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Simulation of the Hα absorption for the hot Jupiter HAT-P-32 b

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Abstract. The paper presents the results of modeling the absorption spectrum in the Hα and He 10 830 Å lines for the hot Jupiter HAT-P-32 b. The simulation was carried out using a 3D hydrodynamic model coupled to a Monte Carlo model of Lyα photon transfer. It was determined that to explain the absorption in both lines at a ratio H/He = 99/1, high values of the XUV flux and stellar Lyα flux are required: $F_{\rm XUV} = 100$ erg cm^{-2} s^{-1} and $I_{\rm Ly\alpha} = 600$ erg cm^{-2} s^{-1}, which may indicate high activity of the star. New parameters were also found that describe the absorption at H/He = 97/3 while requiring less extreme $F_{\rm XUV} = 25$ erg cm^{-2} s^{-1} and $I_{\rm Ly\alpha} = 600$ erg cm^{-2} s^{-1}. Monte Carlo modeling showed that the absorption in the Hα line is formed by stellar photons producing H(2) concentrations at a level of 10^2–10^3 cm^{-3} in the atmospheric layer up to $2R_{\rm p}$, where the absorption occurs.

Keywords: planets and satellites: atmospheres; radiative transfer; scattering; hydrodynamics

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1 Introduction

Over the past two decades, with the help of transit spectroscopy escaping hydrogen and helium atmospheres around many planets have been detected. Initially, the ultraviolet hydrogen line Lyα was used, in which the excess absorption is formed by H(1s) atoms. As well, observations in the optical Hα line began to be used, which are able to probe planetary hydrogen atoms in the excited state H(2). In addition to hydrogen, for some planets it is possible to measure the absorption in the infrared He 10 830 Å line of the helium triplet, which results from the transition between the $2\,^3$S and $2\,^3$P states.

Both the Hα and He 10 830 Å lines are practically not contaminated by the interstellar medium and Earth's atmosphere, which allows the use of ground-based facilities with high spectral resolution and provides high-quality information about the planetary atmosphere. Modeling the absorption in both lines helps constrain the atmosphere physical parameters. The purpose of this work is to constrain the parameters of the upper atmosphere of the hot Jupiter HAT-P-32 b using a 3D hydrodynamic model and a Monte Carlo radiative transfer model as well as to interpret the observed absorption in the Balmer Hα line.

2 Method

To simulate the planetary atmosphere, we used a 3D self-consistent hydrodynamic model (Shaikhislamov et al. 2020). It includes the H, H$^+$, He, He$^+$, and He($2\,^3$S) atoms and free electrons, and the stellar wind is also included in the consideration. The solar parameters for the stellar wind were chosen. A pressure of 1 µbar and a temperature of 1700 K were specified at the lower boundary in the calculations. The metallicity was equal to the solar metallicity: [Fe/H] = −0.04.

The Hα line absorption was calculated based on the Monte Carlo simulations of Lyα radiation transfer (Miroshnichenko et al. 2021). The model takes into account both stellar and atmospheric photons. The atmospheric photons are born as a result of recombination and collisions with electrons, and the stellar ones arrive in the form of a spherical front. The stellar photon frequency is sampled from a double Gaussian distribution centered at ±65 km/s with a width of 38 km/s. We also calculated the absorption in the He 10 830 Å line for additional validation of atmospheric parameters. The absorption in the helium line was calculated in the non-local thermodynamic equilibrium (NLTE) approximation.

3 Observations

Using the CARMENES instrument, Czesla et al. (2022) detected time-dependent absorption in the Hα and He 10 830 Å lines, for which the absorption depth at the transit center was about 5% and 6.6%, respectively. Also in a recent work using the Hobby–Eberly Telescope, Zhang et al. (2023) obtained an absorption in the He 10 830 Å line at a level of 8.2%, which may indicate a high level of activity of the star. HAT-P-32 is an F-type star with a mass $M_\star = 1.160\ M_\odot$, a radius $R_\star = 1.219\ R_\odot$, and an effective temperature of 6000 K. HAT-P-32 b is a hot Jupiter with a mass $M_\mathrm{p} = 0.75 M_J$, a radius $R_\mathrm{p} = 1.789\ R_\mathrm{J}$, and an equilibrium temperature of 1700 K.

It is well known that for most hot Jupiters, the stellar XUV radiation ($\lambda < 912$ Å) is the main energy source to drive planetary winds and atmospheric escape. Based on the spectral energy distribution (SED), we estimated the XUV flux at a reference distance of 1 AU as $F_\mathrm{XUV} = 100\ \mathrm{erg\,cm^{-2}\,s^{-1}}$. Another important parameter for calculating the absorption in the Hα line is the intensity of the star emission in the Lyα line; it was estimated based on Linsky et al. (2013) as $I_{\mathrm{Ly}\alpha} = 45\ \mathrm{erg\,cm^{-2}\,s^{-1}}$. It should be noted that these parameters are widely varied to achieve agreement with the observations. Using a 1D hydrodynamic model, Yan et al. (2024) estimated these parameters as $F_\mathrm{XUV} = 490\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ and $I_{\mathrm{Ly}\alpha} = 460\ \mathrm{erg\,cm^{-2}\,s^{-1}}$, and the ratio H/He turned out to be H/He $\geq 99/1$. Similar results were obtained in earlier works.

4 Results

In this work, we considered different helium abundances in the planetary atmosphere: H/He = 92/8, 97/3, and 99.5/0.5. For each case, the most appropriate F_XUV and $I_{\mathrm{Ly}\alpha}$ at a distance of 1 AU were determined to fit the observations. The approximation was assessed using the χ^2 criterion. For brevity, we present only the spectra in the Hα line.

4.1 H/He = 99/1

Since there are a number of studies (Czesla et al. 2022; Yan et al. 2024) convincingly showing that a helium abundance of 1% describes the observations well, we will first consider this value. Figure 1 shows the absorption spectra in the Hα line which give the best agreement with the observations; for each value of F_XUV, the intensity of the Lyα line varied from 40 to 10^4 $\mathrm{erg\,cm^{-2}\,s^{-1}}$. It can be seen that higher values of F_XUV are in better agreement with the line width but require significantly larger values of $I_{\mathrm{Ly}\alpha}$. Note that even in the case of the smallest $F_\mathrm{XUV} = 25\ \mathrm{erg\,cm^{-2}\,s^{-1}}$, an intensity of the order of $I_{\mathrm{Ly}\alpha} = 400\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ is required, which is approximately 10 times higher than the typical value for F-type stars. The calculations show that for the same intensities of the Lyα line, the absorption depth decreases as F_{XUV} increases. To determine the best option, we additionally considered the absorption in the He 10 830 Å line. Table 1 shows the obtained absorption values and the calculated mass-loss rate in the planet's atmosphere. The best agreement is achieved at $F_{\mathrm{XUV}} = 200\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ and $I_{\mathrm{Ly}\alpha} = 1500\ \mathrm{erg\,cm^{-2}\,s^{-1}}$, but the two adjacent rows of the table also satisfy the observations. At low XUV fluxes, the absorption in the helium line is insufficient and requires a lower H/He ratio.

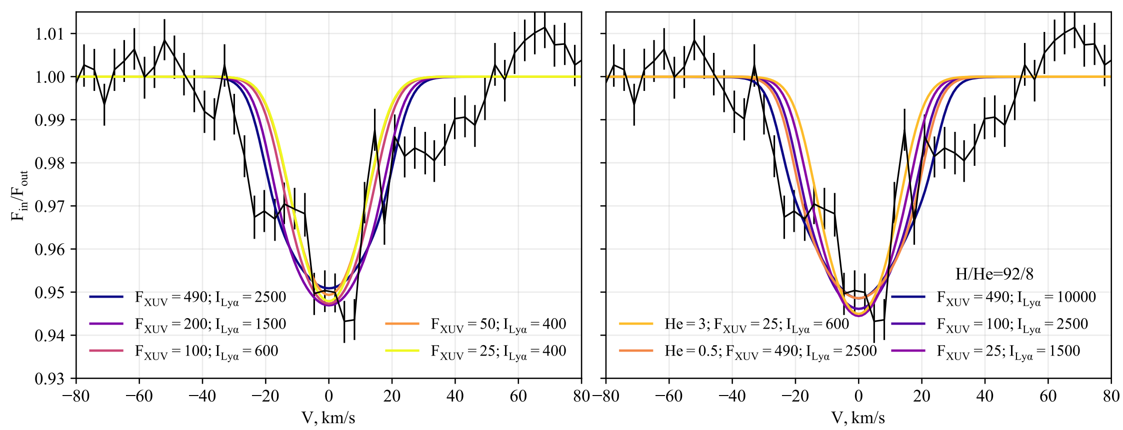

Fig. 1. Calculated best-fit spectra in the Hα line for various atmospheric and radiation parameters.

For F5–G9 stars, there is a limit on the ratio of the flux in the Lyα line to the flux in the X-ray range ($\lambda < 100$ Å). Linsky et al. (2013) found that $0.6 < F_{\mathrm{Ly}\alpha}/F_{\mathrm{X}} \lesssim 100$. Based on SED, $F_{\mathrm{X}} \approx 15\ \mathrm{erg\,cm^{-2}\,s^{-1}}$, which gives an upper limit on the Lyα line intensity of approximately $1500\ \mathrm{erg\,cm^{-2}\,s^{-1}}$. Thus, at the ratio H/He = 99/1, the best parameters are $F_{\mathrm{XUV}} = 100\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ and $I_{\mathrm{Ly}\alpha} = 600\ \mathrm{erg\,cm^{-2}\,s^{-1}}$.

4.2 H/He = 92/8, 97/3, and 99.5/0.5

The spectra that best describe the observations are shown in Fig. 1, the results are also given in Table 1. The ratio H/He = 92/8 requires very high intensities of the Lyα line, which do not satisfy the constraints obtained above. For the case of H/He = 92/8, the values of $F_{\mathrm{XUV}} = 5\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ and $I_{\mathrm{Ly}\alpha} = 2000\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ are required, which describe the Hα absorption line width worse. Thus, it is not possible

Table 1. Calculated absorption depth in the Hα and He 10 830 Å lines and the mass-loss rates. The measured absorptions are 5% and 6.6%, respectively.

$F_{\rm XUV}$, erg cm^{-2} s^{-1}	$I_{\rm Ly\alpha}$, erg cm^{-2} s^{-1}	Hα, %	He($2\,^3$S), %	$\dot{M}$, 10^{12} g/s
		H/He = 99/1		
490	2500	4.91	7.02	4.13
200	1500	5.30	6.18	2.94
100	600	5.27	5.92	2.49
50	400	5.07	4.83	1.71
25	400	5.21	3.49	1.12
		H/He = 92/8		
490	10000	5.14	21.55	3.14
100	2500	5.39	15.80	1.64
25	1500	5.55	9.68	0.76
5	2000	4.99	5.23	0.29
		H/He = 99.5/0.5		
490	2500	5.14	4.29	4.23
		H/He = 97/3		
25	1500	5.51	6.96	1.03

to find parameters that approximate both lines well and satisfy the restrictions, which rejects such a scenario.

Similar results were obtained for the ratio H/He = 99.5/0.5. Such a case, firstly, requires too high values of $I_{\rm Ly\alpha}$ and, secondly, does not agree with the absorption depth in the He 10 830 Å line. To fit the helium line, $F_{\rm XUV} = 10^3$ erg cm^{-2} s^{-1} is required, therefore we also consider this scenario irrelevant.

Unlike the two previous scenarios, for the case of H/He = 97/3 we were able to find parameters that satisfy all the restrictions with less extreme radiation parameters. At values of $F_{\rm XUV} = 25$ erg cm^{-2} s^{-1} and $I_{\rm Ly\alpha} = 600$ erg cm^{-2} s^{-1}, the calculated spectra satisfy the observations. This case has an insignificantly higher χ^2 than the best result for H/He = 99/1, which indicates that a second possible solution has been found.

5 Conclusions

Summing up, we can draw a number of important conclusions. In the case of HAT-P-32 b, the degeneracy of solutions with different helium abundances is observed. A decrease in the H/He ratio requires larger values of $I_{\mathrm{Ly}\alpha}$ to agree with the observed Hα absorption while at the same time a smaller F_{XUV} is required to agree with He 10 830 Å, which in turn narrows the line and increases the absorption depth in Hα and requires even greater intensities. It can also be noted that at the same radiation parameters a decrease in H/He reduces the absorption depth in Hα.

An analysis of the obtained spectra showed that regardless of the radiation parameters the absorption in the Hα line is formed due to the H(2) atomic state excited by stellar radiation. The atmospheric photons make an insignificant contribution to the H(2) generation and absorption. Figure 2 shows the resulting H(2) and temperature profiles along the planet–star line. It can be seen that the maximum H(2) concentration is located approximately at a distance of $1.5R_{\mathrm{p}}$ and amounts to 10^2–10^3 cm^{-3}, and the main concentration and absorption are located in the layer up to $2R_{\mathrm{p}}$. Also, at large F_{XUV} the concentration drops faster, narrowing the absorption region. The temperature profiles peak at 2—2.5 R_{p} at 1.1–1.2×10^4 K, which is consistent with other model results, but they show variation in shape as F_{XUV} falls. Also, a decrease of H/He ratio shifts the temperature peak lower and increases the overall temperature.

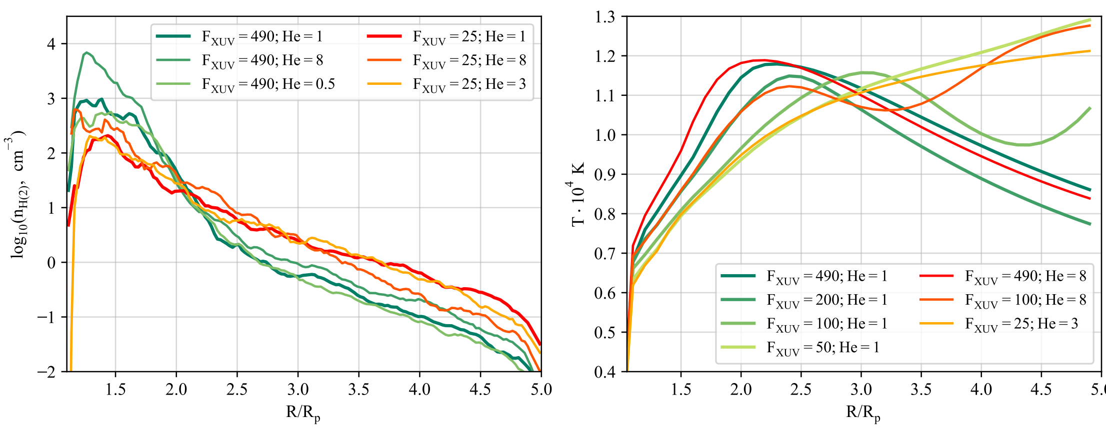

Fig. 2. Obtained H(2) concentrations and the temperature profiles along the planetary atmosphere.

In general, we reproduced the results of other models for the ratio H/He $\geq 99/1$. Also, a new solution was found that alleviates the problem of low helium abundance and requires less extreme parameters of the star radiation.

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