Physical and Chemical Vertical Structure of Magnetostatic Accretion Disks of Young Stars

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Abstract—The vertical structure of accretion disks of young stars with fossil large-scale magnetic field is studied. The equations of magnetostatic equilibrium of the disk are solved taking into account the stellar gravity, gas and magnetic pressure, turbulent heating, and heating by stellar radiation. The modelled physical structure of the disk is used to simulate its chemical structure, in particular, to study the spatial distribution of CN molecules. The disk of the typical T Tauri-type star is considered. Calculations show that the temperature within the disk in the region $r < 50$ au decreases with height and density profiles are steeper than in the isothermal case. Outside the “dead” zone, vertical profiles of the azimuthal component of the magnetic field are nonmonotonic, and the magnetic field strength maximum is reached within the disk. The magnetic pressure gradient can cause an increase in the disk thickness in comparison with the hydrostatic one. The CN molecule concentration is maximum near the photosphere and in the disk atmosphere where the magnetic field strength at the chosen parameters is $\sim 0.01$ G. Measurements of Zeeman splitting of CN lines in the submm range can be used to determine the magnetic field strength in these regions of accretion disks.

Keywords: accretion disks, magnetic field, magnetohydrodynamics (MHD), chemical modeling

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1. INTRODUCTION

Accretion disks of young stars (AD YS) are geometrically thin optically thick gas—dust disks with characteristic sizes of 100—1000 au and masses 0.001—0.1 $M_\odot$. During the evolution, AD YS become protoplanetary disks with conditions favorable for planet formation.

Polarization mapping of thermal radiation of AD YS and observations of outflows and jets suggest that a large-scale magnetic field exists in disks (see review [1]). The spatial resolution and sensitivity of available instruments do not allow detailed conclusions on the AD YS magnetic field geometry. The AD YS magnetic field strength can be indirectly estimated by the remanent magnetization of meteorites of the solar system; its direct measurements using the Zeeman effect are still challenging. A promising direction is the measurement of Zeeman splitting of CN molecule lines in the submm range [2].

An analysis of observations of star formation regions and numerical simulations of star formation resulting from the collapse of magnetic rotating cores of molecular clouds show that the AD YS magnetic field is of fossil nature (see [3]). Within the theory of the fossil magnetic field, Dudorov and Khaibrakhmanov developed a magnetogasdynamic (MHD) model of AD YS [4, 5]. Using it, it was in particular shown that the magnetic field can be dynamically strong in some disk regions.

In the present paper, the approach by Dudorov and Khaibrakhmanov is developed, and the effect of the magnetic field on the vertical structure of the AD YS is considered. Chemical modeling of AD YS is performed and the spatial distribution of CN molecules in the disk is determined.

2. PROBLEM STATEMENT AND BASIC EQUATIONS

Let us consider a low-mass steady-state geometrically thin and optically thick accretion disk with a fossil large-scale magnetic field. The inner radius of the disk is defined by the stellar magnetosphere radius, \[ \text{Deceased.} \]
the outer radius of the disk is defined as the contact boundary with the interstellar medium. The disk surface represents the boundary of its photosphere which is also a contact one.

To study the dynamics of AD YS with large-scale magnetic field, we use MHD equations taking into account the stellar gravity, turbulent viscosity, radiative thermal conductivity, and magnetic field diffusion. In the approximation of the steady-state geometrically thin disk, this system of equations is split into two independent subsystems describing the radial and vertical disk structure.

The basic system of equations for simulating the AD YS radial structure with magnetic field was derived by Dudorov and Khaibrakhmanov and was described in detail in [5]. According to Shakura and Sunyaev [6], it is supposed that the main mechanism of angular momentum transport in the differential rotating disk is turbulence, and the main gas heating mechanism is turbulent friction. In addition to Shakura and Sunyaev equations, equations of shock and thermal ionization are solved, as well as the induction equation taking into account Ohmic dissipation and magnetic ambipolar diffusion, buoyancy, and the Hall effect.

The equations of the magnetostatic equilibrium of the AD YS can be written in cylindrical coordinates \((r, \theta, z)\) as follows [7]

\[
\frac{\partial p}{\partial z} = \rho g_z + \frac{\partial}{\partial z} \left( \frac{B_\phi^2}{8\pi} \right),
\]

\[
\kappa_v \frac{\partial T}{\partial z} = \nabla_z, \tag{2}
\]

\[
\frac{\partial \nabla_z}{\partial z} = \Gamma_{\text{turb}}, \tag{3}
\]

\[
\frac{\partial^2 B_\phi}{\partial z^2} = -\frac{3}{2} \frac{v_k B_z}{\eta} \frac{z}{r^2}, \tag{4}
\]

where \(g_z\) is the vertical component of the stellar gravity, \(\kappa_v\) is the radiative thermal conductivity, \(\nabla_z\) is the flux density of stellar radiation in the vertical direction, \(\Gamma_{\text{turb}} = -\alpha \rho v_k \Omega / \Omega / dr\) is the gas volume heating rate due to turbulent friction, \(\alpha\) is the Shakura and Sunyaev turbulent parameter, \(\Omega\) is the gas angular velocity, \(v_k\) is the Keplerian velocity, \(\eta\) is the magnetic field diffusion coefficient, and \(B_\phi\) and \(B_z\) are the azimuthal and vertical components of the magnetic field.

Equations (1)–(4) imply that a single heating source within the disk is turbulent friction. An additional heating mechanism of upper disk layers is the absorption of stellar radiation. The stellar radiation flux is incident on the disk surface at a very small angle; therefore, for simplicity, it can be considered that it is completely absorbed in the optically thin disk atmosphere. The atmosphere temperature \(T_a\) can be determined from the heat balance condition

\[
\sigma T_a^4 = f \frac{L_\odot}{4\pi r^2}, \tag{5}
\]

where \(L_\odot\) is the stellar luminosity and \(f < 1\) is the geometrical factor defining the fraction of radiation absorbed by the disk at a given distance. The value of \(f\) depends on the disk surface shape and, generally speaking, is a priori unknown. For example, according to detailed calculations by Akimkin et al. [8], \(f\) can vary from 0.015 to 0.15. In the present study, a constant characteristic value of 0.05 is taken.

To solve Eqs. (1)–(4), five boundary conditions should be set.

Let us consider the region from the equatorial plane \(z = 0\) of the disk to its photosphere boundary \(z_s\) characterized by the optical thickness \(\tau = 2/3\). Due to the equatorial plane symmetry, \(\nabla_z = 0, B_\phi = 0\). On disk surface, \(T = T_{\text{eff}}, \nabla_z = \sigma T_{\text{eff}}^4\), where \(T_{\text{eff}}\) is the effective disk temperature. The gas pressure \(p_s\) over disk corresponds to the pressure of the central region of the molecular cloud core with a characteristic density of \(10^9\ \text{cm}^{-3}\) and a temperature of 20 K. The magnetic field strength \(B_\phi\) on the surface is defined in terms of the plasma parameter \(\beta = 8\pi p_s / B_\phi^2\).
3. METHOD FOR SOLVING EQUATIONS AND MODEL PARAMETERS

The induction Eq. (4) can be solved analytically. For the chosen boundary conditions, we derive [7]

\[ B_\phi(r, z) = B_k \frac{z_s}{r} + \frac{1}{4} \frac{v_k z_s}{\eta} B_z \left[ \frac{z_s^2}{r^2} - \left( \frac{z_s}{r} \right)^2 \right]. \]

The system of the first-order ordinary differential equations (1)—(3) is solved numerically by the fourth-order Runge—Kutta method with automatic step selection for a relative accuracy of $10^{-4}$.

In this paper, the structure of the accretion disk of the T Tauri-type star of solar mass with an accretion rate of $10^{-8} M_\odot$ per year and turbulence parameter $\alpha = 0.01$ is simulated. The characteristic radial distances from star $r = 0.25$, 1, 10, and 50 au are considered. The range $0.25 < r < 50$ au corresponds to the dead zone of the disk, where the magnetic field diffusion prevents its generation. The equation coefficients at each $r$ were set from the solution of equations of the radial disk structure within the Dudorov and Khai-brakhmanov model. The induction equation is solved taking into account Ohmic dissipation $\eta = \nu_m = c^2/(4\pi\sigma)$, where $\sigma(x)$ is the plasma Coulomb conductivity, and $x$ is the degree of ionization. Ohmic dissipation is the main dissipative MHD effect in dead zones of accretion disks (see [5]). The degree of ionization was calculated taking into account radiative recombinations and recombinations on dust particles with characteristic average radius of 0.1 $\mu$m, for standard rates of ionization by cosmic rays, X-rays, and radioactive elements. At the chosen parameters, the magnetic Reynolds number $Re_m = v_k H/\nu_m$ characterizing the efficiency of magnetic field diffusion is 3, 68, and 8425 at chosen distances of 0.25, 10, and 50 au, respectively. The plasma beta on the surface is taken equal to unity.

The results of calculations of the physical structure of the disk were used for simulating its chemical composition using the MONACO numerical code [9, 10]. Chemical kinetic equations describing 6002 chemical reactions between 664 atoms and molecules consider gas-phase reactions, reactions on the surface and in the bulk of icy mantles of dusty particles. It is assumed that the dust has a standard chemical composition and is well mixed with gas. The coefficients of the interaction of atoms and molecules with gas-phase reactions, at $x_{CN} = 0.25, 1, 10, 50$ au are taken from [11]. The initial chemical composition was set as a result of simulations of the chemical evolution of the typical molecular cloud for $10^6$ years. The system of chemical balance equations was solved using the DVODE integrator implementing the implicit Adams—Gear method.

4. RESULTS

Figure 1 shows the vertical profiles of the density, temperature, magnetic field strength, and CN molecule concentration in the gas phase relative to hydrogen. According to the performed calculations, at $r = 0.25$, 10, and 50 au the photosphere is at heights $z_s = 3.8$, 2.7, and 2.8 $H$, respectively. Here, $H$ is the scale height determined by the temperature in the equatorial plane.

Figure 1a shows that the density profiles in the region $r < 50$ au, $2H < z < z_s$ (curves 1 and 2) are steeper than in the isothermal case. This is due to the fact that the temperature inside the disk in this range decreases with height (see Fig. 1b). The largest difference is observed in the central region, $r = 0.25$ au, the temperature decreases from $\approx 1000$ K in the equatorial plane to $\approx 300$ K on the surface, and the density near the photosphere, $\rho \approx 10^{-16}$ g cm$^{-3}$, is lower than the hydrostatic one by $4—5$ orders of magnitude. In the outer disk region, $r = 50$ au (curve 3), the temperature is constant in height and the density profile is identical to the isothermal one. On the contact disk surface, $z = z_s$, the temperature abruptly increases when going from the disk whose heating is caused by turbulent friction to its atmosphere whose heating is controlled by stellar radiation. In the disk atmosphere, $z > z_s$, the temperature is constant and the density exponentially decreases with height to the interstellar medium density.

Figure 1c shows that $B_\phi$ increases with height $z$ outside the dead zone, at $r = 0.25$ and 50 au, near the equatorial plane and decreases near the disk surface, i.e., $B_\phi$ takes a maximum value within the disk, e.g., $B_\phi \approx 0.01$ G at $z = 2H$, $r = 50$ au. In this case, the magnetic pressure gradient near the disk surface results in an increase in the characteristic disk thickness in comparison with the hydrostatic one [7].

According to Fig. 1d, CN molecules are distributed along $z$ highly inhomogeneously. The CN content is maximum, $x_{CN} \sim (10^{-10}—10^{-9})$, near the disk surface, $z \approx z_s \approx 3H$, as well as in its atmosphere. Maximum values of $x_{CN}$ in these disk regions are close to the results obtained in [13] for accretion disks of young T Tauri-type stars.
4. CONCLUSIONS

Physical and chemical vertical structure of AD YS with fossil large-scale magnetic was simulated. The model of the vertical disk structure, developed in [7], was complemented for considering the effect of disk atmosphere heating by stellar radiation.

Simulations show that in the inner region, \( r < 50 \text{ au} \), the disk has a smaller characteristic thickness, than in the isothermal case. The magnetic field profiles outside the dead zone are nonmonotonic, the maximum strength \( B_\phi \) is reached inside the disk. In this case, the magnetic pressure gradient can lead to an increase in the effective disk thickness in comparison with the hydrostatic one [7]. Other studies, as a rule, considered the case where the magnetic field strength monotonically increases to the surface, and the magnetic pressure gradient “compresses” the disk (see [12]). Generally speaking, both cases are possible depending on surface conditions.

CN molecule contents in the gas phase are maximum, \( x_{\text{CN}} \sim (10^{-10} - 10^{-9}) \), in the disk photosphere and atmosphere. Measurements of Zeeman splitting of CN lines can be used to determine the magnetic field strength in these regions, where the magnetic field strength for chosen parameters is \( \sim 0.01 \text{ G} \). Quantitative interpretation of available and future observations requires more detailed two-dimensional MHD simulation of the disk.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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