Protostellar Disk Formation and Angular Momentum Transport During Magnetized Core Collapse

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Abstract Theoretical studies of collapsing clouds have found that even a relatively weak magnetic field may prevent the formation of disks and their fragmentation. However, most previous studies have been limited to cases where the magnetic field and the rotation axis of the cloud are aligned, and very few studies investigated the combined effects of magnetic field and turbulence.

We perform three-dimensional, adaptive mesh, numerical simulations of magnetically supercritical collapsing dense cores in both non-turbulent and turbulent environment.

At variance with earlier analyses, we show that the transport of angular momentum acts less efficiently in collapsing cores with non-aligned rotation and magnetic field. We also show that the turbulence is responsible for a misalignment between the rotation axis and the magnetic field and can diffuse out the magnetic field of the inner regions efficiently. The magnetic braking is therefore reduced, and massive disks can be built. If the disks are massive enough and the magnetization not too strong, fragmentation can occur. These results are presented in details in [7, 8].

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1 Introduction

The formation of protostellar disks plays a central role in the context of star and planet formation. Their formation is however still not well understood. Unlike Class I (and more evolved) disks, Class 0 disks formation remains unclear. Recent studies showed no clear evidence for disks or fragmentation for Class 0 protostars [10].

Theoretically, one of the main problems regarding disk formation is the magnetic braking, which transports angular momentum so efficiently that it can prevent massive disk formation, even at relatively low magnetic intensities ($\mu \lesssim 5\!-\!10$, μ being the magnetization parameter [6, 11, 12]), largely compatible with the observational measurements [2].

Most previous simulations have been performed in an idealized configuration, where the magnetic field and the rotation axis are initially aligned. As emphasized in [4] (see also [12]), the results of the collapse depend critically on the initial angle α between the magnetic field $\mathbf{B}$ and the rotation axis (which is the direction of the angular momentum $\mathbf{J}$). Moreover, very few studies investigated the role of turbulence in magnetized low-mass cores (see [9], or [5, 13] for high-mass cores).

Following the previous studies of [4] (see also [1]), we investigate in detail the transport of angular momentum, and the effects of magnetic braking in collapsing prestellar cores with aligned and misaligned configurations (α between 0 and 90°), and in non-turbulent and turbulent environments.

2 Collapse in a Non-turbulent Environment

We first perform 3D AMR-MHD simulations of the collapse of a $1\,\mathrm{M}_\odot$ core with the RAMSES code [3, 14]. The Jeans length is resolved with at least ten cells. We typically have a maximum spatial resolution of $\sim$0.5 AU. The initial density profile is that of a Plummer-like sphere. The magnetization parameter is taken between 2 and 17 (strong and low magnetization cases, respectively). The angle between the initial magnetic field and the initial rotation axis α is taken to be between 0 and 90°.

2.1 Transport of Angular Momentum

In the regions of the disk ($n > 10^9\,\mathrm{cm}^{-3}$) and the adiabatic core ($n > 10^{10}\,\mathrm{cm}^{-3}$) the angular momentum increases with α. Therefore, in misaligned rotators, more angular momentum will be available to "build" centrifugally supported disks.

To have a better understanding of the angular momentum transport, we consider the azimuthal component of the conservation of angular momentum in cylindrical coordinates, given by

$$\partial_t \left(\rho r v_\phi\right) + \nabla \cdot r \left[\rho v_\phi \mathbf{v} + \left(P + \frac{B^2}{8\pi} - \frac{g^2}{8\pi G}\right)\mathbf{e_\phi} - \frac{B_\phi}{4\pi}\mathbf{B} + \frac{g_\phi}{4\pi G}\mathbf{g}\right] = 0. \quad (1)$$

The fluxes of angular momentum of interest in this equation are $r\rho v_\phi \mathbf{v}$ for the mass flow, $rB_\phi \mathbf{B}/4\pi$ for the magnetic field. The integrals are taken over the surface S of a cylinder, corresponding approximately to the disk, of radius $R \simeq 300$ AU and height $h \simeq 150$ AU.

More angular momentum is carried away by magnetic braking from the central region of the collapsing core for relatively small α (below 70°) than for larger α (above 70°). As for the transport by the flow, When the angle α increases, the amount of angular momentum carried away decreases and in the perpendicular case, the total angular momentum transported by the flow is about ten times smaller than in the aligned case. The suppression of the outflows with increasing α is responsible for this decrease (see [1]).

2.2 Disk Formation

When enough angular momentum is left in the envelope, a disk can form around the adiabatic core. A simple rotation criterion is insufficient to define a disk because several parts of the envelope are rotating but do not belong to the disk. We define disks by employing a combination of five different criteria: $v_\phi > v_r$ (disks are expected to be Keplerian), $v_\phi > v_z$ (they are expected to be near the hydrostatic equilibrium), $\rho v_\phi^2/2 > P_{\mathrm{th}}$ (they are rotationally supported), $n > 10^9\,\mathrm{cm}^{-3}$ (to obtain more realistic estimate of the shape of the disk) and a connectivity criterion.

Figure 1 shows that the disk mass increases with the angle α. This agrees with our previous discussions, which indicated that the magnetic braking is more efficient in less tilted configurations, thus limiting the effective mass of disks. It is also clear that for increasing magnetic field strength, thus increasing magnetic braking, disks with masses greater than $0.05M_\odot$ are only found in misaligned configurations. The limiting case corresponds to a magnetization of $\mu = 2$, where the removal of angular momentum by the magnetic field is so efficient that the mass of rotating gas does not exceed $0.05M_\odot$, even in the perpendicular case.

3 Collapse in a Turbulent Environment

The initial conditions are the same as in the non-turbulent simulations, except for the initial mass of the core, which is 5 $M_\odot$. We also impose a turbulent velocity field with a Kolmogorov spectrum and $E_{\mathrm{turb}}/E_{\mathrm{grav}}$ between 0 and 0.5.

Two main effects are stressed here: first, the turbulence is responsible for a misalignment between the rotation axis and the magnetic field, which leads to a decrease of the magnetic braking efficiency, as we discussed previously. It is also responsible for an effective magnetic diffusion, which leads to a decrease of the magnetic field strength and therefore of the magnetic braking.

The mass of the disk as a function of time for different turbulence levels, is presented in Fig. 2. It shows a trend to form bigger disks when E_{turb} is higher;

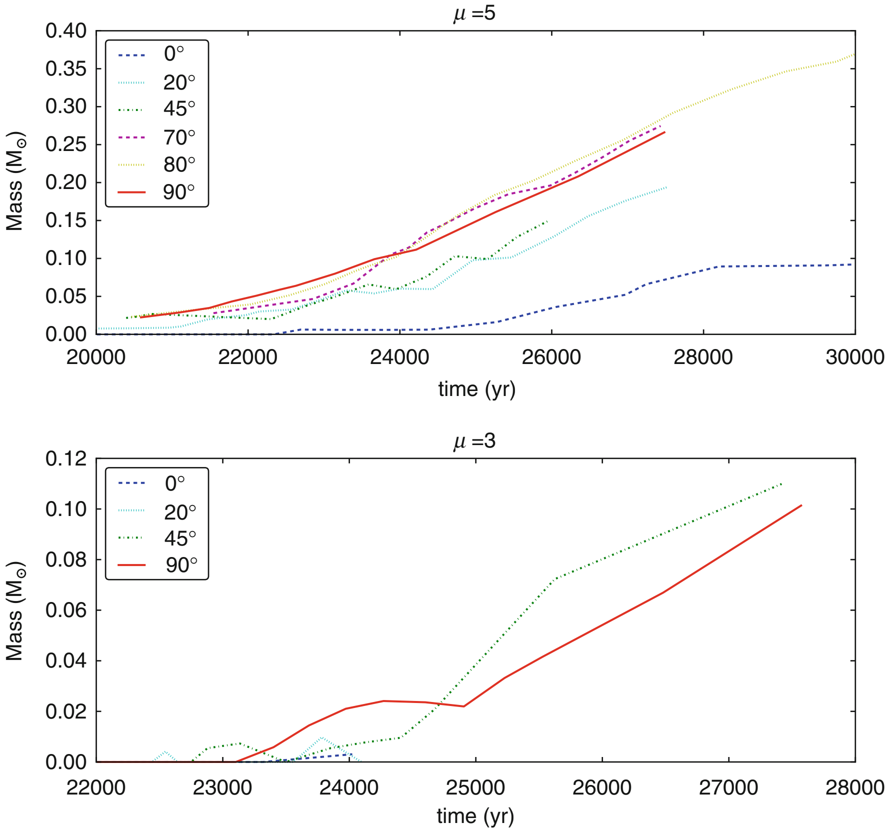

Fig. 1 Mass of the disks as a function of time for $\mu = 5$ and 3

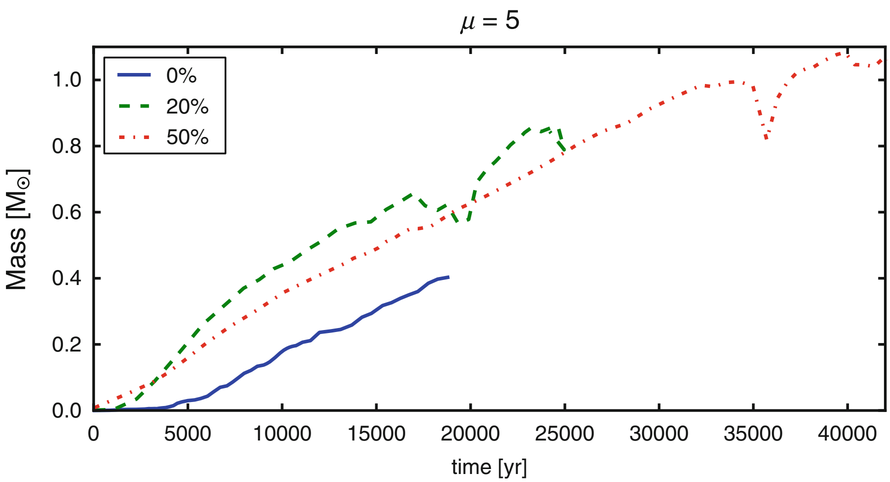

Fig. 2 Mass of the disk evolution for $\mu = 5$, with $E_{\rm turb}/E_{\rm grav} = 0$, 0.2 and 0.5

the possible cause is the reduced magnetic braking, as discussed in the previous sections. At the same time, it is still clear that for increasing magnetic field strength, and thus magnetic braking, disks tend to be smaller.

4 Conclusions

Magnetic braking is not a fatality: the early formation of massive disks can take place at moderate magnetic intensities if the rotation axis is tilted or in a turbulent environment, because of misalignment and turbulent diffusion.

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