

# VSTAR models of the hot Jupiter HD 189733b

Kimberly Bott<sup>1</sup>, Lucyna Kedziora-Chudczer<sup>1</sup> and Jeremy Bailey<sup>1</sup>

<sup>1</sup>Department of Astrophysics, University of New South Wales,  
Kensington, Sydney, Australia  
email: k.bott@unsw.edu.au

**Abstract.** Past analysis of HD 189733b's atmosphere has been a cause for some debate, with conflicting findings regarding water and sodium abundances and the presence of a high altitude haze. We present our models of HD 189733b's atmospheric composition using VSTAR (Versatile Software for Transfer of Atmospheric Radiation). Since the effective temperature of the planet is expected to be approximately 5000K, newly available high-temperature spectral line lists were used.

**Keywords.** planets and satellites: individual: HD 189733b, planets and satellites: atmospheres, planets and satellites: composition, physical data and processes: radiative transfer

---

## 1. Introduction

The 1400 K Hot Jupiter, HD 189733b closely orbits (2.19 day) its K1.5 host star in a—most likely—tidally locked position, promising an extraordinary environment to study (Bouchy *et al.* 2005). Detection of water, CO<sub>2</sub> and possibly methane have been reported in data from NICMOS (*HST*) and *Spitzer* (Swain *et al.* 2008, Tinetti *et al.* 2007). The broadband infrared data around 3.3 and 4  $\mu\text{m}$  suggests the presence of CH<sub>4</sub> or CO, although it is difficult to differentiate between the two currently. Conflicting models are perpetuated by the lack of data points in key absorption bands.

Here we compare our own models derived with VSTAR (Versatile Software for the Transfer of Atmospheric Radiation) to data from Charbonneau *et al.* (2008), Grillmair *et al.* (2008), and Swain *et al.* (2009), as well as to other models, particularly Lee *et al.* (2011), to derive a better understanding of how these effects come into play and to further establish the capability of VSTAR (Bailey & Kedziora 2012). VSTAR's plane-parallel radiative transfer solution utilizes line-by-line absorption and particle scattering.

We ultimately aim to develop a model that can fit a wide range of data including transmission spectroscopy (e.g., Pont 2013), high resolution cross correlation spectroscopy (e.g., de Kok *et al.* 2013) and polarization (e.g., Berdyugina *et al.* 2008, 2011; Wiktorowicz 2009). At present we consider only the spectrum derived from secondary eclipse observations.

## 2. The Lee 2011 Model

We began with attempting to emulate a relatively straightforward model from Lee *et al.* (2011) which included only four molecules (CH<sub>4</sub>, H<sub>2</sub>O, CO and CO<sub>2</sub>) at a constant abundance over all heights and a retrieved Pressure-Temperature profile, well-situated, mid-range of other suggested P-T profiles (e.g., Madhusudan & Seager 2009). Although significance testing is not yet complete, our model, with abundances predicted by

equilibrium chemistry, does appear to be a better fit than the model emulating Lee *et al.* (2011)'s constant ratios with height for the *Spitzer* data.

### 3. Variables

Four P-T profiles were compared from Lee *et al.* (2011) and Madhusudan & Seager (2009). None of the profiles include inversion, as the dayside of HD 189733b appears to lack one Fortney *et al.* (2007), Charbonneau *et al.* (2008). Cooler T-P profiles appear to give better fits, particularly for shorter wavelengths. Further modelling and significance testing is needed to determine the scale of the effects.

Water features in the spectrum of HD 189733b are seen in the data points from NICMOS around 2 microns, however these bands have some overlap with CO, CO<sub>2</sub> and CH<sub>4</sub> Grillmair *et al.* (2008). A more convincing feature is the gap between vibrational modes of water vapour near 6.5 microns seen previously in other models and in our own. The broad absorption bands of water are clearly visible in the relatively well observed 5 to 10  $\mu\text{m}$  *Spitzer* data. The steep slope produced by water absorption around 3.5  $\mu\text{m}$  could be better constrained with further observational data.

The C/O level of HD189733b was estimated to be slightly more than solar (0.54) at 0.65 by Lee *et al.* (2011). Previously, Swain *et al.* (2009) placed the value broadly between 0.5 and 1.0. For most of our models C/O of 0.65 was used and provided a good fit for the majority of the points.

### 4. Results and Discussion

Water absorption, while it seems to be needed for a good fit can have overlap with other bands. The predictable shape of the peaks between bands make it seem unlikely that an amalgamation of other nearby absorption bands is the culprit, but further analysis is needed to determine this.

The models presented here do not include scattering particles. A scattering haze is likely to be important to modelling the transmission spectroscopy (e.g. Pont *et al.* 2013) which appears to be consistent with the presence of Rayleigh scattering, probably due to small dust grains.

### References

- Bailey, J. & Kedziora, L. 2012, *MNRAS*, 419, 1913–1929  
 Berdyugina, S. V., Berdyugin, A. V., Fluri, D. M., & Piirola, V. 2008, *ApJL*, 673, L83–L86  
 Bouchy, F., Udry, S., Mayor, M., *et al.* 1995, *A&A*, 444, L15–L19  
 Charbonneau, D., Knutson, H. A., Barman, *et al.* 2008, *ApJ*, 686, 1341–1348  
 de Kok, R. J., Brogi, M., Snellen, I. A.G., Birkby, J., Albrecht, S., & de Mooij, E. J.W. 2013, *A&A*, 554, A82  
 Fortney, J. J., Lodders, K., Marley, M. S., & Freedman, R. S. 2007, *ApJ*, 678, 1419–1435  
 Grillmair, C. J., Burrows, A., Charbonneau, *et al.* 2008, *Nature*, 456, 767–769  
 Madhusudan, N. & Seager, S. 2009, *ApJ*, 707, 24  
 Lee, J. M., Fletcher, L. N., & Irwin, P. G. J. 2011, *MNRAS*, 420, 170–182  
 Pont, F., Sing, D. K., Gibson, N. P., Aigrain, S, Henry, G., & Husnoo, N. 2013, *MNRAS*, 432, 2917–2944  
 Swain, M. R., Vasisht, G., Tinetti, G., *et al.* 2009, *ApJL*, 690, L114–L117  
 Swain, M. R., Tinetti, G., Vasisht, G., *et al.* 2009, *ApJ*, 704, 1616–1621  
 Tinetti, G., Vidal-Madjar, A., Liang, M.-C., *et al.* 2007, *Nature*, 448, 169–171  
 Wiktorowicz, S. J. 2009, *ApJ*, 696, 1116–1124