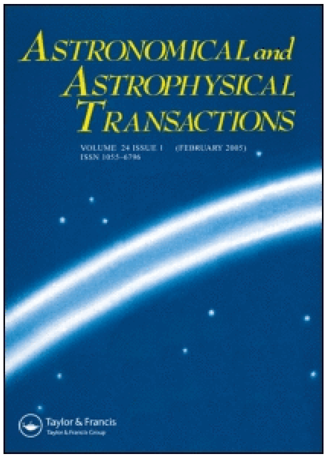

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ANGULAR MOMENTUM EVOLUTION OF PROTOSTELLAR CLOUDS

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The evolution of angular momentum during the collapse of protostellar clouds is investigated. The criteria for the efficiency of magnetic braking of rotation and angular momentum transfer are obtained analytically. These estimations are confirmed by the results of two-dimensional numerical simulations in the case of a frozen-in magnetic field.

KEYWORDS: interstellar medium, star formation, magnetic field, angular momentum

1 INTRODUCTION

According to the observational data the angular velocities of interstellar molecular clouds are comparable with the velocity of the Galactic differential rotation $\omega_0 \approx 10^{-15}\ \mathrm{s}^{-1}$. The angular momentum corresponding to this velocity is greater than the maximal angular momentum of binary stars and multiple stellar systems by several orders of magnitude. The angular momenta of protostellar clouds are greater than the angular momenta of single stars by a factor of $10^4 - 10^5$ (Goldsmith and Arquilla, 1985).

The possible mechanisms of rotation braking and/or redistribution of angular momentum inside the cloud are as follows:

(a) turbulent transport of the kinetic momentum in differently rotating clouds;
(b) redistribution of spin momentum of contracting cloud into orbital momentum of components by fragmentation;
(c) centrifugal wind, jets and outflows;
(d) magnetic braking.

Any of these mechanisms can be considered as the basic mechanism for certain stages of protostellar cloud evolution. The magnetic braking (transport of angular momentum by Alfvén and magnetosonic waves) can work during the whole star formation process. This mechanism can brake the rotation of clouds and can redistribute the angular momentum

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inside the clouds both between their cores and envelopes and between their various fragments after fragmentation. Therefore we must consider magnetic braking as a basic way to solve the angular momentum problem (Dudorov and Sazonov, 1983).

2 ANALYTICAL ESTIMATIONS

Let us consider the angular momentum transport by a large-scale magnetic field during the homogeneous contraction of a spherically symmetric rotating magnetized protostellar cloud. In the kinematic approximation (slow rotation and weak magnetic field) we can obtain the following criterion for the magnetic braking efficiency (Dudorov and Sazonov, 1983):

$$\varepsilon_{\mathrm{m}} > a(\varepsilon_{\mathrm{t}})\varepsilon_{\omega}^{1/2}, \tag{1}$$

where ε_{t}, ε_{m} and ε_{ω} are the initial ratios of the total thermal, magnetic and rotational energies respectively to the absolute value of the gravitational energy. The parameter $a(\varepsilon_{\mathrm{t}})$ can be determined through the estimation of electromagnetic force momentum and using the index k in the power-law dependence of magnetic field on the cloud radius, $B \propto R^{-k}$. The parameter a depends on ε_{t} because the pressure gradient in the region of a rarefaction wave (Dudorov and Zhilkin, 2003). In the case of magnetic flux conservation the index $k = 2$ and the parameter $a \approx 1$.

In the quasimagnetostatic limit the magnetic braking is efficient if

$$\frac{\varepsilon_{\mathrm{m}}}{\varepsilon_{\omega}^{1/2}} \frac{1}{(1 - \varepsilon_{\omega} - \varepsilon_{\mathrm{m}})^{1/2}} > a(\varepsilon_{\mathrm{t}}). \tag{2}$$

Figure 1 shows the regions of efficient and non-efficient magnetic braking obtained in the two-dimensional (ε_{ω}, ε_{m}) diagram both for kinematic and for quasimagnetostatic limits.

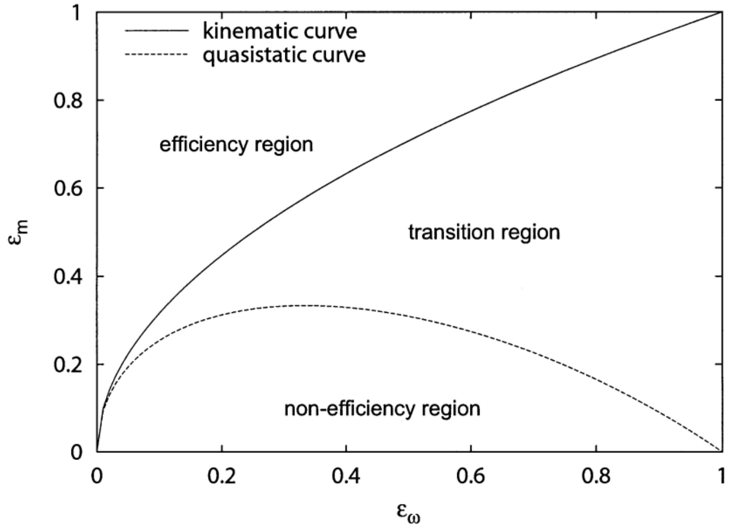

Figure 1. The critical curves of the magnetic braking efficiency for the kinematic and quasimagnetostatic approximations.

The solid and the dashed curves correspond to the kinematic and to the quasimagnetostatic critical curves respectively. For small ε_ω these curves have the same asymptotics. The time of cloud contraction increases with increase in the initial rotation velocity. Therefore the behaviour of the quasimagnetostatic critical curve differs from that of the kinematic curve. The magnetostatic curve has a maximum and decreases to zero for the large values of ε_ω.

3 NUMERICAL RESULTS

For the numerical investigation of magnetic braking efficiency we use the two-dimensional magnetohydrodynamics code Enlil (Dudorov *et al.*, 2003). We simulate the collapse of the rotating magnetized protostellar cloud with the mass $M = 1M_\odot$ temperature $T = 10\,\mathrm{K}$ and parameter $\varepsilon_\mathrm{t} = 0.3$ for several values of the initial magnetic field and angular velocity (Table 1).

Figure 2 gives the numerically obtained profiles of the angular velocity in the cloud's equatorial plane at free-fall time t_ff for three models of the initial values. The magnetic field redistributes efficiently the angular momentum in the collapsing cloud in case 3 when the parameter $\varepsilon_\mathrm{m} = 0.4$.

Table 1. The parameters used in the numerical computations.

Model	ε_ω	ε_m	*Braking*
1	0.05	0.0	Non-efficient
2	0.05	0.05	Non-efficient
3	0.05	0.4	Efficient

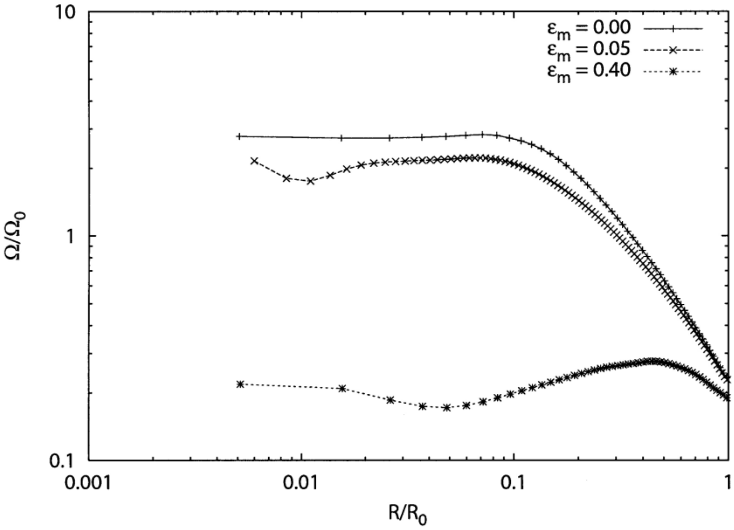

Figure 2. The numerically obtained distributions of the angular velocity $\omega(r)$ at time moment $t = t_\mathrm{ff}$ for three models of initial values.

4 CONCLUSION

The evolution of angular momentum during the collapse of protostellar clouds is investigated analytically and numerically. As a basic mechanism of rotation braking and/or redistribution of angular momentum between the central part of the cloud and its periphery, magnetic braking is considered. This mechanism can work in the cloud owing to the interaction of rotation with the large-scale magnetic field.

With the help of simple analytical estimations the criteria for magnetic braking efficiency are obtained. It is shown that magnetic braking can work efficiently under conditions of ambipolar and Ohmic diffusion. In quasimagnetostatic clouds, even a relatively weak magnetic field can redistribute the angular momentum. The obtained analytical estimations are confirmed by the results of two-dimensional numerical simulations of collapsing magnetized rotating protostellar clouds in an approximation of ideal isothermal magnetohydrodynamics.

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