INTERSTELLAR MASS OUTFLOW TO GALACTIC HALOS BY THE SUPERNOVA-DRIVEN PARKER INSTABILITY

HIDEYUKI KAMAYA, SHIN MINESHIGE, KAZUNARI SHIBATA, AND RYOJI MATSUMOTO

Received 1995 September 25; accepted 1995 December 5

ABSTRACT

We here demonstrate by means of two-dimensional magnetohydrodynamic simulations that even a single supernova (SN) explosion can easily trigger a Parker instability. When SNs occur in the galactic disk with horizontal magnetic fields, an outgoing blast wave will lift up the fields, thus forming an \( \Omega \)-shaped field structure. Hence, the interstellar medium (ISM) can effectively be confined inside the \( \Omega \)-shaped, bent fields because of their decelerating \( \mathbf{J} \times \mathbf{B} \) force. It is thus usually thought that unless unrealistically large numbers of SNs occur, it is difficult for the ISM to blow out into the halo. We find, however, that this is the case only before the Parker instability is excited; namely, for the first several megayears after the explosion. The gas frozen into the \( \Omega \)-shaped magnetic fields will eventually slide down along the fields to the galactic disk by gravity, so the magnetic fields can move upward by an enhanced magnetic buoyancy. In roughly tens of megayears after the explosions the Parker instability will be triggered, giving rise to a blowout of the disk material into the halo. Importantly, a nonlinear Parker instability can be triggered quite generally; i.e., even when the underlying gas layer is stable against infinitesimal perturbations.

Subject headings: ISM: bubbles — ISM: magnetic fields — MHD — supernova remnants

1. INTRODUCTION

The significance of interstellar magnetic fields has been recognized and discussed in many different astrophysical contexts (e.g., Kronberg 1994). It is known that the average field strengths are \( B \sim 3-8 \mu \text{G} \) in the disks of many spiral galaxies (e.g., Rand & Kulkarni 1989). Therefore, the magnetic pressure is comparable to or sometimes even exceeds the thermal gas pressure in the interstellar medium (ISM) (Cox 1988). In other words, the plasma \( \beta \), defined by the ratio of gas pressure to the magnetic pressure, is of order unity or even less. Such strong global magnetic fields will inevitably affect the evolution of the ISM. There have been some studies considering the role of magnetic fields on the evolution of superbubbles (Bernstein & Kulsrud 1965; Kulsrud et al. 1985; Tomisaka 1990; Mineshige, Shibata, & Shapiro 1993). The main conclusion obtained by the studies of such magnetic superbubbles is that plane-parallel global magnetic fields tend to prevent the blowout of the ISM from a galactic disk into halos. Hence, the ISM is effectively confined in the disk by the magnetic fields. In reality, however, the existence of halo heavy elements and high-velocity clouds strongly suggests that the ISM, especially the hot component, cannot be confined in the disks (e.g., Tenorio-Tagle & Bodenheimer 1988). There should be some mechanism that conveys gas and heavy elements from the disk to the halo (e.g., Shapiro & Field 1976).

We thus conjecture that magnetic buoyancy instabilities, such as the Parker instability (Parker 1966), may help blowout of the ISM. Once the Parker instability occurs, in fact, it is expected that the global magnetic fields of disk galaxies will be ineffective in confining the ISM locally. The dynamical and chemical evolution of superbubbles, the ISM, and, hence, of the galactic halo (see Norman & Ikeuchi 1989) will be significantly affected by the Parker instability.

Various aspects of the Parker instability have been studied so far in different astrophysical contexts, such as the disks of spiral galaxies and the solar active regions (see, e.g., Parker 1966; Mouschovias, Shu, & Woodward 1974; Shibata et al. 1989; Matsumoto et al. 1993). The conditions for the Parker instability are that the strength of the magnetic fields decrease in the direction opposite to that of the gravity and that the adiabatic index be lower than the critical value, \( \gamma < \gamma_{\text{cr}} = 1 + 1/\beta \) (see Parker 1979, p. 326).

It is important to note that the Parker instability did not appear in the previous calculations of magnetic superbubbles. The reason is as follows: First, a uniform magnetic field was assumed in most studies (e.g., Tomisaka 1990). Second, large \( \gamma > \gamma_{\text{cr}} \) was assumed in some calculations. Note that when we assume mirror symmetry with respect to the equatorial plane of the disk (no vertical perturbation for fields at the equatorial plane of the disk), the instability criterion becomes \( \gamma < \gamma_{\text{cr}} = (1 + 1/\beta)^2/(1 + 3/2\beta) \) for purely undular perturbations (\( k_z = 0 \), where \( k_z \) is the wavenumber perpendicular to the magnetic field; Horiuchi et al. 1988). Finally, and most importantly, the previous calculations were restricted to limited spatial and time ranges, although to produce the instability simulations, a large horizontal scale (at least \( \sim 10 \) pressure scale heights) and a long timescale (at least \( \sim 10 \) Myr) are both needed.

We are now going to demonstrate by means of rather extensive, two-dimensional MHD simulations that a single supernova (SN) can trigger the Parker instability. The local magnetic field balloons out of the disk, leaving most of the disk material behind. We give the physical assumptions and numerical procedures in §2. The results of the numerical simulations will be presented in §3. Section 4 is devoted to summary and discussion of astrophysical implications.

2. MODEL PRESCRIPTION AND NUMERICAL PROCEDURES

Our calculations are limited to two dimensions. Assuming horizontal magnetic fields along the local azimuthal (\( \theta \)) direction in galactocentric (\( \rho , \theta , z \)) cylindrical coordinates, we adopt Cartesian (\( x , y , z \)) coordinates, where \( \mathbf{x} = \hat{x} \) and \( \mathbf{y} = -\hat{\mathbf{r}} \) for some fixed value of \( \theta \) (\( \hat{x} , \hat{\theta} , \hat{y} , \hat{r} \) represent norm vectors parallel to the \( x-, \theta-, y-, \) and \( r-\)axes, respectively). We make the
following assumptions: (1) The medium is an ideal gas with a ratio of specific heat being $\gamma = 1.05$ or 1.75. (2) The magnetic field is frozen into the gas. (3) The gravitational acceleration is constant in space. (4) We ignore galactic differential rotation and Coriolis force. (5) Only two-dimensional motions are allowed. (6) We ignore radiative cooling and thermal conduction.

The cooling timescale is $\sim 10^4$ yr for a number density of $n = 1$ and temperature of $T = 10^4$ K. Thus, we cannot neglect the effect of radiative cooling for a realistic ISM situation. However, the cooling effect rather helps the growth of the Parker instability. So, as far as the evolution of the pure Parker instability is concerned, we may incorporate the effects of cooling and conduction simply by assigning a low $\gamma$, which represents a high compressibility of the ambient gas (see § 3).

We consider a gas layer that is initially uniform in the x-direction and in magnetohydrostatic equilibrium in the z-direction. The magnetic fields are horizontal and the plasma $\beta$ is constant, $\beta(z) = 1$, initially. We therefore have $B_z(z) = 8\pi p_{\text{gas}}(z) / 1^{1/2}$, where $p_{\text{gas}}(z)$ is gas pressure. Assume the vertical temperature profile to be $T(z) = T_0 + (T_{\text{halo}} - T_0) \Theta(z - z_{\text{halo}})$, where $\Theta(\theta) = \Theta(\theta + 1)/2$, the disk temperature is $T_0 = 10^4$ K, the halo temperature is $T_{\text{halo}} = 25 \times 10^4$ K, the height of the disk-halo interface is $z_{\text{halo}} = 1000$ pc, and the width of the transition layer is $w_r = 20$ pc. The halo is introduced to ensure numerical stability and is not essential in the present study. Once $T(z)$, $\beta(z)$, and $g$ are assigned, the initial density profile, $\rho(z)$, is obtained by integrating the magnetohydrostatic equation, where $g$ is assumed to be constant and the gas scale height $H_0 = 100$ pc. We also assume the number density at $z = 0$ to be $n_0 = p_0/m_p = 1.0$ cm$^{-3}$ ($n_0$ denotes the proton mass). The field strength at $z = 0$ is $B_z = (8\pi p_{\text{gas}} T_0^{1/2})^{1/2} = 4.5 \mu G$, so the total pressure scale height at $z = 0$ becomes $H_0(1 + 1/\beta) = 200$ pc. A point explosion is included as finite-amplitude perturbations around the origin of the coordinates. Numerically, an energy of $E_{\text{exp}}$ and a mass of $M_{\text{exp}}$ are put into a region with volume $V_{\text{exp}} = \pi r_{\text{exp}}^2$, where $r_{\text{exp}} = (x_{\text{exp}} + z_{\text{exp}})^{1/2}$ is 43 pc and $y_{\text{exp}} = 1000$ pc. [Note that, since our model is essentially two-dimensional in order to study the effects of the horizontal magnetic field, the explosion is actually confined in the two-dimensional $(x, z)$-plane. Then we selected $y_{\text{exp}} \sim 1000$ pc, corresponding to the maximum size of magnetic loops.]

We assume mirror symmetry with respect to reflection about $x = 0$ and $z = 0$ and free boundaries for $x = X_{\text{max}}$ and $z = Z_{\text{max}}$. The basic equations are solved numerically by using a modified Lax-Wendroff scheme with artificial viscosity in both the $x$- and $z$-directions. The mesh spacings are $\Delta x = \Delta z = 15.0$ pc. The total number of mesh points is $(N_x \times N_z) = (241 \times 361)$. The total area is $(X_{\text{max}} \times Z_{\text{max}}) = (361H_0 \times 54H_0) = (3600 \times 5400)$ pc. For more details of numerical procedure and the tests of the code, see Mineshige et al. (1993).

We have calculated three models: $\gamma = 1.05$ in model A while $\gamma = 1.75$ in models B and C. Note that the unperturbed layer is unstable against the Parker instability in model A, whereas it is stable for models B and C in the sense of the Parker’s (1979, p. 328) criterion for purely undular perturbation. The input mass and energy are $E_{\text{exp}} = 10^{53}$ ergs and $M_{\text{exp}} = 10M_\odot$ in models A and B, and they are both 10 times larger in model C.

3. RESULTS OF NUMERICAL SIMULATIONS

We first depict in Figure 1 the evolution of the Parker instability for model A. Contours of density are shown in the upper panels by the solid lines, and the contour-level step width is 0.5 in a logarithmic scale with the maximum being $\rho = 10^{-24}$ g cm$^{-3}$. Velocity vectors are also illustrated in the upper panels by the arrows, whose lengths are taken to be proportional to their absolute values. The norm vector, placed in the lower right corner of the lower panels, corresponds to the upward velocity of $10C_{\odot} \approx 120$ km s$^{-1}$, where $C_{\odot}$ is the adiabatic sound speed at the center of disk. Magnetic field lines are depicted in the bottom panels. The elapsed times are 36.8 (left), 121.4 (middle), and 165.4 Myr (right), corresponding to 3.5, 11.6, and 15.8 in the unit of $H_0/C_{\odot}$, respectively. Here $H_0/C_{\odot} = 10.4$ Myr. Time-dependent properties of the supernova-driven Parker instability are summarized as follows:

At the first stage ($36.8$ Myr; left), the magnetic field lines are slightly lifted up by a point explosion during the passage of the blast wave. The energy and mass outflow from the disk is not effective because of magnetic tension force (see Tomisaka 1990).

After this stage, in the middle panels (121.4 Myr), the $\Omega$-shaped loops appear, so the gas frozen into these fields will start to slide down along the field lines. When the buoyancy force exerted on the loop top overcomes the magnetic tension force, the Parker instability is ignited. Note the density enhancement seen at $x = 600$–1100 pc in the upper middle panel. This is caused by the falling of the gas along the curved field lines from above and is a key signature of the Parker instability (Parker 1966).

Finally (165.4 Myr), the $\Omega$-shaped field-line structure further grows and moves upward, carrying confined gas within the magnetic loop (right). This is very reminiscent of a fountain (Shapiro & Field 1976). Now a much more energetic gas outflow (than at the first stage) is driven by the Parker instability. Even if no blowout of ISM occurs during the passage of the blast wave at the first stage, the onset of the Parker instability will provide the ISM with another chance for a blowout.

To find more direct evidence for the Parker instability, we next plot, in Figure 2, the trajectories of nine selected test Lagrangian particles at six different epochs, 36.8, 67.7, 94.9, 121.4, 145.4, and 165.4 Myr (3.5, 6.4, 9.1, 11.6, 13.9, and 15.8 in the unit of $H_0/C_{\odot}$, respectively), in a field of 500 pc $\times$ 500 pc. Let us summarize what is found from this figure: (1) The particles on the top of the $\Omega$-shaped loop fell down by gravity after the formation of the loop. (2) At the final stage, the particles reached the compressed region with large density enhancements (at $\sim 1000$ pc). (3) Furthermore, if we trace three adjacent particles lying initially in the horizontal (x) direction (indicated by filled circles, open circles, and triangles, from left to right, respectively), a particle initially at a left (or right) position took an upper (or lower) position finally.

These three facts indicate that the particles were frozen into and slide down along the $\Omega$-shaped fields, thus producing the density enhancements (see also the upper and lower right panels of Fig. 1). Since constant gravity is assumed in this study, the majority of the gas eventually falls back to the disk on the free-fall timescale of about several tens of megayears, as the galactic-fountain model envisaged. In realistic situations, however, the gravity becomes weaker as $z$ increases, and so blowout gas may not fall back to the disk.

To understand the significance of the Parker instability, we calculated model B, in which no Parker instability appears, and depict the resultant velocity fields and contour maps of density in Figure 3. The elapsed time is $152.5$ Myr ($14.6H_0/C_{\odot}$), similar to that of the right panels of Figure 1. It is clear that no blowout of ISM appears. This is because the Parker instability
does not occur, and hence the ISM can effectively be confined inside the Ω-shaped fields as a result of their decelerating $\mathbf{J} \times \mathbf{B}$ force. Instead, only the global oscillations appear.

We finally demonstrate that even if the unperturbed layer is stable, the Parker instability can be ignited by a point explosion. To do so, we put a 10 times larger energetic explosion in model C than in model B. We show the results at 152.6 Myr $(14.6 \, H_\odot / C_{\nu})$ in Figure 4, which clearly shows the onset of the Parker instability and the blowout of ISM. Although the large $\gamma$ value of the lower layer of gas tends to inhibit the falling motion of the gas from above, the gas can still fall down by gravity. This is because an energetic explosion will strongly lift up the fields, thus producing a large gradient in the field configuration at the side of the Ω-shape. As a result, the buoyancy force can dominate over the tension force.

4. SUMMARY AND DISCUSSION

We have calculated the response of the magnetized layer initially in magnetohydrostatic equilibrium to a point explosion. The results can be summarized as follows: (1) Even when the explosion energy is not enough to cause a blowout of the ISM into the halo, the blowout is always possible once the Parker instability is excited. This is because magnetic fields will spontaneously rise with the ISM by the Parker instability, carrying the ISM upward. (2) Even when an underlying gas layer is stable according to the linear analysis [i.e., $\gamma > \gamma_{\text{crit}} = (1 + 1/\beta)/(1 + 3/2\beta)$], the Parker instability can be triggered by a point explosion.

So far, several SNs were thought to be unlikely to cause a blowout in a magnetized layer for the following reason: After the
explosion the input energy density would decrease with the time because of an adiabatic expansion of the hot bubbles, until thermal energy density would become comparable to magnetic energy density inside the Ω-shaped magnetic loop. The radius of the magnetic loop, $R_e$, at that time would be roughly $E_{\text{mag}} = [B^2/(8\pi)]\pi R_e^2 D$. A blowout would occur only if $R_e \gg H_0 \sim 100$ pc (Tomisaka 1990). For typical field strengths, $B = 5 \times 10^{-4} B_\odot$ G, and for the y-depth $D = 3.0 \times 10^{12} D_{12}$ cm, the minimum energy to cause a blowout would be $E_{\text{mag}} \gg 10^{53} B_\odot^2 D_{12}$ ergs s$^{-1})$. It was thought, therefore, that unless an unrealistically large number of SNe were to occur, a blowout would never take place.

We, however, conclude that the above argument does not always hold. In summary, even small numbers of SNe can induce a blowout of ISM through the Parker instability, though the magnetic tension force generally tends to suppress the blowout of ISM (Tomisaka 1990) during first several megayears after the first SN, since the Parker instability is easily triggered by only a single SN. This blowout by the Parker instability will account for the origin of high-velocity clouds in the galactic halo and the presence of heavy elements in the halos and intergalactic space. In actual situations, more complicated phenomena are expected. These interesting features will be studied in subsequent papers.

This work is supported in part by a Scientific Research Grant from the Ministry of Education, Science, and Culture of Japan (No. 06233101, 07247213; S. M.).

REFERENCES

Horiiuchi, T., Matsumoto, R., Hanawa, T., & Shibata, K. 1988, PASJ, 40, 147