Transit Spectroscopy of Extrasolar Planet HD 209458b: The Search for Water

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Abstract. We are developing a technique to measure the atmospheric composition of extrasolar
planets through transit spectroscopy. Current observational capabilities have not yet reached enough
sensitivity to detect the Earth-like planets that life as we know it requires to evolve. We anticipate,
however, that this technique will detect constituents of the atmospheres of Earth-like planets once
future space-based observatories become sensitive enough.

We are currently using our methods on the extrasolar close-in giant planet HD 209458b. Bulk and
orbital parameters are well constrained for this planet and there are measurements of atmospheric
sodium [1] and hydrogen [2]. However, nothing is known about the abundances of molecules
relevant to life.

We are studying the modulation of the stellar spectrum as the planet transits in front of the star.
Different wavelengths become extinct at different levels in the exoplanet, causing the occulting area,
and therefore the modulation, to be wavelength-dependent. This dependency allows us to identify
atmospheric constituents. Signal-to-noise estimates show that data we have obtained from the Very
Large Telescope (VLT), the Infrared Telescope Facility (IRTF), Palomar, and Keck are sensitive
enough to measure or place useful limits on the atmospheric abundances of water and maybe even
of carbon monoxide and methane.

In order to detect the very weak expected modulation (~ 4 parts in 10000), we are building a
detailed radiative-transfer model to cross correlate with the data. This model will accept atmospheric
cloud distributions, temperature, density, and composition profiles for the planet. We will then be
able to measure the abundance of molecules relevant to life in the atmosphere of an extrasolar planet.

TRANSIT MODULATION

HD 209458b is, as of today, the only transiting system bright enough for spectroscopic
analysis with current instruments. Hence, its atmosphere is currently under intense
scrutiny: [1] detected sodium and [2] detected an extended hydrogen exosphere, but
a search for carbon monoxide was unsuccesful in its first attempt [5], as well as a search
for a secondary eclipse signature [3, 4].

As the planet transits, it blocks a section of the star equal to the area of the planet.
This area depends on the wavelength we use to observe the transit. A light ray passing
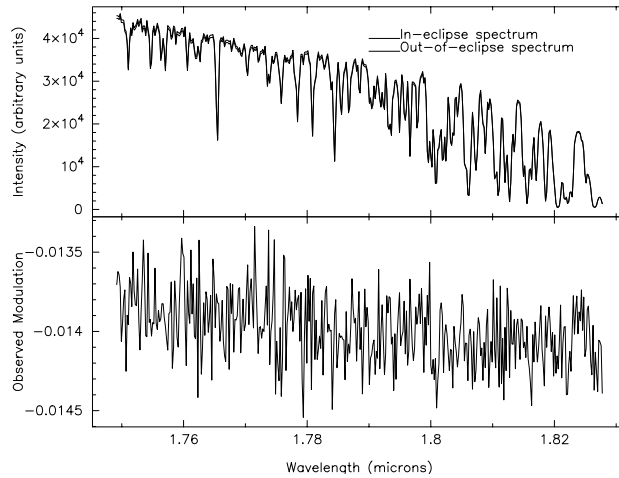
FIGURE 1. Simulated modulation in the data from VLT observations

through the planet's atmosphere becomes dimmer at wavelengths located in the cores of absorption features than at wavelengths where the atmospheric molecules do not absorb much. Hence, the planetary radius at which, say, 90% of the light is absorbed varies with wavelength. Thus, the opaque area of the planet varies with wavelength according to the spectral features of the atmospheric molecules. Because the spectral signature is unique, we can identify the molecules responsible for the modulation. Furthermore, the strength of this modulation will allow measurements of molecular abundances.

The upper panel in Figure 1 shows an observed out-of-transit spectrum and a simulated in-transit spectrum with the expected noise level, while the lower panel shows one minus the ratio of those two spectra.

The expected noise level is high as can be seen when comparing the lower panel of Figure 1 to the noiseless modulation model in Figure 2. Wavelengths in the continuum and wavelegths in the core of some absorption features have a contrast of up to 0.04% between them. This translates to a required S/N of 7500 for a 3σ detection of the effect.

If we cross-correlate the data with the model, the individual pixels in each feature and the multiple features all contribute towards a single cross-correlation peak, increasing the S/N proportionally to the square root of the number of pixels to be combined. There are about 20 excited features of water vapor in the wavelength range of our observations and about 3 pixels per feature, giving us an equivalent S/N above our minimum needs. Figure 3 shows the cross-correlation result from the data and model in Figs 1 and 2.

We are building a detailed radiative transfer model, which will include temperature, pressure, molecular abundances, and cloud profiles for the planet. Profiles will be tested against radiative equilibrium models from various sources [6, 7, 8, 9]. Opacity information for water will be obtained from [10], while one of us (Steyert) is conducting precise laboratory measurements for methane.

The model will include spherical layered symmetry for the planet and effects like ray bending (due to varying atmospheric index of refraction) and stellar limb darkening.
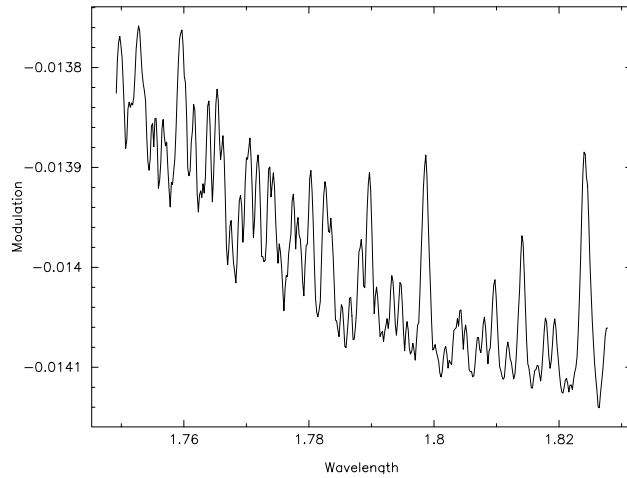
FIGURE 2. Transit model (Seager 2003, private communication). Main plot has the same wavelength range as Figure 1.
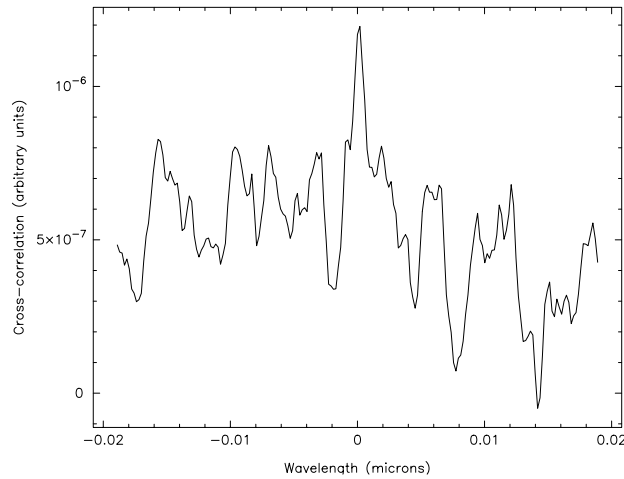

FIGURE 3. Cross-correlation result from simulated data

OBSERVATIONS

We are focusing on the detection of water, carbon monoxide, and methane, all of which are relevant to organic life. In order to succeed in this task we require data quality at the limits of current capabilities. Also, identification of water features in the infrared (IR) requires wavelength resolution of $\lambda/\Delta\lambda \sim 1500$ or more.

Table 1 summarizes the observations undertaken and instruments used. A total of 12 transit nights are available to us now. However, instrument problems and bad weather will limit the validity of some of those nights. Although the Hubble Space Telescope (HST) has an optimal location, it lacks the required spectral resolution in the infrared.

It is of prime importance to discover and cancel any systematic effects that could ruin the result. Shifting the position of the star along the spectrograph slit (nodding) allows us to measure and subtract sky emission. Also, because telluric water vapor usually varies

TABLE 1. Observations and Instruments details

System	Area (m^2)	$\frac{\lambda}{\Delta\lambda}$	CD?[*]	Array length	Nights Trans	Nights Non-	Qty (GB)
Palomar/HNA	20	850	N	256	2	2	0.56
Keck/NIRSPEC	79	25000	Y	1024	4	0	10.28
VLT/ISAAC	50	4000	N	1024	3	1	7.88
IRTF/SpeX	7	1500	Y	1024	3	1	5.06
Total					12	4	23.77

[*] Is the spectrograph cross dispersed?

on timescales of minutes in an unpredictable way, we limit our exposure times to 2 minutes.

Optimal extraction of the spectra from the reduced frames is a critical step. Adapting the algorithm described by [11], we will obtain the most accurate spectra from the observations we made. We combine spectra only from the same telescope whenever the setup was kept the same (in order to avoid systematic errors and rescaling). We anticipate S/N of at least 200 per pixel per spectrum, or 2000 per pixel per transit (after combination).

CONCLUSIONS

Detection of life-relevant molecules on extrasolar planets such as H_2O, CO and CH_4 constituents is possible through transit spectrospcopy. This will be of prime interest once the sensitivity of future space-based observatories reaches levels capable of measuring life-bearing planets.

Even a negative result for this study will be meaningful; it will either place strong constraints on models or it will help to justify the need of space-based instruments.

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