EPSC Abstracts
Vol. 12, EPSC2018-158, 2018
European Planetary Science Congress 2018

Modeling of the UV absorption by OI and CII in exosphere of the hot jupiter HD 209458b

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Abstract

We apply a 2D hydrodynamic multi-fluid code [1, 2] to model the absorption in resonant lines of OI and CII in exosphere of HD 209458b. The absorption in these lines at the level of 10% was observed during several transits, but has not been yet satisfactorily explained. Our simulations show that the upper atmosphere of HD 209458b expands beyond the Roche lobe in the form of two supersonic streams that propagate towards and outwards the star. The heavier species of O and C are dragged within these streams and produce resonant Doppler shifted absorption consistent with the observations.

1. Introduction

Besides Lyα, the primary transit of HD209458b has been also observed with HST/STIS at other far UV wavelengths. In particular, *Vidal-Madjar et al.* (*2004*) reported absorption depths of 13±4.5% and 7.5±3.5% in OI ($2p^2$ 2P – $2p^2$ 2D) and CII ($2p^4$ 3P – $2p^4$ 3S) resonance lines. While the Lyα absorption may be dominated by the natural line broadening mechanism, acting in the exospheric material inside the Roche lobe, the absorption by heavier species, with the abundances 3 to 5 orders of magnitude less than that of hydrogen, offers a possibility to trace the planetary plasma beyond the Roche lobe. However, the previously applied 1D models could not explain the observed absorption width by the resonant broadening, corresponding to the width of the emission lines, up to 40 km/s, while the natural line broadening gave the absorption at the level of only 3-4%. *Koskinen et al.* (*2010*) estimated that such factors as sporadic hot spots on the stellar disk, limb darkening or limb brightening, super-solar abundances, position of H_2/H dissociation front can't provide sufficient increase of the OI transit depth, while *Ben-Jaffel & Sona Hosseini* (*2010*) argued that for the sufficient thermal broadening, O and C inside the Roche lobe should have temperatures up to 10 times higher than that of hydrogen. In the present paper we show that the observed broadening may be generated by a global flow of the escaping planetary upper atmospheric material beyond the Roche lobe.

2. The Model

The minor species were added to the initial atmosphere of the HD209458b, assuming the solar abundances, and then evolved according to the dynamic equations of the used model. The population of different ionization states for each element was calculated assuming the specific photo-ionization and recombination rates. Besides of that, an influence of the resonant charge-exchange reaction with hydrogen $O+H^+ \leftrightarrow O^+ + H$ on the atomic oxygen population was taken into account. The reaction cross-section, $\sim 10^{-15}$ cm^2, is sufficiently large, so that O ionization follows the ionization of H. Because of a much smaller photo-ionization threshold for C, than that for H, the carbon atoms are ionized in the lower thermosphere at heights of about $1.1R_p$. Therefore, we add the already ionized carbon atoms to the modelled atmosphere and follow the dynamics of CII and CIII, taking into account their further photo-ionization and recombination.

3. Results

Figure 1 shows density distributions of hydrogen atoms, OI and CII in the escaping planetary atmosphere of HD209458b. The assumed abundances for O and C are $O/H=8.5\cdot 10^{-4}$ and $C/H=3.6\cdot 10^{-4}$, respectively. The stellar wind (SW) was taken to be very weak, so that it does not affect the numerical solution for the outflowing planetary wind (PW). In our previous simulations [1, 2] it was shown that in case of neglecting the Coriolis force, the expanding PW forms a nearly symmetric double stream structure. Beyond the super-sonic transition point located outside the Roche lobe at $\sim 5R_p$, the escaping PW streams are further accelerated by the tidal force.

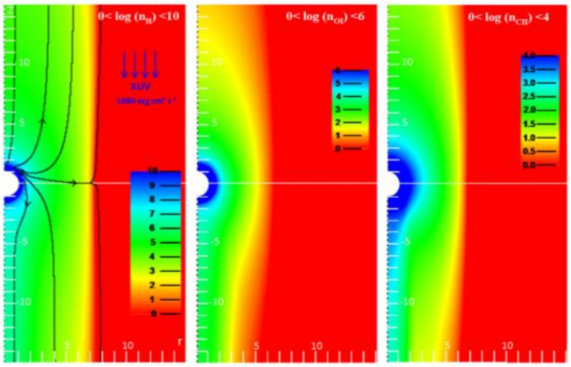

Figure 1. Density distributions of hydrogen atoms (n_H), oxygen atoms (n_{OI}) and carbon ions (n_{CII}) in the PW flow under typical for HD209458b conditions and for a very weak SW. The plotted values are in log scale. The streamlines of the corresponding flows are shown in black. The values outside the indicated variation ranges of the plotted parameters are colored either in red if smaller than minimum, or in blue, if higher than maximum. White circle indicates the planet.

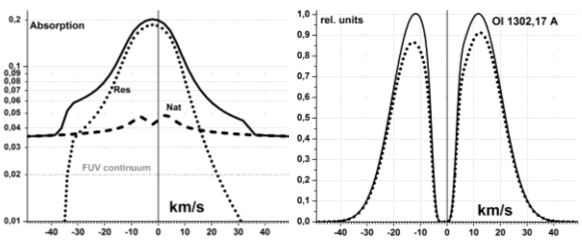

Figure 2. *Left panel*: The absorption profile for OI 1302.17 Å line (thick solid line). The dotted and dash-dotted lines show the decomposition of the OI 1302.17 Å line absorption onto the resonant component and the absorption due to natural line broadening, respectively. *Right Panel*: The shape of OI 1302.17 Å line out-of-transit (solid) and the modeled in-transit (dotted), depleted due to absorption.

The absorption produced by OI, carried within the PW flow, is shown in Figure 2 for the case of the line OI 1302.17 Å, taken as an example. It produces the largest contribution to the whole absorption of the OI multiplet, because of its highest statweight. The decomposition of the calculated absorption shows that its resonant part constitutes a significant portion (5÷15) %, covering almost the whole line from –30 km/s in the blue wing up to 15 km/s in the red wing. The input of natural line broadening by dense exosphere is about 4%, which is the same as in previous works where no PW motion was included. The transit depth of the whole OI multiplet reaches a value of 8.5%. The similarly modeled CII multiplet absorption gets up to 8.7%. In the simulations we also checked how the absorption is affected by such factors as XUV intensity and SW intensity. It was found that sufficiently high total pressure of the SW may stop the dayside PW flow, making the absorption profile strongly asymmetric. This effect enables the probing of the SW intensity.

It has been shown for the first time that with the account of the effect of the species, carried within escaping PW streams, the transit depths observed for oxygen and carbon resonant multiplets can be reproduced assuming the typical solar abundances. The depths can be even larger than that for the Lyα line, reaching values of about 10%. The performed simulations confirm the previously proposed idea that bulk motion of the HD209458b hydrogen atmosphere, escaping the planet with the velocity of several tens of km/s, drags the heavy elements, which sufficiently increase the resonant line broadening in absorption of the corresponding stellar lines.

Acknowledgements

This work was supported by the Russian Science Foundation, project 18-12-00080 and Austrian Science Foundation FWF, projects I2939-N27, S11606-N16, S11607-N16. Parallel computing simulations have been performed at Computation Center of Novosibirsk State University, SB RAS Siberian Supercomputer Center, and Supercomputing Center of the Lomonosov Moscow State University.

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