The influence of the radiative symetric and non- symmetric ion-atom collisions on the stellar atmospheres

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INTRODUCTION

- The aim of this presentation is to draw attention to the processes of radiative symmetric and strongly non-symmetric ion-atom collisions as factors of influence on the opacity of stellar atmospheres .

- Therefore for several ion-atom systems H+H$^+$, He+He$^+$, He + H$^+$ and H + A$^+$, where A = Li, Na etc.) some characteristics have been determined and presented, such as molecular potential curves and dipole matrix elements.

- Using these characteristics, calculations have been carried out to determine coefficients of spectral absorption in the atmosphere of the Sun and of some of DB white dwarfs and etc.

- The standard models of the considered atmospheres have been used in the calculations.

- The significant influence of some ion-atom radiative collision processes on the optical characteristics of the weakly ionized layers of some stellar atmospheres was already established. Here we keep in mind some **symmetric** radiative processes as radiative charge exchange and photo absorption/emission ones, which can be described by

$$A + A^{+} \longleftrightarrow \varepsilon_{\lambda} + A^{+} + A \quad \text{(radiative charge exchange)},$$

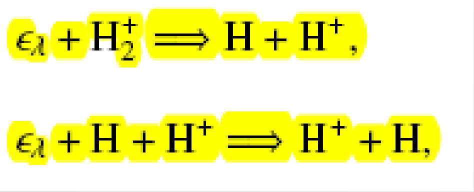
$$A + A^{+} \longleftrightarrow \varepsilon_{\lambda} + A_{2}^{+} \quad \text{(photo absorption)},$$

where A =H(1s) or He($1s^2$), A^+=H^+ or He+(1s), A_2^+ denotes the molecular ion H_2^+ or He_2^+ in the ground electronic states, and ε_λ- the energy of the photon with the wavelength λ.

- It was shown that these processes can influence to the opacity of atmospheres of Sun (Mihajlov et al. 1986, 1992a, 1993, 1994) and some DB and DA white dwarfs (Mihajlov et al. 1992b, 1995, Stancil 1994).

- Opacities of the solar and other stellar atmospheres are naturally caused by a large number of radiative processes.

- In papers (Mihajlov et al. 1993,1994, 2007) were considered absorption processes



$$\epsilon_\lambda + H_2^+ \Longrightarrow H + H^+, \qquad (1a)$$

$$\epsilon_\lambda + H + H^+ \Longrightarrow H^+ + H, \qquad (1b)$$

and their contribution to the opacity of solar atmosphere in different wavelength regions.

- The aim of mentioned papers was to determine the relative importance of the processes of absorption charge exchange (1b), which were not taken into account before, with respect to the photo-dissociation processes (1a), which were already treated in the literature (Mihalas 1978) =>

and compare it with the contribution of other relevant radiative processes

$$\epsilon_\lambda + \begin{cases} \mathrm{H}^- \\ \mathrm{H} + e' \end{cases} \Longrightarrow \mathrm{H} + e'', \qquad \text{(2a)}$$

$$\epsilon_\lambda + \begin{cases} \mathrm{H}^*(n) \\ \mathrm{H}^+ + e' \end{cases} \Longrightarrow \mathrm{H} + e'', \qquad \text{(2b)}$$

- In Mihajlov et al. (1993, 1994a) the part of the wavelength region 365 nm ≤ λ ≤ 820 nm was taken into account. It was found that in this region the processes (1) give a contribution of about **10%** in comparison with processes (2). This fact alone demonstrated that considered ion-atom radiative processes must be taken into account for solar atmosphere modeling.

- That was the reason for expecting significantly increasing contribution of the processes (1) at the short wavelength region $\lambda_b <\sim \lambda < 365$ nm, *where* λ_b 91.1262 nm is the wavelength that corresponds to the ionization threshold of the H(1s) atom, in comparison with processes (2).

- In that paper (Mihajlov et al. 2007) the calculations of the spectral absorption coefficients, that characterize the processes (1a,b) were performed in the region 90 nm ≤ λ ≤ 370 nm. Calculations of the absorption coefficient were performed for the solar photosphere and lower chromospheres by means of a standard solar atmosphere model (Model C, Vernazza et al. 1981), and the total contribution of the processes (1) to the solar opacity was estimated.

Theoretical remarks

- The partial spectral absorption coefficients $k_{i\,a}^{(a)}$ (λ) and $k_{i\,a}^{(b)}$ (λ) can be in the form:

$$\kappa_{ia}^{(a)}(\lambda) = \sigma_{\mathrm{phd}}(\lambda, T) N(\mathrm{H}_2^+),$$

$$\kappa_{ia}^{(b)}(\lambda) = K_{ia}^{(b)}(\lambda, T) N(\mathrm{H}) N(\mathrm{H}^+),$$

where T and N(H), N(H^+) and N(H_2^+) are the temperature *and* the densities of H, H^+ and H_2^+ in the considered layer of the solar atmosphere,

- σ_{phd}(λ, *T)* is the average *cross-section* for photo-dissociation of the molecular ion H_2^+.

take the form

$$\kappa_{ia}^{(a)}(\lambda) = K_{ia}^{(a)}(\lambda, T) N(\mathrm{H}) N(\mathrm{H}^+),$$

$$K_{ia}^{(a)}(\lambda) = \sigma_{\mathrm{phd}}(\lambda, T) \cdot \chi^{-1}, \qquad \chi = \frac{N(\mathrm{H}) N(\mathrm{H}^+)}{N(\mathrm{H}_2^+)}.$$

charge exchange

$$K_{ia}^{(b)}(\lambda, T) = 0.62 \times 10^{-42} \frac{C(R_\lambda)(R_\lambda/a_0)^4}{1 - a_0/R_\lambda} \times \exp\left[-\frac{U_1(R_\lambda)}{kT}\right] \cdot \frac{\Gamma\left(\frac{3}{2}; -\frac{U_1(R_\lambda)}{kT}\right)}{\Gamma\left(\frac{3}{2}\right)},$$

- The total spectral absorption coefficient κ_{ia}*(λ)* as sum,

$$\kappa_{ia}(\lambda) = K_{ia}(\lambda, T) \cdot N(\mathrm{H}) N(\mathrm{H}^+),$$

$$K_{ia}(\lambda, T) = K_{ia}^{(a)}(\lambda, T) + K_{ia}^{(b)}(\lambda, T).$$

- Processes (1) are treated as the result of the radiative transitions between the ground and the first excited adiabatic electronic state of the molecular ion H_2^+ which are caused by the interaction of the electron component of the ion-atom system (H_2^+ or $H+H^+$) with the free electromagnetic field taken in the dipole approximation.

- Apart from the potential curves $U_1(R)$ *and* $U_2(R)$, for determination of $\sigma_{phd}(\lambda, T)$ and $K_{ia}^{(b)}(\lambda, T)$ it is important to know the dipole matrix element $D_{12}(R)$ defined by relations

$$D_{12}(R) = |\mathbf{D}_{12}(R)|, \qquad \mathbf{D}_{12}(\boldsymbol{R}) = \langle 1|\mathbf{D}(\boldsymbol{R})|2\rangle,$$

Results =>

Case 1: solar atmospheres

$$\epsilon_\lambda + H_2^+ \Longrightarrow H + H^+,$$

$$\epsilon_\lambda + H + H^+ \Longrightarrow H^+ + H,$$

$$\epsilon_\lambda + \left\{\begin{array}{l} H^- \\ H + e' \end{array}\right. \Longrightarrow H + e'',$$

$$\epsilon_\lambda + \left\{\begin{array}{l} H^*(n) \\ H^+ + e' \end{array}\right. \Longrightarrow H + e'',$$

ratio

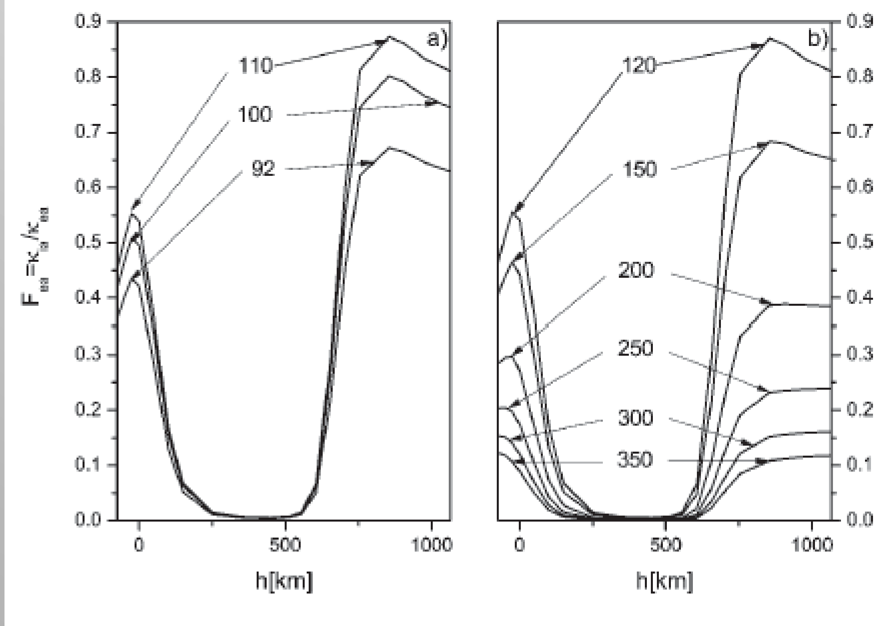


Fig. 4. Behavior of the quantity $F_{\kappa_{ea}} = \kappa_{ia}/\kappa_{ea}$ as a function of λ and h.

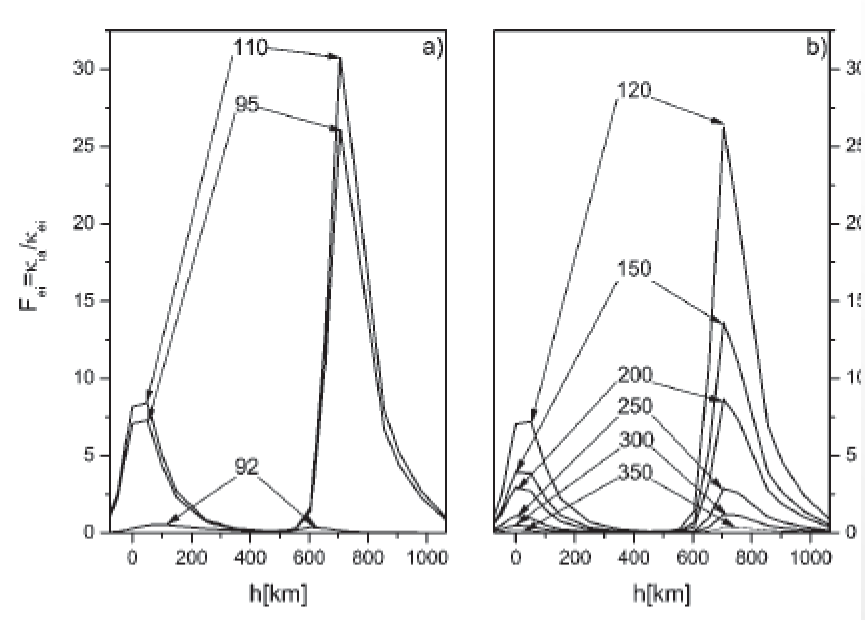


Fig. 5. Behavior of the quantity $F_{\kappa_{ei}} = \kappa_{ia}/\kappa_{ei}$ as a function of λ and h.

-The total contribution of the processes (1) to the solar opacity, and their relative contribution in comparison with the other relevant absorption processes (2), were determined.

-In significant parts of the considered layer (-75 km $\le h \le$ 1065 km) the total contribution of the processes (1) varies from about 10% to about 90% of the contribution of the absorption processes (2a), and it is completely dominant in comparison with absorption processes (2b).

Case 2: DB white dwarfs atmospheres

- Papers Mihajlov et al. 1995, 2009 are dedicated to the symmetric processes of type (A) in DB white dwarfs atmospheres.

$$\epsilon_\lambda + \mathrm{He}_2^+ \Longrightarrow \mathrm{He} + \mathrm{He}^+,$$

$$\epsilon_\lambda + \mathrm{He} + \mathrm{He}^+ \Longrightarrow \begin{cases} \mathrm{He}^+ + \mathrm{He} \\ \mathrm{He} + \mathrm{He}^+ \end{cases},$$

(A)

$$\epsilon_\lambda + \mathrm{He} + \mathrm{e} \Longrightarrow \mathrm{He} + \mathrm{e}',$$

(B)

-The results obtained allow the possibility of estimating which absorption processes give the main contribution to the opacity in DB white dwarf atmospheres in different spectral regions.

-Similar to the solar case are conclusions.

- From results of Mihajlov et al. (2009) it follows that the helium absorption processes (A) are dominant in the region 70 nm < *λ* < *200* nm, while in the region *λ* > *200* nm the He− absorption processes (B) have the principal role.

- Models from Vernazza et al. (1981), Maltby et al. (1986), Koester (1980), Bues (1970).

-It is clear that the helium rich stellar atmospheres contain, in the parts per cent, hydrogen and some metal components, while the hydrogen rich ones contain, also in the parts per cent, helium and some other metal components. Consequently, apart of the processes (1), in the stellar atmospheres can be manifested also the similar symmetric processes where, for an example A=H in the helium rich atmospheres, or A= Si, Ca, etc. in the hydrogen rich atmospheres. It means $Si+Si^+$…(both non-dominant).

-Already in Mihajlov et al. 1986, 1992 it was noted that their influence on the optical characteristics of the stellar atmospheres can be neglected in comparing to the influence of the processes (1).

* * *

Now we are working on: non-symmetric

- The mentioned papers have leaved opened the questions of the significance of the **non-symmetric** ion-atom radiative processes, where one of the partners belongs to the dominant component,

$$A^+ + X \longleftrightarrow \varepsilon_\lambda + AX^+, \qquad (3)$$

$$A^+ + X \longleftrightarrow \varepsilon_\lambda + A + X^+, \qquad (4)$$

where A denotes atom He($1s^2$) in the case of the helium rich stellar atmospheres, or atom H(1s) in the case of the hydrogen rich ones. Here it is understood that $I_X < I_A$, where I_X and I_A are the ionization potentials of the atoms X and A. X is non-dominant component.

- We will consider the ion-atom non-symmetric radiative processes under the conditions characterizing the atmospheres of some DB white dwarfs, in the case of the helium rich ones (Koester 1980), and the solar atmosphere, in the case of the hydrogen rich ones (Vernazza et al. 1981, Maltby et al. (1986)).

- Under such conditions the influence of the emission part of the processes (3) and (4) on the optical characteristics of the corresponding stellar atmospheres can be neglected in comparing to the other relevant emission processes. In the emission case of these processes both partners belong to the underrepresented (non-dominant) components of the considered atmospheres.

- The situation is opposite in the case of the absorption part of the processes (3) and (4), since in this case one of the partners necessarily belongs to the dominant component of that atmospheres. Because of that here we will consider the following absorption processes

$$\varepsilon_\lambda + AX^+ \longrightarrow A^+ + X,$$

$$\varepsilon_\lambda + A + X^+ \longrightarrow A^+ + X,$$

Theory

- In this work the quantum mechanical treatment is applied here to the photo dissociative process (3). The absorption charge exchange processes (4) is described in the semi-classical approximation.

- Dipole matrix element, D(R) operator of dipole moment of AX^+

$$D_{12}(R) =< 1|\mathrm{D}(R)|2 >,$$

$$U_1(R),\ U_2(R)\ \text{and}\ D_{12}^2(R),$$

(3)

- Partial spectral absorption coefficients for (3)

$$\kappa_{ia}^{(a)}(\lambda) \equiv \kappa_{ia}^{(a)}(\lambda;T,N(AX^+)) = \sigma_{phd}(\lambda,T)N_{AX+}$$

$$\kappa_{ia}^{(a)}(\lambda) = K_{ia}^{(a)}(\lambda,T)N(He)N(He^+),$$

$$K_{ia}^{(a)}(\lambda,T) = \sigma_{phd}(\lambda,T)\cdot\chi_{ia}(T),$$

- The photo-dissociation cross-sections for the process (3) is defined by

$$\sigma_{phd}(\lambda, T) = \frac{\sum\limits_{l_1,v_1} (2l_1+1)e^{\frac{-E_{v_1,l_1}}{kT}} \cdot \sigma_{v_1,l_1}(\lambda)}{\sum\limits_{l_1,v_1} (2l_1+1)e^{\frac{-E_{v_1,l_1}}{kT}}},$$

- Partial cross-sections

$$\sigma_{v_1,l_1}(\lambda) = \frac{8\pi^3}{3\lambda}\left[\frac{l_1+1}{2l_1+1}|D_{E_2,l_1+1;v_1,l_1}|^2 + \frac{l_1}{2l_1+1}|D_{E_2,l_1-1;v_1,l_1}|^2\right],$$

$$D_{E_2,l_2;v_1,l_1} =< \Psi_{E_2,l_2}(R)|D_{12}(R)|\Psi_{v_1,l_1}(R) >,$$

- Charge-exchange absorption coefficient for (4), absorption charge exchange processes (4) are described in the semi-classical approximation.

$$\kappa_{ia}^{(b)}(\lambda) = K_{ia}^{(b)}(\lambda, T)N_A N_{X^+},$$

$$K_{ia}^{(b)}(\lambda,T) = 0.62\cdot 10^{-42}\sum_{i=1}^{2}\frac{\left[\frac{2D_{12}(R_{\lambda;i})}{eR_{\lambda;i}}\right]^{2}}{\gamma(R_{\lambda;i})}\times$$

$$\times\left(\frac{R_{\lambda;i}}{a_0}\right)^{4}\exp\left[-\frac{U_1(R_{\lambda;i})}{kT}\right]\cdot X(R_{\lambda;i}),$$

$$\gamma(R_{\lambda;i}) = \left|\frac{dln\left[\frac{U_{12}(R)}{2Ry}\right]}{d(R/a_0)}\right|_{R=R_{\lambda;i}},$$

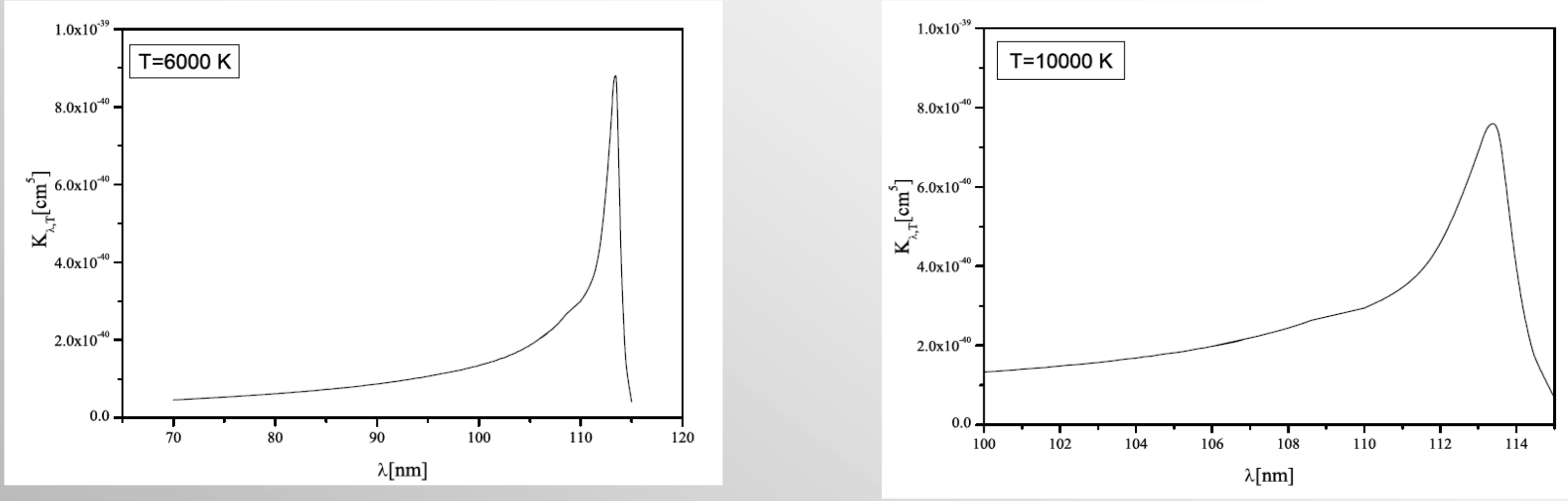
- The total absorption coefficient

$$\kappa_{ia}(\lambda) = \kappa_{ia}^{(a)}(\lambda) + \kappa_{ia}^{(b)}(\lambda)$$

$$\kappa_{ia}(\lambda) = K_{ia}(\lambda,T)N_A N_{X+},\quad K_{ia}(\lambda,T) = K_{ia}^{(a)}(\lambda,T) + K_{ia}^{(b)}(\lambda,T),$$

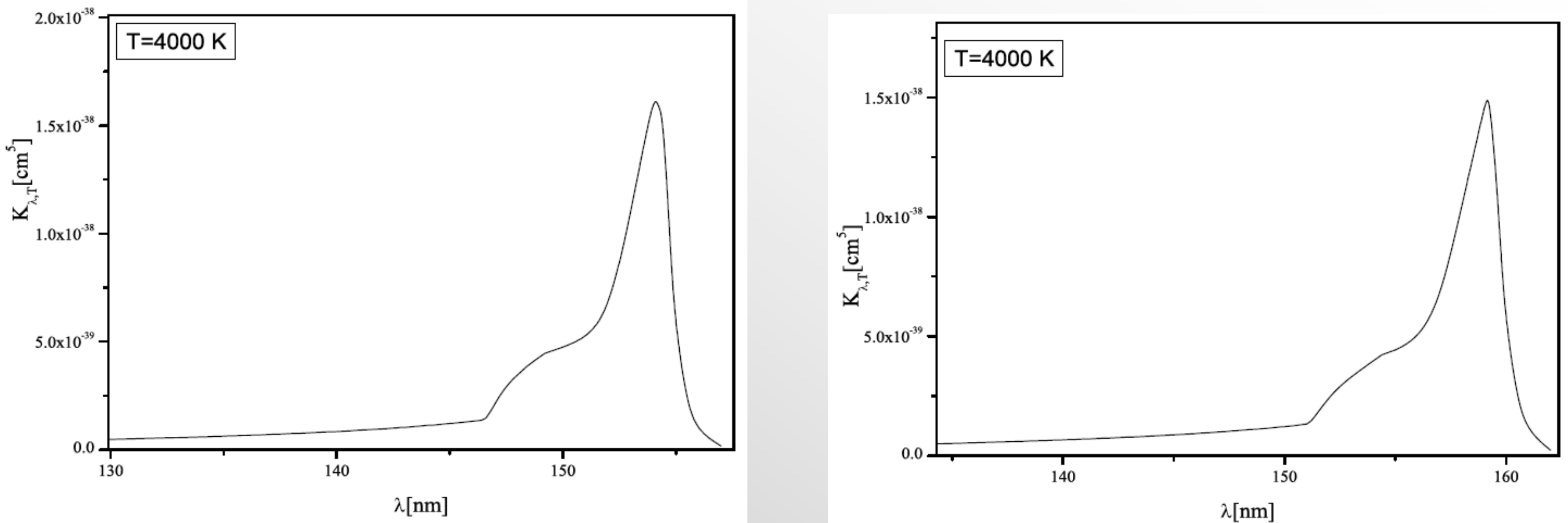
Results and discussion

Steps completed : potential curves, dipole matrix el., rate coeff. (metals: Li, Na, Si, Mg, Al, Ca)



Rate coefficients Kia(λ,T) by T=6000K and 10000K, for HeH^+.

- Within this work photo-dissociation and charge exchange processes are illustrated by Figs.1-4.
- These figures show the behavior of the rate coefficients, which are equal to spectral absorption coefficients $\kappa_{ia}(\lambda,T)$ for $N_A = N_{X+} = 1$, where A = He or H and $X^+ = H^+$, Na^+ , Li^+, Mg^+ ,Si^+,
- In the case $AX^+ = HeH^+$ it is taken that T=6000K and T=10000K. The first value, see Fig. 1, is relevant for *solar photosphere* (Vernazza et al. 1981), and the second value, see Fig. 2 - for the significant part of *atmospheres of some DB white dwarfs* (Koester 1980).



Rate coefficients Kia(λ,T) at T=4000K, for HNa^+ and HLi^+

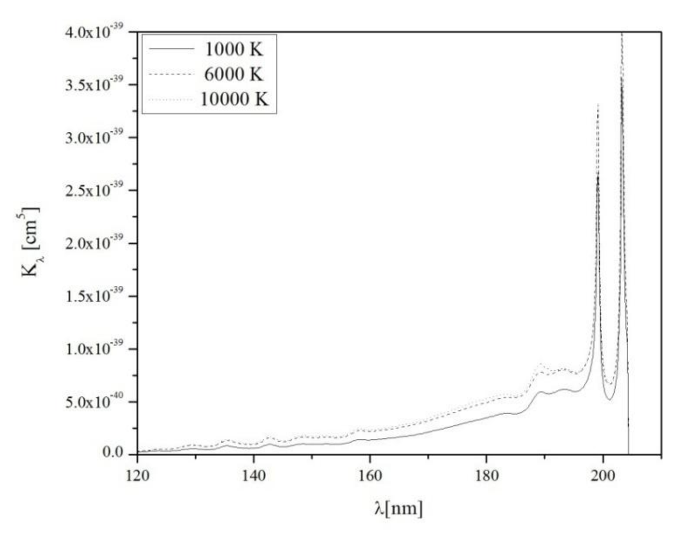
-In the case $AX^+ = HNa^+$, see Fig 3, it is taken that T=4000K which is relevant for the darkest parts of *large sunspot umbra* (Maltby et al. 1986).

- In the case $AX^+ = HLi^+$, see Fig 4, it is taken also that T=4000K. It is relevant for the region of T which is discussed in Hack et al. (1997); North et al. (1998); Shavrina et al. (2003).

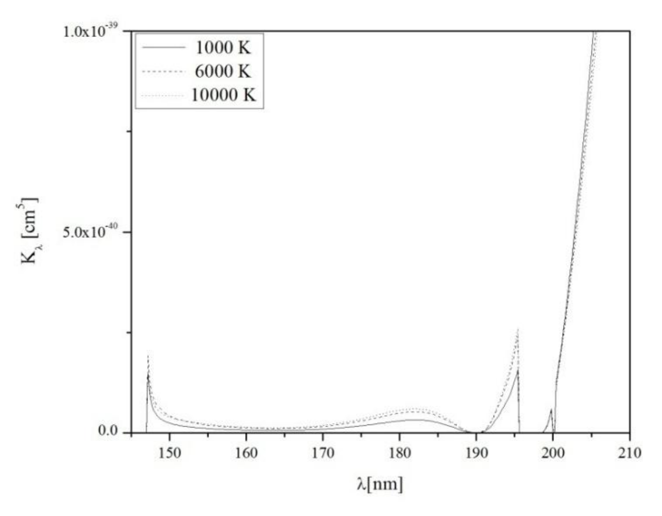
-In the first case, the spectral region 100nm -115nm is considered and in two other cases the spectral region 130nm -165nm.

- Figures 1-4 show that in mentioned spectral regions the processes 1 and 2 generate the characteristic spectral bands. Additional estimations suggest that these bands can be of significance for the stellar opacity in UV and VUV region.

Mg

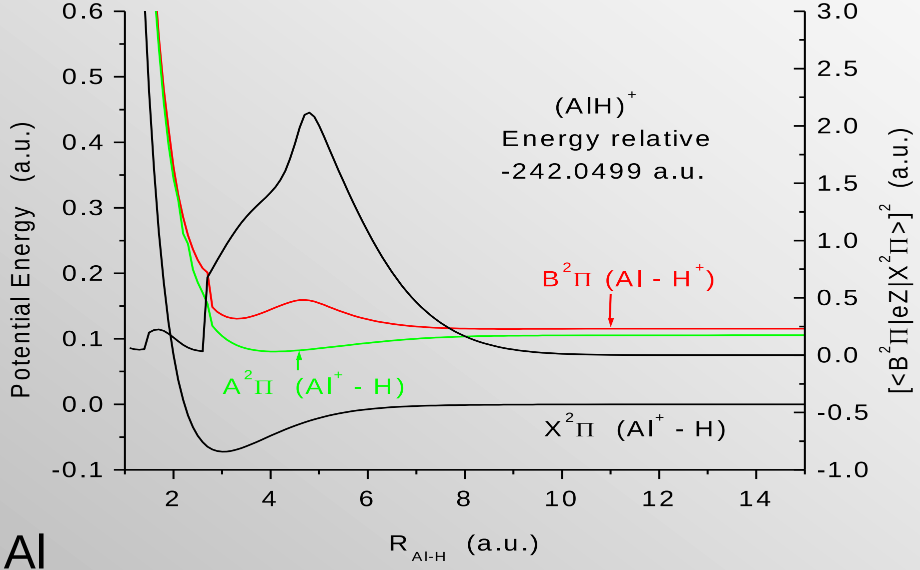


Si

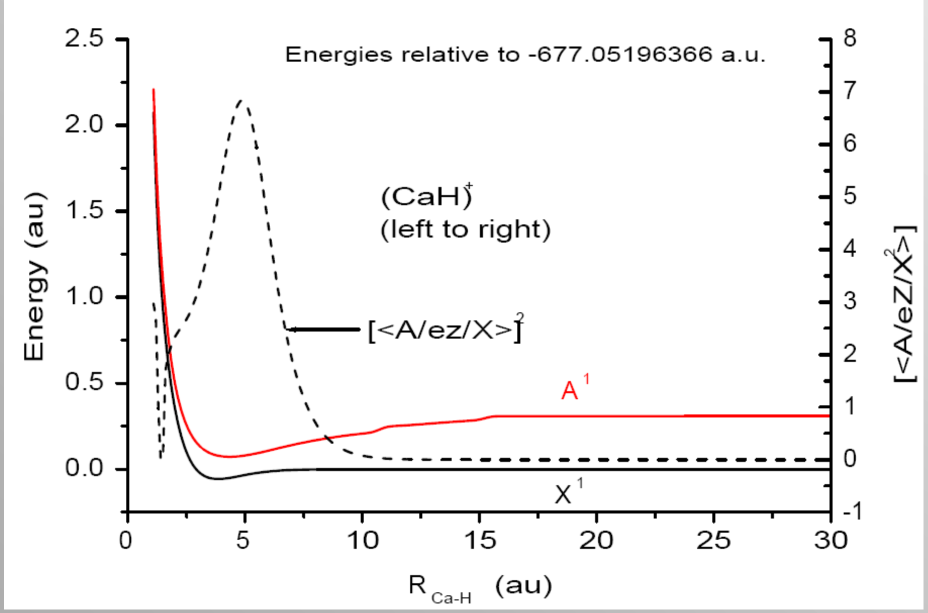


- to do: compare results with H, He rate coefficient and with concurrent ea, ei processes.

Figures: Rate coefficients Kia(λ,T) at T=4000K, 6000K and 10000K for HMg^+ and HSi^+



Al



Ca

- Working on potential curves for Al and Ca, and dipole matrix elements.

- Fe is still in progress.

Conclusions

- The main aim of this work is to draw attention to the possible significance of the considered radiative processes as factors which influence to the opacity of stellar atmospheres in wide region of λ.

Thank you for your attention