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Transit absorption in the oxygen lines for constraining the atmosphere temperature of hot exoplanets

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Abstract. Atomic oxygen, due to its unique chemical properties, is widely used in astrophysics to study chemical composition, nucleosynthesis conditions, and the processes of formation and evolution. The recent detection of the O I 1304 Å and 7774 Å lines in the upper atmospheres of exoplanets using space and ground-based telescopes opens the possibility to evaluate its abundance in these objects and constrain important atmospheric parameters. However, the simple approximation of thermodynamic equilibrium is often inaccurate in describing the formation and absorption for many spectral lines in stars and hot exoplanets. The development of a kinetic model that takes into account detailed radiative and collisional processes in advanced atomic models is required to interpret the observations. In this work we for the first time analyze the advantages of transit absorption measurement of two oxygen lines simultaneously.

Keywords: planets and satellites: atmospheres; line: profiles; atmospheric effects; methods: numerical

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1 Introduction

Detecting oxygen in the atmospheres of other planets is an important aspect of astronomical research. The processes of planet formation and evolution are influenced by oxygen through many molecules it forms (Madhusudhan et al. 2012). Furthermore, the element plays a significant role in the chemical evolution of the Milky Way and possibly other galaxies (Tinsley 1979; McWilliam 1997).

In exoplanet research, the O I 1304 Å transit absorption was measured in the atmospheres of the hot Jupiters HD 209458 b (Vidal-Madjar et al. 2004; Ben-Jaffel & Hosseini 2010) and HD 189733 b (Ben-Jaffel & Ballester 2013) using the Hubble Space Telescope. Recently, the possibility of probing the upper atmospheres of exoplanets by transit observations in the He I 10 830 Å line was proposed (Oklopčić & Hirata 2018). It can be measured by ground-based telescopes since it weakly interacts with the interstellar medium and Earth's atmosphere. Since then, this line has been observed in atmospheres of more than 30 exoplanets, yielding a positive detection in more than half of the instances (Fossati et al. 2021). The first detection of the atomic oxygen line at 7774 Å in the atmosphere of the hot Jupiter KELT-9 b was reported in Borsa et al. (2021). This infrared line can also be observed by ground-based telescopes, greatly increasing our means to detect oxygen in exoplanet atmospheres.

The absorption in the 1304 Å line is connected to the ground state of O I, while that of the 7774 Å line to the excited level with an energy of 9.146 eV. Thus, the measurement of these two different lines opens the possibility to remove the degeneracy in the calculations of oxygen abundance and derive such an important parameter of the atmosphere as temperature. The difference in the line widths can give information on the velocities in the atmosphere. This work aims at evaluating this method in a relatively wide parametric space of planet masses and temperatures, including some particular exoplanets. To this end, we use our newly developed `Astrea`[1] library for space plasma non-local thermodynamic equilibrium (NLTE) kinetics.

2 Modeling

The modeling process can be divided into several stages. The first one is to construct the atmospheric structure. We assume hydrostatic equilibrium at a given temperature and a planet mass to obtain the density profiles of electrons and other elements. For a preliminary study we assume a static atmosphere, which is sufficient in many cases as the largest absorption in the lines of interest comes from a relatively close region around the exoplanet. The solar oxygen abundance is taken. The electron density was

[1] https://astreaproject.ru

obtained from the photoionization – radiative recombination balance (Shaikhislamov et al. 2014; Trammell et al. 2011). The second step is the calculation of the population of the oxygen excited levels taking into account the propagation and absorption of stellar radiation in the modeled atmosphere. Finally, the absorption profiles in the lines are calculated in the 3D geometry.

The computation scheme for the population of the excited levels has the following form:

$$\mathbf{n}_{\tau+1} = P\mathbf{n}_\tau = (I - Q\Delta t)^{-1}\mathbf{n}_\tau, \tag{1}$$

where $\mathbf{n}_{\tau+1}$ is the level population vector at the $\tau + 1$ iteration, $\mathbf{n}_\tau$ is the level population vector at the τ iteration, P is the evolution operator, I is the identity matrix, Q is the overall transition rate matrix, and Δt is the time step. We take the asymptotic stationary solution as a result.

The overall transition rate matrix Q can be expressed from the transition rate matrix R, where each matrix element R_{ab} corresponds to the $a \to b$ transition rate:

$$Q_{ij} = \begin{cases} -\sum_{k\neq i} R_{ik}, & i = j \\ R_{ji}, & i \neq j \end{cases}. \tag{2}$$

The transition rate R_{ab} depends on the transition type (`Astrea` includes ten different radiative and collisional bound-bound and bound-free transitions) and in the general case has the scattering integral form:

$$R_{ab} = n_y \int_{x_0}^{\infty} F(x)\sigma(x)dx, \tag{3}$$

where n_y is the number density of scattering particles, x is the scattering characteristic (frequency, energy, velocity, etc.), x_0 is the line center (x process activation), $F(x)$ is the x value distribution, and $\sigma(x)$ is the process cross section. This paper considers the modified O I–II (51 + 1 levels) model (Sitnova et al. 2013; Barklem 2006).

The spectrally resolved absorption $\alpha(v) = 1 - \kappa(v)$ is calculated as integrals along the line of sight from the stellar disk to the observer at a mid-transit of a planet, using the Tasitsiomi approximation of the Voigt integral (Tasitsiomi 2006; Khodachenko et al. 2017).

3 Results

As the reference parameters we take those of the HD 209458 system with corresponding stellar spectra from Salz et al. (2016). The base atmosphere pressure $p_0 = 0.1$ bar.

Figure 1 shows, as an example, the absorption profiles of the two O I lines for a number of temperatures in the HD 209458 b upper atmosphere. For systematic study we made calculations for three different groups of planet masses from Neptunes to Jupiters and to massive hot Jupiters and for a number of temperatures from 250 to 2.5×10^5 K.

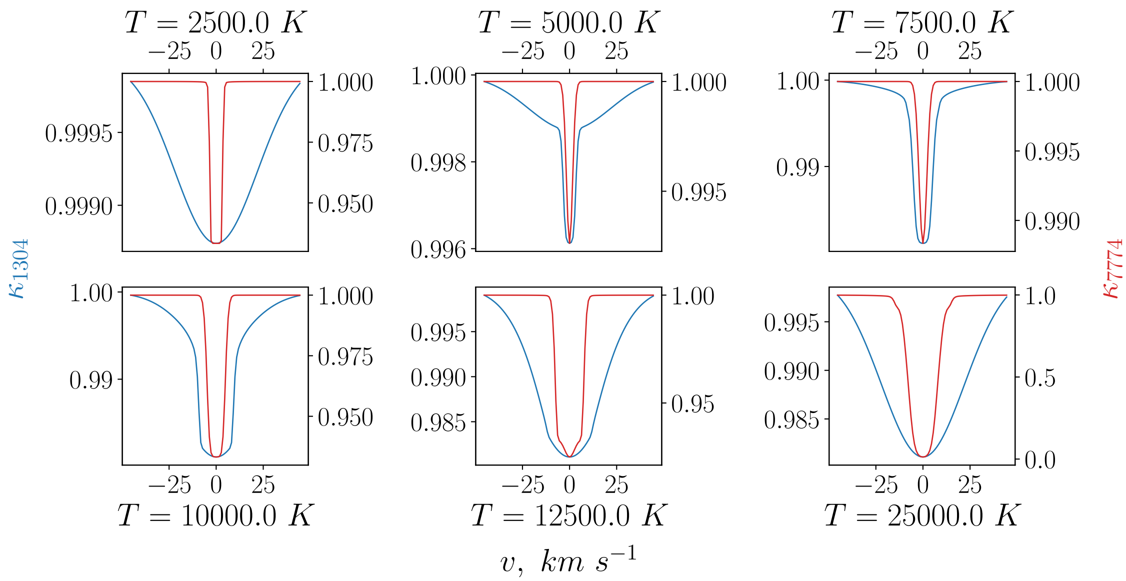

Fig. 1: Examples of the O I 1304 Å and 7774 Å absorption profiles at the mid-transit of HD 209458 b assuming different temperatures of the upper atmosphere. The horizontal axis is in the Doppler velocity units.

The absorptions in the two lines were compared by the integrals over typical line widths and by the maximum amplitudes (Fig. 2). These two methods give qualitatively the same results and prove the following concept: the relation between the two lines indeed varies with temperature in the range of interest ($\approx 10^4$ K). Moreover, the obtained results can be used to estimate the probability of oxygen line detection for different exoplanets (Fig. 3). For example, the 7774 Å line could probably be detected in the transits of KELT-16 b ($T = 3190$ K, $m = 2.75\ m_{\rm J}$) and MASCARA-5 b ($T = 2700$ K, $m = 3.12\ m_{\rm J}$). Interestingly, KELT-9 b is in the parameter space most favorable for observation of the 7774 Å line absorption, corresponding to its actual and so far singular detection (Fossati et al. 2021).

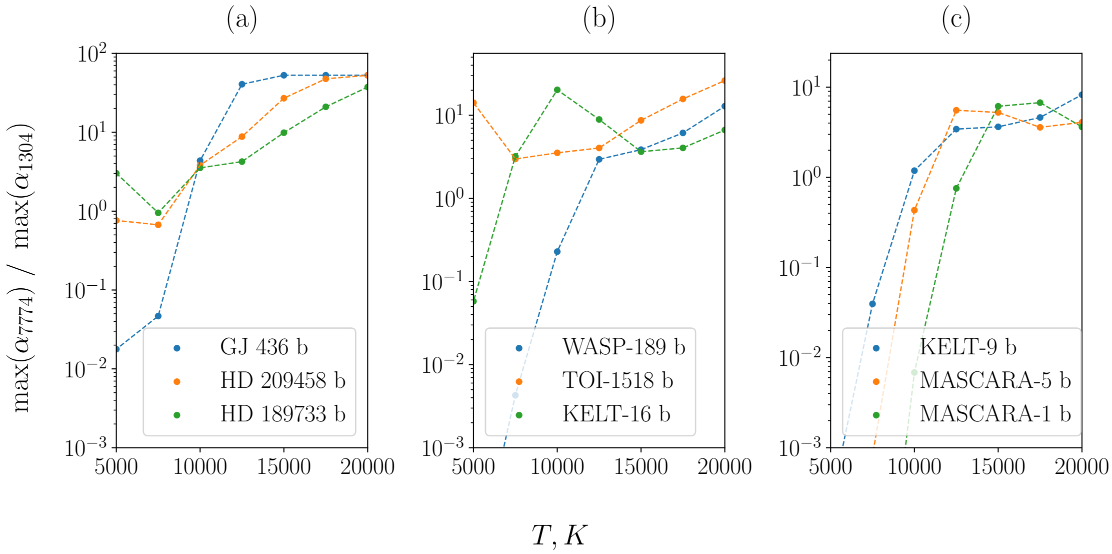

Fig. 2: The ratio between the absorptions in the O I 1304 Å and 7774 Å lines, calculated as the maximum amplitude for three groups of planets: (a), (b), and (c).

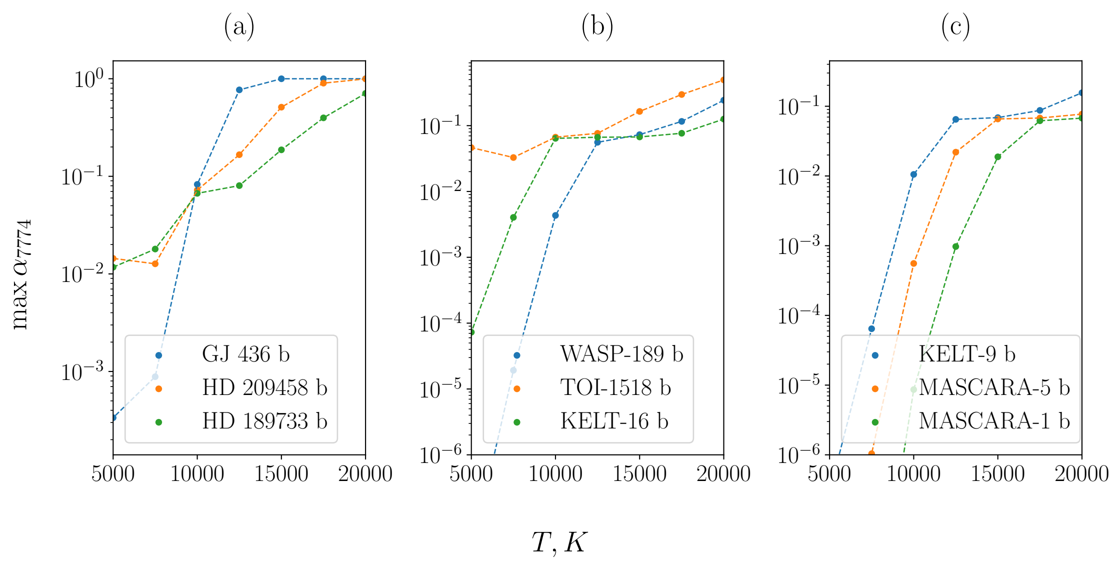

Fig. 3: Absorption at the maximum of the O I 7774 Å line for three groups of planets: (a), (b), and (c).

4 Summary

The absorption in two O I oxygen lines at 1304 Å and 7774 Å in the upper atmospheres of exoplanets was studied using a new NLTE code `Astrea`. We demonstrated that for the hot exoplanets of interest such as hot Neptunes, hot Jupiters, and ultra-hot Jupiters, the relation between these two lines can be used to constrain the temperature of the atmosphere. Also, the parametric study revealed at what kind of planets the detection of transit absorption in the 7774 Å line is possible by ground-based telescopes. Generally, it favors, as expected, hot exoplanets. The next step of the study will include 3D gas-dynamic simulations of particular exoplanets combined with kinetic modeling by the `Astrea` code.

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