

# Influence of Rydberg atom-atom collisional and (n-n')-mixing processes on optical properties of astrophysical and low-temperature laboratory plasmas

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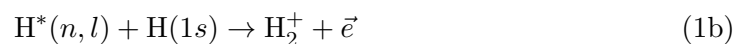
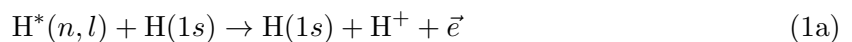
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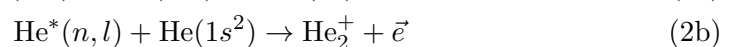
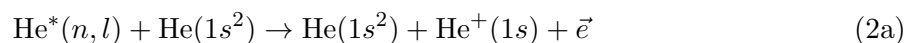
**Abstract.** Here, we will consider the influence of the (n-n')-mixing processes during atom Rydberg-atom collision processes on the intensity of chemi-ionization process. We will take into account  $H(1s) + H^*(n)$  and  $He(1s^2) + He^*(n,l)$  collisional systems, where the principal quantum number  $n \gg 1$ . The corresponding calculations of the chemi-ionization rate coefficients are performed for the temperature region characteristic for the solar and DB white dwarf atmosphere.

## 1. Introduction and the theoretical remarks

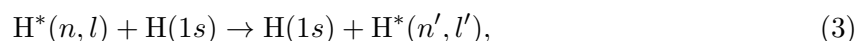
The processes with participation of the Rydberg atoms are still important in the investigation of different stellar atmospheres as well as in the laboratory experiments [1, 2, 3, 4, 5, 6]. The main aim of this paper is the consideration of two kinds of atomic collision processes involving Rydberg atoms which simultaneously occur in the stellar atmospheres and the influence of one on the other. We will analyze the processes of chemi-ionization: in the hydrogen case



and in the helium case



where the principal quantum number  $n \gg 1$ , and the orbital quantum number  $l$  changes in the interval from 0 to  $n - 1$ . Here, we also study the (n-n)-mixing processes:



$$\text{He}^*(n, l) + \text{He}(1s^2) \rightarrow \text{He}(1s^2) + \text{He}^*(n', l'), \quad (4)$$

where the final values of the quantum numbers  $n'$ ,  $l' \neq n, l$ . These processes have always been considered separately, although both processes are caused by the same dipole resonant mechanism [7, 8, 9]. Because of that the inclusion of (n-n')-mixing processes in the procedure of calculation of rate coefficients of the chemi-ionization processes is the main task of this paper. Thus, here will be considered the chemi-ionization processes (1a-1b) and (2a-2b) in the presence of (n-n')-mixing channel (3) and (4) from the astrophysical aspect and analyzed their real influence for the cases of different DB white-dwarf atmospheres and solar atmosphere.

The rate coefficients  $K_{1,2}^a(n, l; T)$  and  $K_{1,2}^b(n, l; T)$  of processes (1a,1b) or (2a,2b) are separately determined for given  $n, l$  and  $T$ . The total rate coefficient  $K_{1,2}^{ab}(n, l; T)$  of processes (1a,1b) or (2a,2b) together, is obtained as  $K_{1,2}^{ab}(n, l; T) = K_{1,2}^a(n, l; T) + K_{1,2}^b(n, l; T)$ . Here, because of further applications, we determined the average total rate coefficient by

$$K_{1,2}(n, T) = \frac{1}{n^2} \cdot \sum_{l=0}^{n-1} (2l+1) \cdot K_{1,2}^{ab}(n, l; T). \quad (5)$$

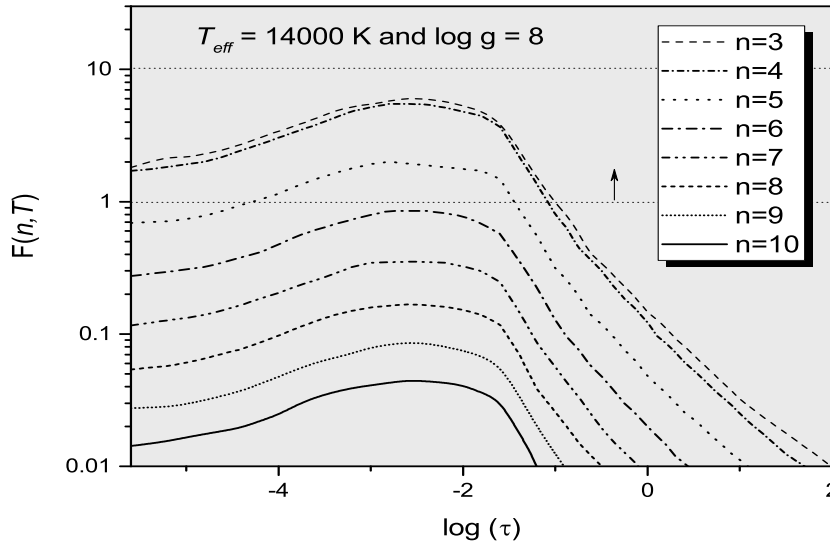
The above mentioned partial rate coefficients  $K_{1,2}^{ab}(n, l; T)$  and  $K_{1,2}^b(n, l; T)$  are determined on the basis of standard expressions  $K_{1,2}^{ab}(n, l; T) = \int_{E_{n,i}}^{\infty} \sigma_{1,2}^{ab}(n, l; E) \sqrt{\frac{2E}{m_{red}}} f_T(E) dE$ , where  $E$  is impact energy,  $\sigma_{1,2}^{ab}(n, l; E)$  is the corresponding cross section,  $m_{red}$  - reduced mass, and  $f_T(E)$  is the Maxwell distribution function. Parameters  $E_{n,i}$ ,  $R_{n,i}$ , cross sections  $\sigma_{1,2}^{ab}(n, l; E)$  and all quantities needed for the calculations are described in details in [10, 11].

## 2. Results and discussion

In accordance with the aim of this work we consider here the model of solar atmosphere from [12] and the model for DB white dwarfs from Koester 2015 (private communication). In order to show the importance of the investigated chemi-ionization processes we compared their efficiencies with the efficiencies of the relevant concurrent processes, i.e. electron-Rydberg atom impact ionization  $\text{H}^*(n) + e \rightarrow \text{H}^+ + e + e$ , in the hydrogen case and  $\text{He}^*(n) + e \rightarrow \text{He}^+ + e + e$ , in the helium case. The main objective of this paper is to demonstrate the impact of these considered processes on the modeling of stellar atmospheres by analysing fluxes caused by atom-Rydberg atom and electron-excited atom impact ionization (using calculated rate coefficients). Fluxes generated in atom-Rydberg atom and electron-excited atom impact ionization are denoted by  $I_{1,2}^{aa}(T; A^*) = K_{1,2}(n, T; A^*) \cdot N(A^*) \cdot N(A)$  and  $I_{1,2}^{ea}(T; A^*) \alpha_{1,2}^{ea}(n, T; A^*) \cdot N(A^*) \cdot N(e)$  where  $A^* = \text{H}^*(n)$  or  $\text{He}^*(n)$ , the rate coefficient  $K_{1,2}(n, T; A^*)$  is given by Eq.(5) and the ionization rate coefficient  $\alpha_{1,2}^{ea}(n, T; A^*)$  is determined on the basis of semiempirical expressions (see [11]). The relative importance of the chemi-ionization processes in comparison with electron-excited atom impact ionization can be characterized by parameters  $F_{1,2}(n, T)$  defined as :

$$F_{1,2}(n, T; A^*) = I_{1,2}^{aa}(T; A^*) / I_{1,2}^{ea}(T; A^*) = \frac{K_{1,2}(n, T; A^*) N(A)}{\alpha_{1,2}^{ea}(n, T; A^*) N(e)} \quad (6)$$

Illustrative calculations were carried out for photosphere of the Sun, for hydrogen case, and some DB white dwarfs with  $\log g = 8$  and temperatures  $T_{eff} = 12000$  K and 14000 K for the case of helium. On the one example (Fig. 1) we show the results of these calculations for DB white dwarf atmospheres with  $T_{eff} = 14000$  K and  $\log g = 8$ . The parameters  $F_{1,2}(n, T; \text{He}^*)$  are shown as functions of  $\log(\tau)$  for DB white dwarfs, where  $\tau$  is the Rosseland optical depth. Fig. 1 shows that for the lower temperatures the chemi-ionization processes are still dominant over electron-excited atom ionization processes, for  $3 \leq n \leq 5$  almost in the whole observed atmosphere. For



**Figure 1.** Parameter  $F_i(n, T; \text{He}^*(n))$  as a function of  $\log(\tau)$ , for principal quantum numbers  $n = 3 - 10$ , for model of DB white dwarf atmosphere with  $T_{eff} = 14000$  K and  $\log g = 8$ .

$6 \leq n \leq 8$  and in the whole observed atmosphere, chemi-ionization processes are comparable with electron-excited atom ionization processes. It can be noticed that if effective temperature  $T_{eff}$  is increasing the influence of chemi-ionization processes begins to decrease. Our analysis shows that the influence of processes (3) decreases with the increase of  $n$ , and for  $n > 10$  it practically does not exist.

From the presented material it is shown that the processes of (n-n')-mixing considerably influence on the rates of chemi-ionization processes, and in spite of the influence of (n-n')-mixing processes with  $n' > n$  in the most parts of the photosphere of the Sun and most parts of white dwarf atmospheres remain dominant or at least comparable to the efficiency of the concurrent processes.

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