ON THE EXISTENCE OF ENERGETIC_ATOMS IN THE UPPER ATMOSPHERE OF EXOPLANET HD209458b

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ABSTRACT

Stellar irradiation and particle forcing strongly affect the immediate environment of extrasolar giant planets orbiting near their parent stars. However, it is not clear how the energy is deposited over the planetary atmosphere, nor how the momentum and energy spaces of the different species that populate the system are modified. Here, we use far-ultraviolet emission spectra from HD209458 in the wavelength range (1180–1710 Å) to bring new insight to the composition and energetic processes in play in the gas nebula around the transiting planetary companion. In that frame, we consider up-to-date atmospheric models of the giant exoplanet where we implement non-thermal line broadening to simulate the impact on the transit absorption of superthermal atoms (H I, O I, and C II) populating the upper layers of the nebula. Our sensitivity study shows that for all existing models, a significant line broadening is required for O I and probably for C II lines in order to fit the observed transit absorptions. In that frame, we show that O I and C II are preferentially heated compared to the background gas with effective temperatures as large as $T_{O I}/T_B \sim 10$ for O I and $T_{C II}/T_B \sim 5$ for C II. By contrast, the situation is much less clear for H I because several models could fit the Lyα observations including either thermal H I in an atmosphere that has a dayside vertical column [H I] $\sim 1.05 \times 10^{21}$ cm$^{-2}$, or a less extended thermal atmosphere but with hot H I atoms populating the upper layers of the nebula. If the energetic H I atoms are either of stellar origin or populations lost from the planet and energized in the outer layers of the nebula, our finding is that most models should converge toward one hot population that has an H I vertical column in the range $[H I]_{hot} \sim (2-4) \times 10^{13}$ cm$^{-2}$ and an effective temperature in the range $T_{H I} \sim (1-1.3) \times 10^6$ K, but with a bulk velocity that should be rather slow.

Key words: line: formation – line: profiles – planetary systems – radiation mechanisms: non-thermal – stars: individual (HD209458) – ultraviolet: stars

Online-only material: color figures

1. INTRODUCTION

The nature of the extended nebula around giant exoplanets orbiting near their parent stars has remained a fundamental unresolved problem since it was raised a few years ago. Of all the exoplanets detected over the last decade, HD 209458b is the first discovered by the transit technique, and the only exoplanet for which rich far-ultraviolet (FUV) space observations were obtained before the Hubble Space Telescope (HST)/STIS instrument went down (Vidal-Madjar et al. 2003, 2004; Ben-Jaffel 2007, 2008, hereafter, respectively, VM03, VM04, BJ07, and BJ08). The collected data set which covers the wavelength range of 1180–1710 Å is a unique tool not only for understanding the composition and structure of the atmosphere of these giant planets but also for characterizing the processes that heat and excite them. Therefore, the interpretation of this data set is of great importance and should ultimately help answer fundamental questions regarding the formation and evolution of extrasolar planets, particularly questions concerning their survival given their close proximity to the harsh environment of their parent stars.

Historically, HD209458b was discovered transiting its parent star and absorbing 1.5% of its flux (Charbonneau et al. 2000; Henry et al. 2000). Extending the technique to space FUV observations at Lyα (1216 Å), an enormous hydrogen nebula was discovered using the HST/STIS spectograph, covering almost $\sim 8.9\% \pm 2\%$ of the stellar disc (VM03, BJ08). This corresponds to a hydrogen nebula extending over an effective area that has at least $\sim 2.47$ planetary radius across the line of sight, tending to support the theory that the coronal hydrogen gas of HD209458b is inflated. The coincidence between the Roche lobe size across the planet–star line and the occultation effective area suggest that the gas is probably filling the exoplanetary Roche lobe (VM03, BJ08). Later, based on new HST/STIS FUV observations in the range (1180–1710 Å) of heavy elements like C and O, an occultation, respectively, of $5\% \pm 2\%$ for H I, $13\% \pm 4.5\%$ for O I and $7.5\% \pm 3.5\%$ for C II were reported (VM04). There is still a great deal of uncertainty regarding the strong absorptions obtained during transit, respectively, for the two heavy minor constituents, yet the drop-off appears comparable to the transit absorption obtained for H I, which, according to VM04, supports a blow-off scenario in the upper atmosphere of HD209458b in which an escaping element (H I) drags other heavy constituents outward. The problem is that both O I and C II are several orders of magnitude less abundant than H I, and yet having the two components filling or even overflowing the planet’s Roche lobe will not help to attain the reported transit absorptions (Garcia Munoz 2007). In addition, it is not yet clear how wide the stellar lines are for the O I and C II multiplets because the HST/STIS observations were obtained in the low-resolution mode that does not help to resolve the emission lines (VM04; Garcia Munoz 2007). Line broadening processes were thus suggested to explain the O I and C II lines’ absorption but they were never implemented in past studies. All these observational, analysis, and modeling uncertainties make the transit absorptions reported for H I, O I, and C II a real challenge for any theoretical model.
In the following, we revisit available HST archive data in the 1180–1710 Å spectral window to conduct a sensitivity study including H i, O i, and C ii abundances together with line broadening processes in play in the upper layers of the atmosphere of HD209458b. Such a global approach is required for any attempt to derive self-consistent observational constraints on the steady-state properties of the nebula around the exoplanet. In Section 2, we recall Lyα absorption rates and profiles obtained during transit from medium spectral resolutions as reported by BJ08 and describe in detail the analysis of the low-resolution observations corresponding to H i (1216 Å), O i (1304 Å triplet), and C ii (1335 Å multiplet). For comparison with our model, a set of four constraints was selected: the absorption line profile at Lyα as derived from the medium-resolution observations and the line-integrated absorption drop-off during transit corresponding to H i (1216 Å), O i (1304 Å triplet), and C ii (1335 Å multiplet) as derived from the low-resolution observations. Our extended atmospheric model, based on the standard model of Garcia Munoz (2007), is set forth in Section 3 and focuses on the description of the tidal bulge region and stellar emission lines’ properties. In Section 4, we describe line-broadening processes that may affect the absorption profiles of the different components. Our results are discussed in Section 5 with the dual aims of deriving a consistent view of the gas distribution and the processes that heat and excite the gas nebula around HD209458b and propounding predictions for future space observations.

2. MEDIUM- AND LOW-RESOLUTION SPECTRAL OBSERVATIONS OF HD209458

Our first data set consists of the HST/STIS archive observation of HD209458 obtained with the G140M medium-resolution grating and the 52′′ × 0′′.1 slit. The analysis of this data set was controversial, with contradictory conclusions obtained for the Lyα transit absorption (VM03; BJ07; VM08) before the conclusive study in BJ08 which we adopt herein. In the global approach that we implement, the transit absorption spectral profile shown in Figure 1 is of particular interest (see also Figure 6 in BJ08). The symmetric shape of the observed absorption profile, due largely to the coincidence of the transit light curves respectively from the blue and red wavelength regions of the Lyα line (see Figure 3 in BJ08), led us to dismiss atmospheric models that produce asymmetric absorption profiles (see BJ08 for more details). In addition, considering standard atmospheric models, we previously showed that the hydrogen nebula around HD209458b should be very opaque, behaving much like a damped system than a classical atmosphere. For reference, it is helpful to recall that damped systems are galactic absorbing systems that show extended Lyα damped wings in the absorption spectra observed toward quasars (Wolfe et al. 1986). For these systems, the [H i] column is usually larger than $2 \times 10^{20}$ cm$^{-2}$ and the temperature is rather cool (H i thermal velocity $\sim 15$ km s$^{-1}$), similar to the values derived for HD209458b’s nebula (BJ08). However, among all possible optically thick models proposed for HD209458b, no unique solution for the atmospheric hydrogen distribution could be derived as hybrid models with a thin layer of superthermal hydrogen, may also produce satisfactory fits to the observed absorption profile. For those reasons, in the past, we intentionally disfavored any particular model in hopes of obtaining additional observations in the future (BJ08).

The second data set included in this study is the HST/STIS archive observation of HD209458 obtained with the G140L low-resolution grating and the 52′′ × 0′′.2 slit (VM04). In this mode, the HST/STIS instrument has a resolution element of $\sim 1.7$ pixels for point sources around Lyα with an average dispersion of $\sim 0.6$ Å per pixel. Generally, 2–3 element resolutions are assumed for the spectral resolution of the instrument. For an extended source, such as the Earth’s geocoronal emissions and the sky’s background emissions which fill the whole slit area, the spectral resolution is $\sim 8$ pixels with the same dispersion. These details are important because the recorded signal in these data is a combination of a stellar point source emission and the geocoronal and sky background extended sources. The HST/STIS selected mode indeed shows a low-resolution spectrum but covers a larger wavelength band spanning a $\sim 1180$–1710 Å window. In the present analysis, we follow exactly the same technique using the time-tag information as described in BJ08. In total, we have four visits during the planetary transit of HD209458, each composed of three long exposures ($\sim 2000$ s) distributed in time over the transit period (see Table 1). All exposures were obtained with the HST/STIS G140L grating and are sampled here using a time bin of 300 s from the available time-tag information. The whole data set resulted in $\sim 67$ bins time series of the HD208458 planet–star system as a function of the orbital phase angle. Coincidentally, the time sampling of the transit period resulted in gaps (lasting, respectively, $\sim 2493$ s, $\sim 1169$ s, $\sim 851$ s, and $\sim 709$ s). The size and number of the gaps, along with the relatively low signal-to-noise ratio (S/N) of the data, make a consistent study of the resulting time series difficult (BJ07). Nevertheless, we are able to fit synthetic light curves into each selected wavelength band before we derive the drop-off in the integrated stellar signal during transit, along with the appropriate statistical errors.

For reference, a stellar spectrum is shown in Figure 2. Aside from the emission lines previously described by VM04 (their Table 1), a stellar continuum must be subtracted before determining the transit drop-off for individual line or band emissions (e.g., Figure 2(a)). For that purpose, we use a low-order polynomial model of the logarithm of the stellar continuum spectrum in order to obtain the best fit with the observed spectra in the wavelength window $\sim 1400$–1700 Å (e.g., Figure 2(a)). After subtraction, we find that no extra correction is needed for any line considered here, which lends
support to the continuum model as a good approximation of the stellar continuum (e.g., Figure 2). The resulting emission lines for the three selected constituents for the in- and out-of-transit periods are shown in Figure 3 with the corresponding statistical errors. Stellar signal drop-off during transit for the transit periods are shown in Figure 3 with the corresponding lines for the three selected constituents for the in- and out-of-

In the following section, we will define our atmospheric model, the different processes of line broadening at play in the hot atmosphere of HD209458b, and the shape of the stellar emission lines before we conduct a simultaneous comparison to the four constraints assumed here.

### 3. SIMULATION OF TRANSIT ABSORPTION: METHOD

In this section, we take a theoretical approach in verifying whether the absorption profile for H\(_i\) (e.g., Figure 1) and the flux drop-off during transit for the H\(_i\), O\(_i\), and C\(_i\) lines (e.g., Table 2) are predictable. To evaluate transit absorption spectra, integration is implemented using a fine grid (see Equation (1) in BJ08), taking into account the varying number density and temperature distributions according to the assumed atmospheric model. We recall that for a target that is not spatially resolved, such as for transiting exoplanets, the observed signal extinction is a weighted average of absorption from different regions of the exoplanetary extended atmosphere, with the outer layers having the maximal weight. In other words, because the planet is not spatially resolved, various sketches of gas distribution around it may lead to the same observed extinction (BJ08). Ingress and egress observations, which are not yet available with high S/N are required to capture more details of the gas distribution around the exoplanet. In our previous study (BJ08), we showed that asymmetric solutions in the velocity space in the example of radiation pressure’s induced flow out of the Roche lobe as proposed by VM03 or energetic neutral atoms (ENAs) produced by the interaction between impinging stellar wind plasma and planetary neutrals (Holmstrom et al. 2008) are not compatible with the rather symmetric full-transit absorption as a function of wavelength (BJ08) if large Doppler-shifted absorptions are assumed. In the example of the ENA model, a slow, external, hot population could be consistent with our data analysis (BJ08) and will be considered here as a potential absorber of the Ly\(\alpha\) photons during transit. In this study, we thus focus on cylinder symmetric atmospheric models with respect to the planet–star line. Any departure from this ideal picture of symmetry that is not detected in our data set could be corrected for afterward starting from the solutions derived in this study.

#### 3.1. Atmospheric Model of Exoplanet HD209458b

In the scenario of atmospheric inflation by stellar radiation and wind particles, exoplanets closely orbiting their parent stars...
suffer in harsh conditions that may lead to distortion of the outer layers of their atmosphere in unpredictable ways (Yelle et al. 2008; Lammer et al. 2009). For example, the presence of a stellar magnetic field may call for an magnetohydrodynamics (MHD) description of its interaction with a possibly magnetized and out-flowing planet. Depending on the planetary and stellar flow regimes, the strength and relative orientation of the two magnetic fields, and the degree of ionization of the plasma, the final configuration of the interacting system could be very complex, as illustrated by similar situations in our solar system such as the interaction between the solar wind and the local interstellar flow (Ratkiewicz & Ben-Jaffel 2002) or the interaction between the Jovian plasma and its satellite Io (Combi et al. 1998; Clarke et al. 2002). The problem is that most models published thus far focus either on a one-dimensional hydrodynamic description that includes chemistry but neglects the interaction with the stellar wind (Yelle 2004; Garcia Munoz 2007; Koskinen et al. 2007), on hydrodynamic simulations that miss most of the underlying micro-physics in the system but include gravity and/or wind interaction with the parent star (Lecavelier et al. 2004; Tian et al. 2005; Schneiter et al. 2007; Murray-Clay et al. 2009; Stone & Proga 2009), or exclusively on the external wind production of energetic neutrals (Holmstrom et al. 2008).

In contrast, this study follows a semi-empirical approach that uses a forward analysis, analyzing simple sketches of the gas distribution in the interaction of the planet–star system and determining how well they fit with the observational constraints. This approach is commonly used and has proven its robustness in several studies of the upper atmosphere of giant planets in the solar system (Gladstone et al. 2004; Ben-Jaffel et al. 2007; Slanger et al. 2008). Our theoretical model is based on sophisticated atmospheric models that include most of the chemistry expected in the HD209458 systems (Garcia Munoz 2007). Within that frame, we assume that the exoplanet is filling its Roche lobe with the configuration of gas distribution as shown schematically in Figure 4. The atmosphere is elongated along the planet–star line by the tidal forces (this is the bulge effect). The size of the spherically symmetric atmospheric model (region I) corresponds exactly to the DIV1 model of Garcia Munoz (2007) that assumes solar abundances. The main feature of this model is that it includes heavy elements chemistry, which directly enhances the abundance of most species compared to other models, as in Yelle (2004) who only considered hydrogen–helium components. The only change we tolerate for this reference model is scaling the abundance of different constituents over the entire expanse of atmosphere. This scaling should encompass most models thus far published either for the enhancement or depletion of the abundance of the different species. Such abundance variation has its origin in the chemistry thus far assumed, large-scale atmospheric processes as observed in the upper atmosphere of the outer planets of the solar system (Ben-Jaffel et al. 1993, 1995; BJ08), or external sources as suggested by recent two-dimensional hydrodynamic simulation of the planetary wind’s interaction with the stellar wind (Stone & Proga 2009).

To account for the tidal bulge (region II), we assume the DIV1 model between $R_{L-1}$ (top of region I) and $R_{L+1}$ (Roche lobe limit) for the number density and temperature reference distributions. The size of the Roche lobe across the planet–star line should not

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**Figure 3.** Typical in- and out-of-transit low-resolution line profiles respectively corresponding to H i (a), O i (b), and C i (c). Statistical error bars are shown for the selected in-transit period.

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**Table 2**

| Atoms | Wavelength Window (nm) | Flux Drop-off* |
|-------|------------------------|---------------|
| H i   | [121.2, 122.0]         | 6.6% ± 2.3%   |
| O i   | [129.9, 131.0]         | 10.5% ± 4.4% |
| C i   | [133.2, 134.0]         | 7.4% ± 4.7%   |
| Continuum | [140.0, 170.0] | 1.96% ± 0.42% |

**Notes.** Flux drop-off during transit of HD209458 derived from HST/SITIS G140L low-resolution observations. Typical in and out transit spectra for the different elements are shown in Figure 3.

*The signal drop-off is derived from a best $\chi^2$ fit to the observed time series using synthetic curves for each individual wavelength band.

b One element is listed but several excited states may also contribute.
be much different from the theoretical value of $R_{L'1} \sim 2.89 R_p$ (Gu et al. 2003; Jaritz et al. 2005). This compares well with the size derived in our previous study of the stellar Ly$\alpha$ extinction observed during transit (BJ07; BJ08). The DIV1 atmospheric opacities calculated for the different spectral bands (1216 Å, 1304 Å, and 1335 Å) considered here are shown in Figure 5. For the reference DIV1 model, the dayside vertical column of the three species along the planet–star line, including the bulge region, is $[\text{H} \text{I}] \sim 1.57 \times 10^{21} \text{ cm}^{-2}$, $[\text{O} \text{ I}] \sim 3.94 \times 10^{17} \text{ cm}^{-2}$, and $[\text{C} \text{ II}] \sim 2.18 \times 10^{17} \text{ cm}^{-2}$.

In addition to the thermal population described above, we consider two sources of hot atoms that are included independently in our transit absorption calculations. First, to account for superthermal populations within the upper layers of the nebula (the internal source of hot atoms), two free parameters are introduced, corresponding to the position of the bottom of that active region in the atmosphere measured from the top of region II and the temperature of the hot atoms of the considered species. Outside of the Roche lobe configuration sketched in Figure 4, we also include the possibility of an external source (region III) of absorbing atoms, described by its own atomic column and temperature. This source could be of stellar origin or populations lost from the planet dayside, nightside, or both. If the external source is of stellar origin, then it coincides with the ENA model proposed by Holmstrom et al. (2008). Along with the scaling factor for the whole atmosphere, this description should cover most scenarios of gas distribution, including thermal and non-thermal populations as well as those with or without the presence of a stellar wind.

In the following section, in order to generate the transit flux drop-off, we evaluate the line profile of the different stellar emissions either directly from observed, unperturbed stellar lines of HD209458 or from available solar emission lines.

### 3.2. Stellar Unperturbed Emission Line Profiles

HD209458 is G0 V solar-like star (Wood et al. 2005) in which a large number of emission lines originate from the chromosphere/corona. For Ly$\alpha$ this is confirmed by several STIS high/medium-resolution observations that show a self-reversal (double horn) shape that has $\sim 1$ Å line’s width, almost the same properties known for the solar Ly$\alpha$ line (VM03; BJ07; Lemaire et al. 2005). In addition, we recall that chromospheric Ca$\text{II}$ H and K lines were observed for HD209458, and these are comparable to solar lines (Shkolnik et al. 2005). If we also consider the comparable size, mass, effective temperature, and age of the two stars (Charbonneau et al. 2000; Henry et al. 2000; Melo et al. 2006; Nordstrom et al. 2004), all of these factors tend to support the conclusion that the O$\text{I}$ and C$\text{II}$ solar line profiles are good estimates for HD209458 lines.

In the specific case of the H$\text{I}$ Ly$\alpha$ emission line, the HST/STIS medium-resolution observations of HD209458 provide a good reference for the stellar line profile (see Figure 3 in BJ07). The so-called unperturbed line profile can be used not only for the analysis of the medium-resolution observations, as done in BJ07, but also can be convolved with the instrument line-spread function of the HST/STIS G140L grating in the $52^\prime \times 0^\prime 2$ slit mode in order to generate a reference Ly$\alpha$ line profile for the low-resolution data analysis. In order to verify the accuracy of this method, one may start from high-resolution observation of HD209458 obtained with the HST/STIS echelle mode but at low S/N (VM03). After convolution with the appropriate line-spread function corresponding to the G140M grating, we confirm that line profiles obtained either directly or after convolution are in agreement.

In the case of the O$\text{I}$ and C$\text{II}$ emission lines, the situation is more complicated because the lines’ profiles are not fully available. With the G140L spectra, obviously we have no way to access the genuine stellar lines because of the poor spectral resolution. Until recently, it was impossible to state the origin of the O$\text{I}$ and C$\text{II}$ absorption during transit with any certainty because so much about the stellar line profiles that compose the O$\text{I}$ and C$\text{II}$ multiplets was unknown. However, we believe the problem can be solved in two steps: first, we derive the weights of the different lines that compose each of the multiplets using available HST/STIS high-resolution spectra of HD209458 (VM03). The data are noisy but the collected spectra allow one to make a good estimate between the lines’ peaks in the ratio 1:1.5:1.17, respectively, for the O$\text{I}$ (1302.17 Å, 1304.86 Å, and 1306.03 Å) lines, and in the ratio 0.5:1.0 for the C$\text{II}$ (1334.53 Å, 1356.0 Å, 1356.7 Å) lines.
is a solar-like star, the second step in modeling the $\text{O} \text{i}$ very weak oscillator strength (e.g., Table 3). Because HD209458 is a multiplet is to determine whether solar spectra of the different $\text{O} \text{i}$ and $\text{C} \text{ii}$ transitions, we start with the solar line profiles to which we apply the un-... ... ... ... ... ...

To obtain the stellar $\text{O} \text{i}$ and $\text{C} \text{ii}$ line profiles at Earth’s position, we start with the solar line profiles to which we apply the interstellar medium (ISM) absorption between HD209458 and Earth. Most lines have an average width of $\sim 45 \text{ km s}^{-1}$ for the $\text{O} \text{i}$ triplet and $\sim 50 \text{ km s}^{-1}$ for the $\text{C} \text{ii}$ multiplet, much larger than the Doppler width at the atmospheric temperature of $1.2 \times 10^4 \text{ K}$.  

### 4. Sensitivity of Transit Absorption to Atmospheric Parameters and Processes

#### 4.1. Thermal Processes: Classical Approach

In the first attempt to compare observations to the transit extinction predicted by our basic model, we consider thermal broadening as the only process responsible for the formation of the atomic absorption profiles. Using the DIV1 atmospheric model of García Muñoz (2007), the calculated transit Lyα absorption profile is slightly wider than the observed profile with $\chi^2 \sim 1.98$ (Figure 7(a)), while the line-integrated transit

| Atoms | Wavelength (nm) | $A_{\text{nl}}(s^{-1})$ | $f_{\text{nl}}$ | $\sigma_0$ (cm$^2$) | $\alpha$ | $x_0$ | $x_1$ |
|-------|----------------|------------------------|--------------|--------------------|--------|-------|-------|
| $\text{H} \text{i}$ | 121.567 | 6.26510$^8$ | 0.4162 | 5.80810$^{-14}$ | 4.69910$^{-4}$ | 4.02 | 4.22 |
| $\text{O} \text{i}$ | 130.217 | 3.1510$^8$ | 0.048 | 2.89810$^{-14}$ | 1.01210$^{-3}$ | 3.67 | 3.80 |
| $\text{O} \text{i}$ | 130.486 | 1.8710$^8$ | 0.0478 | 2.89210$^{-14}$ | 6.0210$^{-4}$ | 3.87 | 3.46 |
| $\text{O} \text{i}$ | 130.602 | 6.2310$^7$ | 0.0478 | 2.89410$^{-14}$ | 2.01010$^{-4}$ | 3.24 | 2.84 |
| $\text{C} \text{ii}$ | 133.453 | 2.410$^8$ | 0.128 | 6.85910$^{-14}$ | 6.84510$^{-4}$ | ... | ... |
| $\text{C} \text{ii}$ | 133.566 | 4.810$^7$ | 0.0128 | 6.85910$^{-14}$ | 1.37110$^{-4}$ | ... | ... |
| $\text{C} \text{ii}$ | 133.571 | 2.8810$^8$ | 0.115 | 6.16810$^{-14}$ | 8.22210$^{-4}$ | ... | ... |
| Continuum | 140.0–170.0 | ... | ... | ... | ... | ... | ... |

Notes. These are the most important lines and continuum considered in the present study. Atomic parameters are provided at a reference temperature of $10^4 \text{ K}$. $\sigma_0$ is the resonance cross section at line center, $\sigma_0$ is the Voigt parameter required to evaluate the atomic absorption profile, and the pair $(x_0, x_1)$ are the parameters that better represent the stellar line as a double Gaussian profile $\sim(\exp(-\frac{(x-x_0)^2}{2\sigma_0^2}) + \exp(-\frac{(x-x_1)^2}{2\sigma_0^2}))$ (Link et al. 1988). The parameter $x$ is the photon’s frequency in Doppler units, and $(x_0, x_1)$ are provided in Doppler units at a reference temperature $10^4 \text{ K}$. The double Gaussian profile only applies for those emission lines that exhibit a double horn shape before absorption by the ISM gas. The $\text{O} \text{i}$ triplet is due to the transition $3s \, 3S \to 2p \, 3P$. The $\text{C} \text{ii}$ triplet results from the transition $2s2p^2 \, 3 \, D \to 2s^2 \, 2p^2 \, 3P^0$.
The measured error bars (see Table 2). The larger than the observed drop-off ($6\%$ scaled by $f$).

The spectral inflection that appears at $\alpha$ in the wings of the Ly$\alpha$ absorption line follows a classical curve of growth compared to the H$\alpha$ column. For reference, for $f_{\text{H}} = 1/10, 1/3, 2/3,$ and 1 cases shown in Figure 7(a), the corresponding $\chi^2$ is, respectively, $\sim 5.68, \sim 2.42, \sim 1.73,$ and $\sim 1.98.$ The best fit for the transit absorption profile is obtained for a scaling factor $f_{\text{H}} = 2/3$ with a $f = 1.7289.$ A transit drop-off of $\sim 6.74\%$ of the stellar flux integrated in the wavelength range $1212–1220$ Å consistently fits quite well with low-resolution observations $\sim 6.6\% \pm 2.3\%$ (e.g., Table 2).

This family of solutions based on scaling the H$\alpha$ abundance was initially proposed in our previous study (BJ08) comparing the gas nebula around HD209458b to damped systems. However, one of our conclusions in BJ08 emphasized that no unique solution could be favored to explain the extinction level observed in the H$\alpha$ Ly$\alpha$ line profile and integrated flux. This multiplicity of solutions is the reason why BJ08 chose not to disseminate quantitative details concerning any particular solution until the present in-depth study.

The next logical step is to determine how the atmospheric model tested in the H$\alpha$ Ly$\alpha$ analysis would work for the O$\alpha$ triplet and the C$\alpha$ doublet. For that reason, we start from the DIV1 model using the gas configuration sketched in Figure 4 and calculate the total opacity as a function of distance from the planet’s center, across the planet–star line. As for H$\alpha$, the O$\alpha$ and C$\alpha$ abundances can be independently scaled by a factor over the whole atmosphere. We assume that all lines that compose the multiplets also contribute to the absorption of the stellar flux. Indeed, for O$\alpha$, the 1302.17 Å line is strongly absorbed by the ISM, making it the largest contributor to the unresolved multiplet signal from the two remaining lines (1304.86 Å and 1306.03 Å) that should be collisionally excited (VM04). For C$\alpha$, the observed multiplet signal should originate respectively from C$\alpha$ 1334.53 Å and C$\alpha^*$ 1335.71 Å the latter being collisionally excited. With the opacity of O$\alpha$ and C$\alpha$ shown in Figure 5, it seems quite difficult for the DIV1 model to fit the extinction observed for O$\alpha$ and C$\alpha$ during transit even after scaling by any factor considered for H$\alpha.$ For reference, for $f_{\text{H}} = 2/3,$ the line-averaged flux drop-off during transit for the O$\alpha$ triplet is $\sim 3.9\%,$ and $\sim 3.3\%$ for C$\alpha.$ As shown in Table 2, these values fall in the bottom range observed for the transit absorption, making thermal broadening in scaled atmospheric models a marginal solution for the O$\alpha$ and probably C$\alpha$ lines.

The challenge we face with O$\alpha$ and C$\alpha$ transit absorptions is twofold. Indeed, assuming the transit absorption shown in Table 2, and despite the large statistical uncertainties, how is it that minor constituents that are 4 orders of magnitude less abundant than H$\alpha$ show similar, if not stronger, absorption during transit? In addition, the transit absorption seems even stronger for neutral O$\alpha$ than for ion C$\alpha.$ It follows that for the O$\alpha$ and C$\alpha$ absorption lines in the HD209458b extended atmosphere, another explanation is required that may compensate for their weaker abundances compared to H$\alpha$ and that might then provide comparable absorption drop-off during transit for the three constituents. The missing mechanism that may explain the high absorption observed for both O$\alpha$ and C$\alpha$ lines may be related to
broadening processes that should be in play in the upper atmosphere of HD209458b. This was discussed qualitatively in the past (Garcia Munoz 2007) but no attempt was made to evaluate the spectral broadening that may explain the large absorption observed during transit. In addition, the unknown spectral shape of the stellar lines at selected wavelengths was a source of great uncertainties on modeling the transit absorption of O \textit{i} and C \textit{ii}. In the following, we elicit key information on the shape of the stellar lines and the unconstrained broadening processes.

4.2. Non-thermal Processes: Global Approach

Here we consider two distinct sources of energetic atoms, depending on the region where the particles are present. For instance, we assume that all energetic atoms produced inside the Roche lobe limit form the so-called internal source, while those produced outside represent the external source. In the frame of our description of the exoplanet’s atmosphere (e.g., Figure 4), the internal source could be present in regions I and II, while the external source is confined to region III.

Generally, the existence of energetic particles results from the departure of their velocity distribution function from equilibrium due to the imbalance between perturbing and restoring processes (Meyer-Vernet 2001). For neutrals, the sources of energetic atoms are chemical- and radiation-induced reactions and/or energization by atmospheric meso-turbulence. For partially ionized plasma, the mechanisms of energization could originate from wave–particle interactions or mesoscale turbulence. The resulting velocity distribution varies from one constituent to another, greatly enhancing the broadening effect for particles of larger mass (Schizgal 2004, 2007). For reference, this mass dependence corresponds to the so-called preferential heating (Schizgal 2004, 2007). For example, Schizgal (2007) evaluated the mass dependence of the velocity distribution function that is sensitive to the neutral or charged state of the background gas (Schizgal 2004, 2007). For particles’ velocity distribution function that is sensitive to the neutral or charged state of the background gas (Schizgal 2004, 2007).

For instance, Schizgal (2007) evaluated the mass dependence of the velocity distribution function to wave–particle interactions that may be quite different from a Maxwellian or even a kappa distribution. Meso-turbulence may also broaden absorption lines in a very complex way, particularly when the gas departs from a steady state (Loucif & Ben-Jaffel 2002).

Our intent is not to conduct such heavy modeling, but rather to follow the rich heritage of the many studies of the atmosphere of solar system’s planets and the heliosphere (Schizgal & Arkos 1996; Shematovich 2004; Fahr et al. 2007; Nagy 2008; Zank et al. 2009, and references therein). Energetic atoms are commonly detected in these objects at all distances from the Sun. When we recall the huge stellar energy available at the orbit of giant exoplanets, we are not persuaded that a sound analysis can neglect or ignore such energetic atoms in their extended atmospheres. Similar to prior studies conducted on the solar corona (Cranmer et al. 1998, 2008) or the Jovian corona (Ben-Jaffel et al. 1993; Emerich et al. 1996; Gladstone et al. 2004), the preferential broadening for the O \textit{i} and C \textit{ii} lines is accounted for by assuming synthetic velocity distributions with one parameter corresponding to the effective temperature $T_{e}$ of the species $i$ that should be derived from the comparison to the transit absorption observed for the selected constituent.

4.2.1. Impact of Internal Source of Energetic Atoms

In our global approach, we start from the DIV1 standard model of Garcia Munoz (2007), but adopt values of $f_{\text{sca}}$ (1, 2/3, 1/2, 1/3, 1/10) for scaling O \textit{i} and C \textit{ii} abundances in the atmosphere. We do not consider larger values of $f_{\text{sca}}$ as models with $f_{\text{sca}} \sim 2/3$–1.0 already correspond to an enriched atmosphere and fit rather well with the transit absorption at H\text{\scriptsize{I}} Ly$\alpha$ (see Figure 7(a)). Independent scaling of each species may help to locate any departure from solar mixing ratios that are assumed deep in the atmosphere.

The region where collisional and wave–particle broadening is acting is placed on top of the atmosphere and defined by the bottom position, the first free parameter. In such an active region, the velocity distribution of an individual constituent is allowed to depart from the background. The departure from equilibrium is defined by the ratio $T_{e}/T_{B}$ of the species’ effective temperature to the background temperature. The results of the comparison of our model to the observed transit absorption are provided as a function of the atmospheric scaling factor adopted and the position of the bottom of the active layer. Our results are summarized in Table 4 and are discussed below to derive key properties of hot populations produced in regions I and II.

First, a quick survey of Table 4 shows that a strong differential heating of O \textit{i} and C \textit{ii} is required with respect to the background atmosphere in order to fit the assumed O \textit{i} and C \textit{ii} transit absorptions. This result is certain because preferential atomic heating is required for O \textit{i} and C \textit{ii} in all possible atmospheric cases in order to recover the transit absorptions observed. In addition, the derived differential heating is here found to be stronger for O \textit{i} than for C \textit{ii}, which nicely follows the mass dependence as derived by theoretical studies Schizgal (2007) and observed in the solar corona (Cranmer et al. 2008). However, the corresponding absorption line broadening depends on the assumed thickness of the non-thermal region and on the scaling factor of the abundance of the species considered over the whole atmosphere. Obviously, our set of observations cannot unambiguously discriminate between the different solutions, yet all of them show a need for a preferential heating of O \textit{i} and C \textit{ii} compared to the background atmosphere (e.g., Table 4).

To illustrate the degeneracy of solutions, we consider the H\text{\scriptsize{I}} (1215.67 Å), O \textit{i} (1304.86 Å), and C \textit{ii} (1334.53 Å) absorption profiles used to fit the transit absorption with our standard atmosphere scaled by a factor $f_{\text{sca}} \sim 2/3$. For H\text{\scriptsize{I}}, no internal hot hydrogen is required because thermal broadening is enough to bring the model to the desired transit absorption at Ly$\alpha$ (e.g., Figure 7(a)). Assuming a hot layer confined to a region above $r \sim 213 \times 10^{3}$ km ($\sim 2.25 R_{\text{p}}$), a differential heating $T_{0,i}/T_{B} \sim 10.75$ is required for O \textit{i} in order to fit the transit absorption observed around $\sim 1304$ Å, while for C \textit{ii}, $T_{C,\text{ii}}/T_{B} \sim 5.5$ is needed to recover the transit absorption assumed around $\sim 1334$ Å. Now, for depleted atmospheres corresponding to smaller scaling factors and for the same position of the active layer, more efficient preferential broadening is required for O \textit{i} and C \textit{ii} lines to balance the loss in absorption due to smaller atomic opacity. As shown in Figure 8, for an atmospheric scaling factor ranging from 2/3 down to 1/10, $T_{0,i}/T_{B}$ varies from $\sim 10.75$ to $\sim 32$ for oxygen, while for C \textit{ii}, $T_{C,\text{ii}}/T_{B}$ increases smoothly from $\sim 5.5$ up to $\sim 12.25$. In other words, the smaller the atmospheric scaling, the stronger the non-thermal broadening needed to fit the observed transit absorptions. Intuitively, this result simply reflects the need for an extra line opacity to compensate for reduced atomic opacity, an extra opacity that is produced by a larger effective temperature. For H\text{\scriptsize{I}}, the fit obtained with an internal source of hot H\text{\scriptsize{I}} is rather poor compared to the fit obtained for thermal broadening (see Figure 7(b)). Moreover, the corresponding Ly$\alpha$ spectral
shape has a pronounced U-shape that seems different from observations with $\chi^2 > 2$ in all cases, making this process an improbable explanation for the observed transit absorption at Lyα. Note, however, that if the internal hot atoms are placed high in the atmosphere, close to the Roche lobe edge, then it would be difficult to distinguish them from the external source, a scenario discussed below. In summary, while a standard model would be difficult to distinguish them from the external source, high in the atmosphere, close to the Roche lobe edge, then it an improbable explanation for the observed transit absorption.

### Table 4

| $R_s$ | Internal Source | $f_{\text{sca}}$ | $H_\text{I}$ ($x^2$; $T_{\text{H}}$) | $O_\text{I}$ ($T_{\text{O}}$) | $C_\text{II}$ ($T_{\text{C}}$) |
|-------|----------------|----------------|-----------------------------------|----------------|----------------|
| $2.26R_p$ | 1/10 | 1/3 | 1/2 | 2/3 | 1 |
| $T_{\text{H}}$ | ($>3.5$; 9) | (2.07; 2.75) | (1.93; 2.5) | (1.72; 1) | (1.97; 1) |
| $f_{\text{sca}}$ | 32 | 13.7 | 11.75 | 10.75 | 9.5 |
| $C_\text{CII}$ | 12.25 | 7.0 | 6.0 | 5.5 | 5.0 |

| $R_s$ | External Source | $f_{\text{sca}}$ | $H_\text{I}$ ($x^2$; $T_{\text{H}}$) | $O_\text{I}$ ($T_{\text{O}}$) | $C_\text{II}$ ($T_{\text{C}}$) |
|-------|----------------|----------------|-----------------------------------|----------------|----------------|
| $2.57R_p$ | 1/10 | 1/3 | 1/2 | 2/3 | 1 |
| $T_{\text{H}}$ | ($>3.5$; 12.5) | (2.18; 2.75) | (1.93; 2.5) | (1.72; 1) | (1.97; 1) |
| $f_{\text{sca}}$ | No | No | No | 94.0 | 38.25 |
| $C_\text{CII}$ | No | 35.5 | 20.75 | 16.0 | 12.0 |

| $R_s$ | $3.32R_p$ | Internal Source | $f_{\text{sca}}$ | $H_\text{I}$ ($x^2$; $T_{\text{H}}$) | $O_\text{I}$ ($T_{\text{O}}$) | $C_\text{II}$ ($T_{\text{C}}$) |
|-------|----------------|----------------|----------------|----------------|----------------|
| $3.63R_p$ | 1/10 | 1/3 | 1/2 | 2/3 | 1 |
| $T_{\text{H}}$ | ($>3.5$; 13.5) | (2.35; 4.0) | (2.0; 3.5) | (1.72; 1) | (1.97; 1) |
| $f_{\text{sca}}$ | No | No | No | No | 369.5 |
| $C_\text{CII}$ | No | 107.0 | 42.0 | 28.0 | 18.25 |

### Notes

Cases for which thermal and non-thermal line broadening could not explain assumed observations are indicated by “No” for the corresponding species. Hot atoms sources are confined above the indicated $R_s$ position, where $R_p$ is the planetary radius. The first five positions are for internal sources (regions I and II), while the last is for an external source (region III).

![Atomic Preferential Heating in HD209458b Atmosphere](image)

**Figure 8.** Ratio of effective temperature to background gas temperature ($T_B$) for the two species considered, $O_{\text{I}}$ and $C_{\text{II}}$, as a function of the atmospheric abundance scaling factor. The scaling factor is applied to the whole atmosphere taken as the DIV1 model from Garcia Munoz (2007). Solid line: energetic atoms confined to region above $2 \times 10^3$ km ($\sim 2.25 R_p$), a position almost $6 \times 10^3$ km below $R_{L1}$. Dashed line: same but for a region confined to a position $3 \times 10^3$ km above $R_{L1}$. Changing the bottom of the hot atoms region not only shifts the whole effective temperature distribution but also may make the region so optically thin for particular values of $f_{\text{sca}}$ that no effective temperature could produce the line broadening required to fit the transit absorption. In the example shown, $O_{\text{I}}$ has no hot source solution for $f_{\text{sca}} = 1/10$ and a source position above $\sim 2.57 R_p$. (A color version of this figure is available in the online journal.)
and a second, more extended distribution in the far wings that originates from hot atoms. It is interesting to note that the jump from one distribution to another appears as an inflection in the absorption line profile that may be confused with a Doppler shifted spectral signature from a putative fast moving population around $\pm 100$ km s$^{-1}$ for H I and $\pm 20$ km s$^{-1}$ for O I and C II. The extra-spectral broadening induced by the change in the hot source position also translates into a shift of the effective temperature as shown in Figure 8 (dashed lines). In any case, the position of the active layer for either O I or C II could not be very high; otherwise, the required heating would be excessive (e.g., Table 4). From another side, it is difficult to maintain a hot layer very deep in the atmosphere because restoring processes become important with increasing pressures, making it unlikely that any forcing process can keep a large differential heating between constituents in a stratified atmosphere.

4.2.2. Impact of External Source of Energetic Atoms

The last parameter of importance in our study is the impact of an external hot atomic source. First, we recall that the spectral signature of such a population should show little to no Doppler shift to be consistent with the medium-resolution Ly$\alpha$ observation (BJ08). Second, we recall our initial conclusion that the atmospheric scaling factor should not exceed 2/3, a value for which no hot population is required to recover the observed transit absorptions at Ly$\alpha$ (e.g., Section 4.1). Third, the origin of the external source could be stellar or populations lost from the planet over time. With that in mind, five values of the atmospheric scaling factor $f_{\text{esc}}$ are considered in the range 1/10–2/3. Then, for each value of $f_{\text{esc}}$, we vary the thickness and temperature of the external hot layer as free parameters in order to minimize the $\chi^2$ corresponding to the Ly$\alpha$ observations. For all values of $f_{\text{esc}}$, our study shows that having an additional, external layer of hot H I atoms yields transit absorptions that compare well with flux-integrated and line profile Ly$\alpha$ observations but with rather different spectral signatures that could not be constrained from the only data available. As shown in Figure 7(b), the external source, the internal source, and the source-free cases show distinct spectral signatures in the absorption profile during transit that should help to discriminate between the different solutions when high-resolution and better S/N observations become available. Despite this degeneracy, our study shows that if the atmospheric scaling factor $f_{\text{esc}}$ is strictly smaller than 2/3, a population of hot H I atoms is then required. If this population is confined on top of the Roche lobe limit, its parameters (hot H I column and effective temperature) should follow the distribution shown in Figure 10. Interestingly, for most solutions, the effective temperature seems to fall around $T_{\text{eff}}/T_B \sim 90$–110 (or $T_{\text{eff}} \sim 1.2 \times 10^6$ K for $T_B = 1.2 \times 10^5$ K) while the hot H I column is in the range $[\text{H I}]_{\text{hot}} \sim (2-4) \times 10^{13}$ cm$^{-2}$. It is remarkable to see that, if assumed of stellar origin, the external H I source derived here compares nicely with the ENA solution proposed by Holmstrom et al. (2008), the only difference being that their bulk speed should be weak.

By contrast, for O I and C II lines, our results show that the transit absorption is insensitive to the presence of hot atoms in region III. This non-sensitivity could be explained by the fact that region III is optically transparent for all UV lines of heavy elements considered here because the corresponding abundances are greatly depleted near the Roche lobe limit ($\sim 10^3$–$10^4$ cm$^{-3}$). For these reasons, such an external population, if it exists, could not on its own explain the strong
absorption observed for O“I and C”II unless an additional non-
thermal line broadening is included yet is deeper inside regions
I and II for the two constituents (see the previous section).

5. EXOPLANET-STAR ENVIRONMENT: ROLE OF
ENERGETIC ATOMS

At this level, it may be worth casting our result in the
general context of a giant exoplanet’s interaction with the
harsh environment caused by its nearby parent star. In that
case, the roles of the stellar wind and its related magnetic
field are not clear, particularly in regard to their merging
with the planetary flow and magnetic field. Assuming that hot
planets are locked with the same side facing the star, some
studies derived that, contrary to our quickly rotating Jupiter,
the strength of their magnetic field should be very weak, or
it may not exist at all (Ip et al. 2004; Sanchez-Lavega 2004;
the strength of their magnetic field should be very weak, or
planets are locked with the same side facing the star, some
with the planetary flow and magnetic field. Assuming that hot
field are not clear, particularly in regard to their merging
context, the roles of the stellar wind and its related magnetic
general context of a giant exoplanet’s interaction with the
system should reveal new pieces of information regarding the
and the outflow from the satellite Io, one may legitimately
such as the interaction between the solar wind and the LISM,
As illustrated by comparable situations in our solar system
such as the interaction between the solar wind and the LISM,
or the interaction between the Jovian magnetospheric plasma
and the outflow from the satellite Io, one may legitimately
postulate that detection of hot atoms from an exoplanetary
system should reveal new pieces of information regarding the
spatial distribution of the plasmas and magnetic fields present
and the strength of the interaction processes in play (Ben-Jaffel
et al. 2000; Ratkiewicz & Ben-Jaffel 2002; Zank et al. 2009;
Combi et al. 1998). While the diagnostic will not be easy,
we believe it is fundamental for deriving key parameters of
the star–planet magnetic environment. It follows, then, that a
self-consistent modeling of the interacting planet–star system,
though difficult, will be much-needed in the near future. The
final configuration will be complex and will surely require three-
dimensional MHD modeling of the interacting plasmas.

In our most recent study, we discussed most of the exist-
ing models proposed to describe the gas distribution in the
HD209458b system based on HST Ly line observations (BJ08).
More recently, one-dimensional and two-dimensional hydro-
dynamic simulations have been proposed in the literature and
draw the interesting conclusion that the stellar wind may, un-
der specific conditions, confine the planetary flow and thereby
possibly enhance the total opacity during transit (Murray-Clay
et al. 2009; Stone & Proga 2009). This possibility offers an addi-
tional, intriguing process for enhancing the system opacity from
outside compared to the internal enhancement induced by heavy
elements chemistry as described in Garcia Munoz (2007). Such
a possibility could prove to be of no small importance in uncov-
ering the balance between thermal and non-thermal processes
in shaping the transit absorption for all species, particularly for
O“I and C”II.

The problem with most models proposed in the literature is
that they fail to recover the observed Ly absorption. For instance,
starting from a one-dimensional hydrodynamic description of the interaction of a planetary wind with a stellar
wind but missing the atmospheric chemistry, Murray-Clay et al.
(2009) derived a transit absorption, corresponding to the wave-
length range defined by VM03 and BJ08, of ∼2.9% that falls short of the 8.4%–8.9% absorption reported in BJ08. These
authors thus questioned the accuracy of the transit absorption
derived at this point from the HST observations, arguing that
the transit Ly absorption reported from other low-resolution
observations was much weaker (VM04). Modeling the fully in-
tegrated Ly line absorption during transit, they thus predicted
∼2.4% absorption that still falls short of the absorption level
reported thus far. Within that frame of reasoning, Murray-Clay
et al. (2009) thus concluded that the origin of the missing ab-
sorption in their wind model at ±100 km s⁻¹ from line center
was uncertain and that a good candidate could be the charge
exchange between the planetary and stellar winds. However, we
recall that an absorption at the “magic number” of ±100 km s⁻¹,
repeatedly discussed in several studies since the first report
of the HST observations in 2003, could be the signature of a
population flowing at that velocity range, yet it could also be
an opacity effect purely related to a simple curve of growth
broadening of an absorption line by the gas opacity (BJ08). For
reference, the wavelength range reported in VM03 and BJ08
was virtually dictated by the wavelength range where the HST
spectrum has a good S/N and is not truly directly related to the
observed object. Second, as we show here (see Section 3),
the low- and medium-resolution observations are now compat-
ible and there is no opposition between the transit absorption line
profile shown in Figure 1 and the transit absorption reported for
the integrated line (e.g., Table 2). It follows that if the Murray-
Clay et al. (2009) predictions for the transit Ly absorption fall short of the observations, respectively, from medium and low
resolutions, this only means that their model does not render an
accurate picture of the gas distribution in the HD209458 system.
As a matter of fact, when scaling the hydrogen content in their
model by a factor of 3–5 as proposed by BJ08, these authors
could obtain a transit absorption comparable to observations.
However, invoking charge exchange without any restriction is
probably not a good idea if the stellar wind speed is strong
enough to leave a spectral signature that is not observed (BJ08).

In contrast to models previously described, here we take a
forward analysis approach that proves very useful, at least for
translating the transit absorptions observed for different species in the HD209458 system into atmospheric parameters
and processes. First, our analysis of the FUV HST/STIS archives
confirms relatively strong absorptions previously reported for
O“I and C”II but with larger statistical errors. For the heavy
elements, our analysis shows that a preferential heating is
required, which is consistent with the energy balance in play
due to the proximity of the parent star, either through tidal
disturbances or the impact of the stellar radiation field and the
stellar wind particles and magnetic field. Indeed, hot atoms are
minor populations that receive energy from both the atmospheric
pool of the H“I dominant species and the stellar impinging
particles and photons. The two sources are connected but
have enough energy to over-heat minor components thanks
to the imbalance between perturbing and restoring processes
(Meyer-Vernet 2001). For example, assuming only 1% of the
thermal energy stored in the background gas (at the background
temperature T_B ∼ 10⁴ K) is transmitted via non-equilibrium
processes to minor constituents (mixing ratio ∼ 10⁻⁴), it is not
difficult to find that minor elements could be over-heated by
large factors that may explain the temperatures reported here.
In addition, the large line broadening required to recover the
observed transit absorptions in all lines of heavy species is
consistent with the theoretical prediction of preferential heating
of heavy species in a non-equilibrium gas. For O“I, the ∼ 2.3σ
transit absorption detection requires hot O“I with an effective
temperature ratio of T_0/T_B ∼ 10 or more, depending on the
thickness of the active region. For C”II, the transit absorption
comes with larger statistical errors, yet it also requires hot C”II

ions with an effective temperature ratio of $T_{\text{Cu}}/T_B \sim 5$ or more, but definitely smaller than the temperature ratio obtained for O1. As shown in Figure 8, the ratio between $T_{\text{O1}}$ and $T_{\text{Cu}}$ seems consistent with theoretical predictions about the mass dependence of the broadening velocity distribution of heavy elements in disturbed plasmas (Schizgal 2007). Conversely, starting from such theoretical models, if non-thermal heating is detected for the O1 atoms (with a mass $M = 16$), as here, then we must expect similar heating of the Cu ions (with a mass $M = 12$), but not as strong as that obtained for O1. With that in mind, we may confidently state that both observational and theoretical results tend to support a scenario of preferential heating of O1 and Cu with respect to the background atmosphere of HD209458b. The answer to exactly how much and where atomic energization (or non-thermal heating) is operating will require future observations with better S/N and spectral resolution.

For the dominant component H1, the observations are better quality, yet the conclusions are still uncertain. Our sensitivity study favors two families of solutions for H1 (see Section 4). The first family requires only thermal H1 in a thick atmosphere with a large dayside vertical column, while the second family is based on H1-depleted atmospheres with respect to the DIV1 model (depletion larger than 3/2), but includes a thin source of hot H1 confined to the outer layers of the Roche lobe limit of the nebula. If the second solution is confirmed (see Figure 7), high-resolution and high S/N Lyα absorption profiles observed from ingress to egress orbital positions should provide the related orbital distribution of energetic neutral H1 (effective temperature and H1 column), which in turn should help map the spatial distribution of the energization processes in play in the system. In addition, if the hot H1 source is of stellar origin, our results place strong constraints on the stellar wind and should require it to be rather slow, consistent with the picture of the exoplanet evolving in the stellar extended corona where the flow still may be slow compared to farther distances (Preusse et al. 2005; Griebmeier et al. 2007). Finally, we note that even if the external source appears to be a potential option for H1, it is not a viable solution for the less-abundant heavy species O1 and C ii, for which an energization process is required deeper in the atmosphere.

At this stage, one may wonder what diagnostic can assist in obtaining the thickness and effective temperature of the regions where the different energetic atoms are confined. First, we note that the preferential heating described here should not be uniformly distributed in a confined region, but rather should be distributed with altitude. Now, depending on the depth at which hot atoms are present, our model calculations seem to indicate that all H1, O1, and C ii absorption line profiles predicted during full transit should show distinct shapes, particularly in the line wings (see Figures 7 and 9). This means that high-resolution and S/N observations obtained for distinct species (the mass effect) may help discriminate between the different solutions. Of particular interest, the O1 and C ii transit absorption profiles should not only constrain the balance between thermal and non-thermal atomic populations for these species, but also help to answer the question of whether heavy elements in hot Jupiters are depleted with respect to solar abundance values. In addition, ingress and egress observations with high S/N should provide more details about the spatial distribution of the occulting plasma, which in turn should bring new insight as to the magnetic configuration and energization processes via the inferred abundance and distribution of the energetic populations.

6. SUMMARY AND CONCLUSIONS

HST archive low- and medium-resolution observations of the HD209458 system in the FUV spectral domain are revisited to uncover the gas distribution and kinetic processes in the nebula that envelops the exoplanet. Within that framework, three important constituents—H1, O1, and C ii—are considered. Our analysis of the low-resolution observations obtained in the wavelength range of 1180–1710 Å shows a transit absorption of $\sim 6.6\% \pm 2.3\%$ for H1, $\sim 10.5\% \pm 4.4\%$ for O1, and $\sim 7.4\% \pm 4.7\%$ for C ii. Past results from the analysis of medium-resolution observations for the H1 Lyα component are utilized here (BJ08). Starting from a standard model that includes most of the important chemistry in play in an atmosphere forced by radiation, particles, and gravity from the star, we built a more sophisticated model to account for broadening processes that may originate from superthermal atoms in the upper layers of the nebula or that may be of stellar origin. To estimate the transit effect, the stellar line profiles must be known. While the stellar Lyα line profile is known to a high degree of accuracy from HST medium- and high-spectral resolution observations, such is not the case for the O1 and C ii lines for which existing solar line profiles are assumed. The major difference between this study and previous ones is consideration of O1 and C ii lines simultaneously with the H1 Lyα line. The challenge was to obtain for O1 and C ii almost the same level of transit absorption as for H1 when the abundance is at least 3 or more orders of magnitude smaller for the heavy elements, particularly when the atomic absorption cross sections for the three sets of lines have the same order of magnitude. A differential process that must compensate for the O1/H1 and C ii/H1 lower abundances is then required in order to determine the comparable magnitude of transit absorption by the three species. Here, we propose particle–particle collisions, wave–particle interaction, and mesoturbulence effects that may enhance line broadening during the stellar radiation transmission. Such processes are driven by huge forces caused by the impact of stellar radiation, impinging particles, and tidal and magnetic distortions, all of which act cumulatively on the exoplanetary atmosphere.

Three families of models are thus considered: first, a case free of energetic atoms; second, a case with hot atoms included internally (inside regions I and II); and third, a case with external hot atoms (within region III). With an independent scaling factor for each species, this description covers most models discussed or proposed to date in the literature. First, the comparison of our theoretical model to HST observations of HD209458 shows that for all models considered, a population of hot O1 and C ii atoms, confined inside the Roche lobe, is required in order to fit with the transit absorption observed for the two species’ lines. Our parametric analysis clearly shows that for all considered cases, a preferential heating of O1 and C ii compared to H1 is required, with a magnitude that depends on the assumed atmospheric model (e.g., Figures 8 and 9) but with an effective temperature that is definitely higher than the background temperature (e.g., Figure 8). In addition, all effective temperatures derived here are higher for O1 than for C ii, consistent with the theoretical prediction of the mass dependence of velocity distribution of heavy elements in a non-equilibrium plasma (Schizgal 2007). Interestingly, the presence of energetic atoms may translate into a spectral inflection that appears $\sim \pm 20$ km s$^{-1}$ from the line center of the O1 and C ii lines (Figure 9). Future detection of this spectral feature would confirm the direct signature of superthermal atoms populating the upper atmosphere of HD209458b.
For H\textsubscript{1}, by contrast, two families of models provide a satisfactory fit to available Ly\alpha observations (see Figure 7). For instance, when considering a model free of energetic H\textsubscript{1} atoms, it is possible to fit both the transit absorption profile and the integrated flux drop-off at Ly\alpha simultaneously with an atmosphere that has a dayside column [H\textsubscript{1}] $\sim 1.05 \times 10^{21}$ cm$^{-2}$, corresponding to a depletion in H\textsubscript{1} by a factor of 3/2 with respect to the DIV1 model of Garcia Munoz (2007). However, if we assume a more depleted H\textsubscript{1} atmosphere with respect to DIV1 model, then a population of energetic H\textsubscript{1} atoms is required in order to fit the observations (e.g., Figures 7 and 10). Our sensitivity study shows that depending on the hot source position, which may be confined inside or outside the Roche limit, distinct spectral features appear at $\sim \pm 100$ km s$^{-1}$ in the wings of the transit absorption profile that only future high-resolution observations with a decent S/N should be able to detect (e.g., Figure 7). Among the two potential sources of hot H\textsubscript{1} atoms that may explain the Ly\alpha observations during transit, the one confined near or outside the planetary Roche lobe is of particular interest because it may be directly related to the stellar wind. Indeed, if this hot H\textsubscript{1} population (region III) is of stellar origin, its parameters may help constrain the stellar wind speed and flux. In most H\textsubscript{1}-depleted models considered here, the required external source has an H\textsubscript{1} column in the range of [H\textsubscript{1}]$_{\text{hot}}$ $\sim (2-4) \times 10^{13}$ cm$^{-2}$ and an effective temperature in the range of $T_{\text{H1}}/T_B \sim 90-110$ (see Figure 10).

In summary, our sensitivity study shows that multi-species observations including H\textsubscript{1} and heavy elements are the key tools essential for understanding the structure and composition of transiting exoplanets and their interaction with the nearby parent star. With all predictions expounded here, we look forward to the upcoming HST/Cosmic Origin Spectrograph and STIS observations that should finally reveal the true balance between thermal and non-thermal populations and, we hope, their spatial distribution.

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