Chemi-ionization in Solar Photosphere: Influence on the Hydrogen Atom excited States Population

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ABSTRACT

In this paper, the influence of chemi-ionization processes in $H^{*}(n \geq 2)+H(1s)$ collisions, as well as the influence of inverse chemi-recombination processes on hydrogen atom excited-state populations in solar photosphere, are compared with the influence of concurrent electron-atom and electron-ion ionization and recombination processes. It has been found that the considered chemi-ionization/recombination processes dominate over the relevant concurrent processes in almost the whole solar photosphere. Thus, it is shown that these processes and their importance for the non-LTE modeling of the solar atmosphere should be investigated further.

Subject headings: atomic processes, — Sun: atmosphere

1. Introduction

In order to improve the modeling of the solar photosphere, as well as to model atmospheres of other similar and cooler stars where the main constituent is hydrogen too, it is necessary to take into account the influence of all the relevant collisional processes on the excited-atom populations in weakly ionized hydrogen plasmas. This is important for modeling since a strong connection between the changes in atom excited-state populations and the electron density exists in weakly ionized plasmas. For example, with an increase of the electron density, caused by a growth of the excited hydrogen atom population, the rate of thermalization by electron-atom collisions in the stellar atmosphere will become higher. A consequence will be that the radiative source function of the line center will be more closely coupled to the Planck function, making the synthesized spectral lines stronger for a given model structure, affecting the accuracy of plasma diagnostics and determination of the atmospheric pressure.

Therefore, in previous papers (Mihajlov et al. 1997, 2003b,a, 2007b), just a group of chemi-ionization and chemi-recombination atom collisional processes in weakly ionized layers of stellar atmospheres (ionization degree less than 10^{-3}) was studied. In order to demonstrate the significance of these processes it was necessary to compare their efficiency, from the aspect of their influence on the free electron and excited atom populations, with the efficiency of the known concurrent processes of electron-atom impact ionization, electron-electron-ion recombination, and electron-ion photo-recombination. In the helium case, considered in Mihajlov et al. (2003b), it was established that the efficiency of chemi-ionization and chemi-recombination processes in weakly ionized layers of the examined DB white dwarf atmospheres was significantly greater than the efficiency of the relevant electron-atom and electron-ion processes or at least comparable to them. In the hydrogen case, considered in Mihajlov et al. (1997, 2003a, 2007b) in connection with solar and M red dwarf atmospheres, the relevant chemi-ionization processes are

$$H^*(n) + H(1s) \Rightarrow H_2^+ + e, \tag{1}$$

$$H^*(n) + H(1s) \Rightarrow H(1s) + H^+ + e, \tag{2}$$

and the corresponding inverse recombination processes are

$$H_2^+ + e \Rightarrow H^*(n) + H(1s), \tag{3}$$

$$H(1s) + H^+ + e \Rightarrow H^*(n) + H(1s), \tag{4}$$

where $H^*(n)$ is hydrogen in one of the excited states with the principal quantum number $n \geq 2$, H_2^+ is the hydrogen molecular ion in the ground electronic state $(1\Sigma_g^+)$, and e is a free electron. Consequently, in this case the efficiency of the chemi-ionization and chemi-recombination processes has to be compared with the efficiency of the processes

$$H^*(n) + e \Rightarrow H^+ + 2e, \tag{5}$$

$$H^+ + 2e \Rightarrow H^*(n) + e, \tag{6}$$

$$H^+ + e \Rightarrow H^*(n) + \varepsilon_\lambda, \tag{7}$$

where ε_λ is the energy of a photon with wavelength λ.

Let us emphasize the fact that in this paper just the hydrogen case is at the focus, since our main aim is to draw attention of astronomers to the processes (1) - (4), and to show that the importance of these processes for non-LTE modeling of solar atmosphere should be investigated. For this purpose, it should be demonstrated that in the solar photosphere the efficiency of these processes is greater than, or at least comparable to, the efficiency of processes (5) - (7) within those ranges of values of $n \geq 2$ and temperature T which are relevant to the chosen solar atmosphere model. However, by now only for chemi-recombination processes (3) and (4) it was qualitatively shown that for $4 \leq n \leq 8$

their efficiency is comparable with the efficiency of the concurrent processes (6) and (7) in a part of the solar photosphere (see Mihajlov et al. (1997)).

Therefore, the results of new complete calculations are presented here, which are necessary for achieving the aim of this work. All the calculations are performed on the basis of the well-known model C of the solar atmosphere from Vernazza et al. (1981), since it is only for this model that all the data needed for various calculations are provided in tabular form. Certainly, we keep in mind also that in Stix (2002) this model is cited as practically the single adequate non-LTE model of the solar atmosphere.

Besides all mentioned, the fact that the processes (1) - (4) are very important for the solar photosphere is supported by the results obtained in (Mihajlov et al. 2003a, 2007b), where these processes were included ab initio in a non-LTE modeling of an M red dwarf atmosphere with the effective temperature T_{eff} = 3800 K, using PHOENIX code (see (Baron & Hauschildt 1998; Hauschildt et al. 1999; Short et al. 1999)). A fact was established that including even the chemi-ionization/recombination only for $4 \leq n \leq 8$, generates significant changes (by up to 50 percent), at least in the populations of hydrogen-atom excited states with $2 \leq n \leq 20$, and if all these processes (with $n \geq 2$) are included, a significant change (somewhere up to 2 - 3 times) is also generated of the free electron density N_e, and, as one of further consequences, significant changes in hydrogen line profiles. Keeping in mind that the compositions of the solar and the considered M red dwarf's photospheres are practically the same and the values of hydrogen-atom density, N_e and T in these photospheres change within similar regions (Vernazza et al. 1981; Mihajlov et al. 2007b), one can expect that the influence of processes (1) - (4) on the hydrogen-atom excited states and free-electron populations in the solar atmosphere will be at least close to their influence in that of the M red dwarf, and that these processes will be very important for weakly ionized layers of the solar atmosphere.

Finally, let us note the fact concerning a group of collision ion-atom radiative processes. Namely, in several papers (Mihajlov & Dimitrijević 1986, 1992; Mihajlov et al. 1993, 1994a,b; Ermolaev et al. 1995; Mihajlov et al. 2007a; Ignjatović et al. 2009) it was suggested that these processes should be included in the stellar atmosphere models, and recently it was actually realized in Fontenla et al. (2009), and Koester (2010). Due to a principal similarity between the mechanisms of processes (1) - (4) and these radiative processes, one can hope that the chemi-ionization/recombination processes will be also included in the stellar atmosphere models.

In this paper all the needed theoretical data, about the chemi-ionization and chemi-recombination processes (1) - (4) are given in Section 2, while in Section 3 the obtained results are presented (in figures) demonstrating the significance of the considered processes. Apart from that, all the data used for the calculation of the rate coefficients of processes (1) - (4) are given here in three tables.

2. Theory

2.1. The chemi-ionization processes: $n \geq 5$

Here we will consider processes (1) - (4) within the regions $n \geq 5$ and $2 \leq n \leq 4$ separately. Within the first region we will determine the rate coefficients for the chemi-ionization processes (1) and (2) directly, using the principle of thermodynamical balance for determination of the rate coefficients for the inverse chemi-recombination processes (3) and (4).

The parameters which are needed in further considerations are the following: $r_n \sim n^2$ - the characteristic radius of Rydberg atom $H^*(n)$; R - the inter-nuclear distance in the collision system $H^*(n) + H(1s)$; $U_1(R)$ and $U_2(R)$ - the adiabatic potential energies of the ground and the first exited electronic states of molecular ion H_2^+.

In accordance with the previous papers (Mihajlov et al. 1997, 2003b,a, 2007b) we will treat processes (1) and (2) with $n \geq 5$ on the basis of dipole resonant mechanism, which was introduced in the considerations of Smirnov & Mihajlov (1971) for inelastic processes in thermal $[H^*(n) + H(1s)]$-collisions. This means that such processes are considered as a result of resonant energy conversion within the electronic component of the collisional system $H^*(n) + H(1s)$, which is realized inside the region

$$R << r_n, \tag{8}$$

where the system $H^*(n) + H(1s)$ can be presented as $[H^+ + H(1s)] + e_n$, and which is caused by the dipole part of the interaction of the outer electron e_n with the subsystem $[H^+ + H(1s)]$. Already in Devdariani et al. (1978) just chemi-ionization processes in atom-Rydberg-atom collisions (the case of alkali metal atoms) were described on the basis of the same mechanism. After that the methods based on the dipole resonant mechanism have been used in practice for investigation of chemi-ionization processes until now (see for example Beterov et al. (2005) and Ignjatović & Mihajlov (2005)). Application of this mechanism is particularly successful within the so-called decay approximation which was examined in Janev & Mihajlov (1980) and immediately demonstrated to be suitable for any inelastic processes in slow $[H^*(n) + H(1s)]$-collisions. Let us note that in the previous papers (Mihajlov et al. 2003b,a, 2007b) a method from Mihajlov & Dimitrijević (1992) and Mihajlov et al. (1996) was used, which is based on this approximation.

Only the decay approximation will be used here for processes (1) and (2) with $n \geq 5$. First, it is assumed that in the region, Equation. (8), the electronic state of the subsystem $[H^+ + H(1s)]$ can be approximated well by one of the two adiabatic electronic states of the molecular ion H_2^+: the ground one $|1\Sigma_g^+\vec{r}_{mi}, R>$ and the first excited $|1\Sigma_u^+\vec{r}_{mi}, R>$, and the state of the outer electron e_n - by one of the hydrogen Rydberg states $|n, l, m, \vec{r}>$. Then, it is assumed that, in the case of chemi-ionization processes (1) and (2), we can consider that the subsystem $[H^+ + H(1s)]$ is in the first excited electronic state $|1\Sigma_u^+ \vec{r}_{mi}, R>$ with a probability of 1/2, which means that we can describe the relative inter-nuclear motion as going on in the reflective potential $U_2(R)$. Finally, it means that we can expect (as a result of the mentioned electron-dipole interaction) a decay of the initial electronic state $|n, l, m, \vec{r}; 1\Sigma_u^+ \vec{r}_{mi}, R >= |n, l, m, \vec{r} > |1\Sigma_u^+ \vec{r}_{mi}, R>$ of the system $[H^+ + H(1s)] + e_n$, with a transition to the final state $|\epsilon, l', m', \vec{r}; 1\Sigma_g^+ \vec{r}_{mi}, R >= |\epsilon, l', m', \vec{r} > |1\Sigma_g^+ \vec{r}_{mi}, R>$ in a narrow neighborhood of the resonant point $R = R_{n;\epsilon}$ which is the root of the equation

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

Here $\epsilon_n \cong -I/n^2$ and ϵ are the energies of the initial (bound) and final (free) states of the outer electron, and I - the ionization potential of the ground-state hydrogen atom. Here it is important that we have almost resonant simultaneous transitions: of the subsystem $[H^+ + H(1s)]$ to the ground electronic state $|1\Sigma_g^+ \vec{r}_{mi}, R>$, and of the outer electron to one of the free states $|\epsilon, l', m', \vec{r}>$.

In accordance with (Janev & Mihajlov 1980; Mihajlov & Dimitrijević 1992; Mihajlov et al. 1996) we will characterize processes (1) and (2) by quantities $W_n(R)$, $P_{ci}^{(a)}(n; \rho, E)$, and $P_{ci}^{(b)}(n; \rho, E)$. The first quantity has the meaning of mean decay velocity of the considered system's initial state and is given by relations

$$W_n(R) = \frac{1}{n^2} \cdot \sum_{l,m} \frac{2\pi}{\hbar} \cdot |< 1u; n, l, m, |e^2 \cdot \frac{\vec{r} \cdot \vec{r}_{mi}}{r^3} |\epsilon_k, l', m'; 1g^+ > |^2 \cdot g(\epsilon), \tag{10}$$

where e is the electron charge, $|1g, \epsilon, l', m' >= |\epsilon, l', m', \vec{r} > |1\Sigma_g^+ \vec{r}_{mi}, R>$, $|1u, n, l, m >= |n, l, m, \vec{r} > |1\Sigma_u^+ \vec{r}_{mi}, R>$, and $g(\epsilon)$ is the density of the free single-electron states in the energy space. Following Janev & Mihajlov (1980) and Ignjatović & Mihajlov (2005) we will transform Equation (10) to the simple form

$$W_n(R) = \frac{4}{3\sqrt{3}n^5} D_{12}^2(R) G_{nk}, \quad D_{12}(R) = |< 1\Sigma_u^+ \vec{r}_{mi}, R| r_{mi;R} |1\Sigma_g^+ \vec{r}_{mi}, R>|, \tag{11}$$

where $r_{mi;R}$ is the projection of $\vec{r}_{mi}$ on the inter-nuclear axis, $G_{nk} \equiv \sigma_{ph}(n,k)/\sigma_{ph}^{Kr}(n,k)$ is the generalized Gaunt factor, defined in Johnson (1972), $\sigma_{ph}(n,k)$ is the mean photo-ionization cross section of the atom $H^*(n)$ for the given ϵ, and $\sigma_{ph}^{Kr}(n,k)$ is the same photo-ionization cross section, but in Kramers's approximation (Kramers 1923; Sobel'man 1979).

The quantities $P_{ci}^{(a)}(n;\rho,E)$ and $P_{ci}^{(b)}(n;\rho,E)$ are the probabilities of the realization of the chemi-ionization processes (1) and (2) respectively, for given ρ and E. In the previous papers (Mihajlov & Dimitrijević 1992; Mihajlov et al. 1996, 2003b,a, 2007b), the influence of the initial state's decay (during the collision) on its amplitude was neglected in order to simplify the used procedure. However, it generates errors which are larger then 10 percent for $n \leq 8$. Consequently, in this work the said influence is taken into account and a procedure similar to the ones from Janev & Mihajlov (1980) and Ignjatović & Mihajlov (2005) is used. Therefore we will present here only the final expressions for the ionization probabilities $P_{ci}^{(a,b)}(n;\rho,E)$, the partial cross-sections $\sigma_{ci}^{(a,b)}(n;E)$ and the corresponding partial rate coefficients $K_{ci}^{(a,b)}(n;T)$, where T is the temperature of the considered plasma, using additional parameters R_n, R_0 and R_E, which are the roots of equations

$$U_{12}(R) = |\epsilon_n|, \qquad U_2(R) = E, \qquad U_{12}(R) = E, \tag{12}$$

respectively.

In the case when only one of the processes (1) and 2) is realized, the ionization probabilities are obtained in the form

$$P_{ci}^{(a,b)}(n,\rho,E) = \frac{1}{2} \cdot \left(1 - e^{-2 \int\limits_{R_0}^{R_n} \frac{W_n(R)dR}{v_{rad}}} \right), \tag{13}$$

and in the case of realization of both processes we have it that

$$P_{ci}^{(a)}(n,\rho,E) = \frac{1}{2} \cdot \left(1 - e^{-2 \int\limits_{R_0}^{R_E} \frac{W_n(R)dR}{v_{rad}}} \right) e^{-\int\limits_{R_E}^{R_n} \frac{W_n(R)dR}{v_{rad}}}, \tag{14}$$

$$P_{ci}^{(b)}(n,\rho,E) = \frac{1}{2}\cdot\left(1-e^{-\int\limits_{R_E}^{R_n}\frac{W_n(R)dR}{v_{rad}}}\right)\left(1+e^{-2\int\limits_{R_0}^{R_n}\frac{W_n(R)dR}{v_{rad}}}\right), \qquad (15)$$

where ρ and $E = m_{red}v^2/2$ are the impact parameter and the atom-Rydberg-atom impact energy, respectively (m_{red} being the reduced mass of the collision system)

$v_{rad} = v_{rad}(\rho, E; R)$ is the radial inter-nuclear velocity, which is given by

$$v_{rad}(\rho,E;R) = \sqrt{\frac{2}{m_{red}}\left[E - U_2(R) - \frac{E\rho^2}{R^2}\right]}. \qquad (16)$$

Then, from Equations. (13) - (16) the partial cross sections $\sigma_{ci}^{(a,b)}(n;E)$ are determined, namely,

$$\sigma_{ci}^{(a,b)}(n,E) = 2\pi\int\limits_{0}^{\rho_{max}^{(a,b)}(E)} P_{ci}^{(a,b)}(n,\rho,E)\rho d\rho, \qquad (17)$$

where $\rho_{(1a,b)}^{max}(E)$ is the upper limit of values ρ, at which the corresponding region R is reached for a given E.

After that, the partial rate coefficients for the chemi-ionization processes (1) and (2) with $n \geq 5$ are determined by expressions

$$K_{ci}^{(a,b)}(n,T) = \int\limits_{E_{min}^{(a,b)}(n)}^{E_{max}} v\sigma_{ci}^{(a,b)}(n,E)f(v;T)dv, \qquad (18)$$

where $\sigma_{ci}^{(a,b)}(n,E)$ is defined by Equation (17), v is the atom-Rydberg-atom impact velocity, $f(v;T)$ is the velocity distribution function for the given temperature T, and: $E_{min}^{(a,b)}(n) = 0$ if $U_2(R_n) \leq 0$; $E_{min}^{(a,b)} = U_2(R_n)$ if $U_2(R_n) > 0$; $E_{max}^{(a)} = U_2(R_{0;1}) = U_2(R_{0;1})$, where $R_{0;1}$ is such a point that $U_1(R_{0;1}) = 0$; $E_{max}^{(b)} = \infty$.

Finally, using partial rate coefficients $K_{ci}^{(a,b)}(n,T)$, we will determine the total one, namely,

$$K_{ci}(n,T) = K_{ci}^{(a)}(n,T) + K_{ci}^{(b)}(n,T), \qquad (19)$$

which characterizes the efficiency of the chemi-ionization processes (1) and (2) together.

2.2. The chemi-recombination processes: $n \geq 5$

Under the conditions which exist in the solar atmosphere, we can determine the chemi-recombination rate coefficients (as functions of T) from the principle of thermodynamical balance for processes (1,2) and (3,4), namely,

$$K_{ci}^{(a)}(n,T) \cdot N_n N_1 = K_{dr}(n,T) \cdot N_{mi}^{(eq)} N_e \equiv K_{cr}^{(a)}(n,T) \cdot N_1 N_{ai} N_e \tag{20}$$

$$K_{ci}^{(b)} \cdot N_n N_1 = K_{cr}^{(b)}(n,T) \cdot N_1 N_{ai} N_e, \tag{21}$$

where the chemi-ionization rate coefficient $K_{cr}^{(a)}(n,T)$ is expressed through the dissociative recombination rate coefficient $K_{dr}(n,T)$ by relation

$$K_{cr}^{(a)}(n,T) \equiv K_{dr}(n,T) \cdot \chi^{-1}(T), \qquad \chi(T) = \left(\frac{N_{ai} N_1}{N_{mi}^{(eq)}} \right), \tag{22}$$

where N_1 and N_n denote the densities of ground- and excited-state hydrogen atoms respectively, while N_{ai} and $N_{mi}^{(eq)}$ are the densities of atomic ions H^+ and molecular ions H_2^+ respectively. The index "eq" denotes that molecular ion density corresponds to thermodynamical equilibrium condition for given T. Factor $\chi(T)$ can be determined as in Mihajlov et al. (2007a) in connection with the contribution of $H^+ + H(1s)$ radiative collision processes to the solar atmosphere's opacity in UV and VUV region.

Taking quantity $K_{cr}^{(a)}(n,T)$ as the rate coefficient for process (3), we can characterize both chemi-recombination processes (3) and (4) in a similar way. Namely, in accordance with Equations (20) and (21), rate coefficients $K_{cr}^{(a)}(n,T)$ and $K_{cr}^{(b)}(n,T)$ are given by relations

$$K_{cr}^{(a,b)}(n,T) = K_{ci}^{(a,b)}(n,T) \cdot S_n^{-1}(T), \qquad S_n(T) \equiv \frac{N_i N_e}{N_n} = \frac{1}{n^2} \cdot \frac{m k_B T}{2\pi\hbar^2} \cdot \exp(-\frac{I_n}{k_B T}), \tag{23}$$

where m is the electron mass and k_B is the Boltzmann constant. Consequently, using such partial rate coefficients, we can introduce here the total one, i.e.,

$$K_{cr}(n,T) = K_{cr}^{(a)}(n,T) + K_{cr}^{(b)}(n,T), \tag{24}$$

which characterizes the efficiency of processes 3) and (4) together for $n \geq 5$.

2.3. The chemi-ionization/recombination processes: $2 \leq n \leq 4$

The reason why the regions $n \geq 5$ and $2 \leq n \leq 4$ are being considered separately is the behavior of the adiabatic potential curves of atom-atom systems $H^*(n) + H(1s)$. Namely, in the first region the atom-atom curves lie above the adiabatic curve of the ion-ion system $H^+ + H^-(1s^2)$ for any R, and the dipole resonant mechanism can be applied for $n \geq 5$ without any exceptions, while in the other region there are points where the atom-atom curves cross the ion-ion one and application of this mechanism generates some errors (see Janev & Mihajlov (1979)). Since the corresponding cross-points for $n \leq 4$ are so far from the point $R = 0$ that their existence could be neglected for $n = 4$ and 3, and with some caution even for $n = 2$, the dipole resonant mechanism was applicable, for example, in Mihajlov & Dimitrijević (1992) and Mihajlov et al. (1996) for $n = 4$ and in Zhdanov & Chibisov (1976) for $n = 3$. However, now we can determine the values of rate coefficients $K_{cr}^{(a)}(n,T)$ of dissociative recombination process (3) for $n = 2$, 3, and 4 using the results deduced from the experimental data of Jones (1977), presented in Janev et al. (1987).

Due to this fact and the mentioned errors, we use here semi-empirical rate coefficients $K_{cr}^{(a)}(n = 3, T)$ and $K_{cr}^{(a)}(n = 4, T)$, which are obtained from Janev et al. (1987), for the dominant processes of the dissociative recombination, i.e., for process (3) with $n = 3$ and 4. The corresponding chemi-ionization rate coefficients $K_{ci}^{(a)}(n = 3, T)$ and $K_{ci}^{(a)}(n = 4, T)$ are obtained then from the principle of thermodynamical balance, as it has been described above. For relatively minor chemi-ionization/recombination processes, i.e. for processes (1) and (3) with $n = 2$, we use here rate coefficients $K_{ci}^{(a)}(n = 2, T)$ and $K_{cr}^{(a)}(n = 2, T)$, which are 10 - 30 percent greater than the corresponding coefficients obtained using the data from Janev et al. (1987), in accordance with the calculated results from Urbain et al. (1991) and Rawlings et al. (1993). It gives a possibility to compensate the decrease of rate coefficients $K_{ci}^{(a)}(n \geq 5, T)$ and $K_{cr}^{(a)}(n \geq 5, T)$ in comparison with the corresponding ones obtained using Janev et al. (1987), due to the fact that here, unlike Janev et al. (1987), the decay of the considered system's initial electronic state has been taken into account. For other chemi-ionization and recombination processes (2) and (4) with $2 \leq n \leq 4$, whose contribution could really be neglected, the corresponding rate coefficients will be determined (in accordance with what was said above) by extrapolation of those from the region $n \geq 5$. Finally, let us note that in further considerations for chemi-ionization and recombination processes (1) - (4) with $n < 5$ we will use also total rate coefficients, which are given by the same expressions (19) and (24), but for $2 \leq n \leq 4$.

3. Results and discussion

3.1. The Considered Model of the Solar Photosphere

In accordance with the aim of this work we consider here model C of solar atmosphere from Vernazza et al. (1981). Namely, this is a non-LTE model which is still actual (see (Stix 2002)), and it is only for this model that all the quantities necessary for our calculations are available in tabular form as functions of height (h) in Solar photosphere. In Figure 1, basic plasma parameters for this model are shown. In Figure 2, deviations of non-LTE populations of excited hydrogen atom states with $2 \leq n \leq 8$ in solar photosphere within the C model of Vernazza et al. (1981) are illustrated. One can see that these deviations are particularly pronounced for $n = 2$. Around $h = 500$ km $N\,(H^*(n = 2))$ is one-half of the corresponding equilibrium density and for h larger than 1000 km it is around ten times greater. These deviations rapidly decrease with an increase of n. However, even for n=8 this deviation is around 40 percent around $h = 500$ km, illustrating the importance of taking into account the considered processes ab initio in the modeling of solar atmosphere.

3.2. The calculated chemi-ionization/recombination rate coefficients

The values of the total chemi-ionization and recombination rate coefficients $K_{ci}(n,T)$ and $K_{cr}(n,T)$, obtained in the described way, are presented in Tables 1 and 2 respectively. These tables cover the regions $2 \le n \le 8$ and $4000K \le T \le 10000K$ which are relevant for solar photosphere considered on the basis of C model from (Vernazza et al. 1981).

Relative contribution of partial chemi-ionization and recombination processes for given n and T characterizes corresponding branch coefficients $X_{ci}^{(a,b)}(n,T)$, namely

$$X_{ci}^{(a,b)}(n,T) = \frac{K_{ci}^{(a,b)}(n,T)}{K_{ci}(n,T)}, \qquad X_{cr}^{(a,b)}(n,T) = \frac{K_{cr}^{(a,b)}(n,T)}{K_{cr}(n,T)}. \tag{25}$$

Since $X_{ci,cr}^{(b)}(n,T) = 1 - X_{ci,cr}^{(a)}(n,T)$ and $X_{ci}^{(a,b)}(n,T) = X_{cr}^{(a,b)}(n,T) \equiv X^{(a,b)}(n,T)$, it is enough to present only the values of one of the coefficients $X^{(a,b)}(n,T)$. Here, the values of the coefficient $X^{(a)}(n,T)$, which directly describe relative contributions of the associative ionization and dissociative recombination processes (1) and (3), are presented in Table 3.

3.3. Comparison of fluxes of the considered processes

Let $I_{ci}(n,T)$, $I_{cr}(n,T)$ be the total chemi-ionization and chemi-recombination fluxes caused by the processes (1,2) and (3,4), i.e.,

$$I_{ci}(n,T) = K_{ci}(n,T) \cdot N_n N_1, \qquad I_{cr}(n,T) = K_{cr}(n,T) \cdot N_1 N_i N_e, \tag{26}$$

and $I_{i;ea}(n,T)$, $I_{r;eei}(n,T)$ and $I_{r;ph}(n,T)$ be the fluxes caused by ionization and recombination processes (5), (6) and (7), i.e.

$$I_{i;ea}(n,T) = K_{ea}(n,T) \cdot N_n N_e, \quad I_{r;eei}(n,T) = K_{eei}(n,T) \cdot N_i N_e N_e, \quad I_{r;ph}(n,T) = K_{ph}(n,T) \cdot N_i N_e, \tag{27}$$

where N_1, N_n, N_i, and N_e are, respectively, the densities of the ground and excited states of a hydrogen atom, of ion H^+, and of free electron in the considered plasma with given T.

Using these expressions, we will first calculate quantities $F_i(n,T)$ given by

$$F_i(n,T) = \frac{I_{ci}(n,T)}{I_{i;ea}(n,T)} = \frac{K_{ci}(n,T)}{K_{ea}(n,T)} \cdot N_1 N_e, \tag{28}$$

which characterize the relative efficiency of partial chemi-ionization processes (1,2) together and the impact electron-atom ionization (5) in the considered plasma. The total chemi-ionization and recombination rate coefficients $K_{ci}(n,T)$ are determined here the way it is described in the previous section, and impact ionization rate coefficients $K_{ea}(n,T)$ are taken from Vriens & Smeets (1980). In Figure 3 the behavior of the quantities $F_{i,ea}(n,T)$ for $2 \leq n \leq 8$ as functions of height h is shown, according to the data (N_1, N_e and T) from Vernazza et al. (1981) for solar photosphere. One can see that the efficiency of the considered chemi-ionization processes in comparison with the electron-atom impact ionization is dominant for $2 \leq n \leq 6$ and becomes comparable for $n = 7$ and 8.

However, in order to compare the relative influence of the chemi-ionization processes (1) and (2) together to that of the impact electron-atom ionization process (5) on the whole block of the excited hydrogen atom states with $2 \leq n \leq 8$, we will calculate quantity $F_{i,ea;2-8}(T)$, given by

$$F_{i,ea;2-8}(T) = \frac{\sum\limits_{n=2}^{8} I_{ci}(n,T)}{\sum\limits_{n=2}^{8} I_{i;ea}(n,T)} = \frac{\sum\limits_{n=2}^{8} K_{ci}(n,T) \cdot N_n}{\sum\limits_{n=2}^{8} K_{ea}(n,T) \cdot N_n} \cdot N_1 N_e, \tag{29}$$

which can reflect the influence of the existing populations of excited hydrogen atom states within a non-LTE model of solar atmosphere. In Figure 4 the behavior of the quantity $F_{i,ea;2-8}(T)$ as functions of height h is shown according to the same data from Vernazza et al. (1981). As one can see, the real influence of the chemi-ionization processes on the total populations of states with $2 \leq n \leq 8$ remains dominant with respect to the concurrent electron-atom impact ionization processes almost in the whole photosphere (50 km $\lesssim h \lesssim$ 750 km). This means that the chemi-ionization processes influence the radiative properties of the whole solar atmosphere in the optical region considerably.

Then, in order to compare the relative influence of chemi-recombination processes (3) and (4) together and electron - electron - H^+ ion recombination process (6) on the same block of excited hydrogen atom states with $2 \leq n \leq 8$, we calculated quantity $F_{r,eei;2-8}(T)$, given by

$$F_{r,eei;2-8}(T) = \frac{\sum\limits_{n=2}^{8} I_{cr}(n,T)}{\sum\limits_{n=2}^{8} I_{r;eei}(n,T)} = \frac{\sum\limits_{n=2}^{8} K_{cr}(n,T)}{\sum\limits_{n=2}^{8} K_{eei}(n,T)} \cdot \frac{N_1}{N_e}, \tag{30}$$

taking rate coefficients $K_{eei}(n,T)$ also from Vriens & Smeets (1980). In Figure 5 the behavior of this quantity as a function of height h is shown. One can see that the considered chemi-recombination processes dominate with respect to the concurrent electron-electron-ion recombination processes within the region 100 km $\lesssim h \lesssim$ 650 km. Consequently, the considered chemi-recombination processes are also very significant for the optical properties of the solar photosphere.

Finally, we compared the relative influence of chemi-recombination processes (3) and (4) together and photo-recombination electron - H^+ ion process (7), also within the block of the excited hydrogen atom states with $2 \leq n \leq 8$. For that sake we calculated quantity $F_{r,ph;2-8}(T)$, given by

$$F_{r,ph;2-8}(T) = \frac{\sum\limits_{n=2}^{8} I_{cr}(n,T)}{\sum\limits_{n=2}^{8} I_{r;ph}(n,T)} = \frac{\sum\limits_{n=2}^{8} K_{cr}(n,T)}{\sum\limits_{n=2}^{8} K_{ph}(n,T)} \cdot N_1, \tag{31}$$

taking rate coefficients $K_{ph}(n,T)$ from Sobel'man (1979). This is necessary since in (Mihajlov et al. 1997) only the states $4 \leq n \leq 8$ were considered. Still, it was a natural expectation that the inclusion of states with $n = 2$ and 3 will increase the influence of photo-recombination electron - ion processes. The behavior of quantity $F_{r,ph;2-8}(T)$ as a function of h is shown in Figure 6. One can see that here a domination of the chemi-recombination processes with $2 \leq n \leq 8$ over the electron-ion photo-recombination processes is confirmed (although to a slightly lesser extent) in a significant part of the photosphere (-50 km $\lesssim h \lesssim$ 600 km).

4. Conclusion

The obtained results demonstrate the fact that the considered chemi-ionization/re-combination processes must have a very significant influence on the optical properties of the solar photosphere in comparison to the concurrent electron-atom impact ionization and electron-ion recombination processes. Thus it is shown that the importance of these processes for non-LTE modeling of solar atmosphere should be necessarily investigated.

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Table 1: Calculated Values of Coefficient K_{ci}[cm^3/s] as a Function of n and T

	n						
T[K]	2	3	4	5	6	7	8
4000	0.150E-11	0.619E-09	0.126E-08	0.576E-09	0.554E-09	0.463E-09	0.366E-09
4250	0.202E-11	0.549E-09	0.106E-08	0.617E-09	0.583E-09	0.482E-09	0.378E-09
4500	0.260E-11	0.501E-09	0.900E-09	0.656E-09	0.611E-09	0.500E-09	0.389E-09
4750	0.324E-11	0.488E-09	0.833E-09	0.694E-09	0.637E-09	0.517E-09	0.400E-09
5000	0.403E-11	0.495E-09	0.815E-09	0.730E-09	0.662E-09	0.533E-09	0.410E-09
5250	0.504E-11	0.501E-09	0.800E-09	0.765E-09	0.686E-09	0.548E-09	0.420E-09
5500	0.623E-11	0.500E-09	0.782E-09	0.799E-09	0.709E-09	0.563E-09	0.428E-09
5750	0.756E-11	0.493E-09	0.764E-09	0.832E-09	0.731E-09	0.576E-09	0.437E-09
6000	0.909E-11	0.490E-09	0.757E-09	0.864E-09	0.752E-09	0.589E-09	0.445E-09
6250	0.108E-10	0.502E-09	0.766E-09	0.895E-09	0.772E-09	0.602E-09	0.453E-09
6500	0.128E-10	0.519E-09	0.783E-09	0.924E-09	0.791E-09	0.613E-09	0.460E-09
7000	0.175E-10	0.540E-09	0.808E-09	0.981E-09	0.827E-09	0.635E-09	0.473E-09
7500	0.232E-10	0.574E-09	0.848E-09	0.103E-08	0.860E-09	0.655E-09	0.485E-09
8000	0.300E-10	0.609E-09	0.891E-09	0.108E-08	0.892E-09	0.674E-09	0.497E-09
8500	0.380E-10	0.650E-09	0.939E-09	0.113E-08	0.920E-09	0.691E-09	0.507E-09
9000	0.470E-10	0.688E-09	0.986E-09	0.118E-08	0.948E-09	0.707E-09	0.516E-09
9500	0.574E-10	0.733E-09	0.104E-08	0.122E-08	0.973E-09	0.722E-09	0.525E-09
10000	0.689E-10	0.787E-09	0.109E-08	0.126E-08	0.997E-09	0.736E-09	0.533E-09

Table 2: Calculated Values of Recombination Coefficient K_{cr}[cm^6/s] as a Function of n and T

	n						
T[K]	2	3	4	5	6	7	8
4000	0.190E-27	0.732E-27	0.390E-27	0.114E-27	0.977E-28	0.831E-28	0.709E-28
4250	0.130E-27	0.458E-27	0.257E-27	0.102E-27	0.880E-28	0.753E-28	0.645E-28
4500	0.918E-28	0.305E-27	0.177E-27	0.914E-28	0.799E-28	0.688E-28	0.591E-28
4750	0.666E-28	0.223E-27	0.135E-27	0.828E-28	0.730E-28	0.631E-28	0.544E-28
5000	0.506E-28	0.174E-27	0.110E-27	0.755E-28	0.671E-28	0.582E-28	0.503E-28
5250	0.403E-28	0.138E-27	0.912E-28	0.693E-28	0.619E-28	0.540E-28	0.467E-28
5500	0.331E-28	0.111E-27	0.763E-28	0.639E-28	0.575E-28	0.502E-28	0.436E-28
5750	0.275E-28	0.889E-28	0.645E-28	0.592E-28	0.535E-28	0.469E-28	0.407E-28
6000	0.233E-28	0.731E-28	0.558E-28	0.551E-28	0.500E-28	0.440E-28	0.382E-28
6250	0.201E-28	0.627E-28	0.498E-28	0.514E-28	0.469E-28	0.413E-28	0.360E-28
6500	0.176E-28	0.548E-28	0.451E-28	0.482E-28	0.441E-28	0.389E-28	0.339E-28
7000	0.139E-28	0.421E-28	0.374E-28	0.427E-28	0.393E-28	0.348E-28	0.304E-28
7500	0.114E-28	0.341E-28	0.322E-28	0.382E-28	0.354E-28	0.314E-28	0.275E-28
8000	0.964E-29	0.284E-28	0.283E-28	0.345E-28	0.321E-28	0.286E-28	0.250E-28
8500	0.834E-29	0.243E-28	0.253E-28	0.314E-28	0.293E-28	0.261E-28	0.229E-28
9000	0.731E-29	0.211E-28	0.229E-28	0.287E-28	0.269E-28	0.240E-28	0.211E-28
9500	0.654E-29	0.187E-28	0.209E-28	0.264E-28	0.248E-28	0.222E-28	0.195E-28
10000	0.590E-29	0.169E-28	0.194E-28	0.245E-28	0.230E-28	0.206E-28	0.181E-28

Table 3: Calculated Values of Coefficient $X^{(a)} \equiv K_{ci}^{(a)}/K_{ci} = K_{cr}^{(a)}/K_{cr}$ as a Function of n and T.

	n						
T[K]	2	3	4	5	6	7	8
4000	0.998	0.955	0.877	0.507	0.408	0.335	0.281
4250	0.969	0.934	0.827	0.484	0.388	0.318	0.266
4500	0.924	0.907	0.765	0.463	0.371	0.303	0.254
4750	0.872	0.881	0.709	0.443	0.354	0.289	0.242
5000	0.819	0.857	0.664	0.425	0.339	0.277	0.231
5250	0.769	0.831	0.619	0.408	0.325	0.265	0.221
5500	0.721	0.800	0.568	0.393	0.312	0.254	0.212
5750	0.673	0.764	0.515	0.378	0.300	0.244	0.203
6000	0.627	0.728	0.466	0.364	0.288	0.235	0.196
6250	0.585	0.699	0.430	0.351	0.278	0.226	0.188
6500	0.546	0.672	0.399	0.339	0.268	0.218	0.182
7000	0.474	0.610	0.336	0.317	0.250	0.204	0.169
7500	0.414	0.558	0.289	0.297	0.235	0.190	0.158
8000	0.363	0.510	0.250	0.280	0.221	0.179	0.149
8500	0.321	0.469	0.220	0.264	0.208	0.169	0.141
9000	0.287	0.429	0.193	0.250	0.197	0.160	0.133
9500	0.258	0.398	0.174	0.237	0.187	0.151	0.126
10000	0.234	0.376	0.160	0.225	0.177	0.144	0.120

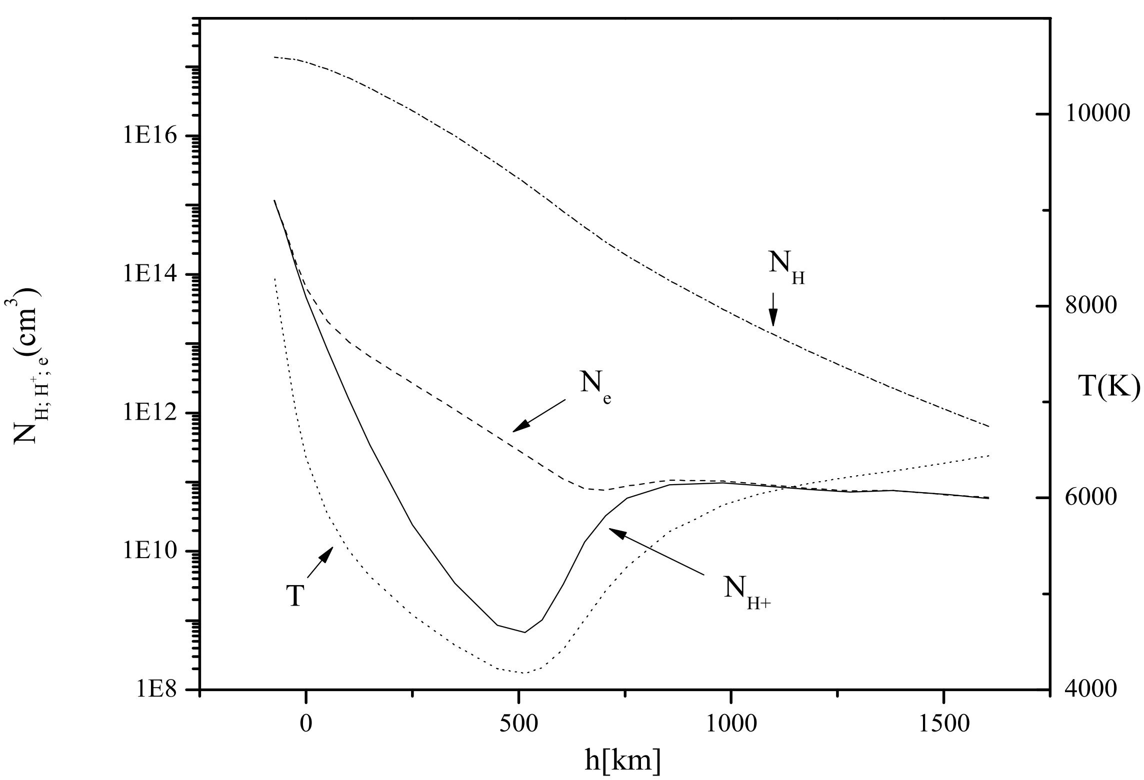

Fig. 1.— Basic plasma parameters, for the solar model of Vernazza et al. (1981), as a function of height h.

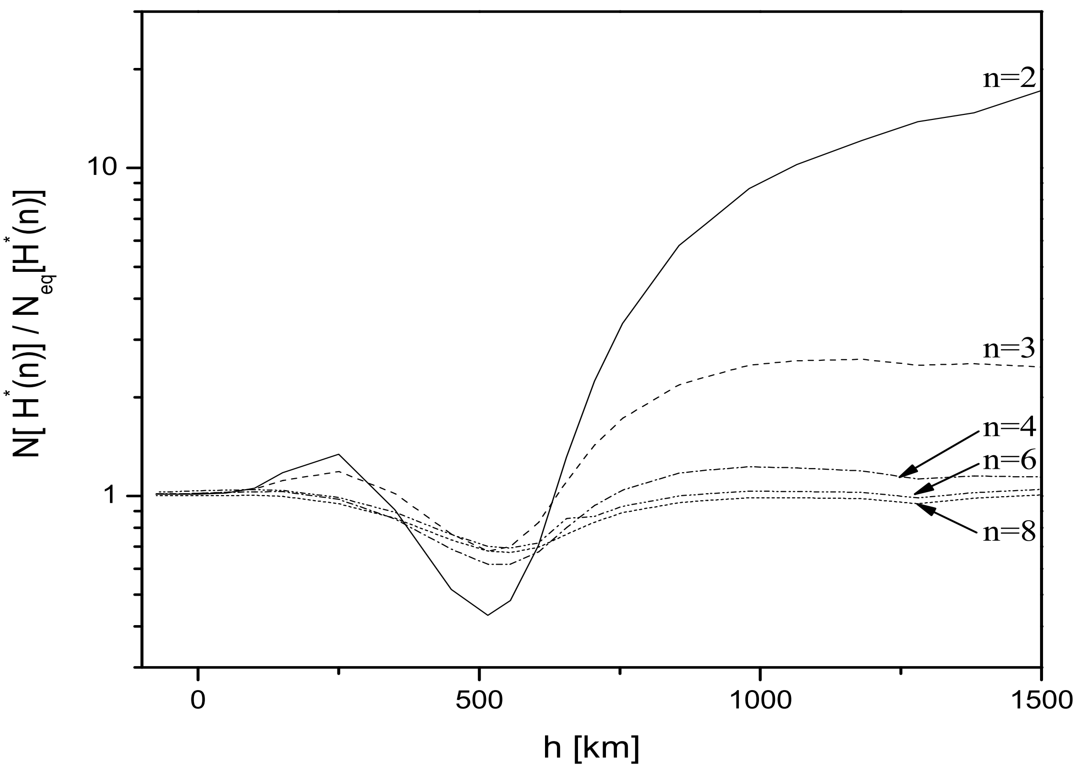

Fig. 2.— Parameter $\eta(n) = N(H^*)(n)/N^{(eq)}(H^*)(n)$, as a function of height h. The index "eq" denotes that excited atom densities correspond to thermodynamical equilibrium conditions for given T.

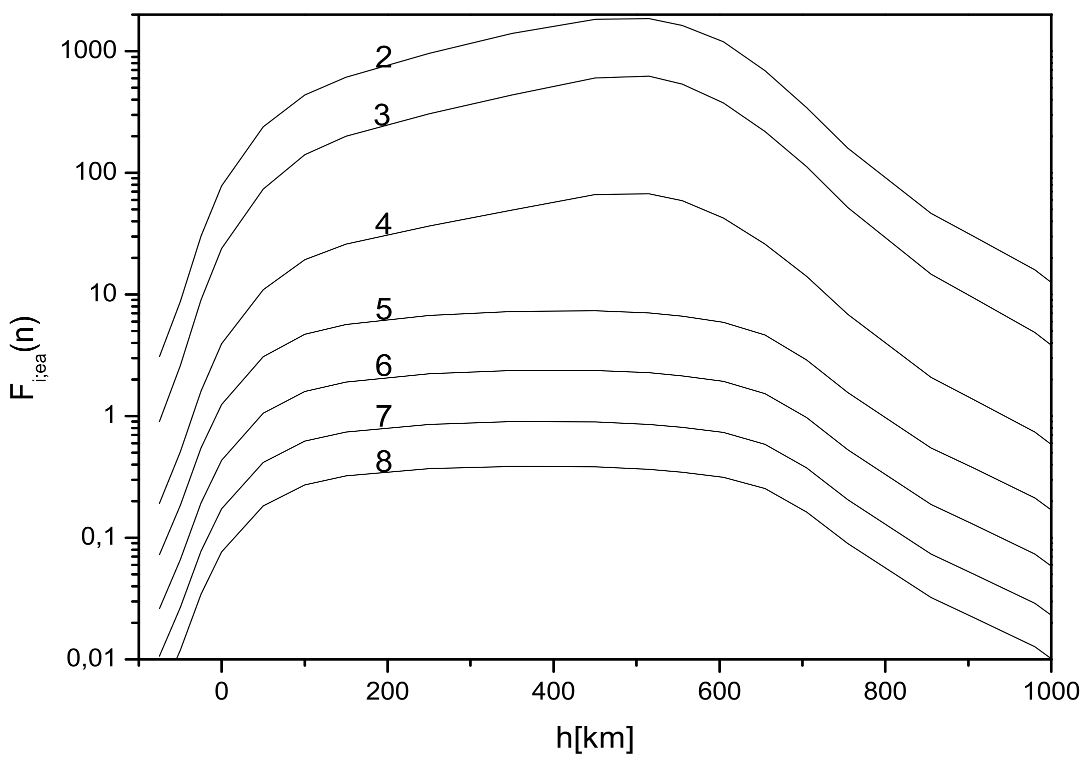

Fig. 3.— Behavior of the quantity $F_{i;ea}^{(ab)}(n)$ given by Equation (5), as a function of height h.

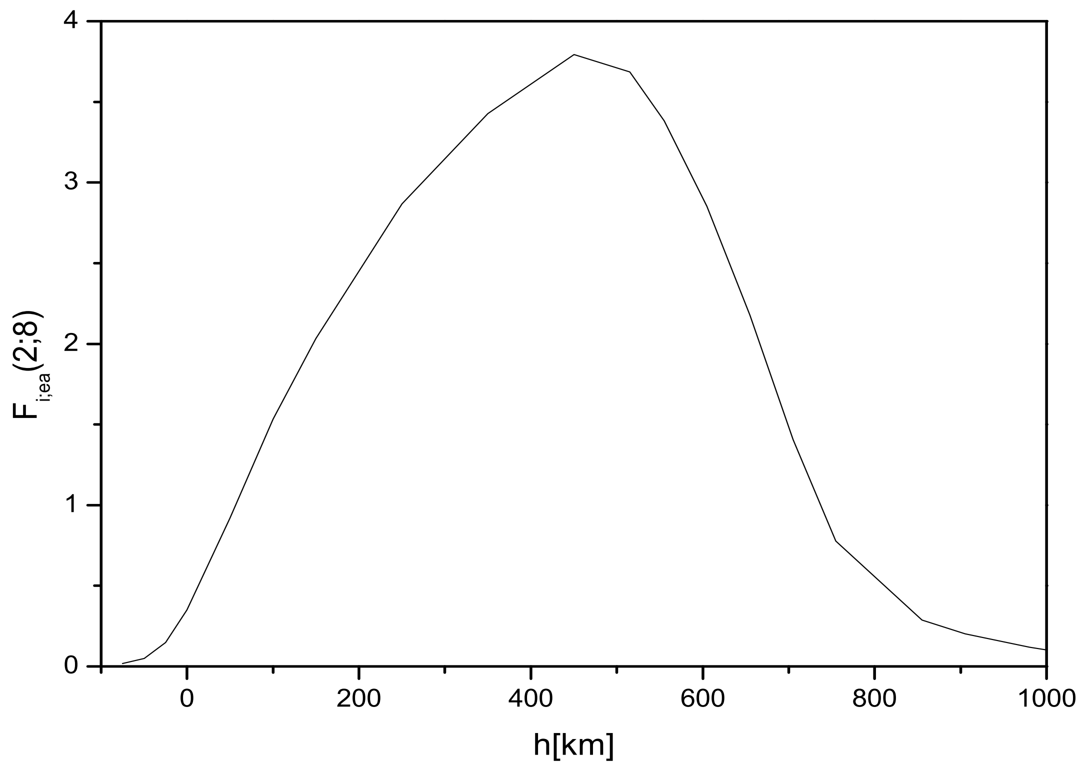

Fig. 4.— Behavior of the quantity $F_{i;ea}(2;8)$ given by Eq. (29), as a function of height h

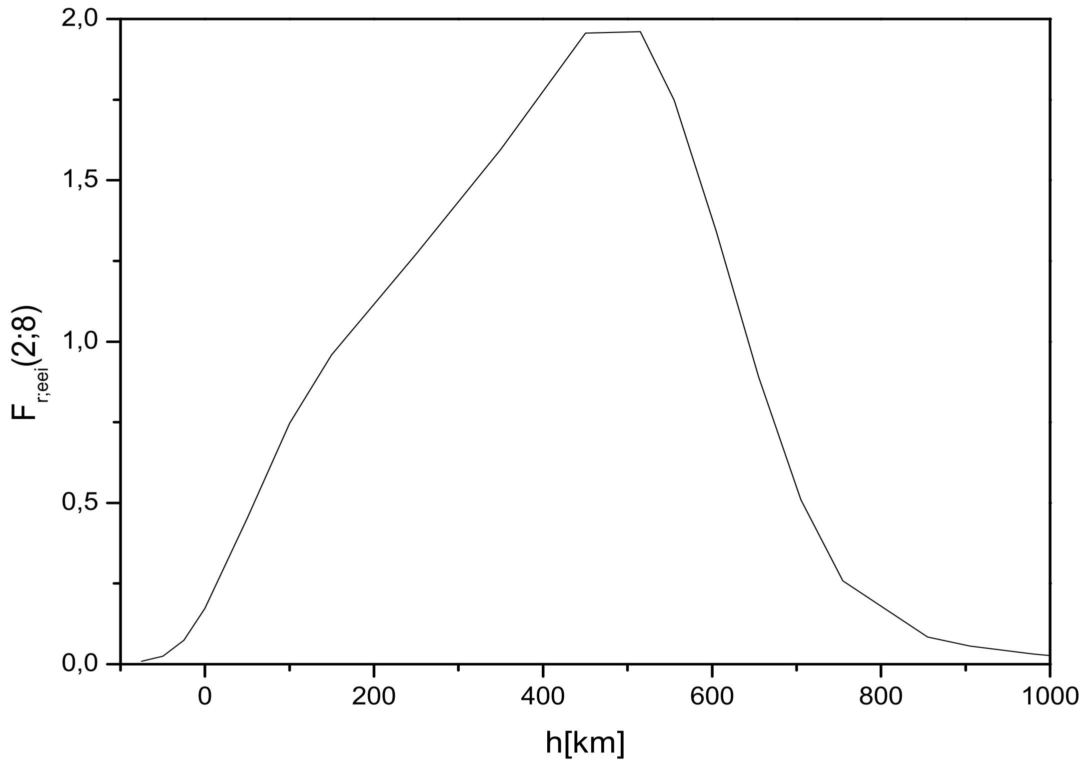

Fig. 5.— Behavior of the quantity $F_{r;eei}(2;8)$ given by Equation (30), as a function of height h.

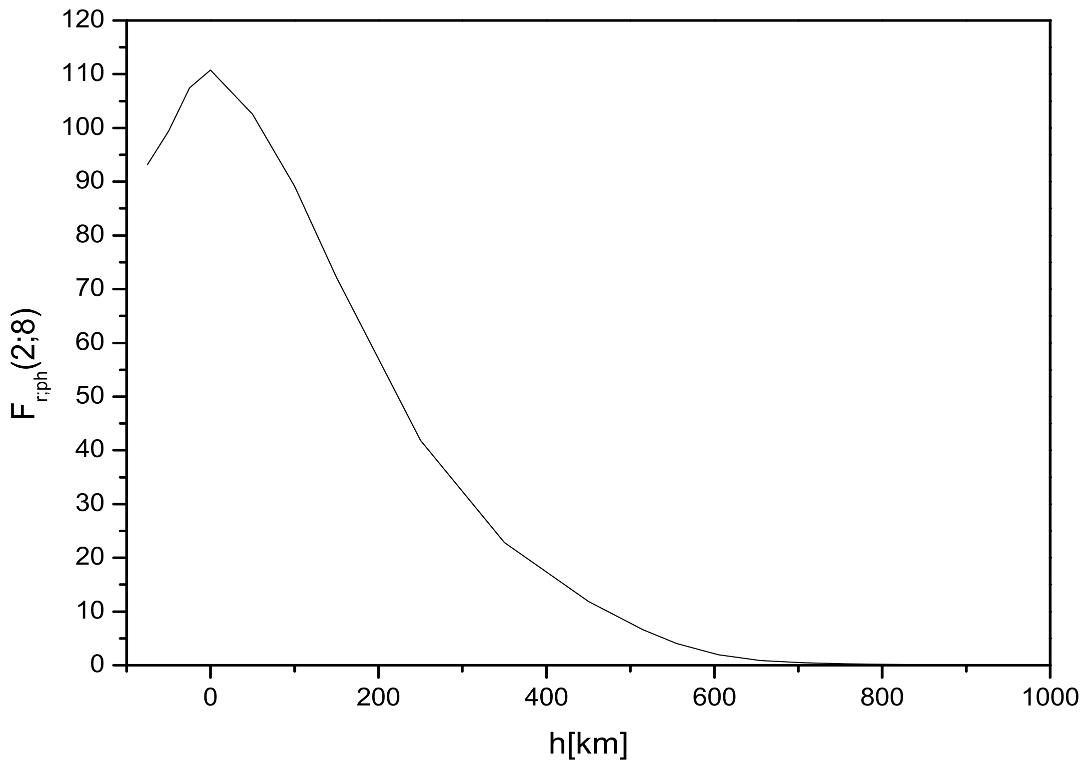

Fig. 6.— Behavior of the quantity $F_{r;ph}(2;8)$ given by Equation (31), as a function of height h.