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The influence of the radiative non-symmetric ion–atom collisions on the stellar atmospheres in VUV region

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The aim of this work is to draw attention to the processes of radiative charge exchange in non-symmetric ion-atom collisions as a factor of influence on the opacity of stellar atmospheres in VUV region. For that purpose calculations of the spectral absorption coefficients for several ion–atom systems, namely He + H^+ and H + X^+, where X = Na and Li, have been performed. On chosen examples it has been established that the examined processes generate rather wide molecular absorption bands in the VUV region, which should be taken into account for the interpretation of data obtained from laboratory measurements or astrophysical observations. This paper discusses the potential significance of the considered radiative processes for DB white dwarfs and solar atmospheres, as well as for the atmospheres of the so-called lithium stars.

Keywords: Atomic processes — stellar atmospheres

1 Introduction

A series of previous papers studied the influence of the processes of radiative charge exchange in symmetric H($1s$) + H^+ and He($1s^2$) + He^+($1s$) collisions and corresponding photo-association/dissociation processes on the opacity of stellar atmospheres. In the hydrogen case, these processes were shown to be important for the atmospheres of the Sun and some DA white dwarfs (Stancil, 1994); in the helium case, for the atmospheres of some DB and DA white dwarfs (Mihajlov and Dimitrijević, 1992; Stancil, 1994). Thus, the mentioned papers made it clear that at least symmetric ion–atom radiative collisions play a significant role in stellar atmospheres. But the question whether some non-symmetric ion–atom radiative processes can also influence the optical characteristics of the considered stellar atmospheres is still open. A detailed study of such non-symmetric processes in connection with stellar atmospheres would require very extensive research, and remains a task for the future. The aim of this short article is to point out at least some objects where such processes could be of

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interest, and to show the possible ways of describing their influence. For this purpose it was natural to start from the same DB white dwarfs' and the solar atmosphere (which were considered in previous papers, since adequate models exist for them). In the case of DB white dwarfs we mean models presented in Koester (1980), as well as in Bergeron et al. (1995). The necessary models of the solar atmosphere were described in Vernazza et al. (1981) and Maltby et al. (1986), and in Fontenla et al. (2006, 2009).

The composition of the mentioned models and the previous results for the ion–atom symmetric radiative process suggest that in the considered atmospheres the following non-symmetric absorption processes have to be taken into account

$$\varepsilon_\lambda + \mathrm{HeH}^+ \longrightarrow \mathrm{He}^+ + \mathrm{H}, \tag{1}$$

$$\varepsilon_\lambda + \mathrm{He} + \mathrm{H}^+ \longrightarrow \mathrm{He}^+ + \mathrm{H}, \tag{2}$$

$$\varepsilon_\lambda + \mathrm{H}X^+ \longrightarrow \mathrm{H}^+ + X, \tag{3}$$

$$\varepsilon_\lambda + \mathrm{H} + X^+ \longrightarrow \mathrm{H}^+ + X, \tag{4}$$

where $\mathrm{He}, \mathrm{He}^+, \mathrm{H} \equiv \mathrm{He}(1s^2)$, $\mathrm{He}^+(1s)$ and $\mathrm{H}(1s)$ respectively, HeH^+ and $\mathrm{H}X^+$ are the molecular ions in the corresponding electronic ground states, and X and X^+ are a metal atom and its ground-state ion. In the general case, apart from these absorption processes, the corresponding inverse emission processes should also be considered. However, it can be shown that, under the conditions of plasma taken from the models mentioned above, the significance of such emission processes can be neglected in comparison with other relevant emission processes. In this work we will consider the absorption processes (1) and (2) in connection with DB white dwarfs and solar atmospheres, and the processes (3) and (4) with $X = \mathrm{Na}$ and $X = \mathrm{Li}$ – in connection with the solar and so-called lithium stars' atmospheres.

2 Theoretical remark

The ground and first excited electronic state of the considered molecular ion (HeH^+ or $\mathrm{H}X^+$) will be denoted here by $|1>$ and $|2>$, and the corresponding adiabatic potential curves – by $U_1(R)$ and $U_2(R)$, where R is the internuclear distance. By $D_{12}(R)$ will be denoted the modulus of the dipole matrix element for the transition $|1> \rightarrow |2>$, i.e. $D_{12}(R) = |<1|\mathbf{D}(R)|2>|$, where $\mathbf{D}$ is the operator of dipole moment of AX^+. Keeping in mind the results of the previous papers, we will treat the non-symmetric radiative processes (1)–(4) within the dipole approximation where the data about $U_1(R)$, $U_2(R)$ and $D_{12}(R)$ are sufficient for all the necessary calculations. In accordance with Mihajlov et al. (2007) and Ignjatović et al. (2009) the quantum-mechanical treatment is applied here to the photo-dissociative processes (1) and (3), while the absorption charge exchange processes (2) and (4) are described within the semi-classical approximation.

The efficiencies of the photo-dissociative process (1) and (3) are characterized here by the partial spectral absorbtion coefficients $\kappa^{(a)}_{1,3}(\lambda) = \sigma^{\mathrm{phd}}_{1,3}(\lambda, T) \cdot N_{\mathrm{mi}}$, where $\sigma^{\mathrm{phd}}_{1,3}(\lambda, T)$ is the the photo-dissociation cross-section, and the absorption charge exchange processes (2) and (4) by the coefficients

$$\kappa^{(b)}_{2,4}(\lambda) \equiv \kappa^{(b)}_{2,4}(\lambda; T, N_{\mathrm{a}}, N_{\mathrm{i}}) = K^{(b)}_{2,4}(\lambda, T) N_{\mathrm{a}} N_{\mathrm{i}}, \tag{5}$$

where T, $N_{\rm a}$, $N_{\rm i}$ and $N_{\rm mi}$ denote the local plasma temperature and the densities of the atoms (He or H), ions (H^+ or X^+) and molecular ions (HeH^+ or HeX^+). Assuming the existence of LTE, we will take the photo-dissociation coefficient $\kappa^{(a)}_{1,3}(\lambda)$ in an equivalent form (suitable for further considerations), given by the relations

$$\kappa^{(a)}_{1,3}(\lambda) \equiv \kappa^{(a)}_{1,3}(\lambda; T, N_{\rm mi}) = K^{(a)}_{1,3}(\lambda, T) N_{\rm a} N_{\rm i}, \tag{6}$$

$$K^{(a)}_{1,3}(\lambda, T) = \sigma^{\rm phd}_{1,3}(\lambda, T) \cdot \chi^{-1}_{1,3}(T), \quad \chi_{1,3}(T) = (N_{\rm a} N_{\rm i})/N_{\rm mi}, \tag{7}$$

where the photo-dissociation cross-section and the quantity $\chi_{1,3}(T)$ are determined in a way similar to that in Ignjatović et al. (2009).

The efficiency of the processes (1) and (2), and (3) and (4) together is characterized by the total spectral absorbtion coefficients

$$\kappa_{12}(\lambda) = \kappa^{(a)}_1(\lambda) + \kappa^{(b)}_2(\lambda) = K_{12}(\lambda, T) N_{\rm a} N_{\rm i}, \quad K_{12}(\lambda, T) = K^{(a)}_1(\lambda, T) + K^{(b)}_2(\lambda, T), \tag{8}$$

$$\kappa_{34}(\lambda) = \kappa^{(a)}_3(\lambda) + \kappa^{(b)}_4(\lambda) = K_{34}(\lambda, T) N_{\rm a} N_{\rm i}, \quad K_{34}(\lambda, T) = K^{(a)}_3(\lambda, T) + K^{(b)}_4(\lambda, T), \tag{9}$$

where $K^{(a)}_{1,3}(\lambda, T)$ is given by Eqs. (7).

3 Results and discussion

The data needed for determination of $U_{1,2}(R)$ and $D^2_{12}(R)$ in the case HeH^+ are taken here from Green et al. (1974). For the molecular ions HNa^+ and HLi^+ the values of $U_{1,2}(R)$ and $D^2_{12}(R)$ are obtained here, using the method of calculation described in detail in Ignjatović and Mihajlov (2005).

As the main aim of this work is to draw attention to processes (1)–(4) as factors of influence on the opacity of the stellar atmospheres in UV and VUV region, the spectral absorption coefficients (for Na, Ni = 1) $K_{12}(\lambda, T)$ and $K_{34}(\lambda, T)$, which characterize the total efficiency of the processes (1) and (2), and (3) and (4) respectively, will be determined. The necessary calculations are performed here in accordance with (5)–(9) in the part of the VUV region, namely 70 nm $\leq \lambda \leq$ 170 nm, for several values of T which are relevant for the photospheres of the Sun and of the considered DB white dwarfs.

The behavior of the total spectral absorption coefficients $K_{12}(\lambda, T)$ for 70 nm $\leq \lambda \leq$115 nm and T = 5500 K and 12000 K is shown in Figs. 1 and 2. The first temperature is characteristic of a large part of the solar photosphere, and the second – of a part of the atmosphere of DB white dwarfs with $T_{\rm eff}$ = 12000 K.

The behavior of the total spectral absorption coefficients $K_{34}(\lambda, T)$, in the case of the processes (3) and (4) with X = Na, for 130 nm $\leq \lambda \leq$ 170 nm and T = 4000 K, is shown in Fig. 3. Let us note that the chosen temperature corresponds to a sunspot (see Maltby et al. (1986)).

Finally, taking into account the existence of the so-called lithium stars, intensively discussed in the literature (see North et al., 1998; Shavrina et al., 2003), Fig. 4 shows the behavior of the total spectral absorption coefficients $K_{34}(\lambda, T)$ in the case of processes (3) and (4) with X = Li for the same λ and T as in the case X = Na.

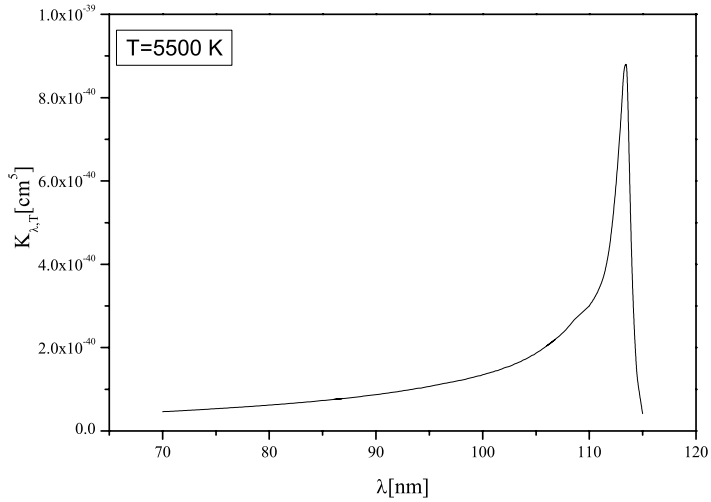


Figure 1 Rate coefficients $K_{\rm ia}(\lambda, T)$ (spectral absorption coefficients for Na, Ni = 1) at $T = 5500$ K, for HeH^+.

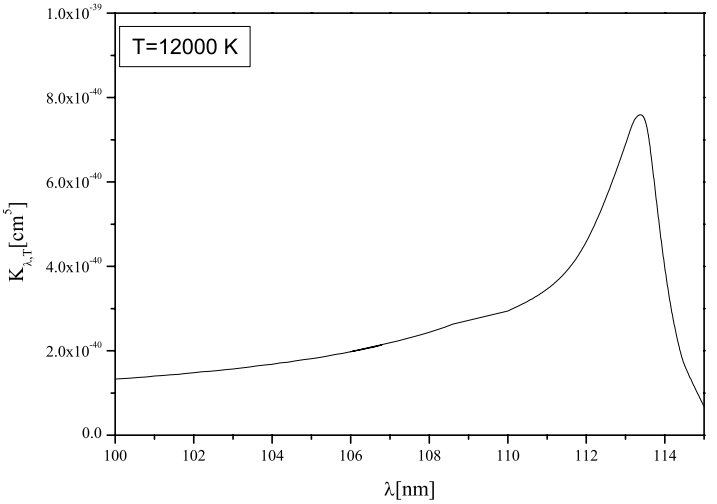


Figure 2 Rate coefficients $K_{\rm ia}(\lambda, T)$ at $T = 12000$ K, for HeH^+.

The presented figures illustrate the fact that the considered non-symmetric processes (1)–(4) generate rather wide molecular absorption bands in the VUV region. Moreover, the comparison of $K_{12}(\lambda, T)$ and $K_{34}(\lambda, T)$ with the corresponding characteristics of other relevant absorption processes (symmetric ion–atom absorption processes etc.), as well as the corresponding particle densities, suggest a conclusion that in the regions of λ which correspond to the most parts of the mentioned bands the efficiency of processes (1)–(4) is at least not negligible, and sometimes it is just these processes that determine the opacity of the considered stellar atmospheres.

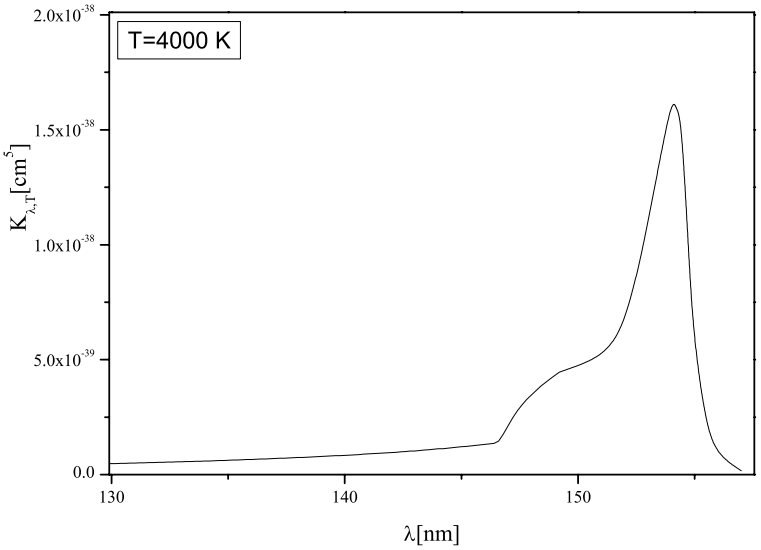


Figure 3 Rate coefficients $K_{\rm ia}(\lambda, T)$ at $T = 4000$ K, for HNa^+.

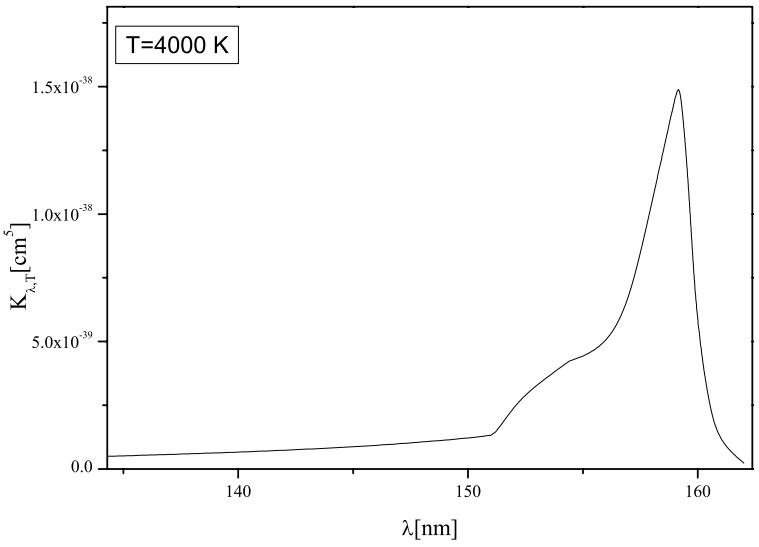


Figure 4 Rate coefficients $K_{\rm ia}(\lambda, T)$ at $T = 4000$ K, for HLi^+.

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