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Supernova remnant evolution in non-uniform media

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Abstract: In this work numerical simulations showing the time evolution of supernova remnants (SNR) in non-uniform interstellar medium (ISM) are presented. We use a hydrodynamic model including a kinematic calculation of the interstellar magnetic field. Our results show that as the SNR forward shock moves from one into another medium of higher density a reflection wave is created at the interface between the two media. This wave is driven back toward the center and drives mass via a nonspherical flow away from the discontinuity. As this wave moves inward it also drags some of the ISM field lines with it and heats the inside of the SNR resulting in larger temperatures in this region. Results are also compared to observations.

Introduction

A supernova explosion of a massive star will result in an expanding supernova remnant (SNR) with speed v typically in the range 10^8 to 10^9 cm s^{-1}, depending on both the ejection energy E_{ej} and ejecta mass M_{ej}. The expansion of a SNR is decelerated due to mass-loading by the swept-up interstellar medium (ISM). During the initial stages the ejecta mass is larger than the swept-up mass and the SNR is in the free expansion phase. See e.g. [1] for different stages of SNR evolution. This phase lasts about 100-1000 years. When the swept-up mass becomes sufficiently larger than the ejecta mass (1.61 larger, [2]) the SNR is in the Sedov [3] phase which may last up to $\sim$ 10000 years. During this phase a reverse shock (RS) will form because of the low pressure of the ejected material which have been adiabatically expanding. The RS will then be driven back into the interior of the SNR [4, 5], and in the process heat the material inside. The remnant is still bounded by a strong blast wave, called the forward shock (FS).

SNR evolution become more complex when the surrounding medium is not uniform [6]. [7] have done hydrodynamic simulations of SNRs interactions with spherical bubbles. [8] have computed the collision between the ejecta of e.g. SN 1987A and its circumstellar ring. Also [9] explored the dynamics of SNRs which developed on the edge of a giant molecular cloud. This was followed by [10] computing the expansion of a SNR into an ISM containing different clouds. These studies all confirm that the evolution of SNRs are more complex in non-uniform media.

In this work SNR evolution in non-uniform media is investigated. Example of this is an SNR moving from one ISM medium to another with different densities, e.g. from the ISM into a molecular cloud. We will restrict ourselves with the simple case where the medium of enhanced density is seen as an infinite plane. Also numerical noise in the form of density peturbations are not included in our computations [11, 12] therefore no Rayleigh-Taylor or other instabilities will occur. Instead we will focus firstly on the interaction of an SNR moving into a denser medium and the subsequent phenomenoma which will occur.

Discussion

To model the evolution of a SNR the well known Euler equations describing inviscid flow are solved. See [13] for details. To compute the compressed ISM magnetic field **B** we solve Faraday's law neglecting the electric force. Note that this is not a full MHD solution because the field is calculated kinematically from the flow [13] and no backreaction on the fluid is considered. In this work we only consider the field of the ISM which gets compressed as the ISM is swept-up by the forward shock of the SNR For the initial and boundary conditions see also [11, 14, 15]

Figure 1 shows an example of the interaction of a typical SNR (computed using our standard parameters) with a medium of enhanced density. Results are shown in terms of the density for an SNR moving from a ISM density of $\rho_{ISM} = 10^{-24}$g cm^{-3} to a medium where $\rho_{ISM} = 10^{-23}$g cm^{-3}. The latter are assumed to be an infinite plane situated 5 pc away from the initial explosion. Shown from top to bottom are different stages in the SNR evolution, e.g. 1000, 3000, 5000 and 7000 years.

Shown in Figure 1 is that as the SNR moves into the higher density medium two important effects occur. Firstly, the blast wave (FS) decelerates because of the increase in mass (momentum conservation). This results in the SNR geometry deviating significantly from a sphere as time increases. Secondly, due to the pressure imbalance, a reflection wave is created which is driven back toward the center. This now drives mass via nonspherical flow from the right to the left resulting in the denser medium no longer exhibiting its planar geometry with a large indent created by interaction with the SNR.

Figure 2 shows the compressed ISM magnetic field. As the blast wave moves outward, the field is compressed by a factor $s \sim 4$. In the case when the FS hits the medium of higher density the reflection wave immediately moves in the opposite direction dragging some of the field lines with it. As material gradually moves toward the center of the SNR the compressed field is transported with it. The result is that the field inside the SNR close to the higher density region is now considerably larger which may have important consequences concerning the acceleration of cosmic rays at the shocks present inside.

These effects can be more qualitatively shown in Figure 3. Computations are shown as radial profiles from the SNR origin in the direction directly toward the more denser medium (solid line) and directly away in the opposite direction (dotted line). The left panels show the parameters at 1000 years, the middle panel at 1500 years and the right panel the parameters at 2000 years.

Most interesting in Figure 3 is the reflected wave which can be easily identified in the bottom panel by a large gradient in pressure. The location of this wave is shown by the dashed line in each panel. Shown here is that this wave is almost immediately created as the FS reaches the denser medium and start to move inward. This is due to the pressure imbalance where the part of the remnant expanding in the more dense medium is strongly decelerated (shown by the third and fourth panels). Also of interest is that this reflected wave catches up with the RS because of the larger speed. As this wave propagates inward it heats the inside of the SNR resulting in larger temperatures compared to the opposite side of the explosion.

Comparison with observations

A reverse shock/reflection wave combination of the SNR of PSR B1823-13 could resulted in the offset PWN towards the south-west, as observed. This would imply a maximal radius of $R_1 = 80$ pc for the FS towards the south-west where the extension is the largest. From our calculations of SNR evolution (See [16]) follows that this radius is achieved after 21 000 yr for a density of 6×10^{-4} cm^{-3},

The remnant G21.5-0.9 is not symmetric relative to its pulsar position: The extension to the north is smaller than the corresponding extension to the south, which indicates that the ISM is denser towards the north. The most dominant feature is the "North Spur", showing bright nonthermal and thermal emission. Since the synchrotron emission in the North Spur is brighter than in the southern part of the SNR, we invoke a situation where the northern FS struck a wall of denser material (e.g. a molecular cloud), which resulted in the relatively smaller FS radius to the north. A reflected wave, originating near the FS radius, is now returning to the origin of the SNR explosion and since it is still in its early phase (located at the North Spur), it still carries significant magnetic azimuthally directed magnetic flux towards the south. Furthermore the magnetic field strength in the reflected wave is larger in the northern half of the SNR compared to the southern mirror points, and the same wave is also expected to carry Fermi accelerated

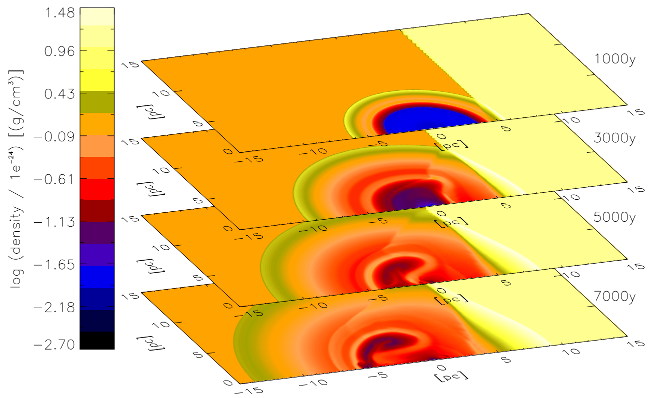

Figure 1: A computed SNR (in terms of density) moving from a ISM density of $\rho_{ISM} = 10^{-24}$g cm^{-3} to a medium where $\rho_{ISM} = 10^{-23}$g cm^{-3}. Shown from top to bottom are different stages in the SNR evolution, e.g. 1000, 3000, 5000 and 7000 years. Note that a logarithmic scaling is used and that the density is normalized by dividing by 10^{-24}

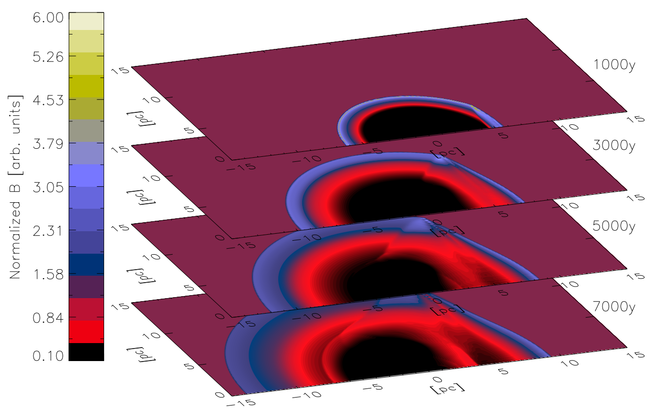

Figure 2: As in Figure 1 except now the compressed ISM magnetic field is shown.

electrons with it. The reason for this is the azimuthal structure of the field in the reflected wave. We therefore get synchrotron emission from both the FS as well as from the reflected wave, giving the appearance of a radially broadened ridge of which the brightest part is the North Spur.

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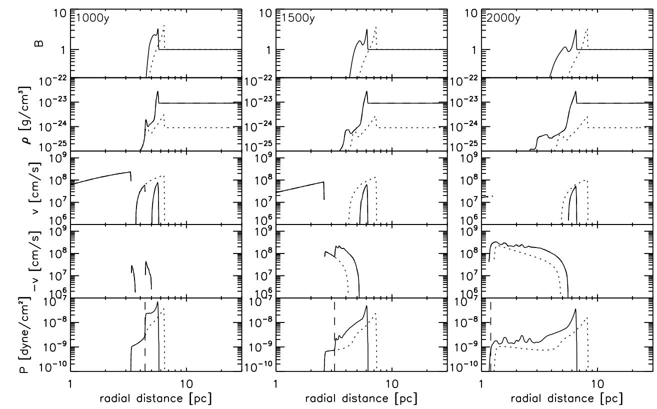

Figure 3: The top panel show B. Shown in the second panel is the density ρ. The bottom three panels show the speed v and $-v$ and pressure P. Computations are shown from the SNR origin in the direction directly toward the more denser medium (solid line) and directly away in the opposite direction (dotted line). The left panels show parameters at 1000 years, the middle panel parameters at 1500 years and the right panel at 2000 years. The location of the reflected wave is shown by the dashed line in the pressure panels

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