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Global 3D multi-fluid aeronomy simulation of the HD 209458b

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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 an exoplanet HD 209458b. The complex spatial structure of the escaping upper atmospheric planetary material, energized by the stellar XUV and driven further by tidal forces, while interacting with the stellar wind plasma is revealed in course of the modelling. We calculate transit absorption in Lyα and find that it is produced by both, dense exosphere inside the Roche lobe, due to the natural line broadening mechanism, and by the fast Energetic Neutral Atoms (so-called ENAs) outside the Roche lobe, due to the resonant thermal line broadening.

1. Introduction

Spectrally resolved transit measurements revealed extended planetary exospheres existing around a number of close-orbit exoplanets. Observed absorption in Lyα and resonant lines of heavier species, e.g., O, C in HD209458b indicates the dynamical expansion of its exosphere and overflowing the Roche lobe. Numerical simulation of this process involves aeronomy processes to describe the heating, chemical transformation and acceleration of the upper atmosphere in the form of an expanding planetary wind (PW) on one hand, and the interaction the PW with the stellar wind (SW) plasma on the other hand. So far the aeronomy simulations have been restricted to 1D models, while global 3D codes of the PW-SW interaction lacked the self-consistency regarding the modeling of the PW formation. Here we present a 3D multi-fluid gasdynamic model, which self-consistently simulates the global dynamics of the expanding PW within the SW environment.

2. The Model

We upgrade our previous 2D model (*Shaikhislamov et al. 2016, Khodachenko et al. 2017*) to a 3D case while keeping included all the details of the aeromomy of upper atmosphere, composed of hydrogen and helium. Using a sufficiently detailed planet based spherical coordinate system with a variable mesh, it is possible to resolve the wavelength- and height- dependent absorption of the ionizing stellar XUV radiation and the molecular hydrogen photo-chemistry in the highly stratified upper atmosphere of the HD209458b. Besides of that, the model simulates the expansion of the PW beyond the Roche lobe and its interaction with the SW under the action of inertia and gravity forces in a large spatial volume extending far beyond the planet orbit. This interaction also includes the generation of ENAs due to charge-exchange of slow planetary hydrogen with fast stellar protons, as well as stellar radiation pressure by the absorbed Lyα flux. For the reproducing of realistic SW parameters and calculation of the shock, formed during the SW-PW interaction, we use the adiabatic specific heats ratio 5/3, instead of the isotropic or polytropic ones, taken in the most of other global models. To sustain the continuous acceleration of the SW, an empirical heating of the stellar plasma inside the orbit ~0.1 a.u. is introduced. By taking certain values for the coronal temperature and density, as the boundary condition, either a slow, or a fast SW regimes can be modeled.

3. Results

We present here our first results on the simulation of the global structure of the dynamical plasma environment around HD 209458b under the conditions of the stellar XUV flux and SW typical for the Sun, and expected for a Sun-like star HD209458. Figure 1 shows the 3D plots of proton density and temperature. The planetary material stretches along the orbit ahead and behind the planet. The SW overflows this structure and forms a shock along the whole length of the ahead streaming part of the PW flow. Due to the SW-PW interaction some planetary material is swept away by the SW.

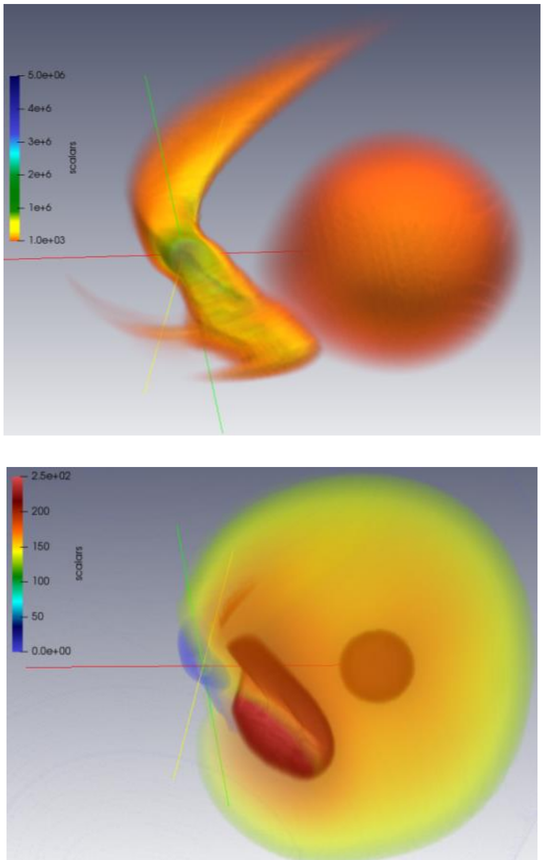

Figure 1: 3D color plots of proton density (upper panel, in cm^{-3}) and temperature (bottom, in units of 10^4 K). The coordinate axes are centered at the planet.

The profiles of the physical quantities along the planet-star line sown in Figure 2, demonstrate a sharp separation of the whole region onto planetary and star dominated domains. The H_2 dissociation front is located at about $1.5R_p$. The maximal temperature of the expanding PW reaches 9000 K at about $2R_p$, while velocity gets up to 40 km/s.

The calculated transit absorption in Lyα reveals that the main contribution comes from the natural line broadening mechanism, operating in the dense planetary exosphere inside the Roche lobe. The resonant Lyα absorption by ENAs (mostly at the blue wing of the line) might be also important, depending on the intensity of XUV flux and the density of SW plasma. This is in general agreement with our previous findings with the 2D axisymmetric model (*Khodachenko et al. 2017*). However, the essentially 3D geometry of the planetary plasma environment shows the new qualitative features and quantitative details, which can be captured only with the self-consistent 3D multi-fluid simulations.

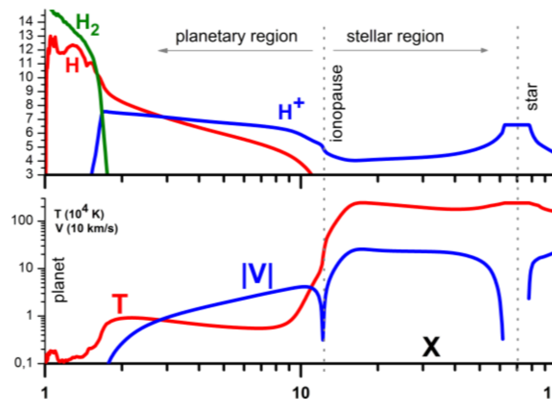

Figure 2: Density profiles for protons, molecular and atomic hydrogen (upper panel, log scale, in cm^{-3}); temperature and velocity distributions (bottom) along the planet-star line.

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References

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