Relative Intensities of Hydrogen Lines as a Tool to Study Astrophysical Plasma

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The hydrogen lines play an important role in diagnostics of astrophysical plasma. In recent years, the lines of higher hydrogen series became the objects of the research, thanks to the rapid development of the infrared spectroscopy. In this paper we investigate the relative intensities of the Paschen and Brackett lines as well as the ratio of $I(L_\alpha)/I(H_\alpha)$ over a large range of the optical depth of gas. The calculations are fulfilled on the basis of the Sobolev approximation for collisional excitations and ionizations of atoms for the electron temperature $T_e < 10000$ K. The behavior of the electron density N_e at the gas thermalization is investigated. It is shown that a very sharp jump in the degree of ionization is observed near the LTE conditions. The obtained results can be used both for the diagnostics of emitting regions and for determining the extinction for the objects with strong absorption.

1 Introduction

Emission hydrogen lines are present in spectra of different astrophysical objects – from cool stars to quasars and Seyfert galaxies. They indicate the deviation from the local thermodynamic equilibrium (LTE). Earlier, the visible spectral range was the basic one, and the Balmer emission lines were observed most frequently, making the theory of Balmer decrement (B.D.) one of the main methods of the diagnostics of emitting gas. The most detailed calculations of B.D. for a multi-level hydrogen atom were carried out on the basis of the escape probability method by V.V. Sobolev [1] for different cases of excitation and ionization of the gas. Boyarchuk [2], Hirata and Uesugi [3] calculated B.D. for radiative excitations and ionizations, Gershberg and Schnol [4], Grinin and Katysheva [5] computed B.D. just for collisional ones. Ilmas [6], Grinin and Katysheva [7] considered both the cases. The relative intensities of the Paschen, Brackett and Pfund series of hydrogen were calculated by Luud and Ilmas [8] to explain the spectra of γ Cas [8].

The Lyman and Balmer decrements for collisional excitations and ionizations were computed in [5] for a wide range of the electron temperatures ($T_e = 10000$–20000 K), electron number densities ($N_e = 10^7$–10^{13} cm^{-3}) and the escape probabilities ($\beta_{12} = 1$–10^{-8}), where β_{12} was the photon escape probability

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in the Lyman α line. This quantity is connected with the optical depth τ_{12} of the Lyman α line (in the 1D model) by the following formula:

$$\beta_{12} = (1 - \exp(-\tau_{12}))/\tau_{12}. \tag{1}$$

In the paper [5] it was originally shown that for $T_e = 10000\,\mathrm{K}$ the theoretical ratio of Lyα and Baα line intensities, $I(L_\alpha)/I(H_\alpha)$, could be of the order of unity or smaller, for large N_e and large optical thickness of emitting gas. On the basis of those calculations, the intensities of the Lyman, Balmer and Paschen lines of quasars and Seyfert galaxies were discussed in [9].

2 The ratio $I(L_\alpha)/I(H_\alpha)$

The progress in new astronomical equipment in recent years allowed an inclusion of the lines of Lyman and far infrared series of hydrogen in the analysis. The ratio $I(L_\alpha)/I(H_\alpha)$ is of considerable interest. The first data on $I(L_\alpha)/I(H_\alpha)$ in solar outbursts, quasars and Seyfert galaxies were obtained in the middle of the 1970s. In the case of the recombination mechanism (Menzel's case A), this ratio is more than 10. Zirin [10], and Canfield and Puetter [11] presented first results of observations of Lyman and Balmer lines. They found that the ratio $I(L_\alpha)/I(H_\alpha)$, on average, was of the order of 1. Then, Allen et al. [12] measured the $I(L_\alpha)/I(H_\alpha)$ ratio for some quasars, where it was in the range 0.8–3. McCarthy et al. [13] found that $I(L_\alpha)/I(H_\alpha)$ was equal to 4.7($\pm$1.8) and 3.5($\pm$1.3) for the radio galaxies with redshift of about 2.4: B3 0731+438 and MRC 0406-244, respectively. Explanations of the discrepancy between Menzel's case A and obtained $I(L_\alpha)/I(H_\alpha)$ were suggested in the papers [14]–[18]. It was shown that a small ratio $I(L_\alpha)/I(H_\alpha)$ could be derived for large optical depth and strong radiation.

In this paper, we continued our calculations and computed the populations of the hydrogen atomic levels and the line intensities on the base of the Sobolev approximation for the case of collisional excitations and ionizations, using our program described in [5]. We considered the model of a 15-level atom for the gas velocity $V = 300$ km/s. The model parameters were: $T_e = 8000$ and $9000\,\mathrm{K}$ and hydrogen density $N_H = 10^{11}$ and 10^{12} cm^{-3}.

In Fig. 1 the dependence of the $I(L_\alpha)/I(H_\alpha)$ ratio on the geometrical depth of the emitting gas, Z, is presented. The graph shows that an increase of Z (and, correspondingly, an increase of the optical depth) leads to a decrease of this ratio – firstly smooth and later sharp – from about 700 down to 1 or less. Such a behavior of the relative intensities is caused by approaching the physical state of gas to the LTE.

It is interesting to consider the electron density N_e as a function of the layer geometrical thickness Z. In Fig. 2 we show results of the calculations for two values of T_e (8000 and 9000 K) and two values of the hydrogen density N_H. We see that for low thickness Z, the degree of ionization is small and N_e is practically constant.

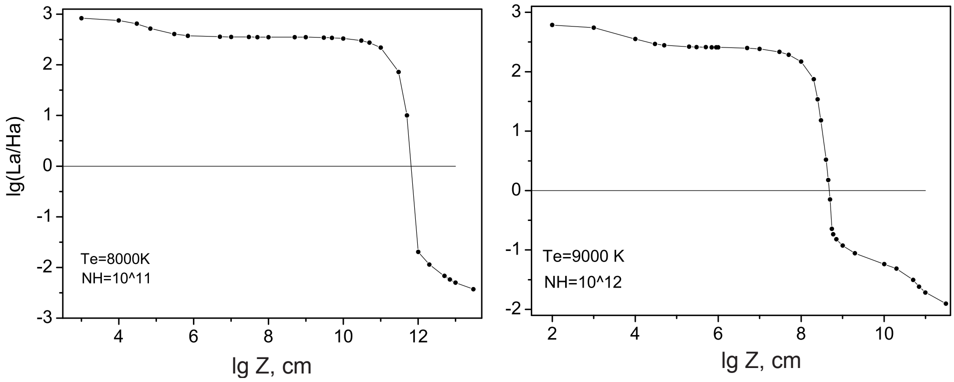

Figure 1: The ratio $I(L_\alpha)/I(H_\alpha)$ vs the geometrical depth Z (in cm) of the emitting gas for $T_e = 8000$ K, $N_H = 10^{11}$ cm^{-3} (left) and $T_e = 9000$ K, $N_H = 10^{12}$ cm^{-3} (right).

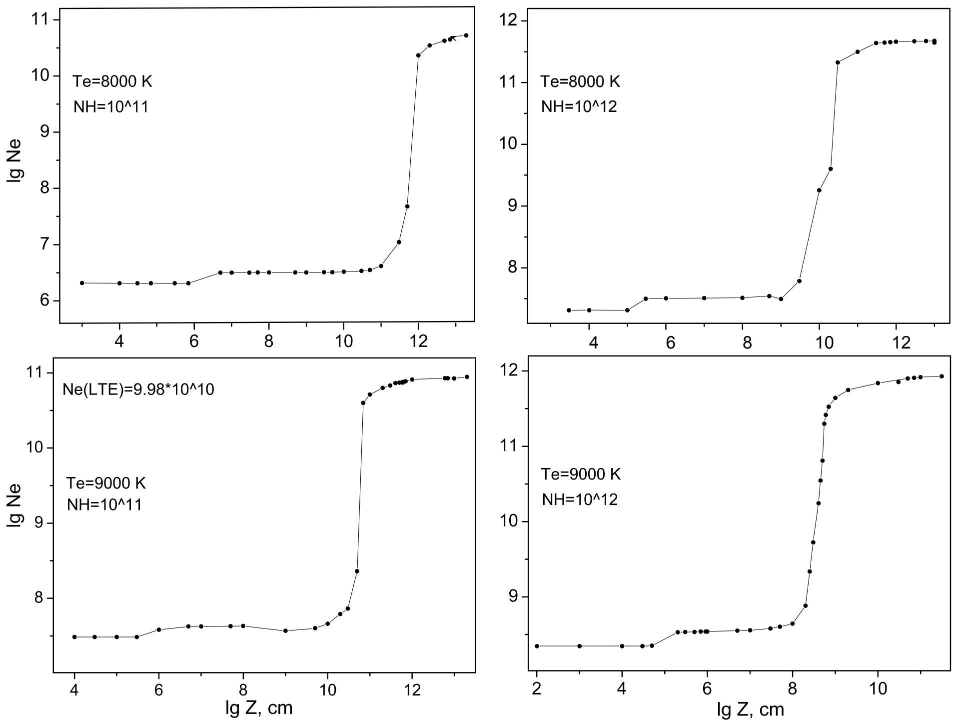

Figure 2: N_e vs the geometrical depth Z for $T_e = 8000$ and 9000 K, $N_H = 10^{11}$ cm^{-3} (left) and 10^{12} cm^{-3} (right).

At $Z \approx 10^5$ cm a small step is visible on the curves as N_e increases slightly due to the blocking of the radiation beyond the Lyman jump. Further growth of Z leads to an increase of the degree of ionization. A dramatic stepwise rise of the degree of ionization by about 10^4 times (!) occurs at a comparatively small interval of Z (depending on T_e and N_H). The comparison of Fig. 2 and Fig. 1 shows that a sharp increase of N_e and a strong decrease of $I(L_\alpha)/I(H_\alpha)$ occur in the same thickness range in which the gas conditions are close to the LTE.

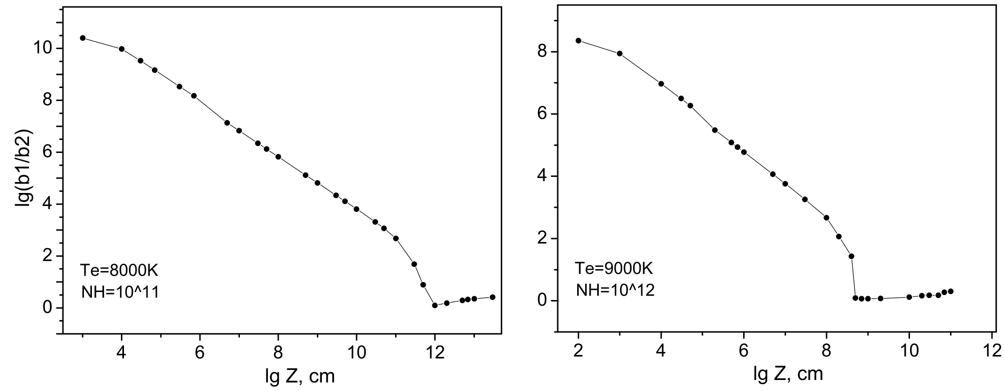

Figure 3: The ratio of Menzel parameters b_1/b_2 as a function of the geometrical depth Z for $T_e = 8000$ K, $N_H = 10^{11}$ cm^{-3} (left) and $T_e = 9000$ K, $N_H = 10^{12}$ cm^{-3} (right).

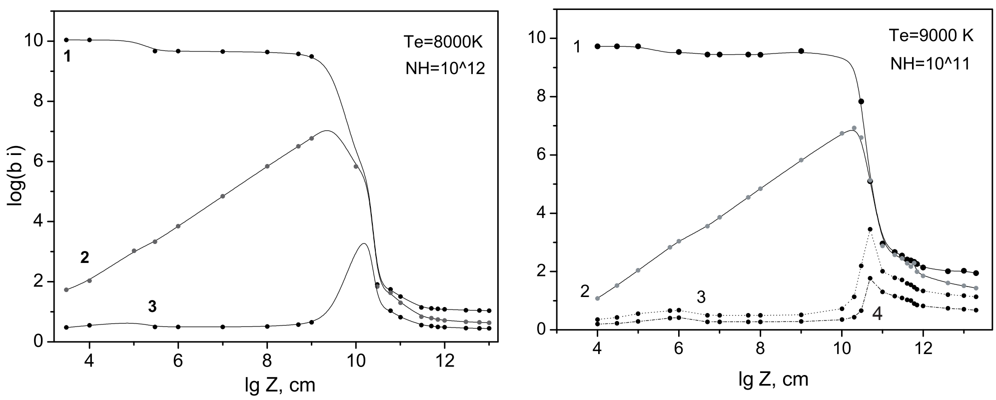

Figure 4: Dependence of b_i on the geometrical depth Z for $T_e = 8000$ K, $N_H = 10^{12}$ cm^{-3} (left) and 9000 K, $N_H = 10^{11}$ cm^{-3} (right). Indices 1, 2, 3 near the curves indicate the number of the atomic level.

What is the reason of such a sharp jump of N_e and, correspondingly, of the degree of ionization? Figs. 3 and 4 show, respectively, the ratio of Menzel parameters b_1/b_2 and the parameters b_1, b_2, b_3 (in a logarithmic scale) as a function of Z. In Fig. 3 we see a graduate decline of the ratio (b_1/b_2) from small Z to a certain geometrical depth, and then the value of b_1/b_2 becomes practically constant. The reason is the large optical depth of gas in the L_α and H_α lines at which the emitting gas becomes thermalized.

In Fig. 4 we see that the curve 1 decreases slowly with the increasing optical depth in the Lyman and then the Balmer lines, while curve 2 increases, and this corresponds to the decline in Fig. 3. If the optical depth of higher series is small, the values b_3 and b_4 change weakly. When the emitting gas becomes optically thick in the Paschen lines, the parameters b_3 and b_4 increase. Further thermalization of gas quickly reduces the Menzel parameters b_1 and b_2, and the role of collisional excitations from the excited levels and multi-cascade ionization increases essentially.

3 Infrared lines

Last years the far infrared spectroscopy developed very actively. For instance, high-resolution IR spectra of hot stars γ Cas, HD 45677, P Cyg with multiple lines of hydrogen (from Pfund to Humphrey series) were obtained. Lenorzer [19] presented ISO (Infrared Space Observatory) spectra and used them to diagnose the radiating gas, by considering fluxes in the lines Hu(14-6), Brα, Pfγ, and their ratios. They showed that on the diagram Hu(14-6)/Brα vs Hu(14-6)/Pfγ, there was a split of optically thin stellar winds and optically thick discs. For example, the fluxes of P Cyg and η Car are close to the optically thin case, whereas γ Cas to the optically thick one. Therefore, the lines of high series can give an additional information about the gas parameters.

Edwards et al. [20] carried out spectroscopic observations of 16 T Tauri stars, analyzed intensities of the Paschen and Brackett lines and compared them to the theoretical ones for Menzel's case B and those calculated by Kwan and Fischer [21]. The statistics of the observed intensity ratios $I(P_\alpha)/I(P_\beta)$ showed that they were less than 1, and P_β/Br_γ ratio was in the range from 3 to 6.

So, the diagnostics of IR-lines could give a significant contribution to study of stellar envelopes. Let us consider the ratio of the line intensities $Br7/P7 = Br_\gamma/P_\delta = 0.420\,\beta_{47}/\beta_{37}$ and $P7/H7 = P_\delta/H_\varepsilon = 0.303\,\beta_{37}/\beta_{27}$. Since these lines are formed by the transitions from the same upper (seventh) level, the intensity ratios of these lines depend only on the corresponding values of the gas optical depths.

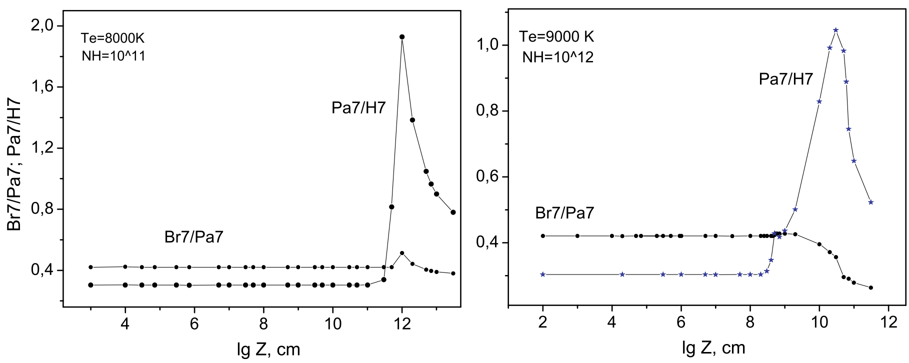

Figure 5: Ratios $I(Br_\gamma)/I(Pa_\delta)$ and $I(Pa_\delta)/I(H_\varepsilon)$ vs the geometrical thickness Z.

Fig. 5 presents the dependence of the ratios $I(Br_\gamma)/I(P_\delta)$ and $I(P_\delta)/I(H_\varepsilon)$ on Z. As it follows from the theoretical relations for the gas optically thin in the Paschen–Brackett series, these values are constant. With an increase of the optical depth $\tau_{L\alpha}$, the Menzel parameters b_i tend to equilibrium ones ($\sim$1).

If we known that the optical depth of P_α is less than 1, then it is possible to use the ratio of the lines mentioned above to estimate the interstellar or circumstellar extinction. Detailed calculations of $I(P_\alpha)/I(H_\alpha)$ have been carried out by Katysheva [9] for the case of collision ionizations and excitations for $T_e = 10000$–20000 K.

4 Conclusion

The results of the calculations presented above show that the role of the multi-cascade ionizations grows rapidly with the increase of the optical depth in the subordinate lines as a result of line-blocking in these lines. This is a natural reaction of the gas approaching the LTE. Such a gas state is observed in the dense emitting regions, for example, in the flares of UV Cet-type stars [22, 23, 24].

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