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Evolution of a Non-Isotropic SN remnant in a Turbulent Background Medium

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We examine how the characteristics of Supernova remnant (SNR) shocks evolve in a non-uniform background with a non-isotropic ejection using the MHD code of Athena++. As an example, the remnant SN1006 is modelled using various scenarios. The turbulent density and magnetic field in the background interstellar medium (ISM) are assumed to have a Kolmogorov spectrum. Using the spherical harmonic function $Y_{l,m}(\theta, \phi)$ as a basis, we model the non-isotropic ejection also by a Kolmogorov-like spectrum in (l,m). We consider cases where the ejecta speed in one direction differs significantly from other directions by adding a Gaussian profile to the ejection profile. Simulation results are compared to cases of an isotropic supernova explosion in both a uniform and non-uniform background. We find that the morphology of the SNR shock looks noticeably different at earlier times for different scenarios. In later times, $\sim 1,000$ years, the differences become smaller. Synthetic synchrotron radiation maps for different scenarios are obtained and compared to observations.

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1. Introduction

Supernova Remnant shocks are long believed to be the acceleration sites of galactic cosmic rays [2–6]. Earlier models have assumed a hydrodynamic code. However, since the interstellar medium is permeated with galactic magnetic field, a proper modeling of SNR shock requires MHD code. While an easy approach is to assume a uniform background field, the presence of turbulence in the interstellar magnetic field can lead to morphological variations of the SNR shock [9]. Other simulations that model SNRs with a turbulent background are [7] and [8]. However, these simulations does not consider the effects of a non isotropic ejection, which can arise naturally due to the presence of strong stellar magnetic field and various instabilities. In a completely different setting, coronal mass ejections at the Sun, which also drive shock waves and accelerate particles, show clearly non-uniform velocity profile [10]. Therefore a natural question one can ask is what is the effect of a non-isotropic eruption on the morphology of the SNR shock?

At late phases, when the swept mass is larger than the driver mass, the effect of a non-isotropic ejection should be small. However, at younger age, fewer than 1,000 years, there can be clear effects of a non-isotropic ejection. This paper examines the effect of a non-isotropic ejection of SNR shock. We use the Athena++ MHD to model the background ISM and the SNR shock. [1]

2. Isotropic SNR in a Uniform Background

The first case considered is an isotropic SNR in a uniform background. We assume the ejected mass of the remnant has a radial speed given by

$$v_r = \frac{(v_{avg} - v_0)}{\frac{3(r_{out}^4 - r_{in}^4)}{4(r_{out}^3 - r_{in}^3)} - r_{in}}(r - r_{in}) + v_0 \tag{1}$$

Following [9], we set the SNR ejected mass to be 1.0 $M_\odot$. It is also assumed that the kinetic energy of the SNR makes up 95% of the total energy, and the gas energy makes up 5% of the total energy. The black circular outline in the figures above is the shock of the SNR.

3. Isotropic SNR in a Turbulent Background

Next, we consider the case of the same isotropic SNR, but now the remnant is expanding in a turbulent background. Both the density and the magnetic field background have a Kolmogorov-like

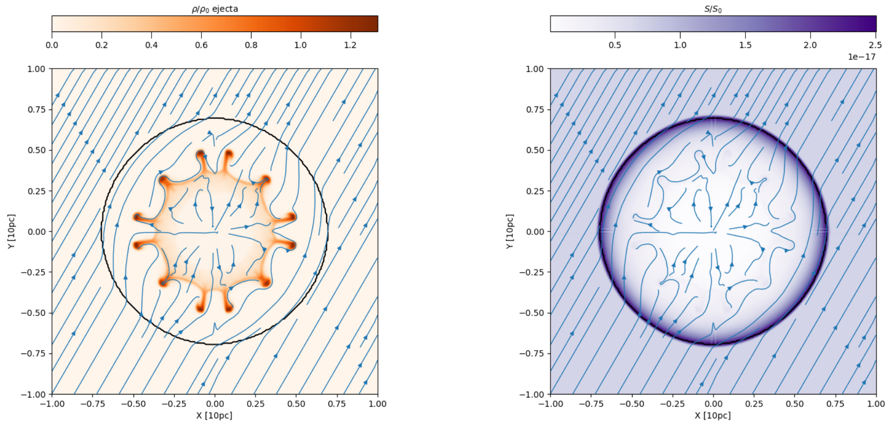

Figure 1: SNR 1006 shock at time 1,125 years showing the shock and initial ejected mass on the left and on the right the shock and the entropy.

spectrum given by

$$
\begin{aligned}
\mathbf{B} &= \mathbf{B_0} + \mathbf{b} \\
\mathbf{B_0} &= B_0[\cos(\beta)\hat{x} + \sin(\beta)\hat{y}] \\
\mathbf{b} &= \sum_{n=1}^{N} A(k_n)[\cos(\alpha_n)\hat{x'} + \sin(\alpha_n)\hat{y'}]\exp(i(k_n z' + \gamma_n)) \\
P(k_n) &= \frac{\Delta V}{1 + (k_n \mathrm{L}_c)^{11/3}} \\
\Delta V &= 4\pi k_n^2 \Delta k_n \\
A^2(k_n) &= \frac{\sigma_B^2 P(k_n)}{\sum_n^N P(k_n)}
\end{aligned}
\tag{2}
$$

The primed coordinates are related to the unprimed coordinates with the following

$$
\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \cos\theta_n \cos\phi_n & \cos\theta_n \sin\phi_n & -\sin\theta_n \\ -\sin\phi_n & \cos\phi_n & 0 \\ \sin\theta_n \cos\phi_n & \sin\theta_n \sin\phi_n & \cos\theta_n \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}
$$

$$
\begin{pmatrix} \hat{x}' & \hat{y}' & \hat{z}' \end{pmatrix} = \begin{pmatrix} \hat{x} & \hat{y} & \hat{z} \end{pmatrix} \begin{pmatrix} \cos\theta_n \cos\phi_n & -\sin\phi_n & \sin\theta_n \cos\phi_n \\ \cos\theta_n \sin\phi_n & \cos\phi_n & \sin\theta_n \sin\phi_n \\ -\sin\theta_n & 0 & \cos\theta_n \end{pmatrix}
$$

4. Non-Isotropic SNR in a Turbulent Background

Next, we consider the case of a non-isotropic SNR. This time the remnant will have angular dependence. The functions describing the remnant's velocity and density may now be expanded in

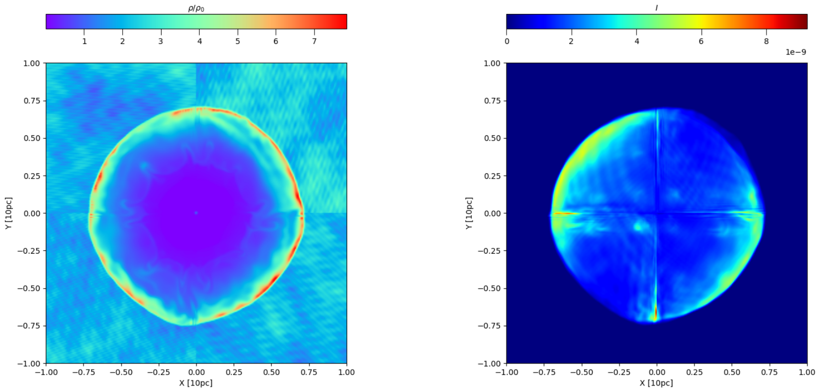

Figure 2: Density and Synchrotron radio emission of a spherically symmetric explosion with ejecta velocity having linear radial dependence with a turbulent density and magnetic field background. σ_B and σ_ρ of the background have value 0.08. Snapshot time is 1,125 years.

terms of the spherical harmonics.

$$
\begin{aligned}
v(r,\theta,\phi) &= v_r(r)[1+\zeta(\theta,\phi)] \\
\langle v(r,\theta,\phi)\rangle &= \frac{3}{4\pi(r_{out}^3 - r_{in}^3)} \iiint v(r,\theta,\phi) r^2 \sin\theta dr d\theta d\phi = v_{avg} \\
\rho(\theta,\phi) &= \rho_0[1 + c\zeta(\theta,\phi)] \\
\langle \rho(\theta,\phi)\rangle &= \frac{1}{4\pi} \iint \rho(\theta,\phi) \sin\theta d\theta d\phi = \rho_0 \\
\zeta(\theta,\phi) &= \sum_{l=1}^{N} \sum_{m=-l}^{l} A(l,m) * Y_l^m(\theta,\phi) \\
A(l,m) &= \left[4\pi\sigma^2 * \Phi(l,m)\right]^{1/2} * \left[\sum_{l=1}^{N} \sum_{m=-l}^{l} \Phi(l,m)\right]^{-1/2}
\end{aligned}
\tag{3}
$$

The energy and pressure of the ejected mass is then expressed as

$$
\begin{aligned}
E(\theta,\phi) &= \frac{1}{2}\rho(\theta,\phi)[v(r,\theta,\phi)]^2 \\
E &= E_{KE} + E_{th} \\
E_{KE} &= 0.95 E(\theta,\phi) \\
E_{th} &= 0.05 E(\theta,\phi) \\
P(\theta,\phi) &= (\gamma - 1) E_{th} \\
\langle E(r,\theta,\phi)\rangle &= \frac{3}{4\pi(r_{out}^3 - r_{in}^3)} \iiint E(r,\theta,\phi) r^2 \sin\theta dr d\theta d\phi
\end{aligned}
\tag{4}
$$

Using a Kolmogorov-like spectrum to model the remnant, we have the following for $\Phi(l,m)$

$$
\Phi(l,m) = \frac{1}{(1 + l^{5/6})(1 + |m|^{5/6})}
$$

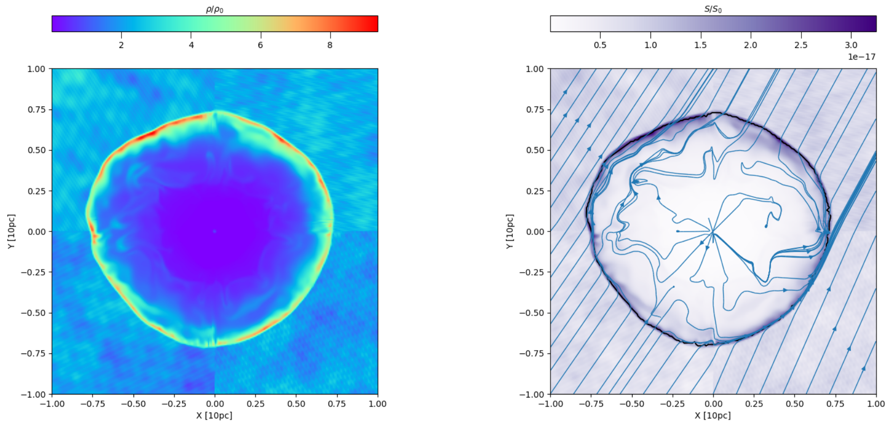

Figure 3: Non-uniform explosion with turbulent background, showing the density on the left and shock and entropy on the right. Snapshot time is 1,125 years.

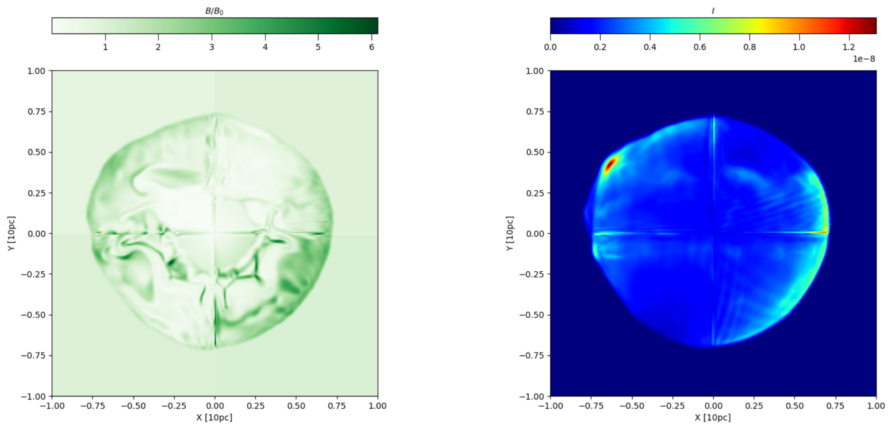

Figure 4: Non-uniform explosion with turbulent background, showing the magnetic field on the left and synchrotron emission map on the right. Snapshot time is 1,125 years.

4.1 Gaussian Model

Finally, we consider the non-isotropic SNR in a turbulent background, but now we include the following to the velocity

$$v(r,\theta,\phi) = v_r(r)[1 + \zeta(\theta,\phi) + \frac{A}{\sqrt{2\pi\sigma^2}} exp(-(\theta-\theta_0)/2\sigma^2)] \tag{5}$$

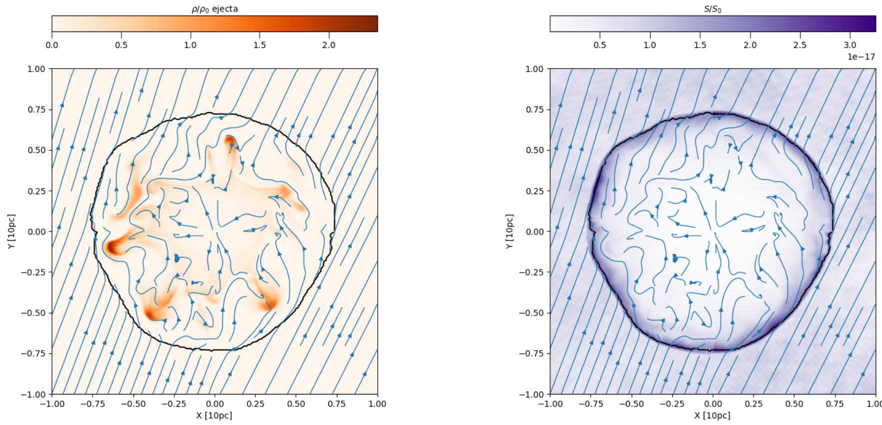

Figure 5: SNR 1006 with Φ (5/6) spectrum for the density and velocity. Explosion in turbulent background. The standard deviation chosen is $\sigma = 0.05$. The plots correspond to time 1,125 years and show the shock and initial ejected mass on the left and on the right the shock and the entropy.

5. Discussion and Conclusion

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