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SYMMETRICAL CHEMI-IONIZATION AND CHEMI-RECOMBINATION PROCESSES IN LOW-TEMPERATURE LAYERS OF HELIUM-RICH DB WHITE DWARF ATMOSPHERES

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ABSTRACT

The influence of symmetrical chemi-ionization and chemi-recombination processes on the helium atom Rydberg states' population in weakly ionized layers of helium-rich DB white dwarfs has been investigated. The ionization processes in $\mathrm{He}^*(n) + \mathrm{He}(1s^2)$ collisions and their inverse recombination processes $\mathrm{He}_2^+ + e$ and $\mathrm{He}(1s^2) + \mathrm{He}^+ + e$ have been considered in domains of principal quantum numbers $n \geq 3$ and temperatures $12,000\ \mathrm{K} \leq T_{\mathrm{eff}} \leq 30,000$ K. These processes have been treated within the frame of the semiclassical theory developed earlier. Their contributions to the Rydberg state populations have been compared with electron-electron-ion recombination, electron-excited atom ionization, and electron-ion photorecombination processes. Results showed that these processes can be dominant ionization/recombination mechanisms in helium-rich DB white dwarf atmosphere layers for $\log g = 7$ and 8 and $T_{\mathrm{eff}} \leq 20,000$ K and have to be implemented in relevant models of weakly ionized helium plasmas.

Subject headings: atomic processes — stars: atmospheres — white dwarfs

1. INTRODUCTION

This work continues our investigations of the influence of ion-atom collisional processes on the properties of weakly ionized layers of helium-rich DB white dwarf atmospheres. It has been demonstrated in Mihajlov & Dimitrijević (1992), Mihajlov, Dimitrijević, & Ignjatović (1994a), and Mihajlov et al. (1995) that the processes of absorption and emission of electromagnetic radiation due to $\mathrm{He}^+(1s)$ and $\mathrm{He}(1s^2)$ collisions have a strong influence on the optical characteristics of DB white dwarf atmospheric layers. In plasma conditions, however, the ion-atom collisional complexes intensively interact not only with the EM field but also with charged particles, most importantly with free electrons. Consequently, it was necessary to consider processes based on $e + \mathrm{He}^+(1s) + \mathrm{He}(1s^2)$ collisions. Moreover, in a weakly ionized plasma the collisional complexes similar to the ion-atom one should be taken into account. These complexes consist of atoms in ground and highly excited (Rydberg) states and interact with an outer weakly bound electron of the Rydberg atom. Therefore, in helium plasmas the processes to be investigated are based on $\mathrm{He}(1s^2) + \mathrm{He}^*(n)$ collisions, with $\mathrm{He}^*(n)$ representing the helium atom in a Rydberg state. The role of these complexes will be analyzed in a manner similar to the role of ion-atom complexes in a solar photosphere and lower chromosphere (Mihajlov et al. 1996, 1997b, 1999; Mihajlov, Ignjatović, & Dimitrijević 1998). We will consider the chemi-recombination processes resulting from free electron scattering on the collisional symmetrical ion-atom complexes and chemi-ionization processes during symmetrical atom–Rydberg atom collisions. The ionization/recombination processes with molecular ions in weakly bound rovibrational states will also be included. Therefore, for weakly ionized helium plasma of a DB white dwarf photosphere, the following chemi-ionization processes,

$$\mathrm{He}^*(n) + \mathrm{He} \Rightarrow \mathrm{He}_2^+ + e\ , \tag{1a}$$

$$\mathrm{He}^*(n) + \mathrm{He} \Rightarrow \mathrm{He} + \mathrm{H}^+ + e\ , \tag{1b}$$

and the corresponding chemi-recombination processes,

$$\mathrm{He}_2^+ + e \Rightarrow \mathrm{He}^*(n) + \mathrm{He}\ , \tag{2a}$$

$$\mathrm{He} + \mathrm{He}^+ + e \Rightarrow \mathrm{He}^*(n) + \mathrm{He}\ , \tag{2b}$$

are considered. He and He^+ are in their ground states $1s^2$ and $1s$, respectively, $\mathrm{He}^*(n)$ is the helium atom in the highly excited (Rydberg) state with the principal quantum number $n \gg 1$, and He_2^+ is the molecular ion in the weakly bound rovibrational state belonging to its ground electronic state ($1\Sigma_u$). The main reasons for including (1a) and (2a) channels with molecular ions are the same as in the case of hydrogen plasmas, discussed in detail in Mihajlov & Ljepojević (1982) and Mihajlov, Ljepojević, & Dimitrijević (1992).

The chemi-ionization (eqs. [1a]–[1b]) and chemi-recombination (eqs. [2a]–[2b]) processes are investigated as mechanisms which may influence populations of helium atom Rydberg states. We will assume that the principal quantum number $n \geq 3$, as in Mihajlov et al. (1996, 1997a, 1999) and Djurić & Mihajlov (2001). The influence of examined processes is determined by comparison with other relevant ionization and recombination processes, namely, electron-Rydberg atom impact ionization,

$$He^*(n) + e \Rightarrow He^+ + e + e , \quad (3)$$

electron-electron-ion recombination,

$$He^+ + e + e \Rightarrow He^*(n) + e , \quad (4)$$

and electron-ion photorecombination,

$$He^+ + e \Rightarrow He^*(n) + \epsilon_{phot} , \quad (5)$$

where ϵ_{phot} denotes the emitted photon energy. The previous results for solar photosphere demonstrated that the influence of the chemi-ionization and chemi-recombination processes on Rydberg atom states populations is important, and in some layers even dominant in comparison with other ionization and recombination processes (Mihajlov et al. 1997b, 1998). It was found that the radiative ion-atom collisional processes are much more important for the helium-rich DB white dwarf than the solar photosphere (Mihajlov et al. 1994b, 1995). Taking into account these differences, we can expect that the importance of the chemi-ionization and chemi-recombination processes in the case of a helium-rich DB white dwarf atmosphere will be considerably greater than in the case of a solar photosphere.

2. THEORY

2.1. *Chemi-Ionization/Recombination Processes*

The importance of the chemi-recombination (eqs. [1a]–[1b]) and chemi-ionization (eqs. [2a]–[2b]) processes in a given plasma, relative to other recombination and ionization processes, is determined by comparing corresponding fluxes. This is performed under the standard assumption that in photosphere plasmas $T_e = T_a = T$, where T_e and T_a are the electron and atom temperatures and T is their common value. Under this assumption the deviation from LTE in a given plasma is manifested through the departure of the excited atom state populations from Boltzman's distribution. The possible cause of such deviations from LTE in the solar atmosphere is ongoing radiation (Vernazza, Avrett, & Loser 1981; Mihajlov et al. 1997b). Therefore, it is necessary to take into account all processes which can influence the excited atom state populations, particularly ionization/recombination processes (1) and (2).

Let $I_i^{(a,b)}(n; T)$ and $I_r^{(a,b)}(n; T)$ denote ionization and recombination fluxes conditioning population and depopulation of excited $He^*(n)$ atomic states due to processes (1a)–(2b), respectively. By definition, we have

$$I_i^{(a)}(n;\ T) = K_i^{(a)}(n, T) \cdot N(He) \cdot N(He^*(n)) ,$$
$$I_i^{(b)}(n;\ T) = K_i^{(b)}(n, T) \cdot N(He) \cdot N(He^*(n)) , \quad (6)$$

where $N(He)$ and $N(He^*(n))$ denote $He(1s^2)$ atom and $He^*(n)$ Rydberg atom ($n \geq 3$) densities, and $K_i^{(a)}(n;\ T)$ and $K_i^{(b)}(n;\ T)$ denote rate coefficients of processes (1a) and (1b). We also have

$$I_r^{(a)}(n;\ T) = K_{dr}^{(a)}(n, T) \cdot N(He_2^+) \cdot N(e) ,$$
$$I_r^{(b)}(n;\ T) = K_r^{(b)}(n, T) \cdot N(He) \cdot N(He^+) \cdot N(e) , \quad (7)$$

where $N(He^+)$, $N(e)$, and $N(He_2^+)$ denote $He^+(1s)$ ion, free electron, and He_2^+ molecular ion (in weakly bound rovibrational states) densities, and $K_{dr}^{(a)}(n, T)$ and $K_r^{(b)}(n, T)$ denote the rate coefficients of processes (2a) and (2b). The rate coefficient of process (2a) is denoted with $K_{dr}^{(a)}$ since this is a process of dissociative recombination. Following our method presented in Mihajlov et al. (1997a), flux $I_r^{(a)}(n;\ T)$ generated by chemi-recombination processes (eq. [2a]) is expressed as

$$I_r^{(a)}(n;\ T) = K_r^{(a)}(n, T) \cdot N(He) \cdot N(He^+) \cdot N(e) , \quad (8)$$

where $K_r^{(a)}(n, T)$ is given by the expression

$$K_r^{(a)}(n, T) = K_{dr}^{(a)}(n, T) \cdot \left[\frac{N(He)N(He^+)}{N(He_2^+)}\right]^{-1} . \quad (9)$$

We are interested in the total influence of processes (1a) and (1b) on the depopulation, and the total influence of processes (2a) and (2b) on the population of helium atom excited states. Consequently, we will consider the total chemi-ionization $I_i^{(ab)}(n;\ T)$ and chemi-recombination $I_r^{(ab)}(n;\ T)$ fluxes, where

$$I_i^{(ab)}(n;\ T) = I_i^{(a)}(n;\ T) + I_i^{(b)}(n;\ T) ,$$
$$I_r^{(ab)}(n;\ T) = I_r^{(a)}(n;\ T) + I_r^{(b)}(n;\ T) . \quad (10)$$

From equations (6)–(8) it follows that these fluxes can be expressed as

$$I_i^{(ab)}(n, T) = K_i^{(ab)}(n, T) \cdot N(He) \cdot N(He^*(n)) , \quad (11)$$

$$I_r^{(ab)}(n, T) = K_r^{(ab)}(n, T) \cdot N(He) \cdot N(He^+) \cdot N(e) , \quad (12)$$

where total chemi-ionization and chemi-recombination rate coefficients $K_i^{(ab)}(n;\ T)$ and $K_r^{(ab)}(n, T)$ are similarly defined as

$$K_i^{(ab)}(n;\ T) = K_i^{(a)}(n;\ T) + K_i^{(b)}(n;\ T) ,$$
$$K_r^{(ab)}(n, T) = K_r^{(a)}(n, T) + K_r^{(b)}(n, T) . \quad (13)$$

The rate coefficient $K_r^{(a)}(n, T)$ is given by equation (9).

The rate coefficients of the processes (1a)–(2b) have been determined by a method based on the semiclassical theory developed for hydrogen and alkalis in Mihajlov & Janev (1981), Mihajlov & Ljepojević (1982), and Mihajlov et al. (1992). This theory is based on the mechanism of resonant energy exchange within the electronic component of the symmetrical atom–Rydberg atom system collision, introduced in Smirnov & Mihajlov (1972), with more details to be found in Janev & Mihajlov (1979, 1980). The semiclassical theory has been adapted for helium in Mihajlov et al. (1996). The method used here is finalized and reviewed in detail in Mihajlov et al. (1997a).

Within the frame of the method used here, chemi-ionization rate coefficients $K_i^{(a)}(n, T)$, $K_i^{(b)}(n, T)$, and $K_i^{(ab)}(n, T)$ are determined directly, while chemi-recombination rate coefficients $K_r^{(a)}(n, T)$, $K_r^{(b)}(n, T)$, and $K_r^{(ab)}(n, T)$ are determined using the thermodynamical balance principle. For example, a simple way to find the partial rate coefficient $K_r^{(a)}(n, T)$ given by equation (9) is by using the thermodynamic balance principle and the partial chemi-ionization rate coefficient $K_i^{(a)}(n, T)$. The chemi-ionization and chemi-recombination processes are additionally characterized by the parameters $X^{(ab)}_{ir;a,b}(n, T)$

$$X^{(ab)}_{ir;a,b}(n, T) = \frac{I_i^{(a,b)}(n, T)}{I_i^{(ab)}(n, T)} = \frac{I_r^{(a,b)}(n, T)}{I_r^{(ab)}(n, T)} , \tag{14}$$

which describe the relative importance of the particular channel ("a" and "b") of the considered processes. From equations (6)–(8), (11), (12), and (14), it follows that

$$X^{(ab)}_{ir;a}(n, T) = \frac{K_i^{(a)}(n, T)}{K_i^{(ab)}(n, T)} = \frac{K_r^{(a)}(n, T)}{K_r^{(ab)}(n, T)} . \tag{15}$$

The procedure to obtain chemi-ionization and chemi-recombination rate coefficients $K_i^{(a,b)}(n, T)$, $K_i^{(ab)}(n, T)$, $K_r^{(a,b)}(n, T)$, and $K_r^{(ab)}(n, T)$ is described in detail in Mihajlov et al. (1997a), and the final expressions are

$$K_i^{(a,b)}(n, T) = \frac{2\pi}{3^{3/2}} n^{-5} a_0^2 v_0 \int_{R_{\min}}^{R_n} \exp\left[\frac{-U_2(R)}{kT}\right] \times X^{(a,b)}(R, T) \frac{R^4 dR}{a_0^5} , \tag{16}$$

$$K_i^{(ab)}(n, T) = \frac{2\pi}{3^{3/2}} n^{-5} a_0^2 v_0 \int_{R_{\min}}^{R_n} \exp\left[\frac{-U_2(R)}{kT}\right] \frac{R^4 dR}{a_0^5} , \tag{17}$$

$$K_r^{(a,b)}(n, T) = \frac{(2\pi)^{5/2}}{3^{3/2}} \frac{(\hbar e a_0)^2}{(mkT)^{3/2}} n^{-3} \exp\left(\frac{I_n}{kT}\right) \times \int_{R_{\min}}^{R_n} \exp\left[\frac{U_{12}(R)}{kT} - \frac{U_1(R)}{kT}\right] \times X^{(a,b)}(R, T) \frac{R^4 dR}{a_0^5} , \tag{18}$$

$$K_r^{(ab)}(n, T) = \frac{(2\pi)^{5/2}}{3^{3/2}} \frac{(\hbar e a_0)^2}{(mkT)^{3/2}} n^{-3} \exp\left(\frac{I_n}{kT}\right) \times \int_{R_{\min}}^{R_n} \exp\left[\frac{U_{12}(R)}{kT} - \frac{U_1(R)}{kT}\right] \times X^{(ab)}(R, T) \frac{R^4 dR}{a_0^5} . \tag{19}$$

The variable I_n denotes the ionization energy of $He^*(n)$ atoms, $U_{12}(R) = U_2(R) - U_1(R)$, R is the internuclear distance, and $U_1(R)$ and $U_2(R)$ are the ground and first excited electronic states of the molecular ion He_2^+ (see Gupta & Madsen 1967). The upper integration limit R_n is the largest root of the equation: $U_{12}(R) = I_n$, and its values for different n can be found in Mihajlov et al. (1997a). The lower integration limit, $R_{\min} = 1$, is determined empirically. The functions $X^{(a)}(R, T)$ and $X^{(b)}(R, T)$ are defined by relations $X^{(a)}(R, T) = \gamma(3/2; \ -U_1(R)/kT)/\Gamma(3/2)$ if $U_1(R) < 0$, where $\gamma(x; \ y)$ and $\Gamma(x)$ are incomplete and complete gamma functions, and $X^{(a)}(R, T) = 0$ if $U_1(R) \geq 0$, and $X^{(b)}(R, T) = 1 - X^{(a)}(R, T)$.

The total chemi-ionization and chemi-recombination rate coefficients, $K_i^{(ab)}(n, T)$ and $K_r^{(ab)}(n, T)$, in the temperature range $7000\ \mathrm{K} \leq T \leq 30{,}000\ \mathrm{K}$ and principal quantum numbers $n = 3$–10, are shown in Figures 1 and 2. The curves $K_i^{(ab)}(n = 3, T)$ and $K_i^{(ab)}(n = 4, T)$ in Figure 1 show an intersection close to the lower limit (7000 K) of the considered temperature range. The intersection occurs because processes (1a)–(1b) have an energy threshold which increases when n decreases. Because of this, when T decreases every rate coefficient $K_i^{(ab)}(n, T)$ decreases faster than any other rate coefficient $K_i^{(ab)}(n', T)$ with $n' > n$, and in domains of sufficiently low temperatures the intersection of the curves occurs.

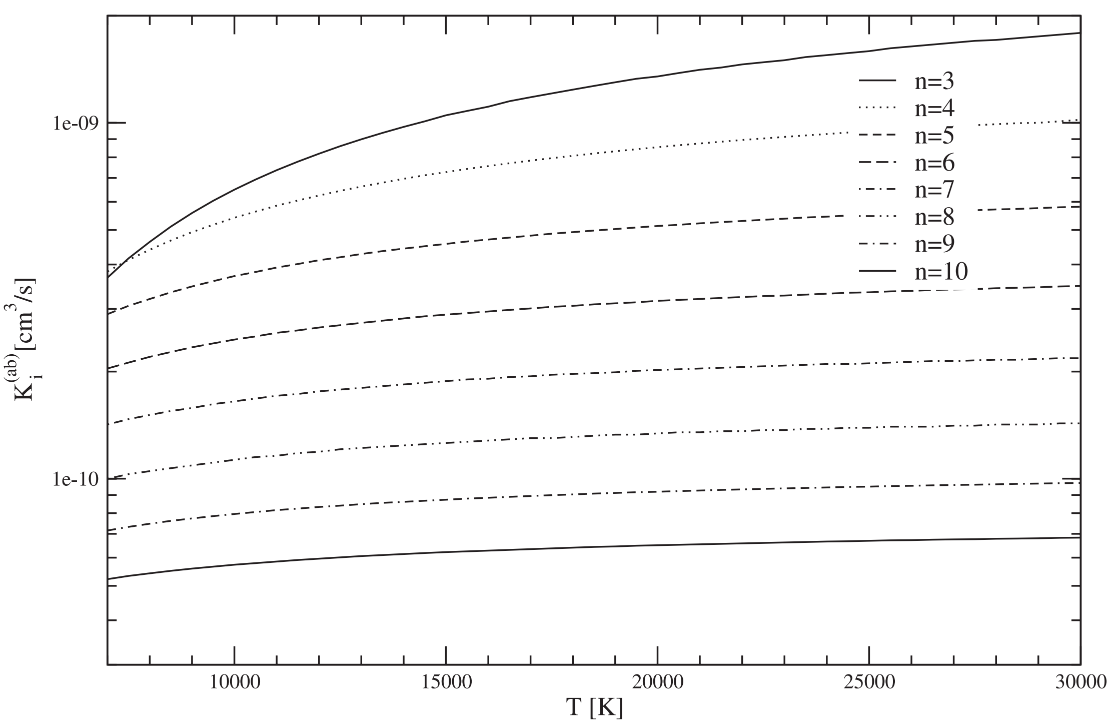

FIG. 1.—Total chemi-ionization rate coefficients, $K_i^{(ab)}(n, \ T)$, with $7000\ \mathrm{K} \leq T \leq 30{,}000\ \mathrm{K}$ and for principal quantum numbers $n = 3$–10

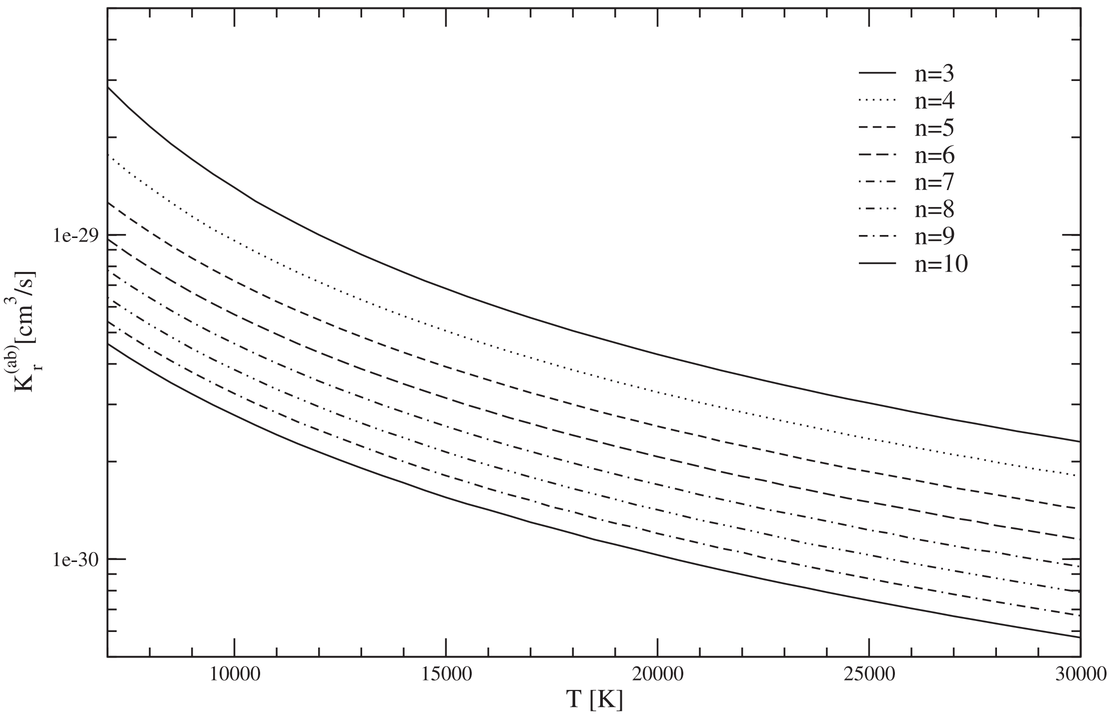

FIG. 2.—Same as in Fig. 1 but for the total chemi-recombination rate coefficients $K_r^{(ab)}(n,\ T)$

The function $X_{ir;a}^{(ab)}(n, T)$ is shown in Figure 3. From this figure and the definition of $X_{ir;b}^{(ab)}(n, T)$ it can be seen that the values of both parameters, in the temperature range $7000\ \mathrm{K} \leq T \leq 30,000\ \mathrm{K}$, are of the same order of magnitude. Consequently, in a given temperature domain the contributions of " a " and " b " channels of chemi-ionization (eqs. [1a]–[1b]) and chemi-recombination (eqs. [2a]–[2b]) processes in the population/depopulation of helium atom Rydberg states are comparable, which justifies the inclusion of both the " a " and " b " channels.

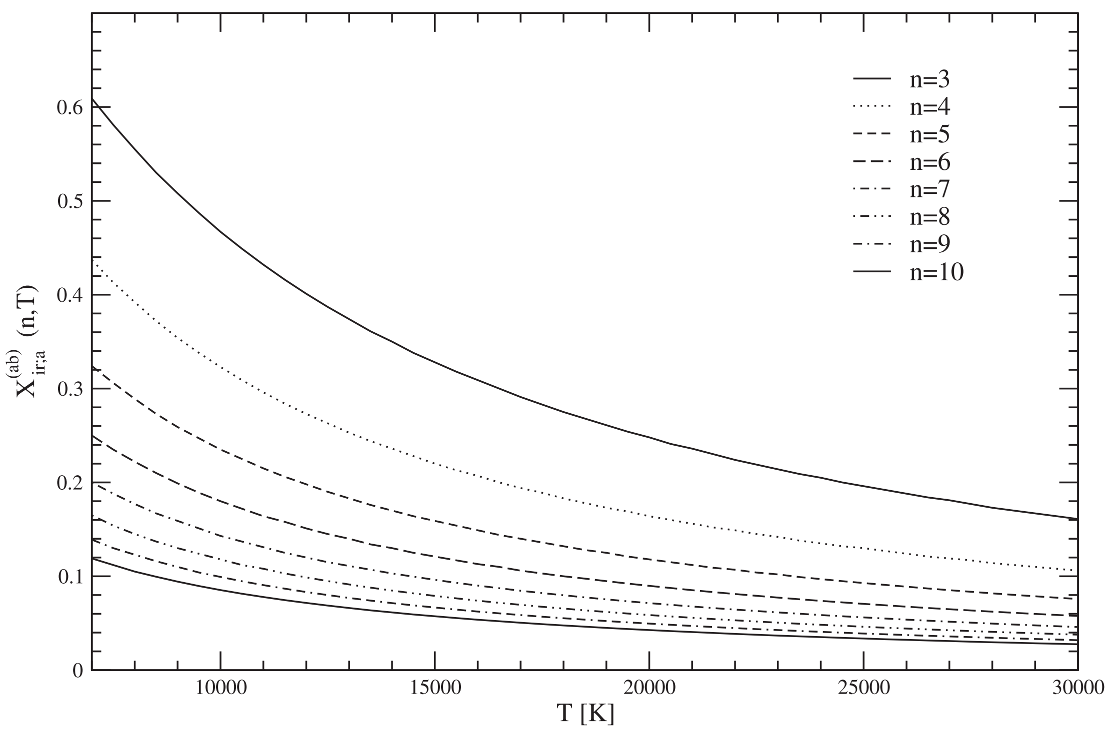

FIG. 3.—Same as in Fig. 1 but for the parameter $X_{ir;a}^{(ab)}(n,\ T)$, characterizing the relative importance of the particular channel (" a " and " b ") for the chemi-ionization and chemi-recombination processes.

2.2. *Other Ionization/Recombination Processes*

Fluxes generated in electron-excited atom impact ionization (eq. [3]) and electron-electron-ion recombination (eq. [4]) processes are given by expressions

$$I_i^{(ea)}(n, T) = \alpha_i^{(ea)}(n, T) \cdot N(\mathrm{He}^*(n)) \cdot N(e) , \qquad (20)$$

$$I_r^{(eei)}(n, T) = \alpha_r^{(eei)}(n, T) \cdot N(\mathrm{He}^+) \cdot N(e) \cdot N(e) , \qquad (21)$$

and the ionization and recombination rate coefficients $\alpha_i^{(ea)}(n, T)$ and $\alpha_r^{(eei)}(n, T)$ are determined by semiempirical expressions from Vriens & Smeets (1980).

Fluxes generated in electron-ion photorecombination (eq. [5]) processes are given by the expression

$$I_{\mathrm{phr}}^{(ei)}(n, T) = \alpha_{\mathrm{phr}}^{(ei)}(n, T) \cdot N(\mathrm{He}^+) \cdot N(e) , \qquad (22)$$

and the photorecombination rate coefficients $\alpha_{\mathrm{phr}}^{(ei)}(n, T)$ could be determined in accordance with Sobel'man (1979). However, these constants are determined here using relations found in our previous work on collisional ion-atom radiative processes (Mihajlov, Dimitrijević, & Ignjatović 1993; Mihajlov et al. 1995).

3. RESULTS AND DISCUSSION

The relative importance of chemi-ionization (eqs. [1a]–[1b]) and chemi-recombination (eqs. [2a]–[2b]) processes in comparison with electron-excited atom impact ionization (eq. [3]), electron-electron-ion recombination (eq. [4]) and electron-ion photorecombination (eq. [5]) processes is characterized by parameters $F_{ir}^{(ab)}(n, T)$ and $F_{\mathrm{phr}}^{(ab)}(n, T)$, defined as ratios of the corresponding fluxes:

$$F_{ir}^{(ab)}(n, T) = \frac{I_i^{(ab)}(n, T)}{I_i^{(ea)}(n, T)} = \frac{I_r^{(ab)}(n, T)}{I_r^{(eei)}(n, T)} ,$$

$$F_{\mathrm{phr}}^{(ab,ei)}(n, T) = \frac{I_r^{(ab)}(n, T)}{I_{\mathrm{phr}}^{(ei)}(n, T)} . \qquad (23)$$

From equations (11)–(12) and (20)–(23), it follows that these parameters can be shown in the form

$$F_{ir}^{(ab)}(n, T) = \frac{K_i^{(ab)}(n, T)}{\alpha_i^{(ea)}(n, T)} \cdot \eta_e^a = \frac{K_r^{(ab)}(n, T)}{\alpha_r^{(eei)}(n, T)} \cdot \eta_e^a , \qquad (24)$$

$$F_{\mathrm{phr}}^{(ab,ei)}(n, T) = \frac{K_r^{(ab)}(n, T) \cdot N(\mathrm{He})}{\alpha_{\mathrm{phr}}^{(ei)}(n, T)} , \qquad (25)$$

where η_e^a denotes He atom and free electron densities ratio

$$\eta_e^a = \frac{N(\mathrm{He})}{N(e)} . \qquad (26)$$

In the case of the DB white dwarf photosphere, all parameters have been determined for $12,000\ \mathrm{K} \le T_{\mathrm{eff}} \le 30,000$ K and $\log g = 7$ and 8. The results presented are for the temperature range $12,000\ \mathrm{K} \le T_{\mathrm{eff}} \le 24,000$ K and $\log g = 8$. The value of $\log g$ is chosen following Mihajlov et al. (1995), where the same DB white dwarf models have been analyzed with respect to radiative ion-atom collisional processes. The results for $\log g = 7$ are qualitatively the same. For temperatures $T_{\mathrm{eff}} > 24,000$ K, electron-excited atom impact ionization (eq. [3]) and electron-electron-ion recombination processes (eq. [4]) are dominant. The processes considered here are compared via parameters $F_{ir}^{(ab)}(n, T)$ and $F_{\mathrm{phr}}^{(ab)}(n, T)$, and the corresponding results are shown in Figures 4–7 and Figures 8–9, respectively. These parameters are shown as functions of $\log \tau$, where τ is the Rosseland optical depth. Temperatures and atom and electron densities needed to determine $F_{ir}^{(ab)}(n, T)$ and $F_{\mathrm{phr}}^{(ab)}(n, T)$ for given τ have been taken from Koester's (1980) DB white dwarf models for given T_{eff} and $\log g$ values. Figures 4, 5, 6, and 7 are related to $T_{\mathrm{eff}} = 12,000$, 14,000, 16,000, and 18,000 K, while Figures 8 and 9 are related to $T_{\mathrm{eff}} = 12,000$ and 24,000 K, respectively.

Our results show that for the lower temperatures the chemi-ionization (eqs. [1a]–[1b]) and chemi-recombination (eqs. [2a]–[2b]) processes are absolutely dominant over electron-excited atom ionization (eq. [3]) and electron-electron-atom recombination (eq. [4]) processes, for $n = 3$, 4, and 5 for almost all $\log \tau < 0$ values. For $n = 6$, 7, and 8 and in the same $\log \tau$ range, processes (1a)–(2b) are comparable with processes (3) and (4). This is illustrated in Figures 4 and 5, where $T_{\mathrm{eff}} = 12,000$ and 14,000 K. With the increase of temperature the influence of processes (1a)–(2b) decreases, which is manifested by the decrease of the $F_{ir}^{(ab)}(n, T)$ values. For example, $F_{ir}^{(ab)}(n, T)$ values for $n = 3$ and 4 decrease from $\sim 10^2$ for $T_{\mathrm{eff}} = 12,000$ K and ~ 10 for $T_{\mathrm{eff}} = 16,000$ K, down to ~ 0.1 for $T_{\mathrm{eff}} = 20,000$ K and ~ 0.01 for $T_{\mathrm{eff}} = 24,000$ K. This behavior indicates the effective temperature range where it is particularly important to take into account processes (1a)–(2b) for correct calculations of excited helium atom state populations.

It should be noted that the increase/decrease of populations with a principal quantum number n for considered plasma conditions causes the population increase/decrease of all states with a principal quantum number larger than n. Consequently, the increase/decrease of the populations with $3 \le n \le 8$ due to chemi-ionization (eqs. [1a]–[1b]) and chemi-recombination (eqs. [2a]–[2b]) processes causes an increase/decrease of all excited states' populations with $n > 8$, for the temperature and free electron density corresponding to the given $\log \tau$.

Regarding the relative importance of chemi-recombination (eqs. [2a]–[2b]) processes in comparison with photorecombination (eq. [5]), our results show that processes (2a)–(2b) are dominant within the whole effective temperature range $12,000\ \mathrm{K} \le T_{\mathrm{eff}} \le 30,000$ K for $n > 4$ within the $\log \tau > -3$ range. For $n = 3$ and 4 the processes (1a)–(2b) are dominant within the $\log \tau > -4$ range. These results are illustrated in Figures 8 and 9, with $T_{\mathrm{eff}} = 12,000$ and 24,000 K.

Functions $F_{ir}^{(ab)}$ and $F_{\mathrm{phr}}^{(ab)}$ have several shallow local minimums/maximums, mainly in the range $\log(\tau) \in (-3,\ -2)$. This behavior was notified and analyzed in detail with respect to $\mathrm{He}^+ + \mathrm{He}$ radiative collisional processes in the same plasma (Mihajlov et al. 1995). The local oscillations of functions $F_{ir}^{(ab)}$ and $F_{\mathrm{phr}}^{(ab)}$ are caused by the temperature oscillations in helium-rich DB white dwarf plasma models, defined in Koester (1980) and used in this paper. Relatively small temperature fluctuations can produce the following effects: (*a*) pronounced oscillations in particles' densities because of the high ionization potential of helium atoms and (*b*) changes in rate coefficient values for all ionization/

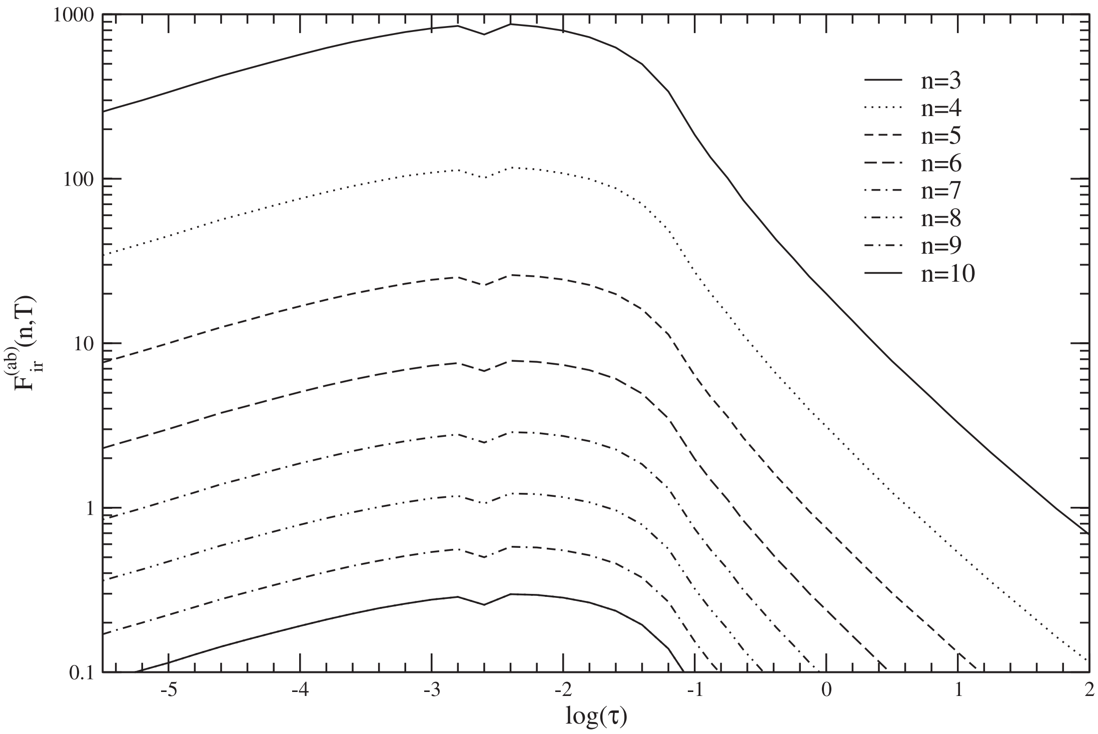

FIG. 4.—Parameter $F_{ir}^{(ab)}(n,\ T)$ as a function of the logarithm of Rosseland optical depth $\log\tau$, for principal quantum numbers $n = 3$–10, with $T_{\rm eff} = 12,000$ K and $\log g = 8$.

recombination processes considered. This is shown in Figures 4–9.

The presented results show a considerably greater influence of the chemi-ionization (eqs. [1a]–[1b]) and chemi-recombination (eqs. [2a]–[2b]) processes on populations of highly excited atomic states in the case of a helium-rich DB white dwarf atmosphere than in the case of the solar atmosphere (Mihajlov et al. 1997b). The reason for this is much

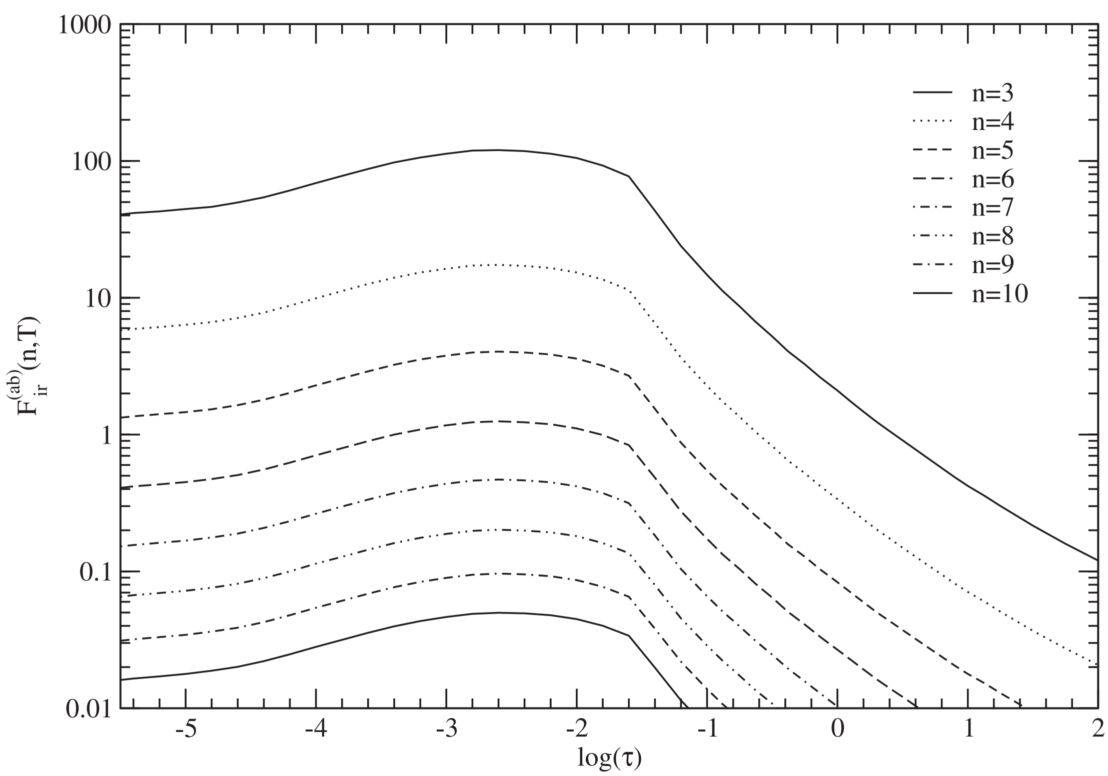

FIG. 5.—Same as in Fig. 4 but for $T_{\rm eff} = 14,000$ K

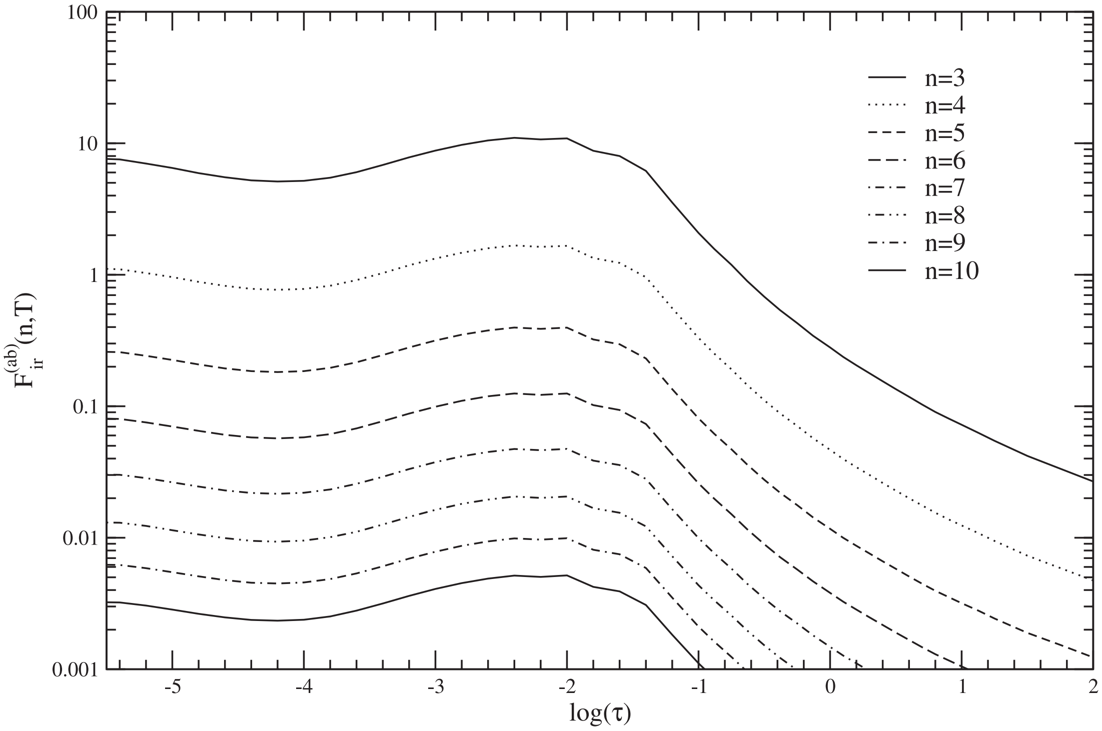

FIG. 6.—Same as in Fig. 4 but for $T_{\rm eff} = 16,000$ K

larger neutral atom densities in the DB white dwarf atmosphere than in the solar photosphere, which react with the same densities of free electrons. This is the consequence of a much higher (for almost 11 eV) ionization potential of helium atoms than of hydrogen. Therefore, for the same pressures and temperatures (~10,000 K) the ionization degree of the helium plasma is several orders of magnitude lower than that of the hydrogen plasma.

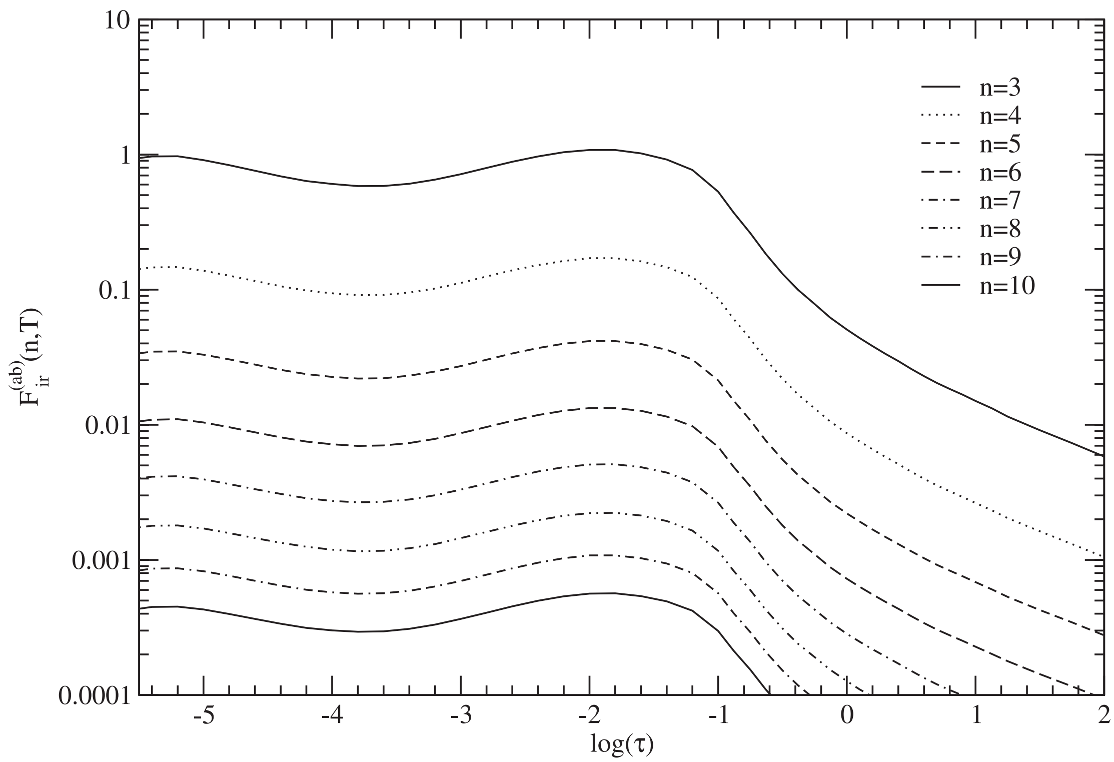

FIG. 7.—Same as in Fig. 4 but for $T_{\rm eff} = 18,000$ K

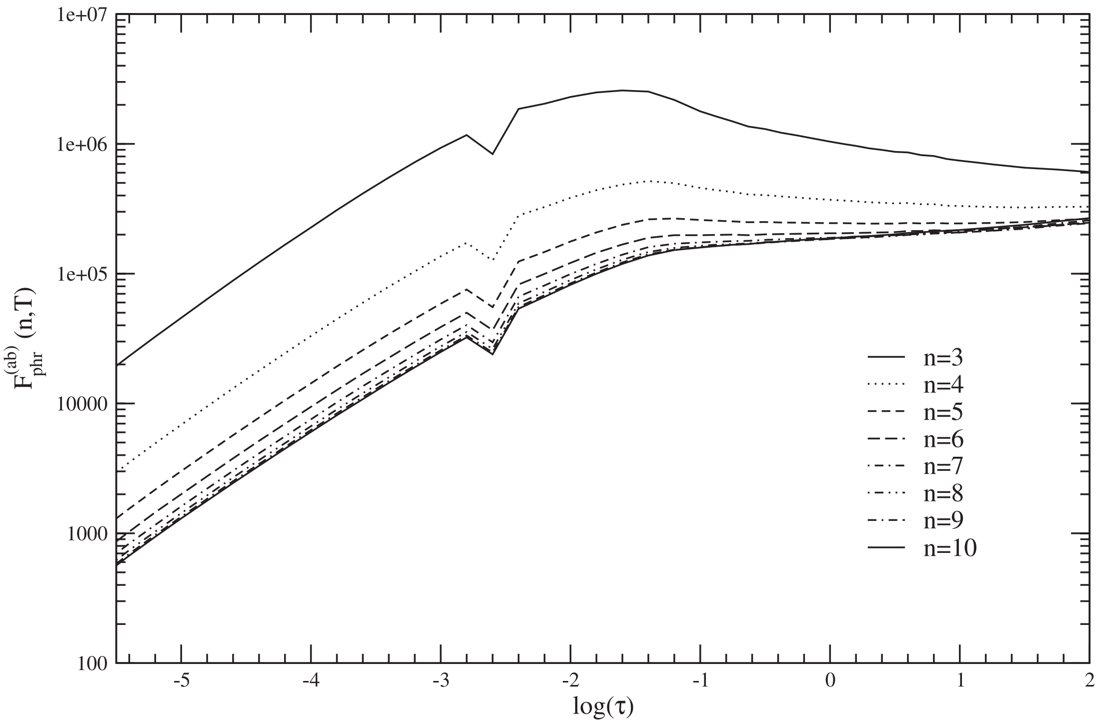

FIG. 8.—Parameter $F_{phr}^{(ab)}(n, T)$ as a function of the logarithm of Rosseland optical depth $\log \tau$, for principal quantum numbers $n = 3$–10, with $T_{eff} = 12,000$ K and $\log g = 8$.

4. CONCLUSION

The influence of the chemi-ionization (eqs. [1a]–[1b]) and chemi-recombination (eqs. [2a]–[2b]) processes shown in this paper must be taken into account for the ab initio modeling of helium-rich DB white dwarf atmospheres, for $\log g = 7$ and 8 and $T_{eff} \leq 20,000$ K, since they would influence the basic structure of the atmosphere model. These results and similar ones for hydrogen solar plasma (Mihajlov et al. 1997b) clearly proved the importance of the symmetrical chemi-ionization and chemi-recombination processes in weakly ionized layers of stellar atmospheres.

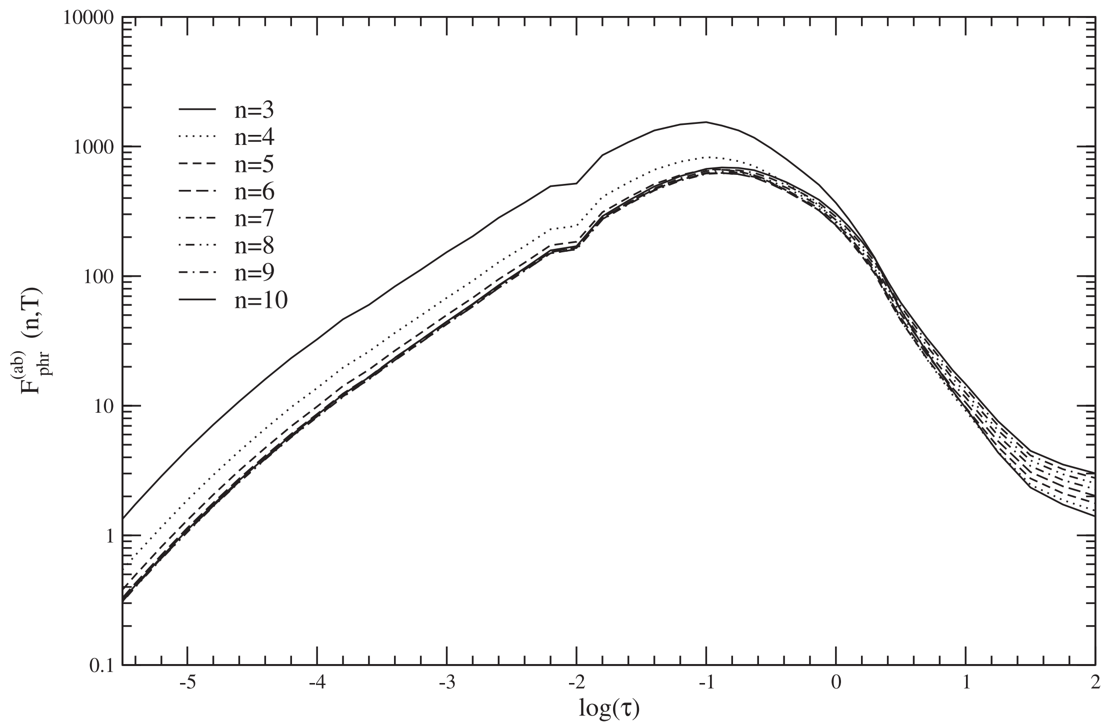

FIG. 9.—Same as in Fig. 8 but for $T_{eff} = 24,000$ K

Further investigations of these processes should be performed by including them in sophisticated stellar atmosphere models and corresponding computing codes.

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