Initial Magnetization of Galaxies by Exploding, Magnetized Stars

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We conduct a series of magnetohydrodynamical (MHD) simulations of magnetized interstellar medium (ISM) disturbed by exploding stars. Each star deposits a randomly oriented, dipolar magnetic field into ISM. The simulations are performed in a Cartesian box, in a reference frame that is corotating with the galactic disk. The medium is stratified by vertical galactic gravity. The resulting turbulent state of ISM magnetized by the stellar explosions is processed with the aid of Fourier analysis. The results leads to the conclusion that the input of magnetic energy from exploding stars is additionally multiplied by differential rotation. The resulting magnetic field appears to grow up in small-scale component, while the total magnetic flux remains limited. Our results indicate that magnetic field originating from exploding stars can be a source of initial magnetic fields for a subsequent dynamo process.

Introduction

There is a strong observational evidence that magnetic fields are present in virtually all galaxies. It is commonly believed that those fields are generated due to an $\alpha\omega$ dynamo process, where differential rotation (ω) and helical turbulence (α) are responsible for creating a strong, large–scale magnetic field from a weak, small–scale initial one [12]. The dynamo can amplify and restructure the magnetic field (see i.e. [16] for a recent review of galactic dynamo theory), yet it cannot create a new one, thus a seed field is required. Although, the origin of the seed, magnetic field is a mystery yet to be solved, a few theories concerning the problem exist. One of these theories [14] points to the very first generation of stars as a possible source of the seed, magnetic fields.

Even if a star is born without any primordial magnetic field, any nonparallelism between the gradient of pressure and the gradients of thermodynamical quantities like density or temperature, results in non–vanishing $\nabla \times \mathbf{E}$ (more details in [11]). That, according to Faraday's law, implies time dependent magnetic field. This effect is known as Biermann battery process [1]. Eventually, the newly created magnetic field is amplified by a stellar dynamo. If, during its evolution, the star explodes as a supernova or undergoes a significant mass loss, the „frozen–in–plasma" magnetic field is spread throughout the ISM, initiating the $\alpha\omega$ dynamo. The aim of this paper is to verify experimentally the hypothesis presented by Rees [14] that young galaxies have been magnetized by processes of stellar origin. As suggested in [14], if we consider that supernova remnant (like the Crab Nebula) deposits flux of order 10^{34} G cm^2, then N such remnants would increase the net flux in galaxy by a factor N^x, where $x \in [1/3, 1/2]$. As far as the authors know, nobody has ever tried to test this hypothesis in a numerical experiment (however, a paper concerning quite similar problem was recently published [5]). Although this quantitative estimation seems to be confirmed by the results of this paper, some qualitatively new effects are being found.

Physical setup and numerical model

We assume that gas forming galactic disk is completely ionized, and apply the standard set of MHD equations (see [9]), supplemented with the vertical gravitational acceleration and rotational pseudo-forces in the equation of gas motion

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{\varrho}\nabla\left(p + \frac{B^2}{8\pi}\right) - 2\mathbf{\Omega}\times\mathbf{v} + \Omega^2 x\hat{x} - g_z + \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{4\pi\varrho}, \tag{1}$$

$$\frac{\partial \varrho}{\partial t} + \nabla\cdot(\varrho\mathbf{v}) = 0, \tag{2}$$

$$\varrho\left(\frac{\partial \epsilon}{\partial t} + \mathbf{v}\cdot\nabla\epsilon\right) + p\nabla\mathbf{v} = 0, \tag{3}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}), \tag{4}$$

$$\nabla\cdot\mathbf{B} = 0, \tag{5}$$

$$\mathbf{j} = \frac{c}{4\pi}\nabla\times\mathbf{B}, \tag{6}$$

with addition of the adiabatic equation of state

$$p = (\gamma - 1)\varrho\epsilon \tag{7}$$

with ($\gamma = 5/3$).

To solve the set of partial differential equations numerically we apply our own parallelized 3D MHD code based on the *relaxing TVD* scheme [10], which is described in details by Trac and Pen [15] and extended for MHD system of equations by Pen et al. [13]. The algorithm of magnetic field evolution, based on the constraint transport (CT) algorithm [2], preserves the divergence-free magnetic field at the machine accuracy.

We chose a reference frame corotating with the disk, at the $R_0 = R_\odot$ (where $R_\odot$ is Sun's galactic radius) and use, in addition to rotational pseudo-forces the shearing-periodic boundary conditions [8], which are a modification of periodic boundary conditions, that is designed to model differentially rotating astrophysical disks. For further details concerning shearing box see Gressel and Ziegler [4]. We introduce the local reference frame by adding the terms of Coriolis force $2\mathbf{\Omega}\times\mathbf{v}$ and the tidal expansion of the combined, effective centrifugal and gravitational potential about R_0 — $\Omega^2 x$, to the equation of motion (1). Following Ferriere [3] the vertical component of galactic, gravitational acceleration (g_z term in (1)) can be expressed as

$$-g_z(R_\odot, z) = (4.4\cdot 10^{-9}\ \mathrm{cm\ s^{-2}})\frac{z}{\sqrt{z^2 + (0.2\ \mathrm{kpc})^2}} + (1.7\cdot 10^{-9}\ \mathrm{cm\ s^{-2}})\frac{z}{1\mathrm{k}pc} \tag{8}$$

Numerical simulations

We perform numerical simulations of the interstellar medium described above, perturbed with randomly distributed magnetized supernova (SN) explosions. Each stellar explosion deposits the dipolar magnetic field within a spherical region of radius 10 pc. The computational domain represents a rectangular region of 0.5kpc × 0.5kpc × 1.5kpc in x, y and z directions respectively, and the grid resolution is 125 × 125 × 375 cells. We assume that stellar explosions are uniformly distributed across the galactic plane, whereas vertical distribution is normal, with $\sigma = 100$ pc. In the present local approximation we neglect the effect of spiral arms, since our computational domain covers only a small volume of the galactic disks. In this approach one could consider a time modulation of the supernova rate, corresponding to the passages of spiral arms through the computational volume, however, we do not expect a significant effects of this modulation on long timescales. Each explosion is realized by adding thermal energy to the gas in sphere of radius 10 pc. The explosion energy is scaled down by several orders of magnitude with respect to the real SN energy output, due to limitations of the present version of our code. Furthermore, each explosion deposits a randomly oriented (directions distributed uniformly on sphere) dipolar magnetic field $\mathbf{B}_{\mathrm{dip}} = \nabla\times\mathbf{A}$, where

$$\mathbf{A}(r,\varphi,\theta) = A_0\frac{r\sin\theta}{(l^2 + r^2 + 2rl\sin\theta)^{3/2}}\mathbf{e}_\varphi \tag{9}$$

where $\mathbf{A}(r,\varphi,\theta)$ is a vector potential of a dipolar magnetic field created by an electric current in toroidal circuit of final diameter l [9], corresponding to the above mentionned size of SN remnant. The assumed density in the galactic plane is $\varrho_0 = 0.32564\mathrm{M}_\odot/\mathrm{pc}^3 \sim 13\ \mathrm{atom/cm}^3$ and star explosions rate is $\sigma = 20\ \mathrm{kpc}^{-2}\ \mathrm{Myr}^{-1}$. Both quantities ρ_0, σ are derived from recent observational data [3].

Results

In this section we discuss the evolution of the interstellar medium which is subject to a gradual magnetization by exploding stars. A typical snapshots displaying greyscale–coded gas density and magnetic vectors $\mathbf{B}$ at $t = 30$ Myr are shown in Fig.1. According to expectations, magnetic field in the disk volume displays a random configuration, which results as a superposition of randomly oriented small-scale dipolar magnetic fields. The fluctuations of gas density result from the input of magnetic and thermal energy in each explosion region.

As we can see in Fig.2, the exponential growth of the mean magnetic flux is visible during the first phase of the simulation. However, after roughly 60 Myr magnetic flux cease to grow, whereas magnetic energy continues to grow due to the ongoing SN explosions activity. We show in Fig.3 a plot of total magnetic energy scaled to the supplied magnetic energy, and spectrum of magnetic energy fluctuations, as a function of time.

As it is apparent in Fig.3, the total magnetic energy grows faster than one would expect from simple summation of magnetic energies from individual explosion events. The growth of magnetic energy is apparently enhanced by differential rotation, which amplifies the toroidal magnetic field component via stretching the radial magnetic field. This effect is described by the induction equation (4), which implies the following approximated equation for the azimuthal magnetic field

$$\frac{\partial B_\varphi}{\partial t} \simeq G B_r, \tag{10}$$

where $G = r d\Omega/dr \simeq \Omega$ is the measure of differential rotation. Since the galactic angular velocity applied in our simulation is $\Omega = 0.05$, the toroidal magnetic field is generated on a timescale of 20 Myr. The respective growth time of magnetic energy should be twice shorter. Since the dipolar magnetic field, is supplied into the initially unmagnetized medium, the growth of magnetic energy is initially slow, but later on the amplification of magnetic field by differential rotation speeds up. As it is apparent in Fig.3, the observed growth time of magnetic energy is consistent with our estimation.

In the right panel of Fig.3 we show the spectrum of magnetic energy at $t = 25$ Myr and $t = 119$ Myr, along x and y directions, obtained by means of Fourier analysis. The two straight lines corresponding to the slope -5/3, shown for comparison, represent the Kolmogorov's spectrum. The spectral analysis of magnetic energy in two different time instants shows a week tendency of steepening of the spectrum of magnetic field fluctuations along the x-direction and flattening in y direction. The results presented in Fig.3 mean that the spectrum of magnetic fluctuations, which is strongly anisotropic at the beginning of the experiment becomes more and more isotropic in course of time. The overall spectrum of magnetic fluctuations at the end of our simulation remains relatively flat with respect to Kolmogorov's spectrum. Magnetic energy cumulated on small spatial scales remains large in comparison to the energy on large scales. Although the simulation period of 120 Myr is still short with respect to the galactic rotation period of the order of 200 Myr, one can say that the evolution of magnetic spectrum is rather weak.

Conclusions

Our results indicate that the structure of stellar origin galactic magnetic field does not fit to the current picture of polarimetric radio-observations of disk galaxies (see [16] for references on observational results of galactic magnetic fields). The resulting magnetic field configuration can serve as an initial condition for further exploration of $\alpha\omega$ dynamo process.

In the next step we plan to extend our physical setup with the cosmic ray component, described by the diffusion-advection equation, as it has been done by Hanasz and Lesch [7]. The presence of cosmic rays leads inevitably to the Parker instability, and a very efficient $\alpha\omega$-dynamo process [6]. We also plan to extend the time of the simulations to at least 1 Gyr, and to simulate the whole galactic disk in full 3D, instead of using local approximation. Summarising, note the following effects of random, magnetized supernova explosions in the differentially rotating interstellar medium:

- limited growth of magnetic flux accompanied with cumulation of energy in small-scale magnetic fields;
- an additional effect of magnetic field amplification by differential rotation;
- a relatively slow evolution of magnetic spectrum, indicating that a subsequent dynamo process involving inverse turbulent cascade is necessary to obtain results compatible with magnetic maps of real galaxies.

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Figure 1. Slices through the computational domain showing density magnetic field at $T = 30$ Myr. The left panel shows a vertical slice through the domain at $y = 0$ pc, while the right panel represents a horizontal slice at $z = 0$ pc.

Figure 2. The total magnetic energy (left panel) and evolution of the mean magnetic flux in time (right panel).

Figure 3. Temporal evolution of the total magnetic energy scaled to magnetic energy supplied in supernova remnants (left panel) and magnetic energy spectrum analyzed along x and y directions (right panel).

Figures are available on YSC home page (http://ysc.kiev.ua/abs/proc14_11.pdf).