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In-transit Lyα absorption by HD 209458b under different regimes of the planetary and stellar winds interaction

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Abstract

The interaction of an escaping upper atmosphere of a hydrogen rich non-magnetized analogue of HD209458b with the stellar wind of its host G-type star is simulated with a 2D axisymmetric multi-fluid hydrodynamic model. Different regimes of the planetary upper atmospheric material escape, depending on the parameters of the stellar wind and XUV flux are considered. The performed simulations enable calculating of the Lyα absorption during transits of HD209458b and quantifying the major mechanisms responsible for its observed features.

1. Introduction

The interpretations of Lyα spectra measured during transits of HD209458b still remain controversial. The existing explanations based on 1D hydrodynamic models of hot Jupiters' material escape suggest that the detected absorption, extending over the high velocity wings (~100 km/s), is due to *non-resonant natural line broadening*, caused by dense and warm exosphere that fills the Roche lobe of the planet. At the same time, the modelling by kinetic codes yields that the *resonant, or thermal line broadening* absorption by fast hydrogen atoms, so-called ENAs, which takes place beyond the Roche lobe might be more important. As the major mechanisms responsible for the ENAs production, the acceleration by radiation pressure (in the same Lyα band) and charge-exchange between stellar wind protons and planetary atoms are considered, while the domination of particular mechanism is still the matter of debate. To shed more light on that issue, we apply a 2D hydrodynamic multi-fluid model that self-consistently describes the expansion of a "hot jupiter's" upper atmosphere composed of hydrogen and helium at partial ratio $x_{He}/x_{H2} = 1/5$ (heated by the stellar XUV), taking into account the interaction between the expanding planetary wind and the stellar wind plasma. The production of ENAs by charge-exchange and acceleration by the radiation pressure are taken into account in the model [1,2].

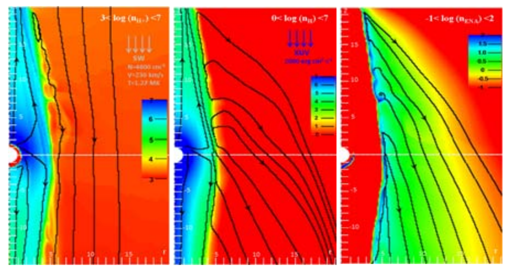

Figure 1: Density distributions of protons (n_{H+}), planetary atoms (n_H) and ENAs (n_{ENA}), in the *"captured by the star"* regime of PW-SW interaction by HD209458b for the *slow* SW (p_{SW}=5x10^{-6} μbar), F_{XUV}=4.466 erg s^{-1}cm^{-2} at 1 a.u.

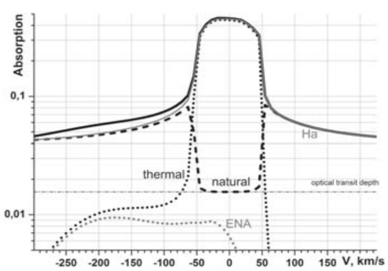

Figure 2: Absorption profile of Lyα line (thick solid) for the regime sown in Figure 1. Black-dotted and black-dashed lines represent the *resonant thermal* and *non-resonant natural* parts of the absorption, respectively; whereas gray-dotted and gray-solid lines show the contribution of ENAs and planetary atomic hydrogen (Ha).

2. Results

Depending on natural (about an order of magnitude) variations in the total pressure of the stellar wind SW, the escaping planetary wind (PW) of HD209458b formed during the expansion of the planetary upper atmosphere energized by the stellar XUV radiation, can exist in two essentially different regimes [1]: 1) the "*blown by the wind*" regime, when sufficiently strong SW stops the escaping PW at the day-side and channels it away from the star into the tail, forming a kind of a paraboloid-shaped planetary plasmasphere, and 2) the "*captured by the star*" regime, when the tidal force exceeds the action of the SW ram pressure and a double-stream structure of the escaping PW is formed along the planet-star line (in the star-wards and tail-wards directions). In both cases the PW is sufficiently dense to remain strongly collisional even rather far from the planet (up to several tens of R_p).

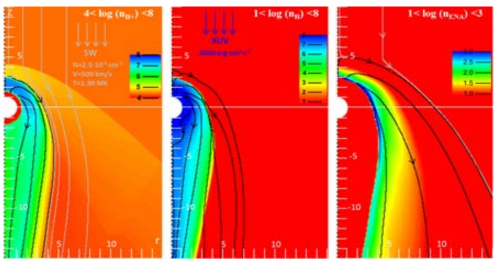

Figure 3: Density distributions of protons (n_{H+}), planetary atoms (n_H) and ENAs (n_{ENA}), in the *"blown by the wind"* regime of PW-SW interaction by HD209458b for the *fast* SW (p_{SW}=1.3x10^{-4} μbar), F_{XUV}=4 erg s^{-1}cm^{-2} at 1 a.u.

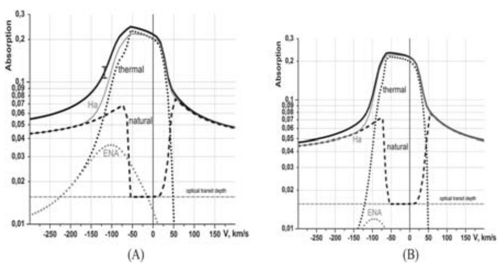

Figure 4: Absorption profile of Lyα line (thick solid) in the *"blown by the wind"* regime of PW-SW interaction by HD209458b for the *fast* SW (500km/s, T_{SW}=2.9MK). **(A)**: F_{XUV}=4 erg s^{-1}cm^{-2} at 1 a.u., n=2.5x10^{4}cm^{-3}; **(B)**: F_{XUV}=8 erg s^{-1}cm^{-2} at 1 a.u., n=5x10^{4}cm^{-3}.

The distributions of density of protons, planetary hydrogen atoms and ENAs realized in the "*captured by the star*" regime of PW-SW interaction for the *slow* SW under the typical for HD209458b conditions, and the decomposition of the corresponding Lyα absorption profile onto the *resonant thermal* and *non-resonant natural* with showing also the contribution of ENAs and planetary atomic hydrogen, is presented in Figures 1 and 2, respectively. The results of similar study for the case of the *"blown by the wind"* regime of PW-SW interaction are shown in Figures 3 and 4.

3. Conclusions

It has been demonstrated that the most crucial factor affecting the ENA environment of HD209458b is the XUV flux. At the same time, the calculations in a wide range of stellar wind parameters and XUV flux values have shown that under the typical conditions expected for HD209458b the amount of generated ENAs is too small, and the observed absorption at the level of 6÷8% can be attributed only to the *non-resonant natural line broadening*. For lower XUV fluxes, e.g., during the activity minima, the number of planetary atoms that survive photo-ionization and give the origin to ENAs, increases resulting in up to 10÷15% absorption at blue wing of Lyα line, caused by *the resonant thermal line broadening*. Similar asymmetric absorption can be seen under the conditions of a fast SW with a sufficiently high total pressure, e.g. during Coronal Mass Ejections, when the escaping PW flow is confined the within a kind of bowshock around the planet. It has been found, that the radiation pressure in all considered cases has a negligible contribution to the production of ENAs and the corresponding absorption.

Acknowledgements

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References

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[2] Khodachenko, M. L., Shaikhislamov, I. F., Lammer, H., et al. ApJ, 2017, 847(2), 126.