Technical Physics, 2023, Vol. 68, No. 12

Mechanisms of Magnetic Field Formation at a Large Distance from the Galactic Center

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Received May 11, 2023
Revised August 28, 2023
Accepted October, 30, 2023

The possibility of generating a magnetic field at a large distance (10–15 kpc) from the center of the galaxy has been investigated. The magnetic field can be generated both by the dynamo mechanism, considering nonlinear effects, and by magnetorotational instability. Presumably, the nonlinear effects of the dynamo mechanism play a more significant role at this distance.

Keywords: Magnetorotational instability, dynamos, galaxies, magnetism.

DOI: 10.61011/TP.2023.12.57732.f232-23

Introduction

At the moment, the existence of magnetic fields of the order of a few microgauss in a number of spiral galaxies is firmly established and practically undoubted [1]. The first observational evidence of their existence was associated with the study of the spatial distribution of cosmic rays and the spectrum of synchrotron emission. Currently, galactic magnetic fields are studied mainly by measuring the Faraday rotation of the plane of polarization of radio waves. The first work for the Milky Way was based on data on radiation from several dozen pulsars [2], while to date more than a thousand sources for our galaxy [3] and millions of objects of extragalactic origin [4] are known.

From a theoretical point of view, the occurrence of large-scale magnetic fields is usually described by the dynamo mechanism, which is based on the helicity of turbulent motions of the interstellar medium and differential rotation, the simultaneous presence of which contributes to the exponential growth of the field [5]. They are counteracted by dissipation, which tends to disrupt the regular structures of the magnetic field. For this reason, the generation of a magnetic field — threshold effect — is possible only if the action of the dynamo is intense enough to resist the dissipative effects [6]. As a rule, these conditions are fulfilled at a relatively short distance to the center of the galaxy (up to 6–8 kpc). For this reason, most studies have explicitly or implicitly assumed that magnetic fields exist only in the inner parts of the galaxy, leaving open the question of the existence of the field at a great distance from the center.

In the meantime, computational studies devoted to the study of the generation of magnetic fields at a distance up to 15–20 kpc from the center of the disk have clearly shown that although the field has a much smaller value there, it can be present in the marginal regions [7] and can grow, despite the fact that the value of the dynamo number is below the critical one, and at first glance the growth of the field must be suppressed by dissipative effects. The generation is probably explained by the Kolmogorov–Petrovsky–Piskunov effect, which is well known for nonlinear parabolic equations of mathematical physics [8]. Another possible mechanism to explain the growth of the magnetic field is magnetorotational instability. In one of the recent works, the question of the excitation of magnetic fields in accretion disks [9] was considered. Apparently, similar results would be expected for galactic objects.

Magnetorotational instability — is a hydrodynamic effect associated with the instability of fluid flow in a magnetic field [10]. For example, in the case of non-magnetic fluid flow, angular velocity gradients must be large enough for the flow to be unstable. At the same time, a decrease in angular velocity with almost any gradient is sufficient for the occurrence of magnetorotational instability. The first works related to the description of this process were devoted to the flows between cylinders that take place in various technical installations. In the meantime, a large number of studies have subsequently appeared, showing the fundamental possibility of the occurrence of magnetorotational instability in other problems, in particular in astrophysics [11]. For example, Shakura et al., investigated this process for accretion disks [9]. Considering that, from a fundamental point of view, the magnetohydrodynamic effects in galactic and accretion disks are similar [12], we use similar considerations for accretion disks.

In this paper, we analyze the possible generation of the field in the outer regions of the galaxy due to the action of both dynamo and magnetorotational instability.

1. Generation of a magnetic field in the outer regions due to the action of the dynamo

Let us consider the planar approximation, which is widely used for thin astrophysical disks. The equations for the magnetic field in dimensionless units (distances are measured in disk radii R and times — in units related to the characteristic dissipation time, magnetic fields — in equipartition units associated with the same magnitude of field energy and turbulent motions) are as follows [13]:

$$\partial B_r/\partial t = R_\alpha \alpha(r) B_\varphi (1 - B_r^2 - B_\varphi^2)$$

$$- \pi^2 B_r/4 + \lambda^2(\partial^2 B_r/\partial r^2 + \partial B_r/r\partial r - B_r/r^2),$$

$$\partial B_\varphi/\partial t = R_\omega B_r r d\Omega/dr - \pi^2 B_\varphi/4$$

$$+ \lambda^2(\partial^2 B_\varphi/\partial r^2 + \partial B_\varphi/r\partial r - B_\phi/r^2),$$

where R_α — characterizes the spirality of turbulent motions (alpha effect), R_ω — differential rotation, $\lambda = h/R$ — dissipation in the disk plane (h — its half-thickness), and the functions $\Omega(r) = \Omega_0(1 + (r/r_\omega)^2)^{-1/2}$, $\alpha(r) = k\Omega(r)$ are also introduced. It can be seen that in such a case the action of the dynamo must be suppressed at great distances.

To study the possibility of excitation of the magnetic field in the outer regions, we considered the following initial and boundary conditions:

$$B_r|_{r=0.5} = B_\varphi|_{r=0.5} = Br|_{r=1.5} = B_\varphi|_{r=1.5} = 0,$$

$$B_r|_{t=0} = 0; \qquad B_\varphi|_{t=0} = A(r - 0.5)(1.5 - r).$$

To solve the problem, an explicit numerical scheme was used due to the convenience of implementing it using parallel calculations (in this case, on video cards). The evolution of the solution is shown in Fig. 1. It can be seen that over time, by the time $t = 10$ billion years, the amplitude of the field increased rapidly, after which the solution reached a certain stationary level. It is also worth noting that as it evolves, the solution front does not change its location, while its decay shifts to the far edge of the computational domain. The structure of the solution will depend on the initial conditions. A special role is played by the number of distinct peaks for the seed field. For accretion disks, this question was studied in [14].

2. Magnetorotational Instability

Let us assume that the dependence of the magnetic field on the vertical coordinate is described using the law $\exp(ik_z z)$ [9]. Perturbations of the azimuthal magnetic field $b(r)$ can be described using the auxiliary function $\psi(r) = b(r)r^{1/2}$. For this we can write an equation that is fundamentally similar to the Schrödinger equation, where k_z^2 plays the role of energy:

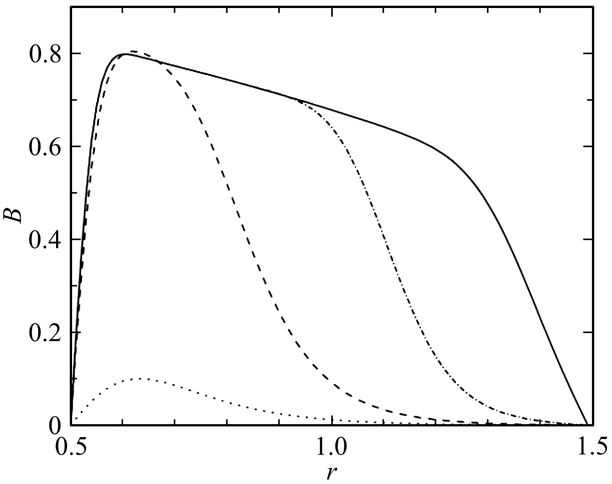

Figure 1. Dependence of the magnitude of the magnetic field on the distance to the center of the galaxy for different values of the time of evolution: dotted line — $t = 5$ billion years, dashed line — $t = 7$ billion years, dashed-dot line — $t = 10$ billion years, solid line — $t = 15$ billion years.

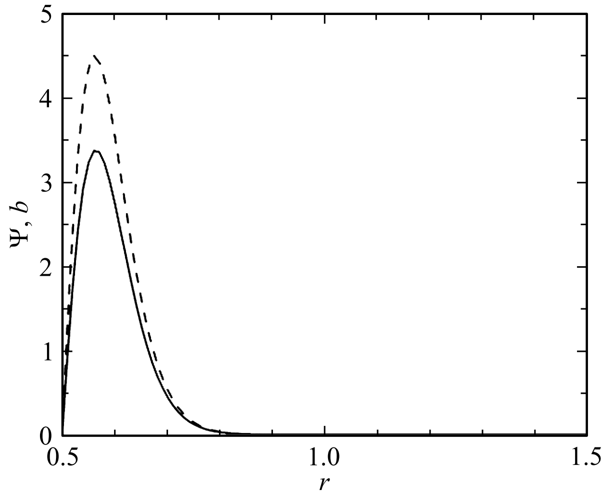

Figure 2. Highest eigenfunction corresponding to eigenvalue $k_z^2 = 2107$, normalized by one: solid line — $\psi(r)$, dashed line — $b(r)$.

$$d^2\psi/dr^2 + 1/r^2(-3/4 + 2V^2/c_A^2)\psi = k_z^2\psi,$$

where V — is the large-scale rotation velocity of the galactic disk, c_A — is the Alfvén velocity.

Let us consider the problem of eigenvalue with boundary conditions:

$$\psi|_{r=0.5} = \psi|_{r=1.5} = 0.$$

The magnetic field corresponding to the oldest eigenfunction obtained by the numerical solution of this problem is shown in Fig. 2. It is important to note that the highest eigenvalue characterizes the vertical scale of the flow $L_z = 2\pi/k_z$. For our solutions, it turns out that $L_z \sim 0.14$ (here $k_z = 46$, and $k_z^2 = 2.1 \cdot 10^3$).

Conclusion

Thus, in this work, we have investigated the possibility of generating a magnetic field at a large distance from the center of the galaxy (in dimensional units, this corresponds to 10–15 kpc). It can be noted that the magnetic field can be successfully generated both by the dynamo mechanism, considering nonlinear effects, and by magnetorotational instability. At the same time, the field that can be formed due to this phenomenon rapidly decreases with distance (Fig. 2). Therefore, it can be assumed that the nonlinear effects of the dynamo mechanism play a more significant role at such a distance. This means that at large distances from the center of the galactic disk, fields comparable to those near the center can be present.

Funding

The work of T.T. Khasayeva was carried out with the support of the Foundation for the Development of Theoretical Physics and Mathematics „Basis“ (project #22-2-2-55-1). The work of E.A. Mikhailov was carried out with the support of the Ministry of Science and Higher Education of Russia (agreement No. 075-15-2019-1621).

Conflict of interest

The authors declare that they have no conflict of interest.

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