Computational estimates for magnetic fields of a variety of disks surrounding Be-stars

E.N. Zhikhareva*[1], E.A. Mikhailov[1,2], E.B. Ryspaeva[3], and A.F. Kholtygin[4]

[1]M.V. Lomonosov Moscow State University, Moscow, 119991, Russia
[2]P.N. Lebedev Physical Institute, Moscow, 119991, Russia
[3]Crimean Astrophysical Observatory, Nauchny, 289409, Russia
[4]Saint Peterburg State University, Saint Peterburg, 199034, Russia

Abstract

We study the decretion disks formed around Be stars and characterized by the outflow of matter, unlike accretion disks. It is shown that, despite the opposite direction of the mass flow, the evolution of a large-scale magnetic field in such disks can be described within the framework of a large-scale dynamo approach. Field generation is considered a result of the combined action of the alpha effect and differential rotation. Peaceman – Rachford method was used to numerically solve the dynamo equation in a thin disk. Based on the observational data, a module simulating periodic emissions of substance and frozen-in magnetic fields was integrated into the computational code. The simulation is quite similar to that for accretion disks. Its results confirm the possibility of magnetic field generation in decretion disks.

Keywords: *dynamo, decretion disk, magnetic field, Be-stars.*

1. Introduction

Accretion disks are gas and dust structures that form around some objects (such as stars, black holes, or neutron stars) during the astronomical processes of the medium falling on a massive object (Jiang et al., 2019). Unlike accretion disks, where matter falls onto a central object, decretion disks are formed due to the outflow of matter from a star and take place in binary systems around a donor star (Lee et al., 1991). One of the most important examples is connected with Be-stars (Rivinius et al., 2013). These objects have high rotational velocity, and even weak perturbations lead to the outflow of matter in the equatorial plane. The ejected material remains in the star's gravitational field, forming a thin disk. Internal dissipative processes in the decretion disk leads to a loss of angular momentum, as a result of which some of the matter returns to the star.

Accretion and decretion disks are systems where magnetic fields play an important role in their evolution(Shakura & Sunyaev 1973). they can transmit the momentum of their motion, influence the flows of the environment, and affect other phenomena. In decretion disks, magnetic fields can be a key factor in explaining the observed variability (Ryspaeva et al., 2021), disk formation mechanisms, and the transport of angular momentum outward, facilitating mass ejection. Analysis of X-ray observations of Be stars has shown that their X-ray emission consists of a large number of short flares (Ryspaeva, 2024, Smith et al., 2016). We propose that during such flares, substances should be injected into the decretion disk and influence on the magnetic field.

In different branches of astrophysics, the dynamo mechanism successfully explains the generation of large-scale magnetic fields in galactic disks due to turbulence and differential rotation (Arshakian et al., 2009). It was shown earlier that the dynamo mechanism can be expected to operate in accretion disks using a mechanism similar to one of galaxies (Boneva et al., 2021). The physical similarity between these types of disks suggests that a similar approach can be applied to decretion disks, despite the reversed mass flow.

A decretion disk is similar to an accretion disk in which matter does not move inward but actively loses mass due to powerful radial flows. The evolution can be described within the framework of a single dynamo approach. Despite the opposite direction of the mass flow (away from the star, not towards it), the dynamics

*zhikhareva.03@mail.ru, Corresponding author

doi:https://doi.org/10.52526/25792776-25.72.2-386

of such disks will be sufficiently similar to those of accretion disks. In particular, it can be expected that the magnetic fields in the decretion disks will evolve in a similar way, while taking into account the opposite direction of the swirling flows.

In this paper, we present a simple approach based on the dynamo model, where the parameters of the disks correspond to observational data and theoretical models for Be-stars and surrounding decretion disks (Vieira et al 2017). It provides a possibility to estimate the magnetic fields in such objects.

2. Dynamo model

Dynamo describes the occurrence of magnetic fields due to both turbulence (the alpha effect) and differential rotation: in accretion disks, the angular velocity is inhomogeneous and decreases with distance from the center according to the law $r^{-3/2}$ (Shakura & Sunyaev, 1973). They compete with turbulent diffusion, which tends to destroy all large-scale structures of the magnetic field. If the alpha effect and differential rotation are intense enough to withstand turbulent diffusion, then a magnetic field is generated. Otherwise, any initial field can only decay. Thus, the dynamo mechanism is threshold (Arshakian et al., 2009).

A large–scale magnetic field can be described using the Steenbeck–Krause–Rädler equation:

$$\frac{\partial \vec{B}}{\partial t} = rot(\alpha \vec{B}) + rot[\vec{V}, \vec{B}] + \eta \Delta \vec{B};$$

To solve the equation, by analogy with accretion disks, we can use the thin disk approximation (Grachev et al., 2023). It is based on the fact that the disk is quite thin, so the problem can be considered only for two components of the field. The derivative of the third component is expressed from the solenoidal condition. The growth of the field cannot be infinite. Therefore, a B* field of equipartition (saturation) arises (Moss et al., 1998). To account for nonlinear saturation, which limits the exponential growth of the field, a standard quenching function is often introduced, which reduces the alpha-effect as the magnetic field energy approaches the kinetic energy of turbulence.

The problem was solved numerically using the Peaceman – Rachford numerical method. It consists of the fact that for odd time steps we use an explicit scheme for the radial coordinate and an implicit scheme for the azimuthal one, and for even steps - vice versa. This approach allows for increased computational stability and avoids the strict limitations on the time step in fully explicit schemes (Simoncini, 2016).

There is a difficulty in implementing an implicit scheme for the derivative of angular coordinates. Considering the need for periodic boundary conditions, we use the Thomas algorithm for periodic systems. This ensures the correct treatment of the azimuthal coordinate, where the physical conditions at 0 and $2 * \pi$ radians are identical.

Table 1. Data for some objects

	HD5394	**HD33328**	**HD110432**	**HD18552**	**HD24534**
Mass of the central object (in solar masses) according to Vieira et al (2017)	25	10	9	3,9	11
Maximal magnetic field in the disk (in G)	1.2	0.2	3.1	0.2	1.1

3. Numerical solution

Based on the data on the frequency of X-ray flares, the average period between emissions was calculated. In the program code, we integrated a module, which simulates emissions of the medium with a frozen-in magnetic field in the central part of the disk, with a period that is associated with X-ray flares. This allows us to simulate the behavior associated with episodic mass loss, which is typical for many stars.

Based on observations of real astrophysical objects, numerical modeling of the evolution of the magnetic field in the decretion disks (Vieira et al 2017) was carried out for some objects. The initial conditions for the simulations included parameters such as the stellar mass, rotation velocity, and mass-loss rate, derived from observational data and theoretical models for typical Be-stars (Vieira et al 2017).

The calculation results demonstrate that the formation of a magnetic field occurs exclusively in the small vicinity of the central object, where the density and speed of rotation of matter reach maximum values (fig.1,

doi:https://doi.org/10.52526/25792776-25.72.2-386

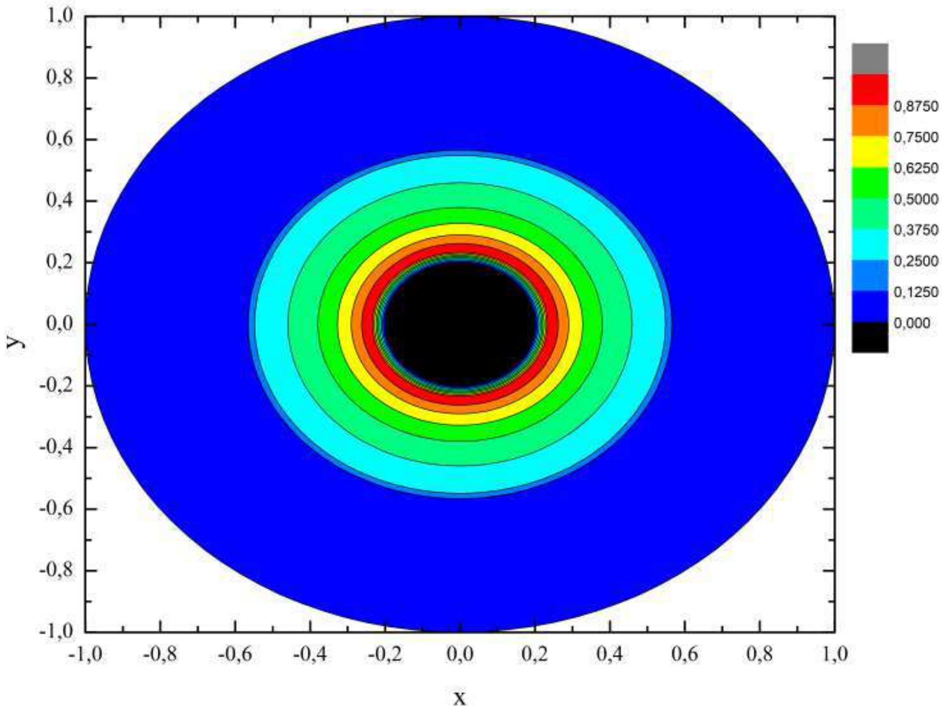

Figure 1. Saturated magnetic field (in G) for HD5394. Distances are measured in radii of decretion disk

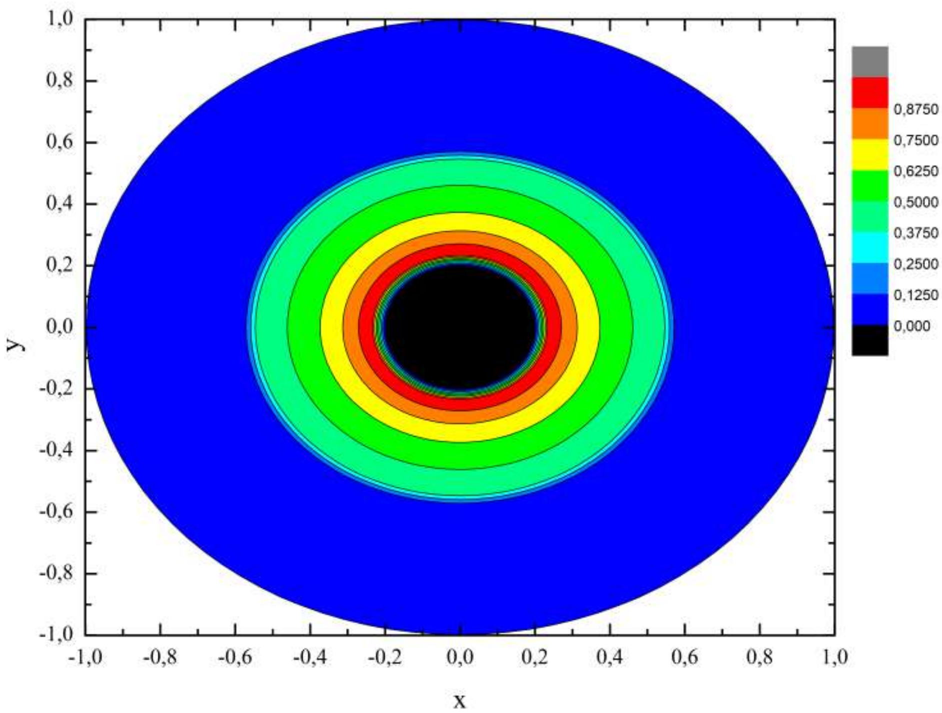

Figure 2. Saturated magnetic field (in G) for HD18552. Distances are measured in radii of decretion disk

doi:https://doi.org/10.52526/25792776-25.72.2-386

fig.2). During moving away from the center, the magnetic field decreases, approaching zero values on the periphery of the disk. The obtained maximum values of the magnetic field in the near-central region are consistent with the observational estimates for this class of objects. The field configuration is predominantly toroidal, generated from a weak initial poloidal field by strong differential rotation. Maximal values of the field are shown in table 1.

References

Arshakian T. G., Beck R., Krause M., Sokoloff D., 2009, Astron. Astrophys. , 494, 21

Boneva D. V., Mikhailov E. A., Pashentseva M. V., Sokoloff D. D., 2021, Astron. Astrophys. , 652, A38

Grachev D. A., Mikhailov E. A., Zhikhareva E. N., 2023, Open Astronomy, 32, 216

Jiang Y.-F., Stone J. M., Davis S. W., 2019, Astrophys. J. , 880, 67

Lee U., Saio H., Osaki Y., 1991, Mon. Not. R. Astron. Soc. , 250, 432

Moss D., Shukurov A., Sokoloff D., 1998, Geophysical and Astrophysical Fluid Dynamics, 89, 285

Rivinius T., Carciofi A. C., Martayan C., 2013, Astron. Astrophys. Rev. , 21, 69

Ryspaeva E., 2024, Proc. XXI Young Scientists Conference, IKI RAS, Moscow, 10–12 April, 12, 108

Ryspaeva E., Kholtygin A., Lyutikov M., 2021, Mon. Not. R. Astron. Soc. , 521, 2427

Shakura N. I., Sunyaev R. A., 1973, Astron. Astrophys. , 24, 337

Simoncini E., 2016, Memorie della Societa Astronomica Italiana, 87, 213

Smith M. A., Lopes de Oliveira R., Motch C., 2016, in Sigut T. A. A., Jones C. E., eds, Astronomical Society of the Pacific Conference Series Vol. 506, Bright Emissaries: Be Stars as Messengers of Star-Disk Physics. p. 299

doi:https://doi.org/10.52526/25792776-25.72.2-386