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Multi-component MHD model for hydrogen-helium extended envelope of hot Jupiter

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Abstract. We describe a numerical model of hot Jupiter extended envelope that interacts with stellar wind. Our model is based on approximation of multi-component magnetic hydrodynamic. The processes of ionization, recombination, dissosiation and chemical reactions in hydrogen-helium envelope are taken into account. In particular, the ionization of neutral hydrogen atoms takes place due to processes of photo-ionization, charge-exchange and thermal collisions. Further, this model is supposed to be used for research on biomarkers' dynamics in extended envelopes of hot Jupiters.

Keywords. magnetic hydrodynamics (MHD), hot Jupiters, chemical reactions

1. Introduction

Hot Jupiters (HJ) are giant exoplanets with mass of the order of Jupiter mass, located in the immediate vicinity of the host star. Due to the close location to the host and relatively large size, gas envelopes can overfill their Roche lobes. This expanding upper atmosphere is called an extended envelope of HJs. The structure of the extended envelope and its physical properties are determined by the influence of several forces: the planet gravity, gravitational force of the star, the orbital centrifugal force, the orbital Coriolis force and the forces determined by the interaction with stellar wind, the radiation of the star and the magnetic field.

The magnetic field in the vicinity of HJs can be determined by different sources: generated in the interior of the planet, induced by electrical currents in the upper layers of its atmosphere, by the stellar wind magnetic field and host star magnetic field. Magnetic field can play an important role in the process of the stellar wind flow around the atmosphere of the HJ. Therefore, we use MHD solution instead of hydrodynamic one for simulation (Zhilkin & Bisikalo 2021). In order to describe specific processes that lead to local changes in the concentration of components we take into account the chemical composition. The model that includes chemical components should be multi-fluid and based on an MHD model.

2. Model

We consider an approximation of 3D multi-component (multi-fluid) magnetic hydrodynamics, which uses equations for mass quantities (density ρ, average mass velocity $\boldsymbol{v}$, average mass internal energy ε), the induction equation for magnetic field $\boldsymbol{B}$, as well as the continuity equations for the components. The individual components (electrons, ions and neutrals of various kinds) of plasma are marked with the index s (Zhilkin & Bisikalo

2021). The continuity equations for each component of the kind s can be written as:

$$\frac{\partial}{\partial t}(\rho\xi_s) + \nabla\cdot(\rho\xi_s \boldsymbol{v}) = S_s, \quad s = 1,\ldots,N, \tag{2.1}$$

where ξ_s is mass fraction of component s, S_s are source functions, which describe changes in the number of particles of the kind s due to chemical reactions, N is the number of components.

The 3D numerical simulation of the model takes into account the continuity equations with the help of a chemical module. Chemical constants from the UMIST database (McElroy et al. 2005) are used to calculate chemical reactions and processes of ionization, recombination and dissociation. We apply these reactions selectively: only the reactions concerned hydrogen-helium envelope of HJ (Shaikhislamov et al. 2020). We use 38 reactions for 9 components in this envelope. We add the module to the existing code of MHD model and solve the equations of chemical kinetics for the selected network of chemical reactions. As a result we have a number density of each component in the range of a quarter of period for HJ orbital motion. These calculations are made in every cell and at every integration step Δt.

3. Conclusion

We considered the multi-fluid MHD model for hydrogen-helium extended envelope of HJ. In this model plasma is described as a combination of components (electrons, ions, and neutrals of various kinds). The model takes into account chemical reactions, processes of ionization, recombination and dissociation of hydrogen molecules. We assume that the hydrogen-helium atmosphere has a homogeneous chemical composition. For numerical simulation we developed and added a chemical module into the MHD code with a specific selection of chemical reactions. Further we plan to extend the chemical model to include additional components and corresponding reactions. In particular, this will allow us to follow in more detail the dynamics of specific components (for example, biomarkers) in the envelopes of hot exoplanets.

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References

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Discussion

Paul Arghyadeep: I was wondering what is the velocity and the magnetic profile of the stellar wind? Also, how is the magnetic field of HJ modelled? Is it a dipole?

Yuliya Gladysheva: The magnetic field is calculated from the wind model. The model corresponds to the paper (Weber & Davis, 1967). The magnetic field of HJ consists of two components: the intrinsic magnetic field of the planet (a dipole one) and the magnetic field induced by electrical currents in the upper layers of atmosphere (not dipole).