing the range of possible equilibrium temperatures to the brightness temperature corresponding to the secondary eclipse depth allows an estimate of the upper bound for the thermal emission, and thus also an estimate of the reflected light fraction. This simple approach is however challenged by the departure from blackbody radiation of hot Jupiter thermal emission spectra. Moreover, the structure of the atmospheric temperature profile might cause visible band measurements to probe thermal emission from deep layers of the atmosphere, for instance in the absence of a stratospheric thermal inversion. Brightness temperature estimates at other wavelengths might definitely help in constraining the energy budget and sample the planetary SED. Ideally, this step would allow a constraint on the possible range of the reflected light contribution alone and exploration of the upper atmosphere properties of those irradiated planets.

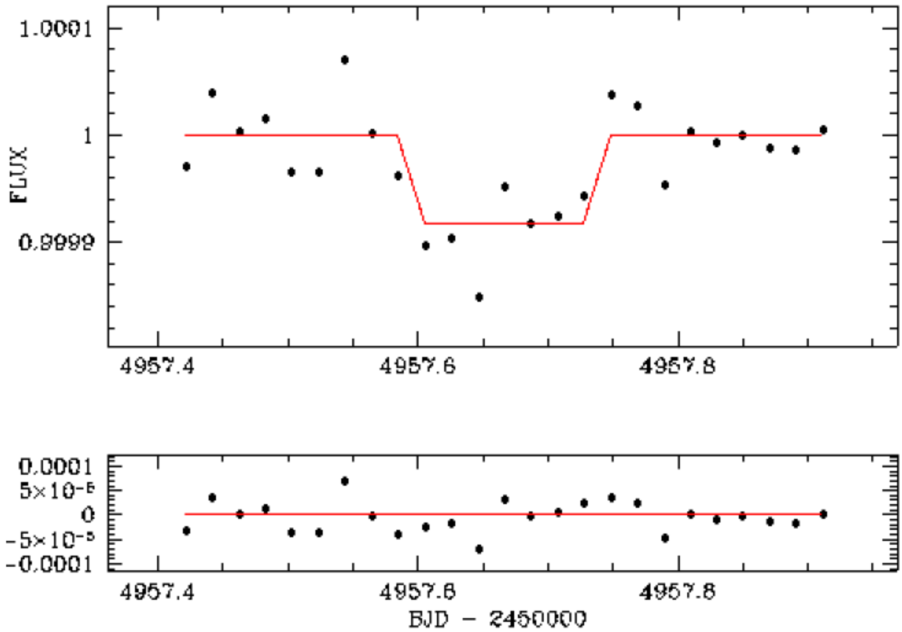

Figure 2: ***Top*** : *Kepler single long-cadence (30min) secondary eclipse lightcurve of the 2.2-day period hot Jupiter HAT-P-7b with the best fit model superimposed. 1-σ error bars are also indicated.* ***Bottom*** *: residuals of the fit. The occultation depth is 82 $\pm$ 12 ppm. Obtained from Kepler Q1 public data, 190 ppm rms /min.*

4. Conclusions

The *Kepler* mission will allow a comparative study of hot Jupiter secondary eclipses in the visible. Disentangling thermal emission from reflected light components is a critical point to address. While alkali metal absorption lines and TiO and VO molecular absorption bands are expected to shape the spectrum of hot Jupiters in the *Kepler* bandpass, the planetary thermal emission is arguably an important contributor for the most irradiated hot-Jupiters. Additionally, clouds are expected to form at the intersection of enstatite and iron compound condensation curves with the planetary temperature structure profile. The altitude of iron and enstatite cloud decks in hot Jupiter atmospheres significantly affects the geometric albedo. How representative are giant irradiated planets harboring high altitude reflective clouds and hazes is one of the several points *Kepler* will be able to address, shedding light on the properties of hot Jupiter atmospheres.

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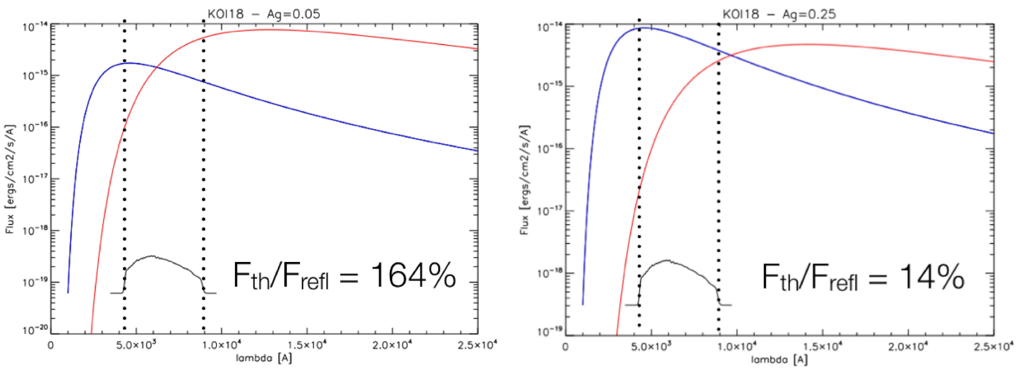

Figure 3: *Thermal (red) vs. reflected (blue) components in the Kepler bandpass for a 3.5-day period and 1.4* R_{Jup} *hot Jupiter. The low geometric albedo case (**left**) assumes* A_g*=0.05, consistent with the value determined for HD209458b by Rowe et al. 2008. The high geometric albedo case (**right**) explores the relative contribution of thermal and reflected fluxes for a highly irradiated and reflective hot Jupiters (e.g. Sudarsky et al. 2000) with* A_g*=0.40. A Lambertian sphere with no energy redistribution (f=2/3, see Lopez-Morales & Seager 2007) are assumed (the radiative timescale is in this case shorter than the advective timescale). To estimate the planetary equilibrium temperature, the Bond albedo is computed from the geometric albedo as* $A_B = \frac{3}{2} A_g$*. Ratios of planetary thermal flux to reflected flux in the Kepler bandpass are indicated for each case.*

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