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The evolution of the fossil large-scale magnetic field in turbulent accretion disks of young stars

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Abstract. We study the fossil large-scale magnetic field evolution in a turbulent accretion disk of young T Tauri star. The coefficient of turbulent viscosity is calculated according to the Shakura and Sunyaev model. The modeling is performed taking into account the weakening of the turbulence in the region of low ionization fraction ("dead" zone). The ionization structure is calculated taking into account thermal ionization, cosmic rays and radioactive elements, radiative recombinations and recombinations on dust grains. The magnetic field is calculated taking into account ambipolar diffusion. The simulations show that the magnetic field is frozen in gas and its strength is proportional to the gas surface density in the inner region of the disk, $R < 0.2$ AU. The magnetic field strength increases from 10^2 G to 10^3 G in this region within 5 Myr. The outer boundary of the "dead" zone depends on the dust grain size and ranges from 30 AU for $a_g = 0.1$ μm to 3 AU for $a_g = 10^3$ μm. The size of the "dead" zone decreases with time. The magnetic field strength inside the "dead" zone remains practically constant at around 10^{-3}–10^{-4} G during the disk evolution.

Keywords: stars: protoplanetary disks, magnetic fields, pre-main sequence

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1 Introduction

Observations indicate that young stars are surrounded by thin rotating accretion disks of gas and dust (Williams & Ciesza 2011). Various instabilities during the accretion disk evolution can lead to planet formation. The disk at this stage is called a protoplanetary disk.

Accretion disks of young stars have large-scale magnetic field (Khaibrakhmanov 2024). The nature of this field is explained by the fossil magnetic field theory (Dudorov 1995). The large-scale magnetic field is associated with angular momentum transport, efficiency of which depends on the magnetic field distribution. The magnetic field can influence the structure of disks (Khaibrakhmanov & Dudorov 2022). Magnetic field is weakened in the regions of low ionization fraction and effective magnetic diffusion ("dead" zones). Dust grains are effective sources of the recombinations and lead to a decrease in the degree of ionization. In this work, we study the large-scale magnetic field evolution in the accretion disk for various dust grains size.

2 Disk model

We consider a thin gas-dust accretion disk in which angular momentum is transferred by turbulence. The evolution of the disk in this approximation can be described using the following equation (Pringle 1981)

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left(R^{1/2}\frac{\partial}{\partial R}\left[\nu \Sigma R^{1/2}\right]\right), \tag{1}$$

where Σ is the surface density [g/cm^2], ν is the coefficient of turbulent viscosity, R is the radial distance from the star, and t is time. The turbulent viscosity coefficient $\nu = \alpha c_s H$ is calculated according to the model of Shakura & Sunyaev (1973), where c_s is the speed of sound, H is the scale height of the disk, α is a dimensionless parameter, that measures the efficiency of angular momentum transport due to turbulence. In order to take into account the weakening of the turbulence in "dead" zones, we assume that α depends on the ionization fraction (x). Inside the "dead" zone ($x < 10^{-12}$) $\alpha = 10^{-4}$, and outside the "dead" zone ($x \geq 10^{-12}$) $\alpha = 10^{-2}$.

The ionization model includes thermal ionization of alkali metals, cosmic rays and radioactive elements, radiative recombinations and recombinations on dust grains (Dudorov & Khaibrakhmanov 2014).

Magnetic field strength in the frozen-in approximation (magnetic Reynolds number $R_m > 1$) is calculated as

$$B_z = (B_{\mathrm{in}}/\Sigma_{\mathrm{in}})\Sigma, \tag{2}$$

where B_{in} and Σ_{in} are the initial values of magnetic field and surface density at the inner boundary. Magnetic ambipolar diffusion operates inside the "dead" zone ($R_m < 1$) and the magnetic field strength is calculated as:

$$B_z = \sqrt{4\pi x \rho^2 \eta_{\mathrm{in}} R |V_r|}, \tag{3}$$

where ρ is the density, η_{in} is the coefficient of interaction between ions and neutrals, V_r is the radial velocity.

We use the solution of eq. (1) with fully implicit conservative scheme of first-order accuracy in time and second-order accuracy in coordinate. The equation is solved for the range from 0.01 AU to 1000 AU on a logarithmic grid with $N = 100$ cells. We used analytical stationary solution of Dudorov & Khaibrakhmanov (2014) as an initial condition and adopted typical parameters of solar mass T Tauri stars. The boundary condition at the inner boundary corresponds to the zero viscous stress tensor, and the equality of the densities of the disk and interstellar medium at the outer boundary.

The dust grains in accretion disks can have different sizes. We perform three simulation runs for sizes of 0.1 μm, 1 μm, 10^3 μm.

3 Magnetic field

In Fig. 1a, we plot initial radial profiles of the magnetic field. In the inner region $R < 0.2$ AU, thermal ionization is effective, and the magnetic field is frozen-in, so the the magnetic field strength is proportional to the surface density and does not depend on a_g, $B \approx 100$ G. The distance $R = 0.2$ AU corresponds to the inner boundary of "dead" zone, where the magnetic field strength decreases by 4 orders of magnitude due to magnetic ambipolar diffusion. In the region $R > 0.2$ AU typical value of magnetic field is $B_z = 10^{-3}$ G for $a_g = 0.1$ μm. The outer boundary of the "dead" zone lies at $R = 30$ AU in this case. The magnetic field strength increases with dust grain size. For example, magnetic field strength at $R = 1$ AU is 10^{-1} G for $a_g = 10^3$ μm, and the outer boundary of the "dead" zone is located at $R = 2$ AU. This is explained by the fact that the degree of ionization increases and the size of the "dead" zone decreases in the case of large a_g (Dudorov & Khaibrakhmanov 2014).

The radial profiles of magnetic field at time $t \approx 5$ Myr are plotted in Fig. 1b. Near the the inner boundary, the magnetic field increased to the values of $B_z = 10^3$ G, which is associated with an increase in surface density. Magnetic field strength does not depend on dust grain size and decreases from 10^{-2} G to 10^{-4} G inside the "dead" zone, $r = 0.2$–2 AU. In the outer region of the "dead" zone, a local maximum is observed, which depends on the radius of the dust grains. The outer boundary of the “dead” zone varies from 30 AU for $a_g = 0.1$ μm to 3 AU for $a_g = 0.1$ μm.

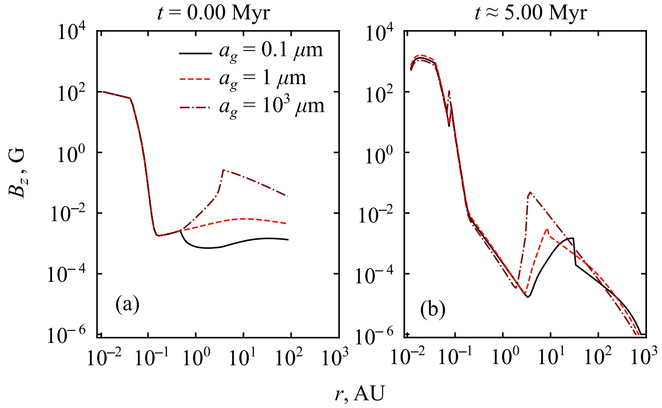

Fig. 1. Radial profiles of the magnetic field for different a_g at the initial moment (a) and at $t = 5$ Myr (b).

4 Summary

The numerical simulations show that the magnetic field changes significantly during the evolution of the disk. In the inner region, the magnetic field increases with increasing density and does not depend on a_g. Inside the “dead” zones, magnetic field remains practically constant with typical values of 10^{-3}–10^{-4} G. Outside the “dead” zone, the magnetic field strength increases with the size of the dust grain. The size of the “dead” zone decreases with time and depends on the size of dust particles. Therefore, it is necessary to take into account the self-consistent evolution of dust grains when studying the evolution of the magnetic flux in disks.

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