The role of magnetic fields in driving the angular momentum evolution of low-mass stars

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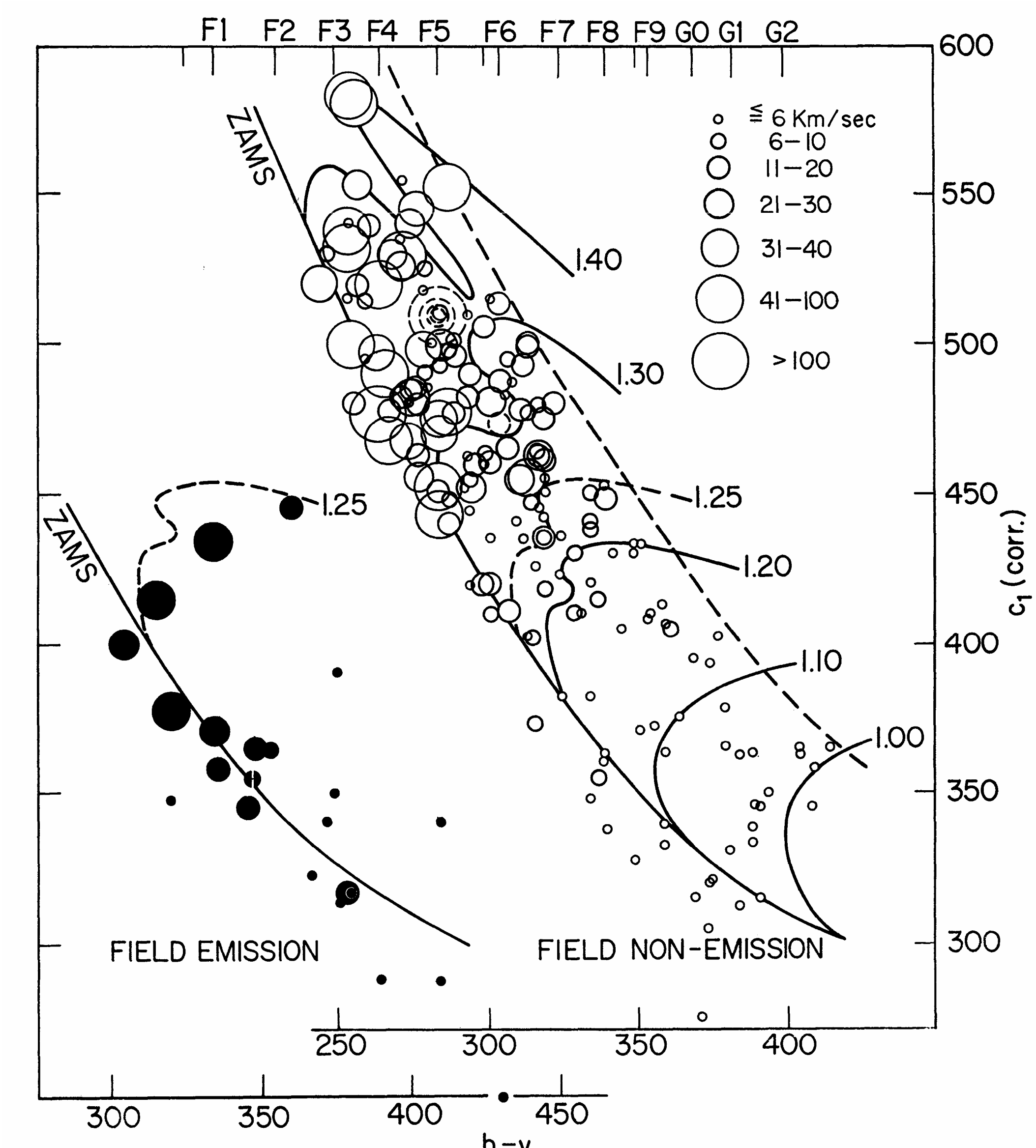
Outline

i. AM evolution on the main sequence
   magnetized stellar winds
ii. AM evolution during the pre-main sequence
   magnetic star-disk interaction
iii. Current models of PMS+MS angular momentum evolution

Angular momentum evolution on the main sequence

Magnetized stellar winds

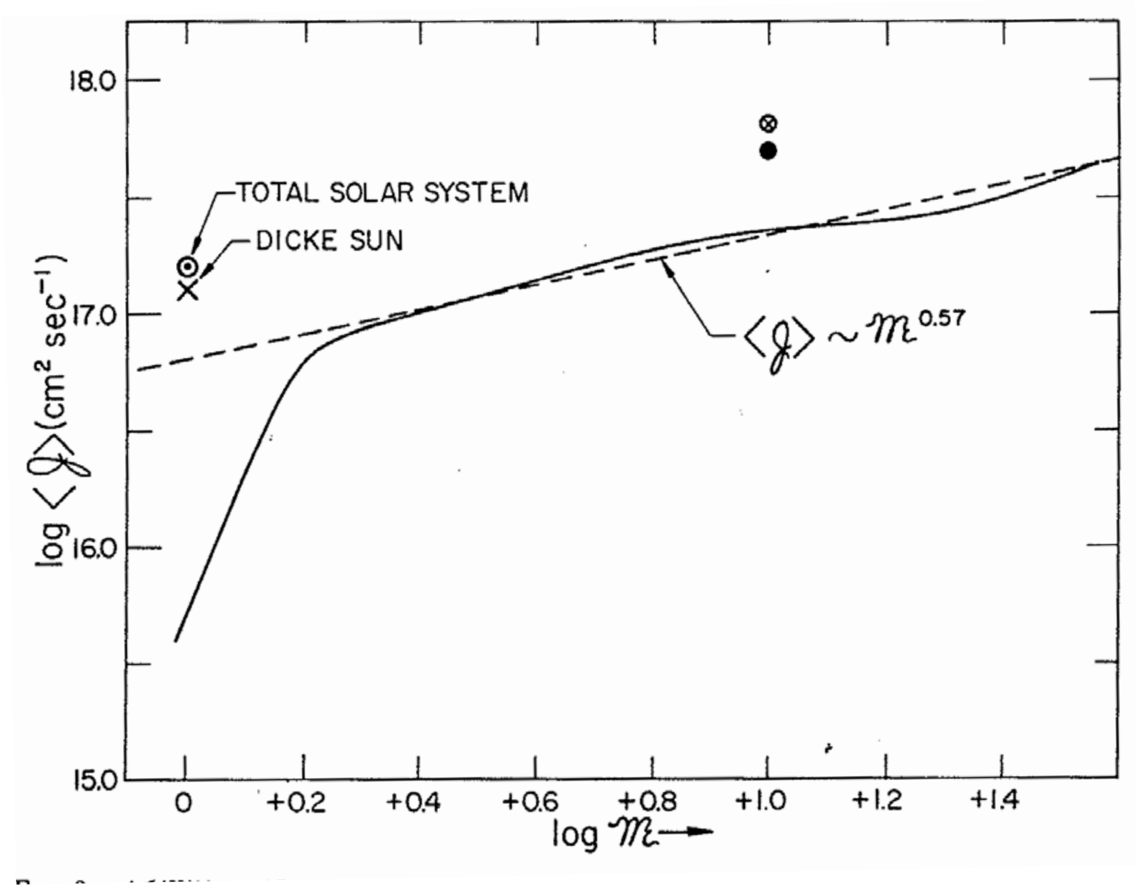
« Stellar rotation » (Kraft 1970)



- High mass stars (Sp.T.≤ F5) have large Vsini
- Low mass stars (Sp.T. > F5-G0) have small Vsini

Main sequence spin down ?

- Specific angular momentum J/M vs M suggests MS spin down for low mass stars



Kraft 1970

Rotational braking by magnetized winds (Schatzman 1962)

$J \approx M.\ R^2.\ \Omega \ \ -> \cancel{dJ/dt \approx dM/dt\ .\ R^2\ .\ \Omega}$

$dJ/dt \approx dM/dt\ .\ R^2.\ (R_A/R)^2\ .\ \Omega$

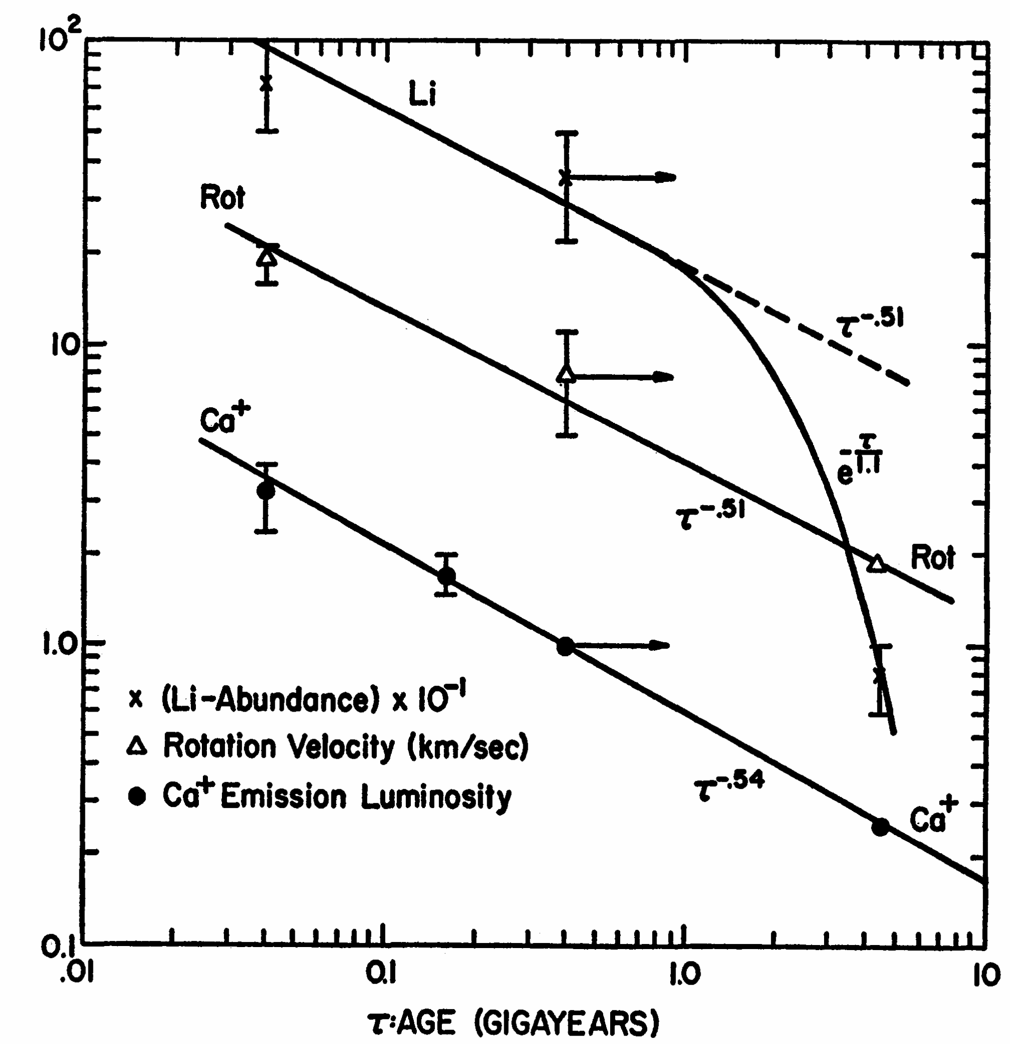
R_A : Alfven radius (magnetic field lever arm)

$(R_A/R)^2 \sim 10^3$ for the Sun -> spin down timescale $\sim 10^8$ yr

Only magnetically active convective stars are spun down

Timescale for rotational braking

Skumanich (1972)



Solar-type stars spin down on the main sequence as :

$$V_{rot} \propto t^{-1/2}$$

Angular momentum loss in low-mass stars (Kawaler 1988)

AM loss from magnetized wind + Dynamo-generated field

$$\frac{dJ}{dt} = \frac{2}{3}\frac{dM}{dt} R^2\Omega\left[\left(\frac{r_A}{R}\right)_{\mathrm{radial}}\right]^n \qquad B_0 = K_B\left(\frac{R}{R_\odot}\right)^{-2}\Omega^a$$

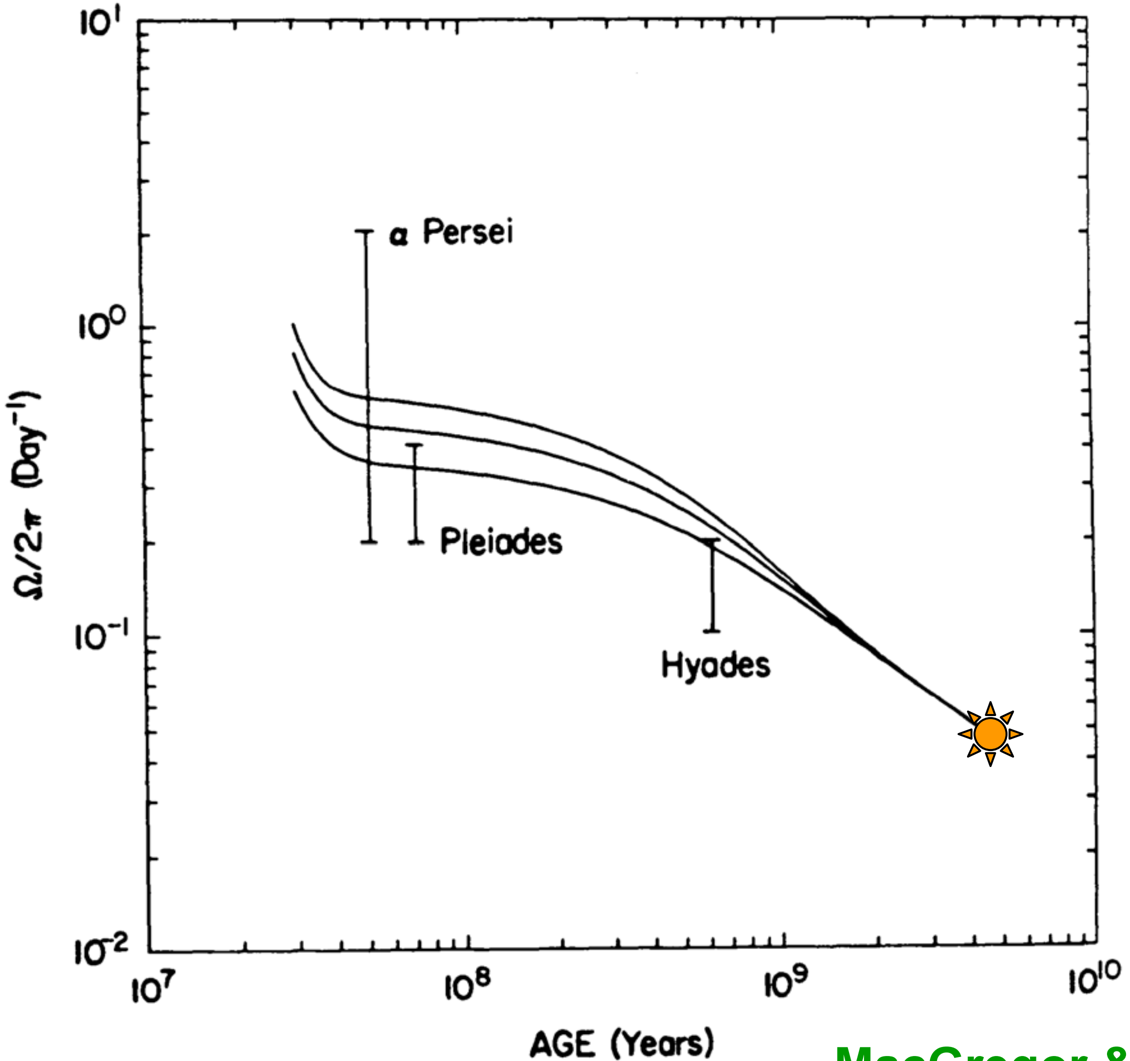
(n=2 radial, n=3/7 dipole)

$$\longrightarrow \quad v_{\mathbf{eq}} \propto t^{-3/4an}$$

For a=1 and n=1.5, yields : $V_{\mathrm{rot}} \propto t^{-1/2}$ (Skumanich)

(and $d\Omega/dt \propto \Omega^3$: larger spin down for faster rotators)

Main sequence spin down



Dynamo $\mathbf{B} \propto \mathbf{\Omega}$

$\mathbf{d\Omega/dt \propto \Omega^3}$

convergence towards slow rotation completed within a few 10^8 yr.

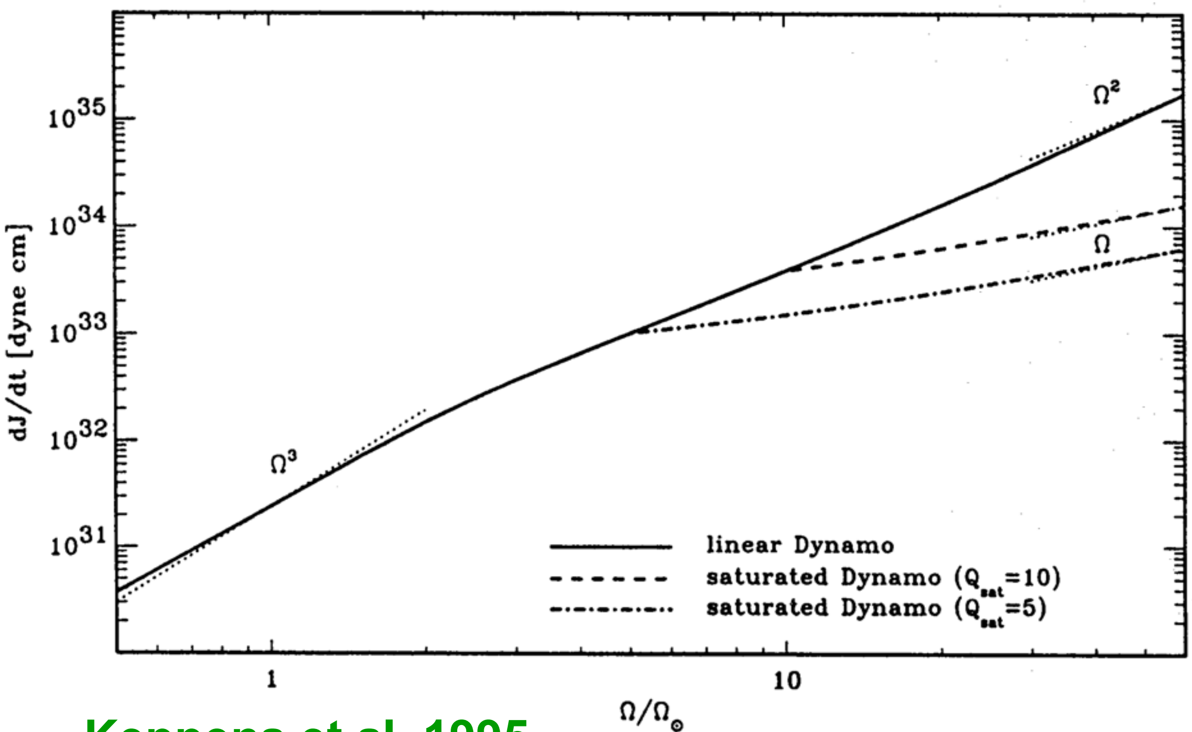
Solar-type stars lose memory of their initial rotation on MS timescales

(except perhaps in the core, but this is an other story…)

MacGregor & Brenner (1991)

A « saturated » dynamo ?

- **B** $\propto$ **Ω** at low rotation ($\Omega<\Omega_{sat}$) : **dJ/dt** $\propto$ **Ω^3**
- **B = cte** at high rotation ($\Omega>\Omega_{sat}$) : **dJ/dt** $\propto$ **Ω**



Keppens et al. 1995

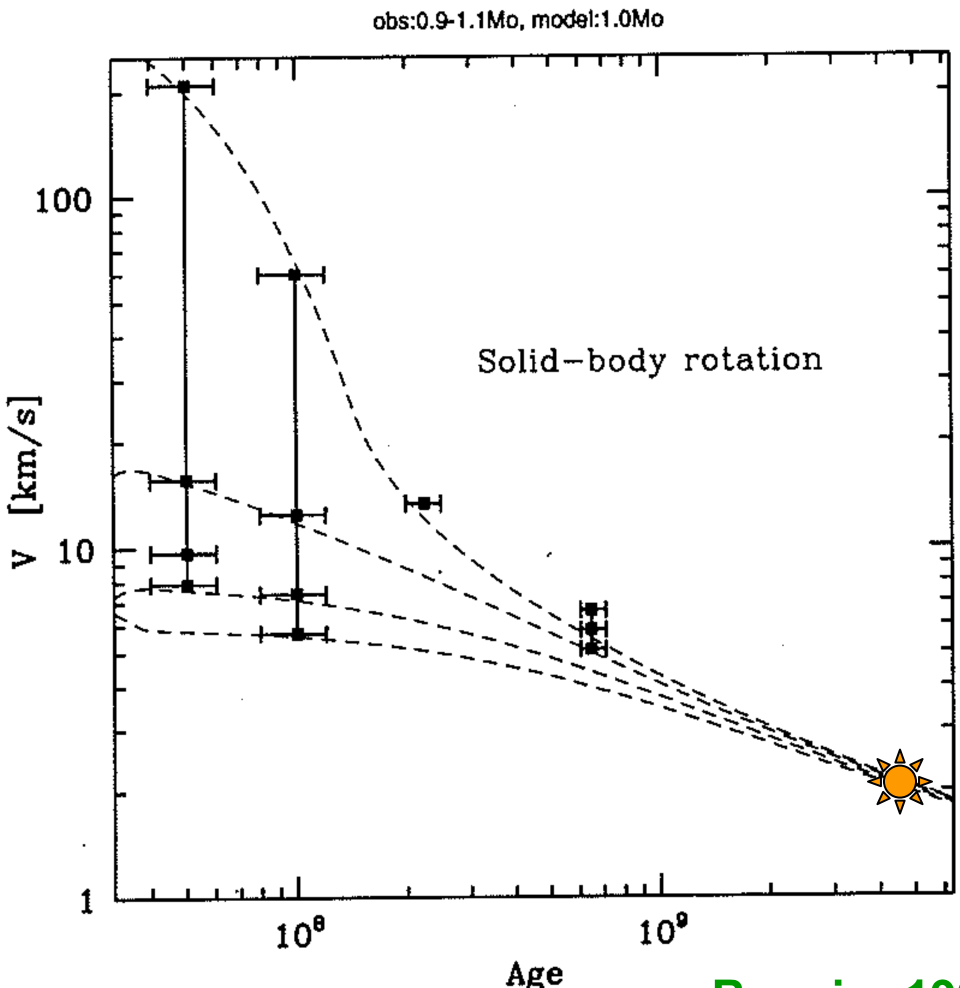
Empirically :

$\Omega_{sat} \propto (t_{conv})^{-1}$

i.e., $R_o \sim$ cte

(Rossby number)

Saturated AM losses on the main sequence



$$\frac{1}{\Omega}\frac{d\Omega}{dt} = \frac{1}{J}\left(\frac{dJ}{dt}\right)_w - \frac{1}{I}\frac{dI}{dt}$$

$$\left(\frac{dJ}{dt}\right)_w = -K\,\Omega^3 \left(\frac{R}{R_\odot}\right)^{1/2}\left(\frac{M}{M_\odot}\right)^{-1/2} \qquad (\Omega < \omega_{sat})$$

and

$$\left(\frac{dJ}{dt}\right)_w = -K\,\Omega\,\omega_{sat}^2 \left(\frac{R}{R_\odot}\right)^{1/2}\left(\frac{M}{M_\odot}\right)^{-1/2} \qquad (\Omega \geq \omega_{sat})$$

Bouvier 1997

AM evolution on the MS: A summary

- **Parametrized** AM loss laws saturating at high velocity provide a reasonable description of main sequence spin down
- Nearly 50 years after Schatzman's pioneering paper, there still is **no physical theory** of AM loss by magnetized winds for convective main sequence stars
- **Open issues :** wind models, magnetic topology, dynamo saturation, core-envelope decoupling

Angular momentum evolution during the pre-main sequence

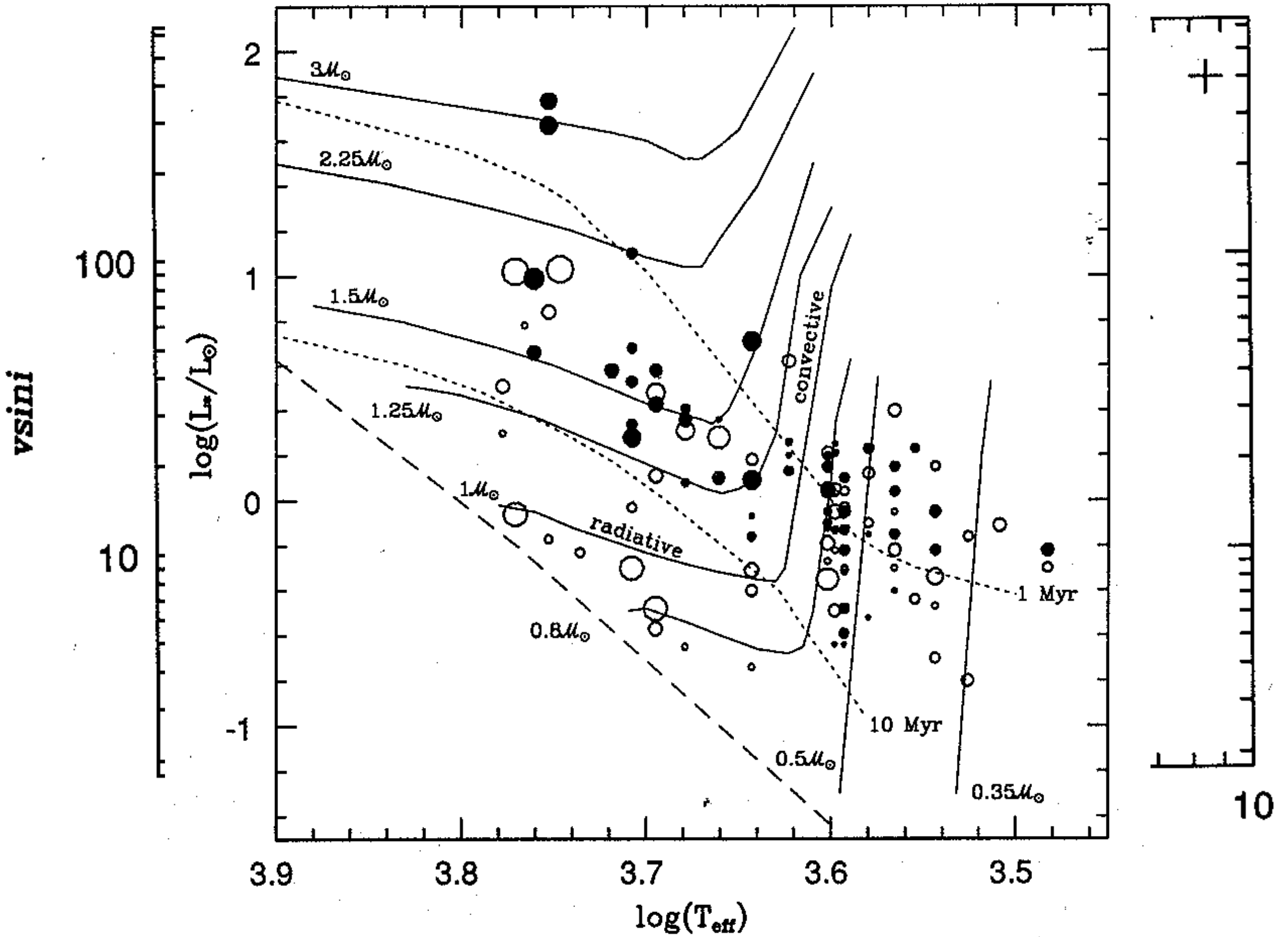
Star-disk magnetic interaction

Early expectations

- Extrapolation of the Skumanich relationship back to the PMS predicts @ 1 Myr:
  V_{rot} ~ 140 km/s
- In addition, accretion of high-AM material from the circumstellar disk is expected to spin up the star at V_{rot} ~ 120 km/s in ~10^6 yr !
- T Tauri stars are expected to be rapid rotators

Early observations…

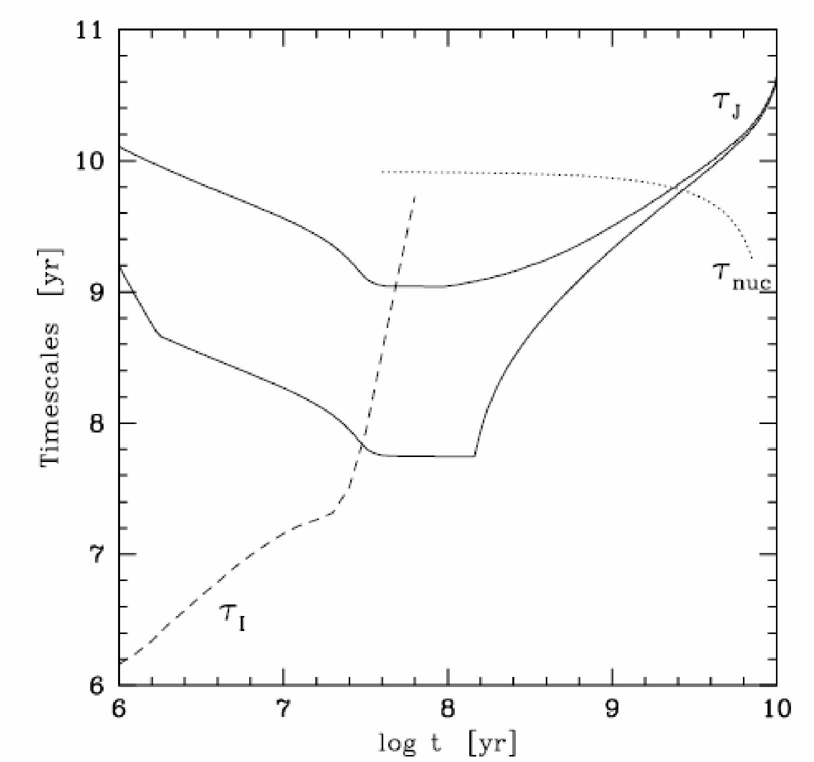
T Tauri stars are slow rotators V ~ 10-25 km/s



Bouvier 1990

Pre-MS wind braking ?

- Solar-type winds are unable to spin the PMS star down against contraction



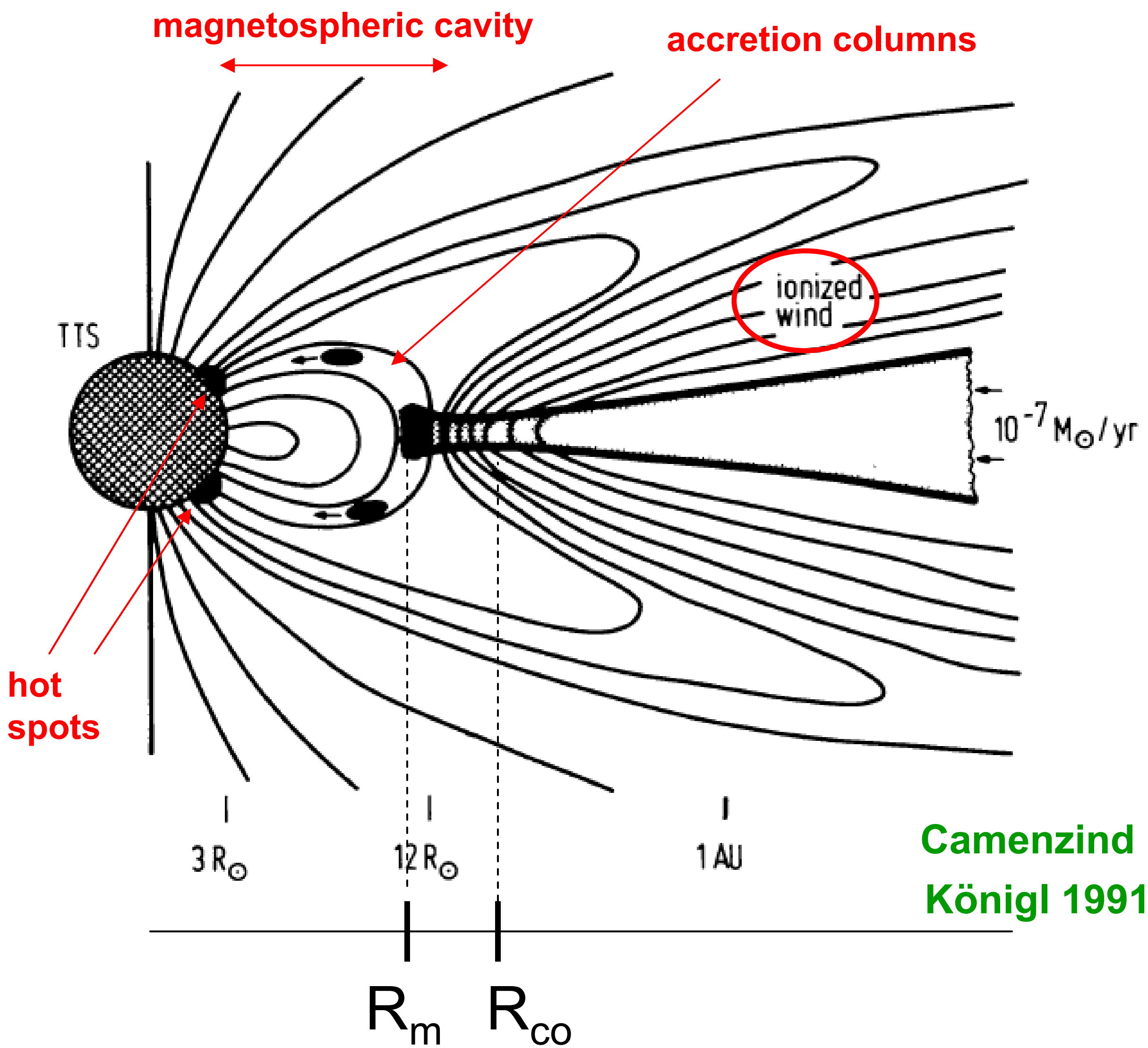
•Another PMS braking mechanism must be called for…

Bouvier et al. 1997

The disk-locking hypothesis

- Accreting TTS rotate on average slower than non-accreting TTS
- It seems that the braking process is related to the accretion process onto the star
- Direct disk accretion onto the star spins it up. However, **magnetically-mediated accretion** onto the star can brake it (cf. neutron stars, Gosh & Lamb 1979).

Magnetospheric accretion and disk locking in classical T Tauri stars

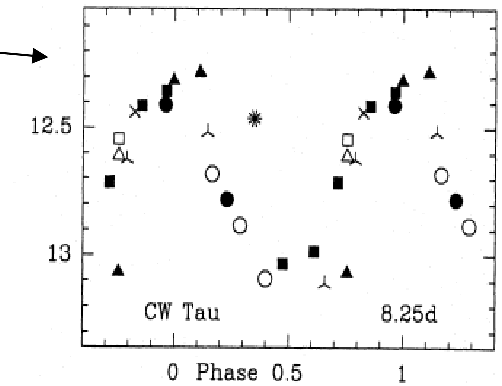


Camenzind 1990

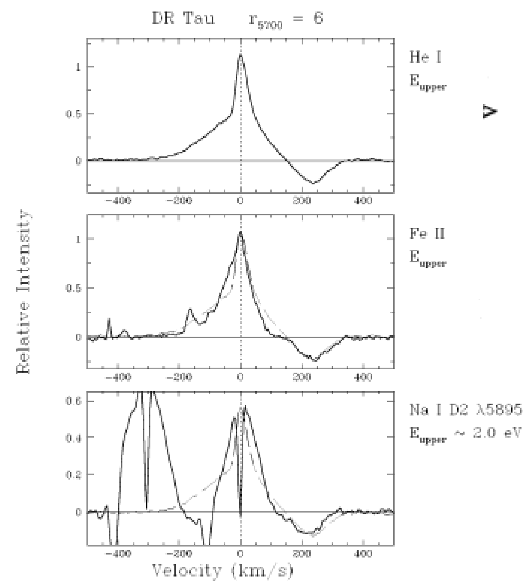
Königl 1991

Evidence for magnetospheric accretion

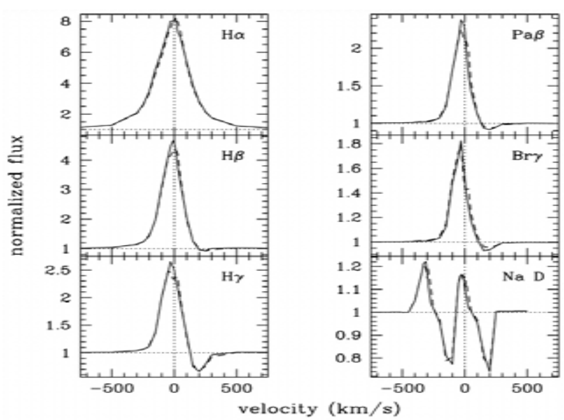
- Hot spots
  rotational modulation
- Accretion columns
  redshifted absorptions
- Magnetospheric cavity model line profiles



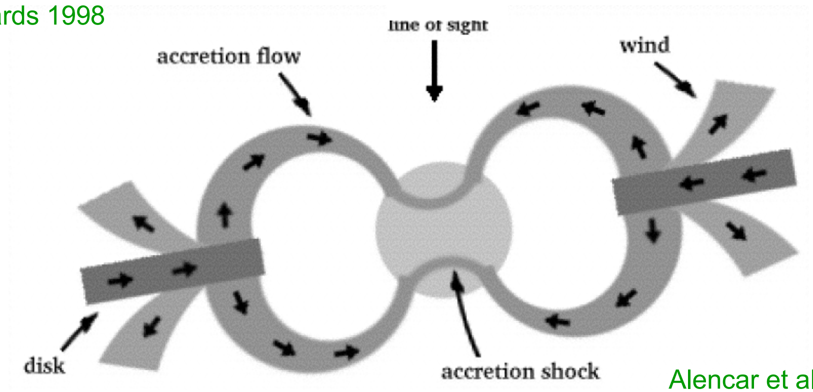
Bouvier et al. 1995



Edwards 1998



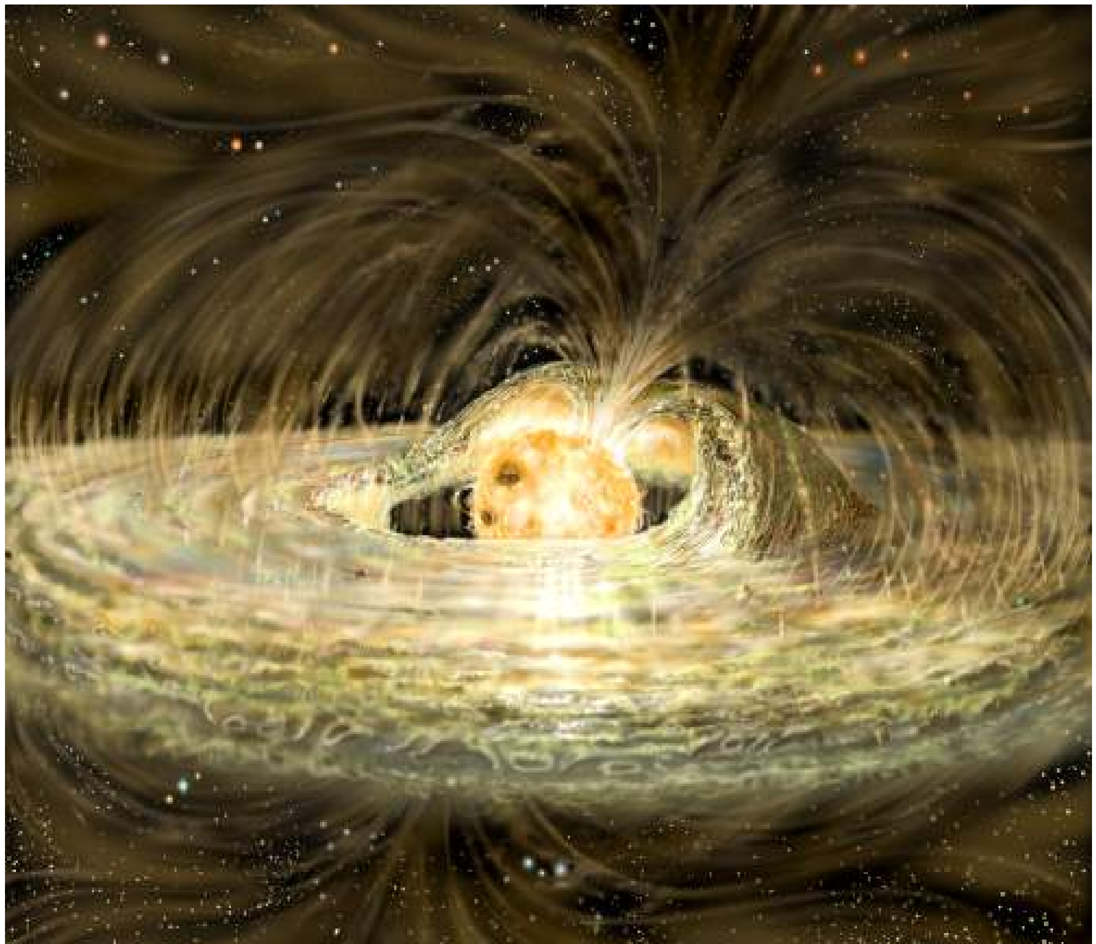
Muzerolle et al. 2001

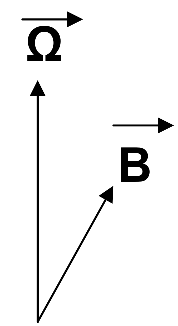


Alencar et al. 2001

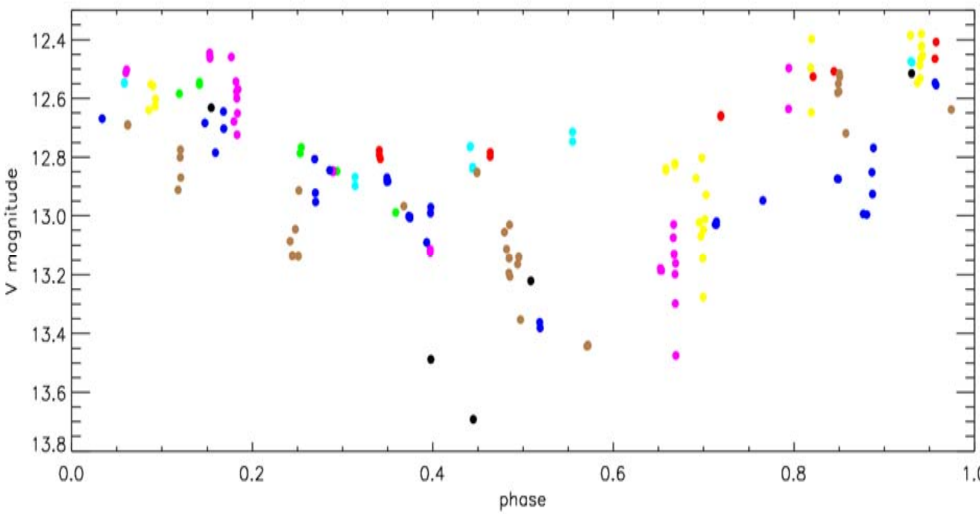
Accretion onto an inclined dipole

(An artist view)





Spectro-photometric synoptic studies : AA Tau

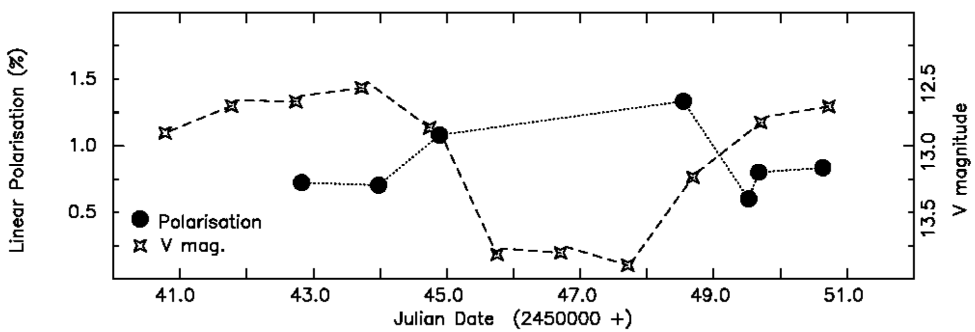


Bouvier et al. (2007)

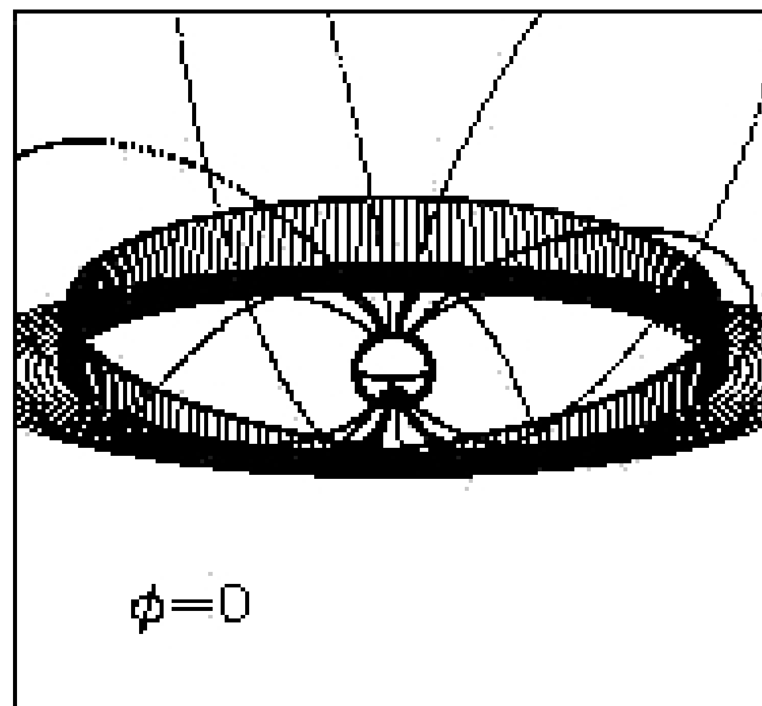
Light curve shows periodical (~ 8.2 days) eclipses of the photosphere.

The linear polarization increases as the system fades.

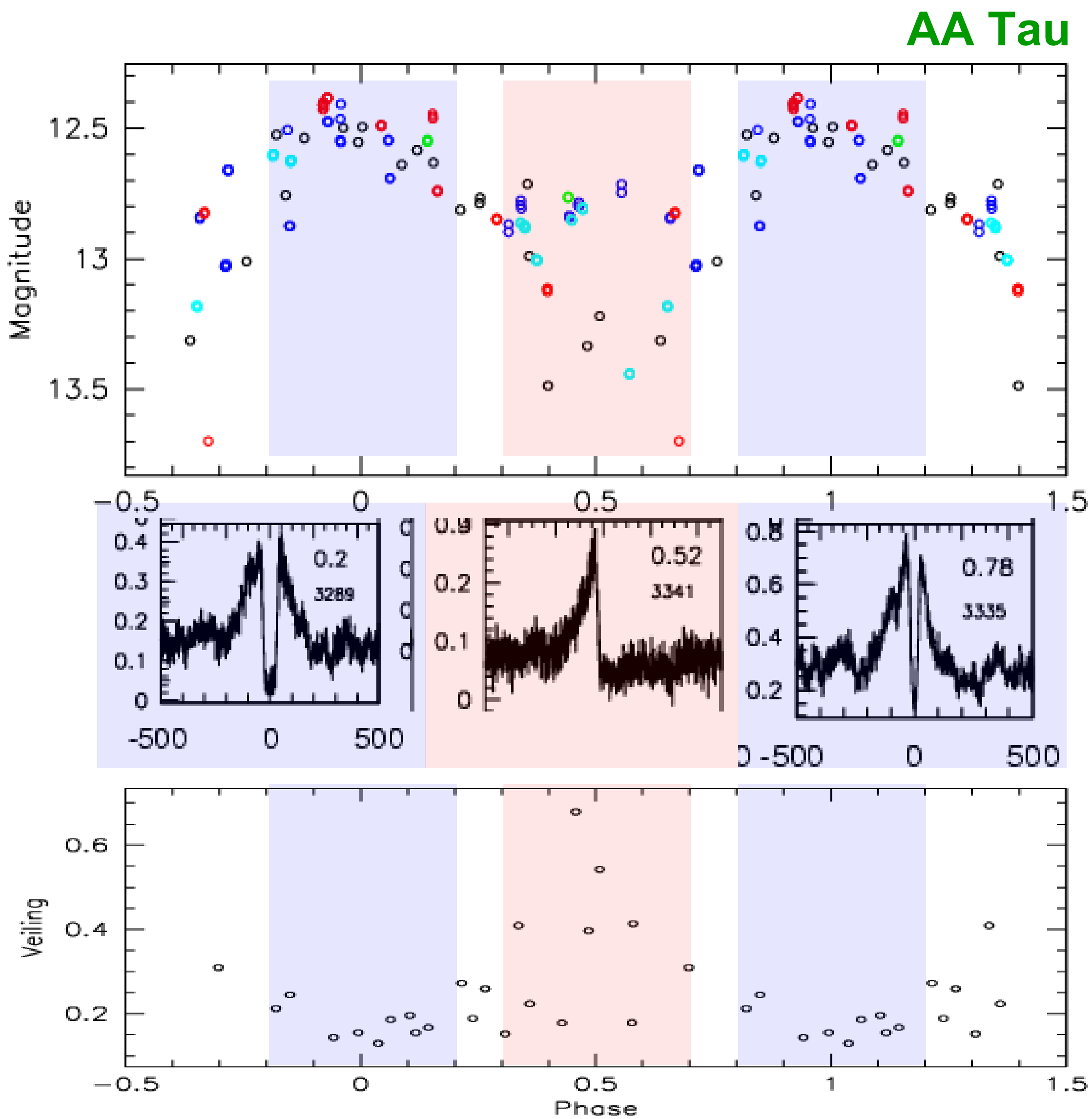
Periodical occultation of the photosphere by an optically thick, magnetically-warped inner disk region



Ménard et al. (2003)



Disk warp, accretion column, accretion shock : all spatially associated



Periodic eclipses

(disk warp)

(P=8.22d)

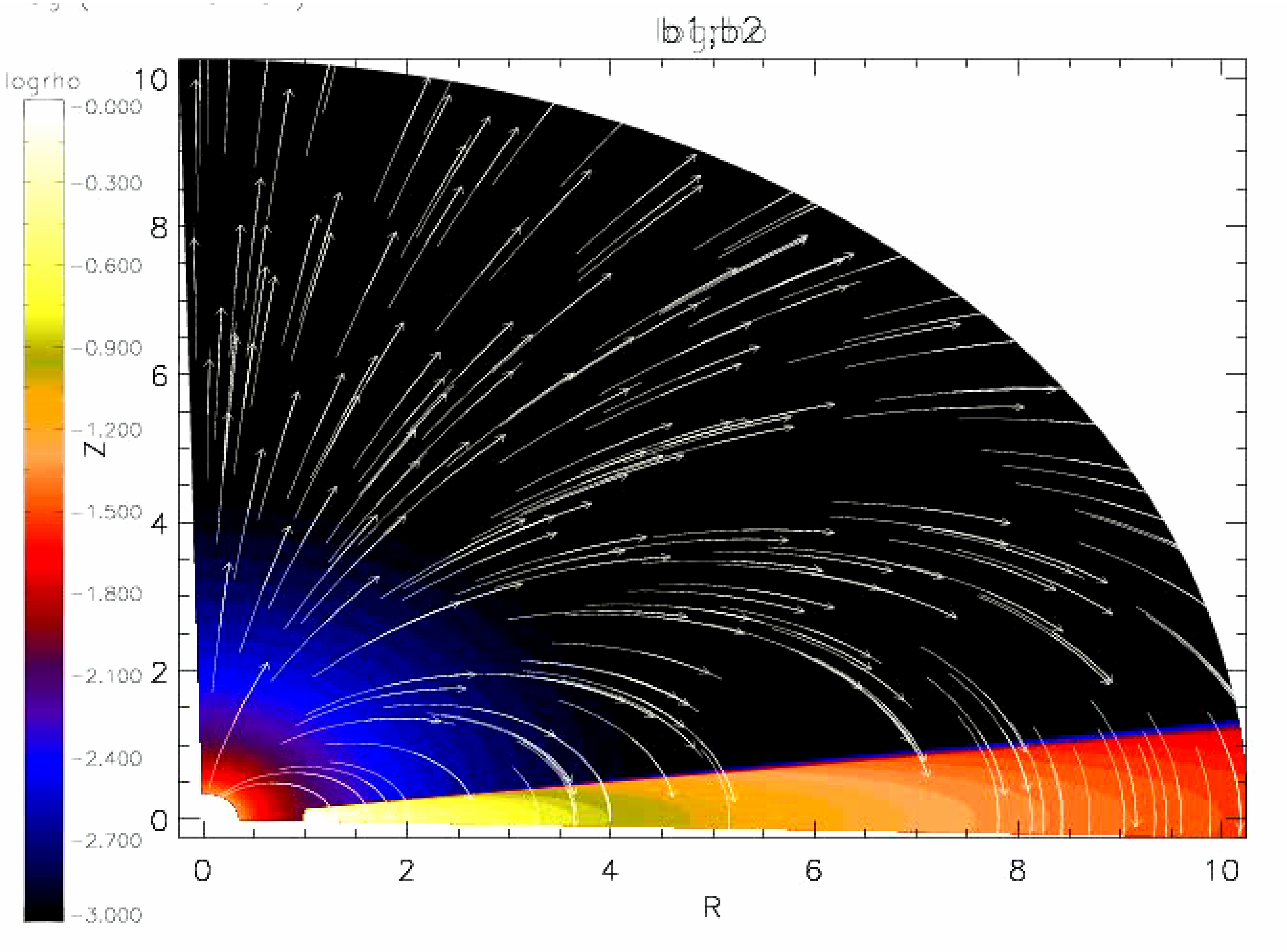
Balmer lines

(accretion funnel)

Veiling

(accretion shock)

2D MHD simulations



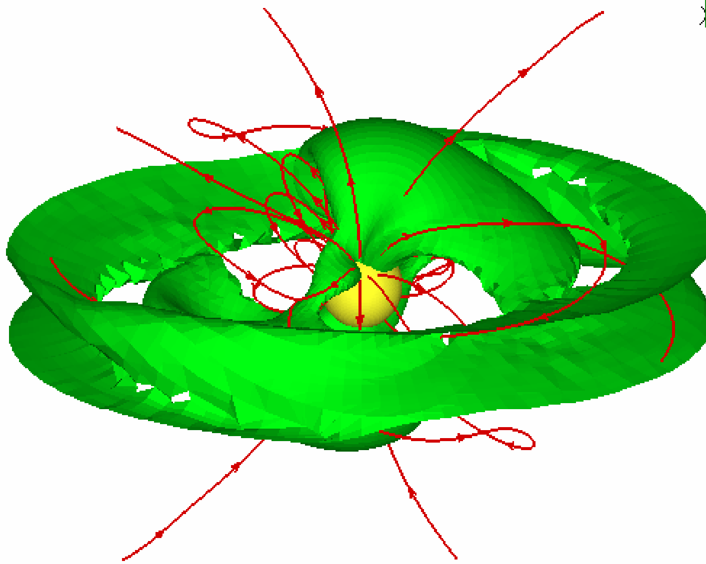
B=140G, M_{acc}=10^{-9}Mo/yr,
M=0.8Mo, R=2Ro, Prot=5d

Bessolaz, Zanni, Ferreira, Keppens, Bouvier 2007

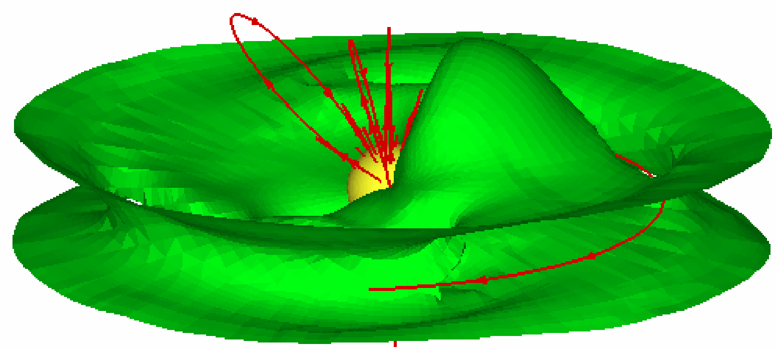
Inclined dipole : 3D simulations

Romanova et al. 2003

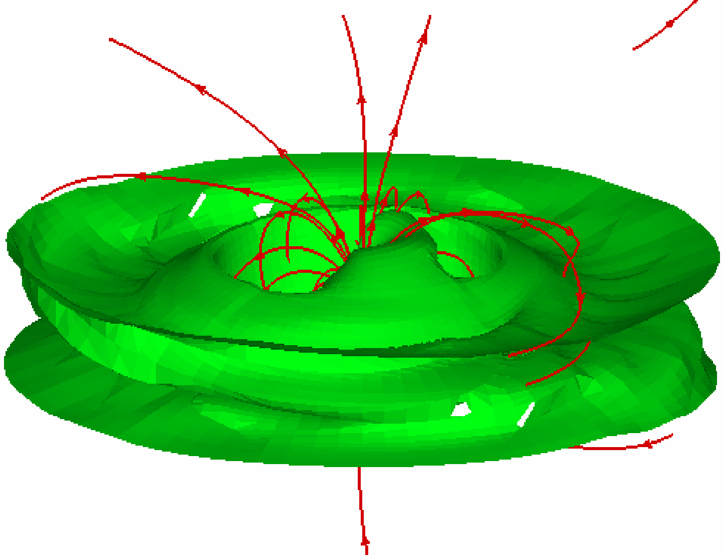
i^B=15



i^B=45

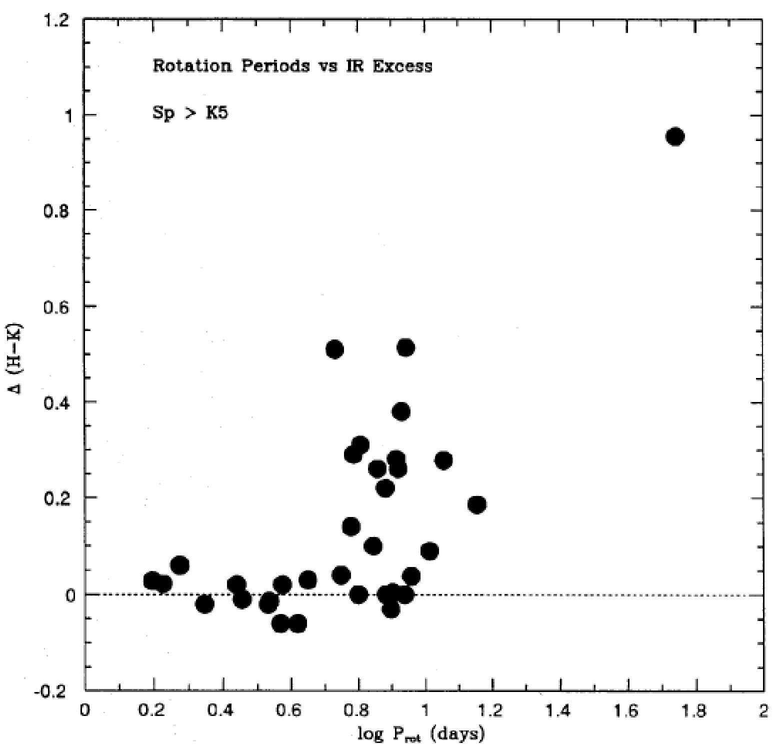


i^B=75

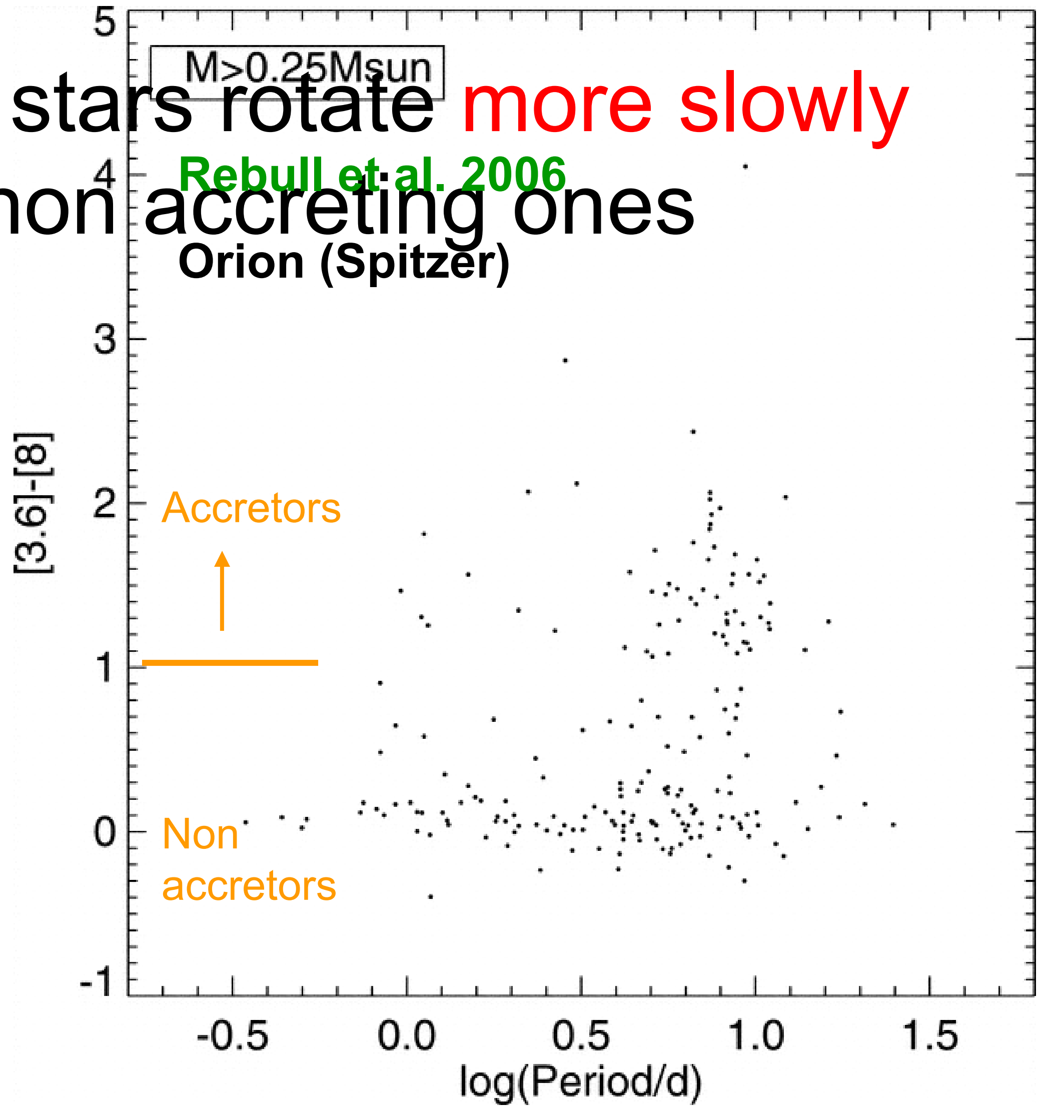


Evidence for disk locking from magnetospheric accretion

- Accreting T Tauri stars rotate more slowly on average than non accreting ones



Edwards et al. 1993



AM evolution during the PMS: A summary

- **Magnetospheric accretion leads to « disk locking »,** i.e., very efficient braking of accreting PMS stars
- Strong observational evidence for both magnetospheric accretion in CTTS and « disk locking »
- Alternative to Gosh & Lamb (1979) picture : accretion-driven stellar winds, reconnection X-winds, etc. (not settled yet)
- **Open issues :** MHD star-disk coupling models, magnetic topology and time variability (*cf. Donati's talk*)

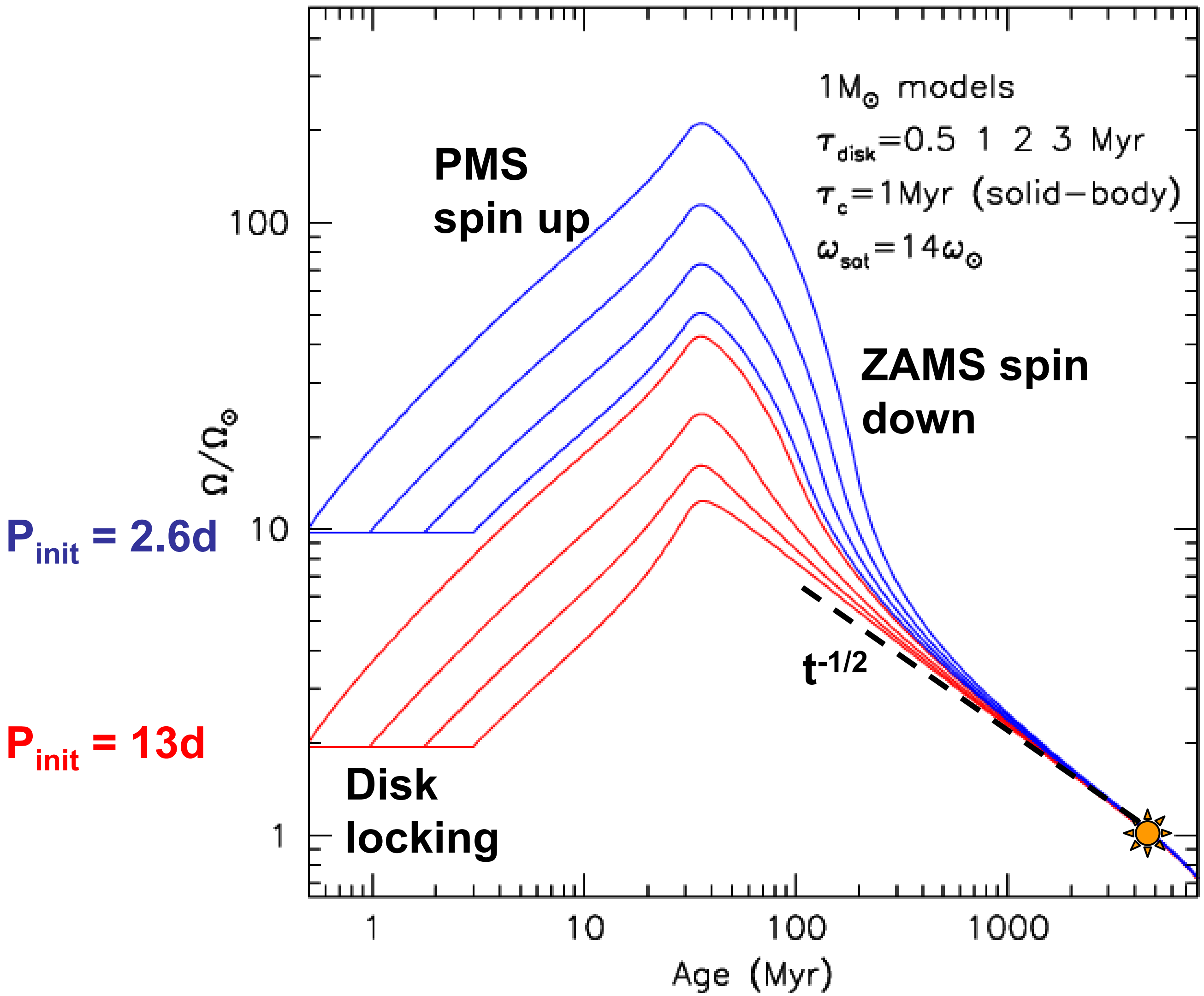
Models of PMS+MS angular momentum evolution

(and associated observational constraints)

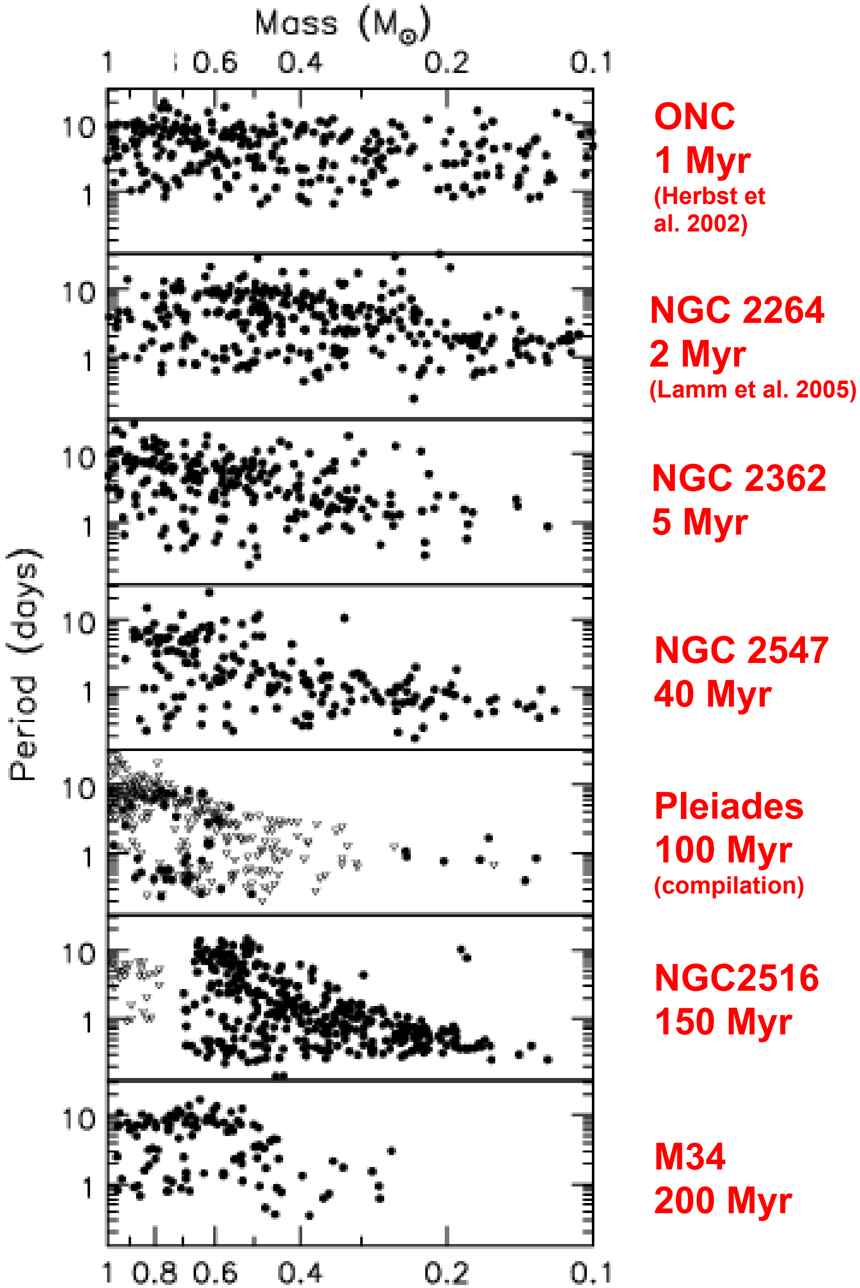
Model assumptions

1) Low mass stars are braked on the MS by magnetized winds (saturated AM-loss law)
2) Accreting PMS stars are disk locked at constant angular velocity (disk locking)
3) Non accreting PMS stars are free to spin up as they contract towards the ZAMS
4) The radiative core and convective envelope exchange AM on a timescale t_c (core-envelope decoupling)

Grids of AM evolution models



The Monitor Project

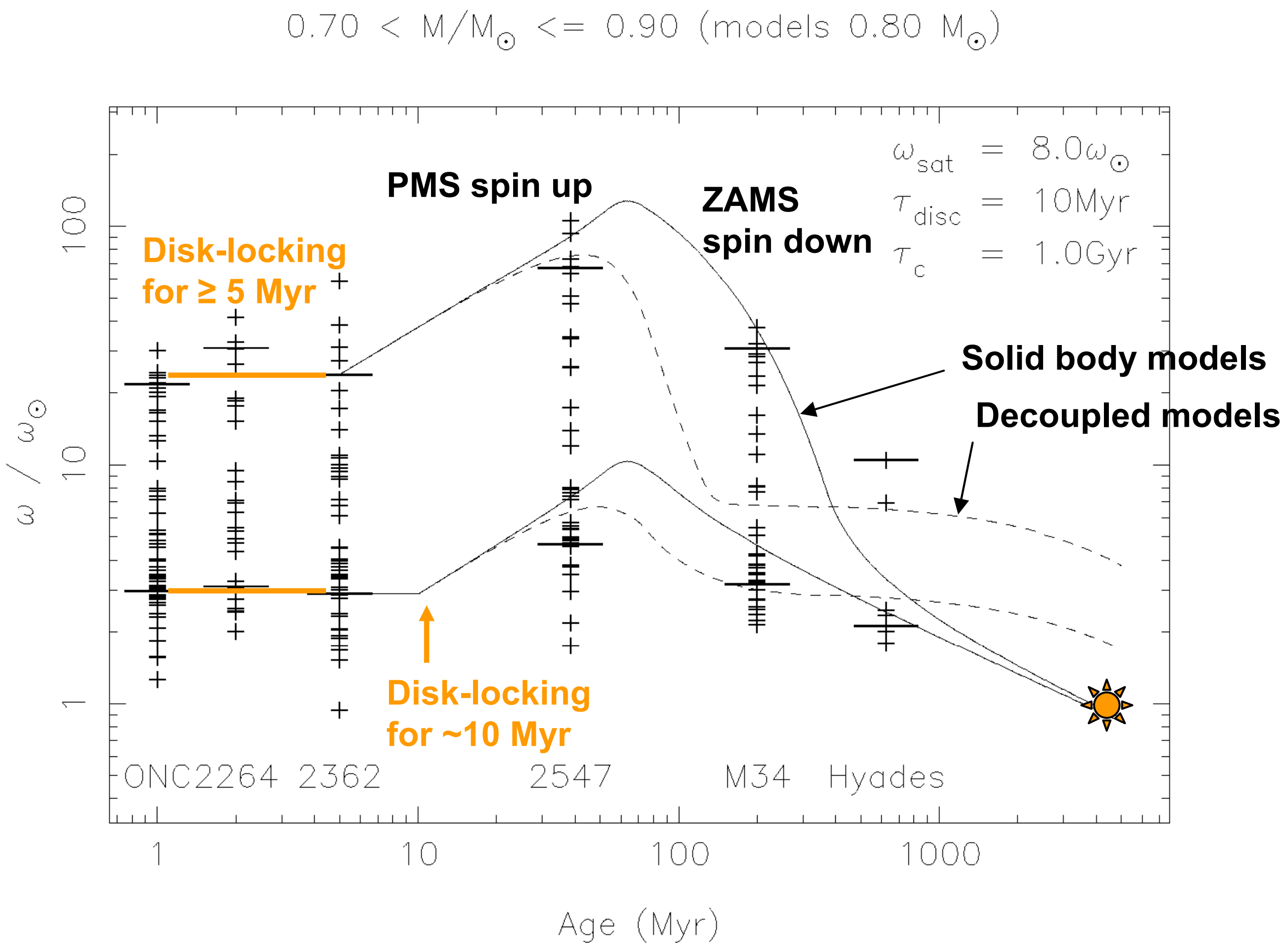


Irwin et al. 2006, 2007abc
Hodgkin et al. 2007
Aigrain et al. 2007

Rotation period measurements for hundreds of stars in the mass range 0.1-1.0Mo in PMS and ZAMS clusters over the age range 1-200 Myr

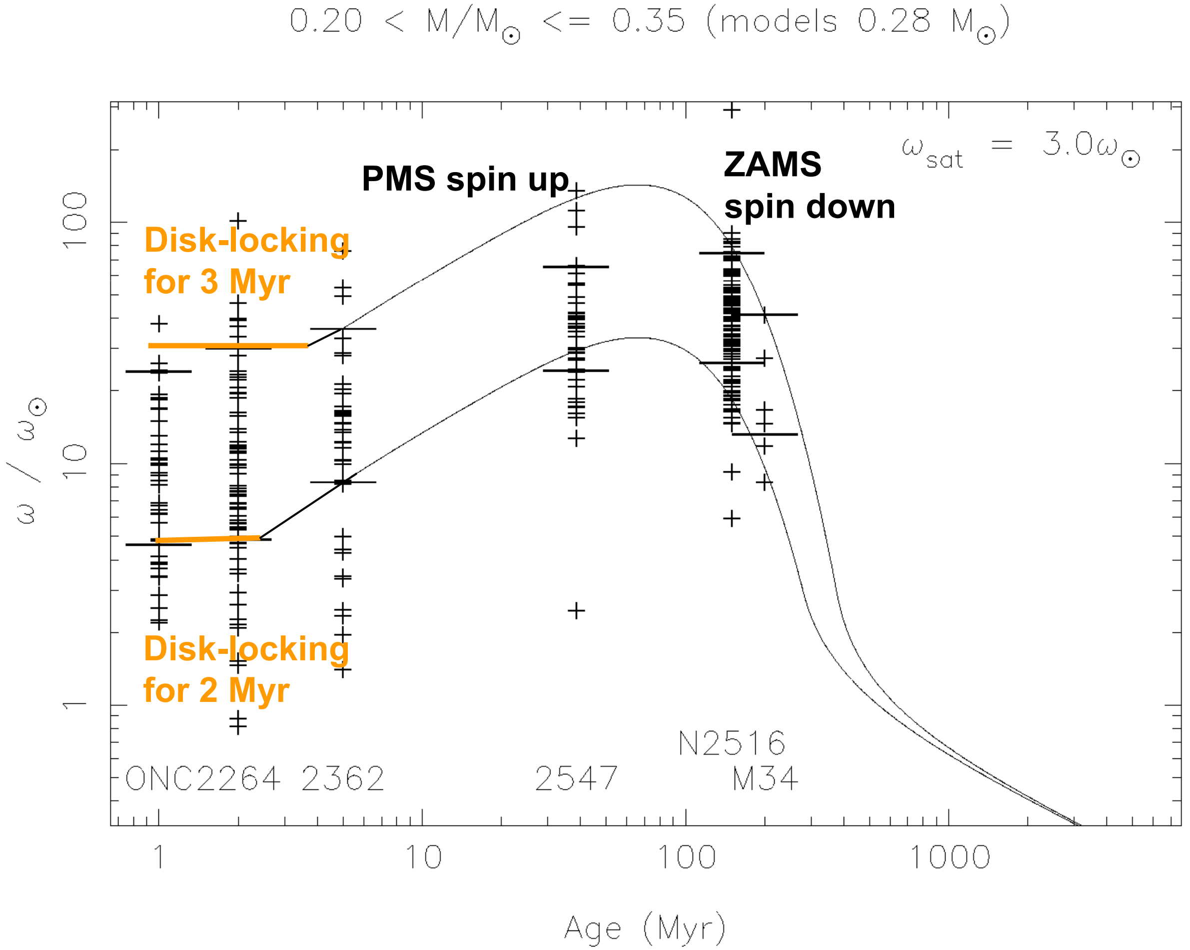
Provides unique constraints on PMS and early ZAMS angular momentum evolution

0.8 M$_o$ models



Bouvier 2007, IAUS 243

0.3 M_o models
(fully convective)



Bouvier 2007, IAUS 243

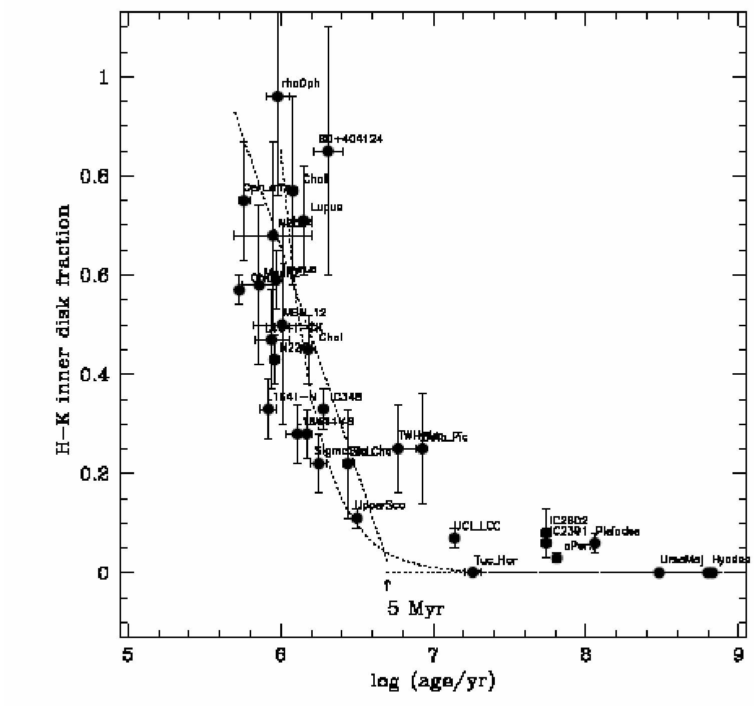
Implications of the models

- Disk lifetime varies from star to star between ~0.5 Myr up to ~10 Myr : timescale for planet building in the accretion disk
- Solar-type slow rotators : core-envelope decoupling on a timescale of ~0.5 Gyr; fast rotators : solid-body rotation. This suggests that AM transport in the stellar interior scales with rotation
- By the age of the Sun, the early rotational history is forgotten (convergence) : search for signature in Lithium abundances ? in activity level ?

Accretion disk lifetimes

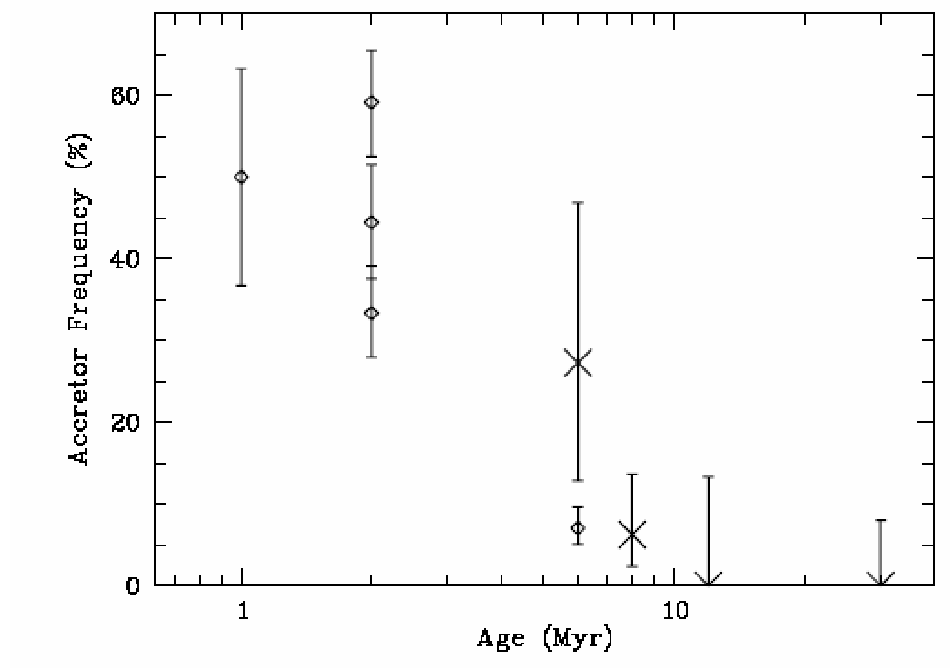
- AM evolution models suggest accretion disk lifetimes in the range 2-10 Myr (disk locking)
- Is this consistent with observed disk lifetimes ?

H-K excess : inner disks



Hillenbrand 2005

Hα 10% width : accretors



Jayawardhana et al. 2006

Summary

- AM loss of low mass stars on the main sequence is dominated by magnetized stellar winds
- AM loss of pre-MS low mass stars primarily derives from the magnetically-channelled accretion process

- Fair (?) agreement between models and observations
- Still many open issues : magnetic field geometry and evolution, dynamo behaviour, MHD star/disk interaction, stellar wind modelling, disk lifetimes, core-envelope decoupling, etc…
- A lot of progress in our understanding of AM evolution, but still a lot to be done…