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Determination of the average ionization and Corona, LTE and NLTE regimes of optically thin aluminium plasmas

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1. Introduction

As it is known, x-rays have special relevance as a major diagnostic tool of the plasma. Thus, x-ray emission is a primary process occurring during both the evolution and the expansion phases of the plasma and it is the main detectable process carrying information on the plasma during the stages of plasma production and heating, and, therefore, the emerging x-ray spectrum provides us information about the electron temperature, ion density and ionization state distribution (Salzmann and Wendin, 1978). Theoretical calculations require accurate computations of x-ray radiation rates. For low and high density plasmas they are usually calculated assuming either corona equilibrium (CE) or local thermodynamic equilibrium (LTE) approaches, respectively. However, neither of them is able to cover the whole range of density and temperature variations. For plasma intermediate densities, the collisional radiative (CR) model (McWhirter and Hearn, 1963) has been widely used. In this work we consider the steady state situation (CRSS) in which the ionization state densities as well as the level population probabilities are time independent. The CRSS model approaches CE and LTE in the low and high density limits, respectively. However, the determination of the level populations using the CRSS model is complicated due to the number of atomic levels and processes involved is huge. This fact implies that the implementation of the CRSS model in plasma simulating codes may consume large amounts of computer time. That is the reason why the determination of LTE and CE plasma regimes in terms of the density and temperature becomes useful, because in these regions it is avoided the resolution of the full set of the rate equations entailing a considerable reduction of the complexity of the problem and computing time. With this purpose, in this work it is established a criterion to determine the plasma conditions under which the LTE and CE approaches are accurate enough in order to obtain average ionizations and ionization state densities. There are available other criteria in the literature to determine when an ion or an atomic level is under LTE or CE conditions (Griem, 1964; Cooper, 1966; Eliezer et al., 1978) Our criterion states the regime of the whole plasma by means of the analysis of ion state populations. We have performed the study for aluminium plasmas. The plasmas are assumed homogeneous and isotropic with constant temperature and electron-number density and optically thin. Therefore, reabsorption is not incorporated. Therefore, the results obtained are applicable only to plasmas in which the redistribution of ionization states due to photoionization is negligible compared to electron-impact ionization.

2. Theoretical Model

All the calculations presented in this work were performed by using ABAKO code, an improvement of ATOM3R one (Florido et al., 2006). The atomic data required for the calculations have been obtained under the relativistic detailed configuration accounting approach into the context of the central field model. The model includes ground and single and double excited states of all the ions involved in the calculations. The effective central potential employed to obtain the atomic magnitudes was an analytical one (Martel et al., 1998). The interactions in the plasma are taken into account by means of the continuum lowering (Stewart and Pyatt, 1966). The CRSS implemented includes the following atomic processes: collisional excitations and desexcitations, collisional ionization and three body recombination, autoionization and electron capture, spontaneous decay and radiative recombination. The rate coefficients of these processes are evaluated using widely known analytical expressions and they are given elsewhere (Florido et al., 2006). ABAKO was proved that provides accurate results for the determination of average ionization and ion state and level population probabilities in the last Kinetic Codes Comparison Workshop (Rubiano et al., 2007).

3. Results and discussion

Our criterion for determining LTE and CE plasma regimes is based on the comparison of ion state population probabilities between those calculated using CRSS model and Saha-Boltzmann or Corona equations. With that aim, we define the following estimator

$$\varepsilon = \sqrt{\frac{\sum_{\varsigma=0}^{Z}\left(p_{\varsigma} - p_{\varsigma,CRSS}\right)^2}{\sum_{\varsigma=0}^{Z} p^2_{\varsigma,CRSS}}} \tag{1}$$

where p_{ς} denotes the population probability of the ion state ς. According to the definition of the estimator, only the most abundant ions will have more influence. Requiring that the estimator to be lower than 0.1, we obtain the map presented in figure 1(a). Along with the map is plotted the average ionization, which is helpful in order to reduce the number of ions include in the calculations. We have plotted in figure 1(b) only up to 140eV because for higher temperatures only helium and hydrogen like species are presented. In figure 2 it is shown, as an example, the behaviour of the average ionization and ion population probabilities for a given temperature as a function of plasma density. We can observe in figure 2(a) how, for 10 eV, the ion population probabilities of the most abundant ions (see figure 1(b)) converge to CE results under densities around 10^{16} cm^{-3} and to LTE ones for densities above 4×10^{19} cm^{-3}, which agrees with figures 1(a) and 2(a).

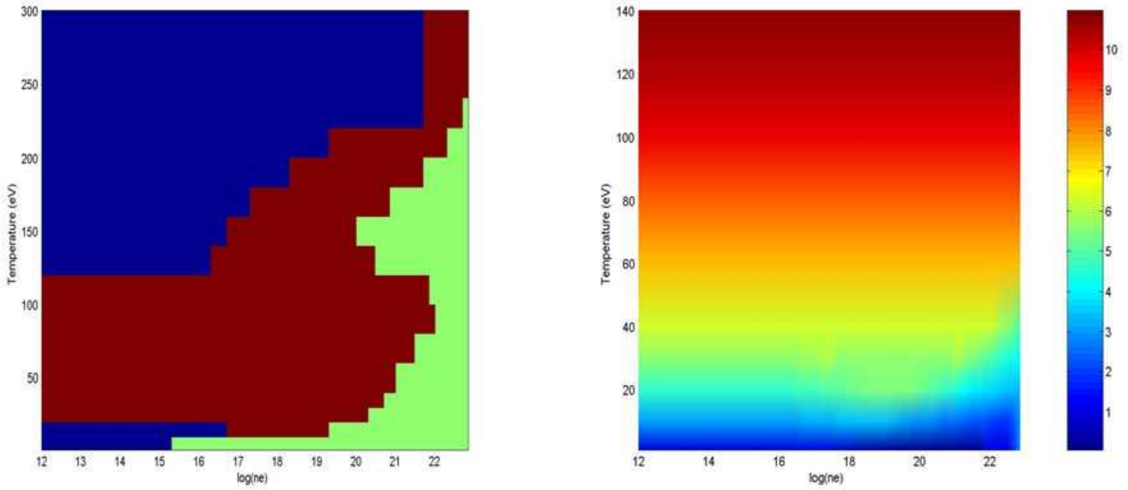

Figure 1. (a) CE, LTE and NLTE regions (blue, green and red colours, respectively) (b) Plasma average ionization. The figures are plotted vs. plasma temperature and electron number density (cm^{-3}).

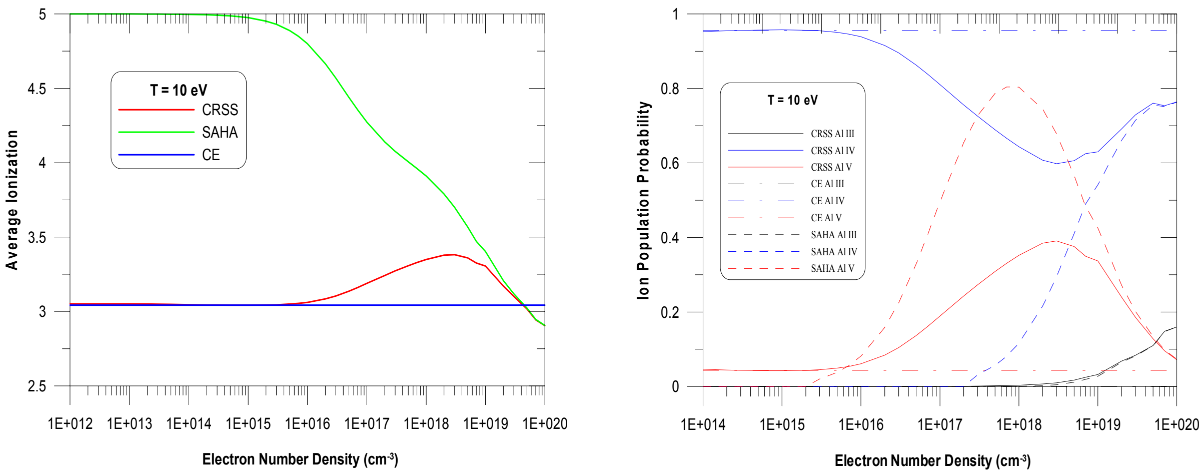

Figure 2. (a) Average ionization vs the density for a temperature of 10 eV. (b) Convergence to CE and LTE results of the population probabilities of the three most abundant ions for 10 eV.

In the low density regime, the ion population probabilities do not change with the density. This behaviour is confirmed by figure 3. The structure of the lines in the emissivity is the same for the two densities. The only difference is that for the higher density the intensity is larger, which is expected since the occupation of the excited levels increase with density.

Finally, in figure 4 we present the excellent agreement for high densities between the results of CRSS and SAHA for the emissivity, and therefore for the level populations, which is a confirmation of our results predicted by the map in figure1.

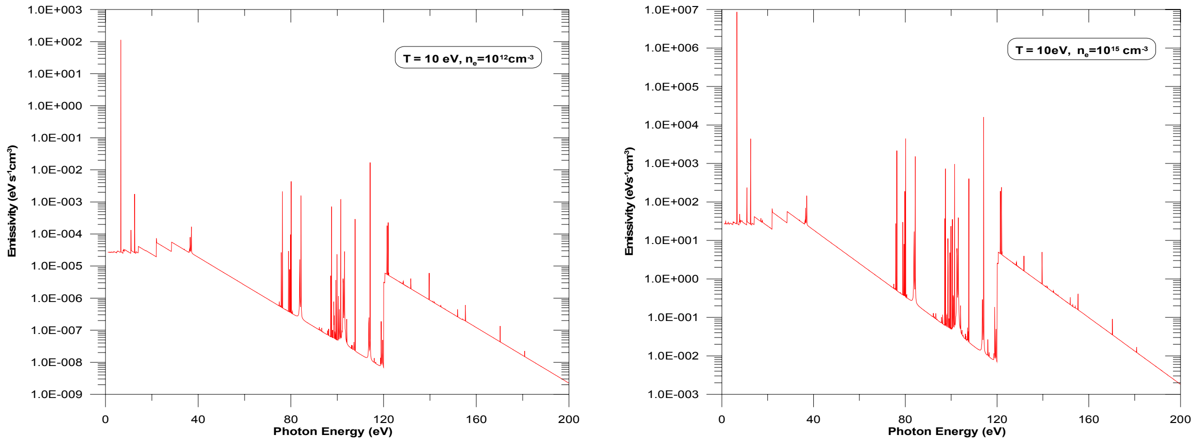

Figure 4. Spectrally resolved emissivities for low density regime.

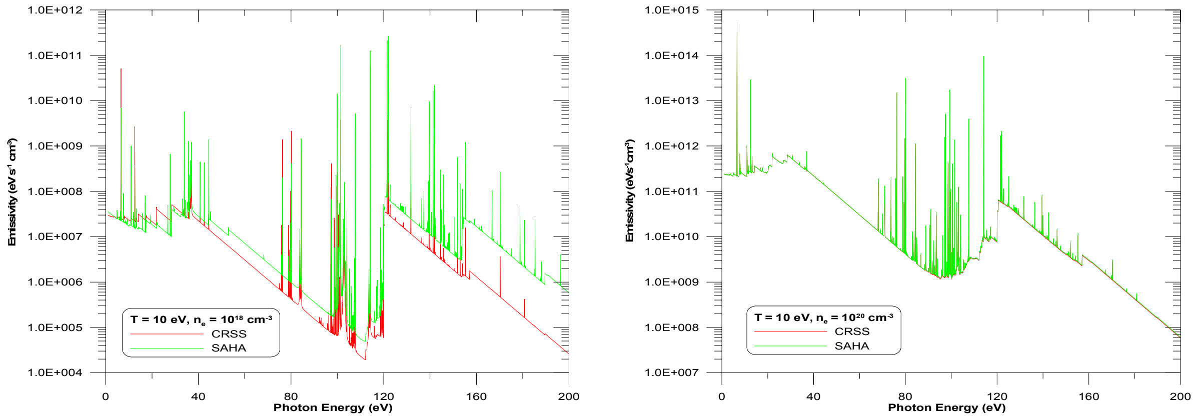

Figure 4. Spectrally resolved emissivities calculated using Saha or CRSS equations.

Acknowledgments

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