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Analysis of microscopic magnitudes of radiative blast waves launched in xenon clusters with collisional-radiative steady-state simulations

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ABSTRACT

Radiative shock waves play a pivotal role in the transport energy into the stellar medium. This fact has led to many efforts to scale the astrophysical phenomena to accessible laboratory conditions and their study has been highlighted as an area requiring further experimental investigations. Low density material with high atomic mass is suitable to achieve radiative regime, and, therefore, low density xenon gas is commonly used for the medium in which the radiative shocks such as radiative blast waves propagate. In this work, by means of collisional-radiative steady-state calculations, a characterization and an analysis of microscopic magnitudes of laboratory blast waves launched in xenon clusters are made. Thus, for example, the average ionization, the charge state distribution, the cooling time or photon mean free paths are studied. Furthermore, for a particular experiment, the effects of the self-absorption and self-emission in the specific intensity emitted by the shock front and that is going through the radiative precursor are investigated. Finally, for that experiment, since the electron temperature is not measured experimentally, an estimation of this magnitude is made both for the shock shell and the radiative precursor.

1. Introduction

The popularity of the field of laboratory astrophysics has grown considerably over the last two decades. Two developments in the field have contributed to the successful design of laboratory astrophysical models: first, it has been demonstrated that the hydrodynamics can be scaled correctly between laboratory and astrophysical scenarios [1–6]; second, the improvement of high-power laser systems allows us to generate plasmas that are in the regimes for certain astrophysical systems. Those experiments permit to explain and predict what occurs in astrophysical phenomena and have the advantage of being repeatable and that the initial conditions are under control. Besides, those experiments also provide important data for verification and validation of several aspects of numerical codes such as atomic physics, equation of state, radiative transfer and hydrodynamics.

One of the most interesting astrophysical phenomena is the shock waves which are ubiquitous throughout the universe and play a crucial role in the transport of energy into the interstellar medium [7]. When the radiation transport is important to the total energy budget, shock waves can be radiatively driven so that its dynamics can be

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significantly modified by radiative processes. At high shock velocity, the shocked medium is heated and ionized emitting radiation, which gives rise to radiative cooling. The radiation emitted in turn heats and ionizes the unshocked medium leading to the creation of a radiative precursor [8]. Radiative shocks are observed around astronomical objects in a wide variety of forms, e.g. accretion shock, pulsating stars, supernovae in their radiative cooling stage, bow shocks of stellar jet in galactic medium, collision of interstellar clouds and entry of rockets or comets into planetary atmospheres [9–11] and they are also observed in laser inertial fusion [12].

Laboratory studies of radiative shocks are, currently, a research area of interest thanks to the advent of experimental facilities that are able to produce high energy-density conditions. Thus, in laboratory, three methods have been commonly used to create radiative shocks in gases [13] and they can be characterized according to the optical depth of the gas ahead of (upstream) and behind (downstream) the shock. The first is to make a *shock tube* [14] by driving a solid density plastic or beryllium piston into a xenon gas cell. These experiments have been conducted at Omega [3,15–18] and LULI [19–22] using kJ lasers obtaining planar geometry. Because the laser pulse is long (≈ns) there is a continuous injection of energy to the shock which produces a stationary structure. The shock speeds reached in this kind of experiments are very high (>50 km s^{-1}) and the shocked gas is highly compressed (>30) due to the strong radiative losses. Because of the high density of the piston the downstream medium is optically thick whereas the upstream medium is optically thin, and for this reason this system is classified as *thick–thin* [23]. An astrophysical example of this kind of systems is the accretion shocks produced in some binary systems.

A different type of shock is produced after a sudden release of energy in a zero-extension and instantaneous explosion. In this case, a shock moves into the surrounding medium creating a blast wave, that is generally described as an expanding shock that is in the process of sweeping up the material that is ahead of the shock. The blast waves have been generated experimentally in two alternative ways. In the first one, by using a kJ laser to irradiate a pin or foil within a moderate to high Z background gas [24,25]. In the second one, the laser energy can be deposited directly into gas formed by atomic clusters to launch shocks [7,26–36]. Clustered gases exhibit extremely efficient absorption of intense laser light creating a hot, high energy density plasma in a low average density target. This plasma subsequently explodes into the ambient gas forming a cylindrical blast wave [26]. Thus, high Mach number shocks can be launched using high intensity lasers ($>10^{17}$ W cm^{-2}) with energies lower than 1 J. For a given shock velocity and a given initial gas pressure, materials with medium or high atomic numbers suit the achievement of the radiative regime, and for this reason, krypton and xenon are commonly used for the medium in which the radiative shock propagates. In these low density gas blast waves both the upstream and downstream medium are optically thin and therefore they can be classified as *thin–thin* [37]. Thin–thin shocks are the most commonly observed in astrophysics. Supernova remnant shocks in dense enough environment are of this type, for example.

In this work an analysis of some microscopic properties of radiative blast waves launched in xenon clusters is made. In particular, their thermodynamic regimes, the photon mean free paths (PMFP), the cooling times, the average ionization and the charge state distributions (CSDs) are studied. This analysis will allow us to characterize the laboratory blast waves launched in xenon clusters. Furthermore, for a particular experiment carried out using the THOR laser system at the University of Texas [33], the influence of the self-absorption and the self-emission is studied, both in the calculation of the specific intensity emitted by the shock front and which is going through the radiative precursor. Furthermore, as the electron temperature of the plasma is not experimentally measured, an estimation of this magnitude is also made both for the shock shell and the radiative precursor. To perform this analysis kinetics calculations under stationary approach were made using the computational package ABAKO/RAPCAL [38]. The next section is devoted to a brief description of this computational package. In Section 3 the analysis of the microscopic magnitudes is performed and finally in the last section conclusions and general remarks are presented.

2. Theoretical model

The calculations in this work were performed using the computational package ABAKO/RAPCAL [38] that consists of two codes, ABAKO [39] and RAPCAL [40].

2.1. ABAKO

ABAKO is devoted to the calculation of the plasma level populations using a collisional-radiative steady-state (CRSS) model. The CRSS model is solved level by level (or configuration by configuration, depending on the atomic description used) and it is applied to low-to-high Z ions under a wide range of plasma conditions: Coronal equilibrium, local and non-local thermodynamic equilibrium (LTE and NLTE, respectively), optically thin and thick plasmas. 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 distribution, under stationary situations, the following system of rate equations is solved:

$$\sum_{\zeta' j} N_{\zeta' j} \mathbb{R}^{+}_{\zeta' j \to \zeta i} - \sum_{\zeta' j} N_{\zeta i} \mathbb{R}^{-}_{\zeta i \to \zeta' j} = 0, \tag{1}$$

where $N_{\zeta i}$ is the population density of the atomic level i of the ion with charge state ζ. The terms $\mathbb{R}^{+}_{\zeta' j \to \zeta i}$ and $\mathbb{R}^{-}_{\zeta' j \to \zeta i}$ take into account all the atomic processes which contribute to populate and depopulate the state ζi, respectively. This set of equations constitutes the so-called CRSS model. In this work, the calculations of the plasma atomic level populations were performed using the CRSS implemented in the computational code named ABAKO [39]. In ABAKO it is assumed that the system has had enough time to thermalize and, therefore, both the electrons and ions have a Maxwell–Boltzmann type