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Using AMR to Simulate the 3-D Hydrodynamic Interaction of Supernova Shocks with Interstellar Gas Clouds

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Abstract. We study the 3-D hydrodynamic interaction of supernova shock fronts with interstellar clouds to investigate the evolution, the morphology and the deviations from equilibrium of ionization. To this end, we use the FLASH code including PARAMESH, an advanced and versatile parallel adaptive mesh refinement package. We present here the preliminary results obtained modeling a representative case of a Mach 50 shock impacting on an isolated cloud with density contrast $\chi = 10$ with respect to the ambient medium. The preliminary analysis of the non-equilibrium ionization (NEI) effects on the ionization stages of oxygen, and iron is discussed.

Key words. Numerical Codes – Hydrodynamics – Interstellar Medium

1. Introduction

The complexity of supernova remnants (SNR) is due, to a large extent, to the complex interaction of the expanding SNR shock front with inhomogeneities of the interstellar medium (ISM). The phenomena at work are certainly complex and involve the interaction of supersonic flows, and the NEI effects. To investigate such phenomena two main approaches have been followed so far: i) modeling the interaction of the shock front with the interstellar clouds, with very few predictions comparable with observations (e.g. Stone & Norman 1992); ii) global estimates from very simplified models compared to observations (e.g, Hamilton & Sarazin 1984; White & Long 1991). There has been, so far, no modeling effort with accurate account of the NEI effects, very important to understand the emitted spectrum, and thus observations.

In this context, we are studying the dynamics of the interaction of a SNR shock wave with an interstellar cloud, considering a representative case. Such a case requires a fully 3-D hydrodynamics in geometry to describe realistically the role of instabilities (e.g. Kelvin-Helmholtz and Rayleigh-Taylor) developing during the interaction. We include the treatment of NEI processes in the simulation, an-

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alyzing the NEI effects on the ionization stages of selected elements, namely oxygen, and iron.

2. The Adaptive Mesh Refinement Algorithm

Our project requires a very advanced numerical multi-D hydrodynamic code with adaptive mesh. Adaptive mesh is required to describe properly the moving steep gradients at the boundaries of the shock front with the cloud and the instabilities. To this end, we use FLASH, a 3-D astrophysical hydrodynamics code for parallel computers (Fryxell et al. 2000). The core of FLASH is based on a directionally split Piecewise-Parabolic Method (PPM) solver to handle compressible flows with shocks. PPM is particularly well-suited to flows involving discontinuities, such as shocks and contact discontinuities.

FLASH uses PARAMESH (MacNeice et al. 2000), a Parallel Adaptive MESH refinement package, for the parallelization and Adaptive Mesh Refinement (AMR) portion of FLASH. The fundamental data structure is a block containing a number of computational zones and forming the nodes of a tree data-structure. PARAMESH handles several tasks in the FLASH code:

– it handles the communication between blocks and between processors;
– it manages the refinement and derefinement processes;
– it manages the distribution of works to processors and it balance the workload by reordering the distribution of blocks amongst the processors;
– it handles the guard cell filling at block boundaries;
– it enforces conservation laws at the interfaces between grid blocks at different refinement levels.

The basic AMR strategy used in PARAMESH is summarized as follows: the computational domain is covered with a hierarchy of numerical sub-grids. These sub-grids, forming the nodes of a tree data-structure, are distributed amongst the processors. Each block is refined or de-refined on the basis of an error estimator. When more spatial resolution is required at some location, the highest resolution sub-grid covering that point, the so-called leaf block, spawns child sub-grids which together cover the line, area or volume of their parent, but now with twice its spatial resolution. After the refinements and de-refinements are complete, the blocks are redistributed amongst the processors, using the Morton ordering in order to achieve the workload balancing. The solution is advanced on the leaf blocks only.

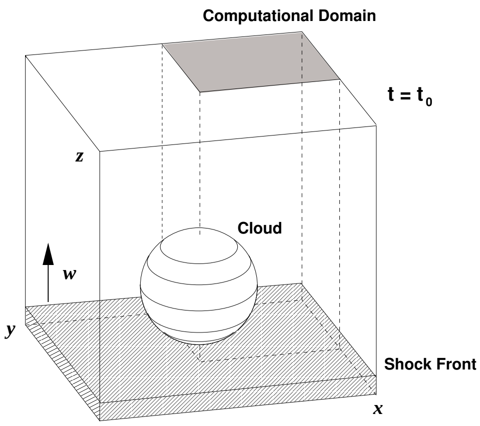

Fig. 1. Initial conditions for the shock-cloud interaction. The shock is moving upwards through the ISM with velocity w. The gray box marks our computational domain.

3. The Simulation

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. In addition, the FLASH code has been upgraded by us in order to include the NEI effects by solving the continuity equations of the ionization species of selected elements.

We adopt a 3-dimensional cartesian (x, y, z) coordinate system (see Fig. 1). The cloud is initially in hydrostatic equilibrium with the ambient medium and the interstellar gas is isothermal and homogeneous with temperature $T_{ism} = 10^4$ K and hydrogen number density $n_{ism} = 0.1$ cm^{-3}. The cloud is assumed spherical with radius $r_{cl} = 1$ pc and isothermal with temperature $T_{cl} = 10^3$ K. In this study we consider a model with the density contrast $\chi = n_{cl}/n_{ism} = 10$ (cloud density $n_{cl} = 1$ cm^{-3}). The post-shock conditions are calculated assuming a strong shock limit (Zel'dovich & Raizer 1966). The shock propagates in the ISM with Mach number $M = 50$ (shock speed $w \approx 570$ km/s), leading to a post-shock temperature of the plasma $T_{psh} \approx 4.7 \times 10^6$ K.

The computational grid spans one-quarter the volume of interest (see Fig. 1) and extends 2.42 pc in both the x and y directions, and 4.85 pc in the z direction. Symmetrical boundary conditions are employed on the $x = x_{min}$ and $y = y_{min}$ planes, inflow conditions are applied on the $z = z_{min}$ plane, while outflow conditions are used on all other boundaries. At the coarsest resolution PARAMESH uniformly covers the computational domain with a mesh of $2 \times 2 \times 4$ top-level blocks. All blocks used in the computation are of size $8 \times 8 \times 8$ cells. We allow for 5 levels of refinement, with resolution increasing by a factor of two at each refinement level. At the finest level the resolution is $\approx 9.5 \times 10^{-3}$ pc (≈ 105 zones per cloud radius). We note that an equivalent uniform mesh calculation would require $N_x \times N_y \times N_z = 256 \times 256 \times 512$ grid points instead of the 10^7 grid points required in average in our simulation. The advantage in using PARAMESH is, therefore, the speed-up given by the ratio $(256 \times 256 \times 512)/10^7 \approx 3$.

Figure 2 shows the density distribution at a relatively early stage of the evolution, $\sim$ 5700 yr since the beginning of the interaction. The interaction between the SNR shock and the cloud leads to the formation of transmitted (into the cloud) and reflected (into the shocked ISM) shocks. The shock transmitted into the cloud has a temperature of $\sim 10^6$ K. The reflected (bow) shock extends into the shocked ISM right below and along the sides of the cloud. The SNR shock has just converged on the symmetry axis, and undergoes a self-reflection (Tenorio-Tagle & Różyczka 1984). The dark portion of the deformed cloud corresponds to the cloud material shocked by the transmitted shock.

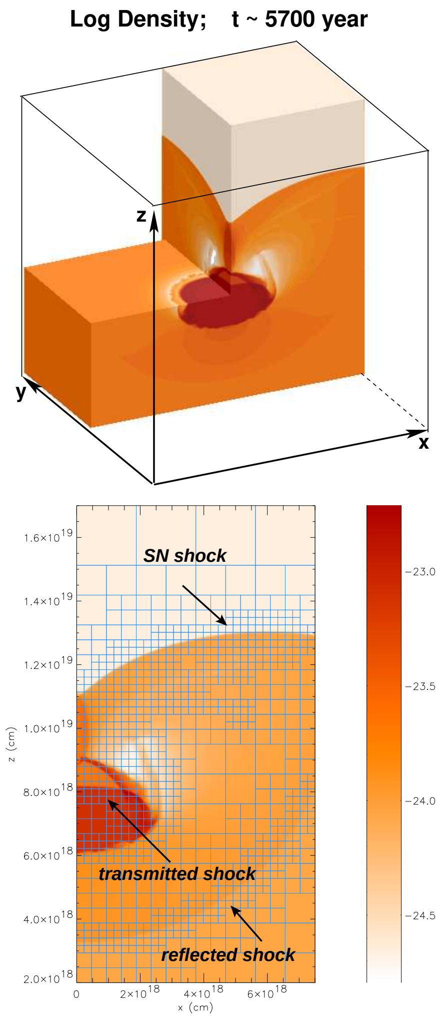

Fig. 2. Density distribution in the model of shock-cloud interaction. The density at 5700 yr since the beginning of the interaction is shown in log scale. Upper panel: 3-D block view of the interaction; lower panel: section in the x-z plane at $y = 0$ cm with the grid block boundaries superimposed to the density distribution.

The dynamics of the system, characterized by fast plasma flows through steep temperature gradients and sudden variations of temper-

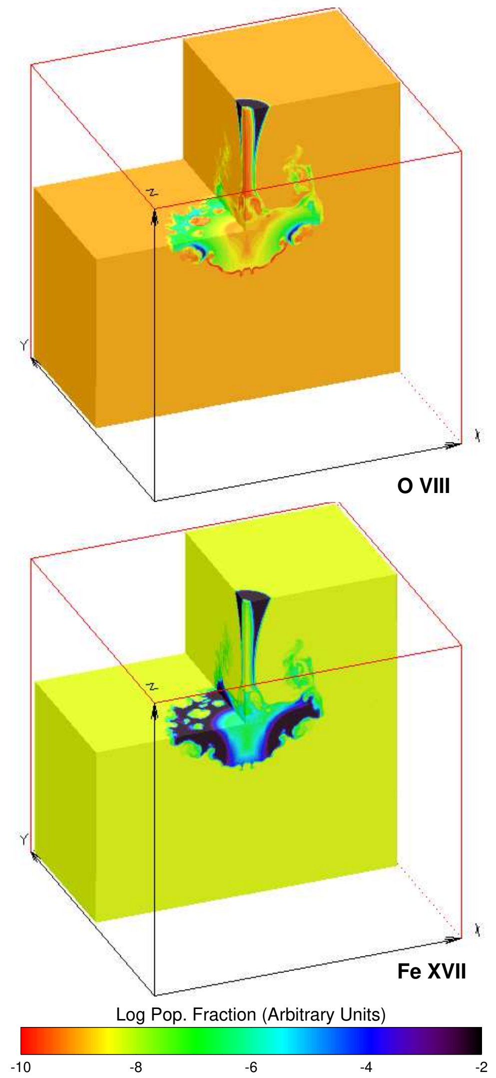

Fig. 3. Distributions of the population fractions of O VIII, and Fe XVII out of equilibrium ionization in the model of shock-cloud interaction. The population fractions at 11400 yr since the beginning of the interaction are shown in log scale.

ature, certainly leads the population fractions of the elements out of ionization equilibrium. An example of the NEI effects induced on the ionization stages of oxygen, and iron which produce important observed emission lines is shown in Fig. 3. The distribution of the population fraction of Oxygen VIII, and Fe XVII is derived in NEI conditions at $t \sim 11400$ yr since the beginning of the interaction.

4. Summary

We are studying the 3-D interaction of a SN shock front impacting on an isolated interstellar gas cloud, and the deviation from equilibrium ionization induced during the interaction. Such a study requires a detailed numerical code with adaptive mesh. We are using, therefore, the FLASH code including PARAMESH, a very sophisticated AMR package. We have described here the basic strategy of PARAMESH and the preliminary result obtained from the analysis of a 3-D purely hydrodynamic simulation of a representative case, including the NEI effects on the ionization stages of oxygen, and iron.

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