The Magnetic field Amplification Downstream of Supernova Blast Wave

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Abstract

We study the interaction between a supernova blast wave and a turbulent interstellar medium and its effect on the downstream magnetic field. We report on two-dimensional ideal MHD simulations with high-order accuracy for supernova shocks propagating through a plasma which contains turbulent density and magnetic field. We show that a population of initial weak magnetic field can be amplified downstream by a factor much larger than that expected from the shock jump condition as a consequence of the irregular shock front interacting with the density fluctuations. The downstream vorticity produced at the rippling shock front can stretch and distort the field lines of force, which leads to a turbulent dynamo process. These results confirm the mechanism previously found for 2-D planar shocks (Giacalone & Jokipii 2007). We find that the magnetic field amplification depends on numerical resolutions. For high resolution simulations the maximum magnetic field and magnetic energy increase are larger than the cases with low resolutions since the process is more rapid at small scales. This provides an explanation for the discrepancy with the previous work. However, in our simulation we did not observe a systematic strong magnetic field within a thin region downstream of the supernova shock. This indicates if the thin X-ray rims seen in young supernova remnants are indeed caused by electron losing energy in synchrotron emission, some other physics such as the effect of cosmic rays is needed to explain the peripheral thin X-ray rims.

1 Introduction

The high mach number shocks of supernova remnants (SNRs) expanding through interstellar medium (ISM) is a remarkable high energy process in astrophysics. It is widely believed that high mach number supernova shocks are the sources of galactic cosmic rays with energies up to at least 10^{15} eV. In the acceleration and emission processes, magnetic field plays an significant role.

It has been inferred from observations that the magnetic field in young SNRs is enhanced to a magnitude much greater than the compression at the shock front. One evidence of strong magnetic field in SNRs is the “thin rims” seen in X-ray emission. The thickness of these thin rims, after considering the projection effect, yields a value of $0.01 - 0.1$ pc [1, 2]. It has been argued that the thin thickness is due to electrons losing energy by synchrotron radiation. A number of authors [1–5] inferred that there must be a strong magnetic field over about $60 - 200\mu G$ close to the shock front. It has also been suggested the thin rims can be explained by turbulent magnetic field decay [6]. Especially in some cases, the thin rims are also seen in radio wavelengths [7]. The electrons which radiate radio emission have a much longer loss time. Another evidence comes from the rapid variation of synchrotron emission [8]. If this rapid time variation indicates the time scale of synchrotron loss, the magnetic field could be as high as 1 mG. Since in both of these evidences the observation could be at least partially contributed by the effect of turbulence [6, 9]. The exact amplification factors remain uncertain.

It has been proposed [10, 11] that the cosmic ray current instability can amplify the magnetic field upstream of supernova shocks. Numerical simulations show this instability saturates easily and the amplification may be limited [12]. Recently, Giacalone & Jokipii [13] proposed an alternative mechanism, in which the interaction between the warped shock front and density fluctuations produces fluid vorticity downstream of strong shocks. That fluid vorticity can stretch, distort and amplify the magnetic field. It is interesting to note that previous three-dimensional MHD blast wave simulation [14] with moderate resolution does not show strong magnetic field enhancement, whereas two-dimensional simulations with high resolutions give strong amplification. The discrepancy between these results warrants some further investigation.

In this work, we perform a series of two-dimensional ideal MHD simulations [15, 16] to study strong supernova blast shock waves propagating into an ISM containing large-scale density and magnetic fluctuations. The blast waves are driven by a high pressure region in the center of the sim-

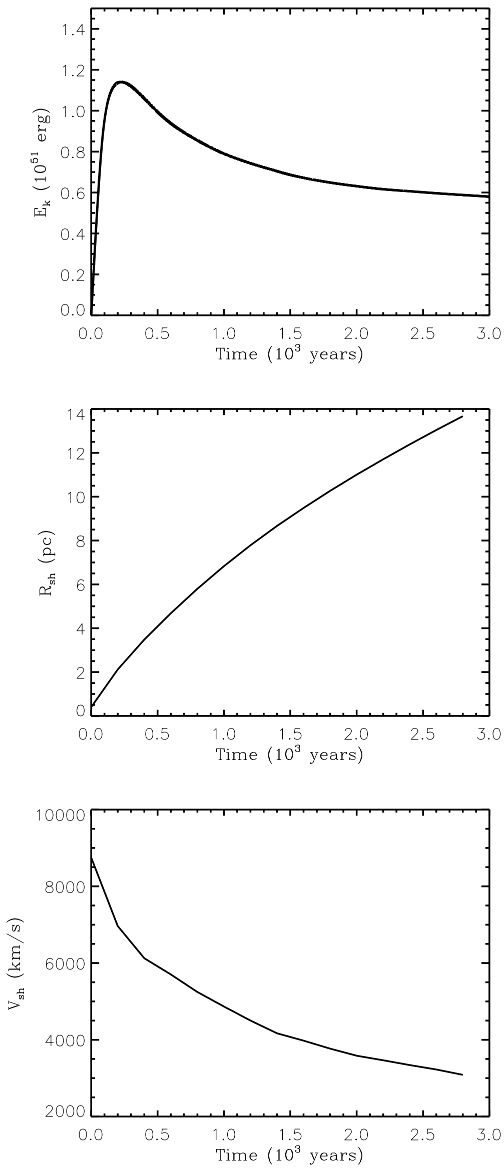

Figure 1: From top to bottom: The evolution of kinetic energy, average radius and average shock speed in run 1.

ulation box. We model the simulation in a two-dimensional Cartesian coordinate (x, y) with uniform grids. The size of the simulation domain is $L_x \times L_y = 30pc \times 30pc$. The supernova blast waves are driven by the initial injection of thermal pressure and mass in the central region ($r < 0.4pc$) of the simulation box. In calculating the injection energy, we assume the length of the simulation box in z direction is $L_z = 0.8pc$. Initially, the circular central region has a thermal energy of 1.5×10^{51} erg and a total mass of 2.98 solar masses. This initial setup for blast waves is similar to the simulation made by [14], except we use two-dimensional simulations with higher resolutions to study magnetic field evolution in young SNRs. The density and magnetic field in background ISM are consist of an averaged component and a turbulent component. We take the mean number density to be $n_0 = 1cm^{-3}$ and the temperature is $T_0 = 10^4K$. The averaged magnetic field $B_0 = 3\mu G$ is along y direction. We assume an isobaric ISM of total pressure $p_0 = n_0 T_0$. For the fluctuating components, we assume both magnetic field and density fluctuations have a two-dimensional Kolmogorov-like power spectrum. The coherence length is set to be $L_c = 3$ pc. The turbulence is generated by summing a large number of discrete wave modes with random phases [17]. The density fluctuation satisfies a lognormal probability distribution [13]. We have simulated four runs. In run 1 the density turbulence amplitude is $\delta n = 0.45 n_0$ and in run 2 we consider no density turbulence. In both of the two cases the resolution is 4000×4000. For run 3 and run 4 the turbulence amplitude is the same as run 1 but the resolutions are 2000×2000 and 8000×8000.

2 Simulation results

Figure 1 shows the time evolution of kinetic energy for run 1, the average radius of the blast wave, and the average speed of supernova shock. In the beginning of the simulation, the region with high density and high pressure expands and drives a shock propagating into the turbulent medium. The kinetic energy increases sharply during the expansion and reaches about 1.15×10^{51} erg. After that the ISM slows down the ejecta so the kinetic energy decreases slowly. In all the cases, the total energy is conserved within a degree of 10^{-6} during the simulation time. Figure 2 shows the snapshot contours of the magnitude of velocity, the magnitude of magnetic field, and density at $t = 1400$ years for run 1. At this time the averaged radius of shock front is roughly 9.5 pc. It is shown that after considering the upstream density fluctuation the velocity field in supernova blast waves is highly irregular. The shock surface is warped when the regions with different density pass through the shock front [13]. This produces strong transverse and rotational flow downstream of shock wave. The flow patten stretches and distorts the field lines of force, which leads to a turbulent dynamo process. We also find the magnetic field in the interface between ejecta and shocked medium is strongly enhanced by Rayleigh-Taylor instability (RTI) at the contact discontinuity [19]. It appears that the magnetic field can be enhanced to about $300\mu G$ in the region where RTI is important.

We focus the magnetic field downstream of forward shock within a thin layer to examine the magnetic field amplification close to the forward shock. In the top panel of figure 3 we plot the probability distribution function (PDF) of magnitude of magnetic field downstream within a distance of 0.3 pc behind the shock front. In this plot the solid line, dot line, dashed line, and dot dashed line indicate the results from run 1, run 2, run 3 and run 4 at $t = 600$ years, respectively. For comparison, a PDF of magnetic field in the same region as the result from run 1 at $t = 0$ is plotted as dashed dot dot line. It is shown that for the cases which include the upstream turbulence, the PDFs in run 1, run 3, and run 4 give a tail of larger value of magnetic field than the case without upstream density turbulence. For higher

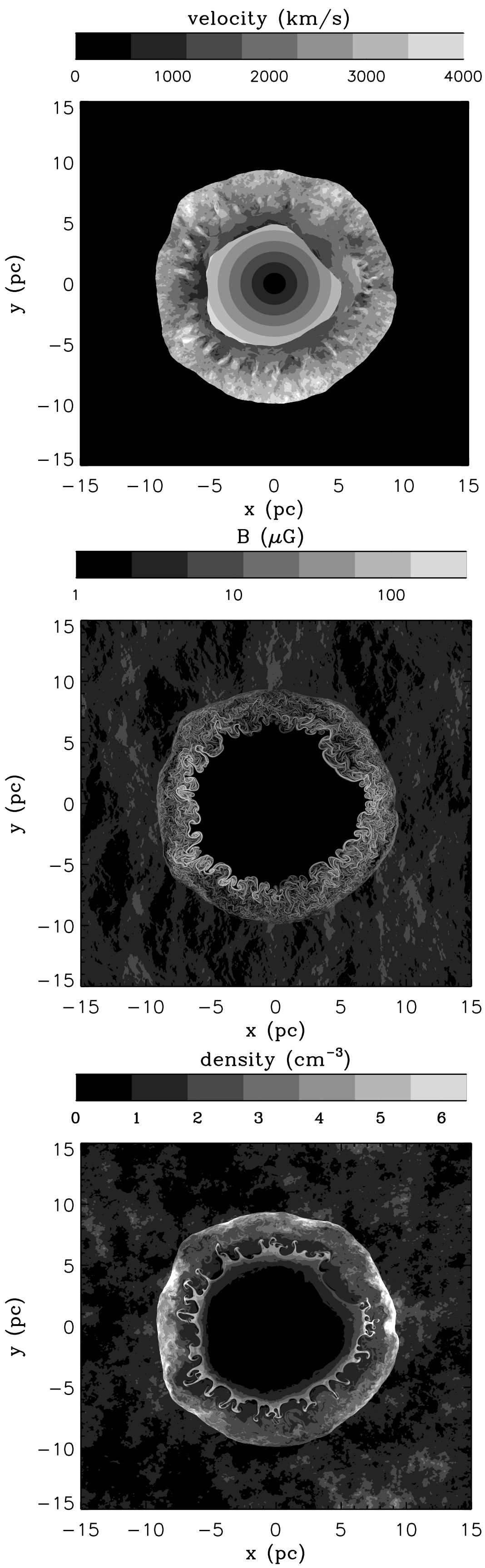

Figure 2: The contours of velocity, magnetic field, and density at $t = 1400$ years for run 1.

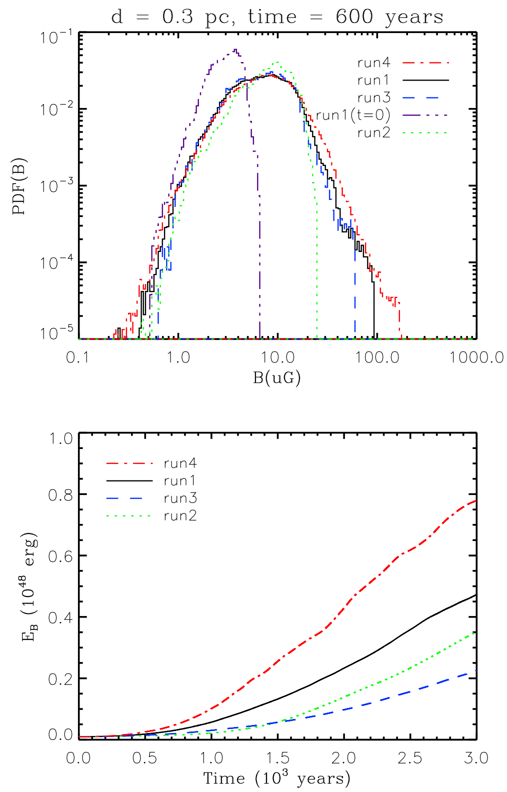

Figure 3: Top: The probability distribution function of magnitude of magnetic field downstream with a distance less than 0.3 pc to the shock front at $t = 600$ years. Bottom: the comparison of total magnetic field energy. The solid line, dot line, dashed line, and dot dashed line indicate the results from run 1 (4000^2), run 2 (no turbulence), run 3 (2000^2) and run 4 (8000^2), respectively. In the upper panel the PDF of pre-shocked magnetic field in the same region as the result from run 1 at $t = 0$ is plotted as dashed dot dot line.

resolutions, the maximum magnetic field can reach higher values. Figure 4 bottom panel shows the evolution of total magnetic field energy for these cases. For run 1, run 3 and run 4, it can be seen that for the same turbulence amplitude, the simulation with higher resolution gives larger magnetic field energy. Although we have not reached a numerical convergence, for the highest resolution case, the energy of magnetic field is on the order of 10^{48} erg, which is about 0.1% of the energy of supernova explosion. For run 2, the magnetic field energy also significantly increase, detailed analysis shows this is mainly caused by the magnetic amplification by Rayleigh-Taylor convection flow.

We have shown that the magnetic evolution in our simulation depends on the numerical resolutions we use. In Figure 4 we present the results at $t = 600$ years from run 4, which has the highest available resolution. It shows the PDFs of magnetic field, within a thin region of 0.15pc (solid line), 0.3 pc (dashed line) and 0.45 pc (dot dashed line) behind the shock front. The PDFs of downstream magnetic field with a distance less than 0.3 pc to the shock for run 2 is also plotted for comparison. It appears that the maximum magnetic field increases with the distance to the shock front. Since it takes time for the shear flow to stretch and amplify the magnetic field, the magnetic field will continue increasing downstream until saturation.

3 Discussion and Conclusion

The detection of strong magnetic field in young SNRs is a significant progress. However the origin of this process is still under debate. Here we study the interaction between a supernova blast wave with an turbulent upstream medium which contains large-scale density and magnetic field fluctuations. The vorticity produced at the rippled shock front can stretches and distorts the magnetic field lines, and that leads to a strong magnetic field amplification downstream [13, 18]. Using two-dimensional MHD simulations of a blast wave, we confirm this process can happen downstream of the blast wave. We show the magnetic evolution downstream is sensitive to the resolutions used in the simulation. For high resolutions, the simulations allow rapid growth at small scales, this leads to more efficient field amplification. The result shows simulations with higher resolutions yields higher maximum magnetic field magnitude and total magnetic field energy. This may provide an answer to reconcile the discrepancy in the previous work [13, 14, 18].

However, in our simulation we did not observe a systematic strong magnetic field within a thin region downstream of supernova shock. For example, for the results of highest resolution case, within 0.15 pc downstream of supernova shock, we only observes 0.8% region which has magnetic field larger than $30\mu G$. This lack of strong magnetic field can be understood as the downstream dynamo process requires an efficient stretching to produce strong magnetic field. The time scale for growth of magnetic field depends on the eddy turnover time. Only after several eddy turnover times the field can get great amplification. Therefore in an ideal MHD process, the magnetic field immediately downstream will not get much amplified. If the thin rims are indeed caused by electron losing energy in synchrotron emission, some other physics such as the effect of cosmic rays is needed to explain the peripheral X-ray thin rims in young SNRs. For observed X-ray hot spots [8], this mechanism could give a magnetic field on the same order as the estimated magnetic field given enough numerical resolution (also see [18]).

Understanding the radio and X-ray emission observed in young supernova remnants requires the detailed modeling about magnetic evolution and particle acceleration, which are closely related. The magnetic turbulence could rise a number of effects on particle acceleration such as hot spots [20, 21, 22] of energetic particles. The possible effects will be considered in the future.

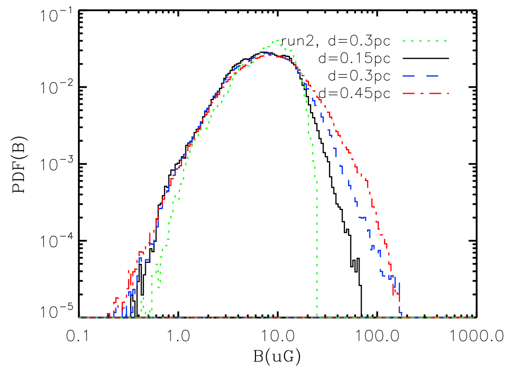

Figure 4: The probability distribution function of magnitude of magnetic field downstream with a distance less than 0.15 pc (solid line), 0.3 pc (dashed line) and 0.45 pc (dot dashed line) behind the shock front for run 12 at $t = 600$ years. The probability distribution function for magnetic field with a distance less than 0.3 pc behind the shock front in run 2 at $t = 600$ years is also plotted for comparison

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