EXOPLANET HD 209458b: INFLATED HYDROGEN ATMOSPHERE BUT NO SIGN OF EVAPORATION

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ABSTRACT

Many extrasolar planets orbit closely to their parent star. Their existence raises the fundamental problem of loss and gain in their mass. For exoplanet HD 209458b, reports on an unusually extended hydrogen corona and a hot layer in the lower atmosphere seem to support the scenario of atmospheric inflation by the strong stellar irradiation. However, difficulties in reconciling evaporation models with observations call for a reassessment of the problem. Here we use HST archive data to report a new absorption rate of $\sim 8.9\% \pm 2.1\%$ by atomic hydrogen during the HD 209458b transit and show that no sign of evaporation could be detected for the exoplanet. We also report evidence of time variability in the HD 209458 Ly$\alpha$ flux, a variability that was not accounted for in previous studies, which corrupted their diagnostics. Mass-loss rates thus far proposed in the literature in the range $5 \times (10^{10} - 10^{11})$ g s$^{-1}$ must induce a spectral signature in the Ly$\alpha$ line profile of HD 209458 that cannot be found in the present analysis. Either an unknown compensation effect is hiding the expected spectral feature or else the mass-loss rate of neutrals from HD 209458 is modest.

Subject headings: line: profiles — planetary systems — stars: individual (HD 209458) — techniques: spectroscopic — ultraviolet: stars

1. INTRODUCTION

Of all the planets discovered outside the realm of our solar system, some of the most dramatic new classes of objects are those in which the planet is a gas giant orbiting at merely a few stellar radii ($\sim 0.02$ AU) from its parent stars. These close-in extrasolar planets are Jupiter-like giants that are exposed to strong fluxes, magnetic fields, and plasma winds—a very harsh and active stellar environment. Because of their stars’ proximity, gravity, through tidal effects, distorts the shape of their atmosphere while the continuous extreme ultraviolet (UV) energy deposition inflates it (Lammer et al. 2003; Baraffe et al. 2004; Lecavelier et al. 2004; Yelle 2004; Jaritz et al. 2005; Tian et al. 2005; Munoz 2007; Villaver & Livio 2007). Unfortunately, little is known about those regions that separate extrasolar giant planets from their stars, particularly the immediate environment of the planet.

One of the most extensively studied extrasolar systems is HD 209458. For reference, HD 209458b was first discovered transiting its parent star and covering 1.5% of its disk (Charbonneau et al. 2000; Henry et al. 2000). Some of the first attempts to learn about the immediate environment of the planet were Ly$\alpha$ (121.6 nm) observations of the system using the Space Telescope Imaging Spectrometer (STIS) on board the Hubble Space Telescope (HST). A first program of observation, obtained with the STIS/G140M grating and the 52” × 0.1” slit, was implemented in 2001 during HD 209458 planetary transit, but no conclusions were reported (see Table 1). Soon after, a second program visited the target during three transits (Vidal-Madjar et al. 2003). An initial analysis of this data set concluded that a huge cloud of hydrogen is covering 15% ± 4% of the stellar disk (Vidal-Madjar et al. 2003); it also claimed that spectral absorption during transit is deeper on the blue side of the stellar line. Accordingly, the hydrogen cloud was required to extend beyond the planetary Roche limit where an intense escape of $\sim 10^{10}$ g s$^{-1}$ of hydrogen is a priori operating. These results, along with other far UV low-resolution observations of heavy constituents, led to the conclusion that the upper atmosphere of HD 209458b should be in a hydrodynamic blow-off state (Vidal-Madjar et al. 2003, 2004).

Numerous studies then followed on different mechanisms for hydrogen loss from hot exoplanets closely orbiting their stars (Lammer et al. 2003; Baraffe et al. 2004; Lecavelier et al. 2004; Yelle 2004, 2006; Jaritz et al. 2005; Tian et al. 2005; Munoz 2007). As noted by Munoz (2007), all loss rates thus far proposed by theoretical models in the range $5 \times (10^{10} - 10^{11})$ g s$^{-1}$ exceed the lower limit provided by Vidal-Madjar et al. (2003). Unfortunately, most studies neglected to quantitatively translate their loss rate to a spectral absorption in the Ly$\alpha$ line profile that could be tested with the HST observation. Independently, pointing out that the observed mass function distribution of extrasolar giant planets (EGPs) follows a trend $M^{-1.5}$ for mass range $\sim 0.2 – 5 M_\odot$, where $M_\odot$ is the Jovian mass, Hubbard et al. (2007) derived the same mass function distribution for highly irradiated EGPs orbiting at distances smaller than $\sim 0.07$ AU. Accordingly, Hubbard et al. (2007) rejected substantial mass loss during EGPs’ migration to smaller distances from their star, unless the loss mechanism is compensated by an unknown process. When combined with the unusual scales derived for the hydrogen extent and escape, all these studies then call for a careful reassessment of the HST Ly$\alpha$ observations thus far obtained on HD 209458, at least in order to provide validated constraints on theoretical models.

2. OBSERVATIONS AND DATA ANALYSIS

In the following, we report a new analysis of archive data obtained during the two HST STIS programs described above. In total, we have four visits of the target corresponding to three exposures of roughly $\sim 2000$ s duration each, resulting in 12 exposures of the systems around the transit period (Table 1). All observations were obtained in the time-tag mode, a technique that keeps track every $125 \times 10^{-6}$ s of photon events during each exposure. The question, then, is why is this mode of observation important in the present case? First, we stress that the transit effect is a weak variation of the stellar signal. As such, its trend is best represented by a dense time series. Second, chromospheric and coronal variabilities of the star are unknown in the Ly$\alpha$ spectral window considered here, and this may seriously corrupt any diagnostic.
light-curve analysis and in/out transit spectra comparison. Following the time

is available. These bands are linearly interpolated using nearby spectra for three gaps, lasting, respectively, 312, 404, and 406 s, appear

system versus the orbital phase angle (Fig. 1). Unexpectedly, 12 exposures, resulting in a unique 53 bin time series of the parameters (Ballester et al. 2007; Knutson et al. 2007). Subspectra and accurate determination of the HD 209458 system parameters (Ballester et al. 2007; Knutson et al. 2007). Subspectra of identical phase positions are accumulated from the initial 12 exposures, resulting in a unique 53 bin time series of the system versus the orbital phase angle (Fig. 1). Unexpectedly, three gaps, lasting, respectively, 312, 404, and 406 s, appear

in the time series, for which no observation is available. Because the three gaps are narrow and well separated from each other, we determined that filling them has a negligible effect on our final conclusions (Schneider 2001). Errors due to photon counting have been propagated, taking into account the correlation between the different phase positions relative to the initial sampling of subexposures time over the full observing time period.

We next define the wavelength domain of contamination by the sky background, including both the Earth’s geocorona and the interplanetary medium emissions. The difficulty comes from the uncertainty about the geocorona’s strength when estimated from a detector sector, along the STIS slit, different from the one where the stellar signal was recorded. First, we subtracted the dark noise of the detector following Vidal-Madjar et al. (2003) and Ballester et al. (2007) and then compared the sky background signal from different sectors along the slit and for different conditions of observation. Our conclusion is that the STIS MAMMA detector has an inherent nonuniformity corresponding to an incompressible uncertainty of 5% on extended sources. Coincidentally, this uncertainty is comparable to photon statistical errors. To ensure that such error will not corrupt the stellar signal per wavelength pixel at the 1% level, we deduce that a void window \([121.541, 121.584]\) nm should be disregarded in any spectral analysis that requires high accuracy, such as for a transit event or short-term stellar variability.

### TABLE 1

| Data Set Name | Program ID | Start Time – TCT (s) | Duration (s) | End Time – TCT (s) |
|---------------|------------|----------------------|--------------|-------------------|
| O42EA4010     | 7508       | −7980.28             | 2600         | −5380.12          |
| O42EA4020     | 7508       | −2202.29             | 2600         | 397.87            |
| O62E01010     | 9064       | −8075.11             | 1780         | −6295.02          |
| O62E01020     | 9064       | −2246.12             | 2100         | −145.96           |
| O62E01030     | 9064       | 3531.89              | 2100         | 5631.98           |
| O62E02010     | 9064       | −10167.67            | 1780         | −8387.50          |
| O62E02020     | 9064       | −4750.68             | 2100         | −2650.52          |
| O62E02030     | 9064       | 1025.31              | 2100         | 3125.46           |
| O62E03010     | 9064       | −11258.45            | 1780         | −9478.27          |
| O62E03020     | 9064       | −5876.47             | 2100         | −3776.29          |
| O62E03030     | 9064       | −102.45              | 2100         | 1997.73           |

**Note.**—All observations were obtained with the G140M grating and the 52 arcsec slit. Transit central time (TCT) is defined by HJD 2,452,826.628521 (Ballester et al. 2007; Knutson et al. 2007).

To properly handle time-tagged data, we partition each time-tag exposure into a set of shorter subexposures, taking into account the heliocentric and barycentric time correction procedure in which ephemerides are retrieved from the archives before the IRAF STSDAS “odelaytime” procedure is applied (Brown et al. 2002). After several trials, we found that 300 s sampling of the time-tag data is a good compromise between acceptable signal-to-noise ratio (S/N) and time coverage. Next, each subexposure is calibrated through the STIS pipeline. The emitting source (the star plus sky background) is presumed extended, an option that allows efficient control of the subtraction of the sky background contamination. Time is then converted to fixed orbital phases measured from the transit central time (TCT), itself carefully taken from the most recent and accurate determination of the HD 209458 system parameters (Ballester et al. 2007; Knutson et al. 2007). Subspectra of identical phase positions are accumulated from the initial 12 exposures, resulting in a unique 53 bin time series of the system versus the orbital phase angle (Fig. 1). Unexpectedly, three gaps, lasting, respectively, 312, 404, and 406 s, appear

![Fig. 1.—Contours of equal flux for the HD 209458 time series vs. wavelength (nm) and time from transit (or planetary orbital phase angle). Top axis shows velocities in the stellar rest frame (∼10 km s⁻¹ from heliocentric system). Horizontal dark bands are time gaps of \(0\) s for which no observation is available. These bands are linearly interpolated using nearby spectra for light-curve analysis and in/out transit spectra comparison. Following the time evolution of the signal (from bottom to top), we observe the transit absorption as a slight dimming of the stellar flux starting ∼5000 s before TCT. The wide, vertical, light purple band corresponds to the spectral window of extinction of the stellar signal by the interstellar gas along the line of sight (Wood et al. 2005) and to contamination by the sky background that has been subtracted. The signal was set at zero in this band to improve the image contrast.](image-url)
than the Roche lobe limit of $\sim 4.08 \, R_p$ (Gu et al. 2003), where $R_p = 1.32 \, R_J$ is the most recent estimate of the radius of HD 209458b (Ballester et al. 2007; Knutson et al. 2007), and $R_J$ is the Jovian one. Now, to capture the trend of the transit curve, we used a sophisticated 2D model of planetary transit at Ly$\alpha$ that accurately accounts for the atmospheric radial structure of the planet (Yelle 2004; Ben-Jaffel et al. 2007) and properly estimates the atmospheric obscuration versus wavelength, including extinction by the interstellar gas intervening along the line of sight (Wood et al. 2005). Our best least-squares fit is shown in Figure 2a. For our purpose of time analysis, we remark that a functional fit could also be a good model to obtain the light curve’s trend.

We can now determine the stellar signal time evolution after we cancel the transit trend using our best fit to the observed light curve (Fig. 2a). The resulting signal is a good indicator of the variability of the HD 209458 Ly$\alpha$ intensity vs. time.

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**Fig. 2.—** (a) Light curve (LC) obtained from our time series (as shown in Fig. 1) by integration of the signal in the spectral windows [121.483, 121.536] nm and [121.589, 121.643] nm. Histogram and related errors (plotted every two bins for clarity) show the LC with a time bin of 300 s, while filled circles with attached error bars represent the LC rebinned to a larger timescale of 8 $\times$ 300 $\approx$ 2400 s. The solid curve is our best least-squares fit to the rebinned LC. A total obscuration of $\sim 8.9\% \pm 2.1\%$ is derived during the planetary transit. (b) Ratio of LC (histogram) to best model fit (solid line) is shown with related statistical error bars. This ratio cancels the transit trend shown in (a). The resulting ratio shows a variable behavior with an average amplitude $\sim 8.6\% \pm 5.6\%$ of the stellar integrated intensity (Fig. 2b). Using the Durbin-Watson statistical test (Durbin & Watson 1951), we found no apparent serial correlation at the 1% confidence level in the corrected signal—a signal that also shows no evident periodicity. HD 209458 was previously suspected to have a relatively moderate chromospheric activity from Ca ii H and K lines that were recorded over full orbits of the system (Shkolnik et al. 2005). Our finding of a time variation of $8.6\%$ on average in the stellar Ly$\alpha$ signal, with peaks that may reach $\sim 20\%$ ($>$3 $\sigma$), seems to support a relatively active corona of the star, presumably up to the planet’s orbit. Such activity could be of common origin (flaring, nonuniformity of the stellar disk during transit, etc.) and/or related to an enhancement of magnetic activity on the star.

planet line (Zarka 2007). Also, one can speculate about the hydrogen cloud topology around the planet and its evolution with time. To that end, comparative studies with interacting binary stars may be useful in clarifying the different regimes of interaction between an exoplanet and its host star (Shore et al. 1994). Unfortunately, the FUV observations thus far obtained do not cover a full orbit of the planet, thereby making it difficult to predict the exact configuration of the star-planet system. In any case, we believe that the unusual 15% obscuration previously reported (Vidal-Madjar et al. 2003) was corrupted by this unaccounted-for variable component in the star-planet system signal. Here we can extract it because we are able to sample the transit period by a dense time series using the information gathered from the time tag mode of HST STIS and $\sim 25\%$ more observation time from the archives.

**4. PLANETARY MASS LOSS OR FLUX VARIABILITY?**

In the following, we compare the in/out of transit stellar line profiles. The impetus of this study is the need to determine the relevance of a blueshifted absorption in the stellar line profile that may occur during transit, as claimed in earlier studies.
(Vidal-Madjar et al. 2003). On the one hand, we derive an average unperturbed profile of the HD 209458 Ly\(\alpha\) emission line by merging all subspectra of the time series that we correct for the transit trend with the best fit shown in Figure 2a. The resulting profile is a good reference that best represents the out-transit stellar line and for which time variability has been reduced to the 1% signal level (Fig. 3a). On the other hand, the in-transit line profile, when corrected for the \(\sim 8.9\%\) drop-off during transit, properly recovers the unperturbed line profile (Fig. 3a), leaving no real possibility of extra absorption as claimed in prior studies (Vidal-Madjar et al. 2003).

To further investigate how time variability of the HD 209458 Ly\(\alpha\) emission line corrupts the diagnostic as it pertains to extra absorption or emission features that may appear in the stellar line during transit, we selected two phase windows inside the transit period for which we compared line profiles to the unperturbed stellar line. As shown in Figure 3b, a direct comparison would indicate that line peaks are equally absorbed for line profile B1, while for line profile B2, the red peak is the most absorbed. On the basis of line profile B2, the diagnostic would be just the opposite of that of Vidal-Madjar et al. (2003), leading to escaping hydrogen toward the star, while for line profile B1, the diagnostic would be no \(H\) escape. The problem is that these interpretations of preferred blueshifted or redshifted absorption do not account for the relatively strong modulation of the stellar signal evidenced in this study. Therefore, any claim of a preferred absorption during transit, either blue- or redshifted, is not realistic, particularly at this relatively modest level of the S/N. It follows that the blueshifted absorption, advanced in previous studies (Vidal-Madjar et al. 2003; Lecavelier et al. 2004) as a signature of atmospheric evaporation in a cometary-like tail of HD 209458b, has, unfortunately, no foundation in the \(HST\) STIS data set as it was only the effect of the stellar signal variability with time that corrupted the diagnostic.

5. CONCLUSION

We use \(HST\) archive observations of the Ly\(\alpha\) emission of HD 209458 to report an absorption rate of \(\sim 8.9\% \pm 2.1\%\) by atomic hydrogen during the transit of the planetary companion. If the planet is sketched as a compact blocking body, our analysis requires an \(H\) cloud effective extent that does not exceed \(\sim 2.47 R_p\)—a size that falls short of the Roche limit \(\sim 4.08 R_p\) of HD 209458b. In addition, time variability of the stellar flux is evidenced, but no sign of extra or Doppler-shifted absorption could be detected during transit. This absence of extra absorption during transit and the relatively small size of the effective area of the hydrogen cloud around the exoplanet make it difficult to conceive of significant atmospheric evaporation from the planet. Of course, we cannot rule out that a complex atmospheric distribution, related to a particular planet-star interaction scenario, may hide or compensate the loss signature during the observing time. Future \(HST\) (when repaired) FUV observation of the system during a full planetary orbit should help to disentangle the different processes in play.

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REFERENCES

Ballester, G., Sing, D., & Herbert, F. 2007, Nature, 445, 511
Baraffe, I., et al. 2004, A&A, 419, L13
Ben-Jaffel, L., Kim, Y., & Clarke, J. 2007, Icarus, 190, 504
Brown, T., et al. 2002, in \textit{HST STIS Data Handbook}, ed. B. Mobasher (Baltimore: STScI), 131
Charbonneau, D., et al. 2000, ApJ, 529, L45
Durbin, J., & Watson, G. S. 1951, Biometrika, 38, 159
Gu, P., Lin, D., & Bodenheimer, P. 2003, ApJ, 588, 509
Henry, G., et al. 2000, ApJ, 529, L41
Hubbard, W. B., et al. 2007, ApJ, 658, L59
Jaritz, G., et al. 2005, A&A, 439, 771
Knutson, H., et al. 2007, ApJ, 655, 564
Lammer, H., et al. 2003, ApJ, 598, L121
Lecavelier des Etangs, A., et al. 2004, A&A, 418, L1

Munoz, G. A. 2007, Planet. Space Sci., 55, 1426
Schneider, T. 2001, J. Climate, 14, 853
Shkolnik, E., et al. 2005, ApJ, 622, 1075
Shore, S., Livio, M., & van den Heuvel, E. 1994, in Interacting Binaries, ed. H. Nussbaumer & A. Orr (Berlin: Springer), 1
Tian, F., Toon, O. B., Pavlov, A. A., & De Sterck, H. 2005, ApJ, 621, 1049
Vidal-Madjar, A., et al. 2003, Nature, 442, 143
———. 2004, ApJ, 604, L69
Villaver, E., & Livio, M. 2007, ApJ, 661, 1192
Wood, B. E., et al. 2005, ApJS, 159, 118
Yelle, R. 2004, Icarus, 170, 167
———. 2006, Icarus, 183, 508
Zarka, P. 2007, Planet. Space Sci., 55, 598