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The influence of H_2^+- photo-dissociation and (H + H$^+$)- radiative collisions on the solar atmosphere opacity in UV and VUV regions

A. A. Mihajlov[1,3], Lj. M. Ignjatović[1,3], N. M. Sakan[1], and M. S. Dimitrijević[2,3]

[1] Institute of Physics, PO Box 57, 11001 Belgrade, Serbia
e-mail: ljuba@phy.bg.ac.yu
[2] Astronomical Observatory, Volgina 7, 11160 Belgrade 74, Serbia
[3] Isaac Newton Institute of Chile, Yugoslavia Branch

ABSTRACT

Aims. To estimate the total contribution of the absorption processes $\epsilon_\lambda + H_2^+(X^2\Sigma_g^+) \Longrightarrow H(1s) + H^+$ and $\epsilon_\lambda + H(1s) + H^+ \Longrightarrow H^+ + H(1s)$ to the opacity of Solar atmosphere in UV and VUV region, and compare it with the contribution of other relevant radiative processes included in standard models.

Methods. The strict quantum-mechanical method was used for the determination of the average cross-section for the photo-dissociation of the molecular ion $H_2^+(X^2\Sigma_g^+)$; the previously developed quasi-static method was used for determination of the corresponding spectral coefficient which characterizes the absorption charge exchange in $H(1s) + H^+$ collisions.

Results. Spectral absorption coefficients characterizing the considered processes were calculated for the solar photosphere and lower chromosphere, within the 90 nm $\leq \lambda \leq$ 370 nm spectral range; the total contribution of the considered processes to the solar opacity was estimated and compared to relevant radiative processes included in standard Solar models.

Conclusions. In comparison with other absorption processes included in standard Solar models, the contribution of the considered processes in the UV and VUV regions is so important that they have to be taken into account in modeling the Solar photosphere and the lower chromosphere.

Key words. Sun: photosphere – Sun: UV radiation – atomic processes – molecular processes

1. Introduction

Opacities of the solar and other stellar atmospheres are naturally caused by a large number of radiative processes. Within development of more sophisticated stellar atmosphere models, we can further investigate known processes and include all processes not considered before.

The Mihajlov & Dimitrijević (1986) were considered absorption processes

$$\epsilon_\lambda + H_2^+ \Longrightarrow H + H^+, \tag{1a}$$

$$\epsilon_\lambda + H + H^+ \Longrightarrow H^+ + H, \tag{1b}$$

were considered, where H = H(1s), H_2^+ is the molecular ion in the electronic ground state $X^2\Sigma_g^+$, and ϵ_λ – energy of a photon with wavelength λ. The aim of this paper is 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). It was demonstrated that the absorption processes (1) in the optical part of spectra should be considered in the Solar photosphere and the lower chromosphere together, since in this case their influences on the opacity are similar. In subsequent papers (Mihajlov et al. 1993, 1994a), the absorption processes (1) were investigated in more detail and their contributions to the solar opacity were determined by using standard Solar atmosphere models (Vernazza et al. 1981; Maltby et al. 1986). Then, these contributions

were compared with the contributions of other relevant radiative processes, namely

$$\epsilon_\lambda + \begin{cases} H^- \\ H + e' \end{cases} \Longrightarrow H + e'', \tag{2a}$$

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

where H$^-$ is a stable negative hydrogen ion, H$^*(n)$ – an excited hydrogen atom in a state with the principal quantum number $n > 1$, and e' and e'' – a free electron with the corresponding energy.

In Mihajlov et al. (1993, 1994a) the part of the optical region 365 nm $\leq \lambda \leq$ 820 nm was taken into account. It was found that in this region the processes (1) give a contribution of 10–12% in comparison with processes (2). This fact alone demonstrated that considered ion-atom radiative processes must be taken into account for Solar atmosphere modeling. Later estimates showed however that the relative influence of the absorption processes (1) on the Solar atmosphere opacity should significantly increase at the transition from the considered wavelength region $\lambda \geq$ 365 nm to the region $\lambda_b \lesssim \lambda <$ 365 nm, where $\lambda_b \cong$ 91.1262 nm is the wavelength that corresponds to the ionization threshold of the H(1s) atom. This requires detailed investigation of these processes within the short wavelength region, since the significant increase of their influence will make the considered processes particularly important for Solar atmosphere modeling, especially due to the observational possibilities provided by development of space astronomy in UV and VUV regions.

In this paper the calculations of the spectral absorption coefficients, that characterize the processes (1) were performed in the region 90 nm $\leq \lambda \leq$ 370 nm. Calculations of the absorption coefficient were performed for the solar photosphere and lower chromosphere 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.

2. Theoretical remarks

The spectral coefficients. The absorption processes (1) separately are characterized here by partial spectral absorption coefficients $\kappa_{ia}^{(a)}(\lambda)$ and $\kappa_{ia}^{(b)}(\lambda)$ taken in the form

$$\kappa_{ia}^{(a)}(\lambda) = \sigma_{phd}(\lambda, T)N(H_2^+), \tag{3}$$

$$\kappa_{ia}^{(b)}(\lambda) = K_{ia}^{(b)}(\lambda, T)N(H)N(H^+), \tag{4}$$

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, and $\sigma_{phd}(\lambda, T)$ is the average cross-section for photo-dissociation of the molecular ion H_2^+. As in previous papers the partial spectral absorption coefficient $\kappa_{ia}^{(a)}(\lambda)$ will also be used in the form

$$\kappa_{ia}^{(a)}(\lambda) = K_{ia}^{(a)}(\lambda, T)N(H)N(H^+), \tag{5}$$

where the coefficient $K_{ia}^{(a)}(\lambda, T)$ is connected with $\sigma_{phd}(\lambda, T)$ by the relations

$$K_{ia}^{(a)}(\lambda) = \sigma_{phd}(\lambda, T) \cdot \chi^{-1}, \qquad \chi = \frac{N(H)N(H^+)}{N(H_2^+)}. \tag{6}$$

The total spectral absorption coefficient $\kappa_{ia}(\lambda)$, which characterizes the processes (1) together, can be taken in the form

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

$$\tag{7}$$

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

In accordance with the definition of the absorption coefficients $\kappa_{ia}^{(a,b)}(\lambda)$ and $\kappa_{ia}(\lambda)$, the coefficients $K_{ia}^{(a,b)}(\lambda, T)$ and $K_{ia}(\lambda, T)$ are given here in units [cm^5].

The methods of calculation. The photo-dissociation cross-section $\sigma_{phd}(\lambda, T)$, as well as the coefficients $K_{ia}^{(a)}(\lambda, T)$ and $K_{ia}^{(b)}(\lambda, T)$, are determined within the approximation where the 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. The mentioned adiabatic electronic states, $X^2\Sigma_g^+$ and $A^2\Sigma_u^-$, are denoted here with $|1\rangle$ and $|2\rangle$ and the corresponding potential curves with $U_1(R)$ and $U_2(R)$, where R is the internuclear distance in the considered ion-atom system. These potential curves are shown in Fig. 1.

Apart from the potentials $U_1(R)$ 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

$$D_{12}(R) = |\mathbf{D}_{12}(\mathbf{R})|, \qquad \mathbf{D}_{12}(\mathbf{R}) = \langle 1|\mathbf{D}(\mathbf{R})|2\rangle, \tag{8}$$
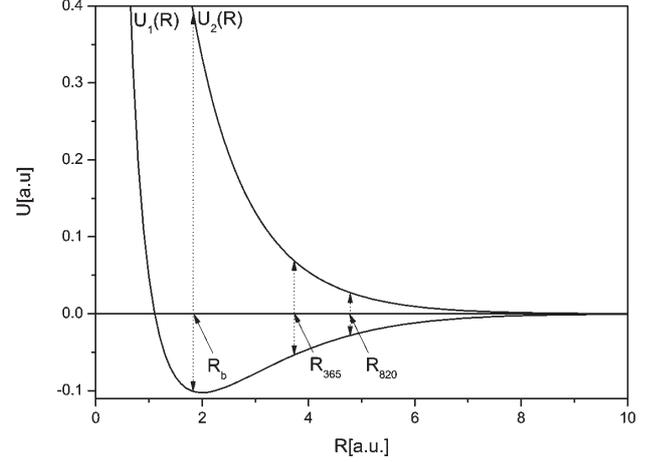

Fig. 1. The potential curves for the molecular ion H_2^+: $U_1(R)$ corresponds to the ground electronic state $X^2\Sigma_g^+$, and $U_2(R)$ – to the first excited electronic state $A^2\Sigma_u^+$.
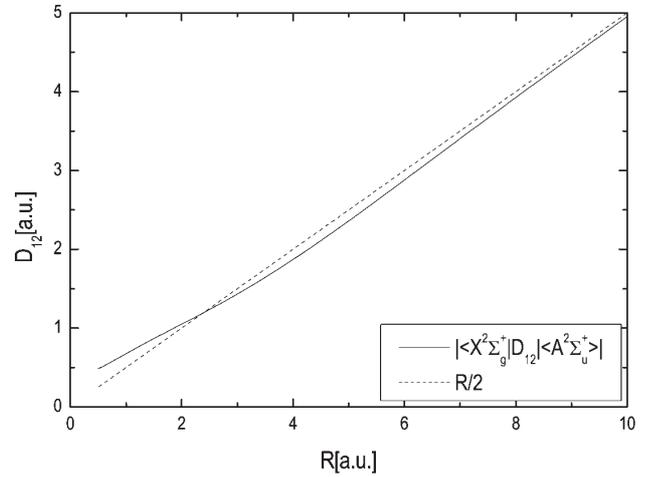

Fig. 2. The matrix element $D_{12}(R)$ for the transitions between the electronic states $X^2\Sigma_g^+$ and $A^2\Sigma_u^+$ of the ion H_2^+.

where $R = |\mathbf{R}|$ and $\mathbf{D}(\mathbf{R})$ is the operator of electron dipole momentum. Here it is assumed that the system $H + H^+$ or H_2^+ is considered within the center-of-mass reference frame, and the vector $\mathbf{R}$ determines the configuration of protons. The dipole matrix element $D_{12}(R)$ is shown in Fig. 2.

The described mechanism of the processes (1) causes absorption of the photon with energy ϵ_λ near the resonant point $R = R_\lambda$, where R_λ is the root of the equation

$$U_{12}(R) \equiv U_1(R) - U_2(R) = \epsilon_\lambda. \tag{9}$$

In Fig. 1 we show the resonant points $R = R_{365}$ and $R = R_{820}$ for absorption/emission of the photons with $\lambda = 365$ nm and $\lambda = 820$ nm, which are the lower and upper boundaries of region of R important for the part of spectra 365 nm $\leq \lambda \leq$ 820 nm examined in Mihajlov et al. (1993, 1994a). In the same figure the resonant point $R = R_b$ for absorption/emission of the photons with $\lambda = \lambda_b \cong 91.1262$ nm is shown.

One can see that the region of $R \gtrsim R_{365}$ is very far from the minimum of the potential curve $U_1(R)$. In Mihajlov et al. (1993, 1994a) it was possible to use the quasi-static method for the determination of spectral coefficients $K_{ia}^{(a,b)}(\lambda, T)$ and $K_{ia}(\lambda, T)$, which was developed in Mihajlov & Dimitrijević (1986) on the

basis of the semi-classical theory from Mihajlov & Popović (1981). Within this method it is assumed that not only the collisional system $H + H^+$, but the molecular ion H_2^+ also are treated in the semi-classical way.

The significant advantage of the quasi-static approach is that the corresponding coefficients $K_{ia}^{(a,b)}(\lambda, T)$ and $K_{ia}(\lambda, T)$ are given by simple analytical expressions. Such an approach, which was applied in Bates et al. (1953), works very well for the radiative ion-atom collision processes at thermal impact energies which can be described in the semi-classical way (see e.g. Boggess 1959; Mihajlov & Popović 1981; Lam & George 1982; Stancil 1994; Ermolaev et al. 1995; Lebedev & Presnyakov 2002). For these reasons the quasi-static method will be applied here to determine of the absorption coefficient $K_{ia}^{(b)}(\lambda, T)$. In accordance with Mihajlov et al. (1994a) this coefficient can be presented in the form

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

where a_0 is the atomic unit of length, and the values of the coefficient $C(R_\lambda)$ for the considered region of λ are given in the Table 1, together with the values of the other parameters of the molecular ion H_2^+.

However, in the short-wave length region 92 nm $\lesssim \lambda <$ 365 nm, the relative contribution of the photo-dissociation processes (1a) significantly increases and the low-lying ro-vibrational states of molecular ion H_2^+ become especially important, which requires quantum-mechanical treatment of the internuclear motion. Consequently, for the spectral absorption coefficient $\kappa_{ia}^{(a)}(\lambda, T)$ expression (3) will be used, where the photo-dissociation cross-section $\sigma_{phd}(\lambda, T)$ is determined in the quantum-mechanical way. In the general case this cross-section can be expressed by the relations

$$\sigma_{phd}(\lambda, T) = Z^{-1} \cdot \sum_v \left[\sum_{odd J} \frac{3}{2}(2J + 1)e^{\frac{-E_{o,o}^{v,J}}{kT}} \cdot \sigma_{v,J}(\lambda) \right.$$
$$\left. + \sum_{even J} \frac{1}{2}(2J + 1)e^{\frac{-E_{o,o}^{v,J}}{kT}} \cdot \sigma_{v,J}(\lambda) \right],$$
$$Z = \sum_v \left[\sum_{odd J} \frac{3}{2}(2J + 1)e^{\frac{-E_{o,o}^{v,J}}{kT}} + \sum_{even J} \frac{1}{2}(2J + 1)e^{\frac{-E_{o,o}^{v,J}}{kT}} \right], \tag{11}$$

$$E_{o,o}^{v,J} = E_{v,J} - E_{v=0,J=0}, \tag{12}$$

where v and J are respectively the vibrational and the rotational quantum number of the individual ro-vibrational states (v, J) of the molecular ion $H_2^+(X^2\Sigma_g^+)$, and $E_{v,J}$ are the corresponding energies. Let us draw attention to the fact that the structure of the expression (11) is a consequence of the consistent taking the proton spin into account (see e.g. Patch 1969; Stancil 1994). With $\sigma_{v,J}(\lambda)$ in that expression is denoted the partial photo-dissociation cross-section of H_2^+ in the ro-vibrational state (v, J) for the same λ, namely

$$\sigma_{v,J}(\lambda) = \frac{8\pi^3}{3\lambda} \left[\frac{J + 1}{2J + 1} \cdot |D_{E,J+1;v,J}|^2 \right.$$
$$\left. + \frac{J}{2J + 1} \cdot |D_{E,J-1;v,J}|^2 \right], \tag{13}$$

Table 1. Parameters of molecular ion H_2^+.

λ [nm]	R_λ [AU]	$C(R_\lambda)$ [AU]	$U_1(R_\lambda)$ [AU]	$U_2(R_\lambda)$ [AU]
90	1.79	0.717	−0.1001	0.4060
100	1.94	0.744	−0.1024	0.3530
125	2.24	0.780	−0.1001	0.2643
150	2.49	0.802	−0.0941	0.2096
175	2.70	0.816	−0.0876	0.1727
200	2.89	0.827	−0.0815	0.1463
225	3.05	0.837	−0.0760	0.1265
250	3.19	0.845	−0.0710	0.1111
275	3.32	0.851	−0.0667	0.0990
300	3.44	0.857	−0.0628	0.0891
325	3.55	0.863	−0.0593	0.0809
350	3.65	0.868	−0.0561	0.0740
370	3.73	0.871	−0.0539	0.0692

where $D_{E,J+1;v,J}$ and $D_{E,J-1;v,J}$ are the radial matrix elements given by relations

$$D_{E,J;v,J'} = \langle \Psi_{2;E,J'}(R)|D_{12}(R)|\Psi_{1;v,J}(R)\rangle, \quad J = J \pm 1, \tag{14}$$

and $D_{12}(R)$ is defined by Eq. (8). Here, with $\Psi_{1;v,J}(R)$ and $\Psi_{2;E,J'}(R)$ the nuclear radial wave functions are denoted, which describe the bound state (v, J) in the potential $U_1(R)$ and the continual state (E, J') in the potential $U_2(R)$, where the energy E satisfies the condition

$$E - E_{v,J} = \varepsilon_\lambda. \tag{15}$$

The wave functions $\Psi_{1;v,J}(R)$ and $\Psi_{2;E,J'}(R)$ are determined by solving the radial Schrödinger equations with the potentials $U_1(R)$ and $U_2(R)$ under the usual normalization conditions

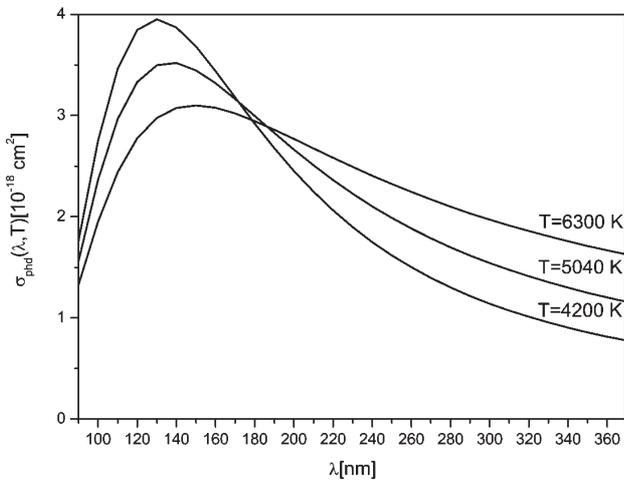$$\int_0^\infty |\Psi_{n;v,J}(R)|^2 R^2 dR = 1,$$
$$\int_0^\infty \Psi_{n;E',J'}^*(R)\Psi_{n;E,J'}(R)R^2 dR = \delta(E' - E). \tag{16}$$

The potentials $U_1(R)$ and $U_2(R)$, as well as the dipole matrix element $D_{12}(R)$, were generated by means of the numerical procedure described in Ignjatović & Mihajlov (2005). The values of these quantities, shown in Figs. 1 and 2, agree with the values presented in Madsen & Peek (1971) and Ramaker & Peek (1973) with accuracy better than 0.1%.

The results of our calculations of the average photo-dissociation cross-section $\sigma_{phd}(\lambda, T)$ are illustrated by Fig. 3. The curves in this figure show the behavior of $\sigma_{phd}(\lambda, T)$ as a function of λ for some temperatures, namely $T = 4200$ K, 5040 K and 6300 K, which are relevant for the solar photosphere. These values of T are chosen because there are calculations of the average photo-dissociation cross-section in Stancil (1994), where the results were obtained with a expression equivalent to Eq. (11), and in Lebedev & Presnyakov (2002), where a simpler expression was used. Here we have in mind the expression obtained from Eq. (11) by replacing the factors 3/2 and 1/2 with 1, which corresponds to neglecting the proton spin. With both approaches one obtains very close results for the considered temperatures (see e.g. Patch 1969). Comparison of our results with the results from Stancil (1994) and Lebedev & Presnyakov (2002) shows that in the whole considered region 90 nm $\leq \lambda \leq$ 370 nm there is a very good agreement among all results mentioned. This fact justifies the applicability of the procedure used for the determination of $\sigma_{phd}(\lambda, T)$ in all other calculations.

Table 2. The coefficient K_{ia} as a function of λ and T.

λ[nm]	K_{ia}[cm^5]					
	4000 K	4500 K	5000 K	6000 K	7000 K	8000 K
90	.262E-37	.111E-37	.553E-38	.196E-38	.932E-39	.533E-39
100	.413E-37	.170E-37	.838E-38	.289E-38	.135E-38	.760E-39
125	.586E-37	.245E-37	.122E-37	.427E-38	.202E-38	.115E-38
150	.539E-37	.236E-37	.122E-37	.454E-38	.224E-38	.132E-38
170	.457E-37	.209E-37	.112E-37	.439E-38	.225E-38	.136E-38
200	.344E-37	.168E-37	.946E-38	.400E-38	.217E-38	.137E-38
225	.273E-37	.140E-37	.817E-38	.366E-38	.207E-38	.135E-38
250	.220E-37	.118E-37	.713E-38	.337E-38	.197E-38	.132E-38
275	.181E-37	.101E-37	.628E-38	.311E-38	.188E-38	.129E-38
300	.152E-37	.874E-38	.561E-38	.289E-38	.180E-38	.126E-38
325	.130E-37	.769E-38	.506E-38	.271E-38	.173E-38	.124E-38
350	.113E-37	.688E-38	.463E-38	.256E-38	.168E-38	.122E-38
370	.102E-37	.635E-38	.434E-38	.246E-38	.164E-38	.121E-38

Fig. 3. The Behavior of average cross-section for the photo-dissociation of the ion H_2^+, as a function of λ and T.

Table 3. The branch coefficient $X^{(a)}$ which characterize the relative contribution of the process (1a).

λ [nm]	$X^{(a)}$					
	4000 K	4500 K	5000 K	6000 K	7000 K	8000 K
90	0.999	0.997	0.994	0.985	0.970	0.951
100	0.999	0.997	0.995	0.986	0.973	0.954
125	0.999	0.997	0.994	0.985	0.971	0.951
150	0.998	0.996	0.992	0.980	0.962	0.939
175	0.997	0.994	0.989	0.974	0.953	0.926
200	0.995	0.991	0.984	0.965	0.939	0.909
225	0.993	0.987	0.978	0.954	0.924	0.889
250	0.989	0.981	0.970	0.942	0.907	0.868
275	0.985	0.975	0.962	0.928	0.888	0.846
300	0.980	0.967	0.952	0.913	0.869	0.823
325	0.976	0.961	0.943	0.901	0.854	0.806
350	0.969	0.952	0.932	0.885	0.834	0.783
370	0.963	0.943	0.921	0.870	0.817	0.764

The relative contribution of the processes (1) can be characterized by the branch coefficients

$$X^{(a)} = \frac{\kappa_{ia}^{(a)}(\lambda, T)}{\kappa_{ia}(\lambda, T)} = \frac{K_{ia}^{(a)}(\lambda, T)}{K_{ia}(\lambda, T)},$$
$$X^{(b)} = \frac{\kappa_{ia}^{(b)}(\lambda, T)}{\kappa_{ia}(\lambda, T)} \equiv 1 - X^{(a)}. \qquad (17)$$

The values of the coefficient $X^{(a)}$ characterizing the photo-dissociation process (1a) are presented in Table 3 for the same regions λ and T. This table shows that in accordance with expectations the relative contribution of the photo-dissociation process (1a) significantly increases with decreasing of λ in the short-wave region.

As the second step, the values of the spectral absorption coefficient $\kappa_{ia}(\lambda, T)$, defined by Eq. (7), are determined as a function of altitude h taking $N(H)$, $N(H^+)$ and T which corresponds to the standard model C from Vernazza et al. (1981). These values are presented in Table 4 for 92 nm $\leq \lambda \leq$ 350 nm and -75 km $\leq h \leq$ 1065 km. Also, at the bottom of Table 4 are given the values of the corresponding spectral optical depth $\Delta\tau$ for the considered layer of the solar atmosphere. These values of $\Delta\tau$ show that the processes (1) cause a significant decrease (25−50%) of the radiation flux which comes from deeper layers of the Sun. So, only the considered layer gives a non-negligible contribution to the total absorption caused by processes (1) in the region $\lambda < 365$ nm.

Because of all the mentioned above factors it is especially important to compare the relative contribution of the

3. Results and discussion

Figure 3 shows that $\sigma_{phd}(\lambda, T)$ in the region $\lambda < 365$ nm significantly increases with decreasing λ and becomes noticeably decreasing only in the region $\lambda < 100$ nm. Such a behavior of $\sigma_{phd}(\lambda, T)$ causes the equal increasing of the partial spectral absorption coefficient $\kappa_{ia}^{(a)}(\lambda, T)$, for the same values of T, $N(H)$ and $N(H^+)$, with the transition from the region $\lambda > 365$ nm into the region 100 nm $\lesssim \lambda < 365$ nm. At the same time the total spectral absorption coefficient $\kappa_{ia}(\lambda, T)$ has to significantly increase within the same region of λ. Since this fact has to reflect the spectral characteristics of the Solar photosphere and the lower chromosphere, the corresponding calculations are made here.

As the first step, the values of the total coefficient $K_{ia}(\lambda, T)$, defined by Eqs. (6) and (7), are calculated in the regions 90 nm $\leq \lambda \leq$ 370 nm and 4000 K $\leq T \leq$ 8000 K and presented in the Table 2. Here it was assumed that in Eq. (6) the quantity χ can be treated as in our previous papers (Mihajlov & Dimitrijević 1986; Mihajlov et al. 1993, 1994b), as a constant of dissociative-associative equilibrium for a given T.

Table 4. The total spectral absorption coefficient $\kappa_{ia}(\lambda)$ for solar photosphere and lower chromosphere, calculated for the model C from Vernazza et al. (1981).

h[km]	κ_{ia}[cm^{-1}]						
	92 nm	100 nm	150 nm	200 nm	250 nm	300 nm	350 nm
1065	0.1978E-14	0.2649E-14	0.4165E-14	0.3676E-14	0.3077E-14	0.2625E-14	0.2309E-14
980	0.6984E-14	0.9370E-14	0.1462E-13	0.1275E-13	0.1056E-13	0.8937E-14	0.7811E-14
905	0.1396E-13	0.1879E-13	0.2900E-13	0.2480E-13	0.2021E-13	0.1689E-13	0.1461E-13
855	0.2222E-13	0.2995E-13	0.4589E-13	0.3876E-13	0.3127E-13	0.2592E-13	0.2228E-13
755	0.4808E-13	0.6526E-13	0.9725E-13	0.7827E-13	0.6071E-13	0.4878E-13	0.4087E-13
705	0.5655E-13	0.7715E-13	0.1126E-12	0.8738E-13	0.6577E-13	0.5160E-13	0.4242E-13
655	0.5718E-13	0.7855E-13	0.1115E-12	0.8243E-13	0.5958E-13	0.4527E-13	0.3627E-13
605	0.3793E-13	0.5252E-13	0.7218E-13	0.5041E-13	0.3473E-13	0.2541E-13	0.1974E-13
555	0.2703E-13	0.3763E-13	0.5060E-13	0.3398E-13	0.2266E-13	0.1615E-13	0.1229E-13
515	0.3019E-13	0.4212E-13	0.5622E-13	0.3727E-13	0.2457E-13	0.1736E-13	0.1312E-13
450	0.6696E-13	0.9325E-13	0.1252E-12	0.8393E-13	0.5586E-13	0.3975E-13	0.3022E-13
350	0.4487E-12	0.6205E-12	0.8571E-12	0.6038E-12	0.4191E-12	0.3084E-12	0.2408E-12
250	0.4546E-11	0.6237E-11	0.8897E-11	0.6633E-11	0.4829E-11	0.3689E-11	0.2969E-11
150	0.8262E-10	0.1123E-09	0.1660E-09	0.1317E-09	0.1010E-09	0.8043E-10	0.6690E-10
100	0.4018E-09	0.5435E-09	0.8211E-09	0.6768E-09	0.5350E-09	0.4365E-09	0.3703E-09
50	0.1913E-08	0.2570E-08	0.3989E-08	0.3445E-08	0.2831E-08	0.2381E-08	0.2070E-08
0	0.8309E-08	0.1106E-07	0.1779E-07	0.1630E-07	0.1411E-07	0.1231E-07	0.1105E-07
−25	0.1820E-07	0.2409E-07	0.3971E-07	0.3797E-07	0.3406E-07	0.3061E-07	0.2808E-07
−50	0.4090E-07	0.5372E-07	0.9132E-07	0.9188E-07	0.8596E-07	0.8019E-07	0.7570E-07
−75	0.7898E-07	0.1030E-06	0.1798E-06	0.1888E-06	0.1830E-06	0.1756E-06	0.1700E-06
$\Delta\tau$	0.29	0.38	0.64	0.64	0.60	0.56	0.53

processes (1) to the opacity of solar atmosphere, with the contribution of the other relevant absorption processes (2). The contribution of these processes will be characterized by the absorption coefficients $\kappa_{ea}(\lambda)$ and $\kappa_{ei}(\lambda)$, defined by relations

$$\kappa_{ea}(\lambda) = K_{ea}(\lambda, T) \cdot N_e \cdot N(H),$$

$$K_{ea}(\lambda, T) = \sigma_{phd}^{(-)}(\lambda) \cdot \chi_{ea}^{-1} + K_{ea}^{(b)}(\lambda, T), \tag{18}$$

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

$$K_{ei}(\lambda, T) = \sum_{n \geq 2} \sigma_n(\lambda) \cdot \frac{N(H^*(n))}{N(H)} \cdot \chi_{ei}^{-1} + K_{ei}^{(b)}(\lambda, T) \tag{19}$$

$$\chi_{ea} = \frac{N_e N(H)}{N(H^-)}, \qquad \chi_{ei} = \frac{N_e N(H^+)}{N(H)}, \tag{20}$$

where $\sigma_{phd}^{(-)}(\lambda)$ is the photo-dissociation cross-section of the negative ion H$^-$, $K_{ea}^{(b)}(\lambda, T)$ – the rate coefficient that describes absorption by (e + H)-collision systems, $\sigma_n(\lambda)$ – average photo-ionization cross-section for the excited atom H$^*(n)$, $K_{ei}^{(b)}(\lambda, T)$ – the rate coefficient that describes absorption by (e + H$^+$)-collision systems, and N_e, $N(H^-)$ and $N(H^*(n))$ – respectively the densities of free electrons, negative ions H$^-$ and excited atom H$^*(n)$. The coefficients χ_{ea} and χ_{ei} are treated here as the constants of dissociative-associative and ionization-recombination equilibrium, respectively, for a given T.

The relative contributions of the processes (1) together, with respect to processes (2) separately, is described by the quantities F_{ea} and F_{ei} defined by relations

$$F_{ea} = \frac{\kappa_{ia}(\lambda)}{\kappa_{ea}(\lambda)} = \frac{K_{ia}(\lambda, T)}{K_{ea}(\lambda, T)} \cdot \frac{N(H^+)}{N_e}, \tag{21}$$

$$F_{ei} = \frac{\kappa_{ia}(\lambda)}{\kappa_{ei}(\lambda)} = \frac{K_{ia}(\lambda, T)}{K_{ei}(\lambda, T)} \cdot \frac{N(H)}{N_e}, \tag{22}$$
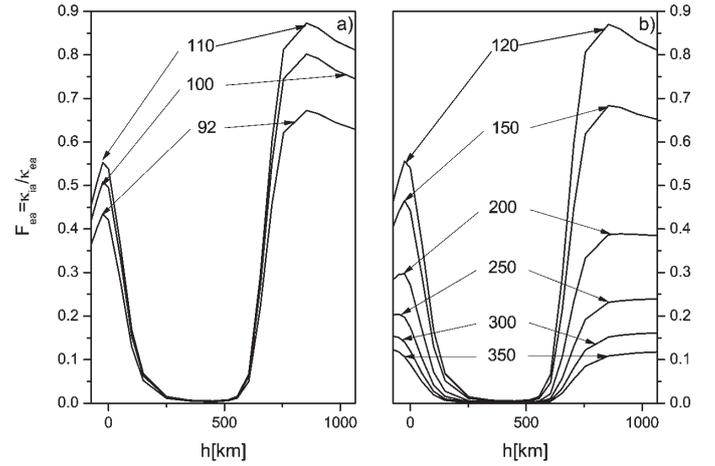
Fig. 4. Behavior of the quantity $F_{\kappa_{ea}} = \kappa_{ia}/\kappa_{ea}$ as a function of λ and h.

where the coefficients $K_{ea}(\lambda, T)$ and $K_{ei}(\lambda, T)$ are given by Eqs. (18)–(20). The values of the coefficient $K_{ea}(\lambda, T)$ are determined by means of data from Stilley & Callaway (1970) and Wishart (1979) for the emission processes inverse to the absorption processes (2a) and the principle of thermodynamic balance. In the case of the absorption processes (2b) the values of the coefficient $K_{ei}(\lambda, T)$ are determined by exact quantum-mechanical expressions for the ionization cross-section $\sigma_n(\lambda)$ and the quasi-classical expression for the coefficient $K_{ei}^{(b)}(\lambda, T)$ from Sobel'man (1979). In the calculations of $\kappa_{ea}(\lambda)$ and $\kappa_{ei}(\lambda)$ the densities N_e, $N(H)$ and $N(H^+)$, as well as the densities $N(H^*(n))$ with $2 \leq n \leq 8$, are taken from Vernazza et al. (1981), while the densities $N(H^*(n > 8))$ were determined by means of Boltzman's formula for given $N(H^*(n = 8))$ and T.

The results of the calculations of the ratios $F_{ea}(h)$ and $F_{ei}(h)$ for 92 nm $\leq \lambda \leq$ 350 nm are presented in Figs. 4 and 5. The first of these figures shows that in the significant part of the considered region of altitudes (-75 km $\leq h \leq 1065$ km) the absorption

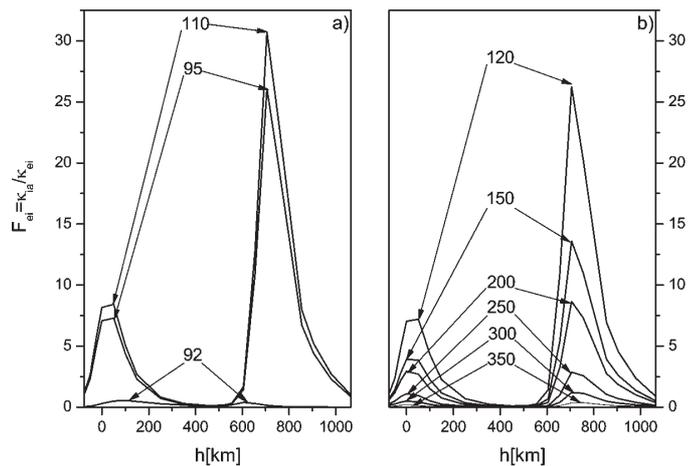**Fig. 5.** Behavior of the quantity $F_{\kappa_{ei}} = \kappa_{ia}/\kappa_{ei}$ as a function of λ and h.

processes (1) together give the contribution which varies from about 10% to about 90% of the contribution of the absorption processes (2a), which are considered as the main absorption processes. In connection with the other known absorption processes (2b) Fig. 5 shows that in the considered region of altitude there are significant parts where the processes (1) completely dominate.

4. Conclusions

Spectral absorption coefficients $\kappa_{ia}(\lambda, T)$, defined by Eq. (7), characterizing the processes (1), were calculated for the Solar photosphere and the lower chromosphere within the 90 nm $\leq \lambda \leq 370$ nm spectral range as functions of altitude h taking $N(H)$, $N(H^+)$ and T corresponding to the standard model C from Vernazza et al. (1981). Also, 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 $\leq h \leq 1065$ 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). The results

obtained demonstrate that, due to the investigated processes (1), the radiation flux that comes from deeper layers of Sun decreases significantly (25−50%). Consequently, the processes (1) have to be treated as a serious factor that influences the continuous part of the absorption spectra of the Solar atmosphere, particularly in UV and VUV regions, and changes accordingly the mechanism of UV and VUV radiative transfer. They influence indirectly and the plasma state within particular layers of the Solar atmosphere, which is formed in an interaction with electromagnetic radiation. Moreover, photo-dissociation of H_2^+ molecular ions, directly influences the kinetics inside the plasma. These facts also have implications in the corresponding equations of state. Due to all these reasons the processes (1) have to be consistently included in standard models of the solar atmosphere.

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