Three-Dimensional Numerical Magnetohydrodynamic Simulations of Magnetic Reconnection in the Interstellar Medium

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ABSTRACT

Strong thermal X-ray emission, called Galactic Ridge X-ray Emission, is observed along the Galactic plane (Koyama et al. 1986). The origin of hot ($\sim$ 7 keV) component of GRXE is not known, while cool ($\sim$ 0.8 keV) one is associated with supernovae (Kaneda et al. 1997, Sugizaki et al. 2001). We propose a possible mechanism to explain the origin; locally strong magnetic fields of $B_{\text{local}} \sim 30~\mu$G heat interstellar gas to $\sim$ 7 keV via magnetic reconnection (Tanuma et al. 1999). There will be the small-scale (< 10 pc) strong magnetic fields, which can be observed as $\langle B \rangle_{\text{obs}} \sim 3~\mu$G by integration of Faraday Rotation Measure, if it is localized by a volume filling factor of $f \sim 0.1$. In order to examine this model, we solved three-dimensional (3D) resistive magnetohydrodynamic (MHD) equations numerically to examine the magnetic reconnection triggered by a supernova shock (fig.1). We assume that the magnetic field is $B_x = 30 \tanh(y/20\text{pc})~\mu$G, $B_y = B_z = 0$, and the temperature is uniform, at the initial condition. We put a supernova explosion outside the current sheet. The supernova-shock, as a result, triggers the magnetic reconnection, and the gas is heatd to > 7 keV. The magnetic reconnection heats the interstellar gas to $\sim$ 7 keV in the Galactic plane, if it occurs in the locally strong magnetic fields of $B_{\text{local}} \sim 30~\mu$G. The heated plasma is confined by the magnetic field for $\sim 10^{5.5}$ yr. The required interval of the magnetic reconnections (triggered by anything) is $\sim 1 - 10$ yr. The magnetic reconnection will explain the origin of X-rays from the Galactic ridge, furthermore the Galactic halo, and clusters of galaxies.

Key Words : Magnetohydrodynamics: Magnetic Reconnection: Galaxy

I. INTRODUCTION

Strong thermal X-ray emission of diffuse hot gas is observed along the Galactic plane (Koyama et al. 1986). It is called Galactic Ridge X-ray Emission (GRXE). It has mainly two components; hot ($\sim$ 7 keV) one and cool ($\sim$ 0.8 keV) one. According to recent observations by ASCA satellite, the cool one is associated with supernovae (Kaneda et al. 1997, Sugizaki et al. 2001). The hot one, however, can not be explained by any point sources, because of the its temperature and ionization parameter etc. Furthermore, the hot diffuse gas can not be confined by the gravity nor gas pressure of typical gas.

In order to solve the problem about the origin and confinement of the hot gas, we propose a possible mechanism to explain the origin; locally strong magnetic fields of $B_{\text{local}} \sim 30~\mu$G heat interstellar gas to $\sim$ 7 keV via magnetic reconnection (Tanuma et al. 1999). The magnetic reconnection is a mechanism to convert the magnetic energy into thermal and kinetic energies rapidly. It plays an important role in solar flares, as observed by X-ray satellite Yohkoh (Shibata 1996). There will be the small-scale (< 10 pc) strong magnetic fields in the Galaxy, which can be observed as $\langle B \rangle_{\text{obs}} \sim 3~\mu$G by integration of Faraday Rotation Measure, if it is localized by a volume filling factor of $f \sim 0.1$.

In previous papers, we examined the possibility of

the magnetic reconnection for the origin of the GRXE gas (Tanuma et al. 1999), and revealed that magnetic reconnection is determined only by the initial magnetic Reynolds number, not type or amplitude of the initial perturbation (Tanuma et al. 2001). In this paper, we extend the model from 2D to 3D, and study 3D effect on the magnetic reconnection triggered by a supernova-shock.

II. Numerical Simulations and Results

In order to examine this model, we solved 2D and 3D resistive magnetohydrodynamic (MHD) equations numerically to examine the magnetic reconnection triggered by a supernova shock (fig.1). We assume that the magnetic field is $B_x = 30 \tanh(y/20\text{pc})~\mu$G, $B_y = B_z = 0$, and the temperature is uniform, at the initial condition. The unit of length, velocity, and time are $H \sim 20$ pc, $C_s \sim 500$ km s^{-1}, and $H/C_s \sim 30$ Myr, respectively. We assume that electric resistivity is η_0 where J/ρ is under the threshold, otherwise $\eta_0 + 0.1(J/\rho - 100)^2$. We put a supernova explosion outside the current sheet.

The supernova-shock, as a result, passes the current sheet. Long after the passage, the current sheet becomes thin gradually, and magnetic reconnection occurs in both models. The magnetic reconnection heats the interstellar gas to $\sim$ 7 keV, and magnetic field con-
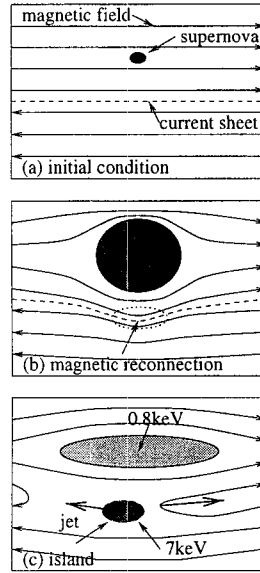
Fig. 1 : Our new scenario for the heating and confinement of the GRXE plasma. The magnetic reconnection generates the hot (7 keV) component from the cool (0.8 keV) component of the GRXE plasma which is generated by supernovae or a point explosion. The strong magnetic field is generated by the galactic dynamo, and super-hot plasma is generated by the magnetic reconnection, as long as our Galaxy rotates. (a) A supernova appears near a current sheet. (b) The magnetic reconnection occurs in the current sheet. (c) A magnetic island is generated by reconnection and confines the heated plasma, as an interstellar jet. The magnetic island is actually a helical magnetic field in three dimensional view.
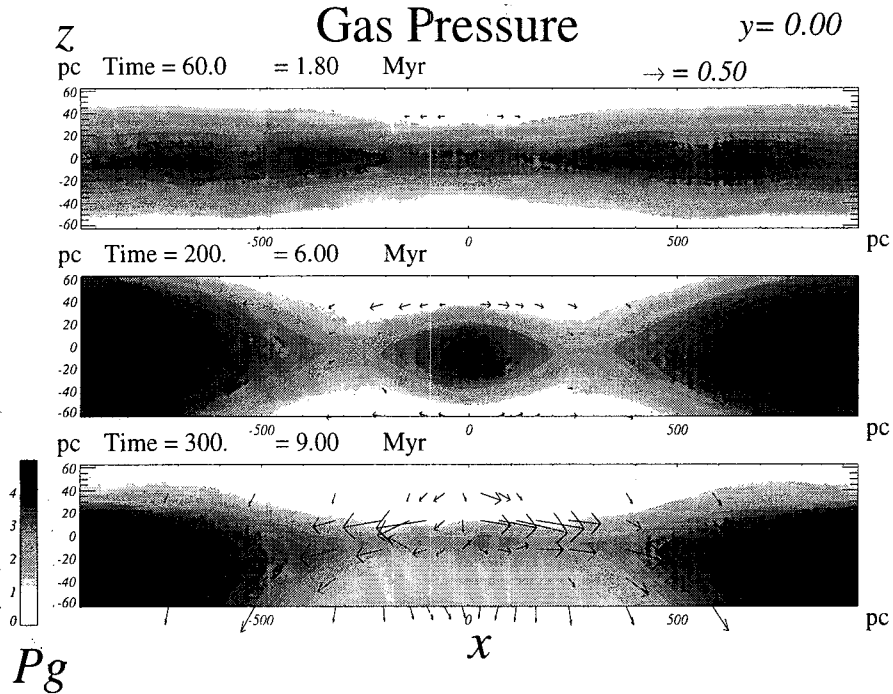

Fig. 2 : Time variation of the 2D distribution of the gas pressure at the reconnection region (x-z plane of the 3D simulation). The magnetic reconnection starts long after the supernova shock passes a current sheet. The magnetic energy is released by the magnetic reconnection.
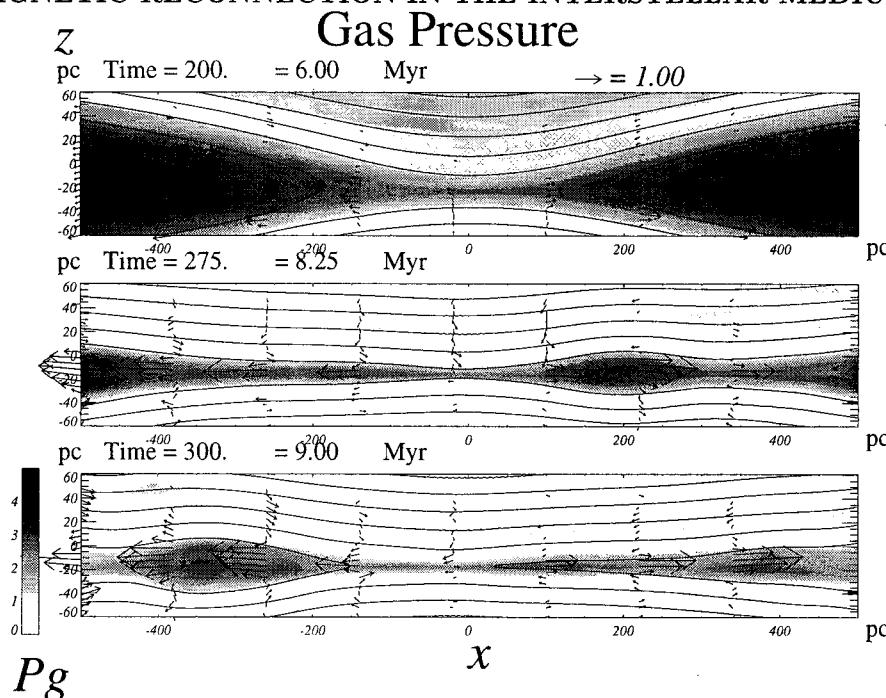
Fig. 3 : Time variations of the 2D distribution of the gas pressure. In 2D model, we use small grid so that we resolve the small structure and examine the secondary tearing instability. Aspect ratio of this figure is different from that of figure 2.

fines the heated gas for a long time.

In 2D model, the initial current sheet evolves as follows: (i) current sheet thinning by the tearing instability in its nonlinear phase long after the passage of supernova-shock, (ii) collapse of the current sheet and Sweet-Parker (slow) reconnection, (iii) secondary tearing instability in the Sweet-Parker current sheet, (iv) plasmoid ejection, onset of anomalous resistivity, and Petschek (fast) reconnection (Tanuma et al. 2001). The supernova-shock, as a result, triggers the tearing instability, Sweet-Parker type reconnection, secondary tearing instability, and the Petschek type reconnection. The plasmoids are generated and ejected along the current sheet by Petschek reconnection. The reconnection rate and magnetic energy release rate increases during plasmoid-ejections. Note that these results depend on only magnetic Reynolds number, which is defined by resistivity, Alfvén velocity, and scale length, not the type or amplitude of initial perturbation.

In 3D model, however, we use rough glid so that we can not resolve the secondary tearing instability and plasmoid ejection. Petschek reconnection starts after current sheet thinning by the (first) tearing instability.

III. Discussion

In this paper, we examine the magnetic reconnection triggered by a supernova-shock in interstellar medium in 2D and 3D MHD simulations. In 3D mode, we can not resolve the secondary tearing instability, because we can not remove the numerical resistivity caused by the rough grids. In future work, we will study 3D effect on the magnetic reconnection in interstellar medium by using enough fine grids.

The magnetic reconnection is a possible mechanism for the origin of the GRXE gas. The required interval of the magnetic reconnections (triggered by anything) is $\sim 1 - 10$ yr for the generation of the GRXE gas. The time depends on the magnetic energy released by the magnetic reconnection. The magnetic reconnection will explain the origin of X-rays from the Galactic ridge, furthermore the Galactic halo, and clusters of galaxies.

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