

Helium-rich white dwarf atmospheres: the non-symmetric ion-atom absorption processes

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Abstract.

Here, the processes of photo-association and absorption charge-exchange in $\text{He} + \text{H}^+$ collisions together with the process of molecular ion HeH^+ photo-dissociation are considered as factors of influence on the opacity of the atmospheres of helium-rich white dwarfs in the far UV region. It is shown that they should be taken into account even in the cases of the atmospheres of white dwarfs with $\text{H}:\text{He} = 10^{-5}$. Also, it is established that in the cases of white dwarfs with $\text{H}:\text{He} \gtrsim 10^{-4}$, especially when $\text{H}:\text{He} \approx 10^{-3}$, these processes have to be included *ab initio* in the corresponding models of their atmospheres.

1. Introduction

This paper is a continuation of our work about some atomic collision processes in white dwarfs atmospheres [1] and transport properties in it [2]. Recently it has been shown in [3, 4, 5, 6], that in order to consider the contribution of the absorption processes connected with binary ion-atom systems to the opacity of the solar photosphere it is not enough to take into account only the processes of absorption charge exchange in $(\text{H} + \text{H}^+)$ -collisions and the molecular ion H_2^+ photo-dissociation. It has been established that in the very important far UV and EUV spectral regions they have to be considered together with the processes of the absorption charge exchange and photo-association in non-symmetric $(\text{H} + \text{X}^+)$ -collisions and molecular ion HX^+ photo-dissociation, where X is one of metal atoms. Namely, it has been proved that only in such case the total efficiency of the ion-atom absorption processes in the mentioned spectral regions approaches the efficiency of the relevant concurrent processes in the whole solar photosphere.

Results from these papers suggest that it is useful to consider again the situation of ion-atom absorption processes in the atmospheres of helium-rich white dwarfs. Let us remind that in the previous papers (see e.g. [7]), dedicated to some DB white dwarf atmospheres (where "D" stands for "degenerate" or "dwarf" and B-stand for spectral type classification where helium lines dominate), the processes of absorption charge exchange in $(\text{He} + \text{He}^+)$ -collisions:



and the processes of molecular ion He_2^+ photo-dissociation were studied



Here ε_λ is the energy of a photon with wavelength λ , $\text{He} = \text{He}(1s^2)$, $\text{He}^+ = \text{He}^+(1s)$ and $\text{He}_2^+ = \text{He}_2^+(1^2\Sigma_u^+)$. By a direct comparison of their efficiencies with the main concurrent process of inverse "bremsstrahlung" in (free electron + He)-collisions, i.e.

$$\varepsilon_\lambda + e + \text{He} \longrightarrow e' + \text{He}, \quad (3)$$

the significance of these symmetric ion-atom absorption processes for the atmospheres of the considered DB white dwarfs was established in [7].

It was established that the processes given by Eqs. (1) and (2) significantly influence the opacity of the considered DB white dwarf atmospheres, with an effective temperature $T_{eff} \geq 12000$ K. But, the same comparison demonstrated also that the dominant role in those atmospheres generally still belongs to the concurrent absorption process given by Eq. (3), while the processes (1) and (2) can be treated as dominant (with respect to this concurrent process) only in some layers of that atmospheres, and only within the part $50 \text{ nm} < \lambda < 250 \text{ nm}$ of the far UV and EUV region.

Hence it follows that in the case of helium-rich white dwarf atmospheres it would certainly be useful to include into consideration some new ion-atom absorption processes, which is principally allowed in accordance with the composition of such atmospheres.

Here we will examine the significance of non-symmetric ion-atom absorption processes with participation of the hydrogen component. We mean the processes of molecular ion HeH^+ photo-dissociation

$$\varepsilon_\lambda + \text{HeH}^+ \longrightarrow \text{He}^+ + \text{H} \quad (4)$$

and the processes of absorption charge exchange and photo-association in the $(\text{He} + \text{H}^+)$ -collisions, namely

$$\varepsilon_\lambda + \text{He} + \text{H}^+ \longrightarrow \text{He}^+ + \text{H}, \quad (5)$$

$$\varepsilon_\lambda + \text{He} + \text{H}^+ \longrightarrow (\text{HeH}^+)^*, \quad (6)$$

where $\text{H} = \text{H}(1s)$, $\text{He} = \text{He}(1s^2)$, $\text{He}^+ = \text{He}^+(1s)$, and HeH^+ and $(\text{HeH}^+)^*$ denote the molecular ion in the ground and the first excited electronic states which are adiabatically correlated with the states of the systems $\text{He} + \text{H}^+$ and $\text{He}^+ + \text{H}$ respectively at the infinite internuclear distance. Already in [3] it was noted that these processes, whose significance was practically neglected for the solar photosphere, could be rather important in the case of helium-rich white dwarf atmospheres.

The main aim was to study when the non-symmetric absorption processes given by Eqs. (4) - (6) can significantly influence the opacity of helium-rich white dwarf atmospheres in UV and EUV spectral region, and to show that the processes (4) - (6) deserve to be included *ab initio* in the corresponding white dwarf atmosphere models.

Therefore the relevant spectral characteristics of the processes given by Eqs. (4) - (6) are determined here for the atmospheres of different helium-rich white dwarfs with $T_{eff} = 12000$ K and 14000 K, $\log g = 8$ and 7 , and for the values of the ratio $\text{H}:\text{He}$ from 10^{-5} to 10^{-3} . The necessary expressions for these spectral characteristics are given in Section 2. Then, with their help, in the Section 3 the values are calculated of the parameters characterizing the relative efficiency of the non-symmetric processes given by Eqs. (4) - (6) with respect to the efficiency of all ion-atom processes, as well as with respect to the electron-atom process given by Eq. (3), which comprise the main direct results of this work.

Here, beside the electron-atom processes given by Eq. (3) the process of photoionization of hydrogen atoms, is also considered, namely

$$\varepsilon_\lambda + \text{H} \longrightarrow e + \text{H}^+, \quad (7)$$

where $H=H(1s)$. It was treated as a concurrent process, potentially necessary in the region $\lambda < \lambda_H$ where $\lambda_H \approx 91.1$ nm corresponds to the threshold of atom H photoionization. That is why in this work the process given by Eq. (7) was again included into the consideration and carefully examined.

One can see that in this work we take into account only such non-symmetric ion-atom absorption processes where, apart from the dominant helium component of the considered atmospheres, only the hydrogen component participates, although they contain also a lot of metal components [8]. This is due to the fact that the existing atmosphere models do not provide the necessary data (about the relevant metals' abundances) which would be needed for the present calculations.

2. The relevant spectral characteristics

2.1. The symmetric ion-atom, electron-atom and hydrogen photo-ionization processes

We have to introduce the spectral coefficients $\kappa_{sim}(\lambda; \log \tau)$, $\kappa_{e-He}(\lambda; \log \tau)$ and $\kappa_{phi}(\lambda; \log \tau)$ which characterize the efficiencies of the symmetric ion-atom absorption processes given by Eqs. (1) and (2) together, the electron-atom processes Eq. (3) and hydrogen photoionization process Eq. (7) respectively. As in [7] we can take these coefficients in the known form:

$$\kappa_{sim}(\lambda; \log \tau) = K_{sim}(\lambda, T) \cdot N_{He} \cdot N_{He^+}, \quad (8)$$

$$\kappa_{e-He}(\lambda; \log \tau) = K_{e-He}(\lambda, T) \cdot N_{He} \cdot N_e, \quad (9)$$

$$\kappa_{phi}(\lambda; \log \tau) = \sigma_{phi}(\lambda; H) \cdot N_H, \quad (10)$$

where N_{He^+} , N_e and N_H are the local densities of ions He^+ , free electrons and atoms H, $K_{sim}(\lambda, T)$ and $K_{e-He}(\lambda, T)$ - adequately defined spectral rate coefficients, and $\sigma_{phi}(\lambda; H)$ - spectral cross-section for atom H photoionization. The absorption coefficient $K_{sim}(\lambda, T)$ is determined in the way which is described in detail in [7], and $K_{e-He}(\lambda, T)$ - by means of the data from [9], and $\sigma_{phi}(\lambda; H)$ is taken from [10].

Here we take into account the fact that all the values of the rate coefficients $K_{sim}(\lambda, T)$ and $K_{e-He}(\lambda, T)$ which are needed for our calculations have already been determined in [7], and that the photo-ionization cross-section $\sigma_{phi}(\lambda; H)$ is given by a known analytical expression. Therefore in the further text we will simply treat these characteristics and, consequently, the spectral absorption coefficients $\kappa_{sim}(\lambda, \log \tau)$, $\kappa_{e-He}(\lambda, \log \tau)$ and $\kappa_{phi}(\lambda; \log \tau)$ as known quantities.

2.2. The non-symmetric ion-atom processes

As the relevant characteristics of the processes given by Eqs. (4), (5) and (6) we will use the corresponding spectral absorption coefficients. They are defined as functions of $\log \tau$, where τ is Rosseland optical depth of the part of the examined atmosphere above the considered layer for the wavelength λ . They are denoted here as $\kappa_{nsim}^{(bf)}(\lambda; \log \tau)$, $\kappa_{nsim}^{(ff)}(\lambda; \log \tau)$ and $\kappa_{nsim}^{(fb)}(\lambda; \log \tau)$, in accordance with the fact that the mentioned processes can be treated as bound-free, free-free and free-bound respectively. These coefficients are determined here within the corresponding atmosphere models, by means of the local temperature and the densities of He atoms and H^+ ions, and used in a similar form, namely

$$\kappa_{nsim}^{(bf,ff,fb)}(\lambda; \log \tau) = K_{nsim}^{(bf,ff,fb)}(\lambda; T) N_{He} N_{H^+}, \quad (11)$$

where $T \equiv T(\log \tau)$, $N_{He} \equiv N_{He}(\log \tau)$ and $N_{H^+} \equiv N_{H^+}(\log \tau)$. It is understood that the photo-dissociation rate coefficient $K_{nsim}^{(bf)}(\lambda; T)$ is given by the known relations

$$K_{nsim;X}^{(bf)}(\lambda; T) = \sigma_{HeH^+}^{(phd)}(\lambda, T) \cdot \chi^{-1}(T; HeH^+), \quad (12)$$

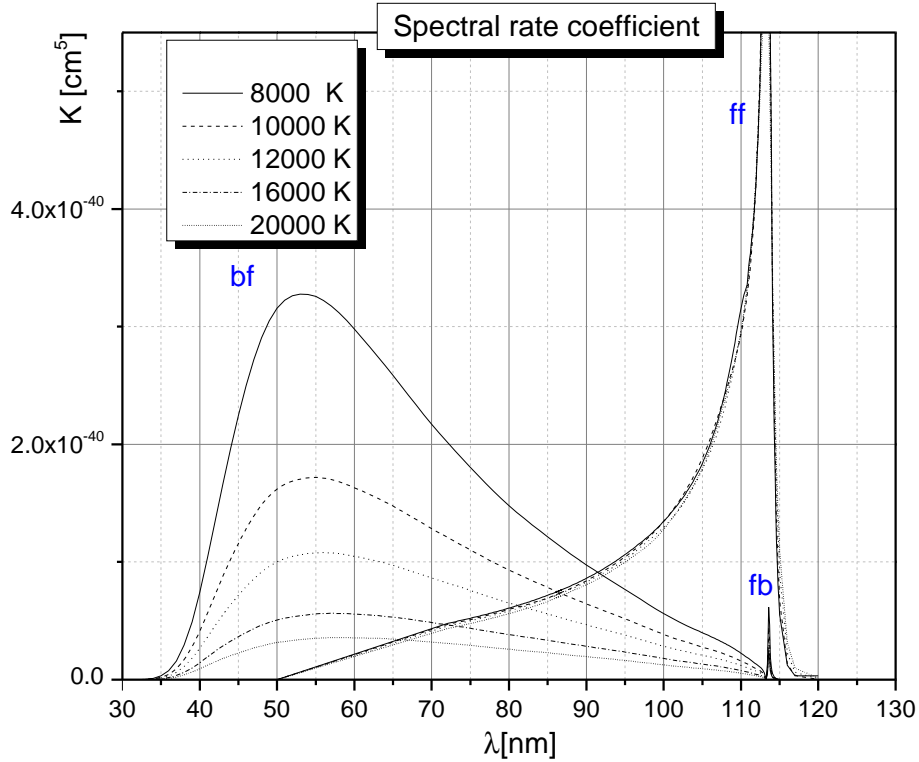


Figure 1. The plots of the bound-free (bf), free-free (ff) and free-bound (fb) spectral rate coefficients $K_{HeH^+}^{(bf,ff,fb)}(\lambda; T)$ for the molecular ion HeH^+ .

$$\chi(T; HeH^+) = \left[\frac{N_{He} \cdot N_{H^+}}{N_{HeH^+}} \right], \quad (13)$$

where $\sigma_{HeH^+}^{(phd)}(\lambda, T)$ is the mean thermal cross-section for the molecular ion HeH^+ photo-dissociation, N_{HeH^+} denotes the local density of these molecular ions, and $\chi(T; HeH^+)$ is determined under condition of local thermodynamical equilibrium (LTE) with given T , N_{He} and N_{H^+} . Let us note that these expressions contain no correction factors which take into account the influence of stimulated emission, since within the actual range of ε_λ/kT ratio for the considered cases the changes due to these factors will be of the order of magnitude of $10^{-3}\%$.

The total efficiency of the non-symmetric processes given by Eqs. (4), (5) and (6) is characterized here by the spectral absorption coefficient $\kappa_{nsim}(\lambda; \log \tau)$ given by the relations

$$\kappa_{nsim}(\lambda; \log \tau) = K_{nsim}(\lambda; T) N_{He} N_{H^+}, \quad (14)$$

$$K_{nsim}(\lambda; T) = K_{nsim}^{(bf)}(\lambda; T) + K_{nsim}^{(ff)}(\lambda; T) + K_{nsim}^{(fb)}(\lambda; T), \quad (15)$$

where the rate coefficients $K_{nsim}^{(bf,ff,fb)}(\lambda, T)$ are determined by means of the necessary characteristics of the considered molecular ion, in a way which was described in detail in [3, 5, 4].

The adiabatic potential curves of the molecular ion in the ground state (HeH^+) and the first excited electronic state ($(HeH^+)^*$), as well as the corresponding dipole matrix element are determined by fitting the corresponding data from [11] and [12] (see [3]).

The behavior of the rate coefficients $K_{nsim}^{(bf,ff,fb)}(\lambda, T)$ is illustrated here by Fig. 1.

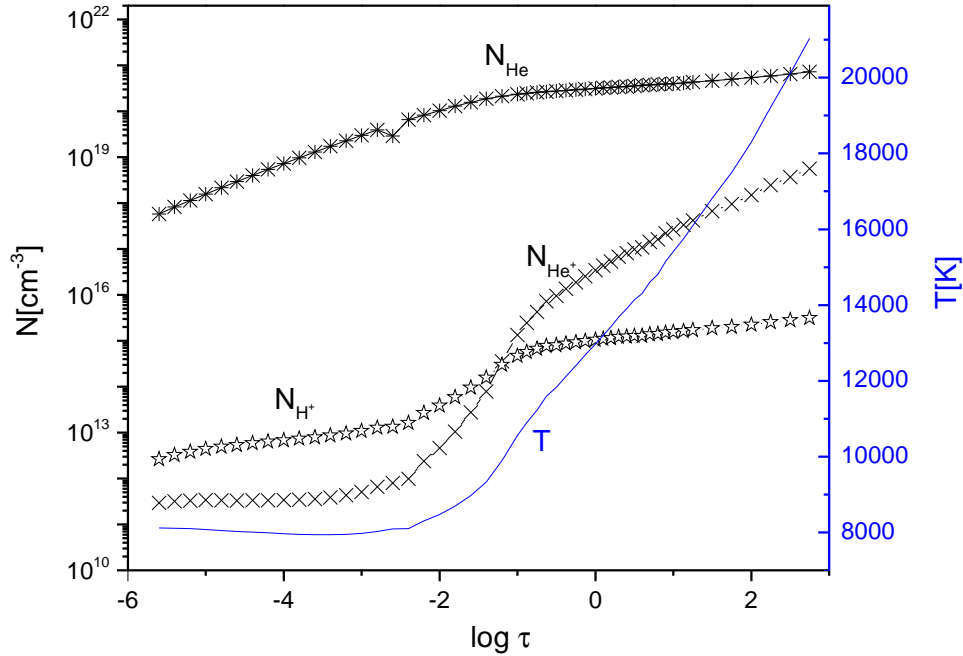


Figure 2. The local densities N_{He} , N_{He+} and N_{H+} and the temperature T as functions of $\log \tau$, where τ is Rosseland optical depth, according to the model of the DB white dwarf atmosphere from [13] for: $T_{eff}=12000$ K, $\log g = 8$ and $H:He=10^{-5}$.

3. Results and Discussion

3.1. DB white dwarfs

As it is well known, the above defined spectral absorption coefficients depend on the wavelength, local temperature, and local particle densities, based on the corresponding models of helium-rich white dwarf atmospheres characterized by certain values of T_{eff} , $\log g$ and the ratio of the hydrogen and helium species (H:He).

Here we will start from DB white dwarf atmospheres with $T_{eff} = 12000$ K and 14000 K, $\log g = 8$ and 7 and $H:He = 10^{-5}$. For the calculations we will use the equilibrium models which are presented in [13]. Although newer atmosphere models for helium-rich white dwarfs now exist (see e.g. the review article of [14]), only the models from [13] contain in a tabular form all the relevant data which are needed for our calculations.

The behavior of the densities of free electrons and ions He^+ and H^+ in the atmosphere of a DB white dwarf with $T_{eff} = 12000$ K and $\log g = 8$ is illustrated by Fig. 2, which shows that the processes given by Eqs. (4) - (6) could be of interest already in the case $H:He = 10^{-5}$. Namely, this figure suggests that for $T_{eff} \lesssim 14000$ K, the ion H^+ density is even larger than that of He^+ in significant parts of DB white dwarfs' atmospheres ($\log \tau < -1$).

In accordance with the aim of this work we have to estimate first the relative efficiency of the non-symmetric processes given by Eqs. (4) - (6) with respect to the total efficiency of all the above mentioned ion-atom absorption processes, which is characterized by the spectral

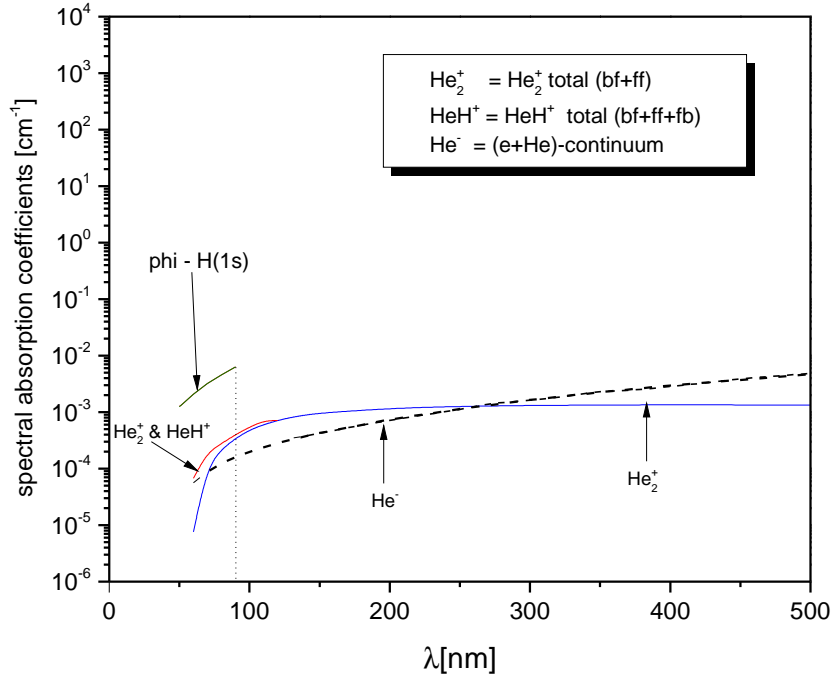


Figure 3. The plots of all considered absorption processes for $\log \tau = 0$ in the case of a DB white dwarf with $T_{eff}=12000$ K, $\log g = 8$ and $H:He=10^{-5}$, from [19].

absorption coefficient

$$\kappa_{ia}(\lambda; \log \tau) = \kappa_{nsim}(\lambda; \log \tau) + \kappa_{sim}(\lambda; \log \tau). \quad (16)$$

The results shows that the non-symmetric processes (4) - (6) are dominant within a significant part of the considered atmosphere ($-5.6 \leq \log \tau \lesssim -0.75$), which corresponds to the part in Fig. 2 where $N_{H^+} > N_{He^+}$.

In order to establish how the inclusion of the non-symmetric processes (4) - (6) into the consideration influences the relative efficiency of the ion-atom absorption processes with respect to the efficiency of the concurrent electron-atom process (3), we calculated their ratio.

The inclusion of the ion-atom non-symmetric absorption processes causes a very significant increase in the relative efficiency of the ion-atom absorption processes in just that region $\log \tau < 0.75$, i.e. where the symmetric processes can be practically neglected.

Then, we established the fact that the relative efficiency of the ion-atom absorption processes with respect to the efficiency of the concurrent is also similar in the cases of DB white dwarf atmospheres with the same value of $H:He$, but with $T_{eff} = 14000$ K and $\log g = 8$, and $T_{eff} = 12000$ K and $\log g = 7$. Based on the above mentioned, it can be concluded that the non-symmetric processes (4) - (6) have a visible significance for the atmospheres of the considered DB white dwarfs with $H:He= 10^{-5}$ and should be included in their models.

It is necessary to draw attention to the fact that this conclusion refers to a spectral region $\lambda > \lambda_H$ where the hydrogen photo-ionization process (7) is impossible. In order to estimate the partial efficiencies of the mentioned processes in the case of the considered DB white dwarf

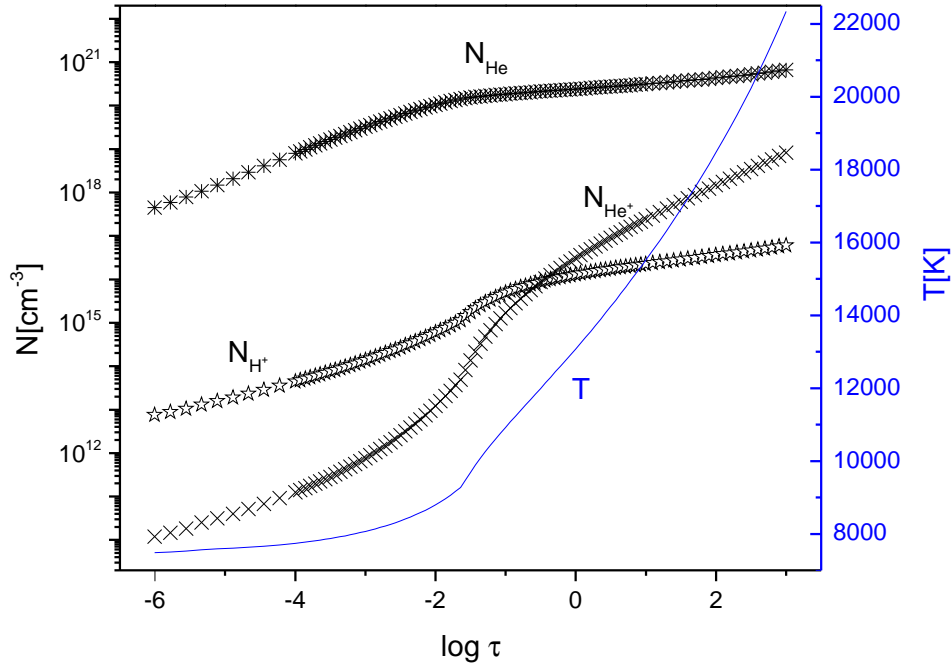


Figure 4. The local densities N_{He} , N_{He+} and N_{H+} , and the temperature T as functions of $\log \tau$, where τ is Rosseland optical depth, according to the developed model of helium-rich white dwarf atmosphere for: $T_{eff}=12000$ K, $\log g = 8$ and $H:He=10^{-4}$.

in the whole region $\lambda > \lambda_{He}$ the corresponding plots of all discussed absorption processes for $\log \tau = 0$ are presented in Fig. 3. From figure one can see that in the region $\lambda_{He} < \lambda < \lambda_H$ the process (7) alone gives the dominant contribution to the opacity of the considered atmosphere. Here it was established that in the considered case this dominance exists for any $\log \tau < 0$.

However, the main results of the research of DB white dwarf atmospheres is the establishment of the fact that the inclusion of the non-symmetric processes causes an increase of the total efficiency of ion-atom absorption processes in the region $0.75 < \log \tau < 2$, where the symmetric processes (1) and (2) are dominant, which is not negligible but rather reaches several percent.

3.2. Other cases of the helium rich white dwarfs.

The mentioned result is important for our further research since it leads to an expectation that the significance of the considered non-symmetric ion-atom absorption processes could be much greater in the cases of the atmospheres of some other helium-rich white dwarfs. We mean the atmospheres with the same or similar T_{eff} and $\log g$, but with the values of the ratio $H:He$ which are larger by one or even two orders of magnitude.

In this context let us note that in [15] some DC white dwarfs with $T_{eff} \approx 12500$ K, $\log g = 8$ and $H:He = 2 \cdot 10^{-4}$ are described. Then, in [16] some weakly magnetic DZ white dwarfs with $\log g = 8$, $T_{eff} \approx 7000$ K and $H:He \approx 10^{-3}$ are discussed. We will remind also that in [17] some DZ white dwarfs with $\log g \approx 8$, $T_{eff} > 12000$ K and $H:He = 10^{-4}$ and 10^{-3} are mentioned, as well as a number of other DZ white dwarfs with $\log g \approx 8$, the values of T_{eff} from about 6500 K to about 10000 K, and the values of $H:He$ from about $10^{-3.2}$ to about $10^{-4.4}$. From the above

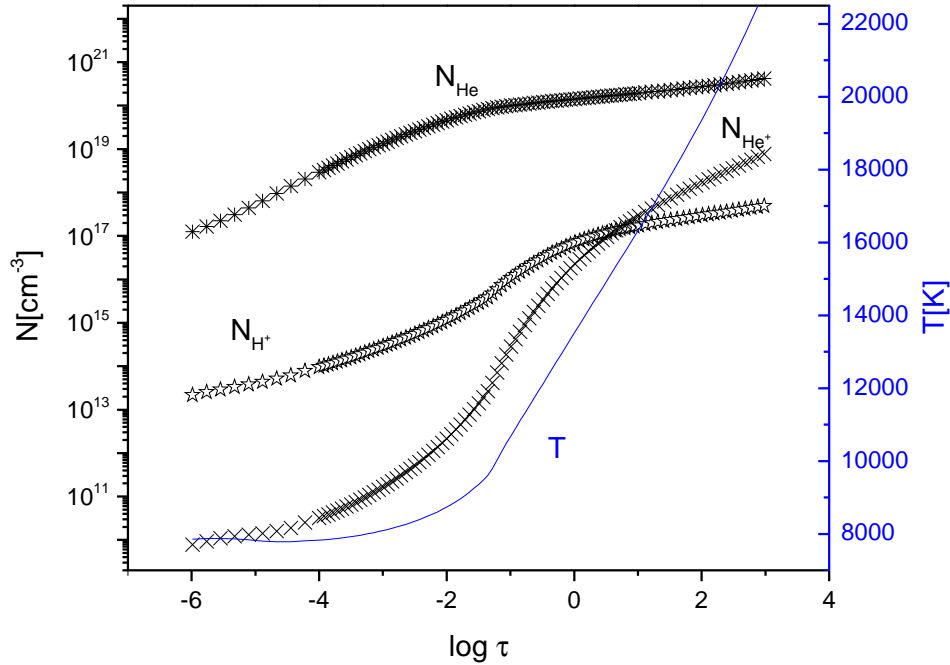


Figure 5. Same as in Fig. 4, but for H:He= 10^{-3} .

mentioned result it follows that the contribution of the non-symmetric processes given by Eqs. (4) - (6) to the opacity of such atmospheres should be very significant. Namely, although the ion H^+ density cannot increase proportionally to the ratio H:He, an increase of this ratio of 10 or 100 times, has to cause an increase of N_{H^+} of at least several times. So, the mentioned increase of several percent in region $-1 < \log \tau \leq 2$ in the case of DB white dwarf atmospheres has to become an increase of several tens of percent in the cases of the helium-rich white dwarfs with $10^{-4} \lesssim \text{H:He} \lesssim 10^{-3}$.

In order to check our expectations we performed calculations simulating the behavior of T , N_{He} , N_{H^+} and other particle densities, in helium-rich white dwarf atmospheres with $T_{eff} = 12000$ K, $\log g = 8$ and $\text{H:He} > 10^{-5}$. All the needed calculations have been performed on the basis of the models taken from [18]. In Figs. 4 and 5 the corresponding densities N_{H^+} , N_{He+} and N_e are shown as functions of $\log \tau$ for $\text{H:He} = 10^{-4}$ and 10^{-3} respectively. One can see, by comparing these figures and Fig. 2, that the considered increase of the ratio H:He indeed causes a very significant increase of N_{H^+} .

From these calculations one can see that for $\text{H:He} \gtrsim 10^{-4}$ the inclusion of the non-symmetric processes given by Eqs. (4) - (6) causes the ion-atom absorption processes to become absolutely dominant with respect to the electron-atom process (3) in the greatest part of this region, namely for $51 \text{ nm} \leq \lambda \lesssim 110 \text{ nm}$, while for $\lambda > 110 \text{ nm}$ the efficiency of ion-atom processes stays close to the efficiency of the process given by Eq. (3).

In order to obtain the complete picture of the discussed absorption processes in the helium-rich white dwarf atmospheres in the cases $\text{H:He} = 10^{-4}$ and 10^{-3} it is necessary again to include into the consideration the hydrogen photo-ionization process given by Eq. (7). The significance of partial absorption processes in such atmospheres within the whole region $\lambda > \lambda_{He}$ is illustrated

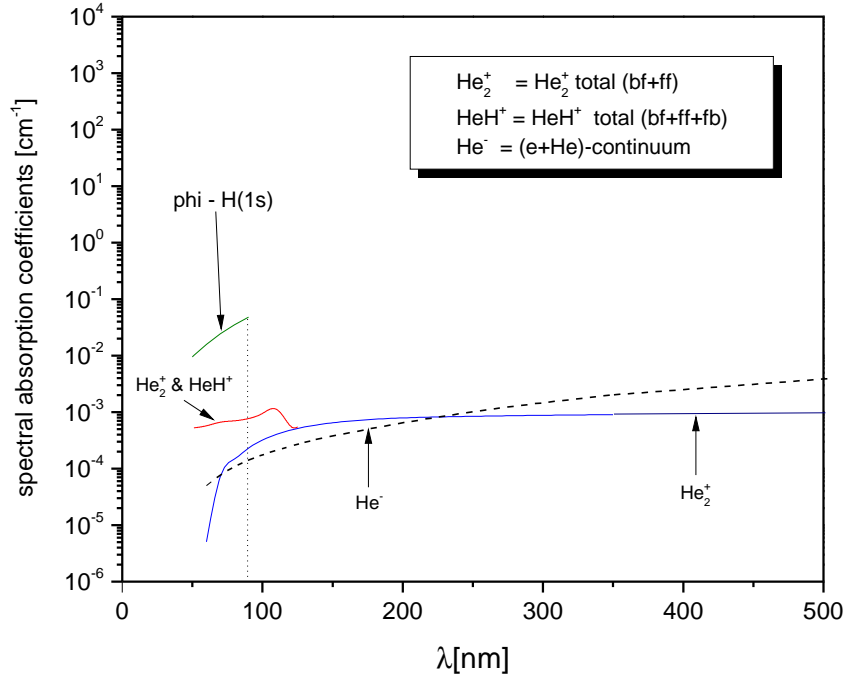


Figure 6. The plots of all considered absorption processes for $\log \tau = 0$ in the case of a helium-rich white dwarf with $T_{eff}=12000$ K, $\log g = 8$ and $H:He=10^{-4}$, from [19].

in Fig's 6 and 7 where the corresponding plots of these processes are presented for $\log \tau = 0$. One can see that, as in the case of DB white dwarf, the process (7) in the region $\lambda_{He} < \lambda < \lambda_H$ gives the dominant contribution to the opacity of the considered atmospheres. Then, it has been established that in these cases this dominance also holds for any $\log \tau < 0$.

In accordance with our considerations, it is necessary to remind that the considered ion-atom absorption processes (symmetric and non-symmetric) can naturally be significant in the helium-rich white dwarf atmospheres with $T_{eff} < 20000$ K, since at the higher temperatures electron-ion absorption processes completely dominate with respect to the considered ion-atom and electron-atom processes. Therefore, it is necessary here to take into account the papers [20] and [21], where the data about numerous helium-rich white dwarfs are presented. Namely, from these one can see that the values $H:He$ which correspond to the helium-rich white dwarfs with $T_{eff} < 20000$ K are mainly situated between 10^{-5} and 10^{-4} , while the values $H:He > 10^{-4}$, especially $H:He$ close to 10^{-3} , have to be treated as certain extremes. But our results are supported by the following facts: from the results obtained it follows that the non-symmetric ion-atom processes cannot be neglected already for the case of atmospheres of DB white dwarfs with $H:He=10^{-5}$, and from these results it follows that the effect of inclusion of the non-symmetric processes in the consideration fully manifests already for $H:He = 10^{-4}$, i.e. far from the extremum ($H:He=10^{-3}$, and remains practically the same further on. This makes important not just a neighborhood of the extremum value $H:He=10^{-3}$, but rather the whole region of $H:He > 10^{-5}$.

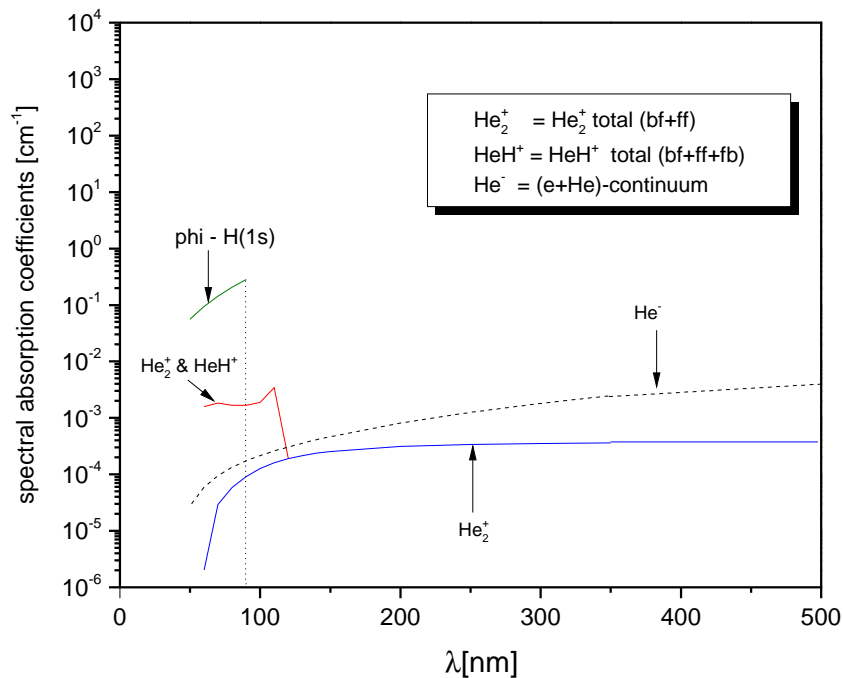


Figure 7. Same as in Fig. 6, but for H:He=10⁻³.

4. Conclusions

From the presented material it follows that the investigated non-symmetric ion-atom absorption processes have to be treated as one of the important channels of influence on the opacity of the atmospheres of helium-rich white dwarfs in the far UV and EUV region. So, it has been shown that even in the case of DB white dwarfs with H:He = 10⁻⁵ such processes should be included in the models of their atmospheres. However, the main result of this research is the establishment of the fact that in the cases of helium-rich white dwarfs with H:He > 10⁻⁵, and particularly with H:He = 10⁻⁴, these non-symmetric ion-atom absorption processes have to be included *ab initio* in the models of the corresponding atmospheres, since in the greater part of the considered far UV and EUV region they could be completely dominant with respect to the referent electron-atom and symmetric ion-atom absorption processes.

Besides, it has been shown that in all the considered cases (H:He = 10⁻⁵, 10⁻⁴ and 10⁻³) the hydrogen photo-ionization processes Eq. (7) yield a dominant contribution to the opacity of the corresponding atmospheres in the region $\lambda_{He} < \lambda < \lambda_H$.

As a task for further investigations in this area is future study of the ion-atom non-symmetric absorption processes with participation of some metal components of the considered atmospheres.

Acknowledgments

The authors are thankful to the Ministry of Education, Science and Technological Development of the Republic of Serbia for the support of this work within the projects 176002 and III4402.

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