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Radiative energy loss in a non-equilibrium argon plasma

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Abstract. The total radiative loss in atmospheric argon plasmas is calculated allowing for deviations from local Saha equilibrium LSE. We have taken into account non-equilibrium excited state populations using numerical and analytical collisional-radiative models. Simple expressions for the different radiation loss mechanisms are given in terms of the electron density, electron temperature and ionization degree. These quantities together with the heavy particle temperature also define the deviation from equilibrium. In the recombining zones the effect of non-equilibrium will have significant influence on the total radiative loss due to line radiation. The dominancy results from the fact that the electron density in a recombining plasma is much larger than the value predicted by Saha. The results of this study can also be used for non-atmospheric argon plasma provided that $n_e > 5 \times 10^{19}$ m^{-3} and $n(1)d > 10^{20}$ m^{-2} in which d is the plasma dimension.

1. Introduction

The use of thermal argon plasmas can be found in various applications. Cascaded arcs are well known in the field of deposition of carbon or silicon based films and radiation source technology. Inductively coupled plasmas (ICP) are used for spectrochemical analysis, plasma spraying, material synthesis and lightsources. For a proper understanding of these types of plasma it is necessary to compare experimental results with theoretical models. By means of this comparative study it might be possible to obtain insight into scaling laws and to optimize the various plasma applications.

The plasma systems under study in general have an ionizing part in which the plasma is created, and a recombining part, i.e. the afterglow, where deposition (cascaded arcs) or spectroscopic analysis (ICP) takes place. In both parts of the plasma significant deviations from local Saha equilibrium (LSE) are known to exist (in the usual nomenclature the abbreviation LTE is used). Plasma radiation, which is an important mechanism of energy loss, has considerable influence on the flow and temperature fields in thermal plasmas [1]. It is important to understand the effect of deviations from LSE on the radiative losses with respect to plasma modelling. However, in the typical temperature range 4000–12 000 K found in thermal argon plasmas there is lack of reliable radiative loss data and the data available are based on the LSE assumption. Recently, Wilbers *et al* (1991) [2] calculated the total radiative loss for isobaric argon plasmas allowing some departures from LSE which were incorporated using a two-temperature model and a non-equilibrium value of the neutral ground state population $n(1)$. The so-called $b(p)$ factors, defined by

$$b(p) = \frac{n(p)}{n^S(p)} \tag{1}$$

where

$$n^S(p) = n_e n_+ \frac{g_p}{2g_+} \left[\frac{h^2}{2\pi m_e k T_e}\right]^{3/2} \exp\left(\frac{E_{p+} - \Delta E}{kT_e}\right) \tag{2}$$

describes the deviation of the population of the excited levels from the Saha population. The symbols used in the formulae are explained in the nomenclature. Using equation (1) we can qualify the plasma studied in [2] by stating that $b(p) = 1$ for $p \neq 1$ whereas $b(1)$ and T_e/T_h are allowed to differ from unity. This condition is denoted by partial local Saha equilibrium (PLSE). It was found that over a wide range of T_e and T_h values ε_{rad}/n_e^2, where ε_{rad} is the total emission coefficient, was a function of electron temperature T_e only and that the radiation loss term is mainly determined by line radiation of which, in particular, the lines in the 4p–4s transitions are the most important. Since PLSE is assumed this means that $n(4p) = n^S(4p)$ which has the typical n_e^2 dependence in a singly ionized plasma ($n_e = n_+$). For $T_e > 10000$ K the results were in agreement with the experimental results of Evans and Tankin [3] fitted by Miller and Ayen [4].

Owano *et al* [5] reported experimental results for radiative losses in argon down to 6000 K. Comparison

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with the models in [2–4] shows good agreement. However, in the interpretation of their results, they relied on equilibrium relations of Boltzmann and Saha in determining the temperature and electron density. Again the conclusion was that the radiation is predominantly generated by line transitions.

The dominancy of line radiation is important since it can be used for a proper understanding of the non-PLSE situation of radiation loss. To construct a model which allows further deviations from LSE we must allow for $n(p)$ departures from Saha equilibrium. This can be done using a combination of experimental and theoretical results.

Measurements of excited state populations in helium afterglows [6] and in a freely expanding cascaded argon arc plasma [7] revealed the fact that these excited states were underpopulated with respect to the Saha population as described in [8]. This will result in a decreased radiative loss in comparison with the PLSE situation and it might affect the dominancy of the line radiation. On the other hand overpopulation of the excited levels in an ionizing low pressure argon plasma were reported by [9, 10] which would increase the radiative loss. Therefore, to be as general as possible, we should also consider these types of PLSE deviation in thermal plasmas.

The aim of this paper is to include non-equilibrium effects in the excited state population and to construct a radiative loss term for a relatively large range of plasma conditions as found in thermal argon plasmas. The radiative loss can be used as an energy loss term in plasma modelling. In order to cover a wide range of conditions we will construct four formulae to calculate the different radiation loss contributions, namely atom and ion free–free, recombination and line radiation.

2. Radiative loss term

2.1. Partial local Saha equilibrium

Before studying non-LSE conditions it is useful to study the equilibrium results as obtained in previous studies. Therefore we reproduce in figure 1 the results as obtained in [2] where the radiative loss due to line, recombination and free–free radiation generated by electron neutral interaction are compared to each other. The left vertical axis shows that the three contributions are normalized to n_e^2. This presentation is possible for the free–free and recombination emission provided the plasma is singly ionized. The same applies for line radiation if PLSE is present whereas the extra demand for the n_e^2 normalization of the neutral free–free radiation is that LSE is present or that the $b(1)$ is constant or known as a function of temperature over the whole temperature range.

We first consider the contribution of the line radiation which is given by

$$\varepsilon_{\text{line}} = \sum_{p,q} n_p A_{pq} \frac{h\nu_{pq}}{4\pi} = \sum_{p,q} b(p) n^S(p) A_{pq} \frac{h\nu_{pq}}{4\pi}. \quad (3)$$

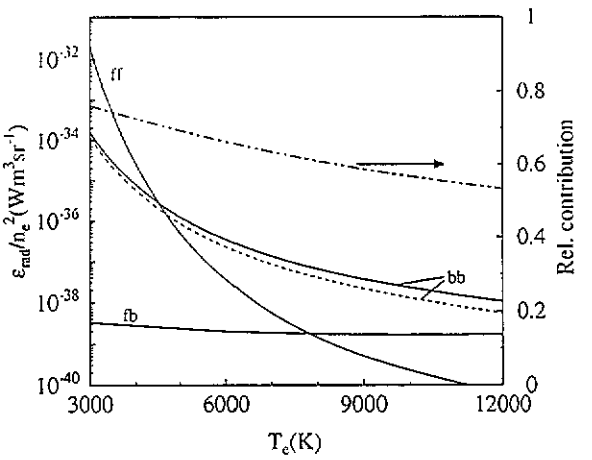

Figure 1. Contributions to the total radiative loss under atmospheric PLSE condition, as a function of temperature normalized to n_e^2, electron neutral free–free (ff), bound–bound (bb), free–bound (fb).

Table 1. The eight strongest lines.

Level	Statistical weight	Energy (eV)	A_{pq} value ($\times 10^8$)	Wavelength (Å)
4p[5/2]	7	13.072	0.366	8115.3
4p[3/2]	5	13.168	0.274	7635.1
4p[5/2]	5	13.091	0.233	8424.7
4p[1/2]	3	12.904	0.212	9123.0
4p'[1/2]	5	13.298	0.244	8408.2
4p[3/2]	3	13.149	0.277	8103.7
4p[5/2]	5	13.091	0.095	8014.8
4p'[3/2]	3	13.279	0.196	7948.2

For the calculation the plasma is assumed to be optically thin except for the resonance radiation for which we assume that the plasma is completely optically thick. As can be deduced from figure 1, in the temperature range 5000 K$\lesssim T_e \lesssim$ 12000 K, line radiation is the main contribution to the total radiative loss under PLSE conditions. The background of the dominancy of line radiation is that for PLSE conditions $n(p) = n^S(p) \propto n_e^2 \exp(E_{p+}/kT_e)$ (cf equation (2)) which increases with decreasing kT_e. Equation (3) indeed shows that the line radiation due to n_e^2 in $n^S(p)$ can also be normalized to n_e^2 provided $b(p) = 1$ or is a function of T_e only. Also of interest is the fact that line radiation is mainly determined by 4p–4s transitions. The broken line represents the radiative loss calculated with the eight strongest lines (cf table 1). As can be seen, these lines already represent 60–70% of the line radiation as shown on the right axis.

As stated before, it is a characteristic feature of the Saha formula (equation (2)) that the line emissivity increases for decreasing electron temperatures if the n_e value is kept constant. This can be illustrated in the power interruption experiment as initiated by Gurevich *et al* [11]. The switch-off of the power generator causing a cooling of the electrons results in an *increase* in the line emission. This rapid increase, with time constant τ_{T_e}, is followed by a much slower decay associated with recombination of the plasma. The results of the power interruption experiment in an ICP of Fey *et al*

[12] demonstrates that the excited levels of argon are governed by the Saha balance at an electron temperature ($T_e \simeq 0.8$ eV) higher than the heavy particle temperature ($T_h \simeq 0.6$ eV). For lower temperatures the deviations from Saha equilibrium increase and the excited state populations are expected to be underpopulated with respect to the Saha population [8]. Therefore it is possible that under recombining non-PLSE conditions the dominancy of line emission might be affected since only line radiation is affected by this departure from Saha.

2.2. Non-partial local Saha equilibrium

To investigate the influence of non-equilibrium values of the $b(p)$ factors, (i.e. $b(p) \neq 1$) on the line emissivity we can use collisional-radiative (CR) models. An instructive expression for the excited state population is [8]

$$b(p) = r^1(p)b(1) + r^+(p) \tag{4}$$

where $r^+(p)$ and $r^1(p)$ are the relative population coefficients for a purely recombining and ionizing plasma respectively. It is clear that we have to distinguish between two cases, i.e. ionizing and recombining plasma parts.

In the ionizing region where the plasma is created under relatively high temperature conditions, $b(1)$ is larger than 1. Typical values for $b(1)$ are $b(1) \sim 10$–10^3 in the active zone of the ICP and cascaded arcs. In low pressure ionizing plasmas the $b(1)$ can be as high as 10^6. However, CR models show that the population coefficient $r^1(4p)$ is of the order of a few 10^{-4} [13] so that the ground state contribution $r^1(p)b(1)$ to the excited state population can remain small for high pressure ionizing systems and we may expect that the PLSE condition is approached closely under high temperature, i.e. ionizing conditions. However to be as general as possible we should be prepared on strong ionizing conditions for which a large $b(1) \gtrsim 10^4$ value propagates to excited levels. From CR models we know that $r^1(p)$ scales with p^{-6} where $p = \sqrt{Ry/E_{p+}}$ is the effective principal quantum number, if the system is collisional dominated [8, 13],

$$r^1(p) = b_0 p^{-6}. \tag{5}$$

In general the coefficient b_0 is a function of T_e and n_e so for a given n_e, T_e and $n(1)$ value the $b(1)$ can be computed using equations (1) and (2). For sufficiently large n_e values, i.e. $n_e \gtrsim 10^{20}$ m^{-3} b_0 is a sole function of T_e. Equation (5) provides information on the enhanced population density, i.e. enhanced line radiation.

On the other hand, in the recombining region such as the afterglow we meet with the low temperature situation. The density $n(p)$ which scales with n_e^2, increases with decreasing temperature due to the exponent (cf equation (2)) so that the radiative loss term becomes relatively important. Van de Sanden *et al* [7] have measured excited state populations of argon in a free expanding arc created plasma jet. In figure 2 the $b(p)$ factors are shown versus $\epsilon_p = E_{p+}/kT_e$ for different positions in the expanding plasma jet corresponding to different temperatures (a) [7] and for an helium afterglow (b) [6]. The $b(p)$ factors are smaller than 1 indicating that the excited states are underpopulated with respect to Saha population. Values up to 10^{-4} are attained so that the emissivity of the line in question is reduced by a factor of 10^{-4}! Symbols indicated by an arrow represent the same argon line transition (4p'[1/2], 7503 Å) under different T_e values. Also shown in figure 2 are theoretical atomic state distribution functions (ASDF) according to calculations of Mansbach and Keck [14] and Biberman *et al* [15] (modified diffusion approximation). The theoretical ASDFs are based on the so-called cold de-excitation saturation balance in which collisional de-excitation prevails over radiation [8]. The ASDF calculated by Biberman *et al* is derived for hydrogen like systems and reads

$$b_{\mathrm{Bib}}(\epsilon_p) = b(1)\chi(\epsilon_p) + [1 - \chi(\epsilon_p)] \tag{6}$$

where

$$\chi(x) = \frac{4}{3\sqrt{\pi}} \int_0^x e^{-t} t^{3/2}\, dt$$

Note that equation (6) is of the same form as equation (4). Recombining systems are characterized by $b(1) \to 0$. For $\epsilon_p > 1$ the function $1 - \chi(\epsilon_p)$ can be approximated by

$$b_{\mathrm{Bib}}(\epsilon_p) \simeq \frac{4}{3\sqrt{\pi}} \epsilon_p^{3/2} e^{-\epsilon_p} \left(1 + \frac{3}{2\epsilon_p} + \dots\right) \tag{7}$$

The ASDF of [14] can be approximated by

$$b_{\mathrm{MK}}(\epsilon_p) \simeq \left(\frac{\epsilon_p^3}{3!} + \frac{\epsilon_p^2}{2!} + \epsilon_p + 1\right) e^{-\epsilon_p}. \tag{8}$$

The difference between the two theoretical ASDFs is due to the different set of cross-sections used in these models [8]. Both equations (7) and (8) state that the underpopulation solely depends on ϵ_p, which means that a level with a large E_{p+} value in a high temperature plasma should behave in the same way as a level with a low E_{p+} value at low temperature. This is confirmed by the fact that the various experimentally obtained values [6, 7, 9] are found to be functions of ϵ_p solely. For high ϵ_p values it is not clear which theoretical ASDF is the most appropriate. For low ϵ_p values the experimental results favour the ASDF of [14]. The same conclusion can be drawn from the measurements of Hinnov and Hirschberg in a helium afterglow (cf figure 2(b)) [6]. For $\epsilon_p \lesssim 6$ the results of [6] are in excellent agreement with equation (8) [8]. For the 4p levels of argon which are dominant in the line radiation loss this corresponds to a temperature range of $T_e >$ 5000 K. Concluding we may state that for recombining plasmas $b(p)$ decreases with decreasing temperature so the line emissivity will increase much more slowly than predicted by the PLSE assumption. Therefore the dominancy of the line emissivity becomes questionable and we have to consider the different radiation loss mechanisms separately. In the next section we will use equations (5), (7) and (8) to calculate the line contribution to the radiative losses.

Table 2. Fit coefficients.

Equation (9)		Equation (13)		Equation (14)	
f_0	-38.11	a_0	2.781	d_0	-52.564
f_1	-1.53×10^{-4}	a_1	-9.512×10^{-4}	d_1	0.0292
f_2	1.33×10^{-8}	a_2	8.183×10^{-8}	d_2	-6.539×10^{-6}
f_3	-3.57×10^{-13}	a_3	-2.541×10^{-12}	d_3	8.362×10^{-10}
				d_4	-6.136×10^{-14}
				d_5	2.402×10^{-18}
				d_6	-3.883×10^{-23}

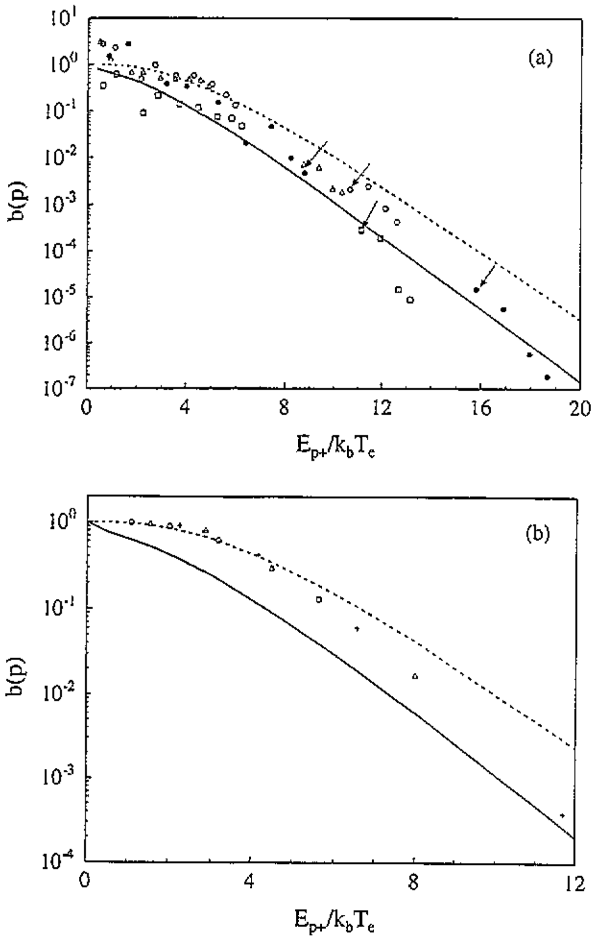

Figure 2. The $b(p)$ factor as function of E_{p+}/kT_e. (a) Experimental values for $b(p)$ in argon for different temperatures in a free expanding cascaded arc jet [9]. $\bullet$: $T_e = 0.144$ eV, $\circ$: $T_e = 0.213$ eV, Δ : $T_e = 0.260$ eV, $\square$: $T_e = 0.204$ eV. (b) Experimental $b(p)$ values in a helium afterglow [6]. $+$: $T_e = 0.13$ eV, Δ : $T_e = 0.19$ eV, $\circ$, $T_e = 0.27$ eV. Also shown are the ASDFs of [15] (full line) and of [14] (broken line).

3. Results

In this section the results of free–free and line radiation will be presented as separate equations. The reason is that in a broad range of non-LSE conditions $n(1)$, n_e and T_e are decoupled. We start with the emissivity contributions due to ion free–free and recombination transitions which do not depend on the state of equilibrium departure. These contributions can be found in [2] and are fitted by (cf table 2)

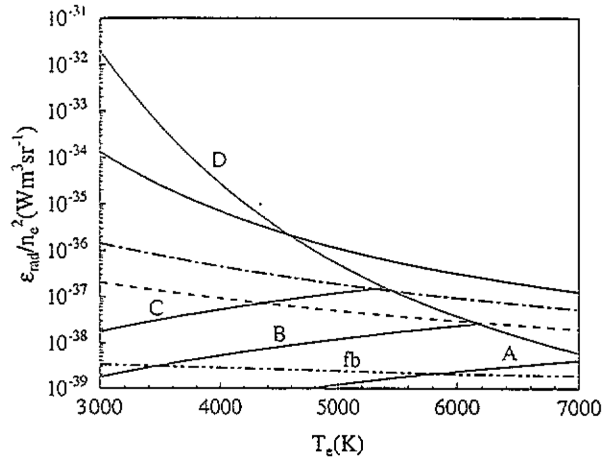

Figure 3. Radiation losses due to line transitions, neutral free–free and recombination radiation (fb). (- - - -), recombination radiation. Line transitions are shown by: (——), PLSE; (– · –), [14]; (– – –), [15]. Neutral free–free radiation is calculated with $\alpha = \max(\alpha_{LSE}, \alpha_{min})$. A: $\alpha_{min} = 10^{-4}$; B: $\alpha_{min} = 10^{-5}$; C: $\alpha_{min} = 10^{-6}$; D: $\alpha = \alpha_{LSE}$.

$$\log_{10}\left(\frac{\varepsilon_{ff}^{ei} + \varepsilon_{fb}}{n_e^2}\right) = \sum_{i=0}^{3} f_i T_e^i. \tag{9}$$

The quantities are expressed in MKS units.

For a proper treatment of the line radiation the line emissivity must be divided into a part originating from the ground state which is related to $r^1(p)$ and from the continuum related to $r^+(p)$ (cf equation (4)). Figure 3 compares the line radiation loss for the ASDF according to Bibermann *et al* (dashed line), Mansbach and Keck (dashed dotted line) and to Saha (full line). The latter, added for the sake of completeness, makes a comparison of this study and those of [2–4] possible. It should be noted that at 4000 K the differences between Bibermann and Mansbach and Keck are more than one magnitude ($b_{MK}(4p[5/2]) \sim 0.5$ and $b_{Bib}(4p[5/2]) \sim 0.01$) whereas the differences between the values of Saha and those of Bibermann are more than four orders of magnitude. The data of the radiative losses originating from the continuum contribution ($r^+(p)$), calculated with the ASDF of Biberman *et al* can be fitted by

$$\varepsilon_{Bib}^{+}(T_e, n_e) = n_e^2 10^{-27.52-1.18\ln(T_e)} \quad \mathrm{W\,m^{-3}\,sr^{-1}} \tag{10}$$

while the radiative losses calculated with the ASDF of Mansbach and Keck leads to

$$\varepsilon_{MK}^{+}(T_e, n_e) = n_e^2 10^{-22.78-1.66\ln(T_e)} \quad \mathrm{W\,m^{-3}\,sr^{-1}} \tag{11}$$

Note that in all cases collisional de-excitation must be dominant which means that $n_e \gtrsim 5 \times 10^{19}$ m^{-3}. In the transition region between ionizing and recombining systems we meet the situation that $\epsilon_p \lesssim 6$. This value corresponds to a 4p level at 5000 K. For $T_e \gtrsim 5000$ K we recommend the use of equation (11) to calculate the line radiation due to the part of the excited level densities which originates from the ions (cf $r^+(p)$ in equation (4)).

The line radiation originating from the ground state contribution of the excited levels (cf equations (4) and (5)) can be calculated by substituting $b(1)b_0p^{-6}$ into equation (3), which yields

$$\varepsilon^1 = \frac{n(1)b_0}{g_1 Ry^3} \sum_{p,q} \exp(-E_p/kT_e) E^3_{p+} g_p A_{pq} \frac{h\nu_{pq}}{4\pi}. \quad (12)$$

It is obvious that the sum in equation (12) is a function of T_e only. For $n_e \gtrsim 5 \times 10^{19}$ m^{-3} the coefficient b_0 is almost independent of n_e [8, 16]. The coefficient b_0 is calculated using the CR model of [13] and can be fitted by (cf table 2)

$$\log_{10} b_0(T_e) = \sum_{i=0}^{3} a_i T_e^i \quad (13)$$

where T_e is expressed in K. Equation (12) is then only a function of $n(1)$ and T_e

$$\varepsilon^1(n(1), T_e) = 6.29 \times 10^{-30} n(1) b_0(T_e) F(T_e)$$
$$F(T_e) = \sum_{i=0}^{6} d_i T_e^i. \quad (14)$$

For low temperatures equation (14) can be used even for n_e values lower than 10^{20} m^{-3} since the ionizing contribution will then be negligible. When ionizing equilibrium departures are small equation (14) is insignificant compared with other radiation loss contributions. Only strong ionizing conditions for which $b(1) \gtrsim 10^4$ may cause equation (14) to contribute substantially.

The neutral free–free emissivity depends on the product $n_e n(1)$ in contrast to all the other emissivity contributions which depend on n_e^2. However, to make comparison possible we write

$$\frac{\varepsilon^{ea}_{ff}}{n_e^2} \sim \frac{n_e n(1)}{n_e^2} = \frac{n(1)}{n_e} = \frac{1}{\alpha} \quad (15)$$

showing that the ionization degree α is a suitable parameter. For higher temperatures it is plausible that the LSE value of α gives a good description for ε^{ea}_{ff}. However, for recombining conditions it is expected that there will be an overpopulation of n_e with respect to its Saha value. This again can be related to the power interruption experiment of Gurevich and Podmoshenkii where it is found that for argon the temperature relaxation time is much smaller than the plasma recombination time so that n_e and T_e are decoupled in contrast with the LSE state [12]. The spectral emissivity ε^{ea}_{ff} can be integrated over the frequency domain yielding

$$\frac{\varepsilon^{ea}_{ff}(T_e, n_e/n(1))}{n_e^2} = \left(\frac{6C_2k}{hc}\right) T_e^{5/2} \left(\frac{n(1)}{n_e}\right) Q(T_e) \quad (16)$$

which is an increasing function of T_e at constant $n_e/n(1)$. Also shown in figure 3 are the ε^{ea}_{ff} contributions (fine lines) for various minimum ionization degrees α_{min} (10^{-6}, 10^{-5} and 10^{-4}). In representing $\varepsilon^{ea}_{ff}/n_e^2$ we assumed an atmospheric LSE plasma for the higher temperature domain. When $\alpha_{LSE} = (n_e/n(1))_{LSE} < \alpha_{min}$ equation (16) is used to calculate ε^{ea}_{ff} with $\alpha = \alpha_{min}$. If $\alpha_{LSE} > \alpha_{min}$ we choose α_{LSE}.

From figure 3, where the radiation losses as predicted by formulae (9), (10), (11) and (16) are compared to each other we may conclude the following: (1) Line radiation using non-LSE formulae for a recombining ASDF is lower than those predicted by Saha. However, it is still dominant provided $\alpha_{min} > 10^{-5}$. (2) With respect to the continuum radiation we may state that the neutral free–free is larger than the recombination radiation for an α value larger than 10^{-4}.

We now have four simple expressions ((9), (11), (14) and (16)) to calculate the total radiative loss which can be used in plasma modelling. The input parameters are T_e, n_e and $n(1)$. It would be convenient to compare the total radiative loss with results from various authors. However, a proper comparison is not possible since T_e, n_e and $n(1)$ are decoupled in our case. In figure 4 the total radiative loss for an atmospheric argon plasma versus temperature is shown. The ionization degrees corresponds with those of figure 3. The curve marked α_{LSE} is obtained when n_e, $n(1)$ and T_e would be related by Saha's relation. In the temperature range $T_e \lesssim 12000$ K line radiation is the main loss contribution provided $\alpha > 10^{-5}$. This is partly based on the fact that for lower temperatures the population density of the excited level will increase. However. one should realize that this increase is much smaller than the value predicted by Saha. Therefore the radiation due to equation (11) will be lower than predicted [2]. The main reason of the dominancy of line radiation in a recombining plasma is based on the fact that the n_e value in such a plasma will be much larger than the value predicted by Saha. The results of this study can also be used for non-atmospheric conditions provided $n_e > 5 \times 10^{19}$ m^{-3} and $n(1)d > 10^{20}$ m^{-2}, where d is the plasma dimension. The reason for the first demand is that the ASDF must be collision dominated and the second demand deals with the fact resonant radiation should be trapped.

4. Conclusions

The model of [2] for the total radiative loss has been extended by allowing larger deviations from LSE. Deviations from LSE are manifested by two important effects. First we take into account the effect of non-equilibrium ASDFs (cf equation (4)). The ground

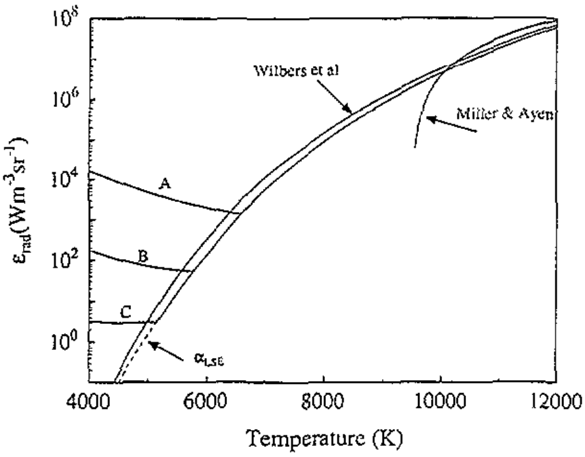

Figure 4. The total radiative loss in which the electron neutral free–free radiation is calculated with $\alpha = \max(\alpha_{LSE}, \alpha_{min})$. A: $\alpha_{min} = 10^{-4}$; B: $\alpha_{min} = 10^{-5}$; C: $\alpha_{min} = 10^{-6}$; D: $\alpha = \alpha_{LSE}$. For comparison the results of Wilbers *et al* [2] and Miller and Ayen [4] are also shown.

state contribution of the non-equilibrium excited state population is calculated with the numerical CR model of [13], while for the continuum contribution the analytical ASDF of [14] has been used. Secondly n_e and T_e are decoupled, especially in the recombining zone. A suitable parameter to account for this deviation from LSE is the ionization degree and plays an important role in the neutral free–free radiation. In the recombining zone the influence of non-LSE on the total radiative loss may be substantial and is due to the fact that line radiation depending on the ASDF does not obey the Saha equation. However, the line radiation will remain dominant. The background is that for low temperatures the actual electron density is higher than the Saha value for the electron density which is obtained using the ground state density and the temperature. An auxiliary LTE deviation is the difference between the heavy particle and electron temperature which can be accounted for by the pressure. The total radiative loss is then a function of the electron density, electron temperature and ionization degree. Analytical expressions and numerical fits for the different radiative loss mechanisms are given (9), (11), (14) and (16) which can then be used in plasma modelling.

Nomenclature

A_{pq}	Transitions probability
$b(p)$	Non-equilibrium parameter
c	Velocity of light
C_2	Electron-neutral continuum constant (1.03×10^{-34} W m^2 K$^{-3/2}$ sr^{-1})
d	Plasma dimension
E_p	Excitation energy of level p
E_{p+}	Ionization energy of level p
ΔE	Lowering ionization potential
g_p, g_+	Statistical weight
h	Planck's constant
k	Boltzmann constant
$n(1)$	Neutral particle density
n_e	Electron density
$n(p)$	Excited state density
n_+	Ion density
$n^S(p)$	Saha population density
p	Principal quantum number
Q	Electron-atom cross-section
Ry	Rydberg energy
$r^1(p), r^+(p)$	Relative population coefficients
T_e	Electron temperature
T_h	Heavy particle temperature
α	Ionization degree
ϵ_p	E_{p+}/kT_e
ε	Emissivity
ν_{pq}	Frequency of radiation

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