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Biermann Battery and Magnetic Fields of Accretion Discs

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Abstract

Magnetic fields should be studied to understand different processes in accretion discs, such as transition of angular momentum which is closely connected with them. There are different ways to describe the growth of magnetic fields of cosmic objects. One of them is based on Biermann battery mechanism which previously has been used to study the origin of magnetic fields in galaxies. It is based on different masses and same absolute values of charges of protons and electrons, which move across the disc. They interact with rotating medium, get azimuthal velocity and produce circular currents that are associated with the magnetic fields in the disc. Such magnetic field influences the motion of the charged particles that created it, and we should take into account the feedback. Mathematical description of this mechanism leads us to the Fredholm-type integral equation of the 2nd kind. In the presented work it is solved numerically using Galerkin methods. Here we give the solutions of different cases.

Keywords: *magnetic fields, Biermann battery, accretion discs*

1. Introduction

It is well-known that a large variety of astrophysical objects have regular structures of magnetic field Arshakian et al. (2009), Beck et al. (1996). They are studied using both theoretical and observational methods. From the observational point of view, magnetic fields can be measured using Zeeman effect or synchrotron emission, where the field influences spectral parameters of the electromagnetic waves. However, nowadays most of the observational results are obtained using Faraday rotation of the polarization plane of the radio-waves which can be detected on modern radio telescopes Zeldovich et al. (1983). Theoretically, the evolution of magnetic fields is studied basing on different models of magnetohydrodynamics Krause & Raedler (1980).

One of the most interesting objects from the point of view of cosmic magnetism is connected with accretion discs. They surround compact astrophysical objects such as black holes, neutron stars and white dwarfs. Magnetic fields describe a large variety of processes there, such as transition of the angular momentum between different parts of the disc Shakura & Sunyaev (1973). Also there are observational works which prove the magnetic field existence. Some papers describe the Faraday rotation measurements in the accretion disc surrounding the central black hole in M87 Kravchenko et al. (1973). It should be associated with regular magnetic field structures and it is the strong argument for the magnetism of accretion discs.

As for generation of the magnetic field in accretion discs, there are various approaches. First of all, the magnetic field can be connected with transfer of the accreting medium Lubow et al. (1994). Moreover, the magnetic field can be generated by interaction with central body. However, these effects seem to be quite weak to describe strong growth of the magnetic field. Different computational models have shown that they cannot fully describe the field evolution and the strengths which are comparable with the equipartition value. So, we should base our theoretical approaches on generation the magnetic field *in situ*, taking into account the motions in different parts of the disc Brandenburg et al. (1995).

Previously it has been shown that the magnetic field of the accretion disc can be explained by the large-scale dynamo which is quite similar to the mechanism which describes field evolution in galactic discs Boneva

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et al. (2021), Moss et al. (2016). Similar geometry gives us an opportunity to use the same approximations, such as no-z model which is based on small half-thickness of the disc Moss (1995), Phillips (2001). It was obtained that the alpha-effect (which is connected with the helicity of the turbulent motions) and differential rotation (non-uniform angular velocity of the disc) can support exponential growth of the field.

However, the dynamo mechanism does not explain the initial magnetic field which should be connected with another process. Most probable explanation of the seed field is connected with the Biermann battery Biermann & Schluter (1951). It has been used to study initial magnetic field of the galaxies Andreasyan & Mikhailov (2021), Mikhailov & Andreasyan (2021). It is connected with the same absolute values of the charge of protons and electrons, and strictly different masses. The particles move in the raidal direction and interact with surrounding medium. It makes them have rotational movements, which is associated with circular currents. Such currents produce vertical magnetic field which can be the source of regular field structures. One of the most important points is connected with taking into account the feedback. It can be done using the integral equation.

In this work we describe the model of the magnetic field in accretion discs based on the Biermann battery effect. It contains basic physical models, and the approximation for movement of the electrons and protons. After that we obtain the 2nd kind Fredholm-type equation and solve it using the Galerkin methods Marchevskii et al. (2022). After that, the results are shown.

2. Biermann battery

We can describe the motion of the particles which fall on the central body which is surrounded by the accretion disc. Here we are focusing on the ones which are associated with the black holes, but the following results can be easily transferred onto other objects such as neutron stars or white dwarfs.

We assume that the protons move under influence of surrounding media, and we should solve their equations of motion. As for the electrons, we can assume that they are "glued" by the radiation. The protons can produce the circular currents which are associated with magnetic field.

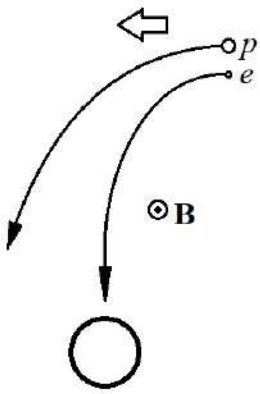

Figure 1. Scheme of the Biermann mechanism in accretion discs.

As for the protons, we can consider the following equation of their motion Mikhailov & Andreasyan (2021):

$$m\frac{d\mathbf{v}}{dt} = \mathbf{F} - \frac{m}{\tau}\left(\mathbf{v} - \mathbf{V}_{rot}\right) + \frac{e}{c}(\mathbf{v} \times \mathbf{B}), \tag{1}$$

where m is the mass of the proton, $\mathbf{v}$ is its velocity, $\mathbf{F}$ describes the force field (can be associated mainly with the gravitational forces), τ is the typical time of interaction between the particle and surrounding medium, $\mathbf{V}_{rot}$ is the rotation velocity of the accretion disc, and $\mathbf{B}$ is the magnetic field. As for our aims connected with the circular currents producing magnetic field, we can reduce this equation to the angular component in the following way:

$$\frac{d\varphi}{dt} = -\frac{2}{r}\frac{dr}{dt}\frac{d\varphi}{dt} - \frac{1}{\tau}\left(\frac{d\varphi}{dt} - \Omega\right) - \frac{e}{rmc}\frac{dr}{dt}B, \tag{2}$$

Taking into account the typical relationship between the parameters (we assume that the typical processes in azimuthal direction are much faster than in the radial one), introducing the value $V = -\frac{dr}{dt}$ and assuming

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that $r \approx R$, we can rewrite the equation as:

$$\frac{d^2\varphi}{dt^2} = \frac{2V}{R}\frac{d\varphi}{dt} - \frac{1}{\tau}\left(\frac{d\varphi}{dt} - \Omega\right) + \frac{e}{Rmc}VB, \tag{3}$$

and obtain the following solution that satisfies trivial initial condition:

$$\omega = \frac{d\varphi}{dt} = \frac{\Omega + \frac{e\tau VB}{Rmc}}{1 - \frac{2V\tau}{R}}\left\{1 - \exp\left(-\frac{t}{\tau}\left(1 - \frac{2V\tau}{R}\right)\right)\right\} \tag{4}$$

It can be seen that the exponential term decreases and quite soon the velocity will be very close to the value (we assume that $\frac{V\tau}{R} \ll 1$):

$$\omega \cong \Omega + \frac{V\tau}{R}\left(2\Omega + \frac{eB}{mc}\right) \tag{5}$$

It is obvious that $\frac{eB}{mc}$ is the cyclotron frequency and it is much larger than the angular velocity of the accretion disc. So, taking into account that $\Omega \ll \frac{eB}{mc}$, we can rewrite it as:

$$\omega \cong \Omega + \frac{V\tau}{R}\frac{eB}{mc}. \tag{6}$$

The magnetic field will grow slower if the qualitative formulae is performed:

$$\Omega \sim -\frac{V\tau}{R}\frac{eB}{mc}. \tag{7}$$

So, we can estimate the magnetic field that can be reached, assuming that $\Omega \sim 10^{-6}$ s, $\tau \sim 1$ s, $R \sim 10^{16}$ cm and $V \sim 10^{10}$ cm s^{-1} and obtain the field:

$$B \sim \frac{\Omega Rmc}{V\tau e} \sim 10^{-4}\ \mathrm{G}. \tag{8}$$

This field is quite large to be the source of the seed field. However, it is quite interesting to find the structure of the field.

3. Detailed structure of the field

If there is a flux of protons falling on the central object of the accretion disc, each of them is associated with a circular current. Taking into account that the large-scale frequency is much smaller than the cyclotron one ($\Omega \ll \frac{eB}{mc}$), we shall obtain:

$$I = \frac{e}{2\pi}\left(\Omega - \frac{V\tau}{R}\frac{eB}{mc}\right). \tag{9}$$

According to the Biot – Savart law, the current with radii R will produce at distance r from the center of the disc the field Mikhailov & Andreasyan (2021):

$$b = \frac{I}{cR}\Phi\left(\frac{r}{R}\right), \tag{10}$$

where we have introduced the special function:

$$\Phi(\alpha) = \int_0^{2\pi} \frac{(1 - \alpha\cos x)dx}{(1 + \alpha^2 - 2\alpha\cos x)^{3/2}}, \tag{11}$$

that can be expressed through full elliptic integrals Korn & Korn (2000).

If we have the density of the particles n and the half-thickness h, each ring corresponding to $-h < z < +h$, and distance from the center in the range $(r, r + dr)$, it produces the field:

$$dB(r) = \frac{4neh\Omega}{c}\Phi\left(\frac{r}{R}\right)dR + \frac{2nhe^2V\tau}{mc^2R}\Phi\left(\frac{r}{R}\right)B(R)dR. \tag{12}$$

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Taking into account the typical models for the accretion discs Suleimanov et al. (2007), measuring distances at outer radii of the disc and fields in their typical values, we can write an integral equation for the field:

$$B(r) = \int_{R_{min}}^{1} \Phi\left(\frac{r}{R}\right) \frac{dR}{R^{9/4}} + \chi \int_{R_{min}}^{1} \Phi\left(\frac{r}{R}\right) B(R) \frac{dR}{R^{1/8}} \tag{13}$$

where we have introduced the parameter $\chi = \frac{2e^2 n_0 h_0 V_0 \tau_0 R_{max}^{7/8}}{mc^2 R_{min}^{7/8}}$. Here n_0, h_0, V_0 and τ_0 are the density of the medium, half-thickness of the disc, velocity and the interaction time corresponding to the case $r = R_{min}$. It is necessary to take into account that usually this parameter is sufficiently higher than one.

The solution for different cases is shown on figure 2. We can see that the field reaches its maximum values near the inner border of the disc. If we take astrophysically important large values of χ, it monotonously depends on r.

4. Role of the outflows

Also there are flows from the central to the outer parts in the discs. Such mechanism is quite important in galaxies, but as for the accretion discs their influence is much weaker. However, it is quite interesting to study them, too.

As for the outflows, we can take the same models for the accretion disc structure and obtain the following equation in dimensionless variables:

$$B(r) = \int_{R_{min}}^{1} \Phi\left(\frac{r}{R}\right) \frac{dR}{R^{19/8}} + \beta \int_{R_{min}}^{1} \Phi\left(\frac{r}{R}\right) B(R) \frac{dR}{R^{15/4}}, \tag{14}$$

where the parameter $\beta = \frac{2e^2 n_0 h_0 V_0 \tau_0 R_{min}^{11/4}}{mc^2 R_{max}^{11/4}}$ has the same meaning as χ in previous case. The results for this case are presented in the figure 3.

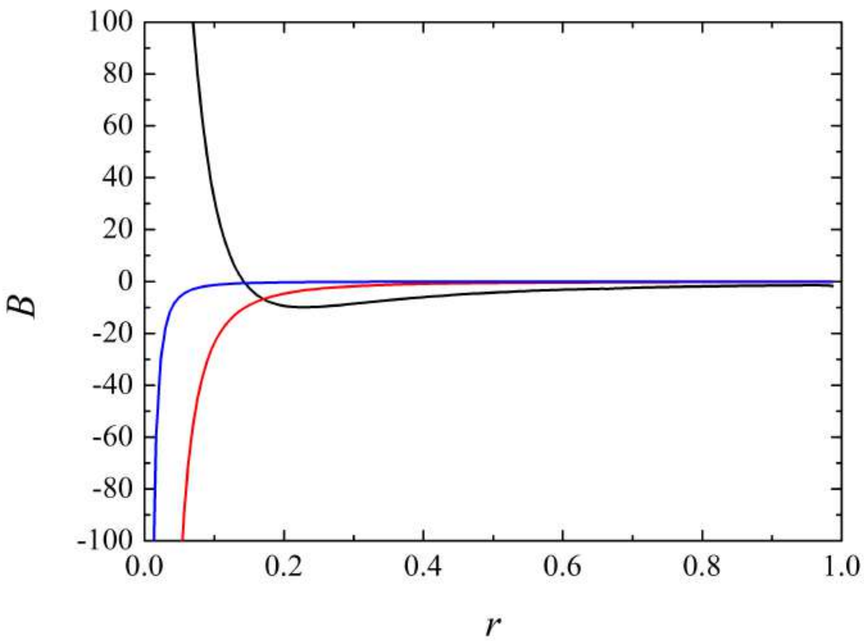

Figure 2. Structure of the magnetic field induced by the radial flows. Black line shows $\chi = 1$, red line – $\chi = 10$, blue line – $\chi = 100$.

5. Conclusion

We have studied the magnetic field produced by the Biermann battery mechanism. It can be very important to generate the vertical magnetic fields in the accretion discs, which are quite comparable with

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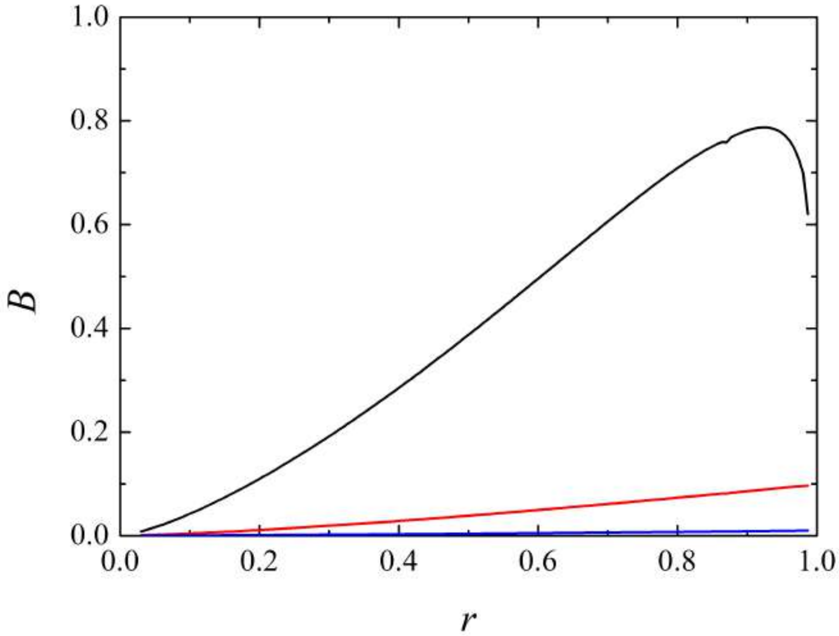

Figure 3. Structure of the magnetic field induced by outflows. Black line shows $\beta = 1$, red line – $\beta = 10$, blue line – $\beta = 100$.

the equipartition one. After that, it can be turned by the turbulent dynamo mechanism and after that strengthened by the large-scale one. So, this step-by-step process can explain the magnetic field generation in the accretion discs from the zero to astrophysically important values.

We have obtained the detailed structure of the field generated by the inflows and the outflows. In our opinion, the inflows are much more important (it is the fundamental difference with the galaxies, where there are no intensive flows towards the center).

Of course, the seed magnetic field can be generated taking into account another mechanisms, such as interaction with the central object or transition with the matter, but the Biermann battery seems to be more important in the generation.

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