Electrical conductivity of plasmas of DB white dwarf atmospheres

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Accepted 2010 March 16. Received 2010 March 16; in original form 2009 December 3

ABSTRACT
The static electrical conductivity of non-ideal, dense, partially ionized helium plasma was calculated over a wide range of plasma parameters: temperatures $1 \times 10^4 \lesssim T \lesssim 1 \times 10^5$ K and mass density $1 \times 10^{-6}$ g cm$^{-3} \lesssim \rho \lesssim 2$ g cm$^{-3}$. Calculations of electrical conductivity of plasma for the considered range of plasma parameters are of interest for DB white dwarf atmospheres with effective temperatures $1 \times 10^4$ K $\lesssim T_{\text{eff}} \lesssim 3 \times 10^4$ K.

Electrical conductivity of plasma was calculated by using the modified random phase approximation and semiclassical method, adapted for the case of dense, partially ionized plasma. The results were compared with the unique existing experimental data, including the results related to the region of dense plasmas. In spite of low accuracy of the experimental data, the existing agreement with them indicates that results obtained in this paper are correct.

Key words: stars: atmospheres – stars: kinematics and dynamics – white dwarfs.

1 INTRODUCTION
DB white dwarf atmospheres belong to the class of astrophysical objects which have been investigated for a long time and from various aspects (Bues 1970; Koester 1980; Stancil, Bab & Dalgarno 1993). Of the previous work, the contribution of the authors of this paper was on the optical properties of DB white dwarf atmospheres within the range of average effective temperatures $1 \times 10^4$ K $\lesssim T_{\text{eff}} \lesssim 2 \times 10^4$ K, Mihajlov & Dimitrijević (1992), Mihajlov, Dimitrijević & Ignjatović (1994) and Mihajlov et al. (1995) worked on the continual absorption in the optical part of electromagnetic spectra, Mihajlov et al. (2003) worked on the chemi-ionization/recombination processes and Ignjatović et al. (2009) investigated the continual absorption in the VUV region of EM spectra.

Recently, the transport properties of helium plasmas, characteristic of some DB white dwarf atmospheres, attracted the authors’ attention, first of all the electrical conductivity. Namely, data on the electrical conductivity of plasma of stars with a magnetic field or moving in the magnetic field of the other component in a binary system (see, e.g. Zhang, Wickramasinghe & Ferrario 2009; Rodriguez-Gil, Martinez-Pais & Rodriguez 2009; Potter & Tout 2010) could be of significant interest, since they are useful for the study of the thermal evolution of such objects (cooling, nuclear burning of accreted matter) and the investigation of their magnetic fields. For example, Kopecký (1970) and Kopecký & Kotrč (1973) studied electrical conductivity for stars of various spectral types, in order to investigate the magnetohydrodynamic differences in their atmospheres. Recently, Mazevet, Challacombe & Kowalński (2007) investigated He conductivity in cool white dwarf atmospheres, since the possibility of using these stars for dating stellar populations has generated a renewed interest in modelling their cooling rate (Fontaine, Brassard & Bergeron 2001). Also, the transport processes occurring in the cores of white dwarfs (see, e.g. Baiko & Yakovlev 1995 and numerous references therein) have been considered. Moreover, electrical conductivity was particularly investigated for solar plasma, since it is of interest for consideration of various processes in the observed atmospheric layers, like the relation between magnetic field and convection, the question of magnetic field dissipation and the energy released by such processes (see e.g. Kopecký 1970 and references therein). For example, Feldman (1993) investigated the role of electrical conductivity in the construction of a theoretical model of the upper solar atmosphere, and Kazeminezhad & Goodman (2006) considered the electrical conductivity of solar plasma for magnetohydrodynamic simulations of the solar chromospheric dynamo. Given that electrical conductivity plays an analogous role in other stars as well, it is of interest to investigate its significance, to adapt the methods for research into stellar plasma conditions and to provide the needed data.

An additional interest for data on electrical conductivity in white dwarf atmospheres may be stimulated by the search for extrasolar planets. Namely, Jianke, Ferrario & Wickramasinghe (1998) have shown that a planetary core in orbit around a white dwarf may reveal its presence through its interaction with the magnetosphere of the white dwarf. Such an interaction will generate electrical currents that will directly heat the atmosphere near its magnetic poles. Jianke et al. (1998) emphasize that this heating may be detected within the optical wavelength range as $H\alpha$ emission. For investigation and modelling of the above-mentioned electrical currents, the data on electrical conductivity in white dwarf atmospheres will be useful.

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One of the most frequently used approximations for consideration of transport properties of different plasmas is the approximation of ‘fully ionized plasma’ (Spitzer 1962; Radke et al. 1976; Adanyam et al. 1980; Kurilkenov 1984; Ropke & Redmer 1989; Djuric et al. 1991; Nurekenov et al. 1997; Zaika, Mulenko & Khomkin 2000; Esser, Redmer & Ropke 2003). It was shown that the electrical conductivity of fully ionized plasmas can be successfully calculated using the modified random-phase approximation (RPA) (Djuric et al. 1991; Adanyam et al. 1994a,b) in the region of strong and moderate non-ideality, while the weakly non-ideal plasmas were successfully treated within the semiclassical approximation (SC) (Mihajlov et al. 1993; Vétel et al. 2001). In practice, even the plasmas with a significant neutral component are treated as fully ionized in order to simplify the considered problems (Ropke & Redmer 1989; Esser & Ropke 1998; Zaika et al. 2000; Esser et al. 2003). However, our preliminary estimates have shown that such an approach is not applicable for the helium plasmas of DB white dwarf atmospheres described in Koester (1980), where the influence of the neutral component cannot be neglected.

Therefore, an adequate method for calculations of electrical conductivity of dense, partially ionized helium plasmas is developed in this paper. This method represents a generalization of methods developed in Djuric et al. (1991) and Mihajlov et al. (1993), namely, modified RPA and SC methods, and gives the possibility of estimating the real contribution of the neutral component to the static electrical conductivity of the considered helium plasmas within a wide range of mass densities ($\rho$) and temperatures ($T$).

The calculations were performed for helium plasma in the state of local thermodynamical equilibrium with given $\rho$ and $T$ for $1 \times 10^{17} \text{K} \lesssim T \lesssim 1 \times 10^{19} \text{K}$ and $1 \times 10^{-6} \text{g cm}^{-3} \lesssim \rho \lesssim 2 \text{g cm}^{-3}$. The obtained results are compared with the corresponding experimental data (Mintsev, Fortov & Gryznavn 1980; Temrov et al. 2002; Shilkin et al. 2003). For the calculations of plasma characteristics of DB white dwarf atmospheres, the data from Koester (1980) were used.

2 Theory

2.1 The plasma electrical conductivity

On the basis of the previous work of Adanyam et al. (1980), a modified RPA method for calculation of the static conductivity of fully ionized plasma was developed in Djuric et al. (1991) and Adanyam et al. (1994a). The principal role of this method is in the formula for energy-dependent electron–electron (ee) and electron–ion (ei) relaxation times $t_{\text{ee}}(E) = t_{\text{ee}}^{\text{RPA}}$, where $E$ is the energy of a single electron state, determined as a sum over the Matsubara frequencies by using the methods of Green function theory. This method is especially suitable for calculation of the electrical conductivity of dense non-ideal plasmas with electron density ($N_e$) larger than $10^{17} \text{cm}^{-3}$. In the region $N_e < 10^{17} \text{cm}^{-3}$ the static conductivity of fully ionized plasmas can be determined well using the SC method developed in Mihajlov et al. (1993), which is also based on electron relaxation time $t_{\text{ee}}(E) = t_{\text{ee}}^{\text{SC}}$. It is important that the SC method gives practically the same results as the RPA method in a wider region of the electron densities around the value of $N_e = 10^{17} \text{cm}^{-3}$. The SC method was tested from this aspect in Vétel et al. (2001), where it was experimentally verified through comparison with the results from Spitzer (1962) and Kurilkenov (1984), just for the helium plasmas.

However, as was already mentioned, the helium plasma of the considered DB white dwarf atmospheres contains a significant neutral atom component, as follows from Bues (1970) and Koester (1980). Because of that, we will start here from the fact that in both RPA and SC methods effective electron relaxation times $t_{\text{ee}}(E)$ can be expressed as

$$
\frac{1}{t_{\text{ee}}(E)} = v_{\text{ee}}(E),
$$

where $E$ is the electron energy, and $v_{\text{ee}}(E)$ – the corresponding total electron–electron and electron–ion collision frequency. This gives the possibility of generalizing the modified RPA and SC methods for the case of partially ionized plasmas, replacing $1/t_{\text{ee}}(E)$ by $v_{\text{ee}}(E)$

$$
v_{\text{ee}}(E) = v_{\text{ee}}(E) + v_{\text{ei}}(E) = \frac{1}{t_{\text{ee}}(E)} + v_{\text{ei}}(E),
$$

where $v_{\text{ei}}(E)$ is an effective electron–atom collision frequency. Consequently, the basic RPA and SC expressions for the static electrical conductivity $\sigma_0$ transform to the corresponding Frost-like expressions

$$
\sigma_0 = \frac{4e}{3m} \int_0^\infty E w(E) \left( \frac{1}{t_{\text{ee}}(E)} + v_{\text{ei}}(E) \right) \frac{df_{\text{FD}}}{dE} \, dE,
$$

where $m$ and $e$ are the mass and the modulus of charge of the electron, $w(E)$ is the density of the single electron states in the energy space, $f_{\text{FD}}(E) = f_{\text{FD}}(E; T, N_e)$ is the Fermi–Dirac distribution function for given $N_e$ and temperature $T$ and $t_{\text{ee}}(E) = t_{\text{ee}}^{\text{RPA}}$ or $t_{\text{ee}}(E) = t_{\text{ee}}^{\text{SC}}$.

On the basis of composition and temperature data of the considered DB white dwarf atmospheres (Bues 1970; Koester 1980), one can note that only four components of these atmospheres are important for determination of $\sigma_0$: free electrons, He$^+$ and He$^{2+}$ ions and helium atoms. In accordance with this, the expression for $1/t_{\text{ee}}^{\text{RPA}}$, from Djuric et al. (1991) can be presented in the form

$$
\frac{1}{t_{\text{ee}}^{\text{RPA}}(E)} = \frac{4\pi m N_e e^4 k_B T}{(2mE)^{3/2}} \int_0^{\sqrt{mE}/h} dq \frac{q}{q} \left\{ Z_i^2 \Pi_{e,i}(q) - \sum_{j=1}^{n} \frac{Z_j^2 \Pi_{i,j}(q)}{N_{i,j}} + \sum_{j=1}^{n} \frac{Z_j^2 \Pi_{i,j}(q)}{N_{i,j}} \right\},
$$

where $h$ and $k_B$ are the Planck and Boltzmann constants, respectively, $Z_i$ and $Z_{i,j}$ are the charges of electron and He$^+$ (1s) and He$^{2+}$ (ions $Z_i = -1$, $Z_{i,j} = 1$, $Z_{i,j} = 2$), $N_{i,j}$ and $N_i$ are the corresponding helium ion densities, $\Pi_{e,i}(q)$, $\Pi_{i,j}(q)$ and $\Pi_{i,j}(q)$ are the electron and ion polarization operators, $\varepsilon_i(q)$ is the dielectric function, $n = 0, \pm 1, \pm 2 \ldots$ and the summation is extended over all the Matsubara frequencies $\Omega_n = 2\pi n k_B T/h$. The detailed expressions for polarization operators and dielectric functions are given in Djuric et al. (1991) and Adanyam et al. (1994a).

The SC expression for $\sigma_0$ is applied to the outer layers of the considered DB white dwarf atmospheres where $N_e < 10^{17} \text{cm}^{-3}$ and the presence of He$^{2+}$ ions can be neglected. Because of that the expression for $1/t_{\text{ee}}^{\text{SC}}$, in accordance with Mihajlov et al. (1993), can be taken in the form

$$
\frac{1}{t_{\text{ee}}^{\text{SC}}(E)} = \left[ \frac{1}{\chi_{\text{ee}}} - \frac{(2m)^{1/2} E^{3/2}}{2e^2 Z_i N_e \ln (1 + \Lambda_i^2)^{1/2}} \right]^{-1},
$$

where $k$ is the Boltzmann constant and $Z_i = 1$. The correction factor $1/\chi_{\text{ee}} = 1/\chi_{\text{ei}}(Z_i, T)$ is determined within the SC method.
while \( r_\text{sc} \sim (4\pi e^2N_e/kT)^{-1/2} \) is the corresponding screening length which is an external parameter of the theory. The values of \( 1/\chi_{ee} \) for \( N_e = 1 \) and \( 10^4 \) \( \text{K} \leq T \leq 10^5 \) \( \text{K} \) are taken from Mihajlov et al. (1993). Here, value \( r_\text{sc} = r_\text{sc} \) is taken as the screening length, where the ion neutrality radius \( r_\text{sc} \) is given by the expressions obtained in Mihajlov, Vitel & Ignjatović (2009). Such a choice of the screening length provides overlapping SC and RPA values of \( \sigma_0 \) in a wider region of electron densities around the value of \( N_e = 10^{17} \text{ cm}^{-3} \).

Finally, the electron–atom collision frequency \( v_{\text{coll}}(E) \) in equation (3) is given by the known expression

\[
v_{\text{coll}}(E) = N_a v(E) \cdot |Q_{\text{el}}^a(E)|^2,
\]

where \( N_a \) is the He(1\( s^2 \)) atom density, \( v(E) = (2E/m)^{1/2} \) is the relative electron–atom velocity and \( Q_{\text{el}}^a(E) \) is the transport cross-section for the elastic e–He(1\( s^2 \)) scattering (Mott & Massey 1970).

### 2.2 The electron–atom transport cross-section

The exact quantum-mechanical calculation of the transport cross-section for elastic electron–atom collisions is a very hard problem in itself. However, in the case of e–He(1\( s^2 \)) scattering the problem becomes easier within the considered temperature range where all non-elastic collision processes can be neglected. Namely, in this case it can be treated as scattering of electrons in an adequately chosen model potential \( U(r) \), where \( r \) is the distance between the electron and the nucleus of the He(1\( s^2 \)) atom. Thus, the electron movement is described by a wavefunction \( \Psi(r, \theta, \phi) = Y_{\ell \mu}(\theta, \phi) \), where \( Y_{\ell \mu}(\theta, \phi) \) is a spherical harmonic function of degree \( \ell \) and order \( m \), while the function \( \chi(r) \) satisfies the radial Schrodinger equation

\[
\left[ -\frac{1}{2} \frac{d^2}{dr^2} + U(r) + \frac{l(l+1)}{2r^2} \right] \chi(r) = E \chi(r)
\]

given in atomic units. Following the previous paper of Ignjatović & Mihajlov (1997), we can write the model potential \( U(r) \) in the form

\[
U_\text{el}(r) = -\frac{Z \alpha}{r} + \frac{q}{r + r_0}, \quad U_\text{in}(r) = \alpha r^2 + br + c, \quad U_\text{at}(r) = -\frac{Z - q}{r_0} + \frac{Z - q}{r_0}, \quad 0 < r < r_1,
\]

\[
U_\text{el}(r) = -\frac{Z \alpha}{r} + \frac{q}{r + r_0}, \quad r_1 < r < r_f, \quad (8)
\]

where \( Z = 2 \) is the charge of the nucleus of a helium atom, \( q \) and \( Z - q \) describe the redistribution of electrons in the 1s shell of the helium atom (0 < \( q < 2 \)), \( \alpha \) is the polarizability of the He(1\( s^2 \)) atom and \( r_0 \) has the meaning of the average radius of an atom. Parameters \( a, b, c \) and \( h \) are determined from the conditions of continuity and smoothness of the potential \( U(r) \) at the points \( r_1 \) and \( r_f \) where 0 < \( r_1 < r_0 \) and \( r_f > r_0 \). The values of the mentioned quantities are given in Table 1.

Equation (7) is solved by the partial wave method described in Ignjatović & Mihajlov (1997). One obtains as the result the phase shifts \( \delta_l(E) \) for \( l = 0, 1, 2, \ldots \), where each \( \delta_l(E) \) corresponds to the partial wave with a given orbital number \( l \). This way of solving equation (7) has advantages since, apart from the transport cross-section

\[
Q_{\text{el}}(E) = \frac{2\pi \alpha}{E} \sum_{l=0}^{\infty} (l + 1) \sin^2(\delta_l - \delta_{l+1}),
\]

it allows determination of the elastic cross-section, as well as cross-sections of higher order (viscosity cross-section, etc.). As one can see in Fig. 1, there is an excellent agreement between the values of \( Q_{\text{el}}(E) \) calculated using the potential (8) and various experimental and theoretical data of other authors.

### 3 RESULTS AND DISCUSSION

In order to apply our results to the study of DB white dwarf atmosphere plasma properties, helium plasmas with electron \((N_e)\) and atom \((N_a)\) densities and temperatures \((T)\), characteristic of atmosphere models presented in the literature (Koester 1980), are considered here. So, the behaviour of \( \rho \) and \( T \) for models with the logarithm of surface gravity \( \log g = 8 \) and effective temperature \( T_{\text{eff}} = 12000, 20000 \) and 30000 K is shown in Fig. 2 as a function of Rosseland opacity \( \tau \). One can see, these atmospheres contain layers of dense helium plasma. In order to cover the considered plasma parameter range reliably, we tested our method for calculation of the plasma electrical conductivity within a wider range of mass density \( 1 \times 10^{-6} \text{ g cm}^{-3} \lesssim \rho \lesssim 2 \text{ g cm}^{-3} \) and of temperature \( 1 \times 10^{3} \text{ K} \lesssim T \lesssim 1 \times 10^{5} \text{ K} \).

The influence of neutral atoms on the electrical conductivity of helium plasma is shown in Fig. 3. In this figure the electrical conductivities for \( T = 15000, 20000 \) and 25000 K are given as functions of mass density \( \rho \). The range between the two vertical dashed lines corresponds to the conditions in the considered DB white dwarf atmospheres. Two groups of curves, calculated using the expression (3), are presented in this figure: (a) the dashed ones, obtained by neglecting the influence of atoms, i.e. with \( v_{\text{coll}} = 0 \); (b) the full-line curves calculated with the influence of atoms included, i.e. with \( v_{\text{coll}} \) given by equation (6). First, one should note that the behaviour of these two groups of curves is qualitatively different: the first one increases constantly with the increase of \( \rho \), while the other group of curves decreases, reaches a minimum, and then starts to increase with the increase of \( \rho \). One could explain such behaviour of the electrical conductivity by the pressure ionization. This figure also clearly shows when the considered plasma can be treated as ‘fully ionized’.

In Fig. 4 we compare our values of the helium plasma conductivity, shown by full curves for \( T = 15000, 20000 \) and 25000 K within the region \( 5 \times 10^{-4} \text{ g cm}^{-3} < \rho < 2 \text{ g cm}^{-3} \), with the existing experimental data. Let us note that these experimental results are uniquely available for comparison so that, in spite of their low accuracy, the agreement with them gives the only possible indication that our results are correct.

Within the region \( \rho < 0.65 \text{ g cm}^{-3} \), i.e. to the left of the vertical line in Fig. 4, there are experimental results from Ternovoi et al. (1999) (\( \diamond \)) and Shilkin et al. (2003) (\( \triangledown \)), where the temperature was determined with an error of less than 20 per cent, which are related to the temperature range 20 000–25 000 K. For \( \rho > 0.65 \text{ g cm}^{-3} \), i.e. right of the vertical line in Fig. 4, are shown several values of the plasma conductivity, obtained by Ternovoi et al. (2002) for the temperature range 15 000–25 000 K. These experimental values are obtained with an experimental error \( \sim 50 \) per cent and can be treated only as characteristic of this temperature region as a whole. These

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**Table 1.** The parameter values of the model potential \( U(r) \) from equation (8) in atomic units.

| \( Z \) | \( q \) | \( a \) | \( b \) | \( c \) | \( h \) | \( r_1 \) | \( r_f \) | \( r_0 \) |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 2     | 0.7   | −0.59597652 | 2.2545472 | −2.19405731 | 1.384 | 0.01 | 0.73 | 1.75 | 0.9 |
data at least indicate that our results for $\rho > 0.65 \, \text{g cm}^{-3}$ lie in the correct domain of the electrical conductivity values.

The developed method was then applied to calculation of plasma electrical conductivity for the models of DB white dwarf atmospheres presented in Fig. 2. The results of the calculations are shown in Fig. 5. First, let us note a regular behaviour of the static electrical conductivity which one should expect considering the characteristics of DB white dwarf atmospheres. Further, the electrical conductivity profiles presented in this figure show that, for the considered DB white dwarf models, plasma electrical conductivity changes over the domain of values where our results agree with the experimental ones (see Fig. 4). This indicates that the theoretical apparatus presented here may be adequate to be used for investigation of DB white dwarfs in the magnetic field of their partners in binary systems and magnetic white dwarfs.

In order to provide the possibility for direct applications of our results to different theoretical investigations, the values of static electrical conductivity $\sigma_0$ of helium plasma in a wide range of $\rho$ and $T$
Figure 3. Static electrical conductivity $\sigma_0$ of dense He plasmas as a function of mass density $\rho$ (full curves), compared to the Coulomb part of the conductivity (dashed curves). The area left of the vertical dashed line marks the region which is of interest for DB white dwarfs.

Figure 4. Static electrical conductivity $\sigma_0$ of helium plasma for various temperatures as a function of the mass density $\rho$. The full line represents the calculations based on the expressions (3)–(6); to the right of the vertical dotted line, there is a region of extremely dense plasmas where one should treat the presented calculation as an extrapolation. – Shilkin et al. (2003), 20 000–23 000 K; – Ternovoi et al. (2002), 15 000–25 000 K; – Mintsev et al. (1980), 20 000–25 000 K.

are given in Table 2. This table covers plasma conditions for all models of DB white dwarf atmospheres presented in Koester (1980) and the corresponding values of $\sigma_0$ were determined for the helium plasmas in the state of local thermodynamical equilibrium with given $\rho$ and $T$.

The method developed in this paper also represents a powerful tool for research into white dwarfs with different atmospheric compositions (DA, DC etc.), and for investigation of some other stars (M-type red dwarfs, Sun etc.). Finally, the presented method provides a basis for the development of methods to
Figure 5. Static electrical conductivity $\sigma_0$ as a function of the logarithm of Rosseland opacity $\tau$ for DB white dwarf atmosphere models with $\log g = 8$ and $T_{\text{eff}} = 12000$ K (full curve), $T_{\text{eff}} = 20000$ K (dashed curve) and $T_{\text{eff}} = 30000$ K (dotted curve).

Table 2. Static electrical conductivity of helium plasma $\sigma_0[1/(\Omega m)]$

| $T$ [K] | 5.00E-07 | 1.00E-06 | 5.00E-06 | 1.00E-05 | 5.00E-05 | 1.00E-04 | 5.00E-04 | 1.00E-03 | 5.00E-03 |
|---------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 8000    | 6.53E+00 | 4.69E+00 | 2.15E+00 | 1.50E+00 | 6.90E-01 | 4.89E-01 | 2.20E-01 | 1.53E-01 | 6.88E-02 |
| 9000    | 4.34E+01 | 3.16E+01 | 1.47E+01 | 1.13E+01 | 5.12E+00 | 3.60E+00 | 1.58E+00 | 1.19E+00 | 5.20E-01 |
| 10000   | 1.69E+02 | 1.30E+02 | 6.74E+01 | 5.02E+01 | 2.38E+01 | 1.72E+01 | 8.12E+00 | 5.73E+00 | 2.56E+00 |
| 12000   | 9.36E+02 | 8.04E+02 | 5.09E+02 | 4.05E+02 | 2.19E+02 | 1.66E+02 | 8.35E+01 | 6.08E+01 | 2.92E+01 |
| 14000   | 2.27E+03 | 2.08E+03 | 1.62E+03 | 1.38E+03 | 8.87E+02 | 6.97E+02 | 3.99E+02 | 3.00E+02 | 1.28E+02 |
| 16000   | 3.64E+03 | 3.55E+03 | 3.15E+03 | 2.87E+03 | 1.45E+03 | 1.18E+03 | 6.85E+02 | 5.28E+02 | 2.75E+02 |
| 18000   | 4.70E+03 | 4.97E+03 | 4.76E+03 | 4.39E+03 | 2.87E+03 | 2.46E+03 | 1.58E+03 | 1.26E+03 | 7.07E+02 |
| 20000   | 6.08E+03 | 6.22E+03 | 6.32E+03 | 5.61E+03 | 4.99E+03 | 4.46E+03 | 3.21E+03 | 2.53E+03 | 1.58E+03 |
| 25000   | 9.95E+03 | 1.02E+04 | 1.02E+04 | 9.09E+03 | 9.09E+03 | 8.62E+03 | 7.74E+03 | 5.95E+03 | 3.74E+03 |
| 30000   | 1.33E+04 | 1.40E+04 | 1.56E+04 | 1.60E+04 | 1.60E+04 | 1.57E+04 | 1.50E+04 | 1.21E+04 | 9.59E+03 |
| 35000   | 1.65E+04 | 1.74E+04 | 2.02E+04 | 2.15E+04 | 2.15E+04 | 2.34E+04 | 2.35E+04 | 2.15E+04 | 1.78E+04 |
| 40000   | 1.97E+04 | 2.09E+04 | 2.43E+04 | 2.61E+04 | 2.61E+04 | 3.06E+04 | 3.18E+04 | 3.22E+04 | 2.80E+04 |
| 45000   | 2.31E+04 | 2.45E+04 | 2.84E+04 | 3.06E+04 | 3.06E+04 | 3.69E+04 | 3.93E+04 | 4.36E+04 | 3.98E+04 |
| 50000   | 3.04E+04 | 3.23E+04 | 3.70E+04 | 3.98E+04 | 3.98E+04 | 4.81E+04 | 5.26E+04 | 6.40E+04 | 5.80E+04 |
| 65000   | 3.81E+04 | 4.08E+04 | 4.65E+04 | 4.98E+04 | 4.98E+04 | 6.00E+04 | 6.56E+04 | 8.20E+04 | 9.82E+04 |
| 75000   | 4.58E+04 | 4.93E+04 | 5.66E+04 | 6.06E+04 | 7.26E+04 | 7.92E+04 | 9.84E+04 | 1.15E+05 | 1.35E+05 |

describe other transport characteristics which are important for the study of all mentioned astrophysical objects, such as the electronic thermo-conductivity in the stellar atmosphere layers with large electron density, electrical conductivity in the presence of strong magnetic fields and dynamic (high frequency) electrical conductivity.

ACKNOWLEDGMENTS

This work was supported by the Ministry of Science and Technological Development of Serbia as a part of the projects ‘Radiation and Transport Properties of the Non-ideal Laboratory and Ionospheric Plasma’ (Project number 141033) and ‘Influence of Collisional Processes on Astrophysical Plasma Line Shapes’ (Project number 146001).

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