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Interpretation of the Balmer-alpha line absorption in the exoplanet WASP-69 b

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Abstract. In this work, the absorption in the Hα line of the exoplanet Wasp-69 b was simulated. A three-dimensional self-consistent multifluid magnetohydrodynamic (MHD) model of the atmosphere was used to calculate the characteristic distributions of density, velocity, and temperature of various components in the atmosphere of WASP-69 b. To obtain the profile of hydrogen atoms excited to the second energy level H(2ℓ), a Monte Carlo model of Lyα photon transport in the atmosphere, obtained by MHD simulation, was used. Three main sources were taken into account as the "pumping" of the atmosphere with Lyα photons in the model: the photons incident from the star, photons generated in the process of collisions of hydrogen atoms with electrons, and photons arising in the process of recombination of electrons and protons in the atmosphere of the planet. Modeling of the resonant scattering of Lyα photons on hydrogen atoms was performed in the approximation of partially coherent isotropic scattering. The calculations have shown that the population of the hydrogen excited to the second energy level due to the pumping by intra-atmospheric Lyα photons is insignificant and does not lead to absorption in the Hα line, but such absorption can appear due to the pumping by stellar photons. Nevertheless, judging by the observed data obtained and their analysis, the absorption in this line was not detected, which may indicate a low intensity of the Lyα line radiation from the parent star.

Keywords: radiative transfer; atmospheric effects; methods: numerical; planets and satellites: atmospheres

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1 Introduction

The warm Neptune WASP-69 b, discovered 10 years ago, is still of interest to researchers. This planet is one of the few that demonstrate sufficiently high absorption in the sodium doublet and metastable helium lines. A comparison of transit absorptions with numerical modeling has shown that the atmosphere of this planet is outflowing at a rate of about 10^{11} g/s, forming a long helium tail of 7 planetary radii. The absorption in the hydrogen Hα line was also measured (Khalafinejad et al. 2021), but despite the high level of absorption in the He I($2\,^3$S) line, the relatively large calculated helium content in the upper layers of the planet's atmosphere, and the intense outflow of planetary matter, all but one of the measurements showed no absorption in the Hα line. In Guilluy et al. (2024), this anomalous observation is associated with the activity of the parent star. The goal of this paper is to model and interpret the absorption in the Hα line.

2 Methods

In order to obtain the absorption spectrum in the Hα line, it is necessary to find the distribution of hydrogen atoms excited to the second energy level H(2ℓ). For this purpose, the transport of Lyα photons in the planet's atmosphere was calculated using the Monte Carlo method. The input atmospheric parameters required for the calculation, such as the distributions of the concentration of hydrogen atoms, free electrons, protons, and temperature, were taken from the results of three-dimensional self-consistent hydrodynamic modeling (Shaikhislamov et al. 2018; Khodachenko et al. 2019). The photon transport model assumes three main ways of "pumping" the atmosphere with Lyα photons: the photons incident from the star, photons generated in the process of collisions of hydrogen atoms with electrons, and photons arising in the process of recombination of electrons and protons in the planet's atmosphere. A detailed description of the Monte Carlo model can be found in Miroshnichenko et al. (2021). Here we only briefly describe the main provisions. The radiation field is represented as a discrete set of photon packets, each packet has coordinates (x, y, z), propagation direction (n_x, n_y, n_z), frequency ν expressed in units of Doppler velocity, and "weight" w reflecting the number of real photons in one photon packet. The photons flying from the star (hereinafter the stellar photons) are generated uniformly along a spherical front incident on the atmosphere. The atmospheric photons include collisional and recombination photons: the photons generated in collisions with electrons and in recombination processes, respectively. The atmospheric photons are distributed uniformly throughout the atmosphere and have an isotropic distribution of their propagation direction. The velocity (frequency) is chosen randomly from the

Maxwell–Boltzmann distribution based on the local temperature, while the influence of suprathermal particles is not taken into account. The "weight" of atmospheric photon packets is calculated according to the rates of Lyα photon production in the corresponding reactions. Packet tracing is performed as follows: an optical path is randomly determined for each packet; after the packet has traveled it, it is absorbed by a hydrogen atom and then re-emitted with new random characteristics. Such a photon exists until it leaves the computational domain or de-excitation occurs as a result of one of the reactions: photoionization, spontaneous relaxation, or collisional de-excitation. Modeling of the resonant scattering of Lyα photons on hydrogen atoms is performed in the approximation of partially coherent isotropic scattering. A full description of the approach and the implementation of frequency sampling after scattering can be found in (Zheng & Miralda-Escudé 2002; Dijkstra et al. 2019). After all photon packets cease to exist in the computational domain, an axisymmetric profile H(2ℓ) is constructed in cylindrical coordinates, based on which the absorption profile $\alpha(v)$ is calculated.

3 Results

The calculation of the absorption in the Hα line was carried out for two sets of parameters since they showed the best agreement with the measured He I($2\,^3$S) absorption line. The results of these calculations were used as initial parameters for the Monte Carlo model.

As for most stars, the emission spectrum at short wavelengths has not been measured for WASP-69. In the Monte Carlo model, one of the main parameters is the Lyα line intensity ($I_{\mathrm{Ly}\alpha}$) at a distance of 1 AU, measured in units of $\mathrm{erg\,cm^{-2}\,s^{-1}}$. The $I_{\mathrm{Ly}\alpha}$ value determines the contribution of stellar photons to the generation of H(2ℓ). It was estimated based on the method proposed in Linsky et al. (2013). The method assumes a relationship between the rotation period of a star, its effective temperature, and the flux in the Lyα line. For WASP-69, the rotation period is 23.07 days and the effective temperature is 4700 K, which gives a flux of $I_{\mathrm{Ly}\alpha} = 17.8\ \mathrm{erg\,cm^{-2}\,s^{-1}}$. Having this estimation, we choose the $I_{\mathrm{Ly}\alpha}$ range from 5 to 20 $\mathrm{erg\,cm^{-2}\,s^{-1}}$ to determine the best fit to the observations.

Figure 1 (left) shows the obtained absorption profiles that demonstrate the best agreement with the observed data. It is evident from the figure that the best agreement is achieved with the parameters $F_{\mathrm{XUV}} = 3\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ and $I_{\mathrm{Ly}\alpha} = 8.9\ \mathrm{erg\,cm^{-2}\,s^{-1}}$, which agrees with both the absorption in the He I($2\,^3$S) line and the estimate based on Linsky et al. (2013). At the same time, regardless of the radiation parameters, the main contribution to the absorption is made by the stellar photons. For the case of $F_{\mathrm{XUV}} = 3\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ and $I_{\mathrm{Ly}\alpha} = 8.9\ \mathrm{erg\,cm^{-2}\,s^{-1}}$, the contribution of the stellar, collisional, and recombination photons was 98.58%, 0.12%, and 1.3%, respectively. Similar relationships are observed for all the obtained results.

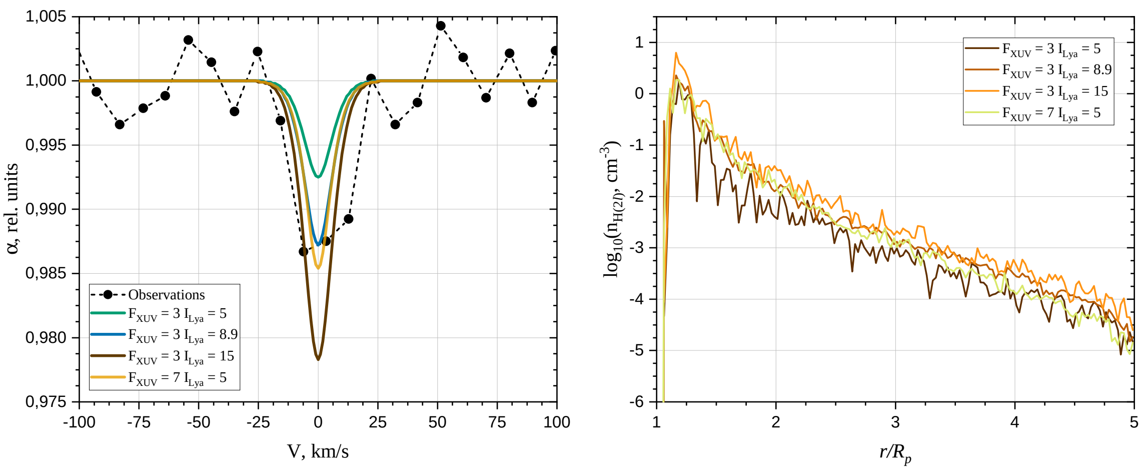

Fig. 1: Left: calculated absorption profiles in Hα for the most suitable parameters. Right: concentration profiles of excited hydrogen atoms along the planet–star axis.

The low contribution of atmospheric photons to the absorption is due to the low rates of Lyα photon production reactions in the atmosphere, which are to a large extent determined by the temperature. Figure 2 shows the rates of Lyα photon production reactions in the recombination and collision processes for $F_{\mathrm{XUV}} = 3$ and $7\ \mathrm{erg\,cm^{-2}\,s^{-1}}$.

Since the reaction rates determine the weight of the photon packets in the model, which in turn reflects the number of real photons, it follows from Fig. 2 that the content of H(2ℓ) generated by atmospheric processes is low. The obtained profiles of the H(2ℓ) concentration along the line connecting the centers of the star and the planet are shown in Fig. 1 (right). In more detail, Fig. 3 presents the contributions of different types of photons to the absorption and generation of H(2ℓ). Thus, the observed absorption and distribution of H(2ℓ) are almost completely determined by the stellar radiation. As suggested by the production reaction rates, the H(2ℓ) profiles are determined by the stellar photons.

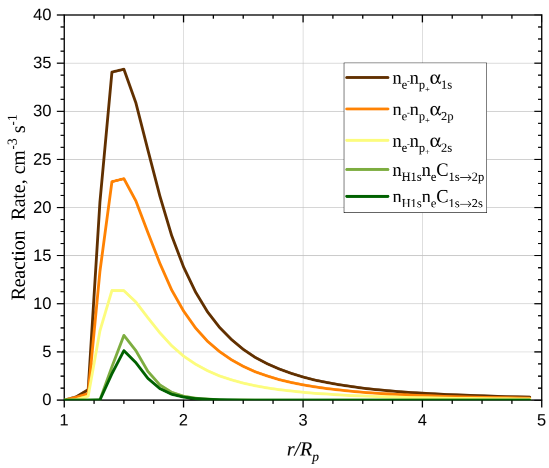

Fig. 2: Reaction rates of Lyα photon generation for $F_{\rm XUV} = 3$ erg cm^{-2} s^{-1} (left) and $F_{\rm XUV} = 7$ erg cm^{-2} s^{-1} (right).

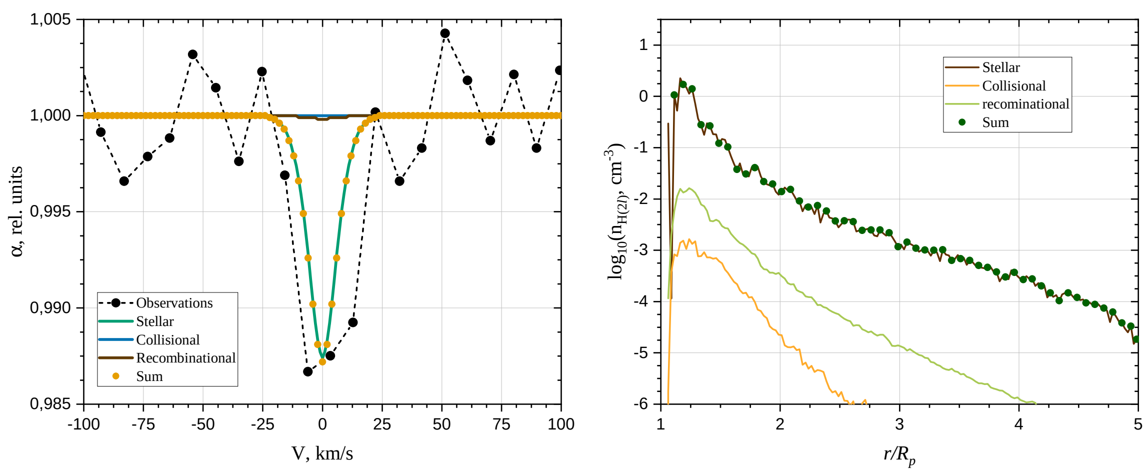

Fig. 3: Left: absorption profiles for different photon types. Right: density profile for H(2ℓ). Here $F_{\rm XUV} = 3$ erg cm^{-2} s^{-1} and $I_{\rm Ly\alpha} = 8.9$ erg cm^{-2} s^{-1}.

4 Summary

Using the Monte Carlo method for tracing Lyα photons in the atmosphere of the exoplanet WASP-69 b, we obtained the absorption spectrum in the Hα line. The model results are in good agreement with the observed data. It was found that the greatest contribution to the absorption is made by the stellar photons, while the photons generated in atmospheric processes have almost no effect on the absorption. In addition, the concentration profiles of the hydrogen atoms excited to the second energy level were obtained, from which it follows that the H(2ℓ) content is within 10^0–10^{-2} cm^{-3} in the atmospheric layer of about 1.5 R_p. It was also found that the main absorption occurs in the same layer. The model results also additionally confirm the estimate of the physicochemical parameters of the system: $n_\mathrm{He}/n_\mathrm{H} = 0.2$ and $F_\mathrm{XUV} = 3$ erg cm^{-2} s^{-1}, since the best agreement with the observed data in the Hα line was obtained with these values.

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