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Infrared Transit Spectroscopy of HD 209458b

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Abstract. We measure spectra during transits of planet HD 209458b in front of its star to determine its composition and temperature. Transits should modulate the stellar spectrum because tangent rays of different wavelengths become extinct at different levels in the extrasolar planet atmosphere, changing the occulting area. S/N calculations show that ground-based spectroscopy can measure or place useful limits on the atmospheric abundances of H_2O, CH_4, and CO. Carbon forms predominantly CH_4 below 1400 K and CO if hotter. Since the equilibrium temperature is $\sim$1400 K, detecting CH_4 and/or CO would constrain atmospheric temperatures. We have observed on 12 transit and 4 non-transit nights from Palomar, Keck, VLT, and IRTF. The expected modulation of the stellar spectrum is model-dependent. Since the effect is subtle compared to the noise in the data, we correlate model vs. observed spectra and average the correlations to test whether the data support a given model. We are developing a tangent-geometry radiative-transfer model to predict the spectrum of a given planetary model, and we are measuring H_2O, CH_4,

and CO in the laboratory at 1300 K, with pressure-broadening by H_2, to make our model spectra realistic at these elevated temperatures. We solicit participation by those who wish to test their planetary models.

1. What is Transit Spectroscopy?

Transit spectroscopy measures the modulation of a stellar spectrum during a planetary transit: brighter stars yield easier measurements. The depth at which tangent rays become extinct depends on the wavelength and atmospheric composition. For example, if CO is present, the planet becomes opaque in a CO absorption feature at a larger radius than in continuum. During transit, the planet appears larger at the wavelength of the feature, yielding a deeper eclipse. Hazes and thermal structure also modulate the spectrum. The effect is most easily measured on large planets with large scale heights, short periods, and bright primaries, such as close-in extrasolar giant planets (CEGPs). HD 209458b's temperature ($T_{eq} \approx 1400$ K) is ten times Jupiter's, but the surface gravity is only about 1/3 Jupiter's. This makes the scale height ($H \propto T/g$) about 30 times Jupiter's, or 750 km. Due to the large scale height, calculations by Hubbard et al. (2001) show a several-percent modulation of the 1.7% eclipse depth (see Figure 1, which is optimistic due to the lack of clouds), so the net effect is about 7 parts in 10^4 of the stellar flux. The most promising wavelength region to search is 0.8–2.5 μm, which contains a forest of H_2O, CO, and CH_4 lines.

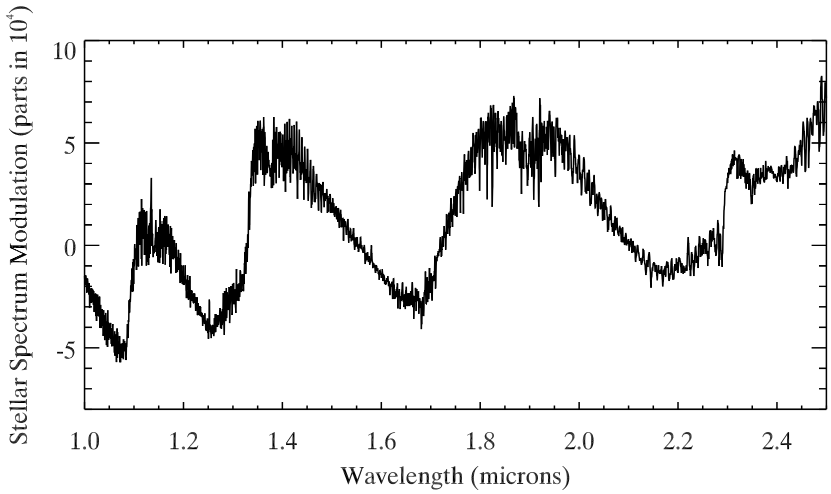

Figure 1. Theoretical opaque radius of HD 209458b vs. wavelength. Cloudless, radiative equilibrium model after Hubbard et al. (2001), provided by Fortney, Hubbard, Sudarsky, and Burrows.

The predicted modulation is model-dependent. Molecular abundances play a strong role, but so do the levels of hazes, the thermal profile, and processes like photochemistry. Transmission spectroscopy can thus test all the planetary models, answering questions like: What is the planetary composition? What is the atmospheric thermal structure? Where is the upper cloud deck? What processes are important in CEGP atmospheres?

With statistics from the transiting planets we expect will be discovered soon, we can also ask: Is the range of planetary compositions greater than the range of stellar compositions? How does planetary composition depend on stellar composition? Are there compositional classes that correspond to particular formation scenarios (e.g., core-accretion vs. disk instability)?

2. Can It Be Done From The Ground?

How can we detect a 0.07% absorption feature in 3 hours of observation? Unambiguous detection of a single line requires S/N$\sim$5000. The individual spectra from our similar secondary eclipse observations (Richardson et al. 2003) have S/N$\approx$200. Richardson et al. obtained 75 of these for each of the in- and out-of-eclipse sets per night, and observed two eclipses, for S/N=2450 per pixel. Fitting data to a model "template" spectrum allows all lines to contribute to the signal, yielding sensitivity to models with lines stronger than 1.4 parts in 10^4, as in Richardson et al. (2003). This is many times better than needed to see the predicted transit lines in ensemble. Even a null result would be highly significant. We find it further encouraging that Brown et al. (2002) achieved 1/3 the required sensitivity with a partial transit in poor weather.

3. Observations and Analysis Methods

Table 1 lists our observations. Conditions were excellent, including 2 nights of 0.3$''$ seeing on both Keck and IRTF and a night with $<$ 2 mm precipitable H_2O at VLT. At Keck, we will have the resolution and collecting area to work with individual lines. IRTF gives broad spectral grasp to search for all lines in ensemble, but at lower resolution and with less area. VLT is a compromise. We are most concerned about systematic errors. There is fringing in NIRSPEC (Keck) at the 1–2% level (with adaptive optics) and possibly in ISAAC (VLT) at the 0.1% level. We observed without adaptive optics or nodding at Keck in order to keep the fringes stable.

Table 1. Observations and Observing System Parameters

System	Area (relative)	Slew (sec)	$\lambda/\Delta\lambda$	XD*	Grasp (μm)	Array (pix$^{1/2}$)	Optics	Nights Tran.	Nights Non-	Qty. (GB)
Palomar/HNA	25	25	850	N	0.1	256	reflect.	2	2	0.55
Keck/NIRSPEC[a]	100	30	25,000	Y	0.2	1024	fringing	4	0	10.28
VLT/ISAAC	64	480	4,000	N	0.12	1024	OK	3	1	7.88
IRTF/SpeX	9	15	1,500	Y	1.7	1024	OK	3	1	5.06
Total				* Cross-dispersed				12	4	23.77

[a] In collaboration with an independent proposal by Charbonneau and Brown.

Uncorrected systematic noise will sharply diminish our chances of success. To avoid variable telluric water features, we look for hot H_2O transitions that are not excited in the Earth's atmosphere. Which transitions we see will constrain the planet's temperature. We observe both at high spectral resolution, to improve contrast, and with broad spectral grasp, to measure many lines at once. SpeX on the IRTF may compete with NIRSPEC on Keck, because it can grasp all the lines in Figure 1 at once, and has no fringing.

The signal is not likely to be prominent even in averaged data. We will cross-correlate model spectra against each observation, averaging the results. Cross-correlation tests the hypothesis that the spectra are shifted by a variety of wavelengths. The absense of peaks at other than the known system Doppler shift tests the method. We determine sensitivity by inserting artificial signals in the data.

To derive the theoretical spectra we will test, we are developing a tangent-geometry radiative-transfer model. This model will accept the thermal profile, abundances, and haze locations in the atmosphere; will follow the analytic method of Burrows and Sharp (1999) to recalculate the molecular abundances; and will calculate the spectral modulation at high spectral resolution. The model requires both high-temperature opacities and planetary model results. To date, there is only theoretical work for the key excited H_2O lines at 1300 K (Partridge and Schwenke 1997), and there are no measurements of CH_4 and CO at elevated temperatures that include pressure broadening. We will also account for the variation in the stellar line shapes from the selective blocking of portions of the stellar surface with different rotational Doppler shifts in transit.

We will test for H_2O, CO, and CH_4 in a radiatively-balanced atmosphere with low or high clouds, but the results of Richardson et al. (2002) and Charbonneau et al. (2002) suggest that HD 209458b may be more complicated. *We therefore solicit the results of physical models of HD 209458b* to be tested against the data. We wish to collect thermal profiles, cloud depths, and abundances from all the models in the literature, to predict transit spectra for them, and to test them against the data. We will also accept predicted spectra.

4. Conclusions

The atmospheric influence of HD 209458b on its primary's spectrum during transit should be observable from the ground. We are developing a model to predict the spectrum that a given atmosphere will produce. We will include measured laboratory lines for H_2O, CO, and CH_4 and the ability to recalculate molecular abundances with varying atmospheric temperature. We have acquired excellent data, and now seek collaborations with planetary modelers who wish to test their models against data.

References

Brown, T. M., Libbrecht, K. G., & Charbonneau, D. 2002, PASP, 114, 826

Burrows, A., & Sharp, C. M. 1999. ApJ, 512, 843

Charbonneau, D., Brown, T. M., Noyes, R. W., & Gilliland, R. L. 2002, ApJ 568, 377

Hubbard, W. B., Fortney, J. J., Lunine, J. I., Burrows, A., Sudarsky, D., & Pinto, P. 2001, ApJ, 560, 413

Partridge, H., & Schwenke, D. W. 1997, J. Chem. Phys. 106, 4618

Richardson, L. J., Deming, D., Wiedemann, G., Goukenleuque, C., Harrington, J., Steyert, D., & Esposito, L. W. 2003, ApJ, in press (astro-ph/0210612)