Simulations of radiative shocks and jet formation in laboratory plasmas

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Abstract. We present the simulations of two relevant hydrodynamical problems related to astrophysical phenomena performed by three different codes. The numerical results from these codes will be compared in order to test both the numerical method implemented inside them and the influence of the physical phenomena simulated by the codes. Under some conditions laser produced plasmas could be scaled to the typical conditions prevailing in astrophysical plasmas. Therefore, such similarity allows to use existing laser facilities and numerical codes suitable to a laser plasma regime, for studying astrophysical processes. The codes are the radiation fluid dynamic 2D ARWEN code and the 3D HERACLES, and, without radiation energy transport, a Smoothed-Particle Hydrodynamics (SPH) code. These codes use different numerical techniques and have overlapping range of application, from laser produced plasmas to astrophysical plasmas. We also present the first laser experiments obtaining cumulative jets with a velocity higher than 100 km/s.

1. Introduction

There is a considerable interest in simulating astrophysical phenomena in terrestrial laboratories. We are performing studies on supernova remnant collision, radiative shocks experiments and adiabatic jet production. These are three examples of astrophysical phenomena that can be scaled to laboratory plasmas\cite{1}. Radiative shocks can be found for instance at the first stages of stellar formation. This is the first type of simulations that we briefly present herein. The second one concerns on the formation and propagation of jets, either by the collision of two shock waves (cumulative)\cite{2, 3} or by two colliding plasmas (radiative). These simulations have to be compared with recent experiments held at the PALS laser facility. The third class of problems concerns the interaction of blast waves. This may occur in the astronomical context with the interaction of supernovae remnants. All of these cases can be used too for testing numerical codes. This paper is concentrated on the first 2 cases: radiative shocks and jets.
2. Numerical simulation codes

2.1. HERACLES

One of the codes we use to perform our simulations is the three-dimensional radiation-hydrodynamics code HERACLES [4, 5]. It is based on the resolution of the Euler equations for the hydrodynamics coupled to the moments equations of the transfer equation. The original analytical $M_1$ closure relation used for the radiative model allows to be exact both in the diffusive and in the transport limit regimes (medium optically thick and thin respectively). This code has been already tested against analytical model and compared with other codes [5], and these tests showed that it can deal with a large variety of astrophysical problems. We have for instance studied the influence of multidimensional radiative effects over the structure of radiative shocks (fig.1), in particular in the context of reaching the stationary limit [6]. This work has to be put into relation with the study of radiative shocks obtained on experiments conducted on the high-energy laser facilities. HERACLES has already been used to setup and analyze a laboratory experiment of such radiative shocks [7]. This cross-validation between experiment and simulation justify then the relevance of HERACLES for dealing with astrophysical situations. Furthermore, HERACLES is under constant numerical development with the recent inclusion of a two-temperature hydrodynamic model (which allows the thermal decoupling of ions and electrons) and the integration of a laser-matter interaction module which is an on-going work. The development of these two features will then make this code even more relevant for the modelling of laboratory experiments.

2.2. ARWEN

The other code used for the simulations is a 2D Adaptive Mesh Refinement multigroup radiation transport (Sn-DSA) code[8]. ARWEN is being used for the simulations of the collision of Supernova Remnants[9] and for the studies of cumulative jets[10, 11]. As we have two codes based on different radiative models at our disposal, we have initiated a comparison between the radiative model included in HERACLES and the one in ARWEN, namely $M_1$ and $S_n$ methods respectively [12]. We have shown that in the case of Marshak wave without matter coupling the two methods gave similar results to a few percent, and with matter coupling the discrepancy is of about 20% on the front position. Finally, a SPH code[13] in 3D and 2D cylindrical geometry is used for simulations of the actual astronomical phenomena, in order to check the proper scaling of the laboratory simulations[14, 15]. Comparisons between ARWEN and SPH code are being done in order to improve the target design for SNR collision experiments[16, 9].
3. Cumulative jets

Jets for laboratory astrophysics studies are usually obtained by collision of plasmas generated by a laser. These jets are characterized by high temperature and velocity but low density. Other way to obtain jets with high density is by cumulative process[10]. This kind of jets could be produced in solar corona when shocks are self-focused[17]. These jets could be used too for equation of state studies, or as a possible ignitor beam for some fast ignition designs.

Experiments are being done at PALS iodine laser that could confirm some of the computational results obtained up to now. This laser provided a 250 ps (FWHM) pulse with the energy of 100 J at the first harmonic (λ = 1.315 µm) and focal spot radius of 150 µm on the target (the focal point was located inside the target). In this case the laser intensity on the flat target surface was $3.5 \times 10^{14}$ W/cm². According to the simulations, the uniformity of the spatial beam profile is very important for the jet production, and it was the reason to use $1\omega$ beam line at PALS. The cones were made of a 9 µm thick Al foil and their radius at the base was set to 300 µm (fig.2). Two cone semiangles were used: 30° and 45°. The average cone wall thickness were 5.2 µm and 6.4 µm for the 30° cone and the 45° cone, respectively. The electron density was measured and plotted in (figs. 3,4), where the sequence of jet production is clearly seen after 3 ns. The experimental results plotted in figs. 3 and 4 are symmetric because the procedure of electron density distribution computation employs the Abel inversion, so input data of phase shift distribution have to be symmetrical. In the case of a small asymmetry, both because of imperfections in the laser or in cone fabrication, the symmetrization of the interferometric data is performed by different mathematical methods. These methods result in some smoothing but conserving some important properties of plasma, which are seen on interferograms.

According to these plots, average jet velocities are 100 – 200 km/s, around 2 times the experimental foil flyer velocities (60 km/s) for this laser intensity. This is the first time that cumulative jets are obtained by irradiating cone targets. The jet structure is better in the 45° case that in the 30°, a result consistent with the simulations, but we expected much higher velocities in the 30° case, something that is not observed in the experiments.

Finally, recent preliminary experiments with $3\omega$ laser and at higher energies did not produce any cumulative jet structure.

Conclusions

We are performing several studies of laboratory experiments linked to relevant astrophyssical phenomena with several codes that use modern numerical methods. It allows to check the accuracy of the results and the sensitivity of the simulations to the numerical method implemented in the codes.
Figure 3. Experimental results for semiangle $\alpha = 30$

Figure 4. Experimental results for semiangle $\alpha = 45$

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References
[1] Ryutov D et al, 1999, Astrophys. J., 518, 821
[2] Chou P. C., Carleone J., Karpp R. R. 1976, J. Appl. Phys., 47, 2975
[3] Zababakhin E., I. Zababakhin I. 1990, Nauka Publishers
[4] González, M., & Audit, E. 2005, ApSS, 298, 357
[5] González, M., Audit, E., & Huynh, P. 2007, A&A, 464(2),429
[6] González, M. et al. 2007, to be submitted to A&A
[7] González, M. et al. 2006, LPB, 24, 535
[8] Ogando, F., & Velarde, P. 2001, JQSRT, 71, 541
[9] Velarde, P. et al. 2006 PoP 13
[10] Velarde, P. et al. 2005, LPB 23, 43
[11] Velarde, P. et al. 2005, NIMA 544, 329
[12] González, M. et al. 2007, ASTRONUM 2007 proceedings
[13] García-Senz, D. et al. 1998, AJPS, 115, 119
[14] Chevalier R. A. 1981, ApJ 258, 790
[15] Drake R. P., et al. 1998, ApJ 500, 157
[16] Williams et al. 1997, Astrophys J., 480
[17] Tarbell T. et al, 1999, Astrophys. J. 514, L47