Non-uniformities of magnetic fields of accretion disks and their stability

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The magnetic fields of accretion disks may play a crucial role in their evolution. Thereare various ways to explain their origin, one of which is the dynamo mechanism. Given the shape of the objects, it is possible to use the thin disk approximation developed for thin disks. The question of whether the long-term existence of large-scale magnetic field non-uniformities are possible in them is of interest. It was investigated using numerical modeling if such features can be maintained in accretion disks. It is found that only axisymmetric structures are stable, azimuthal structures are eroded over time.

Keywords: stability, dynamo, accretion disks, magnetism.

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Introduction

Accretion discs are formed around various massive astrophysical objects. The important role in their evolution must be played by magnetic fields [1], which may carry the moment momentum, impact medium flows and other phenomena. There are different approaches to the explanation of their generation. Thus, several papers suggest that it is related to the impact of the central object [2]. Other authors think that it is introduced in the disc together with the incident substance [3]. Meanwhile, it is hard to assume that this magnetic field will have an ordered structure, therefore, the most probable would be the formation of regular magnetic fields from the dynamo mechanism, which is similar to the one that impacts the Sun, in the galaxies and other astrophysical objects [4]. Previously it was shown that the dynamo mechanism may cause magnetic fields in accretion discs [5,6]. In its turn the field carried with the incident substance may serve as an initial condition along with whatever is related to small-scale (turbulent) dynamo and the result of the battery mechanisms effect [7].

The dynamo describes the occurrence of the magnetic fields due to the conducting medium movements [8]. This happens both at the expense of the turbulence (associated with the so called alpha effect), and the differential rotation: in the accretion discs the angular velocity is heterogeneous and goes down at it moves away from the center according to the law $r^{-3/2}$ [1]. They are opposed by the turbulent diffusion attempting to destroy all large-scale structures of the magnetic field. If alpha-effect and differential rotation are quite intense — to oppose the turbulent diffusion, — magnetic field generation is observed. Otherwise any initial field may only fade away. This is the threshold nature of the dynamo mechanism [9].

The seed fields may be caused by the action of battery mechanisms, transferred together with the incident medium and have the irregular structure. Upon incidence the substance is mixed unavoidably, therefore, the mixing causes a random and heterogeneous field. A question arises on whether such features will exist for a long time and strengthen as the field develops. To study the field evolution, we used planar approximation making it possible to describe the dynamo action in thin discs [10].

1. Main equations

We use the planar approximation that may be used for thin accretion discs. The equation for the field components in the disc plane is as follows:

$$\partial B_r/\partial t = -\alpha B_\varphi/h + V\partial B_r/\partial r - \eta\pi^2 B_r/(4h^2) - \Omega\frac{\partial B_r}{\partial\varphi}$$

$$+\eta\left[\partial^2 B_r/\partial r^2 + 1/r(\partial B_r/\partial r) - B_r/r^2 + \frac{\partial^2 B_r}{\partial\varphi^2}\right],$$

$$\partial B_\varphi/\partial t = rB_r\partial\Omega/\partial r + V\partial B_\varphi/\partial r - \eta\pi^2 B_\varphi/(4h^2) - \Omega\frac{\partial B_\varphi}{\partial\varphi}$$

$$+\eta[\partial^2 B_\varphi/\partial r^2 + 1/r(\partial B_\varphi/\partial r) - B_\varphi/r^2 + \frac{\partial^2 B_r}{\partial\varphi^2}\Bigg],$$

where V — velocity of radial flows, η — turbulent viscosity coefficient, h — disc thickness, l — turbulence scale, r — disc radius, Ω — angular velocity of rotation. The vertical component of the field is substantially smaller, therefore the equation for it is not considered.

If the magnetic field increases, the turbulent movements that are the cause of the field generation become less intense [11]. This may be taken into account with the help of the non-linear modification of the alpha effect:

$$\alpha = \alpha_0(1 - (B_r^2 + B_\varphi^2)/B^{*2}),$$

where $B^* = 0.0148(r/r_{\max})^{-21/16}$ G — the so called magnetic field of equidistribution, which corresponds to the saturation of the magnetic field growth [12].

We use the following boundary conditions [13]:

$$B_r|_{r=r_{\max}} = B_r|_{r=r_{\min}} = B_\varphi|_{r=r_{\max}} = B_\varphi|_{r=r_{\min}} = 0,$$

$$B_r|_\varphi = B_r|_{\varphi+2\pi}, \quad B_\varphi|_\varphi = B_\varphi|_{\varphi+2\pi}.$$

The coefficient for the alpha effect is expressed using the formula $\alpha_0 = \omega_0 l^2/h^2$, where $h = h_0(r/r_{\min})^{9/8}$, $h_0 = 1.1 \cdot 10^9$ cm, $l = 3.8 \cdot 10^8$ cm — turbulence scale, which is by an order less than the disc thickness, $\omega_0 = G^{1/2}M^{1/2}r^{-3/2}$ — angular velocity of rotation, $M = 2 \cdot 10^{33}$ g — mass, r — distance to the center of the disc, $r_{\max} = 1.1 \cdot 10^{11}$ cm — its radius. We took the values here which are typical for the accretion discs surrounding the white dwarves. We also use the velocity of radial flows $V = V_0 r/r_{\min}$ [7], where $V_0 = 3000$ cm/s, $r_{\min} = r_{\max}/100$ — inner radius of the disc. For the turbulent viscosity coefficient we take the value $\eta = 1.9 \cdot 10^{14}$ cm^2/s.

2. Field heterogeneities

With account of the physical nature of the processes it would be reasonable to consider the random initial conditions for the magnetic fields, which will differ in the different domains inside the object. For this purpose the accretion disc was broken into multiple domains of $(r, r + \Delta r)x(\varphi, \varphi + \Delta\varphi)$ type, within the limits of which the magnetic field was determined using a random law, imitating the stochastic magnetic fields transferred by the accretive medium or created by a small-scale dynamo. The typical view of the initial conditions is presented in fig. 1.

This problem was solved numerically with the help of the method of alternating directions widely used to solve parabolic equations and systems therefrom [14]. It consists in the fact that at the odd time steps we use the scheme explicit by the radial coordinate and implicit by the azimuthal one, ans at the even ones it is vice versa. Implementation of the implicit scheme for the derivative with respect to the angular coordinate is particularly problematic. The need for periodic boundary conditions that requires using the method of cyclic sweep is taken into account.

The magnetic field modeling results are shown in fig. 2. One can see that for the objects of the selected type the azimuthal heterogeneities of the magnetic field are practically fully eroded for the times 10^4 s, being rather small compared to many processes in accretion discs. On the other hand, the radial heterogeneities turn out to be quite „long-living". One can see that the mixing plays a key role in the azimuthal direction, at the same time the radial heterogeneities are preserved and amplified due to the action of the dynamo mechanism.

Conclusion

We studied the process of generation of magnetic fields in accretion discs and the possibility of heterogeneous magnetic fields occurrence in them, which are similar to the structures that in case of galaxies commonly referred to as inversions [15]. It was found that the random initial conditions reproducing the actual seed magnetic fields during accretion in double systems make it possible to achieve the axisymmetric contrast structures. At the same time the heterogeneities in the azimuthal direction are eroded for the short duration. This result agrees well with what was obtained previously for the galaxies, where only radial inversions are stable [16]. This may be explained by the intensive differential rotation, which helps to mix the medium with the magnetic field frozen into it. In its turn, it should not go unnoticed that these results were obtained

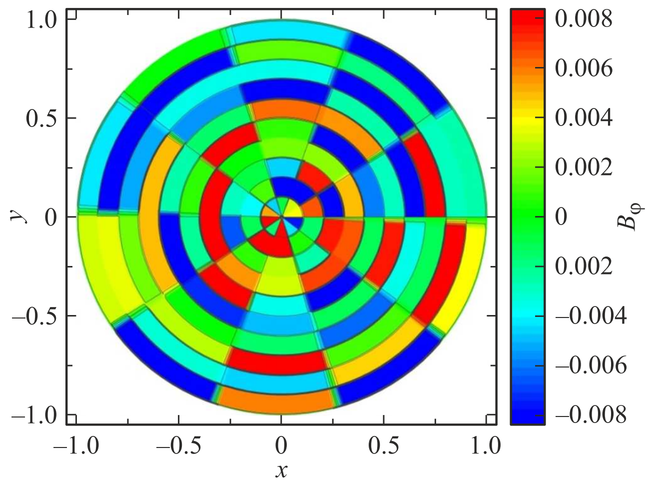

Figure 1. Random initial conditions for angular component of magnetic field B_φ, normalized to magnetic field of equidistribution B^*.

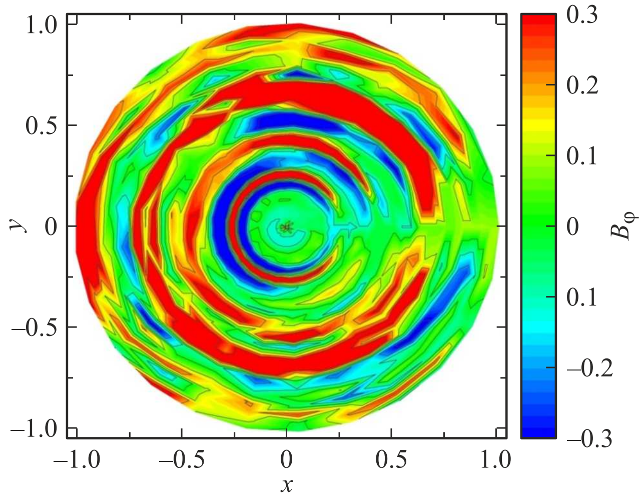

Figure 2. Evolution of the angular component of the magnetic field B_φ for the time of order 10^4 s, normalized to magnetic field of equidistribution B^*.

by relying on rather simple ideas on the evolution of the magnetic fields. Thus, in the future it would be interesting to look at this process with account of the more specific accounting of the mechanism of the field reverse effect at the flows as such and the disc structure [17].

Conflict of interest

The authors declare that they have no conflict of interest.

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