Protostellar disk formation and transport of angular momentum during magnetized core collapse

Marc Joos, Patrick Hennebelle & Andrea Ciardi

Laboratoire de Radioastronomie, ENS - LERMA, Observatoire de Paris, Université Pierre et Marie Curie

Introduction

In the broad context of stars and planets formation, protostellar disk formation is a central question: protostars grow probably by accreting material from protostellar accretion disks, and those disks, at later stages, are the natural progenitors of planets. Nonetheless, it is still not known when circumstellar disks form, and what are their initial properties. They are believed to grow by angular momentum conservation during the collapse.

However, the presence of a magnetic field of typical magnetic intensities greatly modifies the collapse [1, 2], and various authors [3, 4, 5] have concluded that efficient transport of angular momentum through magnetic braking can even suppress the formation of a centrifugally supported disk.

Most of previous simulations were yet performed in a particular configuration, where the magnetic field and the rotation axis are initially aligned. We therefore study in this paper misaligned configurations, following the previous work of [6] (see also [7]), focusing on the transport of angular momentum and in particular the effect of magnetic braking. To do so, a set of 3D ideal magnetohydrodynamics (MHD) AMR simulations were performed with the Ramses code [8, 9].

Magnetic braking timescale

At variance with common belief ad the classical analysis of the magnetic braking during core collapse by Mouschovias [10], we show that the transport of angular momentum by the magnetic field is more efficient when the rotation axis and the magnetic field are aligned.

The key point to this analysis is the geometry of the field lines, which fan out away from the cloud.

An aligned rotator

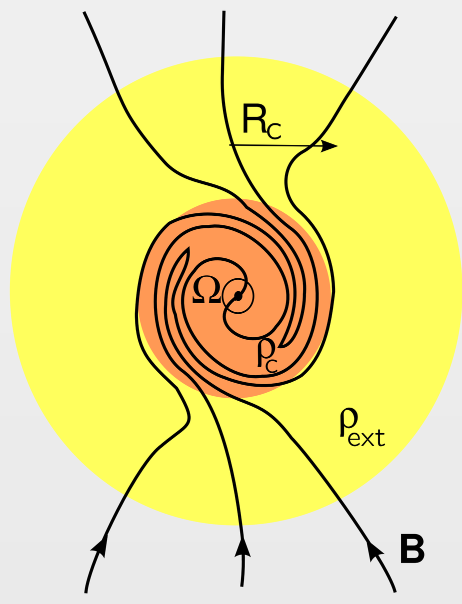
- core with a density ρ_c, a radius R_c, & threaded by B_c
- external medium of density $\rho_{\rm ext}$ threaded by $B_{\rm ext}$
- $\Omega R_0^2\ \pi R_0^2\ \rho_{\rm ext} v_{\rm A,ext} \tau_{//,fo} \sim \Omega R_c^2\ \pi R_c^2\ \rho_c Z$, with R_0 the initial radius, Z the height of the cloud and $v_{\rm A,\,ext}$ the Alfvén speed in the external medium
- therefore, $\tau_{//} = \dfrac{\rho_c}{\rho_{\rm ext}} \dfrac{Z}{v_{\rm A,ext}} \left(\dfrac{R_c}{R_0}\right)^4$

A perpendicular rotator

- same initial conditions, with a pependicular initial field (see figure)
- $\rho_{\rm ext} \left[(v_{\rm A}(R_c)\tau_{\perp,fo})^4 - R_c^4 \right] \sim \rho_c R_c^4$,
- thus, $\tau_\perp \sim \left(\dfrac{\rho_c}{\rho_{\rm ext}}\right)^{1/4} \dfrac{R_c}{v_{\rm A}(R_c)}$

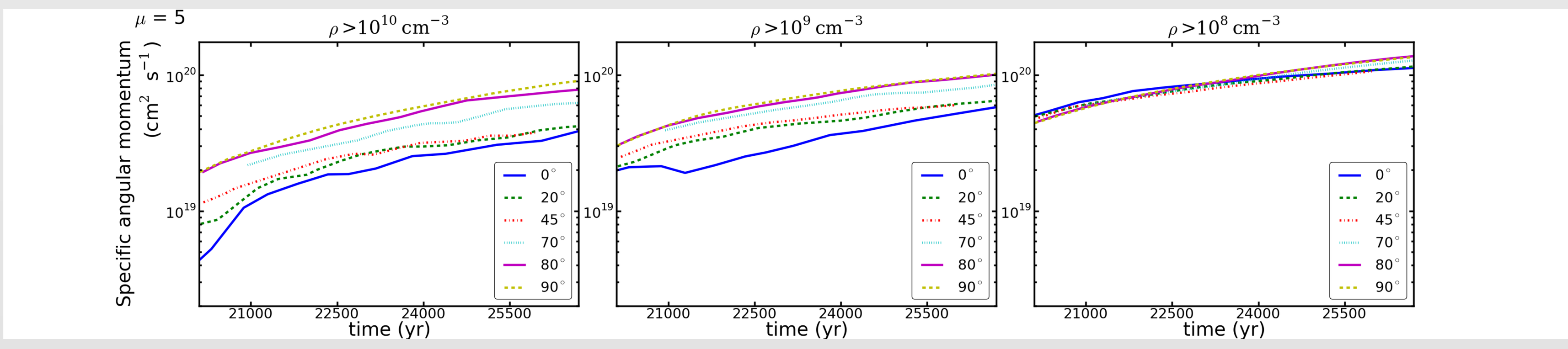
Comparison

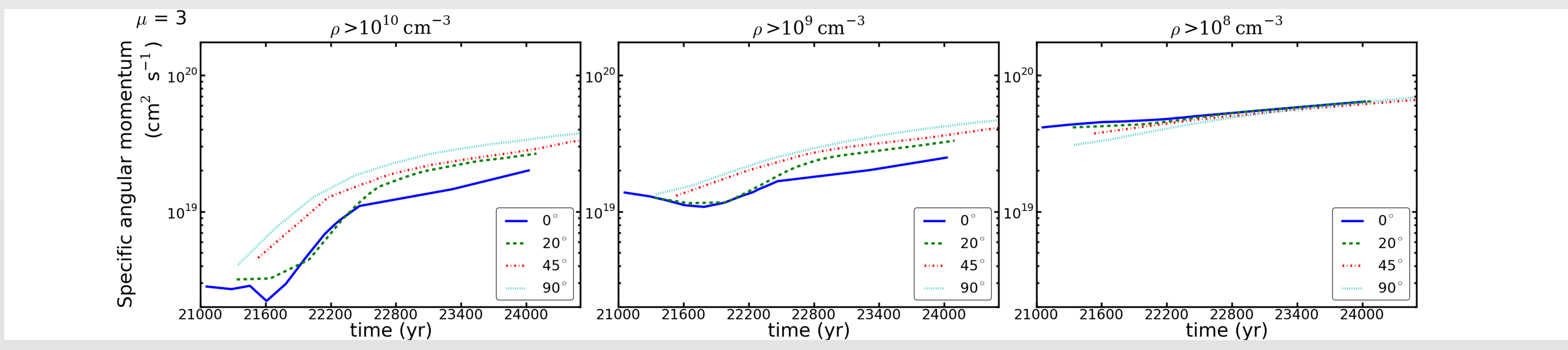
- $\dfrac{\tau_{//}}{\tau_\perp} = \left(\dfrac{R_c}{R_0}\right)^{1/2}$
- $R_c \ll R_0$, thus $\boxed{\tau_{//} \ll \tau_\perp}$



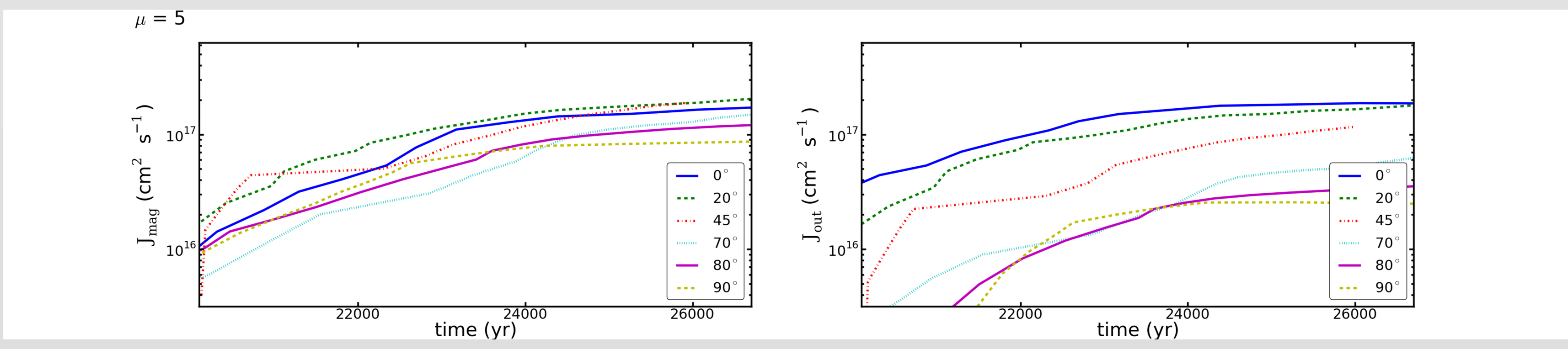
Transport of angular momentum

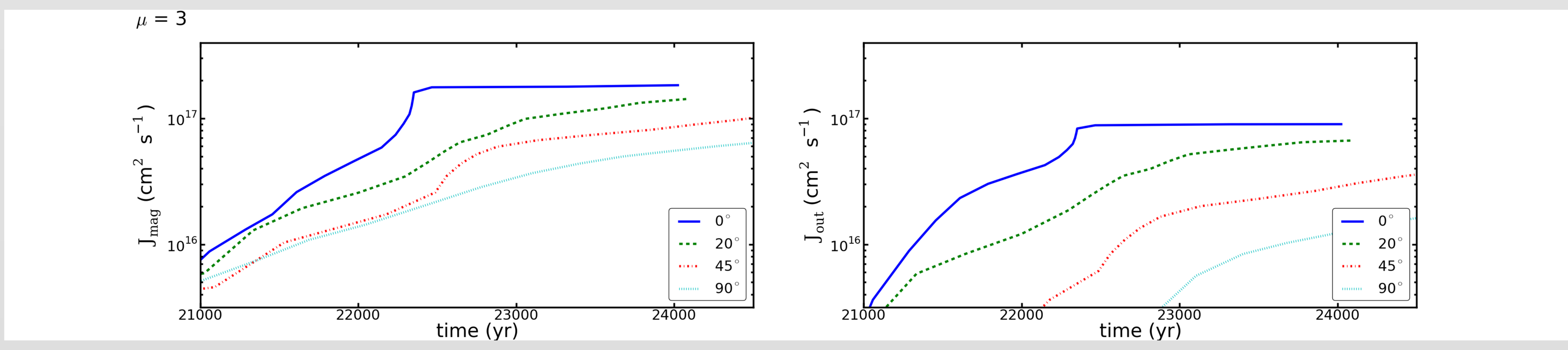
- Specific angular momentum ($1/M \int_{\rho>\rho_c} \mathbf{r} \times \rho v {\rm d}V$) for 3 density thresholds: the more titled the axis of rotation, the less efficient the angular momentum transported





- Specific angular momentum transported by the magnetic field (J_{mag}) and the outflows (J_{out}) within a cylinder of radius 300 AU and height 150 AU





When the magnetization increases, $\mathbf{B}$ transports more efficiently angular momentum. In any case, it transports more efficiently momentum than the outflows. The more tilted the axis of rotation, the less efficient the angular momentum transported, by both processes; the outflows can even be suppressed [7].

Disk criteria

Simple rotation or geometric criterion are not sufficient: the walls of the cavity of the outflows are rotating and disks are not perfect cylinders.

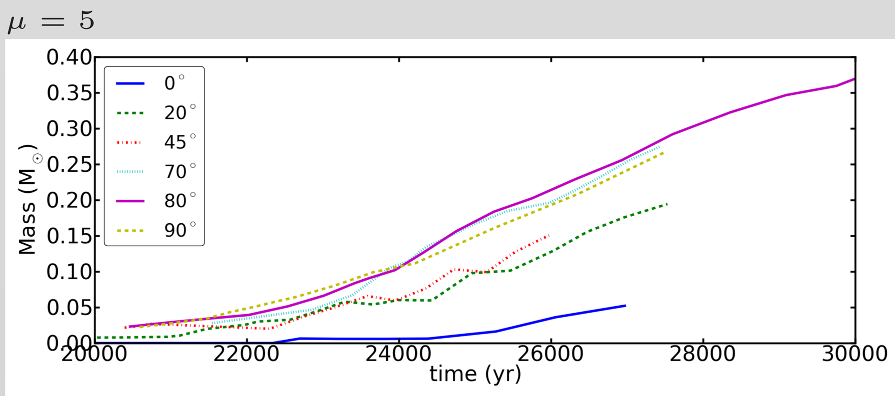
A disk is therefore defined by:

- a rotation criterion $v_\phi > v_r$
- an hydrostatic equilibrium $v_\phi > v_z$
- a rotational support $E_{k,\phi} > P_{th}$
- a connectivity criterion

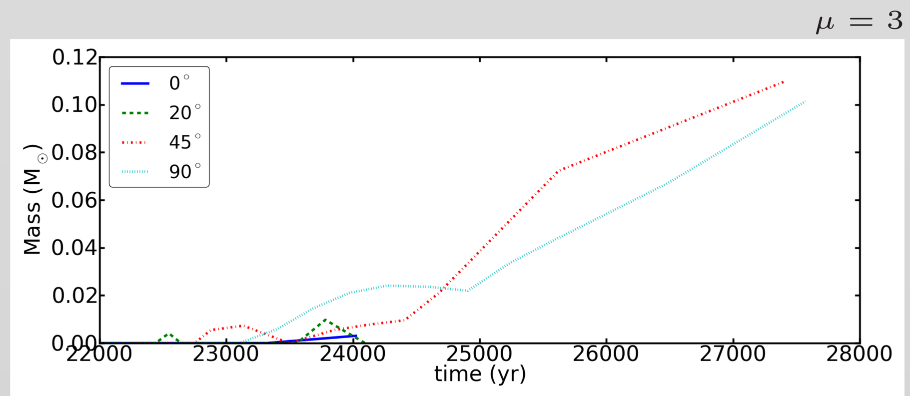
Disk formation

- Mass of the disk as a function of time: the more tilted the rotation axis, the more massive the disk

$\mu = 5$



$\mu = 3$



Conclusions

An original analytical analysis of a collapsing magnetic cloud shows that the magnetic field can remove angular momentum less efficiently when the rotation axis is perpendicular to the magnetic field than when they are both aligned.

Simulations of the collapse of pre-stellar dense core with different magnetization and in aligned and various misaligned configurations shows that the orientation of the rotation axis has a strong effect on the disk formation: it can be suppressed in the aligned configuration for relatively low magnetization (from $\mu \sim 5$), disks can form in misaligned configurations until $\mu \sim 3$. The magnetic transport of angular momentum is less efficient in misaligned configuration than in the aligned case, in agreement with our analytical analysis. Disks have a typical mass of about 0.1 to 0.3 $M_\odot$ and a typical radius of about 200 to 400 AU.

Our conclusions are sensitive to the criterion we use to define disks. We concluded that a simple rotation criteria is not sufficient; a disk is defined as follow: it is supersonic, rotationally supported and near the hydrostatic equilibrium.

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