The inverse bremsstrahlung absorption coefficients and Gaunt factors in astrophysical plasmas

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Abstract. In this paper we present the method of determination of the electron-ion inverse Bremsstrahlung characteristics in order to cover the corresponding stellar atmosphere models. The used method is based on cut-off Coulomb model potential. It is shown that determination of these characteristics i.e. the absorption coefficients and Gaunt factors can be successfully performed in the region of electron densities from $10^{13}\mathrm{cm}^3$ to $3\cdot10^{19}\mathrm{cm}^3$ and temperatures from 3000 K to 50000 K within the wavelength region 100 nm $\leq \lambda \leq$ 3000 nm.

1. Introduction

After examining the existing literature about inverse "Bremsstrahlung" process [1, 2, 3, 4, 5], it could be seen that the most of presented papers are devoted to the determination of the corresponding Gaunt factor. Namely, the exact relation for the differential cross section for the direct "Bremsstrahlung" process exist for a long time [6]. This automatically led to the possibility of the exact term for the inverse "Bremsstrahlung" cross section $\sigma^{(ex)}_{i.b.}(E, \varepsilon_{ph})$, for the considered inverse "Bremsstrahlung". However, the practical applicability of mentioned strict relation was complex, which suggested the search of a practical ways for describing inverse "Bremsstrahlung". Therefor, it has been taken the simple and widely used quasi classical (Kramer's) cross section for the direct and inverse "Bremsstrahlung" process. The idea was to present exact $\sigma^{(ex)}_{i.b.}(E, \varepsilon_{ph})$ in a form

$$\sigma^{(ex)}_{i.b.}(E, \varepsilon_{ph}) = \sigma^{q.c.}_{i.b.}(E, \varepsilon_{ph}) \cdot g_{i.b.}(E, \varepsilon_{ph}), \qquad (1)$$

where $g_{i.b.}(E, \varepsilon_{ph})$ is the adequate defined Gaunt factor. Because of that, further step was to find a simple approximations for the Gaunt factor $g_{i.b.}(E, \varepsilon_{ph})$ in relation (1). The mentioned exact and approximated absorption coefficient are denoted with $k^{(ex)}_{i.b.}(\lambda, T; N_e)$ and $k^{q.c.}_{i.b.}(\lambda, T; Ne)$, where N_e is free electron density. Here it is taken into account that in our case (single charged ions) the ion density is equal to electron density N_e. Consequently, these coefficients are connected with the relation

$$k^{(ex)}_{i.b.}(\lambda, T; N_e) = k^{q.c.}_{i.b.}(\lambda, T; N_e) \cdot G_{i.b.}(\lambda, T), \qquad (2)$$

where $G_{i.b.}(\lambda, T)$ is the required Gaunt factor. The determination of such averaged Gaunt factor as a function of λ and T was the object of investigation in the majority of previous papers devoted to the inverse "Bremsstrahlung" process (see e.g. [1, 2, 3, 4]).

In connection with the relations (1) and (2) it is needed to keep in mind the fact that exact terms for the inverse "Bremsstrahlung" process are determined in the case of scattering of the free electron onto the Coulomb potential. This means that mentioned exact terms are strictly applicable on the case of diluted plasma. It is clear that the same holds for all approximate relations which were obtained by now on the basis of these terms. From above mentioned it follows that all such relations become the unusable in the case of plasma of higher densities, e.g. non-ideal plasma. The aim of this work is to find such relations for $\sigma^{(ex)}_{i.b.}(E, \varepsilon_{ph})$ which could be applicable in the case of different stellar atmospheres (with higher densities), where the values of the electron density changes from $Ne \sim 10^{13}$ cm^{-3} to $Ne \sim 10^{20}$ cm^{-3}.

2. Theory

This work is continuation of our previous investigation devoted to the examination of the opacity of the weakly and strongly ionized parts of the solar photospheres and lower chromospheres and different helium rich white dwarfs atmospheres [7, 8, 9, 10, 11, 12, 13]. The aim of this work is determination of such absorption coefficient $k^{(ex)}_{i.b.}(\lambda, T; N_e)$ and Gaunt factor $G_{i.b.}(\lambda, T)$ which could be applicable on the case of plasma with higher densities. Because of that, we applied a model potential, specially adopted for the description of the electron scattering onto the ion inside plasma i.e. cut-off Coulomb potential, described by the relations $U_{cut}(r) = -\frac{e^2}{r} + \frac{e^2}{r_{cut}}$ if $0 < r \leq r_{cut}$ and $U_{cut}(r) = 0$, if $r_{cut} < r$.

Here, we use the procedure of the determination of inverse Bremsstrahlung cross-section which is improved comparing to [12]. Using this improved procedure in this work were performed calculations of the corresponding Gaunt factor in the wide region of electron densities and temperature which can be used in connection with the different astrophysical and laboratory plasmas. Special calculations were made in order to determine free-free spectral absorption coefficients for the different stellar atmosphere models. Here we take $\kappa^{(ex)}_{i.b.}$ in the form

$$\kappa^{(ex)}_{i.b.}(\varepsilon_\lambda; N_e, T) = N_e^2 \cdot \int_0^\infty \sigma^{(ex)}_{i.b.}(E; E')v \cdot f_T(v) \cdot 4\pi v^2 dv \cdot \left(1 - \exp\left[-\frac{\hbar\omega}{kT}\right]\right), \tag{3}$$

where $f_T(v)$ is the corresponding Maxwellian distribution function for given temperature T. On the other hand quasi classical Kramer's $k^{q.c.}_{i.b.}(\lambda, T; Ne)$ is given by the known expression

$$k^{q.c.}_{i.b.}(\lambda, T; Ne) = N_e^2 \cdot \frac{16\pi^{5/2}\sqrt{2}e^6}{3\sqrt{3}cm^{3/2}\varepsilon^3_{ph}} \frac{\hbar^2}{(kT)^{1/2}} \left(1 - \exp\left[-\frac{\hbar\omega}{kT}\right]\right), \tag{4}$$

where $\varepsilon_{ph} = 2\pi\hbar c/\lambda$. According to this, averaged Gaunt factor $G_{i.b.}(\lambda, T)$ is determined here from Eq. (2), where $k^{(ex)}_{i.b.}(\lambda, T; Ne)$ and $k^{q.c.}_{i.b.}(\lambda, T; Ne)$ are given by Eqs. (3) and (4).

It is important that within this work the inverse "Bremsstrahlung" absorption coefficients $\kappa^{(ex)}_{i.b.}(\varepsilon_\lambda; N_e, T)$ are determined by Eq. (3), where the spectral absorption cross section $\sigma^{(ex)}_{i.b.}(E; E')$ is calculated using the improved procedure from [12], where all relevant quantities are determined strictly numerically without any additional approximation.

3. Results and discussion

The calculations of the Gaunt factor $G_{i.b.}(\lambda, T)$ and absorption coefficients $k^{(ex)}_{i.b.}(\lambda, T; Ne)$ were carried out for the electron densities in the range from $1 \cdot 10^{13}$cm^{-3} to $3 \cdot 10^{19}$cm^{-3} and temperatures from $3 \cdot 10^3$K to $1 \cdot 10^5$K, and the observed wavelength region 100nm $< \lambda <$ 3000nm

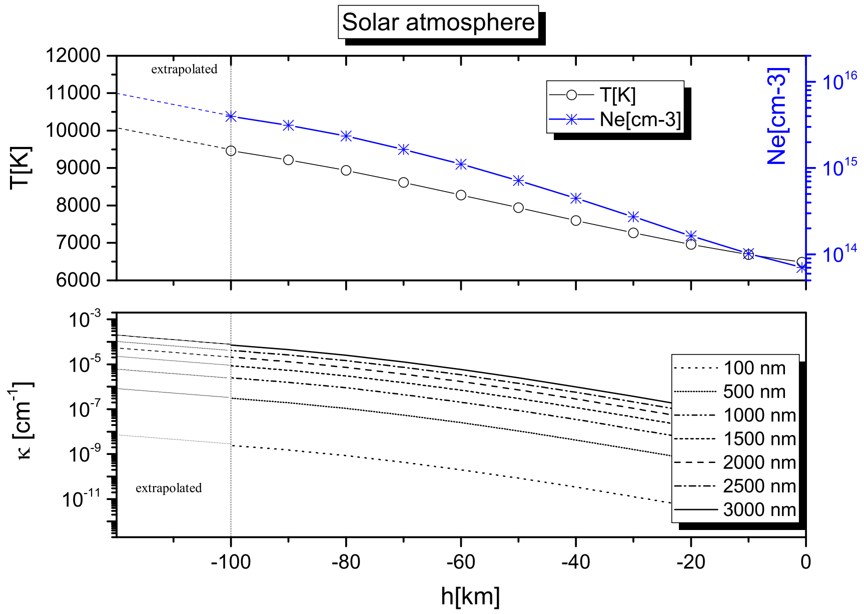

Figure 1. Upper panel: The behavior of T and N_e as a function of height within the considered part of the solar atmosphere model of [14]; lower panel: The absorption coefficient for inverse "Bremsstrahlung" processes within the considered part of the solar atmosphere model.

in order to cover the corresponding stellar atmosphere models. This is illustrated by Fig.1 which shows the behavior of the absorption coefficient for inverse "Bremsstrahlung" processes within the considered part of the solar atmosphere. Also the absorption coefficients for different DB white dwarf atmospheres were carried out. Here we highlight that the presented exact quantum mechanical method can be used to obtain the spectral coefficients for inverse "Bremsstrahlung" process for the broad class of plasma of higher non-ideality. We expect that the cut-off Coulomb potential model results are more accurate in comparison with other methods, which are so far used for cases of stellar plasma with higher non-ideality.

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