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Role of ejecta clumping and back-reaction of accelerated cosmic rays in the evolution of supernova remnants

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Abstract. The thermal structure of the post-shock region of a young supernova remnant (SNR) is heavily affected by two main physical effects, the back-reaction of accelerated cosmic rays (CRs) and the Rayleigh-Taylor (RT) instabilities developing at the contact discontinuity between the ejecta and the shocked interstellar medium (ISM). Here, we investigate the role played by both physical mechanisms in the evolution of SNRs through detailed 3D MHD modeling. Our model describes the expansion of the remnant through a magnetized ISM, including consistently the initial ejecta clumping and the effects on shock dynamics due to back-reaction of accelerated CRs. We discuss the role of the initial ejecta clumpiness in developing strong instabilities at the contact discontinuity which may extend upstream to the main shock and beyond.

Key words. instabilities – magnetohydrodynamics (MHD) – cosmic rays – ISM: supernova remnants

1. Introduction

SNRs are the site where CR diffusive shock acceleration occurs. Indirect evidence of CRs acceleration comes from the separation between the forward shock and the contact discontinuity. In SN 1006, observations have shown that the azimuthal profile of the ratio between the forward shock and the contact discontinuity radii $R_{\rm bw}/R_{\rm cd}$ is fairly uniform and much lower than predicted for a non-modified shock (Miceli et al. 2009). Recently Rakowski et al. (2011) have found and analyzed clumps of ejecta close to or protruding beyond the main blast wave. These findings have been interpreted as a consequence of the energy losses to CRs at the forward shock. However, several authors have shown that extreme energy losses to accelerate the CRs are needed to allow a significant fraction of the ejecta to approach or even overtake the forward shock (e.g Miceli et al. 2009). In addition, the observations show that $R_{\rm bw}/R_{\rm cd}$ is lower than predicted by non-modified shock models even in regions dominated by thermal emission where the CR

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acceleration efficiency is supposed to be low (e.g. Miceli et al. 2009).

An alternative in the data interpretation could be the ejecta structure of the explosion itself. In fact, density inhomogeneities in the ejecta can enhance the growth of RT instabilities potentially allowing them to reach the forward shock. The question is: can the ejecta clumping enhance the growth of RT instabilities up to a level that allows them to reach and possibly overtake the forward shock? In fact, there is a growing consensus that density clumping of ejecta is intrinsic at early phases of the remnant evolution. The density structure of ejecta therefore may naturally explain the small values of $R_{\rm bw}/R_{\rm cd}$ observed in SNRs.

Here we investigate this issue by developing a 3D MHD model describing the expansion of a SNR through a magnetized medium, including consistently both the initial ejecta clumping and the effects on shock dynamics due to back-reaction of accelerated CRs.

2. Three-dimensional MHD Modeling

We improved the 3D MHD model discussed by Orlando et al. (2007, 2011). The SNR is modeled by numerically solving the time-dependent MHD equations of mass, momentum, and energy conservation, including consistently the initial ejecta clumping and the effects on shock dynamics due to back-reaction of accelerated CRs (Orlando et al. 2011, in preparation). The calculations were performed using FLASH, an adaptive mesh refinement multiphysics code for astrophysical plasmas (Fryxell et al. 2000) extended with additional computational modules to handle the back-reaction of accelerated CRs. The latter process is included in the model by following the approach of Ferrand et al. (2010) and extending their method to MHD models. In particular, our model includes an effective adiabatic index $\gamma_{\rm eff}$ evolving in time: at each time-step of integration the time- and space-dependent $\gamma_{\rm eff}$ is calculated at the shock front and then is advected within the remnant, remaining constant in each fluid element. In addition to the approach of Ferrand et al. (2010) we allow $\gamma_{\rm eff}$ to depend on local physical conditions and on the injection rate of particles, by assuming that the index depends on the obliquity angle between the upstream magnetic field and the normal to the shock.

As for the density structure of the ejecta, we have investigated two different initial ejecta density profiles: the exponential profile that has been shown to be the most representative of explosion models for thermonuclear SNe (Dwarkadas & Chevalier 1998), and the power-law profile with $n = 7$ that has been used to represent deflagration models (Nomoto et al. 1984). We assume that the initial ejecta have a clumpy structure, modeled by defining small clumps including a perturbation of the mass density. For each of the initial profiles, we explore density clumps of ejecta with initial size either 2% or 4% of the initial remnant radius. Initially each clump has a random density contrast derived from an exponential distribution that is characterized by a maximum density contrast. We explore maximum contrasts ranging between 1.5 and 5.

As for the reference physical system, we adopted parameters appropriate to describe SN 1006: density of ISM $n_{\rm ism} = 0.05$ cm^{-3}, energy of the SN explosion $E_{\rm SN} = 1.5\times10^{51}$ ergs, mass of ejecta $M_{\rm ej} = 1.4\ M_\odot$, shock velocity after 1000 yrs $V_{\rm shock} = 5000$ km s^{-1}, and diameter of the remnant after 1000 yrs $D = 17$ pc. The initial magnetic field configuration is that suggested by Bocchino et al. (2011) in the case of SN 1006 and resulting from the comparison of radio observations with MHD models. The initial radius of the remnant is 0.5 pc. We follow the remnant evolution for 1000 yrs. Special emphasis was placed on capturing the enormous range in spatial scales in the remnant: in fact we need to perform simulations with sufficient spatial resolution to capture the structures of the ejecta in the initial system configuration and to follow the evolutions of these structures. To this end, we exploited the adaptive mesh capabilities of the FLASH code by using 11 nested levels of resolution; the effective mesh size was $8192 \times 8192 \times 8192$.

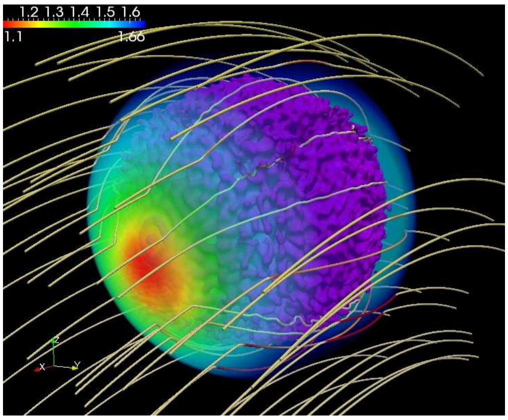

Fig. 1. 3D volume rendering describing the spatial distribution of the effective adiabatic index for a model with an exponential profile of the initial ejecta density after 1000 yrs. The index $\gamma_{\rm eff}$ is minimum in red regions (see color bar). The violet surface tracks the ejecta material and the white lines are sampled magnetic field lines.

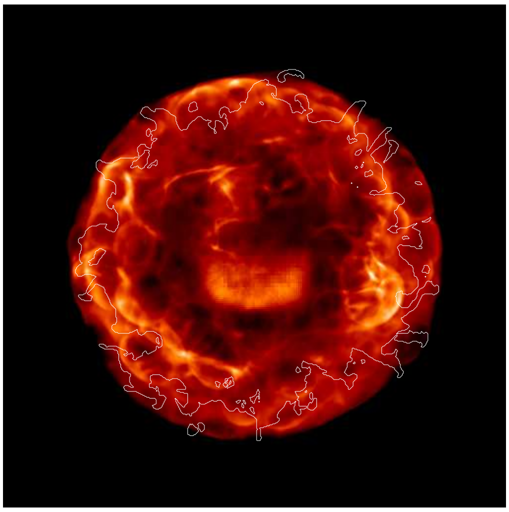

Fig. 2. 3D rendering of mass density for a model with an exponential profile of ejecta after 1000 yrs of evolution. The initial clumps have a size of the order of 4% of the initial remnant radius and a maximum density contrast of 5. The white contour encloses the ejecta material.

3. Results

We first analyzed the back-reaction of accelerated CRs, by considering models accounting for the shock modification but without initial clumping of ejecta. As an example, Fig. 1 presents the results for a model with an exponential profile of the initial ejecta density after 1000 yrs of evolution. In this model we have assumed that the back-reaction of accelerated CRs is modulated by the obliquity angle, being more efficient at parallel shocks where the effective adiabatic index is minimum, namely $\gamma_{\rm eff} = 1.1$ (we are assuming extreme energy losses to accelerate the CRs).

We investigated the effect of accelerated CRs on the separation between the blast wave and the contact discontinuity. To this end, we derived the azimuthal profiles of the ratio between the blast wave and contact discontinuity radii $R_{\rm bw}/R_{\rm cd}$ from the models and compared them with that derived from the observations of SN 1006 (Miceli et al. 2009). In general, we found that the modeled profiles are higher than those observed and are modulated by the obliquity angle (see black line in Fig. 3). The observations can be reproduced only in limited regions where the effects of accelerated CRs is higher. This result suggests that the observations could be reproduced only if the back-reaction of accelerated CRs is extreme (i.e. $\gamma_{\rm eff} \approx 1.1$) at all obliquity angles.

As a next step, we investigated the effects of ejecta clumping on the evolution and morphology of the remnant, considering models without back-reaction of accelerated CRs and accounting for ejecta clumping. As an example, Fig. 2 shows the 3D rendering of mass density for a model with an exponential profile of ejecta. The figure shows that: 1) the RT mixing reaches the forward shock front perturbing the remnant outlines, 2) clumps and filamentary structures are evident within the remnant, and 3) clumps of ejecta are close to or protruding beyond the main blast wave as observed in SN 1006 by Rakowski et al. (2011). In general, we found that increasing the initial size of the clumps or increasing their density contrast, both the perturbation of the remnant outlines and the occurrence of ejecta protrusions increase. Also in this case, we compared the azimuthal profiles of the ratio $R_{\rm bw}/R_{\rm cd}$ derived from the models with that observed in

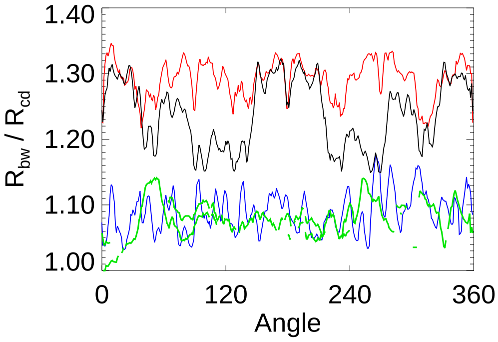

Fig. 3. Azimuthal profiles of the ratio between the forward shock and the contact discontinuity radii for models without ejecta clumping and back-reaction of accelerated CRs (M1, red line), with ejecta clumping and without accelerated CRs (M2, blue), and with accelerated CRs and without ejecta clumping (M3, black). All models assume an exponential profile of the initial ejecta density; M2 assumes a minimum $\gamma_{\rm eff} = 1.1$; M3 assumes a maximum density contrast 2.5 and an initial size of ejecta 4% of the remnant radius. The green line marks the profile observed in SN 1006 (Miceli et al. 2009).

SN 1006. We found that the initial clumping of ejecta makes the azimuthal profiles $R_{\rm bw}/R_{\rm cd}$ fairly uniform and lower than expected for models without clumping. In particular, we found that: the larger the size of initial clumps of ejecta, the lower the value of the ratio; the higher the initial density contrast, the lower the value of the ratio.

As an example, in Fig. 3 we compare the azimuthal profiles derived for models accounting for only one of the effects considered in this paper (either back-reaction of accelerated CRs or ejecta clumping), and for a model without both physical effects. Our analysis has shown that the observed profile can be reproduced by models with a maximum density contrast of ejecta ranging between 2.5 and 5, and an initial size of ejecta clumps of the order of 4% of the remnant radius (see, for instance, blue line in Fig. 3).

4. Summary and conclusions

We investigated the role of ejecta clumping and back-reaction of accelerated CRs on the evolution of young SNRs. To this end, we have developed a 3D MHD model including consistently the back-reaction of accelerated CRs and the ejecta clumping. Particular attention has been devoted to the spatial resolution that is necessary to describe appropriately the structure of the ejecta; to this end, we have exploited the AMR capabilities of the FLASH code. Our starting point was the observational evidence that the azimuthal profile of the ratio between the forward shock and the contact discontinuity radii is fairly uniform and lower than expected for a non-modified shock.

We found that the back-reaction of accelerated CRs alone cannot reproduce the observations unless the CRs energy losses are extreme (that is the effective adiabatic index should be of the order of 1.1) and independent on the obliquity angle. We also found that the clumping of ejecta is an important factor to reproduce the observed values of the ratio and its obliquity dependence. We conclude that the ejecta clumping is important in the description of the evolution of young SNRs.

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