AMPLIFICATION OF GALACTIC MAGNETIC FIELDS BY THE COSMIC-RAY–DRIVEN DYNAMO

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ABSTRACT

We present the first numerical model of the magnetohydrodynamic cosmic-ray–driven dynamo of the type proposed by Parker in 1992. The driving force of the amplification process comes from cosmic rays injected into the Galactic disk in randomly distributed spherical regions representing supernova remnants. The underlying disk is differentially rotating. An explicit resistivity is responsible for the dissipation of the small-scale magnetic field component. We obtain amplification of the large-scale magnetic field on a timescale of 250 Myr.

Subject headings: cosmic rays — galaxies: ISM — galaxies: magnetic fields — magnetic fields — MHD

1. INTRODUCTION

In 1992, Parker discussed the possibility of a new kind of galactic dynamo driven by galactic cosmic rays (CRs) accelerated in supernova remnants. This dynamo contains a network of interacting forces: the buoyancy force of CRs, the Coriolis force, the differential rotation, and the magnetic reconnection. Parker (1992) estimated that such a dynamo would be able to amplify the large-scale magnetic field on timescales of the order of $10^8$ yr.

Over the last decade, we have investigated the different physical properties and consequences of Parker’s idea and scenario by means of analytical calculations and numerical simulations (see, e.g., Hanasz & Lesch 1998, Lesch & Hanasz 2003, and references therein). Here we present the first complete magnetohydrodynamic three-dimensional simulation including the full network of relevant interacting mechanisms.

It is the aim of our contribution to show that Parker’s CR-driven dynamo indeed acts efficiently on timescales comparable to the disk rotation time. In §§ 2 and 3, we describe the physical elements of the model and the system of equations used in numerical simulations, respectively. In § 4, we present the numerical setup. In §§ 5 and 6, we inform the reader about the results on the structure of the interstellar medium (ISM), including CRs and magnetic fields, and about the strength of the amplified magnetic field and the spatial structure of the mean magnetic field, respectively. We summarize our results very briefly in § 7.

2. ELEMENTS OF THE MODEL

We performed computations with the aid of the Zeus-3D MHD code (Stone & Norman 1992a, 1992b), which we extended with the following features:

1. The CR component, which is a relativistic gas described by the diffusion-advective transport equation (see Hanasz & Lesch 2003b for the details of numerical algorithm). Following Jokipii (1999), we presume that CRs diffuse anisotropically along magnetic field lines.

2. Localized sources of CRs, such as supernova remnants,

which explode randomly in the disk volume (see Hanasz & Lesch 2000).

3. Resistivity of the ISM (see Hanasz, Otmianowska-Mazur, & Lesch 2002 and Hanasz & Lesch 2003a), which is responsible for the onset of fast magnetic reconnection (in this Letter, we apply the uniform resistivity).

4. Shearing boundary conditions and tidal forces, following the prescription by Hawley, Gammie, & Balbus (1995), which are aimed to model differentially rotating disks in the local approximation.

5. The realistic vertical disk gravity, which follows the model of the ISM in the Milky Way by Ferriere (1998).

3. THE SYSTEM OF EQUATIONS

We apply the following set of resistive MHD equations:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0, \quad (1)
\]

\[
\frac{\partial \mathbf{e}}{\partial t} + \nabla \cdot (\mathbf{e} \mathbf{V}) = -p(\nabla \cdot \mathbf{V}), \quad (2)
\]

\[
\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} = -\frac{1}{\rho} \nabla \left( \rho + p_{\text{cr}} + \frac{B^2}{8\pi} + \frac{B \cdot \nabla B}{4\pi \rho} \right) - 2\Omega \times \mathbf{v} + 2q\Omega^2 \hat{x} \cdot \mathbf{g} \hat{e} + g \hat{e}, \quad (3)
\]

\[
\frac{\partial B}{\partial t} = \nabla \times (\mathbf{V} \times B) + \eta \Delta \mathbf{B}, \quad (4)
\]

\[
p = (\gamma - 1)e, \quad \gamma = 5/3, \quad (5)
\]

where $q = -d \ln \Omega / d \ln R$ is the shearing parameter ($R$ is the distance to the galactic center), $g_\parallel$ is the vertical gravitational acceleration, $\eta$ is the resistivity, and $\gamma$ is the adiabatic index of thermal gas; the gradient of CR pressure $\nabla p_{\text{cr}}$ is included in the equation of motion (see Hanasz & Lesch 2003b), and the other symbols have their usual meaning. The uniform resistivity is only included in the induction equation (see Hanasz...
et al. 2002). The adopted value $\eta = 1$ exceeds the numerical resistivity for the grid resolution defined in the next section (see Kowal, Hanasz, & Otmianowska-Mazure 2003). The thermal gas component is currently treated as an adiabatic medium.

The transport of the CR component is described by the diffusion-advection equation

$$\frac{\partial e_{cr}}{\partial t} + \nabla (e_{cr} V) = \nabla (K \nabla e_{cr}) - p_{cr} (\nabla \cdot V) + Q_{SN}, \quad (6)$$

where $Q_{SN}$ represents the source term for the CR energy density: the rate of production of CRs injected locally in supernova remnants, and

$$p_{cr} = (\gamma_{cr} - 1)e_{cr}, \quad \gamma_{cr} = 14/9. \quad (7)$$

The adiabatic index of the CR gas, $\gamma_{cr}$, and the formula for the diffusion tensor,

$$K_{ij} = K_0 \delta_{ij} + (K_{xx} - K_0) n_i n_j, \quad n_i = B_i / B, \quad (8)$$

are adopted following the argumentation by Ryu et al. (2003).

4. NUMERICAL SIMULATIONS

We performed numerical simulations in a three-dimensional Cartesian domain $500 \, \text{pc} \times 1000 \, \text{pc} \times 1200 \, \text{pc}$, extending symmetrically around the galactic midplane from $z = -600 \, \text{pc}$ up to $z = 600 \, \text{pc}$, with the resolution of $50 \times 100 \times 120$ grid zones in directions $x$, $y$, and $z$, corresponding locally to cylindrical coordinates $r$, $\phi$, and $z$, respectively. The applied boundary conditions are periodic in the $y$-direction, sheared-periodic in the $x$-direction, and outflowing in the $z$-direction. The computational volume represents a three-dimensional region of the disk of a galaxy similar to the Milky Way.

The assumed disk rotation is represented locally by the angular velocity $\Omega = 0.05 \, \text{Myr}^{-1}$ and by a flat rotation curve corresponding to $q = 1$. We apply the vertical gravity profile determined for the solar neighborhood (see Ferriere 1998 for the formula). We assume that supernovae explode with the frequency of $2 \, \text{kpc}^{-2} \, \text{Myr}^{-1}$, and we assume that $10\%$ of the $10^{51} \, \text{ergs}$ kinetic energy output from a supernova is converted into the CR energy. The CR energy is injected instantaneously into the ISM with a Gaussian radial profile ($r_{SN} = 50 \, \text{pc}$) around the explosion center. The explosion centers are located randomly with a uniform distribution in the $x$- and $y$-directions and with a Gaussian distribution (scale height $H = 100 \, \text{pc}$) in the vertical direction. The applied value of the CR parallel diffusion coefficient is $K_1 = 10^4 \, \text{pc}^2 \, \text{Myr}^{-1} = 3 \times 10^{27} \, \text{cm}^2 \, \text{s}^{-1}$ (i.e., $10\%$ of the realistic value), and the perpendicular one is $K_\perp = 10^3 \, \text{pc}^2 \, \text{Myr}^{-1} = 3 \times 10^{26} \, \text{cm}^2 \, \text{s}^{-1}$.

The initial state of the system is one of magnetohydrostatic equilibrium, with a horizontal, purely azimuthal magnetic field corresponding to $p_{mag}/p_{gas} = 10^{-4}$. The initial CR pressure in the initial state is equal to zero. The initial gas density at the galactic midplane is $3 \, \text{H atoms cm}^{-3}$, and the initial isothermal sound speed is $c_s = 7 \, \text{km s}^{-1}$.

5. STRUCTURE OF ISM RESULTING FROM THE CR-MHD SIMULATIONS

In Figure 1, we show the distribution of CR gas together with the magnetic field and of the thermal gas density together with the gas velocity in the computational volume at $t = 2000 \, \text{Myr}$. One can notice in the $xz$ plane dominating horizontal alignment of magnetic vectors. The CR energy density is well smoothed by the diffusive transport in the computational volume. The vertical gradient of the CR energy density is maintained by the supply of CRs around the equatorial plane in the disk in the presence of vertical gravity. One can notice that the magnetic vectors are inclined with respect to the azimuthal direction; i.e., the radial magnetic field component is on average about 10% of the azimuthal one.
The CR energy density is displayed in units in which the thermal gas energy density corresponds to \( \rho = 1 \) and in which the sound speed \( c_s = 7 \) km s\(^{-1} \) is equal to 1. We note that because of our choice of outflow boundary conditions for the CR component, the CR energy density does not drop to zero at the lower and upper \( z \) boundaries. We note also that an almost constant mean vertical gradient of CR energy density is maintained during the whole simulation.

The velocity field together with the distribution of gas density are shown in Figures 1d–1f. The shearing pattern of the velocity can be noticed in the horizontal slice (Fig. 1f). The vertical slices (Figs. 1d and 1e) show the stratification of gas by the vertical component, acting against the vertical gradients of thermal, CR, and magnetic pressures.

6. AMPLIFICATION AND STRUCTURE OF THE MEAN MAGNETIC FIELD

In Figure 2, we show the efficiency of the amplification of the mean magnetic field that results from the continuous supply of CRs in supernova remnants. First we note the growth of the total magnetic energy, by 7 orders of magnitudes during the period of 2 Gyr. Starting from \( t \sim 300 \) Myr, the growth of magnetic energy represents a straight line on a logarithmic plot, which means that the magnetic energy grows exponentially. The \( e \)-folding time of magnetic energy determined for the period \( t = 400–1500 \) Myr is 115 Myr. Around \( t = 1500 \) Myr, the growth starts to slow down as the magnetic energy approaches an equipartition with the gas energy.

The other three curves in the left panel of Figure 2 show the growth of energy of each magnetic field component. It is apparent that the energy of the radial magnetic field component is almost an order of magnitude smaller than the energy of the vertical magnetic field component, which is almost 1 order of magnitude smaller than the energy of the azimuthal one. This indicates that the dynamics of the system is dominated by the buoyancy of CRs and that magnetic reconnection efficiently cancels the excess of the random magnetic fields.

In the right panel of Figure 2, we show the time evolution of the normalized, mean magnetic fluxes \( \Phi_y(t)/\Phi_y(t = 0) \) and \( \Phi_z(t)/\Phi_y(t = 0) \), where \( \Phi_y(t) \) and \( \Phi_z(t) \) are magnetic fluxes at moment \( t \), threading vertical planes perpendicular to \( x \)- and \( y \)-axes, respectively, and averaging is done over all possible planes of a given type. We find that the radial magnetic flux \( \Phi_r \) starts to deviate from zero, as a result of the Coriolis force and open boundary conditions. Due to the presence of differential rotation, the azimuthal magnetic field is generated from the radial one. The azimuthal magnetic field grows by a factor of 10 in the first 800 Myr of the system evolution and then drops suddenly, reverts, and continues to grow with the opposite sign undergoing amplification by more 3 orders of magnitudes, with respect to the initial value.

In order to examine the structure of the mean magnetic field, we average \( B_x \) and \( B_y \) across constant \( z \)-planes. The results are presented in Figure 3 for \( t = 0 \) (the initial magnetic field) and for \( t = 500, 1000, 1500, 2000, \) and 2300 Myr. We find that the mean magnetic field grows by a factor of 10 within about 500 Myr, which gives an \( e \)-folding time close to 250 Myr. We note that an apparent wavelike vertical structure in \( B_y \) and \( B_z \) formed from the initial, purely azimuthal, unidirectional state of \( B_x \) and \( B_y = 0 \). The evolved mean magnetic field configuration reaches a quasi-steady pattern that is growing in magnitude with apparent vertical reversals of both components of the mean magnetic field. We also note that the magnetic field at the disk midplane remains relatively weak.

A striking feature of the mean magnetic field configuration is the almost ideal coincidence of peaks of the oppositely directed radial and azimuthal field components. This feature corresponds to a picture of an \( \alpha - \Omega \) dynamo: the azimuthal mean magnetic component is generated from the radial one and vice versa.

In order to better understand what kind of dynamo operates in our model, we computed the \( y \)-component of the electromotive force \( \langle \mathcal{E}_{\text{mf,y}} \rangle = \langle v_y B_z - v_z B_y \rangle \), averaged over constant \( z \)-planes and checked that \( \partial \langle B_y \rangle /\partial t = -\partial \langle \mathcal{E}_{\text{mf,y}} \rangle /\partial x \) with reasonable accuracy. However, we found that the space-averaged \( \mathcal{E}_{\text{mf,y}} \) fluctuates rapidly in time, so that the approximation of \( \langle \mathcal{E}_{\text{mf,y}} \rangle \) by \( \alpha_y \langle B_y \rangle \) (where \( \alpha_y \) is a component of the fluid helicity tensor) implies that \( \alpha_y \) oscillates rapidly in time. This property points our model toward the incoherent \( \alpha - \Omega \) dynamo described by Vishniac & Brandenburg (1997). Finally, we checked and found that the magnetorotational instability (Balbus & Hawley 1991) does not seem to play a significant role in our dynamo model. Due to the weakness of the initial mag-
The mean magnetic field, the wavelength of the most unstable mode of this instability remains shorter than the cell size for the first half of the simulation time.

7. CONCLUSIONS

We have described the first numerical experiment in which the effect of the amplification of the large-scale galactic magnetic field was achieved by (1) the continuous (although intermittent in space and time) supply of CRs into the ISM, (2) shearing motions due to differential rotation, and (3) the presence of an explicit resistivity of the medium. We observed in our experiment the growth of magnetic energy by 7 orders of magnitude and the growth of the magnetic flux by a factor of 1300 in 2150 Myr of the system evolution. We found that the large-scale magnetic field grows on a timescale of 250 Myr, which is close to the period of galactic rotation.

Therefore, the galactic dynamo driven by CRs appears to work very efficiently, as suggested by Parker (1992). It will require more work in the future to verify whether or not the model presented in this Letter is a fast dynamo, i.e., whether or not it works with a similar efficiency in the limit of vanishing resistivity.

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