Spin down of protostars through gravitational disk torques

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Introduction

The specific angular momentum of molecular clouds exceed that of observed stars by orders of magnitude. There may exist conditions where magnetic fields are unavailable to remove the excess angular momentum, such as dense environments or the first stars. In this case, it is important to re-examine hydrodynamic processes in star-disk systems. We explore whether or not star-disk gravitational interactions can decrease stellar spin. We examine 3D hydrodynamic simulations of star-disk systems self-consistently formed by cloud collapse.

Collapse Calculations

We consider the evolution of a self-gravitating, inviscid and non-magnetic fluid. The basic equations are the usual Euler equations supplemented by Poisson's equation for self-gravity. The pressure P is calculated from the density ρ via a barotropic equation of state

$$P = c^2\rho\left[1+(\rho/\rho_*)^{2/3}\right], \tag{1}$$

where c is the isothermal sound speed and ρ_* is a fixed transition density such that when $\rho \ll \rho_*$, $P \propto \rho$ (isothermal) and when $\rho \gg \rho_*$, $P \propto \rho^{5/3}$ (adiabatic). This prescription mimics star formation by halting gravitational collapse when density is high. Simulations are initialized with an isothermal sphere of radius r_c, within which the density is

$$\rho = \frac{Ac^2}{4\pi G r^2}, \tag{2}$$

where r is the spherical radius. The dimensionless parameter A relates to a dimensionless accretion rate ξ describing collapse [1]. The region $r \le r_* \equiv qr_c$ is designated as the initial star, where q is a dimensionless parameter. This sets $\rho_* = \rho(r_*)$. The initial azimuthal velocity is

$$v_\phi = 0.2Ac \times \begin{cases} R/r_* & R \le r_* \\ 1 & R > r_*, \end{cases} \tag{3}$$

where R is the cylindrical radius. Other velocity components are zero. We use the Godunov-type ORION code with adaptive mesh refinement to evolve the system in Cartesian co-ordinates. The computational domain is a cube of length $L = 4r_c$. We use a base grid of 128^3 with 6 levels of refinement, giving the highest effective resolution of 8192^3. Given a grid spacing δx, the maximum resolvable density is $\rho_J \equiv \left(\frac{cN_J}{\delta x}\sqrt{\frac{\pi}{G}}\right)^2$ where $1/N_J$ is the number of grids per Jeans length. We use $N_J = 0.125$ and refine if $\rho > \rho_J$. The star is typically resolved by 20 cells in linear dimension.

Self-limited spin-up

We present results from two cases. Case 1 has parameters $A = 4.0$, $q = 0.005$. Fig. 1 summarizes Case 1's early evolution. The star's spin angular momentum, $j_{\rm spin}$, and its rotation rate scaled by break-up speed, $\Omega_{\rm spin}/\Omega_{\rm break}$ first increases to a maximum at $t = 43$kyr, until which the star is highly deformed but no spiral arms are present. After $t = 43$kyr, $\Omega_{\rm spin}/\Omega_{\rm break}$ oscillates with decreasing amplitude and by $t = 70$kyr the star spins just below half its break-up speed. The evolution of kinetic-to-gravitational energy ratio, $T/|W|$, evolves similarly to $\Omega_{\rm spin}/\Omega_{\rm break}$. During $43{\rm kyr} < t < 50$kyr, $j_{\rm spin}$ remains approximately constant and spiral arms develop in the disk ($t = 47$kyr). For $t = 52{\rm kyr} < t < 67$kyr spiral arms are always present , $j_{\rm spin}$ is decreasing and the star exerts a positive torque on the disc. It must then lose spin angular momentum. **The initial spin-up is limited by the increasing spin-down torques from the disk as the star deforms into a bar-like shape.** Notice that most of the stellar angular momentum is in its spin rather than orbital motion ($j_{\rm orb}$).

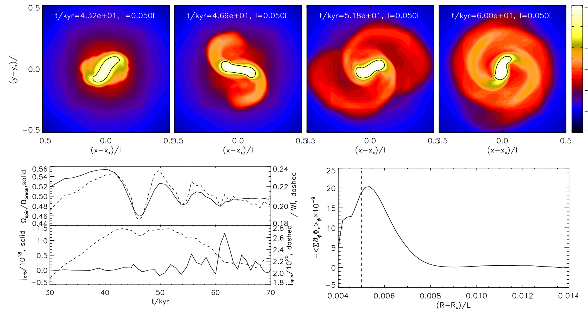

Fig. 1. *Case 1 early evolution. Top: midplane* $\log\rho$. *Bottom left: evolution of stellar spin, kinetic-to-gravitational energy ratio and angular momenta. Bottom right: star-on-disc torque at* $t = 60$*kyr with the dashed line corresponding to average stellar radius.*

Disk modes and spin evolution

The evolution of stellar spin correlates with non-axisymmetric modes in the disk. Fig. 2 compare the long term behaviour of Case 1's spin, angular momenta and disk modes. $\Omega_{\rm spin}/\Omega_{\rm break}$ and $j_{\rm spin}$ remain approximately constant relative to the initial phase. These curves are non-smooth and show episodes of spin-up. Although spin evolution is limited, there are large variations in orbital angular momentum. Between $70{\rm kyr} \le t \le 130$kyr, $j_{\rm orb}$ increases from essentially zero to values comparable to $j_{\rm spin}$.

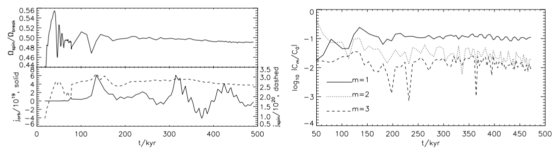

Fig. 2. *Case 1 long term evolution of stellar spin and angular momenta (left) and disk modes (right).*

Notice at $t = 70$kyr, when the early phase spin-down phase stops, is also when the $m = 1$ mode over-takes $m = 2$, shown in Fig. 2. For $t \ge 140$kyr the disk is dominated by an lopsided $m = 1$ disturbance (Fig. 3). This leads the star to execute complicated orbital motions with displacement from the box center comparable to its size ($\sim 0.003L$), but much smaller than the disk radius. **Dominance of the** $m = 1$ **disk mode inhibits spin evolution.**

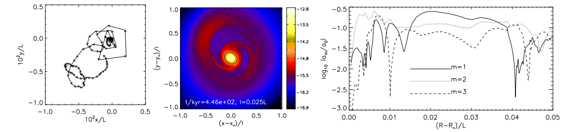

Fig. 3. *Case 1 stellar motion (left), midplane* $\log\rho$ *(middle) and its Fourier transform (right).*

Case 2 is a less massive core, but we consider a larger star. It has physical parameters $A = 2.8$, $q = 0.01$. The phase $t \le 350$kyr is similar to the self-limiting phase in Case 1. However, afterwards Case 2 displays a monotonic decrease in $\Omega_{\rm spin}/\Omega_{\rm break}$ and $j_{\rm spin}$. In Case 2 $|j_{\rm orb}|$ is two orders of magnitude smaller than $|j_{\rm spin}|$ so there is negligible orbital motion of the star compared to its spin. The most important difference between Case 1 and Case 2 is that $m = 2$ disk mode dominates the latter. The angular momentum flux out of the star, due to gravitational torques, corresponds to an α viscosity of ~ 0.2 and dominates over Reynolds stresses. **The gradual spin-down is attributed to the** $m = 2$ **disk mode.**

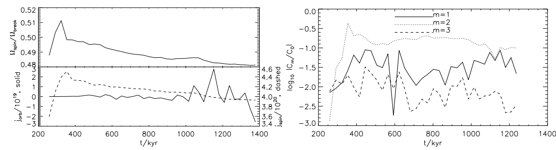

Fig. 4. *Case 2 evolution of stellar spin and angular momenta (left) and disk modes (right).*

Implications

Gravitational torques exerted on the star by its protostellar disk has important effects on stellar spin. It limits the initial spin up due to accretion of material. It may also spin down the star on longer time-scales, but a necessary requirement is the non-dominance of $m = 1$ **in the disk, otherwise the star-disk angular momentum exchange mainly results in the star's orbital evolution instead of spin evolution.**

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References

1. Kratter, K.M., Matzner, C.D., Krumholz, M.R. and Klein, R.I. 2010, *ApJ*, 708, 1585.