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Parametrization of Mean Radiative Properties of Optically Thin Steady-State Plasmas and Applications

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Abstract. Plasma radiative properties play a pivotal role both in nuclear fusion and astrophysics. They are essential to analyze and explain experiments or observations and also in radiative-hydrodynamics simulations. Their computation requires the generation of large atomic databases and the calculation, by solving a set of rate equations, of a huge number of atomic level populations in wide ranges of plasma conditions. These facts make that, for example, radiative-hydrodynamics in-line simulations be almost infeasible. This has lead to develop analytical expressions based on the parametrization of radiative properties. However, most of them are accurate only for coronal or local thermodynamic equilibrium. In this work we present a code for the parametrization of plasma radiative properties of mono-component plasmas, in terms of plasma density and temperature, such as radiative power loss, the Planck and Rosseland mean opacities and the average ionization, which is valid for steady-state optically thin plasmas in wide ranges of plasma densities and temperatures. Furthermore, we also present some applications of this parametrization such as the analysis of the optical depth and radiative character of plasmas, the use to perform diagnostics of the electron temperature, the determination of mean radiative properties for multicomponent plasmas and the analysis of radiative cooling instabilities in some kind of experiments on high-energy density laboratory astrophysics. Finally, to ease the use of the code for the parametrization, this one has been integrated in a user interface and brief comments about it are presented.

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Key words: Parametrization of plasma radiative properties and applications, steady-state collisional-radiative model, optically thin mono- and multi-component plasmas.

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1 Introduction

The role of the plasma radiative properties is known to be of decisive importance to many research fields at plasma physics such as astrophysics, X-ray laser development, laboratory plasma astrophysics, EUV lithography and inertial and magnetic confinement fusion, since they are essential to explain the experiments and the observations. Thus, for example, the opacities are fundamental in the design of hohlraum walls and the radiative power losses play an important role in the current decays after disruptions in magnetic nuclear fusion devices in which disruptions are assumed to be caused by strongly radiating impurities [1]. Furthermore, the data on mean or mean-group opacities and radiative power losses are required in radiative-hydrodynamics simulations and the monochromatic opacities and emissivities are used for plasma spectroscopic diagnostics. Therefore, it is essential to obtain sufficiently accurate data on plasma radiative properties within a wide range of plasma densities and temperatures.

The calculation of the plasma radiative properties implies the computation of the population of the atomic levels in the plasma. At high densities, where the plasma can be considered under local thermodynamic equilibrium (LTE) they can be obtained by means of the Saha-Boltzmann's equation. Also, in the low density regime, where Coronal equilibrium (CE) could be assumed, these quantities can be obtained using the simple equations of the CE model. However, these limit situations are exceptions and non-LTE (NLTE) conditions are commonly found in both laboratory and astrophysical plasmas. In NLTE the calculation of the plasma atomic level populations, and therefore of the radiative properties, shows great complexity because there is not a priori expression for these quantities and one must find them using the so-called collisional-radiative models (CRM) in which one has to solve a set of rate equations, as many as the number of atomic levels included in the model, with coupling of atomic configurations, free electrons and photons. Furthermore, CRMs reproduce, in stationary state, CE and LTE results at the extreme limits of low and high densities, respectively. Taking into account that accurate calculations of both atomic level populations and radiative properties entail to consider in the CRM as many levels as possible, the resolution of the resulting large system of rate equations becomes sometimes unmanageable and approximations must be made. For this reason, the theory of NLTE plasmas is a still very active subject and many NLTE codes have been developed [2–13] since the early proposals [14,15]. The complexity and the computational time cost of the resolution of CRMs has led to develop analytical expressions for the radiative properties in order to provide them in a fast way for in-line radiation-hydrodynamics. However, most of them are accurate only for CE [16–21] since they are density independent or for the range of high photon energies in LTE [22,23], but not for NLTE situations.

In this work we first present a method to parametrize the radiative power losses (RPL), Planck and Rosseland mean opacities and average ionizations, in terms of the density and temperature of the plasma, for steady-state optically thin mono-component plasmas. The databases of these quantities subject to the parametrization are calculated