EXOPLANET HD 209458B (OSIRIS\(^1\)): EVAPORATION STRENGTHENED

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ABSTRACT

Following reanalysis of Hubble Space Telescope observations of primary transits of the extrasolar planet HD 209458 at Ly\(\alpha\), Ben-Jaffel claims that no sign of evaporation is observed. Here we show that, in fact, this new analysis is consistent with the one of Vidal-Madjar and coworkers, and supports the detection of evaporation. The apparent disagreement is mainly due to the disparate wavelength ranges that are used to derive the transit absorption depth. Vidal-Madjar derives a 15\% \(\pm\) 4\% absorption depth during transit over the core of the stellar Ly\(\alpha\) line (from \(-130\) to \(+100\) km s\(^{-1}\)), and this result agrees with the 8.9\% \(\pm\) 2.1\% absorption depth reported by Ben-Jaffel from a slightly expanded data set but over a larger wavelength range (\(\pm 200\) km s\(^{-1}\)). These measurements agree also with the 5\% \(\pm\) 2\% absorption reported by Vidal-Madjar over the whole Ly\(\alpha\) line from independent, lower resolution data. We show that stellar Ly\(\alpha\) variability is unlikely to significantly affect those detections. The H \(\text{I}\) atoms must necessarily have velocities above the escape velocities and/or be outside the Roche lobe, given the lobe shape and orientation. Absorption by H \(\text{I}\) in HD 209458b’s atmosphere has thus been detected with different data sets, and now with independent analyses. All these results strengthen the concept of evaporating hot Jupiters, as well as the modeling of this phenomenon.

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

1. INTRODUCTION

Few detections of extrasolar planets’ atmospheric species are reported so far, but they have been recognized as important steps in our understanding of these objects. Of particular interest are the direct detections with the Hubble Space Telescope (HST) during primary transits of Na \(\text{I}\) by Charbonneau et al. (2002) as well as H \(\text{I}\), O \(\text{I}\), and C \(\text{II}\) by Vidal-Madjar et al. (2003, 2004) (hereafter VM03 and VM04) and Ballester et al. (2007).

The recent Letter by Ben-Jaffel (2007) (hereafter BJ07), however, casts some doubt on many aspects of the H \(\text{I}\) detection in the upper atmosphere of HD 209458b and on the implication that the planet is evaporating due to the large energy input from its nearby host star (e.g., Lecavelier des Etangs 2007). Consequently, a related large number of theoretical studies would have to be revised.

In the present rebuttal Letter, we discuss the BJ07 arguments and show where they are misguiding.

2. WHERE IS THE DIFFERENCE?

BJ07 completed a new data analysis based on sampling the same observations as VM03 in a different temporal manner, and adding data from two HST orbits from an archival program completed at another epoch (two orbits added to the nine HST orbits of the VM03 observations). From the resulting new Ly\(\alpha\) transit light curve, the transit absorption depth is evaluated by integrating the Ly\(\alpha\) flux in two ranges: “blue” (1214.83–1215.36 \(\text{Å}\)) and “red” (1215.89–1216.43 \(\text{Å}\)). This slightly increases the wavelength domain excluded from the analysis because of geocoronal contamination, from 1215.5–1215.8 \(\text{Å}\) in VM03 to 1215.36–1215.89 \(\text{Å}\) in BJ07. This has, however, no significant consequences on the evaluation as shown in Figure 4 of VM03.

BJ07 evaluates the transit depth by fitting a light curve over the observations sampled by 300 s subexposures as a function of the planet orbital phase. The resampled observations show some level of variability mainly due to the variation of the stellar Ly\(\alpha\) flux. The fitting procedure “smooths” these variations as if all observations were made with an average stellar Ly\(\alpha\) flux. This gives an average H \(\text{I}\) absorption during the transit of 8.9\% \(\pm\) 2.1\% by considering a wavelength range from 1214.83 to 1216.43 \(\text{Å}\) which corresponds to \(\sim\) \(\pm 200\) km s\(^{-1}\) in velocity space.

The data analysis of BJ07 is not put into question here. The major differences between BJ07 and VM03 are on the data interpretation. Both analyses provide a Ly\(\alpha\) line flux as a function of time and wavelength, which includes possible stellar variations and planetary transit signature. The differences lie (1) in the wavelength ranges used to convert the spectra, as a function of time, into a single absorption depth measurement, and (2) in the reference flux used to correct for the intrinsic stellar flux variations.

The Ly\(\alpha\) emission of the star can significantly vary from epoch to epoch. Because there is no detectable transit absorption signature in the Ly\(\alpha\) line wings (the nominal 1.5\% obscuration by the planetary disk is below the data S/N), VM03 calculated a relative absorption depth using wings of the Ly\(\alpha\) line as flux reference. This method aims at correcting for any intrinsic and unknown changes in the Ly\(\alpha\) stellar flux (see § 4). As illustrated in Figure 1, VM03 defined two spectral domains: the line core from \(\lambda_1\) to \(\lambda_3\) (called “In” in VM03 and “Core” in Fig. 1; excluding the part of the spectrum contaminated by the geocoronal Ly\(\alpha\) emission), and the remaining wavelength domain in the wings of the line used as a flux

1 Because the escape of H atoms is strengthened in this paper, we renew our proposal to use the nickname “Osiris” for the planet HD 209458b, which loses mass like the Egyptian god.
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reference from 1214.4 Å to \( \lambda_1 \) and from \( \lambda_2 \) to 1216.8 Å (called "Out" in VM03 and "Wing" in Fig. 1). The best domain defined by \( \lambda_1 \) and \( \lambda_2 \) is found by varying the positions of these two wavelengths until the strongest absorption signal is identified. VM03 found that the strongest absorption relative to the line wings takes place in the line core between \( \lambda_1 = 1215.15 \) and \( \lambda_2 = 1216.10 \) Å (excluding the central geocoronal region).

Because the H i absorption takes place only in the central part of the Ly\( \alpha \) line, the absorption depth measurement must decrease for increasing wavelength range, including wings of the line where there is no absorption. This has already been found by VM04 with an independent data set obtained with STIS in the G140L low-resolution mode. In the low-resolution data, the Ly\( \alpha \) stellar emission line is not spectrally resolved and only the total Ly\( \alpha \) flux can be evaluated. VM04 obtained a 5% \( \pm 2\% \) transit absorption depth over the whole line, in agreement with the estimate obtained from the VM03 data set (Table 1).

To compare the VM03 result to that of BJ07, we can also calculate the transit absorption depth over the spectral domain as defined by BJ07 using the spectra of VM03. Keeping the same approach as in VM03 to account for stellar Ly\( \alpha \) variations, we evaluate the planetary absorption during transit using the line wings as flux reference. We find a midtransit absorption of 7.3\% \( \pm 2.0\% \) over the same spectral region used by BJ07, which is in agreement with the BJ07 result of 8.9\% considering that the data set is the same, except for the addition of two HST orbits to the nine used by VM03. This result shows that, considering the same wavelength range, similar transit absorption depths are found in the VM03 and BJ07 spectra (Table 1).

The uncertainty and noise appear to be lower in BJ07 than in VM03. The difference is explained by the larger wavelength range used by BJ07 to estimate the Ly\( \alpha \) flux and by the uncertainty introduced by the correction of the Ly\( \alpha \) variations applied by VM03 (see § 4).

In short, the results given in VM03 and BJ07 for Ly\( \alpha \) absorption depths can be reconciled. The apparent difference is basically due to the width of the spectral domain over which the absorption is computed, acknowledging that the H i absorption does not cover the whole extent of the stellar Ly\( \alpha \) line. When using a larger wavelength domain, the absorption signal is diluted and the absorption depth measurement is lower, as found in BJ07 compared to VM03, and in VM04 compared to BJ07.

3. HIGH-VELOCITY BLUESHIFTED ABSORPTIONS

Another argument, made by BJ07 against the evaporation scenario, is that the blueshifted absorption (produced by hydrogen atoms at speeds up to \( -130 \) km s\(^{-1}\) identified by VM03) is not confirmed in the BJ07 analysis. Velocities of \( -130 \) km s\(^{-1}\) are above the escape velocity of about \( -42 \) km s\(^{-1}\) (at \( 1R_p \)). If observed, high-speed atoms must be escaping the planet.

Following the same approach as above using the VM03 data set, we evaluate the absorption seen during transit within the "blue" and the "red" sides of the wavelength domain defined by BJ07. In this domain, we find 9.8\% \( \pm 1.8\% \) and 5.2\% \( \pm 1.0\% \) absorption in the "blue" and the "red" sides, respectively. Therefore, the large spectral domain defined by BJ07 (including velocities up to \( \pm 200 \) km s\(^{-1}\)) shows a significant absorption in both blue and red sides with, as found in VM03, an absorption stronger in the blue than in the red.

Finally, although very little work has been published to explain these high velocities, they can be produced by radiation pressure from the intense Ly\( \alpha \) flux of the nearby star (see the velocity diagram and the cometary shape of the escaping atoms in Figure 3 of Vidal-Madjar & Lecavelier des Etangs 2004), in which case, a difference between blue and red absorptions is expected.

4. THE LY\( \alpha \) STELLAR VARIATIONS

In previous works, corrections for stellar variations were done either using the wings of the line (VM03) or the observations before and after the transit (VM04), while the BJ07 correction

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**TABLE 1**

| Parameter | Line Core (1215.15–1216.10 Å) (VM03 Limits) | Intermediate (1214.83–1216.43 Å) (BJ07 Limits) | Whole Line (1210–1220 Å) |
|-----------|---------------------------------------------|------------------------------------------------|--------------------------|
| Published absorption (%) | 15 ± 4 | 8.9 ± 2.1 | 5 ± 2 |
| Reference and data set | VM03 | BJ07 | VM04 |
| Absorptions using VM03 data set (%) | 15.1 ± 4 | 7.3 ± 2.0 | 5.7 ± 1.9 |

Absorption evaluated using VM03 data set and following the VM03 method with wings as flux reference.
was done by averaging the flux variations by fitting a standard transit curve over the phase-folded data points (see Fig. 2 in BJ07).

Contrary to the claim made by BJ07, the Lyα variations of HD 209458 are not necessarily relatively large but normal for a quiet solar-type star (Vidal-Madjar 1975). In fact, when data are phase-folded, the apparent variations can be artificially enhanced due to the superimposition of observations made at different dates. Moreover, real stellar fluctuations are combined with significant noise, which is expected to be large because of the limited number of photons in the short temporal bins.

The Sun can be used as a proxy to study the possible variations of the flux and shape of the HD 209458 Lyα line. HD 209458 is a solar-type star (G0 V) whose similarity with the Sun is demonstrated by the observation of the chromospheric Ca II line profiles, which are relatively quiet for both stars. From observations obtained with SOHO (Solar and Heliocentric Observatory; Lemaire et al. 2002), we show that the core-to-wing ratio of the solar Lyα line varies by about ±8%, while it varies by about ±6% for a given total Lyα flux (Fig. 2). HD 209458 is expected to have the same behavior and the 15% transit measurements are unlikely to be due to stellar variations. This is strengthened by the HD 209458 Lyα measurements which present two different groups of core-to-wing flux ratios (Fig. 2): the ratios measured before the transit and the ratios during the planetary transit. Although these measurements are obtained at various epochs, the dispersion within a given group is small and within the error bars, while the difference between the measurements taken during the transit compared to the reference measurements taken before the transit is significant and larger than variations observed in the Sun. This behavior is unlikely to be coincidental and corresponds to the expected signal for a cloud of H i atoms in the environment of HD 209458b.

Moreover, the dispersion of these individual measurements shows no correlation with the total Lyα flux. This shows that the stellar variations are unlikely to be responsible for the observed Lyα core-to-wing variations. The core-to-wing variations are thus more likely related to the planetary transit.

Finally, it is extremely unlikely that stellar variations can mimic a transit light curve as seen in Figure 2 of BJ07, when measurements are phase-folded with the planetary orbital ephemerides.

In summary, the stellar variations are taken into account by VM03 by comparing the variations in the core to the variations in the wings of the line, and by BJ07 by averaging a smooth transit light curve over a fluctuating Lyα stellar flux. The similarity of the resulting absorption depths, using the BJ07 and VM03 data sets, when evaluated over the same spectral domain (Table 1) shows that the Lyα stellar variability does not corrupt the transit evaluation whatever the approach used for the data analysis.

5. THE SIZE OF THE ABSORBING CLOUD AND THE ROCHE LOBE

BJ07 compares the 8.9% absorption depth derived in his work to the absorption caused by an occulting disk with a size of ~4.08Rp, supposed to be the size of the Roche lobe as calculated using equations found in Gu et al. (2003). In the case of HD 209458b, a disk with a radius of ~4.08Rp, corresponds to an absorption depth of about 25% during transit. BJ07 thus concludes that the observed hydrogen atoms are inside the Roche lobe and cannot escape the planet.

First, as discussed above, the BJ07 evaluation of ~9% is only a fraction of the full H i absorption depth in the line core. Second, the formula of Gu et al. (2003) for computing the Roche lobe corresponds to the Lagrangian point L1 between the star and the planet, i.e., the most distant Roche limit position relative to the planet (see eq. [B.8] and discussion in Lecavelier des Etangs 2007). However, the Roche lobe around the planet is not spherical but elongated toward the star (see, e.g., Lecavelier des Etangs et al. 2004). In a transit configuration, the observed limit of the Roche lobe is in a direction perpendicular to the star-planet direction. In this perpendicular direction, the Roche lobe extension is about 2/3 of the extension toward the L1 point. Therefore, it is more appropriate to use an average distance to the Roche lobe, which was given by VM03 to be ~2.7Rp (Paczynski 1971). A filled Roche lobe corresponds to about 12% absorption. This value is comparable to the H i observation of ~10% absorption depth in the line core. We can conclude that H i atoms reach the Roche lobe or beyond, in agreement with the models of atmospheric escape.

In addition, although observation of hydrogen atoms outside the Roche lobe is a direct evidence for escape, it is not a necessary condition. Even filling up half a Roche lobe would imply escape rates large enough to significantly affect atmospheric structure (Lecavelier des Etangs et al. 2004). Thus, whether the hydrogen cloud actually fills up the Roche lobe or not, the large extension of the upper atmosphere (and possibly a cometary shape due to radiation pressure) shows that the atmosphere is indeed escaping.
6. CONSEQUENCE: EVAPORATION IS CONFIRMED

We have demonstrated that the BJ07 analysis is in agreement with H\textsubscript{i} escape from the HD 209458b atmosphere. Even if one considers that the absorption value given by BJ07 is correct, then either (1) this \( \sim 9\% \) absorption depth is taking place over the whole spectral range of \( \pm 200 \) km s\(^{-1} \), or (2) the \( \sim 9\% \) absorption is the result of an unresolved larger absorption within a narrower wavelength range, produced by atoms below the escape velocity of about 42 km s\(^{-1} \). In the first case, H\textsubscript{i} atoms are detected to move at velocities much larger than the escape velocity. In the second case, the absorption takes place over a narrow spectral range, \( \sim 5 \) times narrower than the range considered in BJ07. In this narrow wavelength range, the absorption must be \( \geq 12\% \) and H\textsubscript{i} atoms must be present beyond the Roche lobe. In both alternatives, the result of the data analysis described in BJ07 shows that H\textsubscript{i} must be escaping the planet atmosphere.

7. CONCLUSION

BJ07 called into question the VM03 discovery of the atmospheric escape from the HD 209458b extrasolar planet. BJ07 gives two main arguments: (1) the absorption depth is smaller than previously estimated and the Roche limit is not reached, and (2) the data analysis is corrupted by intrinsic stellar Ly\alpha variations. The first argument is not correct because the absorption is not taking place over the whole Ly\alpha line. The absorption depth measurements depend on the considered wavelength range. In addition, the Roche lobe shape and orientation must be taken into account when comparing the size corresponding to these absorption depths with the size of the Roche lobe. The second objection is rejected by recalling that VM03 corrected for the stellar variations using the overall stability of the line shape and the line wings as flux reference.

Finally, despite the assertion in the introduction of BJ07, works to transpose these observations into estimates of escape rate were made early in VM03 and recently in Schneiter et al. (2007). As stated by our anonymous referee, these “observational” estimates agree with the most recent and sophisticated models which all find rather good agreement with mass-loss rates of \( \sim (3–7) \times 10^{10} \) g s\(^{-1} \). Therefore, at the orbital distance of HD 209458b, atmospheric escape does not strongly affect the evolution of the planets, in accord with the evolutionary studies.

Last, but not least, BJ07 performed an independent, thorough, and careful analysis of the best available data set for measuring the Ly\alpha transit absorption depth. Despite a misinterpretation of the resulting spectra, this work confirms that the signal detected in VM03 is indeed present and is not related to the data reduction process. Therefore, in the atmosphere of HD 209458b, H\textsubscript{i} appears to be the only species to have been detected with two independent data sets, and now with independent data analyses. The BJ07 data analysis strengthens the detection of the extended escaping atmosphere of HD 209458b, in agreement with numerous theoretical studies of this phenomenon (e.g., Lammer et al. 2003; Lecavelier des Etangs et al. 2004; Yelle 2004, 2006; Baraffe et al. 2005; Tian et al. 2005; García Muñoz 2007).

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