EPSC Abstracts
Vol. 13, EPSC-DPS2019-72-1, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

Interpretation of transit observations of GJ436b by 3D gasdynamic modeling

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Abstract

Using a global 3D, fully self-consistent, multi-fluid gas-dynamic aeronomic model, we simulate the dynamically expanding upper atmosphere of a warm Neptune GJ436b. The complex spatial structure of the escaping upper atmospheric planetary material, energized by the stellar XUV and driven further by pressure gradients and tidal forces, while interacting with the stellar wind plasma, is revealed in course of the modeling. We calculate transit absorption in Lyα and find that it is produced moistly by Energetic Neutral Atoms outside the Roche lobe, due to the resonant thermal line broadening.

1. Introduction

A series of observations by HST/STIS (*Kulow et al. 2014, Ehrenreich et al 2015, Lavie et al. 2017*) revealed that the warm Neptune GJ 436b has a very deep transit in Lyα line reaching up to 60%. Moreover, this strong absorption takes place mostly in the blue wing of the line in the range of Doppler shifted velocities of [-120; -40] km/s. The good signal/noise ratio reveals clearly, for the first time in VUV observations of hot gaseous exoplanets, such details of transit curve as early ingress *Ehrenreich et al 2015*) and extended egress (*Lavie et al. 2017*). The quality of obtained data enables quantitative testing of the existing theoretical concepts and numerical models.

The results of the applied, for the first time, a fully self-consistent 3D gasdynamic model (*Shaikhislamov et al. 2016, 2018, Khodachenko et al. 2017*) to simulate the Lyα line absorption features of GJ 436b are reported here. The used multi-fluid aeronomic code includes all the basic reactions of hydrogen plasma-photo chemistry. It was possible with its help not only to determine the parameters of planetary atmospheric material outflow, stellar XUV flux and plasma wind, at which the simulated line absorption profiles and transit curves match the observed ones, but to describe also key physical processes, affecting the observations. It should be noted that HD/MHD modeling of the material escape of hot exoplanets is steadily progressing nowadays from 1D to 3D cases. However, most of the models still have not reached the level of the included physics (i.e., processes/effects), as the first generation of 1D aeronomy models did, allowing self-consistent simulation of planetary outflow. The present model makes a step forward on this way and appears the first one, which can be directly compared with the 1D aeronomy simulations on one hand, and to simulate the complex plasma environment of an exoplanet in the whole 3D domain of the planet-star system on the other. It also includes, for the first time, all the physics present in the Monte-Carlo simulations, such as radiation pressure and charge exchange, so the results of two different modeling approaches can be directly compared.

2. Results

Figure 1 shows spatial structure of interaction between the planetary and stellar winds (PW and SW) for the simulation run with the following assumed typical parameters: base temperature of the planet atmosphere T_{base}=750 K, Helium abundance He/H=0.1; GJ436 ionizing radiation flux F_{XUV}=0.86 erg cm^{-2} s^{-1} at 1 a.u., stellar corona temperature $2\cdot10^6$ K, stellar mass loss rate $M_{sw}^{/}=2.5\cdot10^{11}$ g/s; SW parameters at the planet orbit $T_{sw}=6\cdot10^5$ K, V_{sw}=170 km/s, $n_{sw}=4\cdot10^3$ cm^{-3}. Note that assumed stellar radiation and mass loss are about 5-10 times weaker than those for the Sun, mostly due to smaller size of GJ436. For these parameters the model gives the planetary mass loss rate $M_{pw}^{/}=2\cdot10^9$ g/s.

Plots in Figure 1 show, that SW sweeps the PW away and redirects the escaping planetary material towards the trailing tail. There is a compressed layer (shock) in front of the planet where Energetic Neutral atoms (ENAs) are generated. The neutral atoms of planetary origin which come close to the ionopause penetrate through the shocked region where they become uncoupled from the protons and interact with the SW protons via charge exchange.

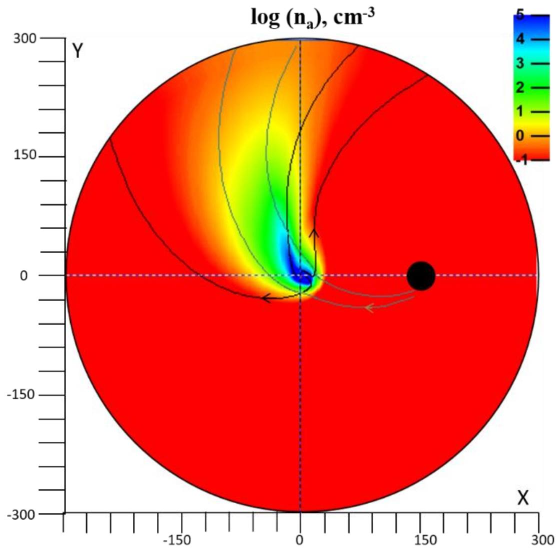

Figure 1. Hydrogen atoms' density distribution in equatorial plane *(X-Y)*. Streamlines of atoms and stellar protons are shown with *black* and *khaki* lines, respectively. The distance is scaled in planetary radii.

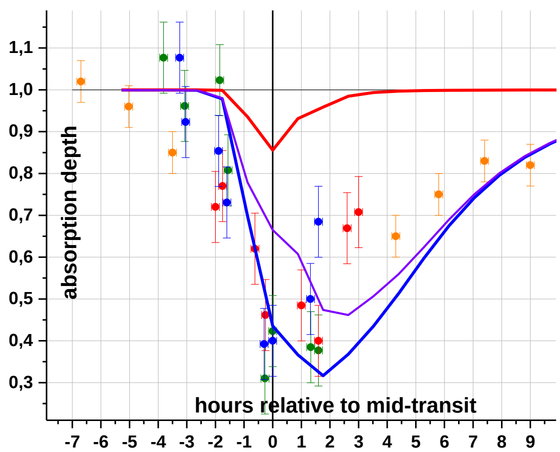

Figure 2. Light curves in blue [-120; -40] and red [30; 110] km/s wings of Lyα (blue and red lines, resp.). Violet line shows the ENAs absorption in blue wing. Colored squares show the measured data from different visits (*Lavie et al. 2017*).

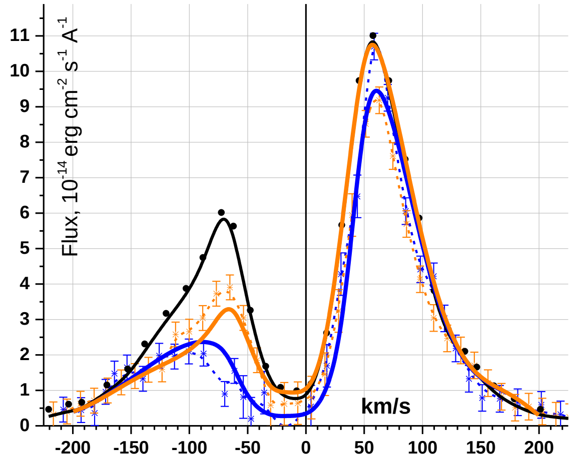

Figure 3. Simulated Lyα line profiles in mid-transit (blue solid) and post-transit t=5 h (orange solid). Measured profiles out of transit and at mid-transit are shown by black and blue dots/symbols respectively.

Figures 2 and 3 describe the modeled absorption in Lyα. For comparison with observation, the measured data are plotted as well. One can see deep absorption with early ingress and long egress, mostly in the blue high velocity part of the line. All these features are in good general agreement with the observations.

Acknowledgements

This work was supported by the Russian Science Foundation RSF project 18-12-00080, SB RAS basic research program (project II.10 №0307-2017-0015), and Austrian Science Foundation FWF, projects I2939-N27, S11606-N16. Parallel computing has been performed at Computation Centre of Novosibirsk State University, Siberian Supercomputer Centre of SB RAS, Supercomputing Centre of the Lomonosov Moscow State University and Joint Supercomputer Center of RAS.

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