IDENTIFICATION OF ABSORPTION FEATURES IN AN EXTRASOLAR PLANET ATMOSPHERE

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ABSTRACT

Water absorption is identified in the atmosphere of HD 209458b by comparing models for the planet’s transmitted spectrum to recent, multiwavelength, eclipse-depth measurements (from 0.3 to 1 μm) published by Knutson et al. A cloud-free model that includes solar abundances, rainout of condensates, and photoionization of sodium and potassium is in good agreement with the entire set of eclipse-depth measurements from the ultraviolet to near-infrared. Constraints are placed on condensate removal by gravitational settling, the bulk metallicity, and the redistribution of absorbed stellar flux. Comparisons are also made to the Charbonneau et al. sodium measurements.

Subject headings: planetary systems — radiative transfer — stars: individual (HD 209458)

1. INTRODUCTION

The discovery of transiting extrasolar planets has opened the door to direct detections and to the characterization of their atmospheres. Observations using the Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope (HST) provided the first glimpse of what the photospheric composition is like for a nearby extrasolar giant planet (EGP). Charbonneau et al. (2002) measured the relative change in eclipse depth for HD 209458b across a sodium doublet (5893 Å), resulting in the first detection of atomic absorption in an EGP atmosphere. Following the Na detection, Vidal-Madjar et al. (2003) discovered an extended hydrogen-rich atmosphere surrounding HD 209458b using a similar technique to Charbonneau et al., but in the UV. At Lyα wavelengths, HD 209458b is ~3 times larger than in the optical. These detections were made using a technique called transit spectroscopy as the planet passes in front of its star. Transit spectroscopy uses the fact that the wavelength-dependent opacity of the planet’s atmosphere obscures stellar light at different planet radii, leading to a wavelength-dependent depth of the light curve during primary eclipse. Consequently, searching for relative changes in eclipse depth as a function of wavelength directly probes the absorption properties of the planet’s atmosphere, with the potential to reveal the presence (or absence) of specific chemical species.

In this Letter, recent measurements of HD 209458b’s radius are combined in a multiwavelength comparison to model atmosphere predictions. Atmospheric molecular and atomic absorptions are identified, and constraints are placed on the basic atmospheric properties.

2. THE LIMB MODEL

Transit spectroscopy probes the limb of a planet; this limb is the transition region between the dayside and the nightside. One would therefore expect that, in the presence of a horizontal temperature gradient between the heated and nonheated hemispheres, the temperatures across the limb would be cooler than the average dayside temperatures (Barman et al. 2005; Iro et al. 2005). Recent Spitzer observations of both transiting and nontransiting hot Jupiters showing large flux variations with phase have provided strong evidence supporting such a day-to-night temperature gradient (Charbonneau et al. 2005; Deming et al. 2005b, 2006; Harrington et al. 2006).

Describing the limb ultimately requires a multidimensional model atmosphere solution; however, as is common practice, a simpler one-dimensional model is used here to represent the average properties of the limb, in both a longitudinal and latitudinal sense. To explore a variety of limb temperature structures, the incident stellar flux has been scaled by a parameter α. A model with α = 0.25 represents an average description of the entire planet in the presence of very efficient horizontal energy transport (Barman et al. 2005). Increasing α to 0.5 increases the heating of the model atmosphere, making it more appropriate for just the dayside, which, in this work, will represent an upper limit to the plausible mean temperatures at the limb.

The basic chemistry across the limb is modeled by assuming chemical equilibrium, which is determined by minimizing the free energy while including grain formation. To understand the effects of the gravitational settling of grains on the chemistry and the transmission spectrum, the removal of grains from the atmosphere is included via two simple approximations that represent opposite extremes. The first is the “cond” approximation used by Barman et al. (2001) and Allard et al. (2001), which simply ignores the grain opacity without altering the chemistry or abundances. The second is the “rainout” approximation, which iteratively reduces, at each layer, the elemental abundances (by the appropriate stoichiometric ratios) involved in grain formation and recomputes the chemical equilibrium with each new set of stratified elemental abundances. This approach is similar to other rainout models (Fegley & Lodders 1996; Burrows & Sharp 1999), except that the depletion of elements is continued until grains are no longer present.

The transmission of stellar fluxes through the limb of HD 209458b is determined by solving the spherically symmetric radiative transfer equation while fully accounting for scattering and absorption of both intrinsic and extrinsic radiation (Hauschildt 1992; Barman et al. 2001, 2002). Spherical geometry, instead of the more traditional plane-parallel geometry, naturally accounts for the curvature of the atmospheric layers and changes in chemistry along the slant paths through the upper atmosphere. The planet radius at a given wavelength (Rλ) is obtained by determining the radial depth at which the transmitted flux is equal to e−1 times the incident starlight along that same path.

3. RESULTS

A cloud-free atmosphere with rainout, α = 0.25, and solar abundances is adopted as the baseline model. This model, along with others, is compared to the relative Rλ measurements of
Knutson et al. (2007) that have a reported precision high enough to constrain many of the basic atmospheric properties. Since a comparison is being made to relative $R_\lambda$ values, the model results were uniformly scaled to match the observations in the 4580–5120 Å wavelength bin; this scaling was always less than 0.005 $R_{\text{Jup}}$. Overall, the baseline model (red solid line in Fig. 1) reproduces the observed rise in $R_\lambda$ toward shorter wavelengths, the increase across the Na doublet, and the increase at the far red wavelengths. The baseline model comparison to the data has a $\chi^2$ that is 3 times smaller than a constant $R_\lambda$.

3.1. Water Absorption

Water is predicted to be one of the most abundant species in an EGP atmosphere and, given its broad absorption features in the infrared, plays a crucial role in regulating the temperature-pressure (T-P) profile. The first major H$_2$O absorption band appears between 0.8 and 1 Å, a region covered by the last two wavelength bins of Knutson et al. (2007). As illustrated in Figure 1, there is excellent agreement between the baseline model and the observations in this part of the spectrum, especially across the longest wavelength bin that sits on top of the H$_2$O band. Qualitatively similar water features are seen in the models of Brown (2001) and Hubbard et al. (2001); however, these models fall many $\sigma$ below the observations. The baseline model also predicts mean $R_\lambda$-peaks equal to 1.330, 1.343, and 1.341 $R_{\text{Jup}}$ for the next three water bands (at $\lambda \sim 1.15$, 1.4, and 1.9 µm, respectively).

A model that excludes H$_2$O line opacity is also shown in Figure 1 and is greater than 10 $\sigma$ below both the observations and the baseline model prediction. Removing H$_2$O opacity also produces a significant drop in $R_\lambda$ near 0.9 µm that further increases the discrepancy between the model and overall red/near-IR observations. No other opacity source could be responsible for the observed rise in $R_\lambda$ across this part of the spectrum.

3.2. Photoionization

After the reported sodium detection in the atmosphere of HD 209458b (Charbonneau et al. 2002), there were several attempts to explain why the strength of this feature was much lower than expected based on earlier models (e.g., by Seager & Sasselov 2000). Barman et al. (2002) explored departures from local thermodynamic equilibrium (LTE) that are capable of producing an inversion in the cores of the Na doublet line profiles. However, the earlier models of Barman et al. (2001, 2002) were constructed under the cond approximation and, consequently, contained a larger number of free metals along with TiO and VO molecular absorption compared to a rainout model. These additional sources of optical/UV opacity lead to a hotter upper atmosphere and a very shallow photoionization depth for Na (only a 5% reduction of Na across the region probed by transit spectroscopy). Fortney et al. (2003) also explored Na photoionization and found that their atmosphere model (which included rainout) could be brought into reasonable agreement with the Na observations. The models presented here account for the angular dependence of ionziation on the limb’s dayside but not on the limb’s nightside. However, Fortney et al. (2003) have shown that Na ionization is still present at ~5° past the terminator for pressures relevant to the transit spectrum modeled here.

Figure 1 compares cloud-free solar abundance rainout models with and without photoionization of Na and K. While these models include photoionization, the LTE approximation on the atomic level populations and line source function is maintained. Ionization (radially) at the limb reaches 50% at $P \sim 0.1$ and 1.2 mbar for Na and K, respectively, and stops at $P \sim 2$ and 7 mbar, respectively, resulting in a reduction of the $R_\lambda$-peaks across the Na and K lines. For K, this reduction extends out to the line wings, resulting in a significantly smaller mean $R_\lambda$ and thus bringing the model into ~3 $\sigma$ agreement with the Knutson et al. measurement. The impact of Na photoionization is mostly confined to the core of the doublet, leading to only a small reduction of the mean $R_\lambda$, but sufficient to bring the model into ~1 $\sigma$ agreement with the observations at these wavelengths. Although not included here, ionization past the terminator onto the nightside should further improve the agreement across the Na and K doublets. The two narrow features on the red wing of the K doublet are due to Rb, which should also be affected by photoionization due to its very low first ionization potential. Photoionization of Rb resulted in a near complete removal of these features but reduced the mean $R_\lambda$ for this bin by less than 0.002 $R_{\text{Jup}}$. **Fig. 1.**—Monochromatic transit radii over the STIS spectral range for the baseline rainout model with (red lines) and without (blue line) photoionization of Na and K. The solid and dotted red lines are the same, except that H$_2$O line opacity is excluded in the latter. Horizontal bars correspond to mean radii across bins with $\lambda$-ranges indicated by the width of each bar. STIS measurements by Knutson et al. (2007) are shown in green with 1 $\sigma$ error bars. Vertical dashed lines mark the narrow $\lambda$-range used by Charbonneau et al. (2002).
Fig. 2.—Relative flux differences (with time from center of eclipse) between a wavelength band centered on the Na doublet and the mean of two wavelength bands on either side of the Na doublet. The total wavelength range is indicated by the vertical lines in Fig. 1. Each model is cloud-free with solar abundances and $\alpha = 0.25$. See figure itself and the text for the distinguishing characteristics of each model. The filled circles are the observations of Charbonneau et al. (2002) with 1 $\sigma$ error bars.

The broad wavelength bins allowed Knutson et al. to obtain very precise relative $R_\lambda$ measurements; however, as illustrated by the Na doublet, such broad bins limit the constraints that can be placed on atomic absorption features. In contrast, the narrow range analyzed by Charbonneau et al. (2002) resulted in much larger $R_\lambda$ error bars but is still precise enough to easily distinguish between the various models shown in Figure 1. The flux differences across the Na doublet as a function of time (measured from the transit center) were computed for each model using the same narrow wavelength bins as Charbonneau et al. (2002), as indicated in Figure 1 by the vertical dashed lines. Figure 2 compares model transit curves to the 2002 Na measurements and shows a large discrepancy between the observations and solar abundance models with pure equilibrium chemistry (cond or rainout). Including photoionization brings the baseline rainout model into rough agreement with the observations. Note that the cond model shown in Figure 2 does not include photoionization (similar to the LTE model from Barman et al. 2002) but illustrates how far off the predicted $R_\lambda$ can be across the Na doublet under simplified assumptions.

3.3. Rainout, Metallicity, and Temperature

The rainout model used here reduces the individual metal abundances with depth iteratively until clouds do not form, thus mimicking efficient gravitational settling. However, the removal of metals is not 100% efficient, leaving behind a variety of atoms (in addition to Na and K) to contribute to the line opacity. The impact of rainout on the planet’s atmosphere is made apparent by comparing rainout and cond models (Fig. 3). In the cond model, grain opacities are simply ignored in the transfer equation, while the chemistry remains that of a pure equilibrium model without any actual removal of refractory elements. Thus, the cond model represents the minimum impact of grain formation on the stratified abundances and leaves behind a considerable amount of free metals along with molecules like TiO and VO. This leads to much stronger atomic lines, including Na and K along with TiO and VO bands.

Apart from a very minor contribution from molecules, the $R_\lambda$ features at $\lambda < 0.8$ $\mu$m are all due to atomic line opacity. These narrow features are due to blended lines from metals like Ca, Al, Fe, Ni, Mn, and Cr. Note that, while Rayleigh scattering does contribute to the opacity in the blue/UV, a removal of atomic line opacity would drop $R_\lambda$ by $\sim 0.02 R_{\text{Jup}}$ for $\lambda < 0.45$ $\mu$m. The top panel of Figure 3 compares the solar abundance rainout model with photoionization (shown in Fig. 1) to a rainout model with 10× solar abundances. Since the metal abundances were uniformly scaled, the grain formation and corresponding removal of refractory elements were also uniformly enhanced. The additional opacity altered the T-P profile as well as the total atmospheric extension. These factors contribute to a similar $R_\lambda$ pattern in the optical but enhanced molecular absorption features in the red/near-IR. The increase in metals increases the H$_2$O absorption feature along with the wings of the Na and K doublets (which form deeper in the atmosphere where photoionization is less effective).

Fig. 3.—Monochromatic transit radii over the STIS spectral range. Top panel: Solar abundance models, cond (black line) and rainout (red line), are compared to a model with 10× solar metal abundances including rainout (blue line). Bottom panel: Solar abundance baseline rainout model with $\alpha = 0.25$ (red line) compared to a similar model with $\alpha = 0.5$ (blue line). Horizontal bars have the same meaning as in Fig. 1.
In the baseline model, the predicted location of clouds (e.g., across both the K doublet and the H2O band) with the observations near 0.9 \( \mu \)m but is noticeably too high across both the K doublet and the H2O band.

Transit spectroscopy can also help constrain the temperatures across the limb. The bottom panel of Figure 3 compares an \( \alpha = 0.5 \) model (i.e., a model with a hotter dayside-like T-P profile) to the cooler \( \alpha = 0.25 \) baseline model. In the hotter model, grain formation is less pronounced, resulting in a greater concentration of most free metals and thus stronger UV/blue absorption lines than in the \( \alpha = 0.25 \) model. Higher temperatures with depth also result in equilibrium concentrations of Na and K that are several times lower than found at the cooler temperatures of the \( \alpha = 0.25 \) model. The net results are two distinctively different \( R_\lambda \) spectra, with the \( \alpha = 0.25 \) model being more consistent with the Knutson et al. measurements.

4. SUMMARY

Photoionization plays an important role for both Na and K, and potentially many other species. No evidence is found to support a large metal enhancement (e.g., \( 10 \times \) solar), although smaller Jupiter-like enhancements are not ruled out. Furthermore, the agreement between model and observations demonstrated here alleviates the need for substantial cloud coverage along the limb between 0.05 and 0.001 bars, which would otherwise truncate and flatten the \( R_\lambda \) spectrum (Brown 2001). In the baseline model, the predicted location of clouds (e.g., MgSiO3) lies just below the minimum \( R_\lambda \) (\( \sim 1.315 \) \( R_{\text{Jup}} \)) across the STIS wavelength range; consequently, deep clouds (and also very high clouds) remain a possibility.

The models presented here also predict \( R_\lambda \) variations (\( \sim 0.02 \) \( R_{\text{Jup}} \)) across the 2–0 \( R \)-branch of CO in the K band. This is inconsistent (at 2.5 \( \sigma \)) with a nondetection of CO based on Keck-NIRSPEC transit spectra taken in 2002 (Deming et al. 2005a). It is likely that using a single T-P profile to represent the horizontal and pole-to-pole variations across the limb averages out too much of the upper atmospheric structure; this simplification might explain the K-band discrepancy. High clouds may also be involved. In addition, the Keck and HST observations were taken between 1 and 2 years apart, and time-dependent atmospheric variations along the limb cannot be ruled out (Menou et al. 2003).

While Knutson et al. (2007) did not attribute their measured \( R_\lambda \) variations to any absorption features (this was not the focus of their paper), the models presented above clearly show that these measurements are consistent with strong water absorption near 1 \( \mu \)m. A detection of water in the limb of HD 209458b is nominally at odds with a recent Spitzer Infrared Spectrograph spectrum that shows no H2O features for this planet (Richardson et al. 2007). These data were taken during secondary eclipse and directly probe the planet’s dayside with negligible contribution from the limb. It is possible that the dayside atmosphere is nearly isothermal (Fortney et al. 2006), which would result in a spectrum with no detectable water absorption features, despite a copious water supply. The transmission spectrum, however, would contain absorption features independent of an isothermal dayside or limb.

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