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Modeling SNR shock waves expanding through the magnetized inhomogeneous interstellar medium

S. Orlando(1)(2), F. Bocchino(1)(2), M. Miceli(3)(1)(2), F. Reale(3)(1)(2)
and G. Peres(3)(1)(2)

(1) *INAF-Osservatorio Astronomico di Palermo*
Piazza del Parlamento 1, 90134 Palermo, Italy
(2) *Consorzio COMETA - via Santa Sofia 64, 95123 Catania, Italy*
(3) *DSFA-Università di Palermo - Piazza del Parlamento 1, 90134 Palermo, Italy*

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Summary. — We review our recent results on the MHD modeling of supernova shock waves propagating through the magnetized and inhomogeneous ISM. We explore the role of different physical processes simultaneously at work, namely magnetic-field–oriented thermal conduction, radiative cooling and MHD effects, in determining: 1) the mass and energy exchanges between different phases of the ISM and 2) the morphology of supernova remnants as observed in different bands. Our projects required an advanced 3D MHD code for parallel computers, FLASH, and high-performance computing. We discuss the results derived from the analysis of the local interaction of strong shocks with inhomogeneities of the ISM, and those derived from the analysis of the overall expansion of supernova blast waves through inhomogeneous and magnetized ISM.

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PACS `98.38.Mz` – Supernova remnants.
PACS `52.35.Tc` – Shock waves and discontinuities.

1. – Introduction

The interaction of shock waves of supernova remnants (SNRs) with the magnetized and inhomogeneous interstellar medium (ISM) is responsible of the great morphological complexity of SNRs and certainly plays a major role in determining the exchange of mass, momentum, and energy between diffuse hot plasma and dense clouds or clumps (see, for instance, [1, 2]). However, the details of the interaction between SNR shock fronts and ISM depend, in principle, on many factors, among which the multiple-phase structure of the medium, its density and temperature, the intensity and direction of the ambient magnetic fields. These factors are not easily determined and this somewhat hampers our detailed understanding of the complex ISM.

We have started a project devoted to study the interaction of SNRs expanding through the magnetized inhomogeneous ISM. The project aims at overcoming some of the limitations found in previous analogous studies which inhibit an accurate interpretation of the high-resolution multi-wavelength observations of middle-aged SNR shells available with the last-generation instruments. In this paper, we review our recent results on the study of: 1) the role of large- and small-scale inhomogeneities of the magnetized ISM on the morphology of SNRs [1, 3-5, 2]; and 2) the effect of fragments of metal-rich ejecta (shrapnels) on the morphology and chemical composition of SNRs [6].

All our calculations have been carried out with the FLASH code [7], using customized numerical modules that treat optically thin radiative losses and thermal conduction, including effects of heat flux saturation (see [1, 2] for more details).

2. – Effects of large-scale inhomogeneities of the magnetized ISM

We explored the effects of large-scale inhomogeneities on the morphology of SNRs by investigating the origin of asymmetries on bilateral supernova remnants (BSNRs). The BSNRs are considered a benchmark for the study of large-scale SNR-ISM interactions, since no small-scale effect like encounters with ISM clouds seems to be relevant. The BSNRs are characterized by two opposed radio-bright limbs separated by a region of low surface brightness. In general, the remnants appear asymmetric, distorted and elongated with respect to the shape and surface brightness of the two opposed limbs.

Our project aimed at exploring two main aspects of the nature of BSNRs: how and under which physical conditions do the asymmetries originate in BSNRs? Is the ambient magnetic field or the non-uniform ISM more effective in determining the morphology and the asymmetries of this class of SNRs?

Answering such questions at an adequate level requires detailed physical modeling, high-level numerical implementations and extensive simulations. To this end, we modeled the propagation of a shock generated by an SN explosion in the magnetized non-uniform ISM with detailed numerical MHD simulations [7]. Two cases of shock propagation have been considered: 1) through a gradient of ambient density with a uniform ambient magnetic field; 2) through a homogeneous medium with a gradient of ambient magnetic field strength. From the simulations, we synthesized the synchrotron radio emission, making different assumptions about the details of acceleration and injection of relativistic electrons.

We found that asymmetric BSNRs are produced if the line-of-sight is not aligned with the gradient of ambient plasma density or with the gradient of ambient magnetic-field strength (see fig. 1). BSNRs with two radio limbs of different brightness (left panel in fig. 1) can be explained if a gradient of ambient density or, most likely, of ambient magnetic-field strength is perpendicular to the radio limbs. BSNRs with converging similar radio arcs (right panel in fig. 1) can be explained if the gradient runs between the two arcs.

3. – Effects of small-scale inhomogeneities of the magnetized ISM

A large effort has been devoted to study the interaction of a SNR shock front with small-scale inhomogeneities (clumps or clouds) of the ISM with the aim to understand the role of the physical effects at work, namely the thermal conduction and the radiative losses, and the role of an organized ambient magnetic field. First, we have investigated the role played by thermal conduction and radiative losses in the unmagnetized case [1]

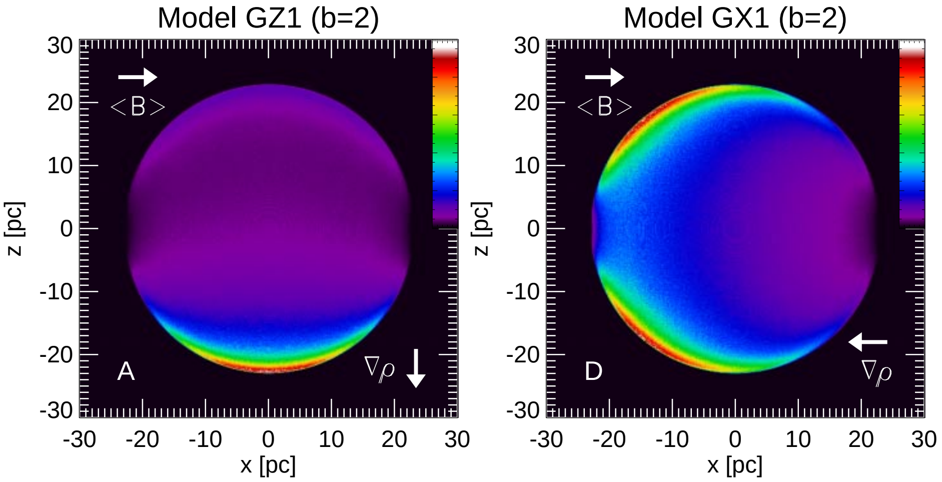

Fig. 1. – Examples of synchrotron radio emission (normalized to the maximum of each panel) synthesized from models assuming a gradient of ambient plasma density when the LoS is aligned with the y-axis (adapted from [5]). The directions of the average unperturbed ambient magnetic field and of the plasma density gradient are shown in the upper left and lower right corners of each panel, respectively.

and we have studied the observable effects of thermal conduction on the evolution of the shocked cloud in the X-ray band [3, 4].

Recently, we have explored the importance of magnetic-field–oriented thermal conduction in the interaction of SNR shocks with radiative gas clouds and in determining the mass and energy exchange between the clouds and the hot surrounding medium [2]. We performed 2.5D MHD simulations of a shock impacting on an isolated gas cloud, including anisotropic thermal conduction and radiative cooling. We considered different configurations of the ambient magnetic field and compared MHD models with or without the thermal conduction.

We found that the efficiency of the thermal conduction in the presence of magnetic field is, in general, reduced with respect to the unmagnetized case. The reduction factor strongly depends on the initial magnetic-field orientation, and it is minimum when the magnetic field is initially aligned with the direction of shock propagation. The thermal conduction contributes to suppress hydrodynamic instabilities, reducing the mass mixing of the cloud and preserving the cloud from complete fragmentation. Depending on the magnetic-field orientation, the heat conduction may determine a significant energy exchange between the cloud and the hot surrounding medium which, while remaining always at levels less than those in the unmagnetized case, leads to a progressive heating and evaporation of the cloud. Finally, we found that the additional heating due to thermal conduction may contrast the radiative cooling of some parts of the cloud, preventing the onset of thermal instabilities.

4. – Role of metal-rich ejecta material

We are investigating the evolution of supersonic fragments of ejecta (shrapnels) originating from the supernova explosion and interacting with shock waves and with the ambient medium. In particular, prompted by the recent discovery of new X-ray emitting ejecta in the Vela supernova remnant [8], we have developed a hydrodynamic model describing the evolution of ejecta shrapnels in the Vela SNR [6].

The model describes the evolution of a supersonic fragment of ejecta and its interaction with the forward and reverse shock waves of the SNR and with the ambient medium. We have performed a set of 2D hydrodynamic simulations taking into account the effects of thermal conduction and radiative cooling. We have explored different values of the physical parameters within the ranges derived by the analysis of the X-ray data and we have studied how the evolution of the system depends on the initial position of the shrapnel with respect to the initial radius of the exploding ejecta and on the density contrast between the shrapnel and the surrounding ejecta.

We found that shrapnels of ejecta may play an important role in determing the morphology of SNRs. Under particular initial physical conditions they can overtake the primary shock front, leading to bow shocks as those observed in the Vela SNR.

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REFERENCES

[1] Orlando S., Peres G., Reale F., Bocchino F., Rosner R., Plewa T. and Siegel A., *Astron. Astrophys.*, **444** (2005) 505.
[2] Orlando S., Bocchino F., Reale F., Peres G. and Pagano P., *Astrophys. J.*, **678** (2008) 274.
[3] Orlando S., Bocchino F., Peres G., Reale F., Plewa T. and Rosner R., *Astron. Astrophys.*, **457** (2006) 545.
[4] Miceli M., Reale F., Orlando S. and Bocchino F., *Astron. Astrophys.*, **458** (2006) 213.
[5] Orlando S., Bocchino F., Reale F., Peres G. and Petruk O., *Astron. Astrophys.*, **470** (2007) 927.
[6] Miceli M., Orlando S., Reale F., and Bocchino F., in *37th COSPAR Scientific Assembly, 13-20 July 2008, Montréal, Canada*, Vol. **37** (2008) p. 2025.
[7] Fryxell B., Olson K., Ricker P. *et al.*, *Astrophys. J. Suppl.*, **131** (2000) 273.
[8] Miceli M., Bocchino F. and Reale F., *Astrophys. J.*, **676** (2008) 1064.