ON THE AMPLIFICATION OF MAGNETIC FIELD BY A SUPERNOVA BLAST SHOCK WAVE IN A TURBULENT MEDIUM

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ABSTRACT

We have performed extensive two-dimensional magnetohydrodynamic simulations to study the amplification of magnetic fields when a supernova blast wave propagates into a turbulent interstellar plasma. The blast wave is driven by injecting high pressure in the simulation domain. The interstellar magnetic field can be amplified by two different processes, occurring in different regions. One is facilitated by the fluid vorticity generated by the “rippled” shock front interacting with the background turbulence. The resulting turbulent flow layers amplifying the magnetic field, consistent with earlier work (Giacalone & Jokipii 2007). The other process is facilitated by the growth of the Rayleigh-Taylor instability at the contact discontinuity between the ejecta and the shocked medium. This can efficiently amplify the magnetic field and tends to produce the highest magnetic field. We investigate the dependence of the amplification on numerical parameters such as grid-cell size and on various physical parameters. We show the magnetic field has a characteristic radial profile that the downstream magnetic field gets progressively stronger away from the shock. This is because the downstream magnetic field needs a finite time to reach the efficient amplification, and will get further amplified in the Rayleigh-Taylor region. In our simulation we do not observe a systematic strong magnetic field within a small distance to the shock. This indicates that if the magnetic-field amplification in supernova remnants indeed occurs near the shock front, other processes such as three-dimensional instabilities, plasma kinetics and/or cosmic ray effect may need to be considered to explain the strong magnetic field in supernova remnants.

Subject headings: shock waves - magnetic field - turbulence

1. INTRODUCTION

Powerful shocks associated with supernova remnants (hereafter SNRs) sweeping through the interstellar medium (ISM) are remarkable high-energy phenomena in astrophysics. It is widely believed that these high-Mach number shocks are the sources of galactic cosmic rays with energies up to at least $10^{15}$ eV. SNRs are also sources of strong radio and/or X-ray emissions. In these high-energy processes, the magnetic field is of great importance. Moreover, it provides information on energetic charged particles, which are presumably accelerated by the supernova shocks.

The ISM is known to be turbulent. Measurements of the ISM radio-wave scintillation have established the existence of large-scale density turbulence which has a Kolmogorov-like power spectrum spanning more than ten decades of spatial scale with an outer scale of several parsecs (e.g., Lee & Jokipii 1976; Armstrong et al. 1981; Rickett 1990; Armstrong et al. 1995; Minter & Spangler 1996). This has been called “the big power law in the sky.” (see, Spangler 2007) The galactic magnetic field is observed to be a few micro-Gauss and has uniform and fluctuating components that are roughly in equipartition (e.g., Beck et al. 1996; Minter & Spangler 1996; Han et al. 2004). The turbulent magnetic field can interact with the shock waves, distorting their surfaces leading to shock ripples (Neugebauer & Giacalone 2005) and the enhanced downstream magnetic fluctuations (Lu et al. 2009). It is also important for efficient particle acceleration (Giacalone 2005; Jokipii & Giacalone 2007; Guo & Giacalone 2010). Turbulence in the upstream medium has also been considered (Balsara et al. 2001) to explain the irregular and patchy emission morphology observed in SNRs (e.g., Anderson & Rudnick 1996).

Recently, it has been inferred from observations that the magnetic field in young SNRs is strongly enhanced to a magnitude much greater than the compression given by the shock jump condition. For example, by assuming that the so-called X-ray “thin rims” seen in several young SNRs (e.g., Bamba et al. 2005) are caused by shock accelerated electrons rapidly losing energy in strong magnetic field through synchrotron radiation, the associated magnetic field may be more than $50 - 100 \mu G$ in order to explain the thickness of the “thin rims” (Berezhko et al. 2003; Volk et al. 2005; Ballet 2006; Parizot et al. 2006). For SNR shocks with higher shock speeds propagating in more inhomogenous media such as Cas A and Tycho, the downstream magnetic fields are inferred to be more enhanced. “Thin rims” are also seen in radio emissions (Reynoso et al. 1997), which cannot be explained by the electrons losing energy in strong magnetic field. This indicates some other mechanism, e.g., decay of magnetic fluctuations may need to be considered (Pohl et al. 2005). Further downstream of the shock, the magnetic field may possibly be even higher than the region right behind the shock (Vink & Laming 2003). The morphology of X-ray emission in SNRs shows filamentary structure and rapid time variation, which indicates that the magnetic field could be as high as $1 mG$ (Uchiyama et al. 2007), over two

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orders of magnitude higher than the background fluid. It should be pointed out this rapid variation of synchrotron emission could be well reproduced in the case of strong magnetic fluctuations (Bykov et al. 2008). Since the effect of turbulence is not fully understood at this point, the actually magnetic-field amplification factors in young SNRs remain uncertain.

Bell & Lucek (2001) and Bell (2004) proposed that cosmic rays accelerated by the SNR forward shock waves provide a current that leads to an instability that can amplify the magnetic field close to the shock front. Numerical simulations show the evidence of this instability, however, it is found to easily saturate and the amplification factor may be limited (e.g., Riquelme & Spitkovsky 2009). Recently, Giacalone & Jokipii (2007) proposed an alternative mechanism, in which the interaction between the warped shock front and large-scale density fluctuations produces fluid vorticity downstream of strong shocks. That fluid vorticity can stretch, distort and amplify the magnetic field. The magnetic-field amplification in this mechanism relies on the dynamics of a magnetized fluid rather than the cosmic-ray kinetic physics. It is interesting to note, however, Balsara et al. (2001) performed three-dimensional MHD blast wave physics. It is interesting to note, however, Balsara et al. (2001) performed three-dimensional MHD blast wave simulation with moderate resolution which does not show amplification depends on a variety of parameters, including the explosion energy, the level of background turbulence, and the numerical resolution, etc. The paper is organized as follows. In Section 2, we describe our numerical model and simulation setup. We present the simulation results in Section 3, and in Section 4 we summarize and discuss our results.

2. BASIC CONSIDERATION AND NUMERICAL MODEL

We have performed a series of two-dimensional ideal MHD simulations with high-order numerical schemes.

The ideal MHD equation can be expressed as:

\[
\partial_t \rho + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)
\]

\[
\partial_t (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{uu} + (p + \frac{B^2}{8\pi}) \mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{4\pi}) = 0 \quad (2)
\]

\[
\partial_t (E) + \nabla \cdot ((E + p + \frac{B^2}{8\pi}) \mathbf{u} - \frac{\mathbf{B}\mathbf{u} - \mathbf{B}\mathbf{B}}{4\pi}) = 0 \quad (3)
\]

\[
\partial_t \mathbf{B} - \nabla \cdot (\mathbf{uB} - \mathbf{Bu}) = 0 \quad (4)
\]

where \(\rho\) is the plasma density, \(\mathbf{u}\) is the fluid velocity, \(\mathbf{B}\) is the magnetic field, \(p\) is the gas pressure, and \(E\) is the total energy density, which is defined as:

\[
E = \frac{p}{\gamma - 1} + \frac{1}{2} \rho u^2 + \frac{1}{8\pi} B^2. \quad (5)
\]

We use a central finite-volume scheme on overlapping grid cells (Liu et al. 2008) to solve the ideal MHD equations. In particular, a high-order divergence-free reconstruction for the magnetic field that uses the face-centered values has been employed (Li 2008, 2010). The magnetic field is advanced with a high-order constrained transport (CT) scheme to preserve the divergence-free condition to machine round-off error. The overlapping cells are natural to be used to calculate the electric-field flux without a spatial-averaging procedure, and hence we can achieve the higher-order accuracy (3rd-order or 4th-order). The central schemes do not need time-consuming characteristic decompositions, and are easy to code and be combined with un-split discretization of the source and parabolic terms. The overlapping cell representation of the solutions is also used to develop more compact reconstruction and less dissipative schemes. For solutions that contain discontinuities, e.g., shocks and/or contact discontinuities, we apply a non-oscillatory hierarchical reconstruction (HR) to remove the spurious oscillations and achieve high resolution near the discontinuities. The HR limiting we have used (Li 2008, 2010) requires information only from the nearest neighbor cells and it does not require characteristic decomposition. The numerical dissipation introduced by the HR limiting is enough to damp out all the artificial oscillations near the shocks and no extra artificial viscosity is needed. To further improve the computational efficiency and reduce the numerical dissipation for the smooth flow, we develop a shock detector to flag the cells near the shock and perform HR only to those cells. The details of the whole algorithm have been documented in (Li 2008, 2010). Our method has been verified to achieve the expected order of accuracy and have very low numerical dissipation. The high-order, low-dissipation, and divergence-free properties of this method make it an ideal tool for MHD turbulence simulations.

We model the simulation in a two-dimensional Cartesian coordinate \((x, y)\) with uniform grids. The size of the simulation domain corresponds to \(L_x \times L_y = 30pc \times 30pc\) in all the simulations. A supernova blast wave is driven by the initial injection of thermal pressure and mass in a small circular region at the center of the simulation box. The physical parameters used in the simulations are listed in Table 1. To calculate the injection energy, we must set a volume for the injection region. We assume a cylinder with radius of \(r = 0.4pc\) and length in \(z\) direction is \(L_z = 0.8pc\), which gives a volume of 0.402pc³.
Initially, the cylinder region has a high pressure $p_{in}$, and a total mass about 3 solar masses. For most cases considered here, we assume that the injected internal energy in the central region is $1.5 \times 10^{51}$ erg. A grid number of $n_x \times n_y = 4000 \times 4000$ is typically used for the simulation domain. This initial setup for blast waves is similar to the simulation made by Balsara et al. (2001), except that we use two-dimensional simulations with higher resolutions to study the magnetic-field evolution in young SNRs. The density and magnetic field in the background ISM consist of an average component and a turbulent component. We take the interstellar background plasma mean number density to be $n_0 = 1 \, \text{cm}^{-3}$. The average magnetic field $B_0$ is along the $y$ direction, whose magnitude is given in Table 1 for different cases. In our model, we assume a constant initial background ISM pressure $p_0$. Its corresponding temperature $T_0$ for each case is listed in Table 1. For the fluctuating components, we assume that both magnetic field and density fluctuations have a power spectrum of the form:

$$P \propto \frac{1}{1 + (kL_c)^{7/3}}.$$  \hspace{1cm} (6)

This is consistent with observations of interstellar turbulence (Armstrong et al. 1995; Chepurnov & Lazarian 2010). The turbulence is generated by summing a large number of discrete wave modes with random phases (Giacalone & Jokipii 1999). In all the simulation cases the coherence length of the background turbulence is chosen as $L_c = 3 \, \text{pc}$. The random component of magnetic field is given by

$$\delta B(x,y) = \sum_{n=1}^{N_m} \sqrt{C_B 2 \pi k_n \Delta k_n P_B(k_n) \sin \theta_n \hat{x} - \cos \theta_n \hat{y}} \times \exp(i \cos \theta_n k_n x + i \sin \theta_n k_n y + i \phi_n)$$  \hspace{1cm} (7)

where $P_B(k_n)$ is the power for wave mode with wavenumber $k_n$, random propagation angle $\cos \theta_n < 1$ and random phase $0 < \phi_n < 2\pi$. $C_B$ is a constant used to normalize the wave amplitude. In this study, the total fluctuating magnetic field is taken to be $\delta B^2 = B_0^2$ in all cases. The density fluctuations satisfy a log-normal probability distribution (Burlaga & Lazarus 2000; Giacalone & Jokipii 2007):

$$n(x,y) = n_0 \exp(f_0 + \delta f)$$  \hspace{1cm} (8)

in which $f_0$ is a constant used to determine the mean density and $\delta f$ given by a similar expression as the turbulent part of the magnetic field

$$\delta f(x,y) = \sum_{n=1}^{N_m} \sqrt{C_f 2 \pi k_n \Delta k_n P_f(k_n)} \times \exp(i \cos \theta_n k_n x + i \sin \theta_n k_n y + i \phi_n)$$  \hspace{1cm} (9)

In Runs 1 - 4 we consider the effect of the amplitude of upstream density fluctuations. In Runs 5 and 6 we examine the effect of different value of $B_0$. In Runs 7 and 8 we examine the effect of different temperatures of the ISM. We have also simulated two different explosion energies in Run 9 and Run 10. In Runs 11 and 12, we examine the effect of the simulation grid-cell size. Runs 1 and 2 are the representative runs with and without pre-specified background turbulence.

3. SIMULATION RESULTS

We now describe the simulation results on the interaction between the supernova blast wave and the turbulent ISM, along with the magnetic-field evolution downstream of the supernova shock. We will first present the results from our representative Run 1. Then we will discuss the spatial distribution of magnetic-field amplification, followed by the effects of numerical resolution and other effects such as the background turbulence and explosion energy.

3.1. Two Regions of Magnetic-field Amplification

Figure 1 shows the time evolution of (a) the total kinetic energy summed over the whole simulation domain, (b) the average radius of the blast wave, and (c) the average speed of the shock for Run 1. The average radius is estimated using the area of the high pressure region for each snapshot of pressure in the simulation, and the average speed of the shock is calculated by taking running differences between the averaged radii. 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 $1.15 \times 10^{51}$ erg, i.e., $\sim 77\%$ of the injected explosion energy is converted to kinetic energy at its peak. After that the swept-up ISM slows down the ejecta so the kinetic energy decreases slowly. In all the cases we have simulated, the total energy is conserved within a degree of $10^{-6}$ during the simulation time. The shock speed decreases from about $8700 \, \text{km/s}$ to about $3000 \, \text{km/s}$ at the end of the simulation. The corresponding Alfvén Mach number changes from $\sim 850$ to $\sim 290$. The radius of the remnant roughly follows $r \propto t^{0.8}$ which is consistent with the self-similar solution (Chevalier 1982). The size, age and shock speed are roughly consistent with the observations of young SNRs, though there is a wide spread in these quantities observationally. After a few times of the ejected mass being swept by the supernova blast wave, the shock speed is expected to slow down and settle into an “Sedov” phase in which $r \propto t^{0.4}$ typically after a few thousand years. Since in three-dimension the interstellar mass swept by supernova shock is proportional to $r^3$ rather than $r^2$ in our two-dimensional simulation, the shock speed in later times (after several thousand years) is likely overestimated. In this work we mainly focus on the evolution of young SNRs.

Figure 2 (a) and (b) display the total magnetic-field energy and the maximum magnetic-field strength in the simulation box for Run 1. It is shown that the magnetic-field energy increases to a level much larger than the initial magnetic-field energy. At the end of the simulation, the magnetic-field energy reaches to $\sim 0.47 \times 10^{48}$ erg. These results are qualitatively consistent with previous studies using the planar shock waves (Giacalone & Jokipii 2007; Inoue et al. 2009). The maximum magnetic field can rapidly increase to $250 \mu G$ within 500 years and finally goes up to about $550 \mu G$ in 3000 years, much larger than what is expected from the jump condition. But the detailed analysis shows that the spatial location of the
maximum magnetic field is typically not near the intermediate downstream region of the shock. We will discuss this result in more detail later.

Figure 3 shows the snapshots of (a) the velocity magnitude, (b) the magnitude of magnetic field, (c) density and (d) temperature at \( t = 1600 \) years for Run 1. It is shown that the velocity field of the blast wave is highly irregular. The shock surface is rippled as regions with different densities pass through the shock front (Giacalone & Jokipii 2007). The flow at the rippled shock transition produces strong transverse and rotational flow downstream of the shock wave. It can be seen from Figure 3 (b) that the magnetic field downstream of the blast wave is strongly amplified. We find the amplification is closely related to the downstream vorticity production (Giacalone & Jokipii 2007). This flow pattern stretches and distorts the field lines of force, which leads to a small-scale dynamo process.

In addition, different from the shock amplification, we find that the magnetic field in the interface region between the ejecta and the shocked medium is also strongly enhanced by the Rayleigh-Taylor instability (RTI) at the contact discontinuity (e.g., Jun & Norman 1996a,b). It appears that the magnetic field can be enhanced to \( \sim 300 \mu G \) in the region where RTI is important. Figure 3 (c) shows “fingers” of enhanced density resulting from the RTI in the interface region, which is quite different from the mechanism discussed above, which occurs just behind the shock. In fact, the magnetic-field amplification by the RTI process contributes almost equally to the total enhanced magnetic energy and the maximum field strength as shown in Figure 2. The nonlinear development of RTI stretches the magnetic field and causes strong amplification. This process has been studied extensively (e.g., see the earlier numerical studies by Jun et al. 1995; Jun & Norman 1996a,b). The RTI amplification process can be studied in more detail when a more realistic initial ejecta profile are taken into account. Though beyond the scope of this paper, it will be worthwhile to see if there are possible observational signatures in the RTI-amplification region.

3.2. Spatial Dependence of the Magnetic-field Amplification

As discussed in the Introduction, some observed X-ray “thin rims” and their coincidence with the inferred shock locations have suggested that magnetic field is amplified at or within a short distance to the supernova remnant shock front. It is thus imperative to investigate whether the MHD simulations can reproduce this feature, although to directly compare to X-ray observations would also require the simultaneous computation of cosmic-ray variation, which is not included in this study.

In Figure 4 we present the results at \( t = 600 \) years for Run 12, which has the highest available resolution. It shows the probability distribution functions (PDFs) of magnetic field, taken within a thin region of 0.15 pc, 0.3 pc and 0.45 pc behind the shock front, respectively. In addition, the PDF of the downstream magnetic field within a distance of 0.3 pc of the shock front for Run 2 (without background turbulence) is also plotted for comparison. The PDFs presented here and in other figures of this paper are normalized by the respective volume from which the distribution is taken. It appears that the magnitude of magnetic field increases with the distance from the shock front. Specifically, for the rim within 0.15 pc downstream, the maximum magnetic field reaches only 70 \( \mu G \). Also the region with magnetic field higher than 30 \( \mu G \) only occupies about 0.8% of the rim.

To explore further the amplification of the magnetic field in both the shock downstream region and the Rayleigh-Taylor region, we plot the average magnitude of magnetic field as a function of radial distance from the shock front at different times from 200 years to 2000 years for Run 12, which is shown in Figure 5. Together with the spatial distribution of magnetic field at these times (not shown here) that is similar to Figure 3, we can separate approximately the two different magnetic-field amplification regions. In Figure 5, the right side of the dashed lines is typically dominated by the shock amplification and the left is by the Rayleigh-Taylor instability. It is shown that Rayleigh-Taylor amplification produces much larger magnetic field than those from the shock amplification. Detailed analysis shows that, locally, the amplified magnetic field in the Rayleigh-Taylor region can easily reach several hundred micro-gauss.

It can be seen from the downstream magnetic-field evolution that the amplification of magnetic field has not reached a saturation. This is probably not surprising, given the fast transit time of the SNR shock and the relatively young age of the SNRs. The gradual increase of the magnetic-field amplitude further downstream from the shock is consistent with the picture that turbulence has longer time to amplify the fields. Before the magnetic field reaches Rayleigh-Taylor region, its maximum value is only about 200 – 300 micro-Gauss, much less than the amplified magnetic field in Rayleigh-Taylor regions.

3.3. Effects of Numerical Resolution

Since the field amplification at the shock front is closely related to the vorticity generation, the numerical resolution is expected to play an important role. Numerical modeling of this process must resolve the vortical motions. In Figure 6 (a) we plot the normalized probability distribution function (PDF) of the magnitude of magnetic field downstream within a distance of 0.3 pc of the shock front for three different grid resolutions. Run 1 and 2 have 4000 \( \times \) 4000, Run 11 and 12 have 2000 \( \times \) 2000, and 8000 \( \times \) 8000, respectively. Figure 6 (b) shows the evolution of the total magnetic-field energy for these cases. It can be seen that higher resolution runs give higher total magnetic-field energy and, even for the highest resolution of Run 12, the total amount of magnetic energy in the simulation domain has not converged. More detailed analysis shows that the kinetic energy and magnetic energy have not reached equal partition in small scales. Note that the total magnetic energy at the end of the simulation (\( \sim 3 \times 10^5 \) yrs) is still a small fraction (\(< 10^{-3}\)) of the injected explosion energy or the available kinetic energy in the simulation.

In Figure 6 (a), by plotting the PDFs within a small downstream region close to the shock front, we can get a more clear view of the effects of the numerical resolution in the shock amplification process near the shock front. The green curve from Run 2 represents the shock amplification without the background ISM density turbulence, whereas Run 1, 11, and 12 represent the shock amplification being significantly enhanced when the background...
ISM turbulence is present. The purple curve represents the initial, un-shocked background ISM magnetic-field distribution in the same region as shown in the cases that include ISM density turbulence. The higher resolution Run 12 obviously produces a greater volume fraction with higher magnetic field and a larger maximum magnetic field in the downstream region of the shock, although one might argue that the difference among these runs is not very large, at least for the region within 0.3 pc of the shock at this particular time.

In Figure 6 (b), however, the difference among different resolutions seems to be much bigger. Such differences are mostly caused by the region where RTI amplifies the magnetic field (see Fig. 3 (b) for field distribution), because the total magnetic energy is a summation of both the shock-amplified region and the RTI region. This is consistent with some previous studies (Jun et al. 1995) where numerical resolutions are shown to be important as well. Such requirements for high resolution might also explain the previous finding that magnetic-field amplification is not as strong (Balsara et al. 2001) when it is difficult to employ very high numerical resolution in three-dimensional MHD simulations. We have also checked the long term evolution (up to $3 \times 10^4$ years) of SNRs similar to Balsara et al. (2001) using two-dimensional high-resolution simulation and we consistently find strong magnetic field larger than $100 \mu G$ in the downstream region.

Figure 6 demonstrates that both the shock and RTI amplification of the magnetic field depends on the numerical resolution (perhaps more strongly for the RTI region). Figure 7 further supports this conclusion where we plot the vorticity distribution of the shocked flows for the low resolution (Run 11) and the high resolution (Run 12), at a time that is the same as in Figure 3. It is not surprising to see that more small scale structures are developed with much larger vorticity magnitudes in Run 12. Note that the two magnetic-field amplification regions can be approximately separated spatially (at least at this time). The small scale structures in vorticity (signifying turbulence) are developed in the immediate downstream of the forward shock region whereas both relatively large (i.e., the density “fingers”) and small scale vorticity features are produced in the RTI region.

3.4. Other Effects

Figure 8 shows the effects of different background turbulence amplitudes. In Figure 8 (a), the PDFs of magnetic field within 0.3 pc behind the shock front for Runs 1 - 4 at $t = 600$ years are shown, respectively. Figure 8 (b) represents the evolution of magnetic-field energy for these cases. It is seen that the larger amplitude density fluctuation tends to lead to stronger magnetic-field amplification. For Run 2, it can be seen that the effect of RTI strongly enhance the magnetic field. The total magnetic-field energy can even exceed the case of Run 4 ($\sqrt{\delta n^2/n_0^2} = 0.3$). Detailed analysis shows the growth of RTI is somewhat suppressed by turbulence which makes the magnetic-field energy in Run 4 less than Run 2 at late times.

We also examine the effect of the magnitude of initial interstellar magnetic field in Run 5 and Run 6. Comparing these two cases with Run 1, we find the shock amplified magnetic field is nearly proportional to the magnitude of initial magnetic field. This is consistent with the fact that the amplified fields have not reached saturation. The effect of the temperature of background medium is also examined in Run 7 and Run 8. We find that the different temperatures do not yield any strong difference in the downstream magnetic-field evolution.

Figure 9 is similar to Figure 8, but for different initial explosion energies, $E = 1.5 \times 10^{51}$ erg, $4.5 \times 10^{51}$ erg, and $4.5 \times 10^{50}$ erg, respectively. The time frames are chosen so the shock radii are roughly the same, the magnetic-field distribution before amplification is therefore roughly the same. We can see the magnetic-field amplification is stronger for the case of higher explosion energy. This is because the central region drives a stronger shock which generates stronger vorticity in the downstream region. The magnetic energy evolution in these three cases follows the same trend.

4. DISCUSSION AND CONCLUSION

The inferred strong magnetic field in young SNRs is a significant result and can be important in the high-energy processes including particle acceleration and thermal/nonthermal emissions. The origin of this process, however, is still under debate. In this work we study the interaction between a supernova blast wave with a turbulent upstream medium which contains density and magnetic-field fluctuations. The vorticity produced at the rippled shock front can stretch and distort the magnetic field lines, and this leads to a strong magnetic-field amplification downstream (Giacalone & Jokipii 2007; Inoue et al. 2009). Using two-dimensional MHD simulations of a blast wave, we confirm the key features of this process. Based on our simulations, we conclude that the increase of magnetic field is dependent on shock speed and background density turbulence amplitudes. Furthermore, the numerical resolution used in the simulations can play an important role as well. Previous work (Balsara et al. 2001) using three-dimensional MHD simulation with moderate resolution shows no magnetic-field amplification beyond $50 \mu G$. Here 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 efficient field amplification.

Furthermore, we find that there are two different processes and spatial regions where magnetic field is amplified. One is associated with the shock amplification immediately downstream and the other is associated with the RTI at the interface between the ejecta and the shocked medium.

However, in our simulations, we did not observe a systematic strong magnetic field within a thin region immediately downstream of the supernova shock. For example, using the results of the highest resolution case, within 0.15 pc downstream of supernova shock, we observe only about 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 the growth of magnetic field depends on the eddy turnover time. Only after a certain time can the field get sufficient amplification. If the thin rims ($0.01 - 0.1$ pc) observed in young SNRs are indeed...
caused by the electrons losing energy in strong fields (~several hundred $\mu G$), some other processes such as three-dimensional instabilities, plasma kinetics or the effect of cosmic rays might be needed to explain the magnetic-field amplification in young SNRs.

We note that in observation there is no one-to-one correspondence between X-ray “thin rims” and inferred shock locations. In fact many “thin rims” and filamentary structures seen in X-ray observation can hardly be related to shock front due to observation limitation. Further understanding about the relationship between the small scale X-ray structure and shock locations is needed to further constraint and distinguish the different mechanisms for amplification of magnetic field.

We also note that the two-dimensional simulation in this study could be significantly different from three-dimensional simulation. It is known that in two-dimensional simulation the dynamics of MHD flow is very different from that for three-dimensional simulation. For example the inverse cascade of enstrophy and the growth rate of two-dimensional simulation of MHD flow could develop other types of instabilities with larger growth rates. Further three-dimensional MHD simulation with high resolution will be useful in confirming the conclusions of this paper.

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There are several recent studies show that magnetic field amplification behind high-mach number shock (Inoue et al. 2011a,b) and in Rayleigh-Taylor region (Stone & Gardiner 2007) can still operate in three-dimensions, which confirm the results found in two-dimensional simulations. Also, in three-dimensional simulation the MHD flow could develop other types of instabilities with larger growth rates. Further three-dimensional MHD simulation with high resolution will be useful in confirming the conclusions of this paper.
The parameters used in the simulations. Number density $n$ is in cm$^{-3}$, magnetic field $B$ is in $\mu$G, temperature $T_0$ is in K, and explosion energy $E$ is in ergs. The last two columns list the average and maximum magnetic-field strength in units of $\mu$G within a thin region (0.15 pc) downstream of supernova shock at 600 years. In all the cases, the fluctuating component of the magnetic field is taken to be $\delta B^2 = B_0^2$.

<table>
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<th>Run</th>
<th>$n$</th>
<th>$\sqrt{\delta n^2/n_0^2}$</th>
<th>$B_0$</th>
<th>$T_0$</th>
<th>$E/m(10^{51})$</th>
<th>Grids</th>
<th>$B_{ave}$ (rim)</th>
<th>$B_{max}$ (rim)</th>
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Fig. 1. — The time evolution of (a) the total kinetic energy summed over the simulation domain, (b) the average radius, and (c) the average speed of the shock for Run 1. The initial injected thermal energy is $1.5 \times 10^{51}$ ergs.
Fig. 2.— The time evolution of (a) the total magnetic-field energy $E_B$ and (b) the maximum magnetic-field strength in the simulation domain $B_{\text{max}}$, for Run 1.
Fig. 3.— Spatial distribution of (a) the velocity magnitude, (b) the magnetic-field strength, (c) density, and (d) temperature for Run 1 at $t = 1600$ years. The background ISM turbulence causes the shock front to become rippled. In addition, the interface between the ejecta and the shocked ISM experiences the Rayleigh-Taylor-like instabilities.

Fig. 4.— The probability distribution function of magnitude of magnetic field downstream with a distance within 0.15 pc (black solid line), 0.3 pc (blue dashed line) and 0.45 pc (red dot dashed line) behind the shock front for Run 12 at $t = 600$ years. The probability distribution functions for magnetic field with a distance within 0.3 pc behind the shock front in Run 2 at $t = 600$ years and the initial background magnetic field are also plotted for comparison.
Fig. 5.— The average magnetic-field magnitude as a function of radial distance to the shock front from Run 12 at different time from 200 years to 2000 years. The dashed lines roughly separate magnetic-field regions dominated by the shock amplification and by Rayleigh-Taylor convective flow.

Fig. 6.— (a) The probability distribution function of magnitude of magnetic field downstream of a distance within 0.3 pc to the shock front at $t = 600$ years for runs with different resolution. The PDF of the background magnetic field in the same region taken from Run 1 at $t = 0$ is also plotted. (b) The comparison of total magnetic-field energy evolution for the same runs.
Fig. 7.— The color-coded images of vorticity (top) and the magnetic-field amplitude (bottom) for Run 11 (low resolution 2000 × 2000, left panels) and Run 12 (high resolution 8000 × 8000, right panels) at $t = 1600$ years.
Fig. 8.— Comparison for different background turbulence amplitudes. (a) The probability distribution function of magnitude of magnetic field downstream within a distance of 0.3 pc behind the shock front at $t = 600$ years. (b) The comparison of the total magnetic-field energy evolution for these runs.
Fig. 9.— Comparison for different initial explosion energies. (a) The probability distribution function of magnitude of magnetic field downstream with a distance within 0.3 pc behind the shock front when the shock radii are roughly the same for these cases. (b) Comparison of the total magnetic-field energy for these runs.