SPIN EVOLUTION AND OPENING OF THE FIELD LINES IN YOUNG STARS.

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ABSTRACT

The usual explanation for the low rotation rates ($v_{eq} < 10$km/s) observed in young low mass stars is based on *disk locking* theory whereby angular momentum is transferred from the star to a surrounding accretion disk. However, recent considerations suggest that the magnetic interaction is indeed, not enough for the braking required by observations. If the star and disk are assumed as perfect conductors, high values of differential rotation between star and disk lead to a progressive inflation and eventually opening of the poloidal component of the magnetic field. In order to quantify the effect of the opening on the stellar rotation rate, we construct a parametrized, time-dependent model for spin evolution of a young solar type star including the effect of the opening through the β parameter and in the aproximation in which the magnetic diffusivity is of the order of magnitude of the disk's effective viscocity. Solutions of this model were compared with those obtained with a classical model without opening (CC93). Results confirm that the spin-down torque is less efficient than predicted by the classical disk locking scenario. We therefore conclude that another loss angular momentum mechanism must be active during the first stages of the stellar formation, possibly through a stellar wind along the open field lines.

1. Description of the Model

The stellar interior is described by a polytrope with index $n = 1.5$ and the surrounding magnetosphere by a conventional stellar dipole model. The structure of the disk is given by a standard α disk (SS73) with the magnetic diffusivity comparable to the turbulent α viscocity. According to the usual assumptions, we use cylindrical coordinates (R, ϕ, z) centered in the star and aligned with the angular momentum of the star and disk which have the same orientation. Stellar magnetic field B_* is taken as dipolar, aligned with the z axis, corotating with the star and slipping azimutally at a speed v_d relative to the gasdisk. For $v_d \rightarrow 0$ gasdisk is strongly coupled to the stellar magnetic field and because of differential rotation, at some radius (R_{out}) the poloidal component of the stellar magnetic field can be desconnected from the star. We will refer this case $v_d \rightarrow 0$ as **opening** meaning that the size of the magnetic connected region within the disk reaches a minimum. For the case $v_d \rightarrow 1$, R_{out} is a maximum. The disk is permeated entirely by the field. We will refer this case as (not opening). The magnetic torque, is strongly dependent on the twist ($\gamma \equiv B_\phi / B_z$) of the poloidal field:

$$N_o = \int_{R_T}^{R_{out}} \gamma \frac{\mu^2}{R^4} dR \qquad (1)$$

where $\mu = (B_* R_*)^3$. The strength of the field is assumed strong enough in order to truncate the disk at some inner location $R_T < R_{out}$ from gasdisk is channelled along magnetic-field lines as it accretes onto star. Regardless of any disk model or any magnetic coupling physics, the largest possible magnetic torque occurs when the maximal twisted is reached (i.e. $\gamma = \gamma_c$). Solving the integral in (1) a parametrized expression for the magnetic torque is obtained (MP05):

$$N_o = \frac{1}{3\beta} \frac{\mu^2}{R_{co}^3} [2(1+\beta\gamma_c)^{-1} - (1+\beta\gamma_c)^{-2} - 2(\frac{R_{co}}{R_T})^{3/2} + (\frac{R_{co}}{R_T})^3] \qquad (2)$$

We use the *diffusion parameter* $\beta \equiv v_d (v_k \gamma)^{-1}$ which parametrizes the coupling of the stellar magnetic field to a inner portion of the disk such that for a fixed γ, $\beta \gg 1$ corresponds to $v_d \rightarrow 0$ (opening) and $\beta \ll 1$ to $v_d \rightarrow 1$ (not opening). The β parameter is the scale factor that compares the slipping speed of the field relative to disk to the keplerian disk speed (MP05).

3. Stellar Spin Evolution

The conservation of the total angular momentum of the system (star plus disk) defines the spin evolution of the star through the equations (37), (38) and (39) of CC93. An additional source of nonlinearity comes from the dependece of the stellar magnetic field strength B_* on Ω_* and R_*. Unfortunately, the origin and evolution of B_* in very young stars is uncertain. Namely, it can be produced either by turbulence inside the fully convective star or due to a *fossil* field trapped inside the star during the collapse of the molecular cloud (Yi 1994). We consider a *fossil* origin with a value at the birth line: $B_*(0) = B_0 \Omega_*(0) R_*^{-2}(0)$ where B_0 is a free parameter. We also assume as in CC93 that accretion rate decays exponentially over a timescale τ_a and with an initial value given by the disk mass M_D at birth line.

4. Numerical Results

In order to follow possible rotational stories dependent on the parameters: B_0, M_D and β, we integrated numerically the three evolution equations: the **exponential decay** for $\dot{M}$ (with $\tau_a = 10^6$yr) together with equations (37) and (39) of CC93, for a cool M star ($T_e = 3500K$) from the birth line up to the end of the Hayashi track ($t \leq 3 \times 10^6$yr). Integrations were made separately for $\beta = 1.0$ (not opening) and for $\beta\gamma_c = 0.001$ (opening), using a fourth-order Runge-Kutta scheme of Press et al. (1994). The initial values at birth line ~30000yr for one solar mass star were fixed at $\Omega_*(0) = 3\Omega_\odot$, $M_*(0) = 1 - M_D$ and $R_*(0) = 6R_\odot$. We assume $\gamma_c = 1.0$ in all simulations. Two values for B_0 were used in order to check the response of rotation to high ($B_0 = 800$G) and moderate ($B_0 = 80$G) magnetic field regimes. For a fixed $\beta\gamma_c$ value, three cases were considered: A1: high B_0 with moderate M_D, A2: moderate B_0 with moderate M_D and A3 moderate B_0 with high M_D as

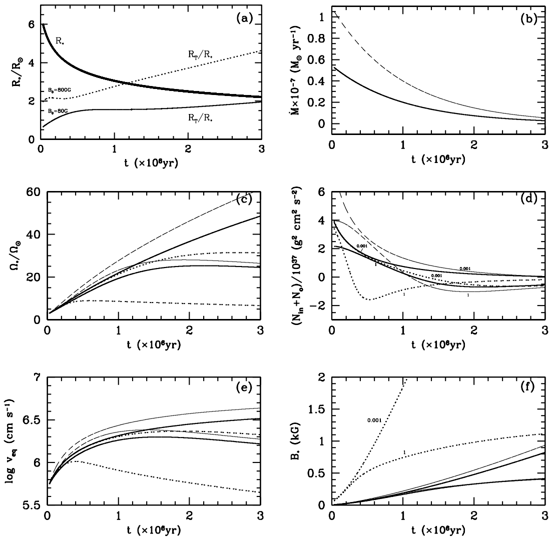

Figure 1: Rotational evolution for a solar type star during the Hayashi track ($t \leq 3\times10^6$yr). At each panel, solutions for the cases A1 (dotted lines), A2 (solid lines) and A3 (dashed lines) are indicated. Initial angular velocity was fixed at $\Omega_*(0) = 3\Omega_\odot$, $R_*(0) = 6R_\odot$ and $M_*/M_\odot(0) = 1 - M_D(0)$ (where M_D is the mass of the disk) in all cases.

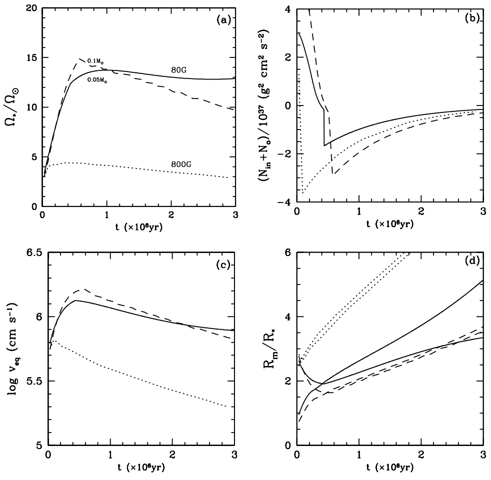

Figure 2: Rotation with time for a set of simulations according with the classical dipole model CC93. Computations were made for the particular case in which the magnetic diffusivity within the disk is due mainly to turbulence and for the cases A1, A2 and A3. IC identical to those used in figure 1.

indicated in table 1. In all cases, at each timestep a value for R_T was calculated using a Newton-Raphson method to solve numerically equation (15) of MP05. This value was then used to compute the net torque $N_{in} + N_o$ (N_{in} is the accretion torque) and then the corresponding values for Ω_* and v_{eq}.

Run	B_0	$\frac{M_D}{M_\odot}(0)$	$\beta\gamma_c$
A1	800	0.05	0.001 and 1
A2	80	0.05	0.001 and 1
A3	80	0.1	0.001 and 1

Table 1: Parameters adopted for the calculations.

In figure 1. The variation of the stellar radius with time is showed in panel (a), in this panel also appears the evolution of the truncation radius R_T (normalized to the radius of the star) for moderate and high magnetic field strengths. The exponential decay of the accretion rate is shown in panel (b) for $M_D = 0.05$ and $0.1M_\odot$ (dashed line). Angular and equatorial velocities are shown in panels (c) and (e), respectively. In Panel (d) the total torque applied onto star is indicated. Small numbers represent the β values. Is clear from this panel that for large opening the torque onto the star is very weak to produce efficient braking. In panel (f) we present the evolution of the stellar magnetic field used in simulations A1, A2 and A3.

4. Discussion & Conclusion

The initial spin-up due to accretion takes place gradually during the beginning of the simulations corresponding to the case A2. Magnetic braking appears only after ~1.4 Myr only for models with $\beta = 0.001$. The magnetic field strength at this age is ~0.25kG. At the end of the Hayashi track, equatorial velocity is 16.2 kms^{-1} for β=1.0 and 31.6 kms^{-1} for $\beta = 0.001$. In A3 runs the high initial accretion rate of $1.05 \times 10^{-7}M_\odot \times yr^{-1}$ spins the models up over $t \sim 10^6$yr. The behavior of the solutions is similar to the case of $M_D = 0.1M_\odot$ except that the initial spin up is larger for high M_D. The rotational evolution of the star depends signigicantly on β. For $\beta = 0.001$, models are spun in the sense of v_{eq} never is lower than 10km/s. For $\beta = 1.0$ the rotational history of the star is similar to those predicted by CC93. However a K-S test shows big differences for low rotators. Another angular momentum loss mechanism must be active during the first evolution stages of young low mass stars. Is quit probable that it arise from magnetic stellar winds.

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