Magnetic Reconnection as the Origin of Galactic-Ridge X-Ray Emission

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Abstract

We present a scenario for the origin of the hot plasma in our Galaxy as a model of strong X-ray emission \[ \sim 3 - 10 \text{ keV}; L_X (2 - 10 \text{ keV}) \sim 10^{38} \text{ erg s}^{-1} \], called Galactic Ridge X-ray Emission (GRXE), which has been observed near to the galactic plane. GRXE is thermal emission from a hot component (\sim 7 \text{ keV}) and a cool component (\sim 0.8 \text{ keV}). Observations suggest that the hot component is diffuse, and that it is not escaping away freely. Both what heats the hot component and what confines it in the galactic ridge still remain puzzling, while the cool component is believed to be created by supernovae. We propose a new scenario: the hot component is heated by magnetic reconnection, and confined by a helical magnetic field produced by magnetic reconnection. We solved two-dimensional magnetohydrodynamic equations numerically to study how magnetic reconnection, triggered by a supernova explosion, creates hot plasmas and magnetic islands (helical tubes), and how the magnetic islands confine the hot plasma in the Galaxy. This is one of the possible mechanisms to trigger reconnection in the Galaxy. We conclude that magnetic reconnection is able to heat the GRXE plasma if the magnetic field is localized in an intense flux tube with \[ B_{\text{local}} \sim 30 \mu \text{G}. \]

Key words: Galaxies: Milky Way — Galaxies: X-rays — Interstellar: magnetic fields — Magnetohydrodynamics — Plasmas

1. Introduction

Bright diffuse X-ray emission has been observed along the galactic plane with various X-ray astronomy satellites, including HEAO-1 (Worrall et al. 1982), EXOSAT (Warwick et al. 1985), Tenma (Koyama et al. 1986b; Koyama 1989), Ginga (Koyama et al. 1989; Yamasaki et al. 1997; Yamauchi, Koyama 1993, 1995), ASCA (Kaneda et al. 1997; Makishima 1994; Yamauchi et al. 1996), and RXTE (Valinia, Marshall 1998). The emission, called Galactic Ridge X-ray Emission (GRXE), is distributed along the galactic latitude \[ |b| \leq 1^\circ - 2^\circ \] and the galactic longitude \[ |l| \leq 60^\circ \] (Warwick et al. 1985) with a scale height of \[ h \sim 100 \text{ pc} \] (Yamauchi, Koyama 1993) and a radius of about 8 kpc. The spatially integrated GRXE luminosity in the 2-10 keV range is \[ L_X \sim (1-2) \times 10^{38} \text{ erg s}^{-1} \] (Koyama et al. 1986b; Warwick et al. 1985; Yamasaki et al. 1997; Yamauchi, Koyama 1993). Koyama et al. (1986b) have revealed that GRXE is optically thin thermal emission from a hot plasma. The hot plasma has mainly two components: hot (\sim 7 \text{ keV}) and cool (\sim 0.8 \text{ keV}) components (Kaneda et al. 1997; Makishima 1994). The hot component of GRXE cannot be explained consistently in terms of an assembly of unresolved point X-ray sources emitting thermal X-rays, because of the observed properties of the surface brightness fluctuations and because of the lack of a corresponding population of discrete X-ray sources (Kaneda et al. 1997; Koyama et al. 1986b; Makishima 1994; Yamauchi et al. 1996). GRXE is, therefore, likely to be thermal emission from a hot plasma distributed diffusely along the Milky Way. The number density of the hot plasma is estimated to be \[ n_h \sim 3 \times 10^{-3} f_h^{-1/2} \text{ cm}^{-3} \] where \[ f_h \] is the volume-filling factor of the hot component (e.g., Kaneda et al. 1997).

The GRXE plasma deviates from ionization equilibrium, as indicated by the center energies of various atomic lines; the observed ionization parameter is
typically \((nt)_{h, \text{obs}} \sim 10^{10-11} \text{ s cm}^{-3}\) (Kaneda et al. 1997; Makishima 1994; Yamauchi, Koyama 1995) in contrast to the value of \(\sim 10^{12} \text{ s cm}^{-3}\) required to attain the full ionization equilibrium (Masai 1984), where \(t\) is the life time of the hot plasma. This observed value means that the lifetime of the hot plasma is \(\tau_{\text{obs}} \sim (nt)_{h, \text{obs}}/n_h \sim 10^{13-14} f_h^{1/2} \sim 10^{5.5-6.5} f_h^{1/2} \text{ yr}\). If the plasma \(\sim 7 \text{ keV}\) was escaping with the sound velocity \((c_s \sim 8 \times 10^7 \text{ cm s}^{-1})\), the hot plasma would run away in \(\tau_{\text{esc}} \sim (h/2)/c_s \sim 10^5 \text{ yr}\), which is shorter than the observed lifetime \(\tau_{\text{obs}}\) derived from the ionization parameter (assuming \(f_h\) to not be too small; Kaneda et al. 1997). This infers that the GRXE plasma is dynamically nearly in equilibrium. The hot plasma cannot be confined by gravity, since its temperature greatly exceeds the gravitational escape temperature \((\sim 0.4 \text{ keV})\) of the Galaxy. The GRXE plasma cannot be confined by gas pressure either, since the GRXE plasma has a pressure of \(p_h \sim 5 \times 10^{-11} f_h^{-1/2} \text{ erg cm}^{-3}\), which is 1-2 orders of magnitude higher than those of ordinary interstellar components (HI gas, cosmic rays etc.) (Kaneda et al. 1997). It has, thus, remained a big puzzle what heats the plasma and what prevents the heated plasma from escaping.

The cool component of the GRXE plasma has a temperature of \(\sim 0.8 \text{ keV}\) and a very low ionization parameter \((\sim 10^8 \text{ s cm}^{-3})\), whose density is estimated to be \(n_c \sim 5 \times 10^{-3} f_c^{-1/2} \text{ cm}^{-3}\) (Kaneda et al. 1997), where \(f_c\) is the filling factor of the cool component. It is roughly distributed in a manner similar to that of the hot component. Kaneda et al. (1997) explained that the plasma responsible for this cool component is an assembly of supernova remnants, because of its lower temperature. This interpretation is traced back to the idea of Koyama, Ikeuchi, and Tomisaka (1986a), who originally argued that the entire GRXE plasma was created by young \(\sim 10^3-4 \text{ yr}\) supernovae in a tenuous \(\sim 0.1-0.01 \text{ cm}^{-3}\) medium. Norman and Ikeuchi (1989) proposed that the GRXE plasma is made of chimneys. Stellar winds and several other sources, such as the cosmic rays, also contribute to heating of the hot plasma in the Galaxy. According to the latest ASCA results, however, the hot component is likely to be emitted by large-scale diffuse plasmas along the galactic plane, which, especially the temperature, cannot be adequately explained as an assembly of discrete objects, such as shell-type supernovae and OB stars (Kaneda et al. 1997). Parker (1992) pointed out the importance of magnetic reconnection for heating of galactic plasma (see also Hanasz, Lesch 1998). In an attempt to solve the puzzle of the GRXE, especially, Makishima (1994, 1995) proposed a view that the GRXE plasma was heated to high temperature via magnetic reconnection, utilizing the great amount of energy in galactic rotation and random stellar motion, and has been confined by interstellar magnetic tubes of \(\sim 30 \mu \text{G}\). This view is further supported by an additional argument that heat conduction would quickly \((\tau_{\text{cond}} \sim 10^{3-4} \text{ yr})\) equalize the temperatures of the hot and cool components unless significant magnetic fields prevent heat conduction across the magnetic field lines.

The purpose of this paper is to extend the magnetic reconnection model suggested by Makishima (1994, 1995) to a more quantitative level. Magnetic reconnection is a fundamental intrinsic property of agitated magnetized, turbulent plasmas. Whenever magnetic fields with different field directions encounter each other, the magnetic energy is rapidly dissipated. Reconnection heats the interstellar gas by releasing interstellar magnetic energy, \(B^2/8\pi\), and accelerates it by a magnetic tension force to the Alfvén velocity. Accelerated gas generates shock heating. Outside the forming current sheet the magnetic field lines are frozen-into the plasma, which is provided by the high electrical conductivity. When the oppositely directed field lines collide with it, the field gradient steepens and the current density increases until strong dissipation sets in (e.g., anomalous resistivity) to trigger fast reconnection (e.g., Hanasz, Lesch 1998). Thus, magnetic reconnection can be triggered by various mechanisms, such as a supernova (or a point-explosion), Parker instability, cosmic rays, and the collision of clouds etc in numerous current sheets.

In this paper, we first calculate the magnetic field strength, filling factor of reconnecting flux tubes, and magnetic energy-release rate due to reconnection, using an order-of-magnitude estimate, and present a possible scenario for the formation of the GRXE plasma. Second, we examine in more detail how magnetic reconnection heats and confines the GRXE plasma when the reconnection is triggered by supernova shock (or a similar blast shock), by discussing the results of two-dimensional (2D) magnetohydrodynamic (MHD) simulations. Note that the supernova-shock-triggered reconnection is one of the possible reconnections creating galactic hot plasmas. The basic physics of reconnection (especially after reconnection starts), however, is applicable to any reconnection mechanisms triggered by other agents, such as the Parker instability and the cloud–cloud collisions.

In the next section, we discuss a new scenario for the origin of GRXE. In section 3 we discuss 2D numerical MHD simulations of magnetic reconnection triggered by a supernova to support the scenario. Finally, section 4 is devoted to a conclusion and discussion.

2. Scenario for Heating and Confinement of the GRXE Plasma

In this section we describe our new scenario on the origin of the hot component of the GRXE. We assume that the cool \(\sim 0.8 \text{ keV}\) component of the GRXE,
initially made by supernovae or superbubbles (sum of supernovae), is re-heated to the hot component (∼7 keV) by magnetic reconnection. In this process, the magnetic energy changes to thermal energy. The rotational energy ($E_{\text{rot}} \sim 10^{55}$ erg) of the gas in the Galaxy is much greater than the thermal energy ($E_{\text{th}} \sim 10^{55}$ erg) of the gas of the GRXE and the magnetic energy ($E_{\text{mag}} \sim 10^{54.5}$ erg) of the galactic field, where we assume that the mean interstellar magnetic field strength is $\langle B \rangle_{\text{obs}} \sim 3$ μG. It is suggested that the galactic rotational energy is converted to the magnetic energy by the galactic dynamo (Makishima 1994, 1995; Sturrock, Stern 1980). The details of our scenario are as follows (figure 1).

**Stage I: Generation of Strong Magnetic Fields:**

The magnetic field is $B = (B_r, B_\phi, 0)$, almost parallel to the galactic plane. We use cylindrical coordinates $(r, \phi, z)$ with $z$ in the direction vertical to the galactic plane and $\phi$ in the azimuthal direction. The galactic rotation amplifies the magnetic field by the $\omega$-effect in the galactic dynamo (Beck et al. 1997; Parker 1992),

$$\frac{dB_\phi}{dt} \approx a\Omega B_r,$$

(1)

where $\Omega = 2\pi/\tau_{\text{rot}}$ is the angular velocity of the Galaxy, $\tau_{\text{rot}} \sim 2 \times 10^8$ yr is the rotation period, and $a$ is a factor representing a nonlinear effect. If a random magnetic field ($B_{r,\text{init}}, 0, 0$) exists locally, it is strengthened to $B_{r,\text{local}} \sim 30$ μG on a time scale of $\tau_{\text{obs}}$, where we assume that the observed mean strength of the interstellar magnetic field is $\langle B \rangle_{\text{obs}} \sim 3$ μG (e.g., Beck et al. 1997; Heiles 1995) and $b = 1$. Note that the small-scale turbulence (Ohno, Shibata 1993) has a radial field, though the global field is almost azimuthal. The azimuthal component is also amplified by a nonlinear effect. The nonlinear effect means that azimuthal component, generated from the radial component, generates a radial component again by some instabilities or Coriolis force. The $z$-component is also generated, and plays a role to amplify the radial and azimuthal components. The magnetic field is localized by various processes (e.g., the random motion of clouds, self-pinch of helical flux tubes, and so on). The filling
factor of the strong magnetic field is assumed to be given by
\[ f_B \equiv \frac{V_B}{V_G} \leq \frac{(B)_{\text{obs}}}{B_{\text{local}}} \left( \frac{B_{\text{init}}}{b} \right) \frac{L}{R^2}, \]

where \( V_B \) is the volume filled by the strong \((B \geq B_{\text{local}})\) magnetic field, and \( V_G \) is the volume of the galactic disk. From equations (1) and (2) we find
\[
\frac{dW}{dt} \approx a\Omega b \left( \frac{(B)_{\text{obs}}}{8\pi} \right)^2 \left( \pi R^2 h \right) \frac{\rho}{\sqrt{3}} \left( \frac{b}{0.5} \right)^2 \left( \frac{(B)_{\text{obs}}}{3\mu G} \right)^2 \left( \frac{R}{10 \text{ pc}} \right) ^2 \left( \frac{h}{100 \text{ pc}} \right) \left( \frac{10^{-15} \text{ erg s}^{-1}}{\Omega} \right) \text{[erg s}^{-1}],
\]
\[
\text{Stage II: Current-Sheet Formation:}
\]
Once strong magnetic fields are created locally, numerous current sheets will be created in these field systems due to the following dynamical effects: (i) supernovae, superbubbles or stellar wind, (ii) Parker instability (1966), Balbus–Hawley instability (1991) or cosmic rays, (iii) random motion or collision of clouds, (iv) galactic rotation, shear motion or Coriolis force. Note that magnetic fields are not necessarily anti-parallel, but can be in sheared (sucked) field configurations in these current sheets. In fact, many magnetic turbulences on all scales and some field reversals exist in the Galaxy (e.g., Beck et al. 1997).

\[
\text{Stage III: Magnetic Reconnection — Heating and Confinement of the GXRB Plasmas:}
\]
Magnetic reconnection occurs at numerous current sheets in the Galaxy. As a result, the cool component, which was originally by supernovae, is heated to the hot component with \( n_h kT \sim B_{\text{local}}^2 / 8\pi \), i.e., \( kT \sim 7 \text{ keV} \), where \( n_h \sim 3 \times 10^{-3} \text{ cm}^{-3} \) and \( B_{\text{local}} \sim 30 \text{ f_g}^{1/4} \mu \text{ G} \). The heated plasma is accelerated to the Alfvén velocity, \( v_A \sim 10^3 \text{ km s}^{-1} \), by a slingshot effect due to the \( \beta \times B \) force as a result of reconnection. In the solar atmosphere, magnetic reconnection heats the plasma from a temperature of \( 7 \times 10^6 \text{ K} \) to several \( 10^7 \text{ K} \) (sometimes several \( 10^8 \text{ K} \)), and accelerates it to \( v \sim 10^{-2} \text{ km s}^{-1} \). It is well-known in solar flares. In galaxies, it may be called a “galactic flare” (Sturrock, Stern 1980) or “galactic jet” driven by the galactic flare, which occurs in the disk and halo. Magnetic reconnection also produces magnetic islands (or helical flux tubes in 3-dimensional view). The diameter of the helical flux tubes is several \( 10^{-10} \text{ pc} \). The density of the hot plasma in the tube is \( n_h \sim 3 \times 10^{-3} \text{ f_g}^{-1/2} \text{ cm}^{-3} \). The helical magnetic fields contribute to the observed random magnetic fields, whose typical scale is \( \leq 100 \text{ pc} \) (e.g., Beck et al. 1997).

We can obtain the filling factor \( f_B \) of strong magnetic fields if we equate the amplification rate (3) with the dissipation rate due to reconnection (e.g., Shibata 1996),
\[
\frac{dW}{dt} \approx \frac{B_{\text{local}}^2}{4\pi} \frac{\epsilon v_{\text{in}} L^2}{u_A^2} \text{[erg s}^{-1}],
\]
where \( \epsilon = v_{\text{in}}/v_A^\text{local} \) is the nondimensional reconnection rate, \( v_{\text{in}} \) is the inflow velocity of plasma into the reconnection region, \( v_A^\text{local} = B_{\text{local}}/(4\pi \rho)^{1/2} \) is the Alfvén speed due to \( B_{\text{local}} \) and \( L^2 \) is the total size of areas which contain many reconnection regions. We find from equations (2), (3), and (4)
\[
\frac{dW}{dt} \approx \frac{2b\epsilon v_{\text{in}} L^2}{a\Omega n h R^2} \left( \frac{a}{3} \right)^{1/3} \left( \frac{b}{0.5} \right)^{1/3} \left( \frac{\epsilon}{0.1} \right)^{1/3} \left( \frac{L}{500 \text{ pc}} \right)^{2/3} \left( \frac{\Omega}{10^{-15} \text{ s}^{-1}} \right) \left( \frac{n h}{3 \mu G} \right)^{1/3} \left( \frac{\rho}{10 \text{ cm}^{-3}} \right)^{-1/6} \left( \frac{h}{10 \text{ pc}} \right)^{-1/3} \left( \frac{\Omega}{10^{-15} \text{ s}^{-1}} \right)^{-1/3},
\]
where \( v_A^\text{local} \) is the mean Alfvén velocity, and \( \Omega \) is the number density of the gas. This value is roughly consistent with the requirement from observations (Kaneda et al. 1997; Makishima 1994, 1995). The ratio of gas to magnetic pressure, \( \rho \sim 8\pi \rho_c B_{\text{local}}^2 \sim 0.2\pi \rho_c f_g^{1/2} f_h^{1/2} \), corresponds to the strength, \( B_{\text{local}} \sim 30 \text{ f_g}^{-1/4} \mu \text{ G} \), if we adopt the gas pressure of the cool (0.8 keV) component of the GXRB, \( \rho_c \sim 1 \times 10^{-11} \text{ f_g}^{-1/2} \text{ erg cm}^{-3} \) (Kaneda et al. 1997).

\[
\text{Stage IV: Further Evolution of Confined Plasmas in Helical Flux Tubes:}
\]
The helical field compresses the plasma within it by a self-pinching effect (Priest 1982). The compressed gas, however, flows along the magnetic tube out of the compressed portion (Lee 1995) so that the density and the gas pressure will not be increased so much locally, though it depends on the local conditions. The final state would be a quasi-magnetostatic equilibrium state with the gas pressure determined by the local strong magnetic fields at the core of helical flux tubes. Once a strong helical field has been created, the field is greatly strengthened by a self-pinch effect. The simplest configuration is a force-free field with \( B \propto 1/D \), where \( B \) is the field strength in a tube and \( D \) is the radial distance from the axis of the tube. The actual situation would not be in a full-equilibrium state, but in a dynamical state.
In some cases, the self-pincho may stimulate star formation, which may further help heating of the super-hot plasma in the helical field. Even if this strong field would eventually rise as an expanding loop due to the Parker instablity, its time scale is $10^{7-8}$ yr, which is much longer than the observational lifetime of the hot plasma [$\tau_{\text{obs}} \sim (nt)_{h,\text{obs}} / n_h \sim 10^{6.5-6.5} f_h^{-1/2}$ yr]. The magnetic field ($< 300 f_h^{-1/4}$ $\mu$G) can also confine the hot plasma in $\tau_{\text{cond}} \sim L_{\text{eff}} / v_{\text{th}} > 10^{5-5}$ yr under non-equilibrium, where $L_{\text{eff}}$ is the effective length of the magnetic field, and $v_{\text{th}}$ is the thermal velocity of electrons, because it can suppress conduction cooling across the magnetic field lines, if $L_{\text{eff}}$ is long enough. The ionization parameter, then, is $nt \sim 10^{10-11}$ s cm$^{-3}$. The radiative cooling time is $n_h kT / [n_h^2 \mathcal{L}(7$ keV]) $\sim 10^{10} f_h^{-1/2}$ yr for a plasma with a density of $n_h \sim 3 \times 10^{-3} f_h^{-1/2}$ cm$^{-3}$ and a temperature of $kT \sim 7$ keV, where $\mathcal{L}(7$ keV) $\sim 2 \times 10^{-23}$ erg cm$^{-3}$ s$^{-1}$ is a cooling function (Spitzer 1962), so that the radiative cooling is negligible in the reconnection-heated hot plasma. This process continues as long as Galaxy rotates.

As long as the gas is confined in a closed magnetic tube, the total thermal energy is conserved, since the transport of heat due to conduction is parallel to the magnetic field lines. When the reconnection outflows collide with each other, they heat the gas to 7 keV again and emit X-rays, even though the heated gas is cooled down once by thermal conduction and adiabatic expansion. Most of the thermal energy is eventually lost by thermal radiation as the GRXE.

3. Numerical Simulations of the Formation of Magnetic Islands (Helically Twisted Flux Tubes) by Magnetic Reconnection Triggered by a Supernova

3.1. The Situation of the Problem

Magnetic reconnection can occur in the Galaxy when the interstellar magnetic field collides with an anti-parallel magnetic field (exactly speaking, magnetic fields need not be strictly anti-parallel). In the present paper we consider the magnetic reconnection triggered by a supernova (or a point explosion, Tanuma et al. 1998) as one possible candidate to generate GRXE. We are interested in the physical process of heating interstellar gas near to the reconnection region. We assume a simple initial condition [with uniform hot (0.8 keV) temperature everywhere, and uniform strong (30 $\mu$G) magnetic field outside the current sheet] and a simulation region which is much larger than the width of a current sheet. We assume that the magnetic fields are anti-parallel to one another for simplicity (figure 2). We solved the magnetohydrodynamic (MHD) equations numerically to see how the magnetic reconnection heats the plasma and how the magnetic field confines the heated plasma in the Galaxy.

Similar MHD numerical simulations of magnetic reconnection triggered by a point explosion were performed by Odstrcil and Karlicky (1997) with different parameters for applications to solar flares.

3.2. Basic Equation

The resistive MHD equations are written as follows:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\rho \frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} + \nabla p &= \frac{1}{c} \mathbf{j} \times \mathbf{B} + \rho \mathbf{g}, \\
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times (\mathbf{v} \times \mathbf{B}) = c \nabla \times (\eta \mathbf{J}), \\
\frac{\partial \varepsilon}{\partial t} + \nabla \cdot [(e + p) \mathbf{v}] &= \eta |\mathbf{j}|^2,
\end{align*}
\]
where $\rho$, $\mathbf{v}$, $\mathbf{B}$, and $\eta$ are the mass density, velocity, magnetic field, and electric resistivity, respectively; $e = p/\rho(\gamma - 1)$ is the internal energy, $\mathbf{j} = c \nabla \times \mathbf{B}/4\pi$ is the current density, $\gamma$ is the specific heat ratio ($=\frac{5}{3}$), and $\mathbf{g}$ is gravity ($=0$). We assume the anomalous resistivity model, as follows:

$$
\eta = \begin{cases} 
\eta_{\text{unif}} & \text{if } v_d \leq v_c \\
\eta_{\text{unif}} + \alpha(v_d/v_c - 1)^2 & \text{if } v_d > v_c
\end{cases}
$$

and it is assumed that the nondimensional resistivity $\eta$ does not exceed unity (Yokoyama, Shibata 1995). The magnetic field dissipates because plasma turbulence occurs if the current density is too high in the current sheet in the model. $\eta_{\text{unif}} = 0.015$ is the uniform resistivity, $v_d \equiv j/\rho$ is the relative ion-electron drift velocity, $\rho$ is the non-dimensional mass density, $v_c = 100$ is the threshold above which the anomalous resistivity sets in, and $\alpha = 0.1$ in this paper. We used 2-steps-modified-Lax-Wendroff method (Yokoyama, Shibata 1995, 1997). We also used Cartesian coordinates $(x, y)$.

### 3.3 Initial Condition and Normalization

The initial condition is as follows: The temperature is constant ($kT = kT_0 = 0.8$ keV) everywhere. The magnetic field is $\mathbf{B} = B_0 \tanh(y/H)\mathbf{e}_x$, where $B_0 = 30f_c^{-1/4}$ $\mu$G. $H$ is 0.5-times the current-sheet width. The gas pressure and density are $p = p_0 + p_{\text{mag}} \cosh^{-2}(y/H)$ and $n = n_0 + (n_0/\beta) \cosh^{-2}(y/H)$, respectively, where $p_{\text{mag}} = B_0^2/8\pi$ is the magnetic pressure outside the current sheet, and the plasma $\beta$ is $\beta = p_0/p_{\text{mag}} = 0.2$ ($|y| > H$). We assume $n_0 = 5 \times 10^{-3} f_c^{-1/2}$ cm$^{-3}$ and $p_0 = 1 \times 10^{-11} f_c^{-1/2}$ erg cm$^{-3}$. These parameters of the gas pressure and density are suitable for the cool component of the GRXE plasma created by supernovae. The total pressure and sound velocity $C_s$
are constant everywhere. We assume a high-pressure region with a finite volume, instead of a point explosion (a supernova) at \((x, y) = (0, 7H)\) as the actual initial condition. Its radius is \(D_{SN} = H\), and the gas pressure is \(p_{SN} = 500p_0\). The initial thermal energy of the supernova is \(E_{SN} = \left[p_{SN}/(\gamma - 1)\right](4\pi/3)D_{SN}^3\) = \([500p_0/(\gamma - 1)](4\pi/3)H^3\), where we assume that the width vertical to the \(x-y\) plane of the numerical simulation is \(\approx D_{SN}\). We normalize all physical values. The unit of length, velocity, and time are

\[
H \simeq 20E_{51}^{1/3}p_{11}^{-1/3} \text{ pc},
\]

\[
C_s \simeq 5 \times 10^2T_7^{1/2} \text{ km s}^{-1}, \text{ and}
\]

\[
\tau = H/C_s \simeq 10^{4.5}E_{51}^{1/3}p_{11}^{-1/3}T_7^{-1/2} \text{ yr},
\]

respectively, where \(E_{51}\) is the explosion energy in unit of \(10^{51} \text{ erg}\), \(p_{11}\) is the gas pressure in units of \(10^{-11} \text{ erg cm}^{-3}\), and \(T_7\) is the temperature in unit of \(10^7 \text{ K}\). We assume the symmetric boundaries for the top \((y \sim 81.7H)\) and the bottom \((y \sim -54.8H)\) surfaces and the periodic boundaries for the left \((x \sim -76.6H)\) and the right \((x \sim 76.6H)\) surfaces. The mesh size is \((\Delta x, \Delta y) = (0.25H, 0.025H)\), and the total number of mesh is \((N_x, N_y) = (303, 604)\). The Alfvén velocity is \(v_A^{\text{init}} = B/(4\pi p)^{1/2} \sim 2.5C_s\) \((|y| > H)\). The magnetic Reynolds number in the simulation is \(R_{m}^{\text{init}} = L_{\text{init}}^2v_A/\eta_{\text{init}} \sim 22500\) where \(L_{\text{init}}\) is initial current-sheet length = 153.

3.4. Result

(a) Typical Case

We examine here the reconnection triggered by a supernova as one of the possible models of galactic reconnection. A supernova explosion generates a blast shock (a fast mode MHD shock) which crosses the current sheet in the early phase \((t < 2\tau, \text{ as shown in figure 3})\). The reconnection, interestingly, does not start immediately after passage of the blast wave, but begins slowly after \(t \geq 40\ \tau\). Figure 4 (Plate 6) shows more detailed evolution of reconnection, from which we can see the following processes: The current sheet is getting thin \((t \sim 80-120\ \tau)\). Magnetic reconnection occurs \((t \sim 120-230\ \tau)\) due to uniform resistivity \(\eta_{\text{init}}\) in a very long current sheet. At this stage, the reconnection is well described by the Sweet–Parker model (Sweet 1958; Parker 1957). The long current sheet is unstable to tearing instability, creating magnetic islands \((t \sim 190, 220\ \tau)\). As the drift velocity increases, anomalous resistivity sets in \((t \sim 230\ \tau)\). Fast reconnection, similar to Petschek (1964) model, begins with various violent phenomena.

Gas flowing into the current sheet is accelerated and heated. Magnetic islands grow and confine the heated plasma \((t \sim 200, 220\ \tau)\). The inflowing plasma is heated to a temperature of \(\sim 10kT_0 \sim 8 \text{ keV}\) after passing through the reconnection region. The heated plasma is accelerated along the current sheet by the magnetic tension force to form a reconnection jet, with a velocity of \(v_{\text{jet}} \sim v_A \sim 2.5C_s \sim 1250T_7^{1/2}\) km s\(^{-1}\) during magnetic reconnection. A magnetic island (helical flux tube) is produced by reconnection, and confines the heated plasmas. The gas pressure is very high inside the magnetic island. The island has a size of \(\sim 2H \sim 40E_{51}^{1/3}p_{11}^{-1/3}\) pc, and moves along the current sheet at \(v_A \sim 1250T_7^{1/2}\) km s\(^{-1}\). We find that the lifetime of an island (and confined heated plasma) is \(\sim 10\ \tau \sim 10^{5.5}E_{51}^{1/3}p_{11}^{-1/3}T_7^{-1/2}\) yr \((\sim\text{current-sheet length}/v_A)\), which is almost consistent with the observationally inferred lifetime of the GRXE plasma \(\tau_{\text{obs}} \sim (nt)_{\text{obs}}/\tau_{\text{th}} \sim 10^{5.5-6.5}f_{11}^{1/2}\) yr. Note that the main energy is from magnetic energy stored in the initial field, not from a supernova. Figure 5 shows how energy con-
version occurs by magnetic reconnection ($|x| \leq 25H$ and $|y| \leq 3H$). The initial thermal energy of the supernova is $E_{SN} \sim 1400$ in non-dimensional units, which is much smaller than the initial magnetic energy $E_{mag}$ of $\sim 62000$ stored in the simulation box. The maximum heating rate is $dE_{th}/d\tau \sim 73$.

We can estimate the X-ray flux from the numerical simulation by $F \sim 2 \times 10^{-7} n^2 T^{1/2} (20 \text{ pc}) \text{ erg cm}^{-2} \text{ s}^{-1}$ when we assume that the reconnection size is $\sim 20 \text{ pc}$. Figure 6 shows the X-ray flux at $t \sim 220, 250, 260 \tau \sim 6.6, 7.5, 7.8 E_{51}^{-1/3} P_{11}^{-1/3} T_{7}^{-1/2} \text{ Myr}$ in the units of $F_0 \sim 2 \times 10^{-8} P_{11}^{1/2} T_{7}^{-3/2} \text{ erg cm}^{-2} \text{ s}^{-1}$. The X-ray flux is high in the magnetic island and along the current sheet. The X-ray flux, derived from this numerical simulation, is much larger than the observed X-ray flux of GRXE because we assumed that a strong magnetic field exists, for simplicity, in a large region in the initial condition, instead of small-scale turbulent magnetic fields and small current sheets under non-equilibrium.

(b) $B(\beta)$-Dependence

We examine the dependence of the numerical results on the magnetic field strength, $B_0 \sim 30(\beta/0.2)^{-1/2} P_{11}^{1/2} \mu G$ (figure 7). Figure 7a shows the $\beta$-dependence of the maximum magnetic energy-release rate ($|x| \leq 25H$ and $|y| \leq 3H$). We can see that the energy-release rate decreases with $\beta$. The rate is determined by the Poynting flux entering into the reconnection region,

$$-\frac{dE_{mag}}{d\tau} \sim \frac{2}{4\pi} B^2 v_{in}$$

$$\propto B^3$$

$$\propto \beta^{-3/2}$$

where $L$ is the reconnection region size, $v_{in} = \epsilon u_A \propto B$ is the inflow velocity to the reconnection region, and $\epsilon \sim 0.1$ is the reconnection rate, which is roughly independent of $B$ (e.g., Magara et al. 1996; Yokoyama, Shibata 1997). This theoretical $\beta$-dependence (19) is also shown in figure 7a by the dashed line $[2(B_0^2/4\pi)Lev_{pix}^{1/3} \sim 6.3^{-3/2}]$, where $\epsilon \sim 0.1$ and $L \sim 5$. It explains the numerical results well. Figure 7b shows the time scale of the reconnection, which is defined by the time when the maximum magnetic energy-release rate (shown in figure 7a) is attained. The numerical results can be explained by an Alfvén time of $\tau_A \propto v_A^{-1} \propto \beta^{1/2}$, or the time scale of the tearing instability, $\tau_7 \propto v_A^{-1/2} \propto \beta^{1/4}$, which are shown in figure 7b by the dashed line ($\propto \beta^{1/2}$) and the dashed-
shown in figure 7c by the dashed line, which is higher than \((1 + 1/\beta)T_0\), because hot gas of SNR is re-heated by reconnection. The gas is accelerated to the Alfvén velocity, \(v_A \propto \beta^{-1/2}\), by the magnetic tension force along the current sheet, which is shown in figure 7d by the dashed line \((\propto \beta^{-1/2}\), which is higher than \(v_A^{\text{ini}}\), because \(v_A\) increases.) The results of numerical simulations depend on \(\beta\), but do not depend on the mesh size. In this simulation, since the magnetic energy does not increase due to the galactic dynamo, magnetic reconnection releases only the magnetic energy \((E_{\text{mag}} \propto B^2/8\pi \propto \beta^{-1})\) stored at \(t = 0\).

4. Conclusion and Discussion

We presented a new scenario for the heating of the interstellar plasma and the magnetic structure through magnetic reconnection, by extending the pioneering idea by Makishima (1994, 1995). Magnetic reconnection plays a role in producing the hot plasma, which emits X-rays as GRXE. We conclude that when there is a cool \((0.8 \text{ keV})\) component of the GRXE plasma generated by supernovae near to the galactic ridge, the magnetic reconnection heats it up to the hot \((7 \text{ keV})\) component of the GRXE plasma if the local magnetic field strength is \(B_{\text{local}} \sim 30f_{\text{h}}^{-1/4} \mu\text{G}\) with a filling factor of \(f_B \leq 0.1\) and a plasma \(\beta_{\text{local}}\) of \(\sim 0.2\) corresponding to the value of \(B_{\text{local}}\), because of the gas pressure of \(p_g \sim 1 \times 10^{-11} f_{\text{c}}^{-1/2} \text{ cm}^{-3}\). The helical magnetic tube confines the heated plasma within it near to the galactic ridge after reconnection. It is to be observed as GRXE. These values of \(B_{\text{local}}\) and \(f_B\) agree with those derived by considering the pressure balance between the local magnetic field and the gas pressure of the GRXE plasma (Kaneda et al. 1997; Makishima 1994, 1995).

The most crucial point in our scenario is whether there actually exists strong \((\sim 30 \mu\text{G})\) magnetic fields in our Galaxy. We give two arguments supporting this conjecture.

Observations often show the locally strong magnetic field components, such as \(B_{\text{local}} \sim 25 \mu\text{G}\) (Simard-Normandin, Kronberg 1980) or \(\sim 20 \mu\text{G}\) (Inoue, Tabara 1981). On the other hand, the observed mean interstellar magnetic field strength is \(\langle B_{\text{obs}} \rangle \sim \langle \text{a few} \mu\text{G}\). We may miss the random field, which is very strong locally, since we measure the interstellar magnetic field strength by the integrated Faraday Rotation Measure. Hence, the local magnetic field would be much stronger than the mean field. Ohno and Shibata (1993) showed that the amplitude of the galactic random field is \(\sigma_B \sim 4-6 \mu\text{G}\) for cell sizes of \(\sim 10-100 \text{ pc}\). However, since the method of the differential Rotation Measure used by Ohno and Shibata (1993) cannot detect the field strength in cells smaller than \(\sim 10 \text{ pc}\), the filling factor of 0.1 for 30 \(\mu\text{G}\)
can be compatible with Ohno and Shibata (1993) if there is some correlated fields, such as strong (~ 30 μG) thin flux tubes with typical scales < 10 pc (S. Shibata, private communication 1998). Sofue (1998, private communication) pointed out that if there are such strong magnetic fields with 30 μG, those fields would be observed as bright regions in the radio continuum as the result of synchrotron emission. This is true if those regions contain a large number of high-energy electrons. However, we do not know how many high-energy electrons are trapped by strong magnetic fields. Generally speaking, particles (either nonthermal or thermal) and magnetic fields tend to separate due to a diamagnetic effect of the particles. Hence it is an open question as to whether these strong field regions are bright or not in the radio continuum. At present, we also do not know the filling factor of these strong fields. Future observations must clarify these points.

Shibata, Tajima, and Matsumoto (1990) suggested that the low-β (< 1) region appears as the result of shearing motion inside the disk (called low-β disk or magnetically cataclysmic disk) in the case of accretion disks, which are similar to galactic disks from the MHD point of view. The large dynamic pressure of the rotational motion of a disk can transiently confine the large magnetic pressure so that the strong fields are maintained. The dynamic pressure, $p_{\text{rot}}^2$, is usually $10^{-3}$ times greater than the magnetic pressure in accretion disks (and galactic disks). Matsumoto (1998) carried out global 3D MHD numerical simulations of the Balbus–Hawley instability coupled with the Parker instability in accretion disks, and showed that spirally shaped, filamentary low-β regions appear inside the disk. We expect that low-β regions are also generated in galactic disks, since the basic MHD physics in galactic disks is similar to that in accretion disks. It should be noted here that the average plasma $\langle β \rangle$, obe is $\sim 1$ in Galaxy, which indicates the presence of locally low-β regions in galactic disk, since $β$ is very non-uniform in actual galactic disk.

Zimmer et al. (1997) performed 2D numerical simulation of magnetic reconnection in galactic halo. They assumed, as an initial condition, that uniform temperature, density, gas pressure exist everywhere, and that the total pressure is low in a current sheet, which is not under pressure equilibrium. They tried to explain that gas is heated in galactic halo. They assume that magnetic reconnection is triggered by high-velocity clouds (HVCs), which fall onto the galactic disk and compress the interstellar magnetic fields. They explain that the kinetic energy of HVCs is converted to magnetic energy by collisions, which is converted to thermal energy by reconnection. Birk et al. (1998) performed 2D numerical simulations of magnetic reconnection, including ionization and recombination. Their initial condition is uniform in temperature and total pressure. They perturbed the current sheet by a localized enhancement of the recombination coefficient to trigger reconnection. They tried to explain that gas is heated and ionized by reconnection in the galactic halo. Our results of simulations can also be applied to the galactic halo.

X-ray emission from the galactic center is one order of magnitude stronger than GRXE (Koyama 1989; Yamauchi et al. 1990). It may also be explained by a similar mechanism, because the magnetic field strength and the gas density near to the galactic center are much higher than those near to the galactic plane. In our future work, we will study the effect of galactic rotation, the galactic dynamo, and the self-pinching of a magnetic flux tube by using three-dimensional simulations, including also magnetic reconnection driven by the Parker instability, superbubbles or cosmic rays. Furthermore, we will study the X-rays from a cluster of galaxies (Valinia et al. 1996; see also Tajima, Shibata 1997), where strong magnetic fields will play a similar role.

The numerical computations were carried out on VPP300/16R and VX/4R at the National Astronomical Observatory of Japan.

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