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Hydrodynamic interaction of SNR shocks with thermally conducting, radiative clouds

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Abstract. Supernova remnants (SNRs) are privileged laboratories to investigate the physical and chemical evolution of the galactic interstellar medium (ISM) and the mass distribution of the plasma in the Galaxy.
Here, we study the interaction of an evolved SNR shock front with on a small interstellar gas cloud. Our model takes into account the hydrodynamics and the effects of the radiative losses and of the thermal conduction. We study the interplay between the radiative cooling and the thermal conduction during the cloud evolution and their effect on the mass and energy exchange between the cloud and the surrounding medium. We find that in cases dominated by the radiative losses the cloud fragments into cold, dense, and compact filaments surrounded by a hot corona which is ablated by the thermal conduction; instead, in cases dominated by the thermal conduction, the shocked cloud evaporates into the ISM in a few dynamical time-scales. In all the cases analyzed we find that the thermal conduction suppresses the hydrodynamic instabilities at the cloud boundaries.

Key words. hydrodynamics – shock waves – ISM: clouds – ISM: supernova remnants

1. Introduction

The complexity of SNR is due, to a large extent, to the complex interaction of the expanding SNR shock front with inhomogeneities (e.g clouds) of the ISM, involving thermally conducting supersonic flows, radiative losses, non-equilibrium of ionization (NEI) effects, etc.. To investigate such phenomena and to understand the details of the mass and energy exchange between the cloud and the intercloud medium sophisticated numerical simulations have been required. However, in spite of the extensive literature on this subject (e.g. Klein et al. 1994 and references therein; Xu & Stone 1995; Fragile et al. 2004), several aspects of the shock-cloud interaction remain unexplored, for instance: how do the effects of ra-

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diative losses and thermal conduction combine on the interaction and subsequent evolution of shocked clouds?

In this context, we have started a project devoted to study the shock-cloud interaction through detailed and extensive numerical modeling; one of the aims is to investigate the role of thermal conduction and radiative losses in the dynamics of the shock-cloud interaction (Orlando et al. 2005). Here, we discuss two representative cases of shock-cloud interaction in two very different physical regimes in which the radiative losses or the thermal conduction is the dominant process.

Our calculations are carried out with the FLASH code (Fryxell et al. 2000) using customized numerical modules that treat optically thin radiative losses and thermal conduction, including effects of heat flux saturation. FLASH is a multidimensional hydrodynamics code for simulating astrophysical plasmas. It uses the PARAMESH (MacNeice et al. 2000) library for block-structured adaptive mesh refinement and is designed for portability and efficiency on massively parallel computers using MPI-based message passing.

2. The model

We model the impact of a plane parallel supernova shock front with an isobaric spherical cloud by solving numerically the time-dependent fluid equations of mass, momentum, and energy conservation, taking into account the thermal conduction and the radiative losses from an optically thin plasma:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \,, \tag{1}$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \rho \mathbf{u}\mathbf{u} + \nabla P = 0 \,, \tag{2}$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + P)\mathbf{u} = - \nabla \cdot q - n_e n_H \Lambda(T). \tag{3}$$

Here $E = \epsilon + \frac{1}{2}|\mathbf{u}|^2$,

is the total gas energy (internal energy, ϵ, and kinetic energy), t is the time, $\rho = \mu m_H n_H$ is the mass density, $\mu = 1.26$ is the mean atomic mass (assuming cosmic abundances), m_H is the mass of the hydrogen atom, n_H is the hydrogen number density, n_e is the electron number density, $\mathbf{u}$ is the gas velocity, T is the temperature, q is the conductive flux, and $\Lambda(T)$ represents the radiative losses per unit emission measure (e.g. Raymond & Smith 1977; Mewe et al. 1985 and subsequent upgrades). We use the ideal gas law, $P = (\gamma - 1)\rho\epsilon$.

Following Dalton & Balbus (1993), the thermal conductive flux

$$q = \left(\frac{1}{q_{spi}} + \frac{1}{q_{sat}} \right)^{-1} ,$$

switches smoothly from the "classical" flux, q_{spi} (Spitzer 1962), to the "saturated" flux, q_{sat} (Cowie & McKee 1977).

We performed hydrodynamic simulations both with or without the thermal conduction and the radiative losses, adopting a 2-D cylindrical coordinate system and, where necessary, a 3-D cartesian coordinate system.

3. Results

The role of thermal conduction and radiative losses has been investigated by comparing models calculated with these physical processes switched "on" or "off". We show here two representative cases: a Mach 30 shock wave impacting on an isolated cloud 10 times denser than the surrounding medium (density ratio $\chi = 10$); and a Mach 50 shock impacting on a cloud with $\chi = 10$. In the former case the radiative losses are the dominant process, whereas in the latter case the thermal conduction is dominant. Figure 1 shows the evolution of the shock-cloud interaction in both cases; each panel shows the density distribution at a given time either without (left half panels) or with (right half panels) the thermal conduction and the radiative losses.

In the Mach 30 shock case (upper panels in Fig. 1), the shock-cloud evolution is dominated by the radiative losses which strongly affect the structure of the transmitted shock,

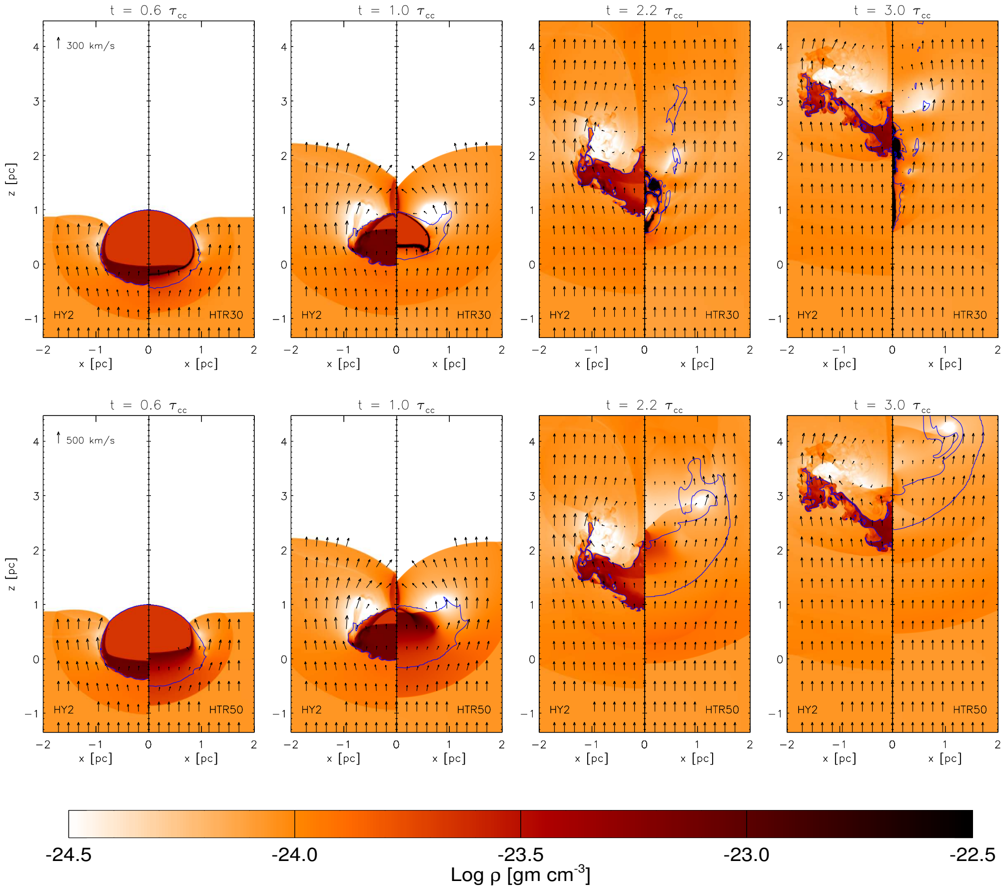

Fig. 1. 2-D sections in the (x, z) plane of the mass density distribution (gm cm^{-3}), in log scale, in the Mach 30 (upper panels) and Mach 50 (lower panels) shock case, sampled at the labeled times in units of the cloud-crushing time, τ_{cc}, i.e. the characteristic time for the transmitted shock to cross the cloud (adapted from Orlando et al. 2005). Each panel shows the simulation without (left half panels) and with (right half panels) the radiative losses and thermal conduction. The velocity arrows scale linearly with respect to the reference velocity shown in the upper left panel. The contour encloses the cloud material.

leading to thermal instabilities; the strong cooling in the post-shock cloud region results in the rapid accumulation of the cooled material in a thin dense shell as well as in the substantial weakening of the transmitted shock. At the same time, a diluted outer part of the cloud starts to develop a hot corona surrounding the dense shell. In the last stages, the strong cooling leads to cool and dense material accumulating along the symmetry axis (see Fig. 1). The cooling-dominated cloud material ultimately fragments into dense, cold, and compact filaments which survive until the end of our simulation, whereas the hot corona gradually evaporates under the effect of the thermal conduction.

In the Mach 50 case (lower panels in Fig. 1), the thermal conduction is the dominant process during the whole evolution and the radiative losses do not contribute to the dynamics of the shocked cloud. The front face of the cloud, overrun by the shock, is strongly diffused and the shocked cloud material is quickly heated. A transition region from the inner part of the cloud to the ambient medium gradually grows during the evolution, after the expansion of the cloud. In such a region, the density and temperature gradients (very steep in the model without thermal conduction) vary very smoothly in the radial direction. In the last stages analyzed, the cloud is progressively heated up to the temperature of the surrounding medium and diluted down to the ambient density.

In all the cases examined, the thermal conduction is very efficient in suppressing the hydrodynamic instabilities which otherwise develop at the cloud boundaries, reducing the mixing of cloud material with the ambient medium driven by such instabilities.

4. Conclusions

In this paper we studied the hydrodynamic interaction of a supernova shock wave and an isolated gas cloud. In particular, we have investigated the role played by thermal conduction and radiative losses during the shock-cloud interaction.

In our subsequent studies, we aim to extend the present work investigating also the deviations from equilibrium ionization that are likely to be induced during the complex dynamics of the shock-cloud interaction. Our project will include the synthesis, from the numerical simulations, of spatially and spectrally resolved X-ray observations as they would be collected with the last-generation instruments (e.g. Chandra, XMM-Newton, Astro-E2), with the aim to derive detailed predictions to be compared with observations.

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