Signatures of hot hydrogen in the atmosphere of the extrasolar planet HD209458b

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Of the extrasolar planets detected so far, about 10% consist of giant planets which orbit very close to their parent stars. The atmospheres of these "hot-Jupiters" are largely heated by the immense stellar irradiation[1−5]. In the case of the planet HD209458b, this energy deposition results in a hydrodynamic state in the upper atmosphere, allowing for sizable expansion and escape of neutral hydrogen gas[2−6]. HD209458b was the first extrasolar planet discovered that transits in front of its parent star[7]. Transiting planets offer a unique opportunity to determine the planetary size by measuring the total optical obscuration of the stellar disk produced while the planet is transiting. We may also study the structure and composition of extrasolar planetary atmospheres by additional signatures in the stellar spectrum due to atmospheric absorption during transit. Here we report the first detection of absorption by hot hydrogen in the optical and near-ultraviolet Balmer jump and continuum in any planet. So far, the lower atmosphere and the full extended upper atmosphere of HD209458b have been observed[8,2,6]. Here we probe a layer where the escaping gas forms in HD209458b's upper atmosphere, providing a new way to study the atmospheric structure and complex

escape processes of extrasolar hot-Jupiters.

An extensive study of the HD209458 planetary transits with the Hubble Space Telescope (HST) was first performed in the optical using the G750M grating of the Space Telescope Imaging Spectrograph (STIS) and the CCD camera detector[9]. A similar STIS study has recently been reported with the G430L and G750L gratings by Knutson et al. (2006)[10] spanning the full 2900-10,300 Å region. This latter study refined the system parameters of HD209458 by assuming a limb-darkening law for the star (based on a stellar model by R. Kurucz[11]) and simultaneously fitting the shapes of the planetary transit curves over ten different bandpasses. In particular, a new significantly smaller planetary radius R_p = 1.320 R_{Jup} was obtained as compared to the previous 1.35 R_{Jup} standard. We adopt the new system parameters in our work and use the same G430L dataset (now public) to present a transit flux ratio spectrum, useful for identifying specific spectral features from atmospheric absorption. This work was borne while using these data to calibrate independent transit observations of HD209458 made with the HST Advance Camera for Surveys (ACS) near-UV prism at the overlap 3000-5500 Å region (work in progress, A. Vidal-Madjar et al. 2006).

The far-UV H I Lyman-α line is the strongest absorption line of atomic hydrogen. Far-UV HST transit observations of HD209458b discovered a hydrogen obscuring disk which is $\sim$15% the size of the stellar disk[2], much larger than the $\sim$1.5% obscuring planetary disk seen in the optical. This material encompasses an enormous obscuring area larger than that defined by the Roche Lobe, where the stellar gravity overpowers the planet's gravitational pull. Furthermore, the spectrally-resolved H I Lyman-α line clearly showed blue-shifted absorption, indicating that absorbing hydrogen atoms are moving away from the star due mainly to radiation pressure[2,3], forming a comet-like tail. The estimated hydrogen escape rate is enormous, 10^{10} gm/s or larger, while the upper atmospheric temperature ($\sim$ 10,000 K[1−5]) is not hot enough to produce significant thermal (Jeans) escape. This atmosphere must have a hydrodynamic outflow[3−6], similar to the solar corona. Instead of hydrostatic equilibrium, there is a net upward velocity of the dominant light hydrogen gas. This outflow is maintained by the continual energy input supplied by the strong extreme-UV flux from the star located only 9 stellar radii away (0.045 AU). If the hydrodynamic outflow is real and robust enough (e.g., "blow-off"), then the lighter gas can drag along heavier species, and indeed, an extended atmosphere has also been detected in HD209458b in the abundant O I and C II species by their far-UV absorption[6]. In contrast, a small 0.02% absorption by atomic sodium in the strong yellow D lines has been detected in HD209458b[8], and this absorption must be produced in the lower atmosphere. We also present here a small 0.03% absorption in the Balmer jump and continuum, but as we shall see below, a significant hot hydrogen population is needed at higher atmospheric altitudes to produce this absorption.

The small 0.03% extra absorption can be seen in a photometric transit light curve and in a transit flux ratio spectrum, both derived from the HST G430L spectroscopic dataset. Details of the data reduction and stellar limb-darkening corrections necessary[11,12] can be found in the Supplementary Information. We derive what would be a larger planetary radius for the near-UV/violet region 3000-4000 Å compared to that from the blue 4500-5500 Å region. The corresponding photometric light curves (data and model) are depicted in Fig. 1 along with model curves corrected for limb-darkening. We fit a 1.3200±0.0002 R_{Jup} planet radius for the blue light curve and 1.3300±0.0006 R_{Jup} for the near-UV/violet curve. The errors correspond to the relative uncertainty between the two bandpasses, not the total uncertainty which depends on the stellar radius and mass[10]. Our results are consistent with the independent analysis by Knutson et al. (2006)[10], who used the data to refine the planetary radius based on broadband photometric results.

A transit flux ratio spectrum shows the wavelength dependence of the absorption features, valuable information that is lost when integrating the flux over spectral bandpasses for the photometric studies. Any wavelength dependent increase in absorption will appear as a flux ratio lower than 0.9855 during mid-transit. Figure 2 shows the mid-transit flux ratio spectrum derived from the data. No obvious narrow absorption lines are evident, but there does appear to be a broadband absorption shortward of about 4000 Å, consistent with the photometric results. The broad absorption appears to be relatively flat between 3000-3800 Å where we find an average transit flux ratio of 0.98523±0.00006 (s.e.m.). This is 0.030±0.006% below the 0.98545±0.00002 (s.e.m.) we derive for the blue region as well as the value of 0.9855 calculated from the latest values for the radius of the planet (1.320 R_{Jup}[10]).

The simplest candidate for creating the broadband absorption observed is bound-free absorption by atomic hydrogen in the first excited state (F. Herbert, private communication 2006). The observed absorption starts around 3900 Å and remains relatively flat below 3650 Å. This region corresponds to the Balmer jump which occurs at 3646 Å, although in practice there is significant absorption redward of 3646 Å due to the pile-up of Balmer transition lines. In order to have a significant bound-free absorption by H I at near-UV and optical wavelengths, there must be a significant population of H I in the first excited state (n=2). The relative population of n=2 hydrogen atoms is very sensitive to temperature and peaks around 10,000 K[13,14]. In general, at temperatures of a few thousand Kelvin the thermal n=2 population is very small, and above $\sim$15,000 K the ionized (H^+) population with its associated free-free absorption becomes dominant. The upper atmosphere of this hot-Jupiter should reach temperatures of $\sim$10,000 K due to the immense heating by the stellar extreme-UV input[1−5].

In order to check whether there is a significant population of excited H I and the amount of absorption it would produce during planetary transit, we numerically evaluated the equation of radiative transfer using the most detailed model to-date of the HD209458b upper atmosphere by Yelle (2004,2006)[4,5] (see Supplementary Information for calculation details). In this 1D aeronomy model, many aspects are explicitly calculated, including the effects of the immense stellar extreme-UV heating, hydrogen and helium photochemistry, ionization, hydrodynamics, as well as the atmospheric escape rate. (The atmospheric escape rate derived from this model[4] was recently clarified[5] to be in the same regime found from the H I Lyman-α HST observations[2]). The model shows a sharp temperature rise from $\sim$750 K at r = 1 R_{pl} to $\sim$10,000 K at r = 1.14 R_{pl}, at which point H I becomes the dominant species in the atmosphere. At higher radial distances the temperature increases further and the H^+ population becomes dominant. Our calculation based on the Yelle[4,5] model yields a net absorption contrast of 0.03% beginning at the Balmer jump, with similar values in the continuum down to $\sim$3000 Å. The absorption contrast that we derive from the HST data is also $\sim$0.03% on average. The similarity may be coincidental, but the results show that we are in the correct regime and such absorption should be detectable. As the model suggests, the data show that the upper escaping atmosphere of HD209458b should have a hot enough layer at high enough densities to produce a Balmer jump and continuum absorption signature.

Various studies[15] indicate that the lower atmosphere of the hot-Jupiter HD209458b has a temperature on the order of 1200 K (at least on the dayside) which is too low to produce any significant n=2 H I population. Our observations therefore indicate that this planet possesses a hot dense region at higher altitudes, producing a 0.03% Balmer-continuum absorption which is a new constraint for atmospheric models. Using the Yelle (2004,2006)[4,5] upper atmospheric model of HD209458b, we find that the absorption can be readily produced in a 1000 km, 5000 K layer at an altitude of 8500 km in agreement with the observations. This absorption layer is in a region of rising temperatures and accelerating outflow, between the lower colder atmosphere and the hotter (10,000 K or more) upper themospheric region of the hydrodynamically escaping atmosphere. This layer is only a small fraction of the full escaping upper atmosphere that produces a 15% Lyman-α absorption by the most prevalent n=1 (ground state) H I population[2].

Finally, we point out that we cannot detect the absorption from isolated narrow Balmer lines, in particular Hγ at 4340 Å and Hβ at 4861 Å, which are included in our spectral window. At the relatively high temperature ($\sim$5000 K) found for the peak absorbing layer of the Balmer continuum, the thermal line broadening is approximately ten times smaller than our spectral resolution, so the individual lines cannot be resolved. Unsuccessful attempts have been made to detect the strongest Balmer line, Hα at 6563 Å. The optical depth of Hα would be very high in the absorbing layer, producing an opaque disk with a radius of $1.09\,\mathrm{R}_{pl}$. However, this disk would only produce a $\sim$0.3% absorption in Hα, and this combined with the narrow $\sim$0.3Å width of the line makes detection very difficult. Our detection of the 0.03% absorption in the Balmer continuum is possible because it spans a large $\sim$550 Å wavelength range and the data were taken with HST, which has numerous advantages over ground-based telescopes.

The HST observations presented here constitute the first detection of Balmer jump and continuum absorption in a planetary atmosphere, and the first detection of an isolated hot layer in the lower thermosphere of the transiting planet HD209458b. These discoveries provide a new valuable tool to probe the thermospheres of hot-giant extrasolar planets which orbit close to their parent stars by placing empirical constraints on the thermosphere.

1. Burrows, A. & Lunine, J. Extra-solar planets - astronomical questions of origin and survival. *Nature*, **378**, 333 (1995).

2. Vidal-Madjar, A., Lecavelier des Etangs, A., Désert, J.-M., Ballester, G.E., Ferlet, R., Hébrard, G. and Mayor, M. An extended upper atmosphere around the extrasolar planet HD209458b. *Nature*, **442**, 143-146 (2003).

3. Lecavelier des Etangs, A., Vidal-Madjar, A., McConnell, J. C. & Hébrard, G. Atmospheric escape from hot Jupiters. *Astron. Astrophys.*, **418**, L1-L4 (2004).

4. Yelle, R. Aeronomy of extra-solar giant planets at small orbital distances. *Icarus*, **170**, 167-179 (2004).

5. Yelle, R., Corrigendum to “Aeronomy of extra-solar giant planets at small orbital distances [Icarus 170 (2004) 167 179]”. *Icarus*, **183**, 508 (2006).

6. Vidal-Madjar, A., Désert, J.-M., Lecavelier des Etangs, A., Hébrard, G., Ballester, G. E., Ehrenreich,D., Ferlet, R., McConnell, J.C., Mayor, M. & Parkinson, C.D. Detection of oxygen and carbon in the upper atmosphere of the extrasolar planet HD 209458b. *Astrophys. J.*, **604**, L69-L72 (2004).

7. Henry, G.W., Marcy, G.W., Butler, R.P., & Vogt, S.S. A transiting “51-Peg-like” planet. *Astrophys. J.*, **529**, L41-L44 (2000).

8. Charbonneau, D., Brown, T.M., Noyes, R.W. & Gilliland, R.L. Detection of an extrasolar planet atmosphere. *Astrophys. J.*, **568**, 377-384 (2002).

9. Brown, T.M., Charbonneau, D., Gilliland, R.L., Noyes, R.W. & Burrows, A. Hubble Space Telescope time-series photometry of the transiting planet of HD209458. *Astrophys. J.*, **552**, 699-709 (2001).

10. Knutson, H., Charbonneau, D., & Noyes, R. W. Using stellar limb-darkening to refine the properties of HD209458b. astro-ph/0603542 (2006).

11. Kurucz, R., stellar model and associated spectra for HD209458, http://kurucz.harvard.edu/

12. Mandel, K. & Agol, E. Analytic light curves for planetary transit searches. *Astrophys. J.*, **580**, L171-L175 (2002).

13. Carroll, B. W. and Ostlie, D. A. ”An Introduction to Modern Astrophysics”, Ch. 8, Addison-Wesley Pub. (1996).

14. Mihalas, D., “Stellar Atmospheres”, 2nd edition, p.99, W. H. Freeman & Company (1978).

15. Deming, D., Seager, S., Richardson, L. J., and Harrington, J. Infrared radiation from an extra-solar planet. *Nature*, **434**, 740-743 (2005).

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Figure 1 | Photometric transit light curves of HD209458. Plotted are the STIS G430L transit light curves for the near-UV/violet 3000-4000 Å (diamonds, dark) and blue 4500-5500 Å (filled circles, light) bandpasses. The corresponding curved lines are the theoretical limb-darkened models for comparison with the data. The dashed curves are the theoretical transit curves for zero stellar limb-darkening using the two different planetary sizes found (see text), the bottom curve corresponds to a larger planetary radius derived for the near-UV/violet. Note that the near-UV/violet radius is an interpretation, since we find in the modeling of the data that the absorption should arise from a relatively-thin high-altitude isolated layer (see text). For fitting the theoretical transit curves we used the system parameters derived from the full G430L and G750M STIS dataset by Knutson et al. (2006)[10]: orbital inclination i = 86.929°, orbital period = 3.52474859 days, zero transit time 2452826.628521 (HJD), stellar mass M_{star} = 1.101 M_{Sun}, and stellar radius R_{star} = 1.125 R_{Sun}. Overplotted are representative 1-sigma error bars (s.e.m.) estimated from the pipeline data errors (dominated by photon counting statistics), and propagated while integrating the flux in each photometric bandpass per exposure.

Figure 2 | Transit flux ratio spectrum. Shown is the transit flux ratio spectrum: (middle) smoothed with stellar limb-darkening correction (dark, thick); (bottom) without limb-darkening correction both smoothed (dark, thick) and unsmoothed (light, thin). The transit flux ratio spectrum was obtained by co-adding the limb-darkening-corrected spectra between orbital phases 0.987 and 1.012 (around mid-transit) and dividing the resulting spectrum by that from the co-added out-of-transit spectra. The errors (s.e.m.) were estimated by propagating the pipeline data errors while co-adding the spectra and deriving the spectral flux ratio. The smoothed spectral ratio depicted are boxcar smoothed over 33 points for clarity, and the corresponding 1σ error bars propagated in the smoothing are plotted at the top. Overplotted are also the mid-transit flux ratios derived from the two planetary radii using the photometric light curves for the near-UV/violet 3000-4000 Å (light, long-dash) and blue 4500-5500 Å (dark, short-dash) bandpasses, respectively. The derived limb-darkening-corrected spectrum (middle, dark, thick) is relatively flat, but shows an extra broad-band absorption shortward of 3900 Å, consistent with the photometry (see text).