Primary Disks and Their Observational Appearance in Collapsing Magnetic Rotating Protostellar Clouds

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Abstract—The collapse of the magnetic rotating protostellar cloud 10 $M_\odot$ mass is numerically studied. The initial ratios of the thermal, magnetic, and rotational energy to the cloud gravitational energy magnitude are 0.3, 0.2, and 0.01, respectively. The emphasis is on the evolution and properties of the quasi-magnetostatic primary disk formed at the isothermal stage of the collapse. Simulations show that the primary disk size and mass increase during evolution from 1500 au to 7400 au and from 0.3 to 5.2 $M_\odot$, respectively. Magnetic fields are quasi-radial in the cloud envelope and quasi-uniform within the primary disk. A toroidal magnetic field is generated behind the front of the fast shock MHD wave propagating from the primary disk boundary and in the region of the outflow formed near the first hydrostatic core. The hierarchical structure of collapsing protostellar clouds can be revealed in observations by the magnetic field geometry and the angular momentum distribution.

Keywords: magnetic fields, magnetohydrodynamics (MHD), numerical simulations, star formation, interstellar medium

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1. INTRODUCTION

The current star formation occurs in magnetic rotating cores of molecular clouds, i.e., protostellar clouds (hereafter, PSCs). During the gravitational collapse of the PSC, a protostar is formed at its center, which is observed as an infrared source (see [1]). The young protostar immersed in an extended envelope is observed in the submillimeter range as a Class 0 young stellar object (hereafter, YSO). Characteristic features of Class 0 YSOs are outflows [2]. In Class 0 YSOs, flattened envelopes 200–10000 au in radius are observed, as well as small probably Keplerian disks 5–50 au in radius [3, 4]. In YSO envelopes, a large-scale magnetic field with hourglass geometry is detected; within disks, a pinch magnetic field and indications of a toroidal magnetic field are observed (see [5]). The angular momentum distribution changes in going from the disk to the envelope [6].

The first calculations of the PSC collapse showed that the collapse is inhomogeneous with the formation of the first hydrostatic core at the cloud center [7]. During the collapse, the magnetic rotating PSC takes a shape oblate along magnetic field lines and/or the rotation axis [8]. The PSC magnetic flux evolution and properties of formed stars are substantially controlled by ionization, recombination, and diffusion MHD effects, in particular, ambipolar diffusion [9].

The basic questions in the star formation theory are the problems of the angular momentum and catastrophic magnetic braking [8, 10].

The modern numerical calculations are mostly devoted to the accretion stage of the solar-mass PSC collapse (see [11, 12]). To solve the angular momentum problem, it is important to comprehensively study initial PSC collapse stages, when magnetic braking is most efficient.

Previously, Khaibrakhmanov et al. [13] studied the isothermal collapse of magnetic PSCs 1 and 10 $M_\odot$ mass. Calculations showed that a hierarchical PSC structure is formed during isothermal collapse, which consists of a geometrically thick and optically thin envelope, with a geometrically and optically thin quasi-magnetostatic primary disk (hereafter PD) inside.
The PD boundary is characterized by a sharp jump in velocity profiles, when almost free fall of the gas from the cloud envelope to its center transforms to slow almost radial motion. At the PD boundary, a fast shock magnetogasdynamic (hereafter MHD) wave is formed, which moves to the cloud periphery.

In the present study, the approach by Khaibrakhmanov et al. [13] is developed; the collapse of the magnetic rotating PSC $10 M_\odot$ mass is numerically simulated taking into account the formation of the first core. The PD evolution is studied, its mass, size, angular momentum, magnetic flux, and lifetime are determined. Possible observational manifestations of PDs are discussed.

2. PROBLEM STATEMENT AND NUMERICAL METHOD

A homogeneous spherically symmetric rotating PSC $10 M_\odot$ mass and a temperature of 20 K in a uniform magnetic field is considered. The initial cloud density is $4 \times 10^4$ cm$^{-3}$, the initial cloud radius is 0.1 pc. The main parameters defining the collapse dynamics are the ratios of the thermal $\varepsilon_t$, magnetic $\varepsilon_m$, and rotational $\varepsilon_w$ energies to the gravitational energy magnitude. In this paper, we consider the simulation with $\varepsilon_t = 0.3$, $\varepsilon_m = 0.2$, and $\varepsilon_w = 0.01$.

The PSC collapse is studied using gravitational MHD equations. Numerical simulation is performed using the Enlil two-dimensional MHD code [14, 15]. The PSC thermal evolution is simulated using the gas law with a density-dependent effective adiabatic index $\gamma_{\text{eff}}$ [16]. For the isothermal collapse, $\gamma_{\text{eff}} = 1.001$ is taken. At the density $\rho = 10^{-13}$ g/cm$^3$, when the first hydrostatic core is formed [7], $\gamma_{\text{eff}} = 5/3$. This approach allows us to calculate the PSC collapse taking into account the first core formation.

3. EVOLUTION OF THE PRIMARY DISK DURING THE PROTOSTELLAR CLOUD COLLAPSE

The performed simulations confirm the conclusions by Khaibrakhmanov et al. [13]. At the isothermal collapse stage, the cloud gains a hierarchical structure: the envelope takes a shape oblate along magnetic field lines and the rotation axis; a quasi-magnetostatic PD is formed within it. Let us consider the general picture of the PD evolution with the emphasis on the angular momentum distribution.

Figure 1 shows the quarter of the central part of the collapsing PSC at different time points. The time $t$ is measured in the units of the characteristic collapse time taking into account the effect of electromagnetic and centrifugal forces: $t_{\text{fmm}} = t_\text{ff}(1 - \varepsilon_m - \varepsilon_w)^{-1/2}$, where $t_\text{ff}$ is the free fall time [10]. At the PD formation point, $t = 0.9081 t_{\text{fmm}}$ (Fig. 1a), its radius is $R_{\text{pd}} \approx 0.07 R_0 \approx 1500$ au, and the ratio of its maximum half-thickness to the radius is $Z_{\text{pd}}/R_{\text{pd}} = 0.039$. At the time point $t = 0.9268 t_{\text{fmm}}$ (Fig. 1b), the PD radius is $R_{\text{pd}} \approx 0.22 R_0 \approx 4500$ au. At the PD boundary, a fast MHD shock wave is formed, which propagates into the cloud envelope (see [13]). The first core is formed at the time point $t = 0.9645 t_{\text{fmm}}$ (Fig. 1c). Near the core, in the region $r < 0.04 R_0 \approx 800$ au, the PD thickness abruptly decreases, i.e., quasi-magnetostatic equilibrium is broken in this region. Then, gas in this region begins to move from the cloud core to the periphery in parallel to the rotation axis, i.e., the outflow is formed (Fig. 1d). The PD radius continues to increase and by the time of $t = 0.9966 t_{\text{fmm}}$ (Fig. 1f) reaches $R_{\text{pd}} \approx 0.36 R_0 \approx 7400$ au. During evolution, the PD becomes geometrically thinner, $Z_{\text{pd}}/R_{\text{pd}} = 0.028$, and the outflow region sizes increase.

At the PD formation moment (Fig. 1a), the magnetic field is quasi-radial, $B_r \sim B_\phi$, in the envelope and quasi-homogeneous $B_r \ll B_\phi$, within the PD. At the following time points, behind the front of the fast shock MHD wave and in the outflow region, the magnetic field takes a toroidal geometry, $B_\phi \sim (B_r, B_\theta)$.

After the PD formation, the specific angular momentum is accumulated at its boundary (Fig. 1b), which is further removed from the PD boundary to the PSC envelope by the fast shock MHD wave (Fig. 1c). From the first core, the angular momentum is removed by the outflow (Figs. 1d—1f).

An analysis of the simulation shows that the PD mass increases with time from $0.3 M_\odot$ to $5.2 M_\odot$. On the contrary, the PSC envelope mass decreases from the time of the PD formation. The total angular momentum of the PSC decreases by 15% relative to its initial value $J_0$.

4. CONCLUSIONS AND DISCUSSION

The present paper evolves the study [13] in which the isothermal stage of the PSC collapse was studied. Two-dimensional numerical MHD simulation of the collapse of the magnetic rotating PSC $10 M_\odot$ mass was performed taking into account the first hydrostatic core formation.
Simulations show that the PSC hierarchical structure formed at the isothermal collapse stage [13] is retained during the further evolution. The first hydrostatic core is formed at the quasi-magnetostatic PD center. Near the core, \( r < 0.04 R_0 \approx 800 \text{ au} \), the quasi-magnetostatic equilibrium is broken, and, afterwards, the outflow arises. The PD size and mass increase from 1500 au to 7400 au and from 0.3 to 5.2, respectively. These values are close to characteristics of observed Class 0 YSO envelopes [3, 4]. Therefore, it can be assumed that the observed large-scale oblate envelopes of Class 0 YSOs are PDs.

The obtained results confirm the conclusions by Khaibrahmanov et al. [13] on the PD lifetime and magnetic field geometry in the collapsing PSC. The PD is a long-living structure which continues to evolve after the first core formation. The magnetic field geometry is different in the hierarchical PSC structure. The magnetic field within the envelope is quasi-radial; behind the front of the fast MHD wave emerging from the PD soon after its formation and in the outflow region, it is toroidal; within the PD, the magnetic field is uniform. The PD plays an important role in the evolution of the specific angular momentum in the cloud. The angular momentum is transferred by the front of the fast shock MHD wave going from the PD boundary to the cloud envelope, as well as by the outflow formed near the first core. The total angular momentum of the cloud by the time \( t = 0.9645 t_{\text{fmw}} = 0.1936 \) million years, when a typical hierarchical PSC structure with outflows forms, decreased by 15% relative to the initial value.

Based on the obtained results, it can be assumed that the hierarchical structure of collapsing PSCs can be revealed in observations by the distribution of the magnetic field geometry and the angular momentum. To determine the magnetic field geometry at various hierarchy levels, polarization maps of Class 0 YSOs should be constructed in the submillimeter range with high spatial resolution.

![Fig. 1. Distribution of the angular momentum (color filling), velocity field (arrows), and magnetic field (white lines) near the primary disk at time points: \( t = (a) 0.9081 t_{\text{fmw}}, (b) 0.9268 t_{\text{fmw}}, (c) 0.9645 t_{\text{fmw}}, (d) 0.9762 t_{\text{fmw}}, (e) 0.9896 t_{\text{fmw}}, \) and \( (f) 0.9966 t_{\text{fmw}} \). The green line is the primary disk boundary.](image)
The further study will be directed to the determination of the mass, size, total angular momentum, PD magnetic flux, and the first hydrostatic core during the collapse of magnetic rotating PSCs with various initial cloud parameters and taking into account magnetic field diffusion.

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REFERENCES
1. Zhang, G.-Y., André, Ph., Men’shchikov, A., et al., Fragmentation of star-forming filaments in the X-shape Nebula of the California molecular cloud, *Astron. Astrophys.*, 2020, vol. 642, p. A76. https://doi.org/10.1051/0004-6361/202037721
2. Andre, Ph., Ward-Thompson, D., and Barsony, M., Submillimeter continuum observations of rho Ophiuchi A: the candidate protostar VLA 1623 and prestellar clumps, *Astrophys. J.*, 1993, vol. 406, p. 122. https://doi.org/10.1086/172425
3. Ohashi, N., Hayashi, M., Ho, P.T.P., and Momose, M., Interferometric imaging of IRAS 04368+2557 in the L1527 molecular cloud core: a dynamically infalling envelope with rotation, *Astrophys. J.*, 1997, vol. 475, pp. 211–223. https://doi.org/10.1086/303533
4. Wiseman, J., Wootten, A., Zinnecker, H., and McCaughrean, M., The flattened, rotating molecular gas core of protostellar jet HH 212, *Astrophys. J.*, 2001, vol. 550, pp. L87–L90. https://doi.org/10.1086/319474
5. Lee, C.-F., Kwon, W., Jhan, K.-S., et al., A pseudodisk threaded with a toroidal and pinched poloidal magnetic field morphology in the HH 211 protostellar system, *Astrophys. J.*, 2019, vol. 879, p. 101. https://doi.org/10.3847/1538-4357/ab2458
6. Caselli, P., Benson, P.J., Myers, P.C., and Tafalla, M., Dense cores in dark clouds. XIV. N$_2$H$^+$ (1-0) Maps of dense cloud cores, *Astrophys. J.*, 2002, vol. 572, pp. 238–263. https://doi.org/10.1086/340195
7. Larson, R.B., Numerical calculations of the dynamics of collapsing proto-star, *Mon. Not. R. Astron. Soc.*, 1969, vol. 145, p. 271. https://doi.org/10.1093/mnras/145.3.271
8. Scott, E.H. and Black, D.C., Numerical calculations of the collapse of nonrotating, magnetic gas clouds, *Astrophys. J.*, 1980, vol. 239, pp. 166–172. https://doi.org/10.1086/158098
9. Dudorov, A.E. and Sazonov, Yu.V., Hydrodynamic collapse of interstellar clouds IV. The ionization fraction and ambipolar diffusion, *Nauchn. Inf.*, 1987, vol. 63, pp. 68–86.
10. Dudorov, A.E. and Sazonov, Yu.V., Hydrodynamic collapse of interstellar clouds. 2. The role of magnetic fields, *Nauchn. Inf.*, 1982, vol. 50, pp. 98–112.
11. Hennebelle, P. and Fromang, S., Magnetic processes in a collapsing dense core I. Accretion and ejection, *Astron. Astrophys.*, 2008, vol. 477, pp. 9–24. https://doi.org/10.1051/0004-6361:20078309
12. Zhao, B., Tomida, K., Hennebelle, P., et al., Formation and evolution of disks around young stellar objects, *Sol. Sys. Res.*, 2020, vol. 216, p. 43. https://doi.org/10.1007/s11214-020-00664-z
13. Khaibrakhmanov, S.A., Dudorov, A.E., Kargaltseva, N.S., and Zhilkin, A.G. Simulations of the isothermal collapse of magnetic protostellar clouds, *Astron. Rep.*, 2021, vol. 65, no. 8, pp. 693–704. https://doi.org/10.1134/S1063772921090043
14. Dudorov, A.E., Zhilkin, A.G., and Kuznetsov, O.A., Numerical simulations of the astrophysical MHD flows, in *Astrophysics and Space Science Library*, vol. 240: *Numerical Astrophysics*, Ed. by Miyama, S.M., Tomisaka, K., and Hanawa, T., Dordrecht: Kluwer, 1999, p. 389. https://doi.org/10.1007/10011-4780-4_116
15. Zhilkin, A.G., Pavlyuchenkov, I.N., and Zamozdra, S.N., Modeling of protostellar clouds and their observational properties, *Astron. Rep.*, 2009, vol. 53, pp. 590–604. https://doi.org/10.1134/S1063772909070026
16. Masunaga, H. and Inutsuka, Sh., A radiation hydrodynamic model for protostellar collapse II. The second collapse and the birth of a protostar, *Astrophys. J.*, 2000, vol. 531, pp. 350–365. https://doi.org/10.1086/308439

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