Transiting Planets
Proceedings IAU Symposium No. 253, 2008
Frédéric Pont, Dimitar Sasselov & Matthews Holman, eds.

doi:10.1017/S1743921308027117

Atmospheric composition and structure of HD209458b

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Abstract. Transiting planets like HD209458b offer a unique opportunity to scrutinize their atmospheric composition and structure. Transit spectroscopy probes the transition region between the day and night sides, called the limb. We present a re-analysis of existing HST/STIS transmission spectra of HD209458b's atmosphere. From these observations we identify H2 Rayleigh scattering, derive the absolute Sodium abundance and quantify its depletion in the upper atmosphere, extract a stratospheric T-P profile and find a temperature inversion and explain broad band absorptions with the presence of TiO and VO molecules.

1. Introduction

Because of the wavelength-dependent opacities of absorbing species, measurement of relative changes in eclipse depth as a function of wavelength during primary transit has the potential to reveal the presence (or absence) of specific chemical species (Seager *et al.* 2000a, Hubbard *et al.* 2001, Brown *et al.* 2001).

In the case of HD209458b's atmosphere, the transmission spectroscopy method led to the detection of sodium (Charbonneau *et al.* 2002, Sing *et al.* 2008b). In the UV, absorptions of several percents for H I Lyman-α, O I and C II have been measured in the hydrodynamically escaping upper atmosphere (Vidal-Madjar *et al.* 2003, 2004, 2008, Désert *et al.* 2004, Lecavelier 2007, Ehrenreich *et al.* 2007).

We use public archived *STIS* spectra obtained during planetary transit at two spectral resolutions (low and medium). Both datasets are combined to extend the measurements over the entire optical regime to quantify possible absorbers appearing in the transmission spectrum (Sing *et al.* 2008a).

Here we present the identification of Rayleigh scattering by H_2 molecules (Lecavelier *et al.* 2008b), the depletion of NaI as well as the extraction of a P-T profile with inversion (Sing *et al.* 2008b). Finally, we derived the upper limits for the TiO/VO molecular abundances in the atmosphere of the planet (Désert *et al.* 2008).

2. Observed features in the spectrum and interpretation

The *HST-STIS* G750L, and G430L low resolution grating observations (2003) of HD209458b analyzed here are also detailed in Knutson *et al.* (2007a), Barman (2007), Ballester *et al.* (2007) and Sing *et al.* (2008a). For both the G750L, and G430L gratings, two visits were done for each grating, of five consecutive orbits each. Together they cover the combined range 2900-10300 Å, with some overlap around 5300 Å with a resolving power $R = 500$.

Lecavelier Des Etangs *et al.* (2008a) show that the observed Absorption Depth (AD) is well approximated by:

$$AD_\lambda = AD_0 \left(1 + \frac{2H}{R_P} \ln \frac{\sigma_\lambda}{\sigma_{\lambda_0}}\right) \tag{2.1}$$

where AD_0 is the depth at $\lambda = \lambda_0$ and H the scale height. Thus the observed mean absorption depth over a wavelength range of a given spectral element, is proportional to the temperature and to the logarithm of the cross section.

We use the absorption depth curve as a function of the wavelength from 4000 Å to 8000 Å obtained by Sing *et al.* 2008a. The spectrum at wavelength below 8000 Å is considered here where the absorption due to water molecules is negligible (Barman *et al.* 2007). This spectrum is composed of three remarkable features (see Fig. 2):

(*a*) *Rayleigh scattering.* The feature in NUV, at wavelength $\lambda \leqslant 5000$ Å, was first reported by Ballester *et al.* 2007 and explained by the absorption of a hot hydrogen layer within the atmosphere. Here we propose an alternative explanation invoking the Rayleigh scattering by H_2 molecules (Lecavelier *et al.* 2008b).

(*b*) *Na depletion and atmospheric structure.* Within the same datasets, we find that the Na spectral line profile is characterized by a wide absorption with a sharp transition to a narrow absorption profile at higher altitudes values (Sing *et al.* 2008b). This sharp transition is interpreted by condensation or ionization which deplete Na atoms in the upper atmosphere. Using a global fit to these data, from 3000 Å to 6200 Å, we determine the average pressure-temperature profile ($P - T$), see Fig. 1, at the planetary terminator (Sing *et al.* 2008b).

(*c*) *TiO/VO.* A third broad band absorption feature in the range 6200 Å – 8000 Å appears on the absorption depth spectrum and is still unexplained. Although no typical TiO and VO spectral signatures have been identified unambiguously in the observed spectrum, we suggest that the opacities of those molecules are the best candidates to explain the remaining continuous broad band absorption observed in this wavelength domain (Désert *et al.* submitted). Using the P-T profile from Sing *et al.* 2008b, we derived upper limits for the TiO and VO abundances. We found that the abundance of TiO should be around 10^{-4} to 10^{-3} solar, and the abundance VO around 10^{-3} to 10^{-2} solar (Désert *et al.* submitted).

3. The Irradiated Atmospheres of HD209458b

The temperature inversion leads to high temperature at both low and high pressure. This temperature bifurcation was very well predicted by atmospheric models of strongly irradiated planets (Hubeny *et al.* 2003). In the lower part of the atmosphere (~30 mbar), the temperature is found to be in the range 1900 − 2400 K (Lecavelier *et al.* 2008b), which corresponds to the M/L/T brown dwarf regime, as expected for a hot Jupiter such as HD209458b (Kirkpatrick *et al.* 2005).

However, depending on the effective temperature, a large number of diatomic and polyatomic molecules are predicted to be present according to various models of brown dwarf and hot Jupiter (Burrows *et al.* 1999, Lodders *et al.* 1999, Allard *et al.* 2001, Lodders *et al.* 2002, Hubeny *et al.* 2003). Among those molecules and at a temperature above 1800 K, titanium oxyde (TiO) and vanadium oxyde (VO) in gas phase equilibrium are

https://doi.org/10.1017/S1743921308027117 Published online by Cambridge University Press

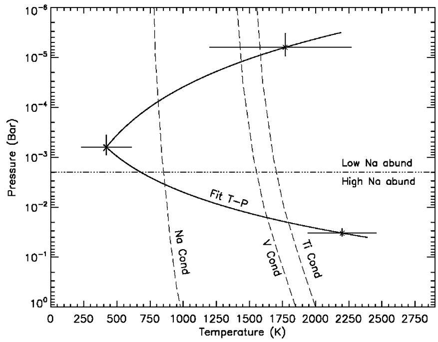

Figure 1. The atmospheric Temperature-Pressure profile (P-T profile) with error bars. The dashed lines correspond to the condensation curves for Titanium, Vanadium and Sodium. The three points of this T-P profile are derived from the fit of the observed absorption depth curve. The hot point at a pressure of 0.05 Bar is imposed by the Rayleigh scattering (See Lecavelier *et al.* 2008).

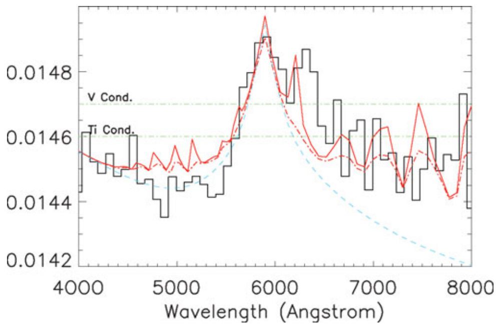

Figure 2. The low resolution STIS measurements of the planetary transit absorption depth (AD) corrected from limb-darkenning effects and binned by 60 pixels (histogram). The dashed line corresponds to the best fit model assuming Rayleigh scattering and sodium absorption with the physical T-P profile plotted in Fig. 1. Overplotted in continuous line, is the same model, with best fit models assuming Rayleigh scattering, NaI, TiO and VO absorptions. The dot-dash line correspond to the model with a cold-trap. The two altitudes of condensation for the TiO and VO molecules are plotted horizontally.

most probably present with a high abundance in strongly irradiated planet atmospheres (Seager *et al.* 1998, Hubeny *et al.* 2003, Fortney *et al.* 2007). Furthermore, the low albedo measurements of HD209458b (Rowe *et al.* 2006) rule out most of the absorbants, but TiO and VO. Recently, it has been found that a theoretical fit to the HD209458b near infrared observation at secondary eclipse requires that the dayside atmosphere of HD 209458b have a thermal inversion and a stratosphere (Knutson *et al.* 2008, Burrows *et al.* 2007c, Burrows *et al.* 2008). Hubeny *et al.* (2003) and Fortney *et al.* (2007) highlight the importance of gaseous TiO and VO opacity in their model of highly irradiated close-in giant planets. The last authors define two classes of irradiated atmospheres. Those which are warm enough to have a strong opacity due to TiO and VO gases ("pM Class" planets), and those that are cooler ("pL Class" planets) dominated by Na I and K I. Our possible detection of TiO/VO and Na I in the hot atmosphere of HD209458b confirm that this planet is located in the transition region between the two classes defined by these authors.

Further observation are necessary to better characterize the two different type planets using TiO/VO. More planets can be likely studied using transit observations which allowed discoveries, detection, and characterization of extrasolar objects such as planets and comets (Lecavelier des Etangs *et al.* 1995, 1999a, 2005).

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https://doi.org/10.1017/S1743921308027117 Published online by Cambridge University Press