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SUNSPOTS OPACITY: THE ION-ATOM ABSORPTION PROCESSES

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Abstract. As a continuation of the previous investigations of the symmetric and strongly non-symmetric ion-atom absorption processes within the models of the quiet Sun photosphere, we studied these processes within a model of the sunspots in the far-UV region. We considered the processes of the photodissociation of the H_2^+ and HM^+ molecular ions and absorption processes in the H(1s)+H^+ and H(1s) + M^+ collisions, where M is one of the metal atoms: M = Na, Ca, Mg, Si and Al. The significance of these processes in far UV and EUV regions in comparison with the concurrent absorption processes, especially with the processes of the photo-ionization of the metal atoms (Na, Mg, Ca, Al, Fe, etc.) was analyzed. Calculated results show that the influence of the analyzed ion-atom absorption processes on the opacity of sunspots in the considered spectral region, 100 nm $\leq \lambda \leq$ 250 nm, is not less and in some parts even larger than the influence of the referent electron-atom processes. It is shown that the considered ion-atom absorption processes should be included ab initio in the corresponding models of sunspots of solar-type and near-solar-type stars.

1. INTRODUCTION

In the previous investigations the significant influence of the relevant ion-atom absorption processes on the solar photosphere opacity was already demonstrated. So, in our previous papers have been studied such **symmetric ion-atom processes**, as the molecular ion H_2^+ photo-dissociation

$$\varepsilon_\lambda + H_2^+ \longrightarrow H + H^+, \tag{1}$$

and the absorption charge exchange in (H^+ + H)-collisions

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

where H=H(1s), H_2^+ is the hydrogen molecular ion in the ground electronic state, and ε_λ – the energy of a photon with the wavelength λ.

The total contribution of the processes (1) and (2) to the solar photosphere opacity is characterized by the total spectral absorption coefficient which is defined by relation

$$\kappa_{sim}^{(tot)}(\lambda; h) = \kappa_{sim}^{(bf)}(\lambda; h) + \kappa_{sim}^{(ff)}(\lambda; h), \tag{3}$$

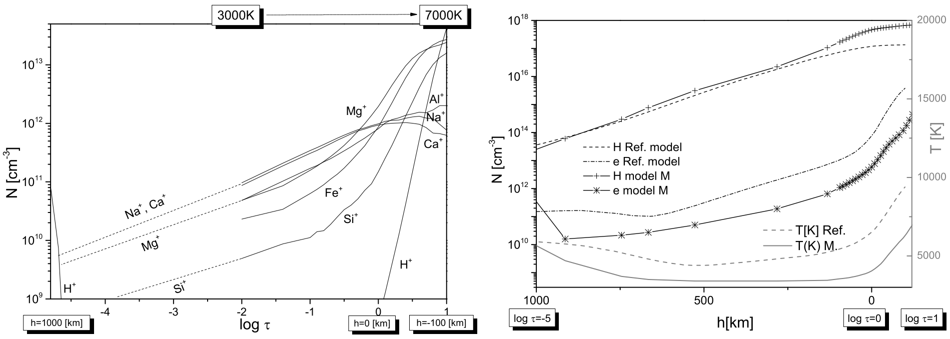

Figure 1: *Left:* The densities of hydrogen and metal ions N_{H^+} and N_{M^+} *Right:* The densities $N(e)$, $N(H)$ and T for the sunspot model M and referent model of the quiet Sun atmosphere (Maltby et al. 1986).

and described in details in Mihajlov et al. (2012, 2013). Then, in Mihajlov et al. (2013) was undertaken the investigation **non-symmetric ion-atom absorption processes**, namely the photo-dissociation and photo-association of the molecular ions

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

$$\varepsilon_\lambda + \mathrm{H} + M^+ \longrightarrow (M\mathrm{H}^+)^*, \tag{5}$$

and the absorption charge-exchange in the ion-atom collisions

$$\varepsilon_\lambda + \mathrm{H} + M^+ \longrightarrow \mathrm{H}^+ + M, \tag{6}$$

where M is the ground state atom of one of metals, relevant for the used solar photosphere model, whose ionization potential I_M is smaller than the hydrogen atom ionization potential I_{H}, M^+ - the corresponding atomic ion, $\mathrm{H}M^+$ - the molecular ion in the electronic states which are adiabatically correlated (∞ internuclear distance) with the states of the ion-atom systems H + M^+ and H$^+$ + M respectively.

The basic task of this investigation is to estimate the significance of the symmetric and non-symmetric ion-atom absorption processes in the case of the sunspot with respect to the processes of the negative hydrogen ion H$^-$ photo-detachment and inverse "bremsstrahlung" in (e + H)-collisions, namely

$$\varepsilon_\lambda + \mathrm{H}^- \longrightarrow \mathrm{H} + e', \tag{7}$$

$$\varepsilon_\lambda + e + \mathrm{H} \longrightarrow \mathrm{H} + e', \tag{8}$$

where e and e' denote the free electron in initial and final channel, which are treated here as the referent processes.

It is clear that in the case of this atmosphere just the electron-atom processes (7) and (8) can be taken as the referent ones. Because of that in these previous papers many other radiative processes have not been considered, including the certainly important processes of the metal atom photo-ionization, which were already discussed in the literature in connection with the quiet Sun atmosphere. We mean the processes

$$\varepsilon_\lambda + (M)^*_g \longrightarrow M^+ + e', \tag{9}$$

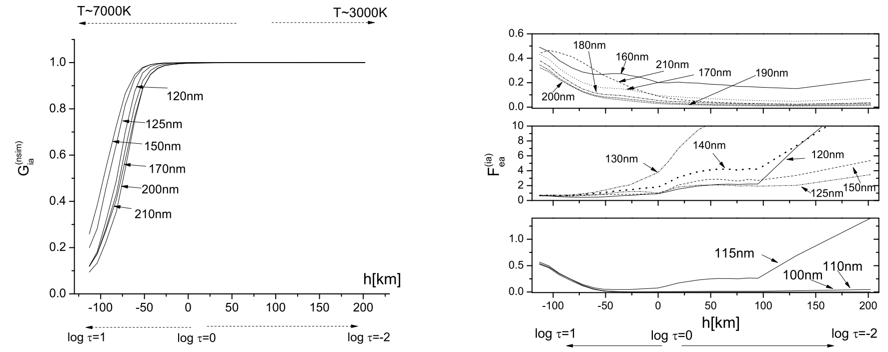

Figure 2: *Left*: The behavior of the quantity $G_{ia}^{(nsim)}(\lambda; h)$, given in Sec. 2. *Right:* The behavior of the quantity $F_{ea}^{(ia)}(\lambda; h)$, given in Sec. 2.

where $(M)_g^*$ denotes the given metal atom in the ground state, i.e. M, or in any possible excited state, i.e. M^*. However, within the sunspot we have a significantly smaller temperature than in the quiet Sun photosphere (see Fig. 1) and consequently it is possible to expect there more larger efficiency of these photo-ionization processes, so that the position of the mentioned electron-atom processes as the referent ones is not so clear. Because of that the processes of the metal atom photo-ionization were taken into account from the beginning of this investigation (some of them were considered already in Sreckovic et al. 2014). It follows that the efficiency of bf-, ff- and fb-absorption channels (4)-(6) together for one of the considered metal species M is characterized by the partial absorption coefficient $\kappa_{\mathrm{H}M^+}(\lambda; h)$ defined by the

$$\kappa_{\mathrm{H}M^+}(\lambda; h) = \kappa_{\mathrm{H}M^+}^{(bf)}(\lambda; h) + \kappa_{\mathrm{H}M^+}^{(ff)}(\lambda; h) + \kappa_{\mathrm{H}M^+}^{(fb)}(\lambda; h), \tag{10}$$

and described in details in Ignatovic et al. (2014a,b) and Sreckovic et al. (2014). Consequently, the total contribution of the mentioned non-symmetric ion-atom processes to the absorption of the solar radiation on the height h is described by the total spectral absorption coefficient which is given by

$$\kappa_{nsim}^{(tot)}(\lambda; h) = \sum \kappa_{\mathrm{H}M^+}(\lambda; h), \tag{11}$$

where the summing is performed over all considered metal species M.

2. RESULTS AND DISCUSSION

Firstly, we performed the calculations and analysis of the spectral absorption coefficients $\kappa_{sim}^{(tot)}(\lambda)$, $\kappa_{nsim}^{(tot)}(\lambda)$ and $\kappa_{tot}(\lambda) = \kappa_{nsim}^{(tot)}(\lambda) + \kappa_{sim}^{(tot)}(\lambda)$ which characterize the total efficiencies of all, symmetric and non-symmetric ion-atom absorption processes. For that purpose we calculate the quantity $G_{tot}^{(nsim)}(\lambda) = \frac{\kappa_{nsim}^{(tot)}(\lambda)}{\kappa_{tot}(\lambda)}$, which describes the relative contribution to the sunspot photosphere opacity of the non-symmetric processes (4) - (6) with respect to the contribution of all ion-atom absorption processes. The behavior of this quantity (for several values of λ) is illustrated in Fig. 2 in the interval of heights: -125 km $\leq h \leq$ 200 km. Then we calculate the quantity

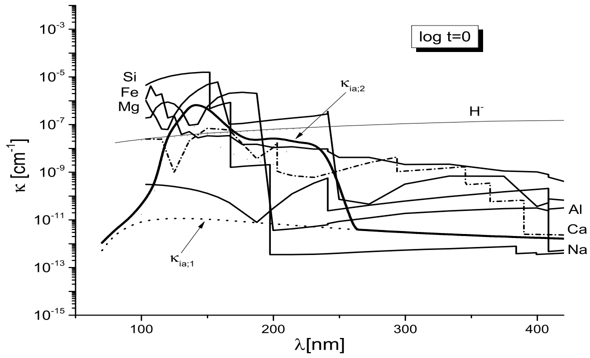

Figure 3: All considered absorbtion processes for log $t = 0$ in the case of the sunspot (model M): Mg, Si, etc. - the abbreviations for the spectral coefficients $\kappa_{phi;M}$ of the metal atoms photo-ionization processes; κ_{ea} - H^{-}-continuum; $\kappa_{ia;1}$ - symmetric ion-atom processes; $\kappa_{ia;2}$ - ion-atom symmetric and non-symmetric processes.

$F_{ea}^{(tot)}(\lambda) = \frac{\kappa_{tot}(\lambda)}{\kappa_{ea}(\lambda)}$, where $\kappa_{sim}^{(tot)}(\lambda)$ and $\kappa_{nsim}^{(tot)}(\lambda)$ are defined by Eqs. (3), (11) and $\kappa_{ea}(\lambda)$ - defined in Sreckovic et al. (2014). This quantity describes the relative contribution to the sunspot photosphere opacity of the all ion-atom absorption processes with respect to the contribution of H- continuum (presented in Fig 2). Finally, we compare within the same part of the sunspot (Fig.1) the total efficiencies of the ion-atom and referent electron-atom absorption processes together (H- continuum) and spectral coefficients $\kappa_{phi;M}$ of the metal atoms photo-ionization processes in the considered part of the far-UV region of λ with all ion-atom absorption processes. (Fig. 3). From the presented material, it follows that the considered ion-atom absorption processes should be included ab initio in the corresponding models of sunspots or solar-type stars.

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