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Biermann battery mechanism as a source of magnetic fields in galactic and accretion discs

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The Biermann mechanism is studied in relation to accretion disks. The role of the Biermann mechanism in the appearance of seed fields is determined. The studies were carried out using both averaging methods and within the framework of N-body simulation.

Keywords: galaxies, accretion discs, magnetism.

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Introduction

The presence of magnetic fields of several microgauss in galaxies has been firmly established to date [1]. They were studied by measuring the Faraday rotation of the radio waves polarization plane [2] and the synchrotron emission spectrum [3]; the spatial distribution of cosmic rays also proves their presence in the Milky Way. According to modern concepts, the generation of magnetic fields in most of these objects is caused by dynamo mechanism [4,5]. It is associated with the combined effect of the alpha effect (characterizes the helicity of turbulent motions) and differential rotation, and leads to an exponential growth of magnetic fields. There are also reasons to believe that magnetic fields are present in accretion disks, explaining processes such as angular momentum transition [6]. The large-scale structures of the magnetic field there can also be caused by dynamos [7]. There is also observational evidence of the existence of such fields related to the study of Faraday rotation [8].

Meanwhile, although dynamo makes it possible to describe the exponential growth of magnetic fields, it requires non-zero initial conditions associated with other mechanisms. In the case of accretion disks the transfer of the frozen field together with the incident medium can play a certain role. Howeber, in the case of galaxies everything is more complicated. The presence of seed magnetic fields may be explained, among other reasons, by Biermann mechanism [9,10]. It is associated with propagation of proton and electron fluxes in the radial direction. Due to the fact that the charge modules of particles are the same, while their masses differ, they interact differently with the rotating medium, which leads to the appearance of circular currents [11]. These currents are associated with magnetic fields. Although the estimates show [10] that they are small, such structures can serve as initial conditions for other mechanisms of the field growth.

The study of the fields structure is somewhat a more complicated problem. If we average them on a fairly large scale, we come to a II kind integral equation, where different terms take into account both the growth of the field and its saturation [12,13]. Their features are connected with singular equations. The integrals in them shall be interpreted using the main values. Solving it with sufficiently high accuracy is not a trivial problem and requires significant computing resources [14].

An alternative approach involves N-body modeling by considering the motion of protons and electrons. In this case, the equation of motion for individual particles is solved, taking into account their interaction with each other. Such procedure is quite expensive, therefore, in practice, the particles are united in „beams“. On the other hand, a characteristic feature of all particle methods is the simplicity of creating parallel realizations of computational algorithms, which makes it possible to efficiently perform calculations, which also can be carried on GPUs.

1. Particle motion equation

When a charged particle (proton or electron) moves, its azimuthal angle φ satisfies the equation

$$\varphi''(t) = -2V\varphi'(t)/r - [\varphi'(t) - \Omega]/\tau - qVB/mcr,$$

where V — velocity of radial motion; r — distance to the center; Ω — angular velocity of disk rotation; B — magnetic field; m — mass of a particle; q — charge of the particle; τ — characteristic time of interaction between the particle and the medium. Circular current corresponds to each pair of particles ($\varphi'_e(t)$ — angular velocity of electron, $\varphi'_p(t)$ — proton)

$$I = e[\varphi'_p(t) - \varphi'_e(t)]/2\pi,$$

and generates magnetic field at a distance R from the center

$$b(R) = I\Phi(R)/cR, \quad \Phi(x) = \int_0^{2\pi} \frac{1 - x\cos\varphi}{1 + x^2 - 2x\cos\varphi} d\varphi.$$

2. Integral equation for magnetic field

It can be expected that the angular velocity of particles „adjusts“ quickly enough to the rotation of the medium and depends mainly on the distance to the center. Then there will be a stationary distribution of the magnetic field, which is described by the equation [12]:

$$B(r) = \alpha \int_{R_{\min}}^{1} Q(r, R)B(R)dR + F(r),$$

where distances are measured in disk radii; α — a coefficient that includes disk dimensions, particle density, etc.; $R_{\min}$ — inner radius of the disk. For the galaxies case the following is true [12]:

$$Q(r, R) = -\Phi(r/R)/R^2, \quad F(r) = \int_{R_{\min}}^{1} Q(r, R)R^{-1}dR,$$

$$\alpha = 2nhq2V\tau\varepsilon m^{-1}c^{-2},$$

where n — typical concentration of particles near the inner disk boundary, h — semi-thickness of disk, ε — ratio of internal and external disk radii. The values q, τ and m correspond to the proton [12]. The coefficient α is quite large, which causes some computational difficulties. Therefore, we used values that are somewhat lower, but at the same time allow us to reproduce the basic qualitative properties of magnetic field. The result of solving the integral equation for galaxies is shown in Fig. 1. Note that magnetic field is measured in dimensionless units [12] (so, for the Milky Way, this is a value of the order of 10^{-15} G).

For the accretion disks the expression looks a bit more complicated:

$$Q(r, R) = -[1 - 0.9(R_{\min}/R)^{1/2}]^{-16/5}\Phi(r/R)R^{7/8},$$

$$F(R) = -\int_{R_{\min}}^{1} Q(r, R)[1 - 0.9(R_{\min}/R)^{1/2})]^{39/10}R^{-11/8}dR,$$

$$\alpha = 2nhq2V\tau\varepsilon^{1/8}m^{-1}c^{-2}.$$

The result for accretion disks is illustrated in Fig. 2. The values α are also quite large here, so values were taken that make it possible to investigate the main characteristics of the field through computations. Note that it has a different sign: this is due to the prevailing currents of the medium towards the center.

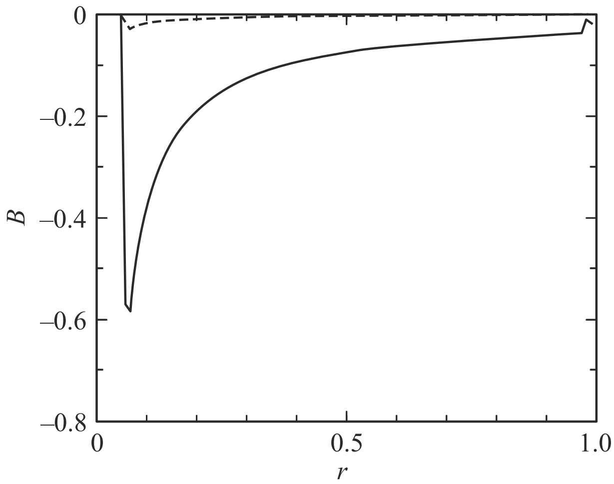

Figure 1. Magnetic field in a galaxy (solution of integral equation). $\alpha = 30$ (solid line), 600 (dashed line).

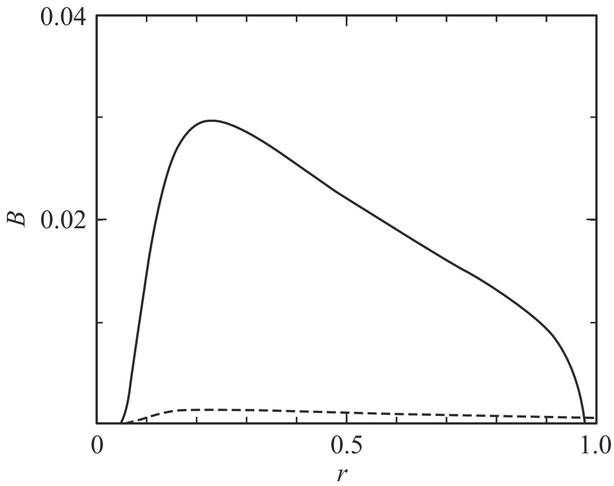

Figure 2. Magnetic field in the accretion disk (solution of integral equation). $\alpha = 30$ (solid line), 600 (dashed line).

3. N-body modelling

Another approach involves modeling the motion of individual particles. Let's consider the „clusters grqq of particles, which correspond to particles located at the same distance to the axis. For the particles of each of the „clusters“ it is necessary to solve the motion equations, as well as calculate the magnetic field generated by it, which is then used to find further motion of the particle. This problem was solved numerically using our own program code. The modeling results confirmed the theoretical assumptions that the characteristics quickly reach the steady-state values. The generated magnetic field for the galaxies case is shown in Fig. 3. It can be seen that the results are in good agreement with the analyzed data of the previous model. The values used correspond to the value of the parameter $\alpha \sim 10^{1\dots2}$ (however, due to different

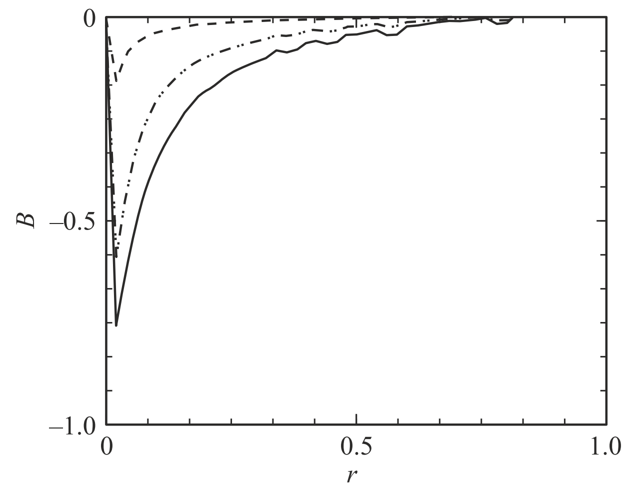

Figure 3. Magnetic field in a galaxy (multi-particle modeling). $N = 1.7 \cdot 10^{43}$ of particles (solid line), $9.4 \cdot 10^{42}$ of particles (dash-dot line), $1.7 \cdot 10^{42}$ of particles (dashed line).

model assumptions, a direct comparison should be made with caution). Nevertheless, it should be noted that the total number of particles N is not very large due to limited computing resources.

Conclusions

In this paper, the process of magnetic field generation due to Bierman mechanism in galaxies and accretion disks is investigated. To achieve this, we used both, an approach related to averaging and solving the integral equations, and the computation of magnetic fields using multi-particle modeling. It is shown that the structure of the magnetic field turns out to be fundamentally similar for both models.

Conflict of interest

The authors declare that they have no conflict of interest.

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