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# Analysis of the influence of the plasma thermodynamic regime in the spectrally resolved and mean radiative opacity calculations of carbon plasmas in a wide range of density and temperature

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## ABSTRACT

In this work the spectrally resolved, multigroup and mean radiative opacities of carbon plasmas are calculated for a wide range of plasma conditions which cover situations where corona, local thermodynamic and non-local thermodynamic equilibrium regimes are found. An analysis of the influence of the thermodynamic regime on these magnitudes is also carried out by means of comparisons of the results obtained from collisional-radiative, corona or Saha–Boltzmann equations. All the calculations presented in this work were performed using ABAKO/RAPCAL code.

## 1. Introduction

The role of the radiative properties is known to be of decisive importance to many research fields of plasma physics, such as astrophysics or nuclear fusion both inertial and magnetic confinement, since they are essential to explain and analyze the experiments or observations and a key radiative property is the opacity, which quantifies how transparent or opaque the plasma is to the radiation. Thus, in astrophysics, the opacities of stellar mixtures control the energy transfer in stars, which affects the stellar structure and evolution [1], and rule the levitation of metals in stellar interiors [2]. In the research of inertial confinement fusion the opacities are essential in the design of hohlraum walls. Furthermore, they are involved in radiative-hydrodynamic simulations where the energy of the matter and the radiation are of the same order, and, also, the theoretical calculations of opacity also provide a method to the temperature and density diagnostics of hot plasmas.

Due to its relevance, research on radiative opacities has greatly developed during the past several decades, though most of them were focused on Local Thermodynamic Equilibrium (LTE) regime [3–8]. However, Non-Local Thermodynamic Equilibrium (NLTE) plasmas are found in a wide range of density and temperature conditions as for example in inertial confinement fusion (both direct and indirect-drive fusion schemes), in magnetic confinement fusion (both in tokamaks and stellarator devices), $z$-pinch plasmas, coherent X-ray sources, ultrashort pulse laser-produced plasmas or stellar atmospheres. On the hydrodynamic time scales, NLTE thermodynamic regime is favored when the plasma presents strong time and space gradients and hence there is not enough time for equilibrium to be achieved, or even in the

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case of homogeneous and time independent plasma, NLTE conditions exist if plasma is of finite size and the photon can escape from it.

In principle, the calculation of opacity for LTE plasmas is as similar as that for NLTE plasmas except that the calculation of the atomic level populations is different. In the first case, the level populations are obtained by solving the Saha–Boltzmann (SB) equations, and in the second one, the populations are obtained by solving the rate equations, being the so-called collisional-radiative model (CRM) an essential tool for these calculations. However, the complexity of the rate equations, which requires a huge amount of atomic data and collisional and radiative atomic processes, makes much more difficult to give accurate level populations and radiative properties for NLTE plasmas than for LTE ones. For this reason, during the recent years many groups have been developing NLTE radiative properties calculations and codes [7–26], and new models and results are always welcomed.

Carbon is one of the most important elements under investigation in several research areas: in astrophysics, due to its abundance in the stars; in magnetic nuclear fusion confinement, because it is likely to be a major plasma-facing wall component in the international experimental reactor (ITER) and it is present as impurity in a lot of devices; and it plays a major role in inertial fusion scenarios, for example, in the direct-drive implosion cores where the deuterium target has a thickness plastic shells. In a previous work [27], we presented a systematic calculation of average ionization, ionic and level populations of the optically thin carbon plasma in a wide range of plasma conditions. We assumed that the comparison between the average ionization and ion and level populations calculated from collisional-radiative steady state (CRSS), Corona (C) and SB equations can provide information about the thermodynamic regime of the plasma, determining the plasma conditions where Corona equilibrium (CE), LTE or NLTE could be assumed. This work is a continuation of the previous one, since it is performed a study of spectrally resolved, multigroup and mean opacities of carbon plasmas. The interest in multigroup and mean opacities is related to the resolution of the radiative transport equation. It is well known that this equation is very complicated and, in general, one must approximate the radiative equation in order to obtain an analytical solution or to reduce the cost of the numerical solution. The aim of a large number of applications is to obtain numerical solution of the specific intensity in the space and time, and approximations on the angle and frequency dependence are commonly done. Usually, the angular dependence is represented by a spherical harmonic expansion in the low order angular or diffusion approach which is obtained when only the first two terms in the expansion are considered. There exist many methods to approximate the frequency dependence, and we can divide these into two families. The first one, the multigroup methods in which the frequency spectrum is discretized into $n$ frequency contiguous groups, assigning a frequency group to a given photon and a mean opacity for each frequency group from the average of the spectrally resolved opacity. Finally, the radiative transport equation is solve for each group. The second method is based on the key recognition that transport of photons depends on the value of the opacity not the value of the frequency. In this case one can discretize spectrally resolved opacity into $n_b$ opacity contiguous groups and reorganize the frequency spectra according to the value of the opacity. This creates disjoint sets of frequencies, the bins or pickets, with similar spectrally resolved opacity. Now we assign a mean opacity for each bin and solve the transport equation for each one. Both methods require a procedure or definition to obtain the mean opacity, which consist in the selection of the photon distribution function or weighting function, and this can of course be made by different ways. Special cases commonly used are the Planck mean opacity, which is appropriate in the time independent radiative transport in a LTE optically thin plasmas, or if the equilibrium diffusion approximation is considered, the Rosseland mean opacity.

The temperature and density conditions analyzed in this work were $10^{-12}-10^{-1}$ g cm$^{-3}$ and 1–10$^3$ eV, respectively. These ranges of plasma conditions cover LTE and NLTE thermodynamic regimes. This fact will allow us to provide the opacity data of carbon plasma in a wide range of plasma conditions and to study the influence of the thermodynamic regime into opacities by means of the comparisons between opacities calculated by using level populations obtained from CRSS and SB equations. The study will be carried out analysing spectrally resolved, multigroup and mean opacity magnitudes, we have assumed Planck and Rosseland multigroup and mean opacities, and all the calculations presented in this work were performed using the ABAKO/RAPCAL computational package [22,26,28]. The atomic data have been obtained under the detailed-level-accounting (DLA) approach including configuration mixing using FAC code [29]. In the next section, the theoretical model is briefly described. In Sections 3 and 4 results and conclusions are presented, respectively.

## 2. Theoretical model

The calculations in this work were performed using the computational package ABAKO/RAPCAL [28] which consists in two codes, ABAKO [26] and RAPCAL [21,22] devoted to the calculation of the plasma level populations and radiative properties, respectively. A brief description of both codes is given in the following.

### 2.1. Atomic data and level populations

In order to determine the plasma level populations, in ABAKO is implemented a collisional-radiative steady state (CRSS) model. Following the standard NLTE modeling approach, where an account of the existing atomic states is made and the microscopic (radiative and collisional) processes connecting these states are identified, a rate equation system describing the population density of the atomic states is built and solved, giving the population distribution. Therefore, to find the level population