Absorption non-symmetric ion–atom processes in helium-rich white dwarf atmospheres

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ABSTRACT
In this work, the processes of absorption charge exchange and photoassociation in He+H+ collisions, together with the process of ion HeH+ photodissociation, are considered as factors influencing the opacities of the atmospheres of helium-rich white dwarfs in the far-UV and extreme ultraviolet (EUV) regions. It is shown that they should be taken into account even in the case of atmospheres of white dwarfs with H:He = 10−3. It is then established that in the case of white dwarfs with H:He ≳ 10−4, particularly when H:He ≳ 10−3, these processes have to be included ab initio in the corresponding models of their atmospheres, since in the far-UV and EUV regions they become dominant with respect to known symmetric ion–atom absorption processes.

Key words: atomic processes – molecular processes – radiation mechanisms: general – radiative transfer – stars: atmospheres – white dwarfs.

1 INTRODUCTION
It has been shown recently in Mihajlov et al. (2013) 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 (H + H+) collisions and molecular ion H2+ photodissociation. These processes were studied in Mihajlov & Dimitrijević (1986), Mihajlov, Dimitrijević & Ignjatović (1993), Mihajlov et al. (1994b) and Mihajlov et al. (2007) and are already included in one of the solar photosphere models (Fontenla et al. 2009). It has been established that in the very important far-UV and extreme ultraviolet (EUV) spectral regions they have to be considered together with the processes of absorption charge exchange and photoassociation in non-symmetric (H + X+) collisions and molecular ion HX+ photodissociation, where X is one of the metal atoms. Namely, it has been proved that only in such cases does the total efficiency of ion–atom absorption processes in the spectral regions mentioned approach the efficiency of the relevant concurrent processes in the whole solar photosphere.

These results suggest that it is useful to consider anew the situation of ion–atom absorption processes in the atmospheres of helium-rich white dwarfs. Let us recall that in previous articles (Mihajlov & Dimitrijević 1992; Mihajlov, Dimitrijević & Ignjatović 1994a; Stancil 1994; Mihajlov et al. 1995; Ignjatović et al. 2009), dedicated to certain DB white dwarf atmospheres, the processes of molecular ion He2+ photodissociation were studied:

\[ \varepsilon_\lambda + \text{He}_2^+ \rightarrow \text{He} + \text{He}^+, \] (1)

along with absorption charge exchange in (He + He+) collisions:

\[ \varepsilon_\lambda + \text{He}^+ + \text{He} \rightarrow \text{He} + \text{He}^+, \] (2)

where \( \varepsilon_\lambda \) is the energy of a photon with wavelength \( \lambda \), He = He(1s²), He+ = He+(1s) and He2+ = He2+(1Σ_u+). The significance of these symmetric ion–atom absorption processes for the atmospheres of DB white dwarfs was established in Mihajlov et al. (1994a, 1995) and Ignjatović et al. (2009) by a direct comparison of their efficiencies with the main concurrent process of inverse ‘bremsstrahlung’ in (free electron + He) collisions, i.e.

\[ \varepsilon_\lambda + \text{e} + \text{He} \rightarrow \text{e}' + \text{He}, \] (3)

where \( \text{e} \) and \( \text{e}' \) denote a free electron in the initial and final energetic states respectively. For that purpose, data from the corresponding DB white dwarf atmosphere models (Koester 1980) have been used. It was established that processes (1) and (2) significantly influence the opacity of the DB white dwarf atmospheres considered, with an effective temperature \( T_{\text{eff}} \geq 12,000 \, \text{K} \), which fully justifies their...
inclusion in one of the models of such atmospheres (Bergeron, Wesemael & Beauchamp 1995). However, the same comparison also demonstrated that the dominant role in those atmospheres generally still belongs to the concurrent absorption process (3), while the processes (1) and (2) can be treated as dominant (with respect to this concurrent process) only in some layers of the atmospheres and only within the region 50 < \lambda < 250 nm of the far-UV and EUV. In Fig. 1, where Planck’s curves for $T_{\text{eff}} = 12,000$ and 14,000 K are shown, this part is denoted by ‘I’. Its boundary (from the short-wavelength side) is determined by the value of wavelength $\lambda_{\text{He}} \approx 50.44$ nm, which corresponds to the threshold of atom He photoionization. Hence it follows that in the case of helium-rich white dwarf atmospheres it would certainly be useful to take some new ion–atom absorption processes into consideration, which is allowed in principle in accordance with the composition of such atmospheres (Bues 1970).

Let us note in this context that in the case of white dwarf atmospheres with a dominant helium component, among all possible symmetric ion–atom absorption processes that are allowed by their composition (Bues 1970), only processes (1) and (2) have to be taken into account. This means that in this case we can find new relevant absorption processes only among the processes connected with non-symmetric ion–atom systems, particularly processes that can provide efficiency in the same part ‘I’ of the far-UV and EUV regions. Here we will examine the significance of non-symmetric ion–atom absorption processes with participation of the hydrogen component. By this, we mean the processes of molecular ion HeH$^+$ photodissociation:

$$\varepsilon_{\lambda} + \text{HeH}^+ \rightarrow \text{He}^+ + \text{H},$$  \hspace{1cm} (4)

and the processes of absorption charge exchange and photoassociation in (He + He$^+$) collisions, namely

$$\varepsilon_{\lambda} + \text{He} + \text{He}^+ \rightarrow \text{He}^+ + \text{H},$$  \hspace{1cm} (5)

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

where $H = H(1s)$, He = He(1$s^2$), He$^+$ = He$^+$(1s) and HeH$^+$ and (HeH)$^+$ denote the molecular ion in the ground and first excited electronic states, which are adiabatically correlated with the states of the systems He + H$^+$ and He$^+$ + H respectively at infinite internuclear distance. Already in Mihajlov et al. (2013) it was noted that these processes, the significance of which was practically neglected for the solar photosphere, could be rather important in the case of helium-rich white dwarf atmospheres. This assumption was worthy of attention, particularly due to the fact that the characteristics of the non-symmetric molecular ions considered (see Fig. 2) provide manifestations of processes (4)–(6) only in part ‘I’ of the far-UV and EUV regions.

In connection with this fact, let us recall that part ‘I’ is rather important for such values of $T_{\text{eff}}$. Namely, let $\lambda_{\text{max}}$ denote the positions of the maxima of spectral intensities characterizing the electromagnetic (EM) emission of the atmospheres considered, which are determined from the well-known Wien’s law: $\lambda_{\text{max}} T_{\text{eff}} = 2.898 \times 10^6$ nm K. We then have, for the DB white dwarfs considered, $\lambda_{\text{max}} < 250$ nm, so that the mentioned maxima lie just within region ‘I’.

It was just for the above-mentioned reason that this investigation was undertaken. The main aim was to study the situations in which non-symmetric absorption processes (4)–(6) can significantly influence the opacity of helium-rich white dwarf atmospheres in part ‘I’ of the UV and VUV spectral regions and to show that processes (4)–(6) deserve to be included $\text{ab initio}$ in the corresponding white dwarf atmosphere models. Therefore the relevant spectral characteristics of processes (4)–(6) are determined here for the atmospheres of different helium-rich white dwarfs with $T_{\text{eff}} = 12,000$ and 14,000 K, log $g = 8$ and 7 and for values of the ratio H:He from $10^{-5}$–$10^{-3}$. The necessary expressions for these spectral characteristics are given in Section 2. Then, with their help, in Section 3 the values of the parameters characterizing the relative efficiency of non-symmetric processes (4)–(6) are calculated with respect to the efficiency of all ion–atom processes, as well as with respect to the electron–atom process (3). This comprises the main direct results of this work.

Let us note that already in Ignjatović et al. (2009), besides the electron–atom processes (3) the process of photoionization of hydrogen atoms was also considered, namely

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

where H = H(1s). It was treated as a concurrent process, potentially necessary in the region $\lambda < \lambda_{\text{HI}}$, where $\lambda_{\text{HI}} \approx 911$ Å corresponds to the threshold of atom H photoionization. However, Bergeron (private communication) brought to our attention the fact that the importance of this absorption channel was significantly underestimated. That is why, in this work, process (7) was again taken into consideration and examined carefully. 

Figure 1. Planck curve for $T_{\text{eff}} = 12,000$ and 14,000 K. ‘I’ and ‘II’ denote the regions $50.44 \leq \lambda \leq 250$ nm and $50.44 \leq \lambda \leq 120$ nm, respectively.

Figure 2. The potential curves $U_\lambda(R)$ and $U_s(R)$ for the ground and first excited electronic states of the molecular ion HHe$^+$ and the corresponding dipole matrix element $D_{12}(R)$, where $R$ is the internuclear distance.

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One can see that in this work we take into account only non-symmetric ion–atom absorption processes where, apart from the dominant helium component of the atmospheres considered, only the hydrogen component participates, although they also contain many metal components (Bues 1970). This is due to the fact that existing atmosphere models do not provide the necessary data (for the relevant metal abundances) that would be needed for the present calculations. However, we consider that a demonstration of the fact that, for the atmospheres considered, processes (4)–(6), where one of the ‘minor’ components participates, are rather significant is sufficient reason for treating non-symmetric ion–atom absorption processes in general as potentially significant for those atmospheres.

2 THE THEORETICAL REMARKS: THE RELEVANT SPECTRAL CHARACTERISTICS

2.1 The non-symmetric ion–atom processes

As the relevant characteristics of processes (4), (5) and (6) we will use the corresponding spectral absorption coefficients. They are defined as functions of log τ, where τ is the Rosseland optical depth of the part of the atmosphere examined above the considered layer for wavelength λ. They are denoted here as κ_{nsim}^{bf}(λ; log τ), κ_{nsim}^{ff}(λ; log τ) and κ_{nsim}^{fb}(λ; log τ), in accordance with the fact that the processes mentioned 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

\[ \kappa_{\text{nsim}}^{b\text{f},f\text{f}}(\lambda; \log \tau) = \kappa_{\text{nsim}}^{b\text{f},f\text{f}}(\lambda; T)N_{\text{He}}N_{\text{H}^+}, \]  

where T = T (log τ), N_{\text{He}} = N_{\text{He}} (log τ) and N_{\text{H}^+} = N_{\text{H}^+} (log τ). Of course, it is understood that the photodissociation rate coefficient K_{\text{nsim}}^{b\text{f}}(\lambda; T) is given by the known relations

\[ K_{\text{nsim,}\chi}^{b\text{f}}(\lambda; T) = \sigma_{\text{HeH}^+}(\lambda, T)\chi^{-1}(T; \text{HeH}^+), \]  

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

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

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

\[ \kappa_{\text{nsim}}(\lambda; \log \tau) = \kappa_{\text{nsim}}(\lambda; T)N_{\text{He}}N_{\text{H}^+}, \]  

\[ K_{\text{nsim}}(\lambda; T) = K_{\text{nsim}}^{b\text{f}}(\lambda; T) + K_{\text{nsim}}^{f\text{f}}(\lambda; T) + K_{\text{nsim}}^{f\text{b}}(\lambda; T), \]

where the rate coefficients \(K_{\text{nsim}}^{b\text{f},f\text{f}}(\lambda; T)\) determined by means of the necessary characteristics of the molecular ion considered, in a way that was described in detail in Mihajlov et al. (2013).

The characteristics mentioned, i.e. the adiabatic potential curves of the molecular ion in the ground state (HeH\(^+\)) and first excited electronic state ((HeH\(^+\)^\*)), as well as the corresponding dipole matrix element (not shown in Mihajlov et al. 2013), are presented here in Fig. 2 as functions of the internuclear distance R. This figure also shows in a schematic way the bound–free (bf), free–free (ff) and free–bound (fb) transitions between the energy states of the ion–atom system considered, corresponding to processes (4), (5) and (6). The potential curves are denoted in Fig. 2 by \(U_1(R)\) and \(U_2(R)\) and the dipole matrix element by \(D_{12}(R)\). Their values as functions of R are determined here by fitting the corresponding data from Green et al. (1974a,b).

Let us note that these data have a shortcoming: they are not sufficiently complete and do not guarantee that different ways of fitting give close values of \(U_1(R)\), \(U_2(R)\) and \(D_{12}(R)\). It is possible that this shortcoming causes the observed differences between our values of the partial cross-section for photodissociation of the ion HeH\(^+\) from its ground rovibrational state and the values presented in Dumitriu & Saenz (2009), which were calculated by means of the same data. However, here we used just the data from Green et al. (1974a,b), since, as yet, only these articles provide at least some data covering both the necessary potential curves (of the ion HeH\(^+\)) and the corresponding matrix element. Also, we keep in mind that development of numerical procedures that would be suitable for improvement of the data presented in Green et al. (1974a) and Green et al. (1974b) far exceeds the aim of this work. Apart from that, we consider that the deviations of the potential curves \(U_1(R)\) and \(U_2(R)\) from the hypothetical exact ones do not cause any large errors in the obtained results and consequently cannot influence the final conclusions strongly.

Since all processes (4)–(6) are connected with the transition between the ground and the first excited electronic states of a strongly non-symmetric ion–atom system (HeH\(^+\) or He + \(H^+\)), the range of values of the splitting term \((U_2(R) \equiv U_2(R) - U_1(R))\) characterizes well the range of photon energies that is relevant for those processes. It is due to this that we could state above that processes (4)–(6) have to be manifested in part ‘I’ of the far-UV and EUV spectral regions (see Fig. 1).

Although the behaviour of the rate coefficients \(K_{\text{nsim}}^{b\text{f},f\text{f}}(\lambda, T)\) has already been discussed in Mihajlov et al. (2013), it is also illustrated here by Fig. 3, since the range of temperatures characterizing the solar photosphere is not relevant in our case. These figures give
the possibility that the processes (4)–(6) can be significant in the spectral region denoted in Fig. 1 by ‘II’.

2.2 The symmetric ion–atom, electron–atom and hydrogen photoionization processes

For the sake of the following considerations, we have to introduce the spectral coefficients $\kappa_{\text{sim}}(\lambda; \log \tau)$, $\kappa_{e-He}(\lambda; \log \tau)$ and $\kappa_{\text{ph}}(\lambda; \log \tau)$, which characterize the efficiencies of the symmetric ion–atom absorption processes (1) and (2) together, the electron–atom processes (3) and hydrogen photoionization process (7) respectively. As in Ignjatović et al. (2009), we can take these coefficients in known form:

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

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

$$\kappa_{\text{ph}}(\lambda; \log \tau) = \sigma_{\text{ph}}(\lambda; H)N_{He^+},$$

where $N_{He^+}, N_e$ and $N_{He}$ are the local densities of ions He$^+$, free electrons and atoms H, $K_{\text{sim}}(\lambda, T)$ and $K_{e-He}(\lambda, T)$ are adequately defined spectral rate coefficients and $\sigma_{\text{ph}}(\lambda; H)$ is the spectral cross-section for atom H photoionization. The absorption coefficient $K_{\text{sim}}(\lambda, T)$ is determined in the manner described in detail in Ignjatović et al. (2009), $K_{e-He}(\lambda, T)$ by means of the data from Somerville (1965) and $\sigma_{\text{ph}}(\lambda; H)$ taken from Bethe & Salpeter (1957).

Here we take into account the fact that all values of the rate coefficients $K_{\text{sim}}(\lambda, T)$ and $K_{e-He}(\lambda, T)$ that are needed for our calculations have already been determined in Ignjatović et al. (2009) and that the photoionization cross-section $\sigma_{\text{ph}}(\lambda; H)$ is given by a known analytical expression. Therefore, in the remaining text we will simply treat these characteristics and, consequently, the spectral absorption coefficients $\kappa_{\text{sim}}(\lambda, \log \tau)$, $\kappa_{e-He}(\lambda, \log \tau)$ and $\kappa_{\text{ph}}(\lambda; \log \tau)$ as known quantities.

3 RESULTS AND DISCUSSION

3.1 DB white dwarfs

As is well known, the spectral absorption coefficients defined above 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 $T_{\text{eff}}$, log $g$ and the ratio of hydrogen and helium species (H:He). Here we will start from DB white dwarf atmospheres with $T_{\text{eff}} = 12 000$ and $14 000$ K, log $g = 8$ and H:He = $10^{-5}$. For their description we will use the equilibrium models presented in Koester (1980). As in Mihajlov et al. (1994a, 1995) and Ignjatović et al. (2009), this is due to the fact that, although newer atmosphere models for helium-rich white dwarfs now exist (see e.g. the review article of Koester 2010), only the models from Koester (1980) contain in a tabular form all the relevant data needed for our calculations.

The behaviour of the densities of free electrons and ions He$^+$ and H$^+$ in the atmosphere of a DB white dwarf with $T_{\text{eff}} = 12 000$ K and log $g = 8$ is illustrated by Fig. 4, which shows that processes (4)–(6) could be of interest in the case H:He = $10^{-5}$. Namely, this figure suggests that, for $T_{\text{eff}} \lesssim 14 000$ K, the ion H$^+$ density is even larger than that of He$^+$ in significant parts of DB white dwarf atmospheres (log $\tau < -1$).

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

$$\kappa_{\text{si}}(\lambda; \log \tau) = \kappa_{\text{sim}}(\lambda; \log \tau) + \kappa_{\text{sim}}(\lambda; \log \tau).$$

For that purpose we use the quantity

$$G_{\text{si}}^{\text{sim}}(\lambda; \log \tau) = \frac{\kappa_{\text{sim}}(\lambda; \log \tau)}{\kappa_{\text{si}}(\lambda; \log \tau)}.$$  

One can see that the definition of this quantity guarantees the validity of the relations $0 < G_{\text{si}}^{\text{sim}}(\lambda; \log \tau) < 1$ for any $\lambda$ and log $\tau$. This is important, since other possible quantities, i.e. $\kappa_{\text{si}}(\lambda; \log \tau)/\kappa_{\text{sim}}(\lambda; \log \tau)$ and $\kappa_{\text{sim}}(\lambda; \log \tau)/\kappa_{\text{sim}}(\lambda; \log \tau)$, could not be presented in practical fashion in the corresponding figure.

The behaviour of the quantity $G_{\text{si}}^{\text{sim}}(\lambda; \log \tau)$ for a DB white dwarf atmosphere with $T_{\text{eff}} = 12 000$ K, log $g = 8$ and H:He = $10^{-5}$ is illustrated by Fig. 5. This figure shows that non-symmetric processes (4)–(6) are dominant within a significant part of the atmosphere considered ($-5.6 < \log \tau \lesssim -0.75$), which corresponds to the part of Fig. 4 where $N_{H^+} > N_{He^+}$.
In order to establish how taking non-symmetric processes (4)–(6) into consideration influences the relative efficiency of ion–atom absorption processes with respect to the efficiency of the concurrent electron–atom process (3), we calculated the quantities

\[
\begin{align*}
F^{\text{(sym)}}_{e-\text{He}}(\lambda; \log \tau) &= \frac{\kappa^{\text{sym}}(\lambda; \log \tau)}{\kappa_{e-\text{He}}(\lambda; \log \tau)}, \\
F^{\text{(ia)}}_{e-\text{He}}(\lambda; \log \tau) &= \frac{\kappa_{\text{ia}}(\lambda; \log \tau)}{\kappa_{e-\text{He}}(\lambda; \log \tau)}.
\end{align*}
\]  

Comparison of these two quantities gives the possibility of estimating the change of the above-mentioned relative efficiency. The behaviour of these quantities in the case of the DB white dwarf atmosphere considered (\(T_{\text{eff}} = 12\,000\,\text{K}, \log g = 8\), H:He = 10^{-5}) is shown in Fig. 6. From this figure, one can see that the inclusion of ion–atom non-symmetric absorption processes causes a very significant increase in the relative efficiency of ion–atom absorption processes in just region \(\log \tau < 0.75\), i.e. where symmetric processes can be practically neglected.

We then established the fact that the behaviour of the quantities \(G_{\text{ia}}^{\text{(sym)}}(\lambda; \log \tau), F^{\text{(sym)}}_{e-\text{He}}(\lambda; \log \tau)\) and \(F^{\text{(ia)}}_{e-\text{He}}(\lambda; \log \tau)\) is also similar in the cases of DB white dwarf atmospheres with the same value of H:He, but with \(T_{\text{eff}} = 14\,000\,\text{K}\) and \(T_{\text{eff}} = 12\,000\,\text{K}\) and \(\log g = 7\). Based on the above, it can be concluded that non-symmetric processes (4)–(6) have a visible significance for the atmospheres of 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 \(\lambda > \lambda_{\text{H}}\) where the hydrogen photoionization process (7) is impossible. In order to estimate the partial efficiencies of the processes mentioned in the case of the DB white dwarf considered in the whole region \(\lambda > \lambda_{\text{H}}\), the corresponding plots of all discussed absorption processes for \(\log \tau = 0\) are presented in Fig. 7. One can see that in the region \(\lambda_{\text{H}e} < \lambda < \lambda_{\text{H}}\) the process (7) alone gives the dominant contribution to the opacity of the atmosphere considered. Here it was established that, in the case considered, this dominance exists for any \(\log \tau < 0\).

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

3.2 Other helium-rich white dwarfs

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

In this context, let us note that in Wegner & Koester (1985) some DC white dwarfs with \(T_{\text{eff}} \approx 12500\,\text{K}, \log g = 8\) and H:He = 2 × 10^{-4} are described. Then, in Dufour et al. (2006) some weakly magnetic DZ white dwarfs with \(\log g = 8, T_{\text{eff}} \approx 7000\,\text{K}\) and H:He = 10^{-3}–10^{-4} are discussed. Finally, we remind the reader also that in Dufour et al. (2007) some DZ white dwarfs with \(\log g \approx 8, T_{\text{eff}} > 12000\,\text{K}\) and H:He = 10^{-4} and 10^{-5} are mentioned, as well as a number of other DZ white dwarfs with \(\log g \approx 8\), values of \(T_{\text{eff}}\) from about 6500 K to about 10 000 K and values of H:He from about \(10^{-3.2}\) to about \(10^{-4.5}\). Purely from the above-mentioned result, it follows that the contribution of non-symmetric processes (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 \(N_{\text{H}^+}\) of at least several times. Thus, the mentioned increase of several per cent in region \(-1 < \log \tau < 2\) in the case of DB white dwarf atmospheres has to become an increase of several tens of per cent in the cases of helium-rich white dwarfs with \(10^{-4} \lesssim \text{H:He} \lesssim 10^{-3}\).

In order to check our expectations, we performed calculations of the quantity \(G_{\text{ia}}^{\text{(sym)}}\), as well as of the quantities (\(\lambda; \log \tau\)), \(F^{\text{(sym)}}_{e-\text{He}}(\lambda; \log \tau)\) and \(F^{\text{(ia)}}_{e-\text{He}}(\lambda; \log \tau)\), simulating the behaviour of 7, \(N_{\text{He}^+}, N_{\text{H}^+}\) and other particle densities in helium-rich white dwarf atmospheres with \(T_{\text{eff}} = 12000\,\text{K}, \log g = 8\) and H:He > 10^{-5}. All the required calculations have been performed on the basis of models taken from Koester (private communication). In Figs 8 and 9 the corresponding densities \(N_{\text{He}^+}, N_{\text{H}^+}\) and \(N_{\text{e}}\) are shown as functions of \(\log \tau\) for H:He = 10^{-4} and 10^{-5} respectively. One can see, by
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Figure 8. The local densities $N_{\text{He}}$, $N_{\text{He}^+}$ and $N_{\text{H}^+}$ and the temperature $T$ as functions of log $\tau$, where $\tau$ is the Rosseland optical depth, according to the model of a helium-rich white dwarf atmosphere developed for $T_{\text{eff}} = 12\,000$ K, log $g = 8$ and $\text{H}:\text{He} = 10^{-4}$.

Figure 9. Same as Fig. 8, but for $\text{H}:\text{He} = 10^{-3}$.

comparing these figures and Fig. 4, that the considered increase of the ratio $\text{H}:\text{He}$ indeed causes a very significant increase of $N_{\text{H}^+}$.

The behaviour of $G_{\text{nsim}ia}(\lambda; \log \tau)$ in the spectral region considered (denoted by ‘II’ in Fig. 1) is shown in Fig. 10 for $\text{H}:\text{He} = 10^{-4}$ and in Fig. 11 for $\text{H}:\text{He} = 10^{-3}$. By comparing Figs 10 and 5, it can be seen that for $51\,\text{nm} \leq \lambda \leq 125\,\text{nm}$ an increase of the ratio $\text{H}:\text{He}$ from $10^{-5}$ to $10^{-4}$ causes a visible increase of participation of the non-symmetric processes considered (with respect to the total ion–atom spectral absorption coefficient) for log $\tau > -1$ and a significant increase for log $\tau > 0$. Then, by comparing Figs 5 and 11, it is seen that an increase of the ratio $\text{H}:\text{He}$ from $10^{-5}$ to $10^{-3}$ causes a very large increase of the aforementioned participation in the whole region log $\tau > -1$.

The way in which an increase of the ratio $\text{H}:\text{He}$ influences the increase of the relative significance of ion–atom absorption processes with respect to the concurrent electron–atom process (3) in the spectral region mentioned is illustrated by Figs 12 and 13, which show the behaviour of the quantities $F_{\text{nsim}e-\text{He}}(\lambda; \log \tau)$ and $F_{\text{ia}e-\text{He}}(\lambda; \log \tau)$ for $\text{H}:\text{He} = 10^{-4}$ and $10^{-3}$ respectively. From these figures, one can see that for $\text{H}:\text{He} = 10^{-4}$ the inclusion of non-symmetric processes (4)–(6) causes 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 $51\,\text{nm} \leq \lambda \leq 110\,\text{nm}$, while for $\lambda > 110\,\text{nm}$ the efficiency of ion–atom processes stays close to the efficiency of process (3).
In order to obtain the complete picture of the absorption processes discussed in helium-rich white dwarf atmospheres in the cases H:He = 10^{-4} and 10^{-5}, it is again necessary to take into consideration the hydrogen photoionization process (7). The significance of partial absorption processes in such atmospheres within the whole region $\lambda > \lambda_{\text{He}}$ is illustrated in Figs 14 and 15, where the corresponding plots of these processes are presented for log $\tau = 0$. One can see that, as in the case of DB white dwarfs, the process (7) in the region $\lambda_{\text{He}} < \lambda < \lambda_{\text{H}}$ gives the dominant contribution to the opacity of the atmospheres considered. Thus, 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 the reader that the ion–atom absorption processes considered (symmetric and non-symmetric) can naturally be significant in helium-rich white dwarf atmospheres with $T_{\text{eff}} < 20000$ K, since at higher temperatures electron–ion absorption processes completely dominate with respect to the ion–atom and electron–atom processes considered. Therefore, it is necessary here to take into account the articles of Bergeron et al. (2011) and Voss et al. (2007), where data for numerous helium-rich white dwarfs are presented. Namely, from these one can see that the values H:He corresponding to helium-rich white dwarfs with $T_{\text{eff}} < 20000$ K are mainly situated between $10^{-5}$ and $10^{-4}$, while values H:He > 10^{-4}, especially H:He close to 10^{-3}, have to be treated as certain extremes. However, our results are supported by the following facts.

(i) First, from the results obtained it follows that non-symmetric ion–atom processes cannot be neglected for the case of atmospheres of DB white dwarfs with H:He = 10^{-5}.

(ii) Secondly, from these results it follows that the effect of inclusion of non-symmetric processes is fully manifested for H:He = 10^{-4}, i.e. far from the extremum (H:He = 10^{-3}), and remains practically the same further on. This means that not only the neighbourhood of the extremum value H:He = 10^{-3} is important, but rather the whole region H:He > 10^{-5}.

Since from the results presented it follows that ion–atom absorption processes should be especially significant in helium-rich white dwarf atmospheres with H:He = 10^{-4}, this case is additionally illustrated by Fig. 16. In this figure plots of the ion–atom absorption processes examined (symmetric and non-symmetric together) and the relevant electron–atom process (He−–continuum) are presented for log $\tau = -2, -1, -0.5, 0$ and 0.5 for the case H:He = 10^{-4}. From Fig. 16, we can clearly see how the contribution of non-symmetric ion–atom processes and the total efficiency
of all ion–atom processes with respect to electron–atom processes change with a change of log τ in the whole region λ > λ_{H\alpha}.

At the end of this section, in Fig. 17, the behaviour of the total ion–atom spectral absorption coefficient \( k_{\text{tot}}(\lambda; \log \tau) \) (see equations (11), (13) and (16)) is illustrated for examples of atmospheres of helium-rich white dwarfs with \( T_{\text{eff}} = 12\,000 \, \text{K} \) and log \( g = 8 \), for H:He = \( 10^{-5} \), H:He = \( 10^{-4} \) and H:He = \( 10^{-3} \).

4 CONCLUSIONS

From the material presented, it follows that the non-symmetric ion–atom absorption processes considered have to be treated as one of the important channels of influence on the opacity of atmospheres of helium-rich white dwarfs in the far-UV and EUV regions. It has been shown that, even in the case of DB white dwarfs with H:He = \( 10^{-3} \), such processes should be included in the models of their atmospheres. However, the main result of this research is establishment of the fact that in the case of helium-rich white dwarfs with H:He > \( 10^{-3} \), and particularly with H:He = \( 10^{-3} \), these non-symmetric ion–atom absorption processes have to be included \textit{ab initio} in the models of the corresponding atmospheres, since in the greater part of the far-UV and EUV regions considered they could be completely dominant with respect to the relevant electron–atom and symmetric ion–atom absorption processes.

Additionally, in this article attention has again been paid to the role of the hydrogen component in the atmospheres of helium-rich white dwarfs. Namely, it has been shown that in all cases considered (H:He = \( 10^{-3} \), \( 10^{-4} \) and \( 10^{-3} \)) the hydrogen photoionization processes (7) yield a dominant contribution to the opacity of the corresponding atmospheres in the region \( 4000 < \lambda < 7000 \, \text{A} \).

As a possible area for further investigation, we mention the atmospheres of helium-rich white dwarfs with smaller effective temperatures (\( \approx 7000 \, \text{K} \)), where the significance of the hydrogen component can be greater than in the cases described. Also, taking ion–atom non-symmetric absorption processes with participation of some metal components of the atmospheres into consideration would be useful.

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Table 1. The spectral absorption rate coefficient \( K_{\text{sim}}(\lambda; T) \) (see equation (12)), calculated under the condition of the existence of local thermodynamic equilibrium.

| \( T \) [10^3 K] | \( \lambda \) [nm] | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|-----------------|-----------------|---|---|---|---|---|---|---|
| 51              | 3.24E-40        | 1.68E-40 | 1.04E-40 | 7.22E-41 | 5.37E-41 | 4.19E-41 | 3.39E-41 | 3.39E-41 |
| 55              | 3.36E-40        | 1.83E-40 | 1.19E-40 | 8.58E-41 | 6.66E-41 | 5.43E-41 | 4.58E-41 | 4.58E-41 |
| 60              | 3.19E-40        | 1.85E-40 | 1.26E-40 | 9.54E-41 | 7.70E-41 | 6.51E-41 | 5.68E-41 | 5.68E-41 |
| 65              | 2.89E-40        | 1.78E-40 | 1.28E-40 | 1.01E-40 | 8.39E-41 | 7.29E-41 | 6.52E-41 | 6.52E-41 |
| 70              | 2.65E-40        | 1.75E-40 | 1.33E-40 | 1.09E-40 | 9.36E-41 | 8.31E-41 | 7.54E-41 | 7.54E-41 |
| 75              | 2.33E-40        | 1.61E-40 | 1.26E-40 | 1.06E-40 | 9.31E-41 | 8.38E-41 | 7.68E-41 | 7.68E-41 |
| 80              | 2.09E-40        | 1.53E-40 | 1.24E-40 | 1.07E-40 | 9.61E-41 | 8.80E-41 | 8.20E-41 | 8.20E-41 |
| 85              | 1.93E-40        | 1.48E-40 | 1.25E-40 | 1.11E-40 | 9.02E-40 | 8.94E-41 | 8.49E-41 | 8.49E-41 |
| 90              | 1.84E-40        | 1.49E-40 | 1.30E-40 | 1.19E-40 | 9.11E-40 | 9.45E-41 | 9.04E-41 | 9.04E-41 |
| 95              | 1.83E-40        | 1.56E-40 | 1.41E-40 | 1.32E-40 | 1.25E-40 | 1.05E-40 | 1.00E-40 | 1.00E-40 |
| 100             | 1.91E-40        | 1.73E-40 | 1.61E-40 | 1.53E-40 | 1.47E-40 | 1.43E-40 | 1.40E-40 | 1.40E-40 |
| 105             | 2.24E-40        | 2.16E-40 | 2.05E-40 | 1.97E-40 | 1.92E-40 | 1.90E-40 | 1.89E-40 | 1.89E-40 |
| 110             | 3.38E-40        | 3.10E-40 | 3.07E-40 | 3.06E-40 | 3.04E-40 | 3.03E-40 | 3.02E-40 | 3.02E-40 |
| 115             | 5.53E-41        | 6.74E-41 | 7.70E-41 | 8.65E-41 | 9.49E-41 | 1.02E-40 | 1.10E-40 | 1.10E-40 |
| 120             | 3.14E-42        | 2.75E-42 | 2.62E-42 | 2.48E-42 | 2.25E-42 | 1.93E-42 | 1.62E-42 | 1.62E-42 |
| 125             | 3.11E-42        | 2.58E-42 | 2.51E-42 | 2.45E-42 | 2.19E-42 | 1.75E-42 | 1.31E-42 | 1.31E-42 |

Figure 17. The behaviour of the total ion–atom spectral absorption coefficient \( k_{\text{tot}}(\lambda; \log \tau) \) (see equations (11), (13) and (16)) for the atmospheres of helium-rich white dwarfs with \( T_{\text{eff}} = 12\,000 \, \text{K} \) and log \( g = 8 \), for H:He = \( 10^{-5} \), H:He = \( 10^{-4} \) and H:He = \( 10^{-3} \).
