Open Access Online Journal on Astronomy and Astrophysics
Acta Astrophysica Taurica
www.astrophysicataurica.org

Acta Astrophys. Tau. 5(1), 8–10 (2024) doi:10.34898/aat.vol5.iss1.pp8-10

Calculations of hydrogen and helium line emission for conditions in stellar chromospheres

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Received 4 October 2022

ABSTRACT

We perform calculations of the intensities of hydrogen Balmer lines and the HeI λ 5876 line. The input gas parameters such as temperature, concentration, and column density correspond to solar and solar-type star atmospheres. The influence of fast particles (electrons) is also considered. The radiative transfer in spectral line frequencies is treated in the frame of the Sobolev – Biberman – Holstein approximation in such a way that hydrogen lines have the convolution of the Doppler and Holtzmark profiles, and helium lines have the Voigt profile. In equations describing the hydrogen and the helium energy level occupation, the terms encompass the rates of bound-bound, bound-free radiative and collisional processes. The Balmer decrement in cold gas (6000 K) is quite steep without fast particles, being sloping with fast particles. In warm gas (12 000 K), decrement can change into increment. The HeI λ 5876 flux becomes as large as several percent of the Hα flux only in the hot atmosphere (>15 000 K) or the atmosphere affected by a strong fast particle flux.

Key words: Balmer decrement, HeI λ 5876 line, transition rates, photon escape probability, fast particles

1 Introduction

In the optical range of the solar and solar-type star spectra, emission lines of the Balmer series and helium atom lines are often observed during flares (Gershberg, 2015). Among them, HeI λ 5876, HeI λ 4471, and HeI λ 4026 lines can be distinguished. The infrared line of He λ 10830 is sufficiently bright. A distinctive feature of this gas emission problem is that these lines are typically formed above the photosphere in the regions where the optical depth in the continuous spectrum is small and can be neglected to a first approximation, but self-absorption at the frequencies of spectral lines needs to be considered.

2 Problem statement

We consider the conditions in atmospheres of cold main-sequence stars. The emitting chromosphere is represented by a plane-parallel homogeneous layer of gas. The input parameters include the gas temperature T_0 ranging from 6000 to 16 000 K; gas concentration n_0 ranging from 10^{12} to 10^{15} cm^{-3}; and column gas density N_2 ranging from 10^{20} to 10^{21} cm^{-2}. To account for the influence of photospheric radiation, the black body temperature T_* was set between 4000 and 5500 K. The possible role of suprathermal particles was considered. To simulate the effect of hot particles on the emission spectrum in lines, a relatively small number of electrons with high temperature $T_{\rm fast}$ = 200 eV and flux$_{\rm fast}$ up to 10^6 erg/cm^2/s were included. Calculations were also performed for $T_{\rm fast}$ = 400 eV and 1 keV. This did not lead to a qualitative change in decrement and helium line brightness. Radiative transfer was taken into account within the Sobolev – Biberman – Holstein model. The escape probability at line frequencies was calculated for the convolution of the Doppler and Holtzmark profiles in the case of hydrogen and for the Voigt profile in the case of helium atoms. Hydrogen was considered to be the main electron donor.

2.1 Atomic data

The system of kinetic balance equations describing the stationary occupation of energy levels of hydrogen and helium atoms has been solved. The photo processes occurred under diluted blackbody radiation from the photosphere with the temperature T_*. The rates of hydrogen photoionization, spontaneous and induced photorecombination were calculated using the Kramers theory and extensively described in Belova, Bychkov (2018); oscillator strengths, collisional excitation rates, and collisional ionization rates of hydrogen were taken from Johnson (1972). The rates of reverse processes – collisional deactivation and triple recombination – were computed using the Boltzmann and Saha formulas at the corresponding gas temperature. Atomic data for HeI collisional processes were extracted from Vainstein et al. (1973), while Einstein coefficients and oscillator strengths were obtained from the NIST database[1]. We accounted for the definite number of discrete states based on the Inglis – Teller criterion: 15 for hydrogen and 29 for helium atoms (principal quantum number $n = 1 \div 5$, orbital quantum number $l = 0 \div 4$).

[1] https://www.nist.gov/pml/atomic-spectra-database

3 Results

Let us examine the Balmer decrement without fast particles and in the presence of $\text{flux}_{\text{fast}} = 5 \times 10^5$ erg/s/cm^2. The ratio Hα/Hβ in cold gas decreases from large values around $\sim 7 \div 8$ to $\sim 1 \div 1.5$ at a temperature of 7000 K; then it starts to slightly increase (Fig. 1, panel *a*). A change from decrement decrease to a weak increase is explained by optical line thicknesses: Hα remains optically thick over the entire temperature range T_0 considered, whereas Hβ remains optically thin at temperatures below $\sim$ 7000 K, leading to its

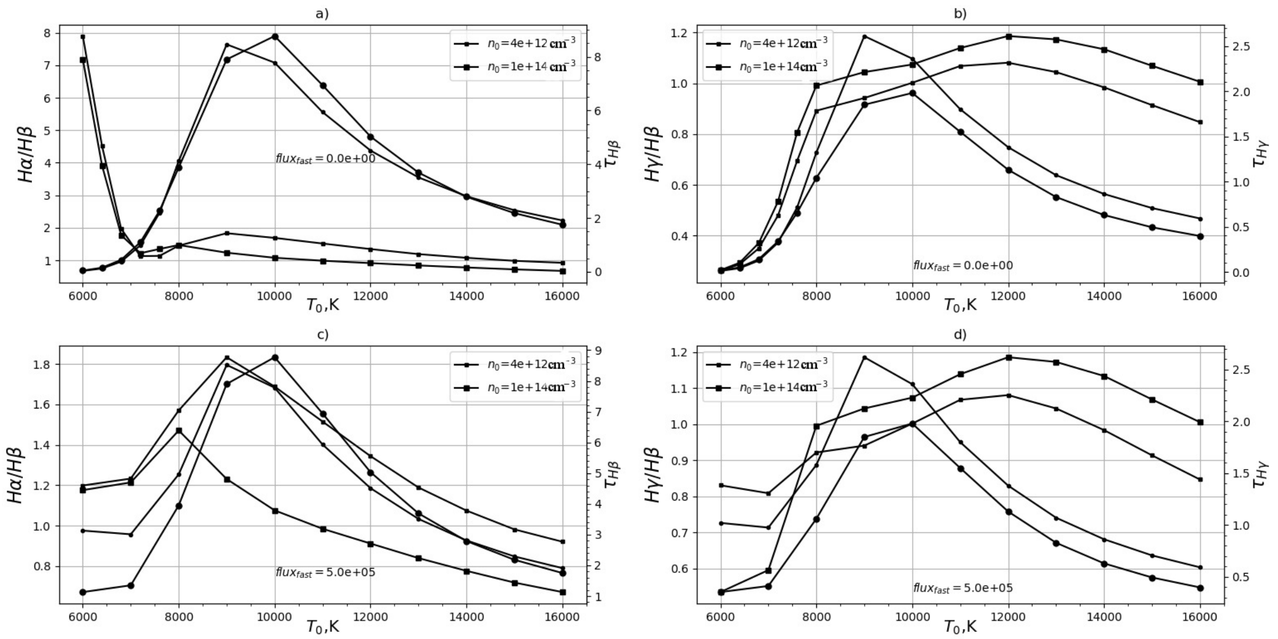

Fig. 1. Dependence of the Balmer decrement of Hα/Hβ, Hγ/Hβ (squares; values are plotted along the left axis) and the optical thickness at the center of the Hβ, Hγ lines (circles; values are plotted along the right axis) on the gas temperature T_0. The graphs are shown for the values of parameters $T_* = 5500$ K, $N_2 = 4 \times 10^{20}$cm^{-2}. Symbols of different sizes correspond to different gas density n_0. Panels *a*, *b* are shown for the zero flux of suprathermal electrons, while panels *c*, *d* are for $\text{flux}_{\text{fast}} = 5 \times 10^5$ erg/s/cm^2.

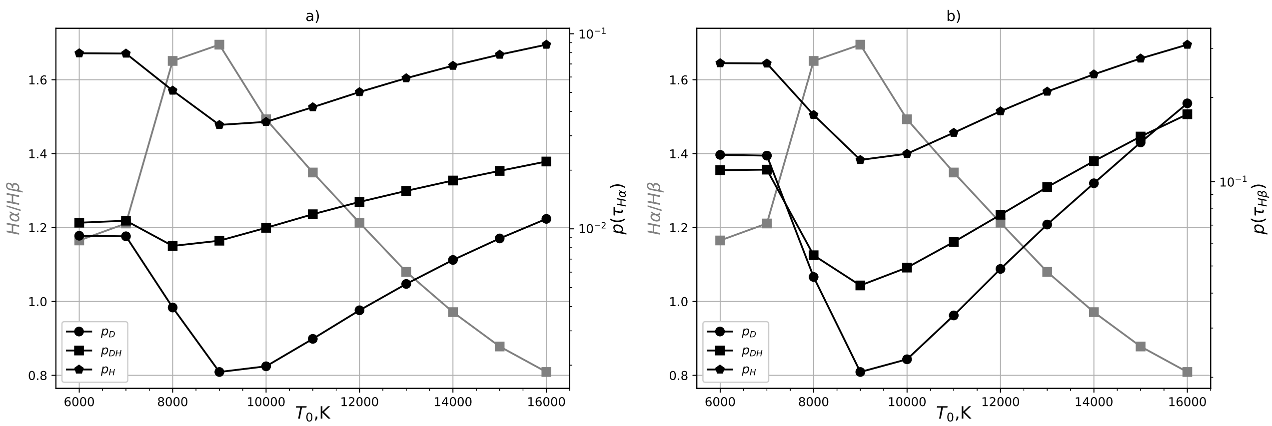

Fig. 2. Dependence of the Balmer decrement of Hα/Hβ (in gray; values are plotted along the left axis) and the escape probability of p quantum (in black, values are plotted along the right axis) at the frequencies of the Hα line (panel *a*), and Hβ line (panel *b*) on the gas temperature T_0. The probability values for escape from the Doppler profile (p_{D}) are denoted by circles; from the Holtzmark profile (p_{H}), by pentagons; and from their convolution (p_{DH}), by squares. The graphs are shown for the values of parameters $T_* = 5500$ K, $N_2 = 4 \times 10^{20}$ cm^{-2}, $\text{flux}_{\text{fast}} = 5 \times 10^5$ erg/s/cm^2, $n_0 = 10^{13}$ cm^{-3}.

intensity increasing much faster with rising T_0 compared to the intensity in Hα.

At high temperatures, the ratio decreases slightly. The Hγ line increases in intensity up to a value of Hγ/H$\beta \approx 1.2$ at a temperature of 12 000 K. In even hotter gas, hydrogen ionizes significantly, leading to a decrease in intensity. Thus, as the temperature scale T_0 moves toward higher values, the steep Balmer decrement is replaced by mildly-sloping or even an increment, where F(Hα) < F(Hβ) < F(Hγ). In the presence of a flux of fast particles, the decrement of Hα/Hβ does not decrease at low temperatures from 6000 K to 7000 K: the flux of suprathermal electrons leads to a significant occupation of the 3rd and 4th levels of the hydrogen atom, resulting in the first two lines of the Balmer series becoming optically thick (Fig. 1, panel *c*). There is a high flux in the Hγ line, especially at low particle concentrations. At high temperatures (> 8000 K), the decrement behaves similarly as in the absence of fast particles.

A shift from increasing to decreasing, observed for the Hα/Hβ ratio at a temperature of ~ 9000 K (Fig. 2), can be explained by a higher occupation of the 4th level of the hydrogen atom and by changes in the line profile characteristics: the convolution of the Doppler and Holtzmark profiles becomes less similar to a purely Doppler profile.

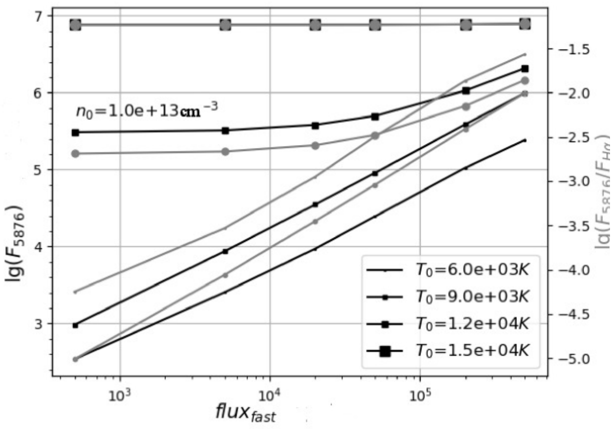

Fig. 3. Logarithms of the absolute (squares; values are plotted along the left axis) and relative (circles; values are plotted along the right axis) fluxes in the HeI 5876 line depending on the flux of superthermal electrons flux$_{\rm fast}$ (in erg/s/cm^2). Symbols of different sizes correspond to different gas temperatures T_0. The graphs are shown for the values of parameters $T_* = 5500$ K, $N_2 = 4 \times 10^{20}$ cm^{-2}, $n_0 = 10^{13}$ cm^{-3}.

Graph 3 shows the fluxes in the helium atom line at the wavelength $\lambda = 5876$ Å. At the gas temperature $T_0 = 6000$ K, both the absolute flux and the flux relative to the Hα line increase with flux$_{\rm fast}$, indicating a similar flux increase in both the hydrogen and helium lines at low temperatures. The excitations of the levels are entirely determined by fast particles. A similar intensity growth with flux$_{\rm fast}$ can be explained by the analogous structure of the energy levels of the two elements: the excited levels of both elements are located very high relative to the ground state. At higher temperatures (~ 12 000 K), fast particles only determine the line intensity at fluxes above 10^5 erg/s/cm^2. In the highly heated atmosphere at 16 000 K, the line brightness is entirely determined by the collisions of thermal particles, which is expressed in the absence of the dependence of the F(5876) value on flux$_{\rm fast}$, while the helium line remains optically thin.

4 Discussion

This study represents an advancement of the long-standing approach to interpreting line emission from gas that is transparent in the continuum. For instance, Grinin, Katysheva (1980a, b) extensively examined the emission in hydrogen lines, while Katysheva (1993) focused on the hydrogen and helium lines. The RADYN program (Allred et al., 2005) is also used. It considers transitions between six levels of the hydrogen atom (including the continuum) and discrete transitions between the ($1s^2$) level, 2s-, 2p-singlets, and triplets of helium, with the calculations incorporating the Voigt profile (Carlsson, 1986). In contrast to the RADYN program, we, firstly, take into account a significantly larger number of highly excited levels, which is required to reliably calculate the ionization state (Belova, Bychkov, 2017a, b). The number of levels considered is consistent with the Inglis – Teller criterion. Secondly, we take into account that for hydrogen a convolution of the Doppler and Holtzmark contours should be used, rather than the Voigt contour.

The model problem for a homogeneous gas layer has been considered. In real objects, it is necessary to account for gas stratification, which requires refining the Biberman – Holstein – Sobolev method. Additionally, gas dynamic effects are observed during flares, which require explanation. We hope to carry out this work in the future.

Acknowledgements. The authors express their gratitude to L.A. Vainshtein, senior researcher at the Lebedev Physical Institute, for providing atomic data on helium.

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