RE-VISIT OF HST FUV OBSERVATIONS OF THE HOT-JUPITER SYSTEM HD 209458: NO Si III DETECTION AND THE NEED FOR COS TRANSIT OBSERVATIONS

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ABSTRACT

The discovery of O I atoms and C II ions in the upper atmosphere of HD 209458b, made with the Hubble Space Telescope Imaging Spectrograph (STIS) using the G140L grating, showed that these heavy species fill an area comparable to the planet’s Roche lobe. The derived ~10% transit absorption depths require super-thermal processes and/or supersolar abundances. From subsequent Cosmic Origins Spectrograph (COS) observations, C II absorption was reported with tentative velocity signatures, and absorption by Si III ions was also claimed in disagreement with a negative STIS G140L detection. Here, we revisit the COS data set showing a severe limitation in the published results from having contrasted the in-transit spectrum against a stellar spectrum averaged from separate observations, at planetary phases 0.27, 0.72, and 0.49. We find variable stellar Si II and C II emissions that were significantly depressed not only during transit but also at phase 0.27 compared to phases 0.72 and 0.49. Their respective off-transit 7.5% and 3.1% flux variations are large compared to their reported 8.2 ± 1.4% and 7.8 ± 1.3% transit absorptions. Significant variations also appear in the stellar line shapes, questioning reported velocity signatures. We furthermore present archive STIS G140M transit data consistent with no Si II absorption, with a negative result of 1.7 ± 18.7 including ~15% variability. Silicon may still be present at lower ionization states, in parallel with the recent detection of extended magnesium, as Mg I atoms. In this frame, the firm detection of O I and C II implying solar or supersolar abundances contradicts the recent inference of potential 20–125× subsolar metallicity for HD 209458b.

Key words: planetary systems – planets and satellites: atmospheres – stars: individual (HD 209458) – techniques: spectroscopic – ultraviolet: stars

1. INTRODUCTION

UV detection of both hydrogen and heavy species on the extended atmospheres of hot exoplanets orbiting inside 0.1 AU from their stars provides a useful tool for understanding the properties of these uppermost planetary layers, the energy input from the immense stellar X-ray and UV (XUV) radiation and the processes of interaction with the incident stellar wind magnetized plasma. Provided information on the velocity distribution can be estimated in the transmission signature, the relative abundance of heavy species can be constrained to in turn reveal compositional properties that also pertain to the lower atmosphere and nature of the exoplanet. UV studies of exoplanets can thus provide unique information for their characterization that is usually inaccessible with IR and optical observations. Most of what we understand about hot-Jupiter upper atmospheres is based on far-ultraviolet (FUV) Hubble Space Telescope (HST) transit observations and extensive modeling of HD 209458b, which orbits a G0V star at 0.047 AU. However, as we show in this paper, the full HST FUV observational potential of this target has yet to be reached. Using the Space Telescope Imaging Spectrograph (STIS) with the G140M medium-resolution (R ~ 10,000) grating, a ~10% absorption in Lyα was discovered by H I atoms in an inflated atmosphere reaching the Roche lobe distance of ~2.9 R⊕ (Vidal-Madjar et al. 2003, 2008; Ben-Jaffel 2007, 2008). A Lyα absorption with an enhanced blueshifted component was first reported from the average of three medium-resolution G140M transits by Vidal-Madjar et al. (2003), while Ben-Jaffel (2008), who included a fourth partial transit, found a more symmetric average absorption in the red and blue wings. Existing theoretical models have tried to reproduce the H I observations assuming the solar XUV input where the atmospheric inflation results from heating at the base of the thermosphere around 0.01–1 μbar, yielding a mean temperature of order 10,000 K that drives a hydrodynamic outflow. Most models find enough thermal atomic hydrogen to reproduce the symmetric absorption profile originally reported in Ben-Jaffel (2008) for the HD 209458b transits (Ben-Jaffel 2008; Ben-Jaffel & Hosseini 2010; Koskinen et al. 2010, 2013a, 2013b). However, some issues remain unresolved regarding the exact total thermal H content that depends on the atmospheric solar or supersolar abundances assumed (Ben-Jaffel & Hosseini 2010; Koskinen et al. 2010, 2013a, 2013b), on the strength of the outflow and the tidal effects (e.g., Lammer et al. 2003; Yelle 2004; Tian et al. 2005; García Muñoz 2007; Murray-Clay et al. 2009; Stone & Proga 2009; Guo 2011, 2013; Bourrier et al. 2014), on the geometrical distribution of the gas which can be global or quite likely confined at low (magnetic) latitudes due to the presence of a planetary magnetic field (Adams 2011; Trammell et al. 2011, 2014; Khodachenko et al. 2012; Cohen & Glover 2012; Owen & Adams 2014), as well as on the presence of non-thermal processes affecting the energetics and line broadening (Ben-Jaffel & Hosseini 2010), and on the strength of the stellar XUV heating (G. E. Ballester et al. 2015, in preparation). Charge exchange with the incident stellar wind protons (Holmström et al. 2008; Bourrier & Lecavelier 2013; Tremblin & Chiang 2013) and stellar radiation pressure (Vidal-Madjar et al. 2003) are also key mechanisms that predict an asymmetric Lyα transit absorption profile, but the relevance of these processes depends
on the inclusion of natural line broadening (Ben-Jaffel 2008) and self-shielding (Bourrier & Lecavelier 2013), and a comprehensive analysis is required including the presence of a planetary magnetic field (Kislyakova et al. 2014) and the inherent absorption by the interstellar medium (ISM) that may erase the asymmetric absorption feature if the Doppler shift is not strong enough. The ISM absorption and the relatively low signal-to-noise ratio (S/N) probably limit the H i Lyα data analysis and interpretation, yet all studies agree on the important result that an area equivalent to the size of the Roche lobe is filled on HD 209458b, a finding that has many implications on our understanding of these atmospheres when connected with transit signatures in other species (Ben-Jaffel & Hosseini 2010). However, we must stress here that available observations already show that we are close to making a final diagnostic on the very nature of the transit absorption as shown by the comparison between light curves derived for the blue and red wings of the H i Lyα line (e.g., Figure 3 in Ben-Jaffel 2008). For the relatively good signal to noise reported thus far (Ben-Jaffel 2008), repeated new STIS G140M medium-resolution transit observations of HD 209458b should help converge our determination of the H i Lyα transit absorption profile for this planet, and definitely elucidate any asymmetric spectral absorption signature. Additionally, time variation may be present in the H i Lyα spectral signature of HD 209458b, as can be seen in Figure 3(b) of (Ben-Jaffel 2007). Similarly, time variation has been clearly identified in the H i Lyα absorption of the hot-Jupiter HD 189733b (Lecavelier et al. 2012; Bourrier et al. 2013). On HD 189733b, one STIS observation showed no H i Lyα absorption while on another date it showed absorption that was enhanced in the blue wing. An STIS observation of GJ 436b has also shown an extended hydrogen atmosphere on this warm Neptune, revealing a post-egress signature from a hydrogen tail with an enhanced blueshifted H i Lyα absorption (Kulow et al. 2014).

On HD 209458b, the STIS detection of extended neutral oxygen atoms and singly ionized carbon (the two dominant forms of the species for this environment) also extending to near Roche lobe distances has also been of great importance, since these components can provide additional critical diagnostics of the upper atmosphere (Vidal-Madjar et al. 2004; Ben-Jaffel & Hosseini 2010). Their detection shows that heavy species are effectively entrained in the hydrodynamic outflow of the lighter hydrogen gas (through collisions with the neutral hydrogen atoms and the protons) and overcome diffusive separation (García Muñoz 2007; Koskinen et al. 2010, 2013a, 2013b). The transit absorption depths in the O I at 1304 Å and C II 1335 Å multiplets derived from the STIS G140L observations of HD 209458b were, respectively, 12.8 ± 4.5% and 7.5 ± 3.5% (Vidal-Madjar et al. 2004), or 10.5 ± 4.4% and 7.4 ± 4.7% from a re-visit of the observations (Ben-Jaffel & Hosseini 2010) and correspond to 2.8σ and 2.2σ, or 2.4σ and 1.6σ detections. These large absorption depths cannot be explained by 10,000 K thermal populations at solar abundances since line profiles that would result from thermal and natural broadening for vertical distributions from 1D hydrodynamic models are not wide enough to significantly absorb the broad stellar lines (with solar line widths) during transit. This is explored in various papers (see below). Since the line absorption profiles and thus the velocity distributions of the absorbers were unresolved with STIS (using the G140L grating at R ~ 1000), substantially different interpretations have been put forth.

To broaden the absorption profile while keeping solar abundances, energetic super-thermal populations have been invoked (with effective temperatures 5–100× larger than a ~10,000 K background H-dominated gas), such as from processes that preferentially energize minor species involving chemistry, radiation, and wave–particle interactions, or from turbulence and the stellar wind interaction (Ben-Jaffel & Hosseini 2010). Ben-Jaffel and Hosseini have shown that the final transit absorption profile is strongly dependent on the vertical distribution of the super-thermal population, a diagnostic that could be used if medium-resolution transit spectra are obtained. Alternatively, to enhance the optical thickness of the thermal population, some hydrodynamic models find that 3–5× supersolar abundances would be required accompanied by a hotter thermosphere from stellar XUV input twice that from the mean Sun (Koskinen et al. 2013b). (A previous hydrostatic approximation invoked quite large 4–40× supersolar abundances with an unreasonably strong XUV flux 5–10× higher than the mean Sun; Koskinen et al. 2010). However, recent findings are now showing an unexpected long-term low activity on the star HD 209458, and this low activity does not support scenarios that invoke even moderately high XUV fluxes, such as those of solar mean or maximum activity, to heat and inflate the atmosphere to the extent required by the observations (G. E. Ballester et al. 2015, in preparation). As there appears to be an energy crisis in the upper atmosphere of this planet due to the low XUV input, new information on super-thermal processes that may operate in the upper atmosphere of this planet are needed, and such evidence is uniquely accessible with transit observations that resolve the line absorption profiles and thus velocity and energy distribution of the heavy species.

The Cosmic Origins Spectrograph (COS) on HST provides higher sensitivity than STIS, and it can improve the S/N of the transit absorption in C II 1335 Å and in O I 1304 Å as well as resolve the multiplets and the line absorption profiles at medium spectral resolution (with the G130M grating at R ~ 20,000) as has been demonstrated for the case of HD 189733b (Ben-Jaffel & Ballester 2013, 2014). FUV observations of the HD 209458 system were made with COS G130M by Linsky et al. (2010). Absorption by the planet during transit was reported in the C II 1335 Å doublet lines with a depth of 7.8 ± 1.3% in the −50 to +50 km s⁻¹ interval, similar to the line-integrated absorption detected with STIS. Tentative velocity signatures were reported, with absorption at −10 to 15 km s⁻¹ and less certain features at −40 and +30–70 km s⁻¹, and no absorption at zero velocity. The larger velocities would agree with the presence of an upper atmospheric hot population, or of plasma with large motions around the planet (Linsky et al. 2010; Koskinen et al. 2013b), with great implications about the properties of HD 209458b’s upper atmosphere.

From the same COS data set, Linsky et al. (2010) also reported an 8.2 ± 1.4% transit absorption by Si iii ions in the 1206.5 Å line. In sharp contrast, no Si iii at 1206.5 Å absorption was detected in the average of the four HST transit observations made with STIS G140L that detected O i and C ii, where a negative result of 0.0±0.0% was derived in Si iii (Vidal-Madjar et al. 2004). To fit the COS Si iii results, Koskinen et al. (2013b) found similar 3–5× supersolar abundances and higher
stellar energy input requirements for the upper atmosphere, similar to the inferences made for the O i and C ii.

The composition at high atmospheric altitudes (as modified by the stellar ionization, thermal balance, and charge-exchange processes) reflects the species and abundances at the base of the thermosphere, and it is thus diagnostic of the properties of the lower atmosphere and overall planetary abundances and energy budget (e.g., García Muñoz 2007; Koskinen et al. 2013a, 2013b; Lavvas et al. 2014). This is particularly the case for a hot Jupiter with its strong 3D atmospheric circulation and large effective eddy mixing (e.g., Showman et al. 2009; Parmentier et al. 2013), and where the detection of extended O i and C ii on HD 209458b itself shows that diffusive separation of the heavy species in the upper atmosphere is impeded by the hydrodynamic outflow (Koskinen et al. 2013a, 2013b). For O i and C ii the key lower atmospheric components are H2O, which does not condense on hot Jupiters, and CO, the dominant carbon-bearing species on hot Jupiters (e.g., Moses et al. 2011). For refractory species like silicon, the situation is more complex and uncertain. For silicon to be present in the thermosphere, Koskinen et al. (2013b) find that it cannot condense into silicate clouds in the lower atmosphere, and that the vertical transport should be strong to keep any condensate particles lofted. Furthermore, silicon must be predominantly in the Si ii ionization state, and charge exchange with protons (and He+) can then supply a significant Si ii population to be detected. It may well be that silicon is not effectively removed by vertical and horizontal cold traps on this planet, given the recent detection of Mg i in the upper atmosphere (Vidal-Madjar et al. 2013), but we must first address the validity of the reported COS detection of silicon ions, at least as Si ii, given the contradiction with the negative STIS G140L results.

In this paper we re-visit the COS observations of the HD 209458 system given that these observations were not made in the standard fashion of observing immediately before and/or after the transit to contrast the in-transit fluxes with the actual stellar fluxes around the time of transit. Instead, the in-transit stellar fluxes were ratioed against the average fluxes measured on three separate HST visits that were obtained over a period of one to two weeks with the planet off transit. The limitation of this approach is that the stellar activity, even if it is low, can cause significant flux variations in the FUV line emissions such as over a stellar rotation period, and from stochastic or flare activity (e.g., Parke Loyd & France 2014). This is indeed the case for the Sun for which a variation of ~27% was reported for the Si ii 1206.5 Å line during a rotation period (e.g., Table 3 in Ben-Jaffel & Ballester 2013). It is thus possible that the transit absorptions derived from the COS data could be related to stellar variation rather than to the true planetary transit signature. Linsky et al. (2010) deduced their approach to be valid because the flux level and line shape in the Si iv 1393.7 Å line was similar in the in-transit data and in the averaged off-transit data. We find, however, that this use of the averaged off-transit data requires reassessment.

In Section 2 we re-evaluate the COS observations in the Si iii 1206.5 Å line, C ii 1335 Å doublet, Si iv 1393.7 Å line, and 1364.8–1390.7 and 1405.6–1423.6 Å continua, taking advantage of the temporal information of the data, both from the time-tagging and from comparison of the average stellar fluxes per HST visit. We find indeed significant time variation in the stellar emissions that render the previously derived transit absorptions for Si iii 1206.5 Å line and the C ii 1335 Å doublet from this COS data set unreliable. Complications in using the COS data set for a derivation of velocity signatures in the absorption are also addressed. Moreover, we also present previously unpublished Si ii transit observations of HD 209458b from a re-visit of the original STIS G140M data set that discovered extended H i in Lyα absorption, since these exposures also sampled the Si ii 1206.5 Å line. We find no evidence of a Si ii transit absorption, in agreement with the first STIS G140L findings. We present and discuss the STIS data in Section 3. We also discuss some issues related to the conditions that would be needed in the lower atmosphere to obtain silicon ions in the upper atmosphere. We finish by establishing the need for COS FUV transit observations of this exoplanet, in particular for the unexploited diagnostics in the O i 1304 Å and C ii 1335 Å transit signatures.

### Table 1

| Exp. No. | Start Time in 2009 (UT) | Exp. Time (s) | Planet Mid. Orbital Phase | Grating Wavelength Setting |
|----------|------------------------|--------------|---------------------------|---------------------------|
| 01       | Sep 19 10:10            | 2340         | 0.255                     | 1291                      |
| 02       | Sep 19 11:36            | 0955         | 0.270                     | 1300                      |
| 03       | Sep 19 11:55            | 1851         | 0.275                     | 1309                      |
| 04       | Sep 19 13:11            | 0560         | 0.288                     | 1300                      |
| 05       | Sep 19 13:24            | 2235         | 0.294                     | 1318                      |
| 06       | Sep 24 13:12            | 2340         | 0.710                     | 1291                      |
| 07       | Sep 24 14:38            | 0945         | 0.724                     | 1300                      |
| 08       | Sep 24 14:57            | 1787         | 0.730                     | 1309                      |
| 09       | Sep 24 16:14            | 0925         | 0.743                     | 1300                      |
| 10       | Sep 24 16:33            | 1798         | 0.748                     | 1319                      |
| 11       | Oct 02 14:32            | 1045         | 0.993                     | 1291                      |
| 12       | Oct 02 14:53            | 1096         | 0.997                     | 1300                      |
| 13       | Oct 02 15:55            | 1400         | 0.010                     | 1309                      |
| 14       | Oct 02 16:22            | 1405         | 0.015                     | 1319                      |
| 15       | Oct 18 10:51            | 1057         | 0.490                     | 1291                      |
| 16       | Oct 18 11:18            | 1093         | 0.494                     | 1300                      |
| 17       | Oct 18 12:20            | 1401         | 0.507                     | 1309                      |
| 18       | Oct 18 12:46            | 1405         | 0.512                     | 1319                      |

The spectral ranges covered per grating wavelength setting respectively for detector Segments B and A are: (1291) 1132–1274 and 1291–1433 Å; (1300) 1141–1283 and 1300–1442 Å; (1309) 1153–1294 and 1309–1449 Å; and (1318) 1163–1303 and 1319–1459 Å.

### 2. COS OBSERVATIONS

#### 2.1. Observations and Data Reduction

HD 209458 was observed with COS on 2009 September–October during four HST visits, two or three HST orbits each, with the planet around orbital phases $\phi = 0.27, 0.72, 0.0, 0.49$ (Table 1). The COS G130M grating was used, covering the $\sim$1130–1460 Å region at medium spectral resolution ($R \sim 20,000$, $\sim 15$ km s$^{-1}$, with 0.01 Å sampling). Throughout each visit the exposures were made alternating between four grating central wavelength settings referred to as 1291, 1300, 1309, and 1318. COS FUV spectra are sampled by two detector segments, A and B, that are separated by a small gap. Some of the grating settings either did not sample the important O i 1304 Å triplet or had the lines near the edge of the detector (Table 1), so this stellar emission could not be evaluated as was possible for transit observations of HD 189733b (Ben-Jaffel & Ballester 2013, 2014). Note also that the C ii 1335 Å feature is a
triplet, but it is detected as a doublet with a line at 1334.5 Å and two unresolved lines at 1335.7 Å.

The time-tagged exposures were reprocessed into 100 s segments, but since the S/N was low, the segments were averaged into 1000 s sub-exposures so that the temporal flux variations (depicted in Figure 1) were not dominated by the photon noise level. To extract the stellar emission line fluxes, a weak stellar continuum was first subtracted from each spectrum based on a linear fit to the spectral regions devoid of obvious emission lines identified in a high-resolution solar spectrum (Curdt et al. 2001). For the Si iv 1206.5 Å line we also subtracted a linear fit of the blue wing of the stellar Hα Lyα line which is very broad as detected by COS. This is a relatively small correction compared to the potential planetary absorption, and the associated errors have been included in the propagated errors. The stellar line fluxes, depicted in Figure 1, were extracted by co-aligning the given line in all the spectra, and integrating the spectral fluxes out to about 10% of the averaged peak intensity (Ben-Jaffel 2007). This integration spanned about ±28 km s⁻¹. Photon noise errors were propagated in all reduction steps and problematic pixels (with dq_wgt = 0) were ignored.

### Table 2

| Spectral Feature | Planet | Photon Noise | Intra-visit Flux | Intra-visit Error | Intra-visit Error |
|------------------|--------|--------------|------------------|------------------|------------------|
| Si iv 1393.7 Å   | 0.27   | 0.37         | 0.018            | 0.054            | 0.057            |
| Si iv 1390.7 Å   | 0.72   | 0.964        | 0.020            | 0.056            | 0.059            |
| Si iv 1364.8 Å   | 0.00   | 0.853        | 0.023            | 0.079            | 0.082            |
| Si iv 1364.9 Å   | 0.49   | 1.000        | 0.025            | 0.074            | 0.078            |

a The fluxes have been normalized with respect to the average of visit 4 (ϕ = 0.49), given by: 2.12 × 10⁻¹⁵ for Si iv; 2.33 × 10⁻¹⁵ for C ii; 0.96 × 10⁻¹⁵ for Si iv, and; 4.87 × 10⁻¹⁵ ergs cm⁻² s⁻¹ for the continuum.

b The intra-visit error is the standard deviation of the scattering of the stellar flux during the given visit.

### 2.2. Absolute Wavelength Scale

The determination of a common absolute wavelength scale, and thus of any planetary velocity signature reported from the COS data set, was complicated because of having alternated between the four G130M central wavelength settings during each visit. The original purpose of that setting was to minimize fixed-pattern noise and grid-wire shadow effects (France et al. 2010; Linsky et al. 2010), while for most other transit observations of exoplanets keeping instrumental settings fixed has proven best for measuring relative changes due to the planetary transmission alone. The grid-wire shadow effects are now automatically corrected by the COS pipeline software, as in the CALCOS 2.14.4 and 2.18.5 pipeline versions used for the time-tagged flux analysis and the wavelength study, respectively. The main complication is that the repositioning of the grating is not exactly repeatable due to thermal flexures (Shaw et al. 2009). Although in principle the absolute wavelength scale for each exposure could be set by co-aligning the C ii 1334.5 Å line based on the dip from the ISM absorption of this line as done by Linsky et al. (2010), we found that the S/N is too low to accurately find the center of this absorption in each exposure. To co-align the spectra, for the Segment-A data we compared co-aligning the spectra against each line of the C ii 1335 Å doublet and also against the full doublet. Significant differences were found when using only one line or the full doublet, when the data were smoothed or not, and when different exposures were chosen as the template. Comparing results from fitting against exposures 1 and 15 (Table 1), using only the C ii 1334.5 Å line or the full doublet, and with or without smoothing, we found offsets in the centering of the
ISM 1334.5 Å line absorption of about 10 km s$^{-1}$ (about 5 pixels). This error, though somewhat smaller than the 15 km s$^{-1}$ spectral resolution, produces large differences in the resulting line profiles and in the corresponding transit absorption line profile. In Figure 2 (Section 2.4) we show a sample result of line profiles from co-alignment against exposure 15, using the full doublet, and with the data box-car smoothed by 5.

The Si III 1206.5 Å line data, sampled by the detector Segment B, was co-aligned separately. The wavelength shift found from the CII 1335 Å doublet in the Segment A data differed from that found for Segment B by up to ±4 pixels (while Linsky et al. 2010 applied the same shift to data from both segments). This turned out to be expected since the COS pipeline calibration calculates the spectral offset for each detector segment independently. The SHIFT1A and SHIFT1B in the processed data differ by about 4–7 pixels, similar to the offsets that we found.

2.3. Time Variation of the Stellar Fluxes

Figure 1 shows the time-resolved fluxes for the Si m 1206.5 Å line, C II 1335 Å doublet, Si iv 1393.7 Å line, and 1364.8–1390.7 and 1405.6–1423.6 Å continua. Black symbols show the fluxes from the 1000 s sub-exposures, and gray symbols show the averaged fluxes per HST visit. For each feature, the fluxes have been normalized by the corresponding average value for visit 4 ($\phi \sim 0.49$) to ease the interpretation of the results. The error bars for the sub-exposures are propagated statistical photon noise, while the error bars for the visit-averaged fluxes include the non-statistical flux scattering within a given visit defined as the standard deviation from the mean. The variations within an HST visit can be stellar but there can also be instrumental effects (e.g., Linsky et al. 2012). Since the intra-orbit flux variations do not seem repeatable from orbit to orbit, they cannot be systematically corrected for. The stellar fluxes averaged per visit are provided in Table 2 with both the photon-noise errors as well as errors that include the intra-visit scattering. In the discussion below we refer to the photon-noise errors for direct comparison with the results by Linsky et al. (2010).

To evaluate the validity of deriving a transit absorption from this COS data set we look at the normalized fluxes averaged per HST visit (Table 2). For the C II 1335 Å doublet we find that although the flux during transit ($\phi = 0.0$) is low at 0.880 ± 0.021, the flux is also relatively low for $\phi = 0.27$ at 0.929 ± 0.017. In contrast, the flux for $\phi = 0.72$ of 0.982 ± 0.018 is similar to the reference value of 1.0 ± 0.023 for $\phi = 0.49$ within the errors. Although the transit depth relative to the mean of the off-transit fluxes (at $\phi = 0.27$, 0.72, and 0.49) would be 9.3 ± 2.4%, which is somewhat deeper than the 7.8 ± 1.3% reported by Linsky et al. (2010), the range of depths relative to the different average fluxes for the off-transit visits spans from 5.3 ± 2.9% to 12.0 ± 2.9%. The detection and depth of the C II 1335 Å transit signature of the results.
HD 209458b associated thus far with the COS instrument
remains unconfirmed given the inappropriate observing method
that was employed.

The Si\textsc{iii} 1206.5 Å line also shows a strong time variation. A
low flux of 0.837 ± 0.018 is observed at $\phi = 0.27$ and a similar
value of 0.853 ± 0.023 is seen during transit. Furthermore, the
flux of 0.964 ± 0.020 observed at $\phi = 0.72$ is comparable to
the reference value of 1.00 ± 0.025 at $\phi = 0.49$ within the
errors. Deriving a transit absorption for Si\textsc{iii} is therefore
misleading, given the large time variations. A detection of Si\textsc{ii+}
ions in the upper atmosphere of HD 209458b is not valid from
this COS data set.

The 1364.8–1390.7 and 1405.6–1432.6 Å continuum con-
sists of the photospheric continuum (that decreases toward
shorter wavelengths) and a white continuum emission from the
chromosphere (that increases toward shorter wavelengths; Linsky et al. 2012). No large continuum-flux variations are
observed in tandem with the line emissions, indicating that no
large common-mode instrumental effect was at play. This
chromospheric component is expected to vary with stellar
activity, yet the variability at these wavelengths should be
smaller than in any of the emission lines (e.g., Snow et al.
2010). Although in the observation at $\phi = 0.27$ the continuum
did not appear relatively low as in the other features but was
instead somewhat larger, and during the transit visit it was
relatively low, which could be due to the transit of the planetary
disk, the fluxes are all similar within the errors.

For the Si\textsc{iv} 1393.7 Å line (significantly brighter than the
other 1402.8 Å line of the doublet), we find that the fluxes are
relatively low not only at both $\phi = 0.0$ and 0.27, but also at
$\phi = 0.72$ unlike for Si\textsc{iii} and C\textsc{iii} for which the fluxes at
$\phi = 0.72$ were higher and comparable to the fluxes at $\phi = 0.49$.
Thus, the stellar Si\textsc{iv} emission turns out not to be an accurate
proxy for the C\textsc{iii} and Si\textsc{iii} emissions.

The variations of the emissions as observed in the off-transit
visits are listed in Table 3. Clearly, the 7.5% variation (or
19.4 ± 8.3% max/min) of the Si\textsc{iii} 1206.5 Å flux is quite large,
more so than for the C\textsc{iii} 1335 Å or Si\textsc{iv} 1393.7 Å fluxes
although there may be some overlap if the intra-visit scatter is
included in the errors.

It is interesting to note that the 3.1% variation (or
7.2 ± 10.7% max/min) of the Si\textsc{iv} 1393.7 Å line is smaller than
the 7.5% variation of the Si\textsc{iii} 1206.5 Å line (or
19.4 ± 8.3% max/min) for the same set of observations
(although again they overlap within the larger error bars).
Since the Si\textsc{iv} 1393.7 Å emission originates from a hotter layer
in the stellar atmosphere (at log $T = 4.75$ for the Sun) than the
C\textsc{iii} 1335 Å and Si\textsc{iii} 1206.5 Å emissions (at log $T = 4.10$ and
4.25, respectively; Woods et al. 2000) it would be expected in
general to vary more strongly or at least comparably to the Si\textsc{iii}
1206.5 Å line (based on more variability at higher temperature
regions).

Solar observations indicate that the Si\textsc{iv} 1398 Å doublet
variability is comparable in general to that of the Si\textsc{iii}
1206.5 Å line, or somewhat larger at high activity as known
from short-term and long-term observations and from observa-
tions of flares (Brekke et al. 1996; Woods et al. 2000).

However, a recent evaluation of the solar variability in the FUV
emission lines relevant to hot-Jupiter transit studies has been
made by Ben-Jaffel & Ballester (2013) using 2003–2007
spectra from the Solar Stellar Irradiance Experiment instrument
on board the Solar Radiation and Climate Experiment
obtaining more detailed or relevant results for exoplanet FUV
HST work. The data were divided into periods of low, medium,
high, and extreme flare activity, where the lower activity should
include the emission from plages and enhanced network. In
three out of four flare level categories, the variability of the
Si\textsc{iv} 1398 Å doublet is comparable to that of the Si\textsc{iii}
1206.5 Å line, and somewhat larger for the cases of high
activity in agreement with the findings by Woods et al. (2000).
In that study, there was a separate evaluation for the Si\textsc{iv}
1393.7 Å line (see bottom part of Table 3 in Ben-Jaffel &
Ballester 2013). The solar Si\textsc{iv} 1393.7 Å line showed, in
contrast, that the variability with solar 27 days rotation and
11 yr cycle was somewhat smaller, at 22% and 60%,
respectively, compared to 27% and 73% for the Si\textsc{iii}
1206.5 Å line. (These variabilities are also standard deviations
from the mean.) The solar lines do show more variability than
the COS results for HD 209458, but the COS data set is
extremely limited to three samples. Here we present results for
the Si\textsc{iv} 1393.7 Å line and not the doublet, since this was the
line used by Linsky et al. (2010) as a proxy for the stellar
activity given that it is about twice as bright as the second line
in the doublet. In a separate analysis of the COS data set (not
presented here) in which we have not divided the exposures
into time-tagged segments, we see that the variation in the full
doublet is larger and more comparable to that of the Si\textsc{iii}
1206.5 Å line, due to inclusion of the more variable and/or
noisier second line in the doublet. Parke Loyd & France (2014)
report on temporal variations on FUV fluxes of Sun-like stars
in 60 s time intervals. For HD 209458 they report upper limits
for the variation in the Si\textsc{iii} 1206.5 Å line and Si\textsc{iv} 1398 Å doublet
emissions (which is not surprising given the relatively low S/N of the data), and their upper limit variation for the Si\textsc{iv}
doublet is a bit larger than for the Si\textsc{iii} line. Therefore, from the various lines of evidence presented, it is
unclear at this point if the relatively low visit-to-visit variation
of the Si\textsc{iv} 1393.7 Å line compared to the larger variation in the
Si\textsc{iii} 1206.5 Å line is significant and distinct for this star
compared to the Sun. The degree of intra-visit scatter for both
features seems comparable, however, although the COS data is
extremely limited. Future observations should shed more light
into the simultaneous temporal FUV flux variations on this star.

Finally, it is also interesting that the Si\textsc{iii} 1206.5 Å and C\textsc{iii}
1335 Å emissions may have shown a stellar rotational varia-
tion. Visits 1, 2, 3, and 4 were made on days 0 (reference date),
5, 13, and 29. Using the stellar rotation periods of
~11.2–14.1 days derived from the Rossiter–McLaughlin effect
and the stellar line widths provided in the literature (c.f., G. E.

Table 3
HD 209458 Average Stellar Fluxes from COS Data set, and Apparent Visit-to-
visit Variations from Off-transit Data

| Feature               | Flux[$^a$,$^b$] (10^{-15} ergs cm^{-2} s^{-1}) | %Variation$^b$ as a Std. Dev. | %Variation$^b$ as a Max/Min |
|-----------------------|-----------------------------------------------|--------------------------------|---------------------------|
| Si\textsc{iii} 1206.5 Å line | 1.98 ± 0.15                                  | 7.5%                           | 19.4 ± 8.3%               |
| C\textsc{ii} 1335 Å doublet     | 2.26 ± 0.07                                  | 3.1%                           | 7.7 ± 5.4%               |
| Si\textsc{iv} 1393.7 Å line     | 1.47 ± 0.05                                  | 3.1%                           | 7.2 ± 10.7%              |
| 1364.8–1390.7 Å doublet         | 4.94 ± 0.07                                  | 1.4%                           | 3.2 ± 5.0%               |

$^a$ Mean spectral flux and standard deviation.
$^b$ Errors include intra-visit noise.
Ballester et al. 2015, in preparation), these visits corresponded to stellar rotational phases of 0 (reference phase), 131–165, 336–63, and 20–212°. Therefore, visits 1 and 3 that showed the lowest fluxes should correspond to similar stellar phases, around the reference phase 0°.

We emphasize, however, that the COS data set at hand is extremely limited, consisting of only a single in-transit observation visit and three off-transit visits on separate dates. To definitely ascribe a stellar rotational modulation to the Si m 1206.5 and C n 1335 Å stellar fluxes would be premature, since there can be stochastic effects. Furthermore, to derive a reliable transit absorption based on the observing technique used for the COS data set, one would have to observe many times with the planet both in-transit and off-transit, to hopefully average out potential rotational, stochastic, small flaring activity, and long-timescale magnetic cycle variations in the stellar fluxes. Such extensive observations are not viable with HST. Instead, the standard transit method of directly measuring the actual stellar flux immediately before and/or after transit is by far the most direct and least ambiguous FUV transit observational method, as well as the one that would utilize the least HST resources. Already, the time variation found in the stellar fluxes in this COS data set clearly demonstrates this argument.

2.4. Problems with the Reported Velocity Distribution of the Absorbers

COS G130M transit observations of HD 209458b have high enough sensitivity and spectral resolution to potentially determine the velocity distribution of the absorption by the heavy species on the planet at similar S/N as in the STIS G140M observations of the H i Lyα line absorption (Vidal-Madjar et al. 2003, 2008; Ben-Jaffel 2007, 2008; Ben-Jaffel & Hosseini 2010). This has been demonstrated for both the C n 1335 Å doublet as well as the O i 1304 Å triplet transit observations of HD 189733b (Ben-Jaffel & Ballester 2013). This figure 2 shows the average C n 1335.7 Å line profiles for the four HST/COS visits of HD 209458. Although there may be real planetary atmospheric absorption during transit (ϕ = 0), we find an apparent visit-to-visit variation in the average off-transit stellar line shapes that precludes a proper evaluation of the velocity signature in the planetary absorption. For these reasons of potential intrinsic time variation in the stellar line shapes, the velocity distribution of the absorbers reported by Linsky et al. (2010) for HD 209458b from the COS data set at hand is invalid. We note that the apparent stellar line-shape variation may be related instead to errors in the co-alignment of the spectra that was needed since the multiple grating wavelength settings were not exactly repeatable as described in Section 2.2, but this cannot be fully explored with this data set. Proper COS transit observations are needed, with consecutive data with the planet in and out of transit, and using a single grating wavelength setting (Section 2.2).

3. STIS G140M AND G140L OBSERVATIONS: NO SI III DETECTION

The HST STIS medium-resolution G140M transit observations that discovered the extended hydrogen atmosphere on HD 209458b (Vidal-Madjar et al. 2003; Ben-Jaffel 2007) also sampled the Si m 1206.5 Å line. With a resolving power of R ~ 10,000, the line is spectrally resolved and well separated from the wings of the Lyα line although the S/N is relatively low. Three transit observations were made (Table 4). Figure 3 shows the line fluxes per HST visit, integrated at 1206.5–1207.14 Å and normalized to the average of the first two points of 1.56 × 10−15 ergs cm−2 s−1. No Si m transit absorption is detected. The ratio of the average of the three points within 3000 s from mid-transit to the first three off-transit points yields a negative result of 1.7 ± 18.7% absorption. The 1.7% absorption, if real, would represent the 1.5% obscuration by the disk of the planet.

Although the S/N is low, large temporal variations are clearly present, from visit to visit, and intra-visit. The standard deviation is 13% for the off-transit points, and 15% for all the data. Thus, as with the COS observations discussed in Section 2.3, we find significant variation in the stellar Si m emission. The 13% standard deviation variation of the off-transit data found with STIS is about twice the 7.5% value found with COS.

The original STIS G140L observations sampled four partial transits and a negative detection in Si m 1206.5 Å was reported with a transit absorption of 0.0 ± 0.0% by Vidal-Madjar et al. (2004). The non-detection was later confirmed by Ben-Jaffel &
Absorption depths from transit light curve FUV observations

| Instrument Mode | Species Feature (Å) | Species Feature (Å) | Species Feature (Å) | Species Feature (Å) | Ref. |
|----------------|--------------------|--------------------|--------------------|--------------------|-----|
| FUV observations |                  |                  |                  |                  |     |
| O I 1304        | C II 1335          | Si ii 1206.5      | Si iv 1393.7      |                   |     |
| doublet         |                    | line              |                   |                   |     |
| STIS G140L      | 12.8 ± 4.5%        | 7.5 ± 3.5%        | 0.0 ± 6.5%        | Vidal-Madjar et al. (2004)* |
|                 |                    |                   |                   |                   |     |
| STIS G140L      | 10.5 ± 4.4%        | 7.4 ± 4.7%        | confirmed         | Ben-Jaffel & Hosseini (2010)* |
|                 |                    |                   |                   |                   |     |
| STIS G140M      | n/a                | n/a               | 1.7 ± 18.7%       |                   |     |

Invalid depth estimates from COS 2009 data set from in-transit data against data from other dates

| Instrument Mode | Species Feature (Å) | Species Feature (Å) | Species Feature (Å) | Species Feature (Å) | Ref. |
|----------------|--------------------|--------------------|--------------------|--------------------|-----|
| COS G130M      | C II 1335          | Si ii 1206.5      | Si iv 1393.7      |                   |     |
| Doublet        |                    | line              |                   |                   |     |
| * , this work  | 7.8 ± 1.3%         | 8.2 ± 1.4%        | 0.0 ± 0.01%       | Linsky et al. (2010)b |
| * , this work  | 9.3 ± 2.4%         | 8.6 ± 2.7%        | 3.1 ± 4.2%        | vs. off-transit, ave, photon noisec |
| * , this work  | 5.3 ± 2.9%         | −1.9 ± 3.5%       | 1.5 ± 4.9%        | vs. φ = 0.27, photon noised |
| * , this work  | 9.3 ± 8.4%         | 8.6 ± 9.5%        | 3.1 ± 12.1%       | vs. off-transit, ave, intra-visit var.e |
| * , this work  | 5.3 ± 9.8%         | −1.9 ± 12.0%      | 1.5 ± 16.8%       | vs. φ = 0.27, w intra-visit var. f |

Notes:
* The STIS G140L and G140M results were respectively derived from 4 and 3 transit observations.
* Invalid “transit depth” reported by Linsky et al. (2010), not from a transit light curve but from the average of data with the planet off-transit at orbital phases φ = 0.27, 0.72 and 0.49, and with errors for photon noise only.
* As in item a, for comparison with the Linsky et al. results, with photon noise only.
* Sample invalid “transit depth” from contrasting the in-transit data against off-transit observation at φ = 0.27. A negative detection is obtained in Si ii, and a smaller transit depth is obtained in C ii.
* Invalid “transit depths” derived as in items c or d but including the intra-visit standard-deviation variations (Table 2) in the errors. No previous HD 209458b UV transit study has included this variation. Full transit light curves are needed for a proper assessment of these variations and thus of the true potential of the COS transit measurements of HD 209458b.

Hosseini (2010). Although a limitation of the low-resolution G140L data is the contamination of the Si ii line by the blue wing of the stellar Lyα line, and the S/N in the (lower sensitivity) G140M data is low, taken together, there are now seven transits observed with STIS that do not show Si ii absorption.

A summary of the current transit results of heavy species on HD 209458b with STIS and COS is provided in Table 5, including the new results from STIS. We also include transit depths from Linsky et al. (2010) from the 2009 COS data set and those discussed in Section 2 for comparison, although all of these depths are not valid since the stellar flux around the time of transit is unknown. For valid COS results new observations are required sampling the transit light curve.

4. DISCUSSION: NEW LIGHT ON CONTRIBUTION OF UV STUDIES TO EXOPLANETARY ATMOSPHERIC SCIENCES

The abundance of heavy species in the upper atmosphere has major implications on all pressure levels from the top to the bottom of a planetary atmosphere. The link of the FUV transit observations with properties of the planet and its lower atmosphere are often underplayed. The mere detection of extended O i and C ii absorption in HD 209458b’s upper atmosphere with STIS G140L (at low spectral resolution) already requires solar or supersolar abundances, a firm result that is in sharp disagreement with the recent inference of potential x20–125 low metallicity on this planet (Madhusudhan et al. 2014). This low metallicity has been raised as one of two explanations for an inferred low H2O abundance in the planet’s lower atmosphere: either a low metallicity and C/O < 1 since water would be the major oxygen-bearing species in this case, or a high metallicity but C/O > 1. A 20–125× low metallicity would be highly unexpected on a hot Jupiter. (Note that HD 209458 has a solar metallicity [Fe/H] = −0.0 ± 0.2; Mazeh et al. 2000.) The goal of Madhusudhan et al. (2014) is to explain a low contrast 1.4 μm band absorption reported for this planet from HST Wide-Field Camera 3 transit data, yet it is possible that some level of haze scattering is present (Deming et al. 2013), as well as that the data need further work (T. Evans et al. 2015, in preparation). Since species in the upper atmosphere derive from dissociation products in the lower atmosphere, issues of metallicity and C/O ratio are directly testable with FUV observations—provided high quality data resolving the transit absorption line shapes are obtained.

The presence of Si ii in the upper atmosphere of HD 209458b would have implied that silicon gas is not effectively depleted by cloud condensation in the lower atmosphere (Koskinen et al. 2013a, 2013b; Lavvas et al. 2014). This turns out to possibly still be the case as demonstrated by the recent detection of 6.2 ± 2.9% absorption (or 8.8 ± 2.1% if there was still post-egress absorption) by extended Mg i on this planet at near-solar abundance (Vidal-Madjar et al. 2003), because magnesium and silicon condense together into silicate grains of fayalite and enstatite (Visscher et al. 2010). The detection of magnesium in the thermosphere of HD 209458b indicates that the balance of day-to-night temperature (Showman et al. 2009; Moses et al. 2011; Crossfield et al. 2012) against the strong vertical and horizontal 3D dynamics (Showman et al. 2009; Spiegel et al. 2009; Parmentier et al. 2013) impedes significant condensation and
settling of refractory silicate species on this planet (Koskinen et al. 2013a, 2013b; Lavvas et al. 2014). If condensation takes place, such as on the nightside, the transport of fine silicate grains onto hotter high-altitude dayside regions may allow for effective sublimation on this hot Jupiter. Such a strong transport of fine grains has been found to be possible on HD 209458b based on 3D global circulation modeling that included test particles and found a strong circulation with large effective eddy coefficients of for example $K_{see} \sim 10^{10} \text{cm}^2 \text{s}^{-1}$ at $P \sim 1 \text{ mbar}$ (Parmentier et al. 2013).

With respect to the FUV and NUV observations and the upper-atmosphere modeling, the disagreement lies in the predicted Si m and observed Mg i ionization states, such that silicon might be present mainly as either Si i or Si m. In the latter case charge-exchange reaction rates invoked to convert part of the Si m into Si m would need to have been overestimated so that no significant Si m 1206.5 Å absorption is detected in transit. The charge exchange of Si m with protons (Si$^+ + p^+ \rightarrow Si^{++} + H$) was first proposed by Linsky et al. (2010) as the main source of Si m since this reaction has been found to be relevant for the Sun. In their detailed upper-atmosphere models for HD 209458b that included heavy metal species, Koskinen et al. (2013a, 2013b) confirmed that this reaction is key in producing detectable amounts of Si m to fit the $\sim$8% transit depths reported by Linsky et al. from the COS data set. However, our new STIS G140M negative finding for Si m on this planet, which is consistent with the previous negative detection by Vidal-Madjar et al. (2004, Table 5), poses new questions into the modeling and/or the state of the upper atmosphere of this planet. It may be that the model temperatures are too high since temperatures above $\sim$15,000 K are required for the Sun to produce significant Si m abundances (Baliunas & Butler 1980) and these temperatures do not necessarily apply to this planet. The model temperature depends on the chemical composition, on the stellar XUV input and the heating efficiency, and on the velocity of the outflow since it can adiabatically cool the atmosphere, although there are always uncertainties in these calculations. We find in the literature that only models with high stellar XUV input and high heating efficiency seem to reach high temperatures of 15,000 K and beyond, such as all the model cases in Tian et al. (2005), the sub-sonic cases in García Muñoz (2007), and the models in Koskinen et al. (2013a, 2013b) that explicitly assume a 10x or 100x higher solar XUV input for the star. Other models reach about 12,000–14,000 K peak temperatures, such as the Yelle (2004) model, the super-sonic cases in García Muñoz (2007), and the Koskinen et al. (2013a, 2013b) models with solar XUV input. In the modeling of the upper atmosphere of a non-magnetized HD 209458b and its interaction with the stellar wind, Murray-Clay et al. (2009) find that the peak temperature reaches $\sim$10,000 K for a solar XUV flux, while for a 1000 times larger XUV flux typical of young T-Tauri stars the peak temperature reaches only slightly larger values due to radiative H I Ly$\alpha$ cooling rather than by the expansion of the gas. In a separate work we are finding evidence that the star HD 209458 has a surprising long-term low activity, and this indicates that the star provides a significantly lower XUV input to the planet than assumed in all previous modeling (G. E. Ballester et al. 2015, in preparation). In that work we apply the detailed photochemical hot-Jupiter upper-atmosphere models of García Muñoz (2007) that include detailed photochemistry for both ion and neutral species of H, D, He, O, C and N and for which we have updated our best current estimate of the stellar X-ray and UV input. The modeling indeed finds peak atmospheric temperatures (for solar abundances) of only $\sim$10,000 K. Given the Mg i detection, and accompanying non-detection of Mg ii (Vidal-Madjar et al. 2013), the dominant silicon ionization state may be Si i since Mg i and Si i have similar ionization potentials. Nevertheless, the finding that Mg i dominates in the upper atmosphere of this planet is highly unexpected, since significant photoionization ($\lambda < 1621$ Å) should be present while Mg ii was not positively detected. This seems to require very large electron densities for the dielectric recombination required to counteract photo-ionization: for example, at the reference altitude of $r = 3 R_p$, Bourrier et al. (2014) require at least two orders of magnitude higher electron densities than estimated from current hydrodynamic models (García Muñoz 2007; Koskinen et al. 2013a, 2013b; Guo 2013; Lavvas et al. 2014, G. E. Ballester et al. 2015, in preparation). This is something that is rather hard to explain.

Another finding is that the Mg i 2853.0 Å line absorption seems to be blueshifted to $\sim$62 to $\sim$19 km s$^{-1}$ (Vidal-Madjar et al. 2013). This finding is quite compelling to some and unexpected to others, as per the discussion in the Introduction related to the H i Ly$\alpha$ line. Again, the large electron densities required for dielectric recombination and the fast outflows needed at the exobase to explain the Mg i blueshifted absorption by stellar radiation pressure (Bourrier et al. 2014) are difficult to reconcile with current upper atmosphere models. Yet, if confirmed, the Mg i blueshifted absorption reveals a net anti-solar motion that may apply to one or more components of the upper atmosphere. Do the O i and C ii species also show a net blueshifted absorption? Are the motions of the ions and neutrals fully coupled (e.g., García Muñoz 2007; Adams 2011; Trammell et al. 2011) or are they decoupled at large enough distances and low collision rates (e.g., Koskinen et al. 2014)? The latter could be expected from effects by different radiation pressure, charge exchange with the stellar wind protons, close and open planetary magnetic-field lines and decaying field strength with distance, and net magnetospheric currents and convection. Velocity-resolved transit data on the C ii 1335 and O i 1304 Å lines, even if only separating the blue- and red-component absorptions, would provide much needed tools for characterizing the state of the upper atmosphere of HD 209458b that is still an enigma. Such data can be obtained with COS.

5. CONCLUSIONS

We have presented new STIS G140M transit data reinforce which the original results with STIS G140L that Si m ions are not detected in the thermosphere of HD 209458b. Silicon may still be present in the upper atmosphere, but at a lower ionization state that may even be Si i, based on the independent HST detection of extended Mg i on this planet which also indicates that silicate condensation and cold trapping is not 100% effective in the lower atmosphere. The models for HD 209458b by Koskinen et al. (2013a, 2013b) that include refractory species already predict Si m to be the dominant silicon species in the upper atmosphere, so what is needed as a first step is to limit the yield for Si m. A second step that is much harder to address would be whether the silicon is in the Si i or Si m state, given the positive Mg i but negative Mg ii detection on HD 209458b by Vidal-Madjar et al. (2013) and that Si i and Mg i have similar ionization potentials. The lack of
a positive Si III detection in the extended atmosphere of the planet reported in this work, together with the positive Mg I detection and the long-term low activity now being identified for the star (G. E. Ballester et al. 2015, in preparation), indicate that a revision to our present understanding of the upper atmosphere of this planet is needed. Much new insight can be obtained with new COS FUV transit observations.

The existing COS G130M observations of the HD 209458 system were not standard transit observations and significant stellar flux variations found in the data invalidate previously reported transit results. Proper FUV transit observations with COS are needed, sampling the transit light curve (at a single grating wavelength setting). These observations will independently confirm and measure transit depths in the O I and C II species at high S/N, and furthermore resolve the velocity distribution of the O I and C II species with major implications on upper atmospheric dynamics, energetics, and magnetospheric processes, as well as on the species abundances that are also relevant for the characterization of the planet and its lower atmosphere. In this frame, the detection of O I and C II in the upper atmosphere of HD 209458b using only unresolved lines already requires solar or supersolar abundances that are in disagreement with a very low metallicity as recently considered in the literature. In the near future, upper atmospheric UV studies of exoplanets may prove key for unraveling the thus far elusive properties of low mass exoplanets.

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