Magnetic star-disk interaction in young stars

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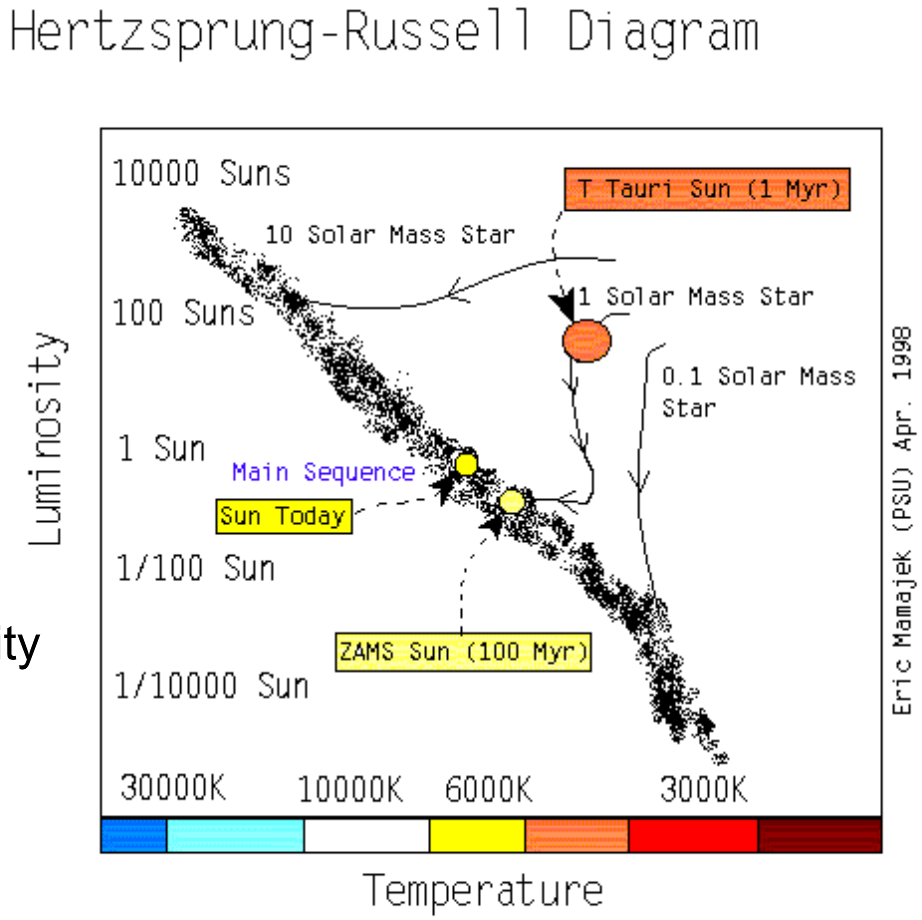
Classical T Tauri Stars

- pre-main sequence
- low mass ($M < 2\ M_\odot$)
- accretion disk
- optically visible



Main observable characteristics

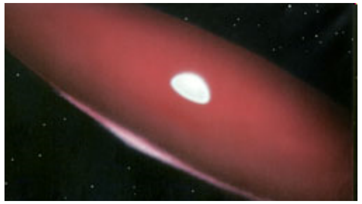
- Li I (6708Å) in absorption
- broad emission lines
- spectroscopic and photometric variability
- UV, optical and IR excesses
- strong magnetic fields (~ 2 kG)
- X-ray emission

Outline

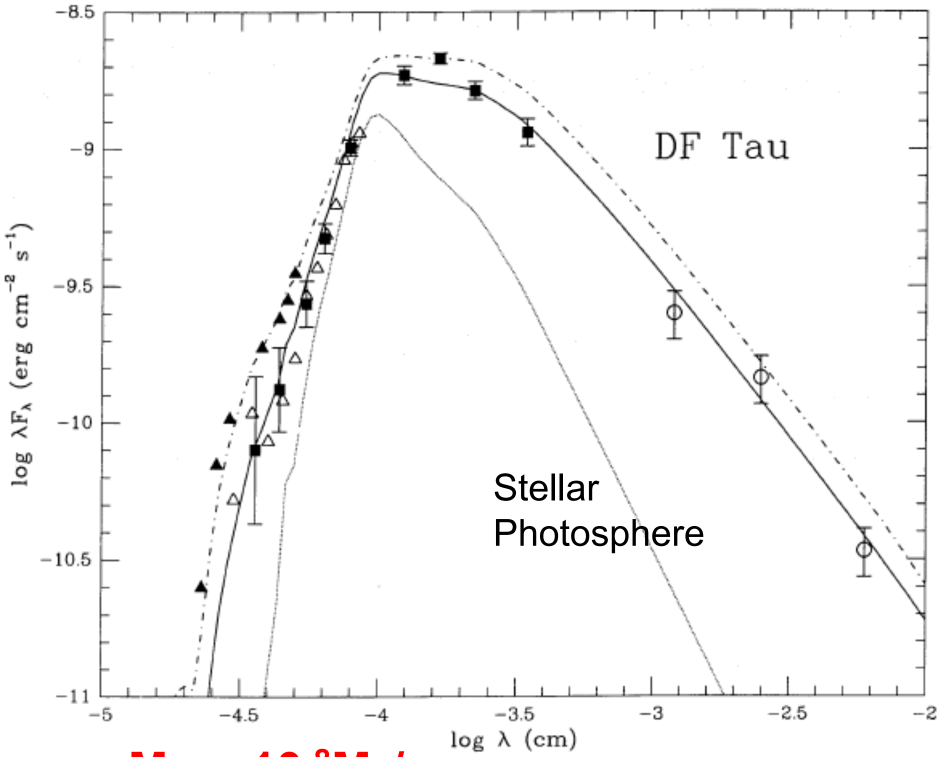
- Accretion disks : from boundary layers to magnetospheric accretion
- Magnetic field measurements in young stars
- Magnetically-controlled star-disk interaction : obs. and models
- The time variability of accretion/ejection : inner disks warps, funnel flows, accretion shocks
- Impact on angular momentum evolution, disc lifetimes and planet formation

A short historical note : from boundary layer accretion to magnetospheric accretion

Accretion disks



Accretion disks in young stars account in a simple and elegant way for their exotic properties, most notably their UV and IR continuum excesses.



M_{acc}~$10^{-8}M_o$/yr

Viscous energy dissipation rate in the disk :

$$F_V(r) = \frac{3GM_* \dot{M}}{8\pi r^3}\left[1 - \sqrt{\frac{R_*}{r}}\right]$$

→ IR excess

Boundary layer (energy dissipation in a narrow equatorial belt) :

$$4\pi R_* \delta\sigma T_{\mathrm{BL}}{}^4 = \frac{GM_* \dot{M}}{2R_*}$$

→ UV excess

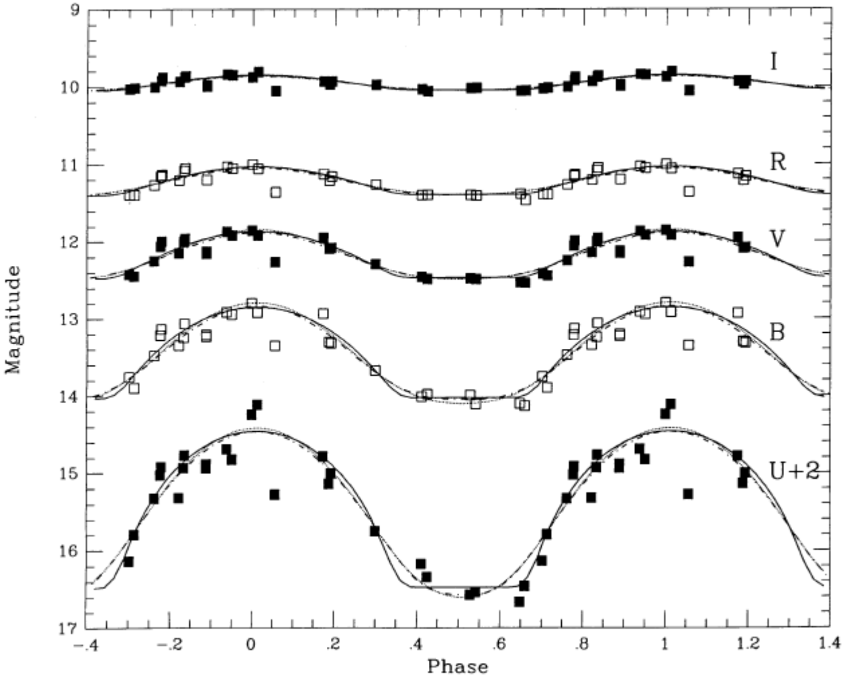
Accretion luminosity : $L_{\mathrm{acc}} = \dfrac{GM_* \dot{M}}{R_*}$ **≤ L_{star}**

Bertout, Basri, Bouvier 1988

Boundary layer accretion ?

Periodic modulation of the UV and optical excesses indicative of "hot spots" at the stellar surface.

DF Tau (P=8.5d)



Hot spot : f~1%, T~8000K

→ **Luminosity ~ ½ L_{acc}**

Accretion shock at the base of a magnetically-channeled accretion flow ?

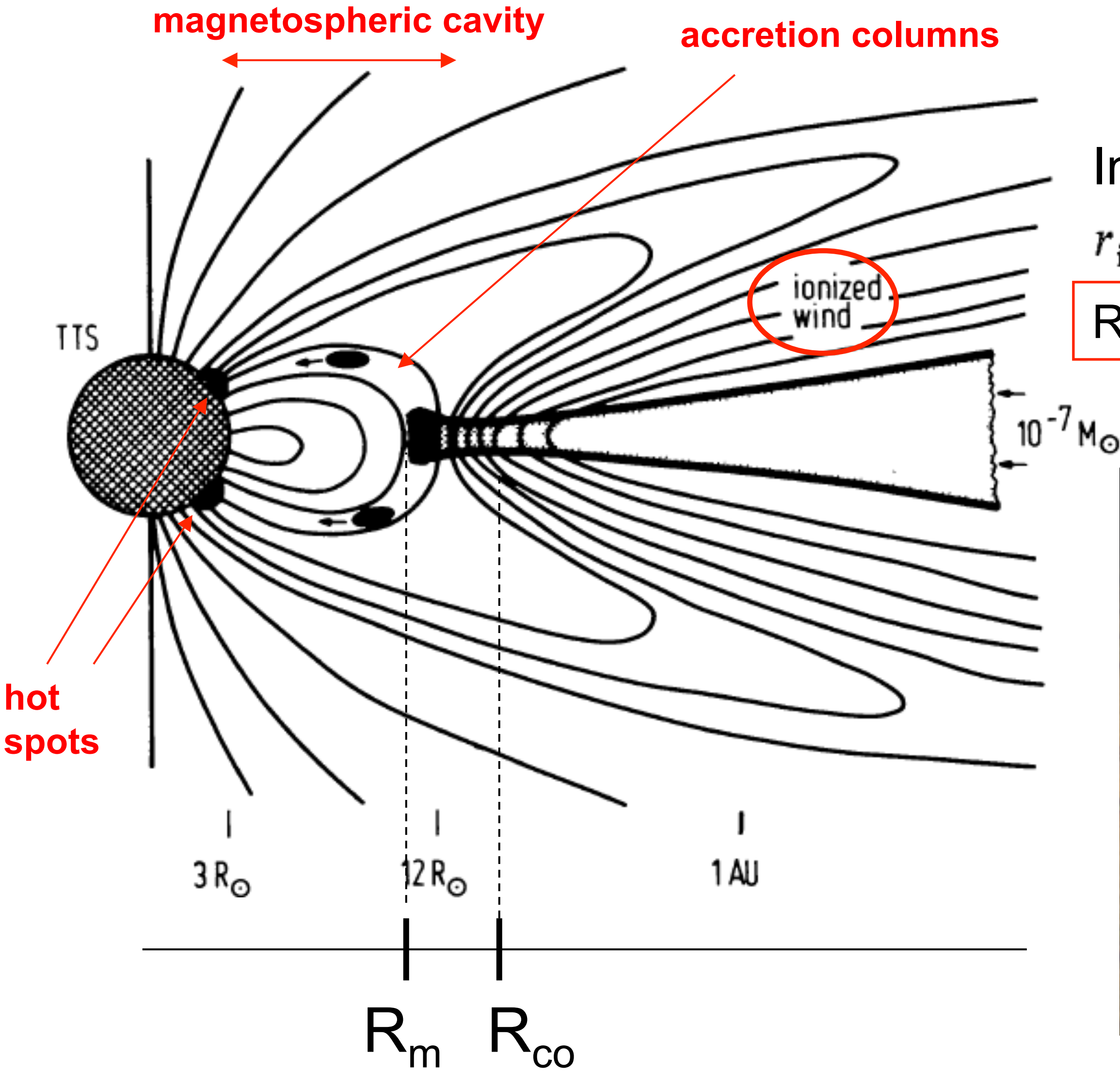
Bouvier & Bertout 1989

The angular momentum problem

- Accretion of high angular momentum material from the disk is expected to spin up the star at $\mathbf{V_{rot} \sim V_{break\text{-}up}}$ in $\sim 10^6$ yr !
- T Tauri stars are **slow rotators** $V \sim 10\text{-}25$ km/s = $0.1\ V_{break\text{-}up}$
- Accreting young stars rotate on average slower than non-accreting ones : **braking linked to the accretion process ?**
- **Magnetically-controlled accretion** to get rid of angular momentum excess? (cf. X-ray binaries, Gosh & Lamb 1979)

Magnetospheric accretion

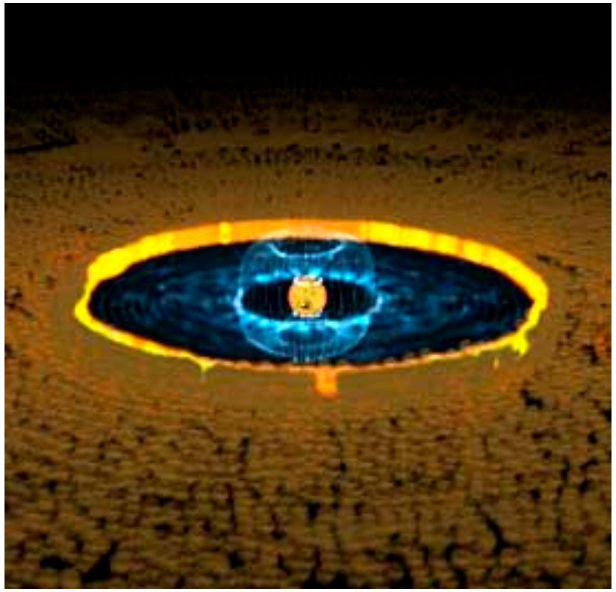
Camenzind 1990
Königl 1991



Inner disk truncation:

$$r_{in} = \beta \mu_*^{4/7} (2GM_*)^{-1/7} \dot{M}^{-2/7}$$

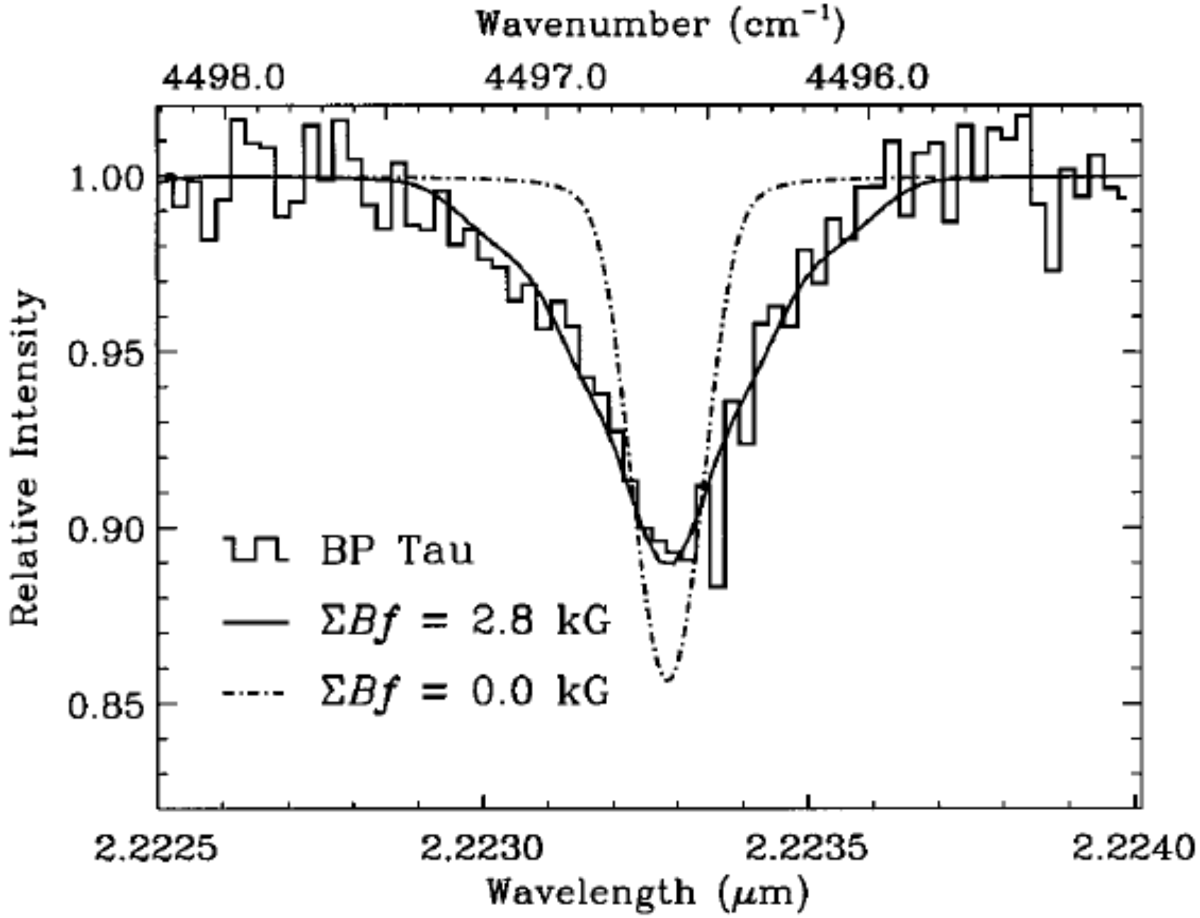
Requires $B_* = \mu_*/R_*^3$ ~ 1kG



Magnetic fields in young stars

Direct magnetic field measurement from Zeeman broadening

$$\Delta\lambda = \frac{e}{4\pi m_e c^2}\lambda^2 gB = \pm 4.67 \times 10^{-7}\lambda^2 gB \text{ m Å kG}^{-1}$$



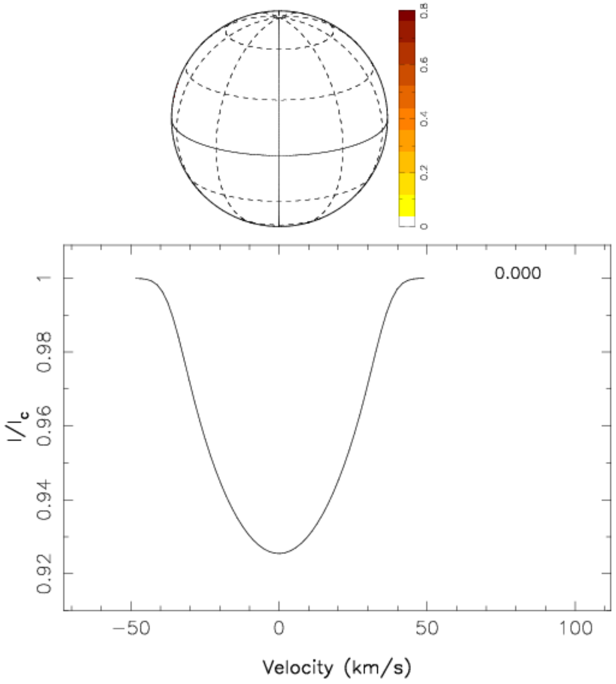
BP Tau

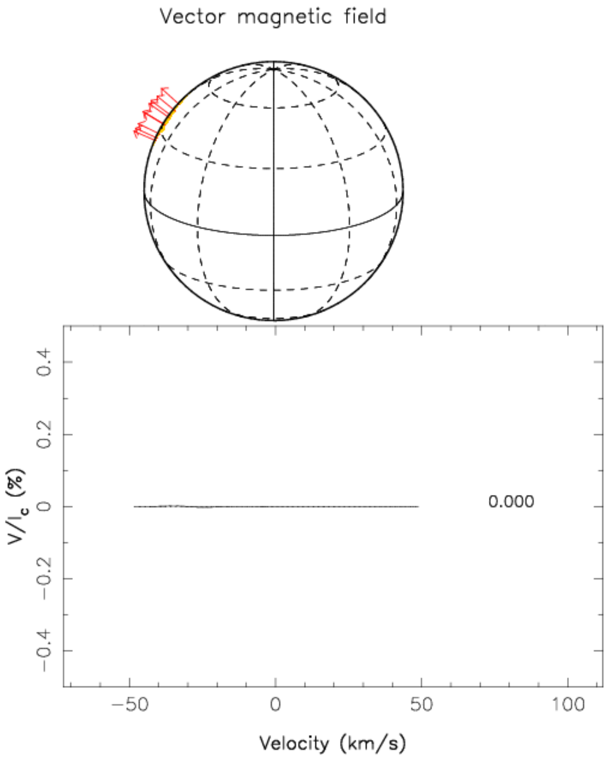
Ti I 2.2μm line

Surface averaged
<f.B> = 2.8 kG

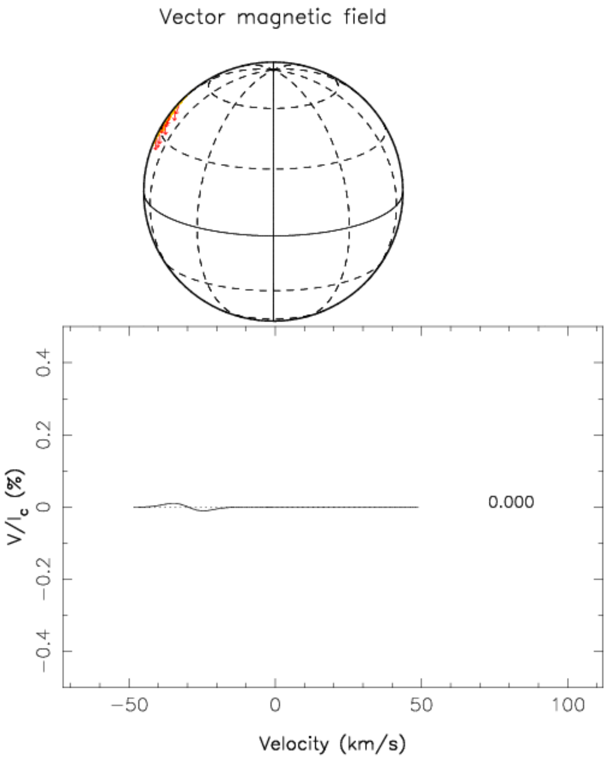
Johns-Krull et al. 1999

Zeeman-Doppler imaging from spectropolarimetric measurements





Radial B field



Azimuthal B field

Unpolarized line profile :
brightness map
(Doppler imaging)

Circularly polarized line profile :
magnetic map : intensity + topology
(Zeeman-Doppler imaging)

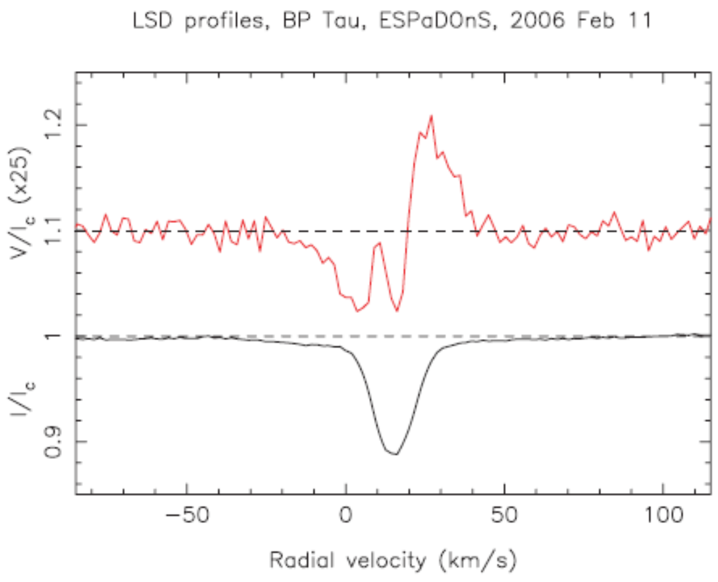
Donati et al. 1997

ZDI : BP Tau and V2129 Oph

- ZDI analysis of 2 accreting T Tauri stars

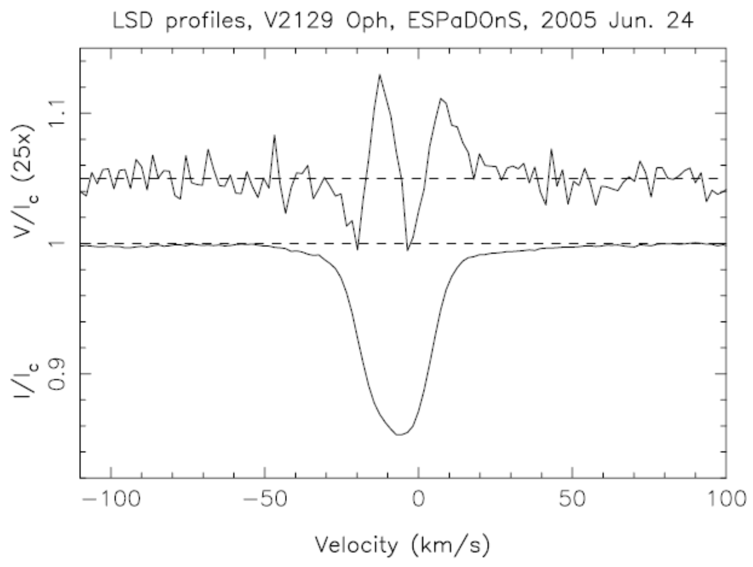
BP Tau (1.5 Myr)

$M=0.7M_o$; M_{acc}~$3.10^{-8}M_o/yr$



V2129 Oph (2 Myr)

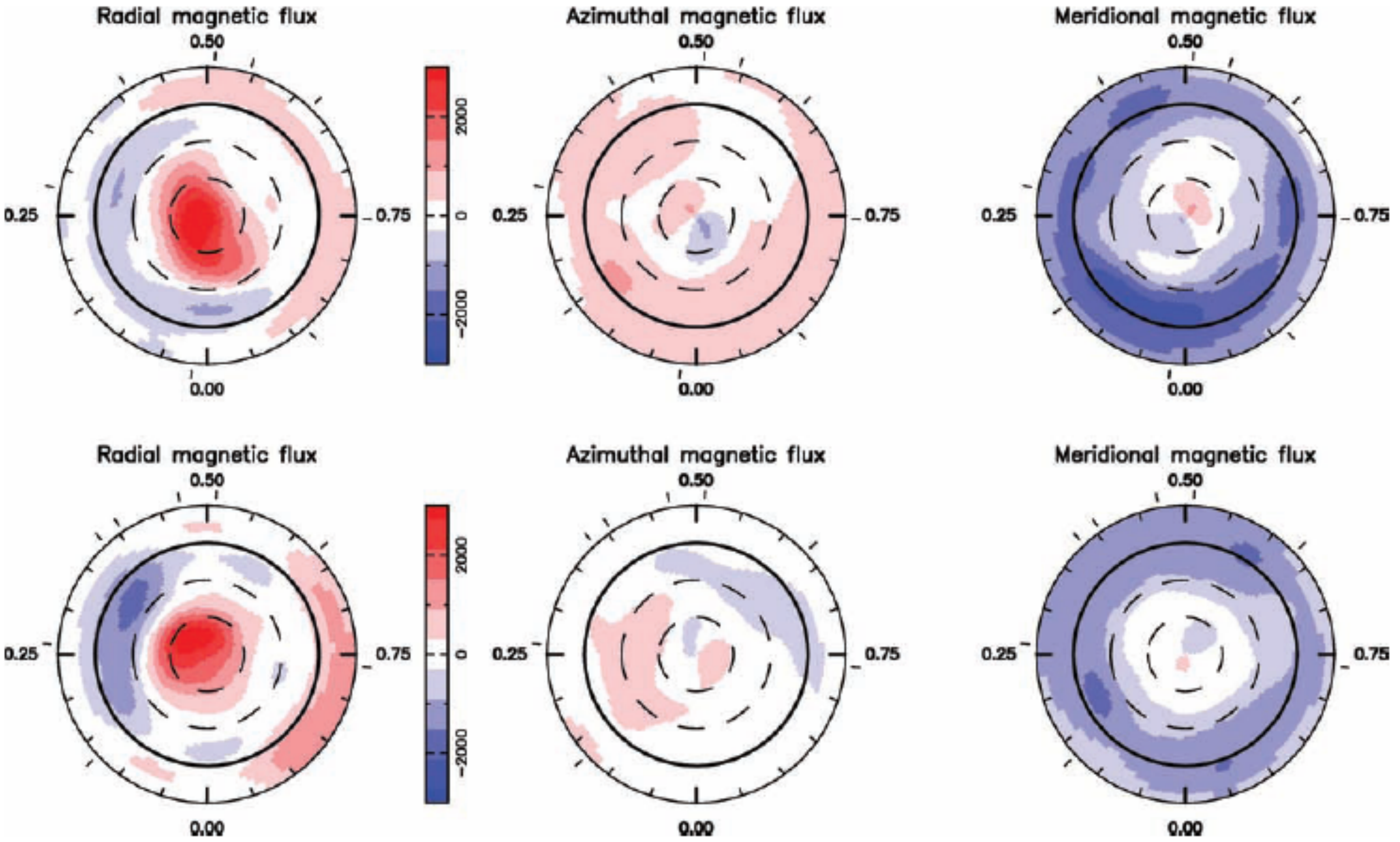
$M=1.35M_o$; M_{acc}~$10^{-8}M_o/yr$



Donati et al. 2007, 2008

Surface magnetic map of BP Tau

Magnetospheric accretion on the cTTS BP Tau 1247



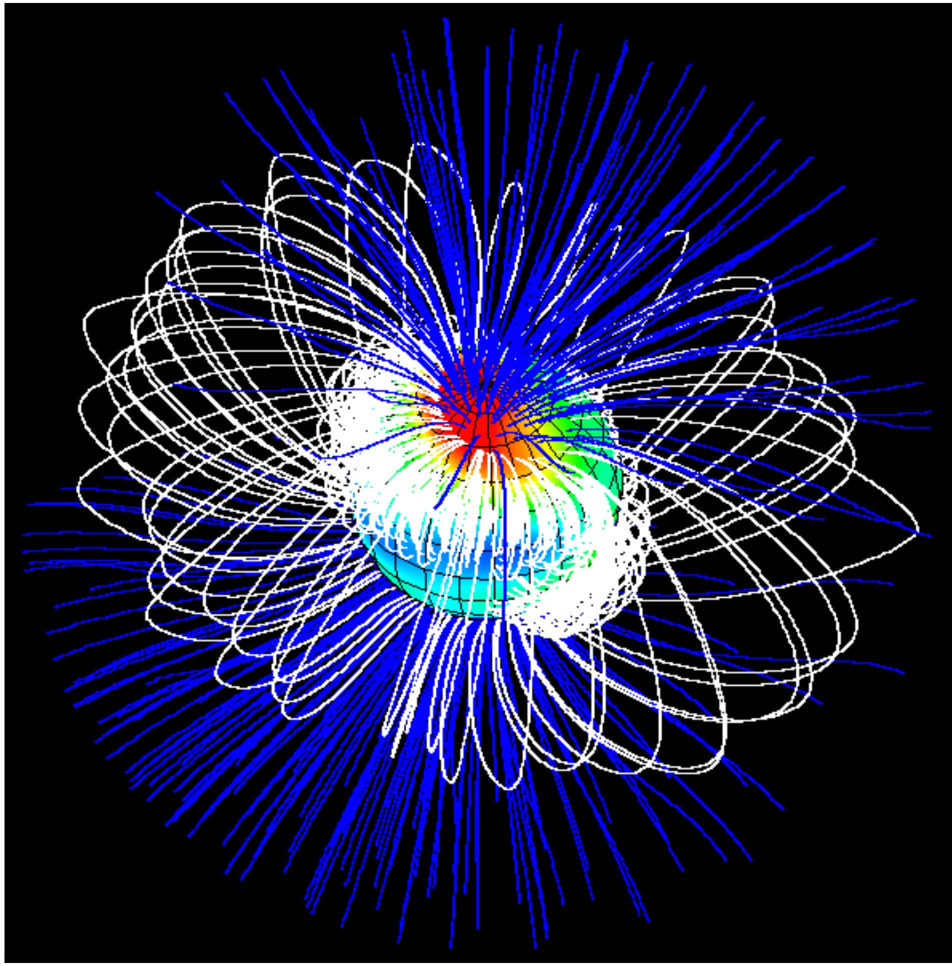
Feb.06

Dec.06

Donati et al. 2008

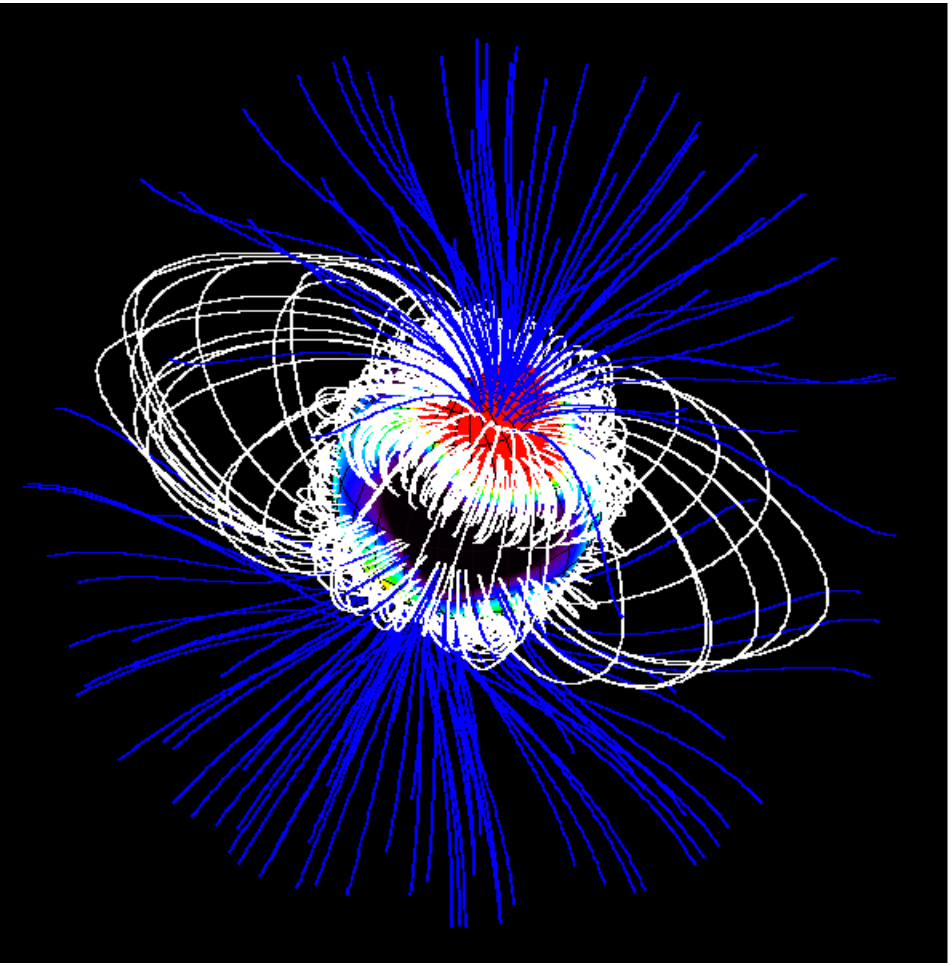
Magnetic structure of CTTS

1.2 kG dipole + 1.6 kG octupole



BP Tau **(Donati et al. 2008; Gregory et al. 2008)**

0.35 kG dipole + 1.2 kG octupole



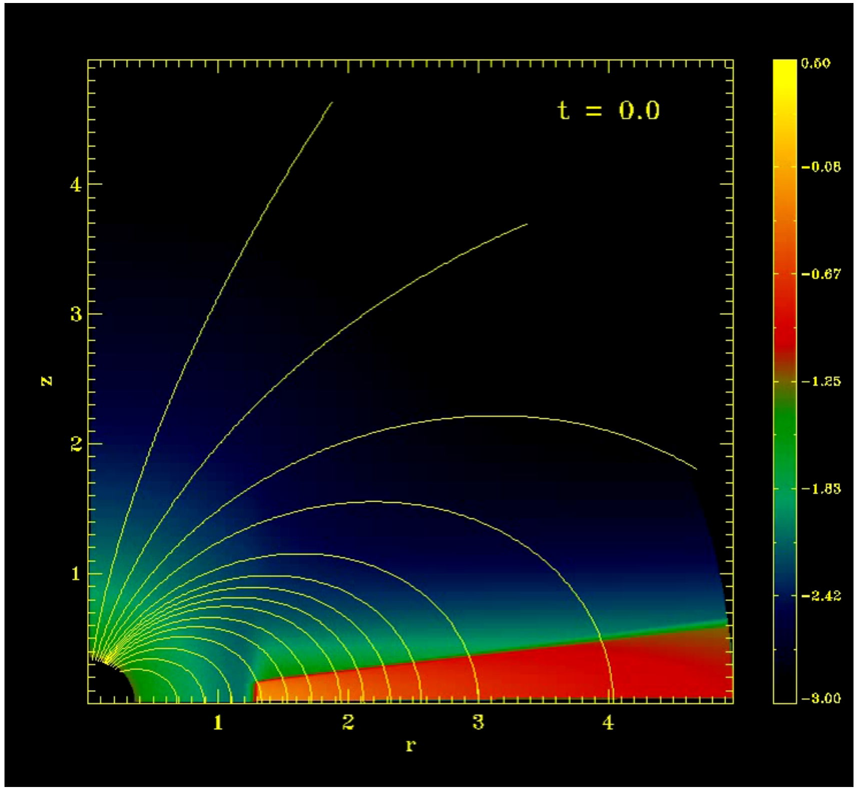
V2129 Oph **(Donati et al. 2007; Jardine et al. 2008)**

Magnetospheric star-disc interaction in young stars

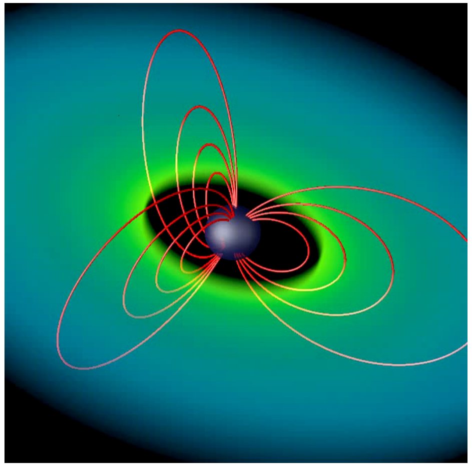
Star-disk magnetic coupling

2D MHD simulation of disk accretion
onto an aligned dipole

Zanni et al. 2009



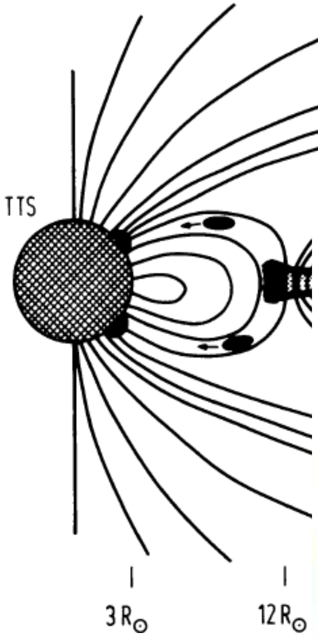
(mpg)



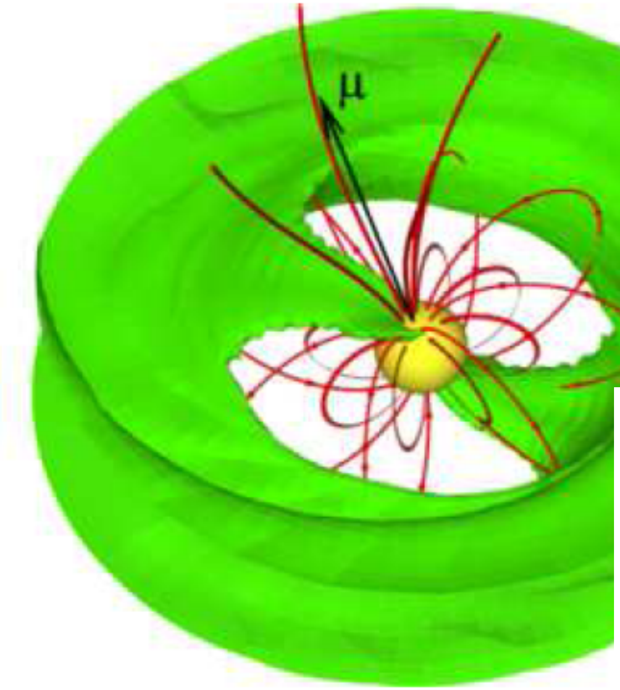
M_{star} = $0.8M_o$; $R_{star}=2R_o$

B_{dipole} = 800 G; $dM_{acc}/dt = 10^{-8}$ M_o/yr

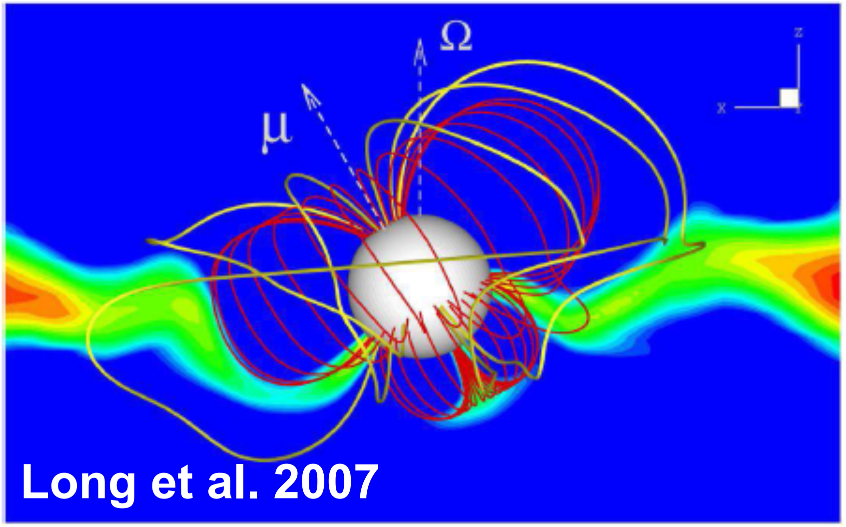
Magnetospheric accretion on complex magnetic fields



Camenzind 1990



Romanova et al. 2003



Long et al. 2007

The observational evidence for magnetospheric accretion

- Inner disk truncation
- Funnel flows
- Accretion shocks

Inner disk truncation

Disk truncation radius

- The disk is truncated at a radius where the magnetic field pressure balances the ram pressure of the accreting material

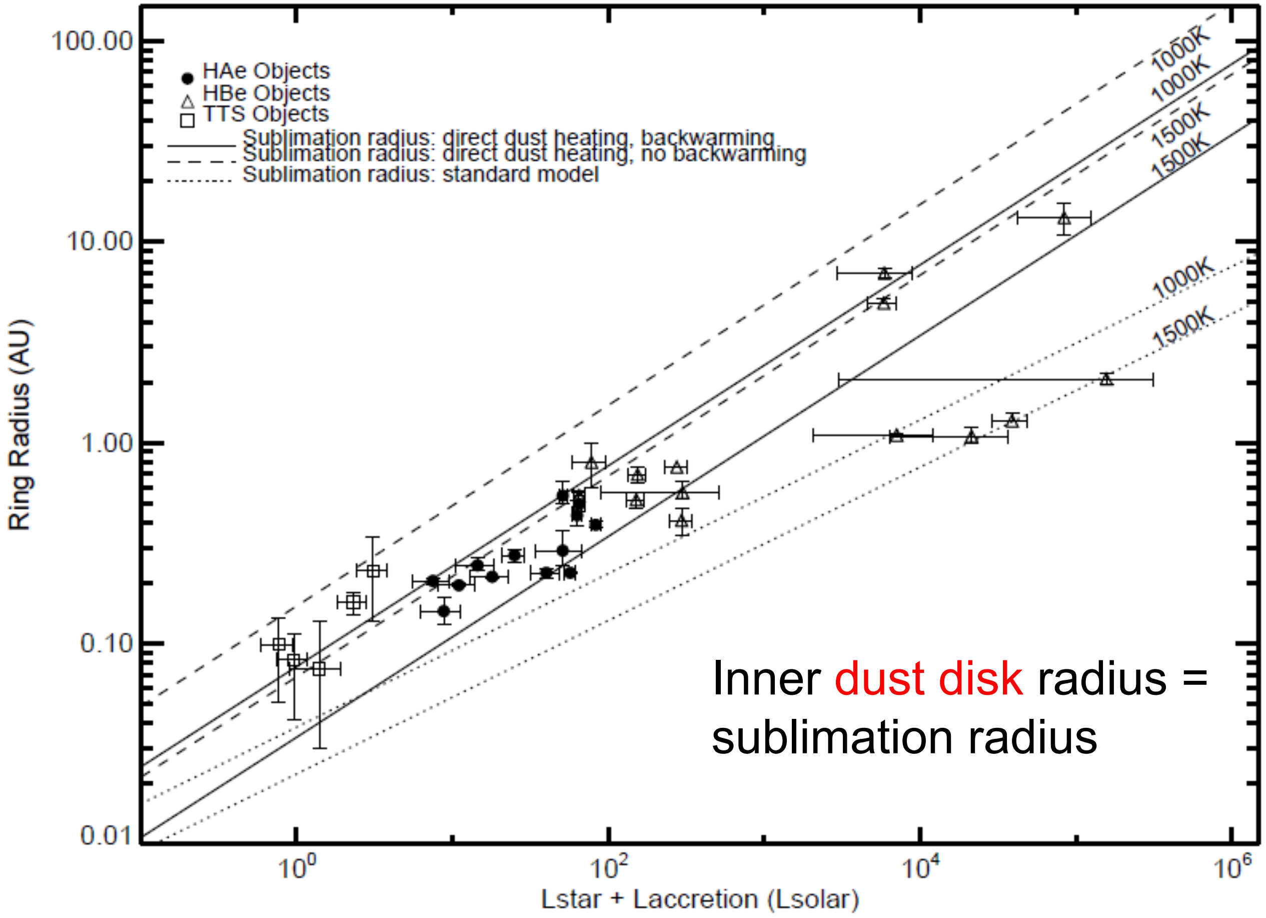
$$\frac{R_T}{R_*} = \frac{B_*^{4/7} R_*^{5/7}}{\dot{M}^{2/7}(2GM_*)^{1/7}} = 7.1 B_3^{4/7} \dot{M}_{-8}^{-2/7} M_{0.5}^{-1/7} R_2^{5/7},$$

- For typical values of B~1 kG, M_{acc}~$10^{-8}M_o$/yr

$\boxed{R_T \sim 3\text{-}7\ R_{star}}$ ~ 0.03-0.07 AU

Dusty disk inner radius

Interferometric measurements in the near-IR

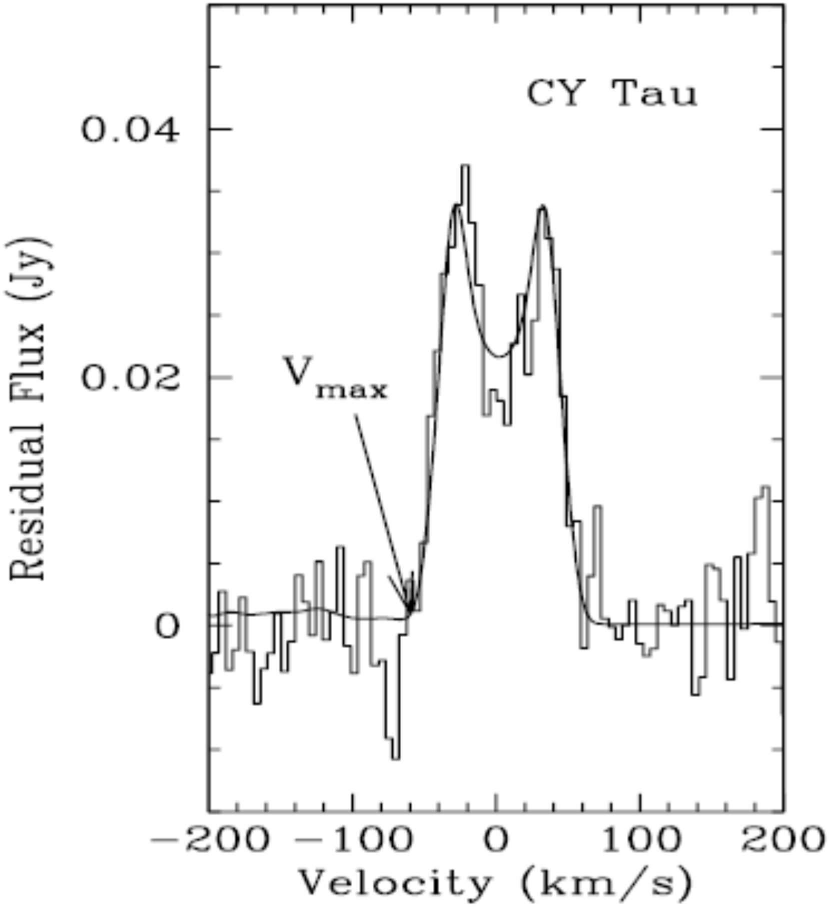


Inner dust disk radius =
sublimation radius

Millan-Gabet et al. 2007

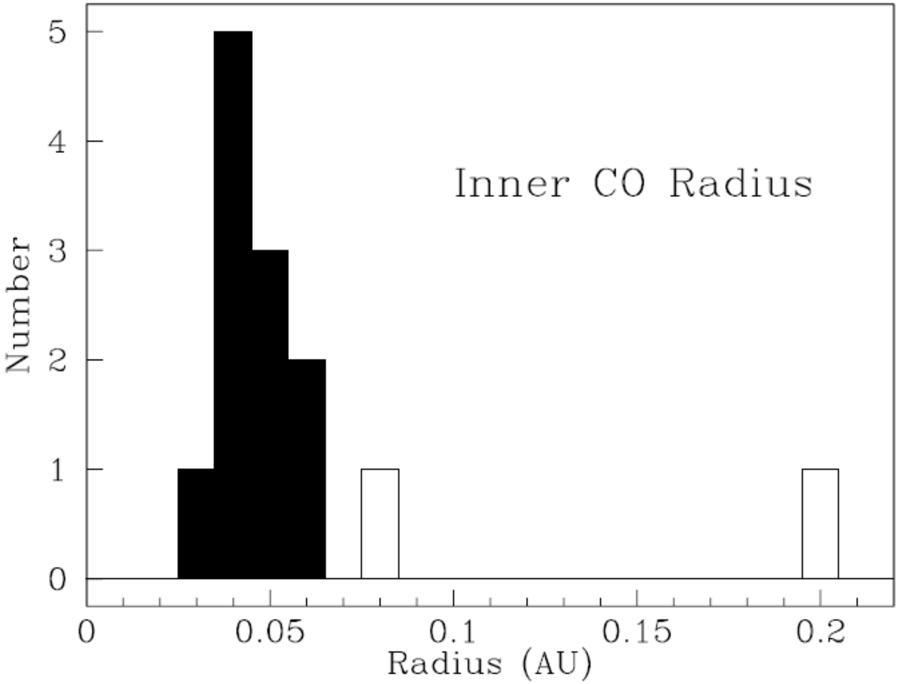
Gaseous disk inner radius

CO overtone bandhead profile (2.3µm)
T~2000-4000K, probes the inner disk



Keplerian motion measured from CO double-peaked line profile + inclination + central mass

=> inner gas disk radius



Carr 2007

- *Cautionary note : keplerian rotation is assumed in the inner disk*

Funnel flows

Accretion funnel flows

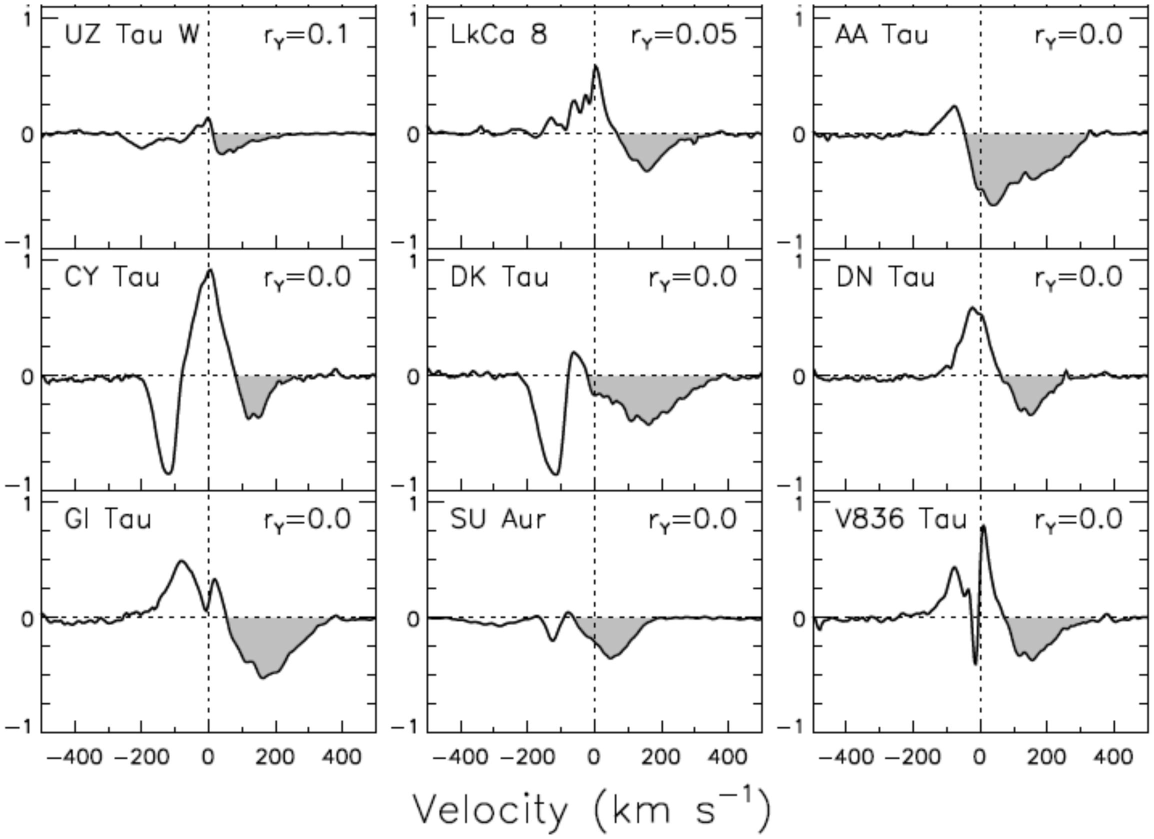
- Deep, high-velocity redshifted absorption components in the emission line profiles

He I λ10830 profiles

Redshifted absorptions

V_{max}/V_{esc} ~ 0.6-1.0

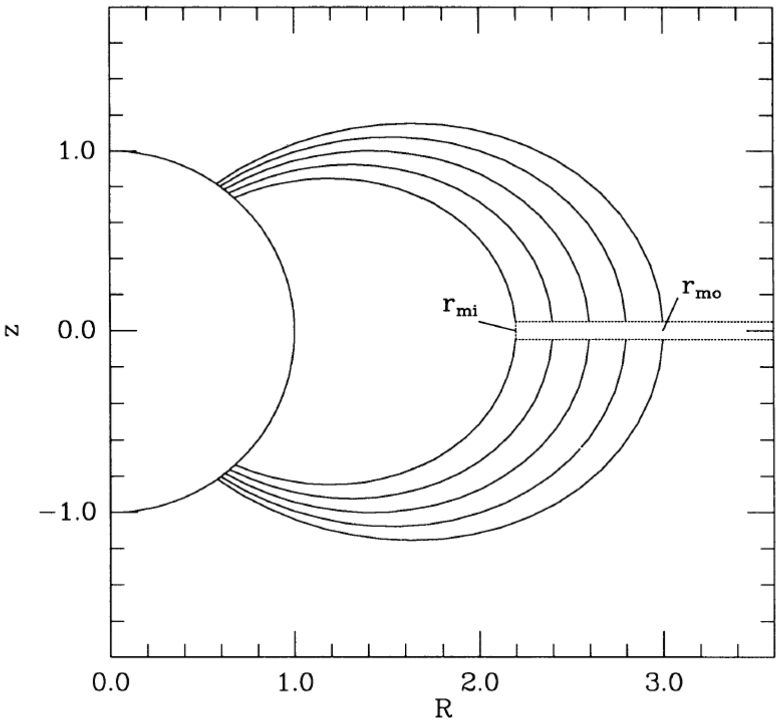
→ $R_{infall} \geq 2R_{star}$

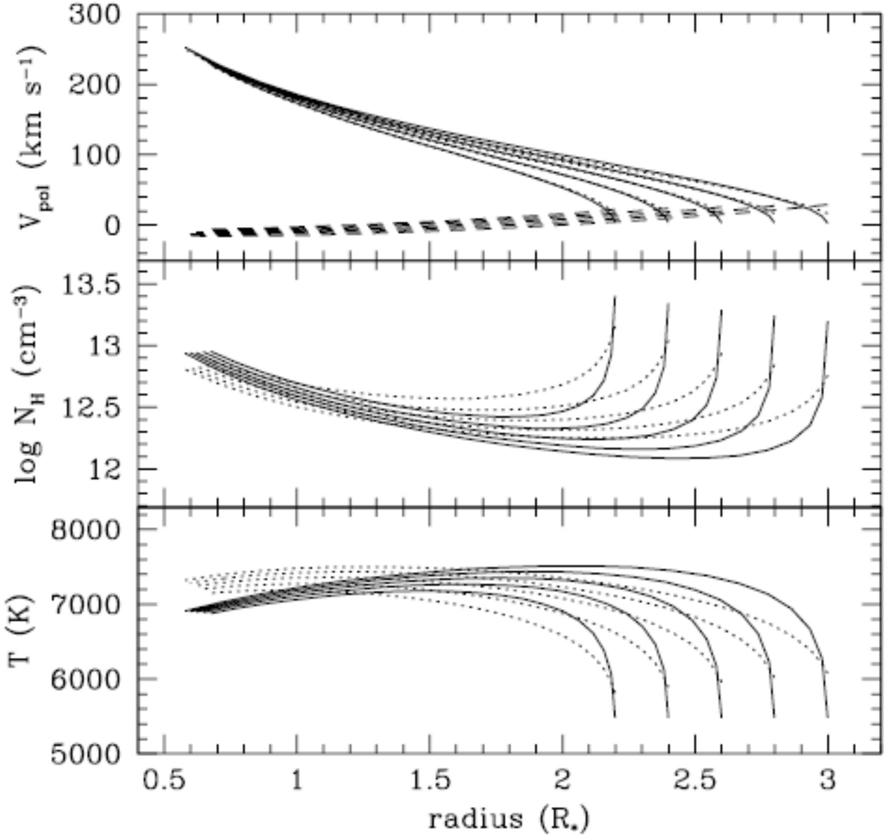


Fischer et al. 2008

Line profile modelling

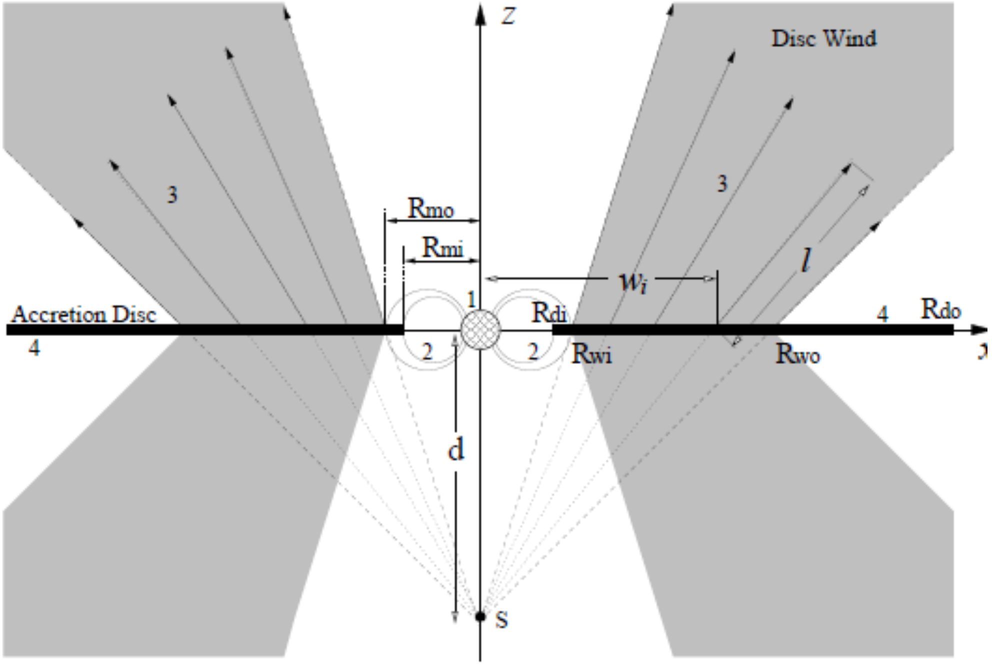
- Radiative transfer in a dipolar geometry

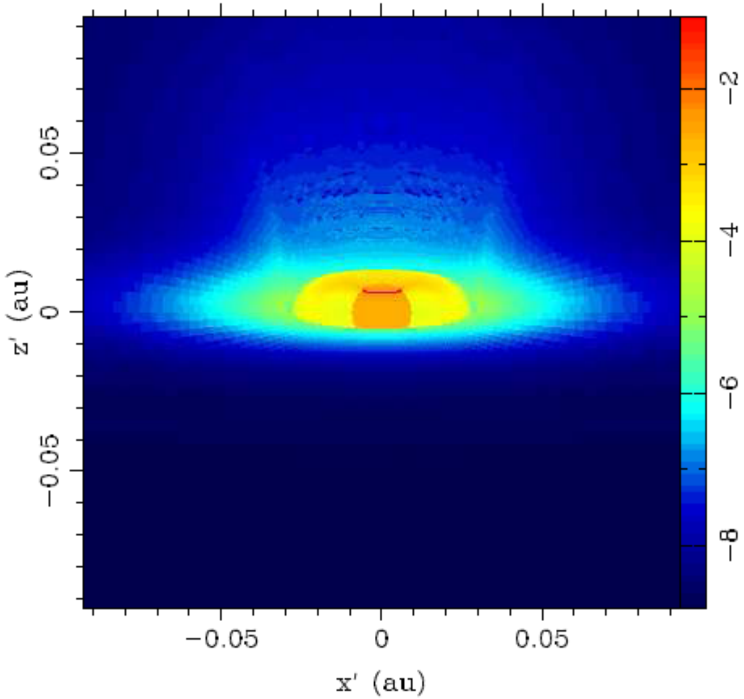




Hartmann et al. 1994

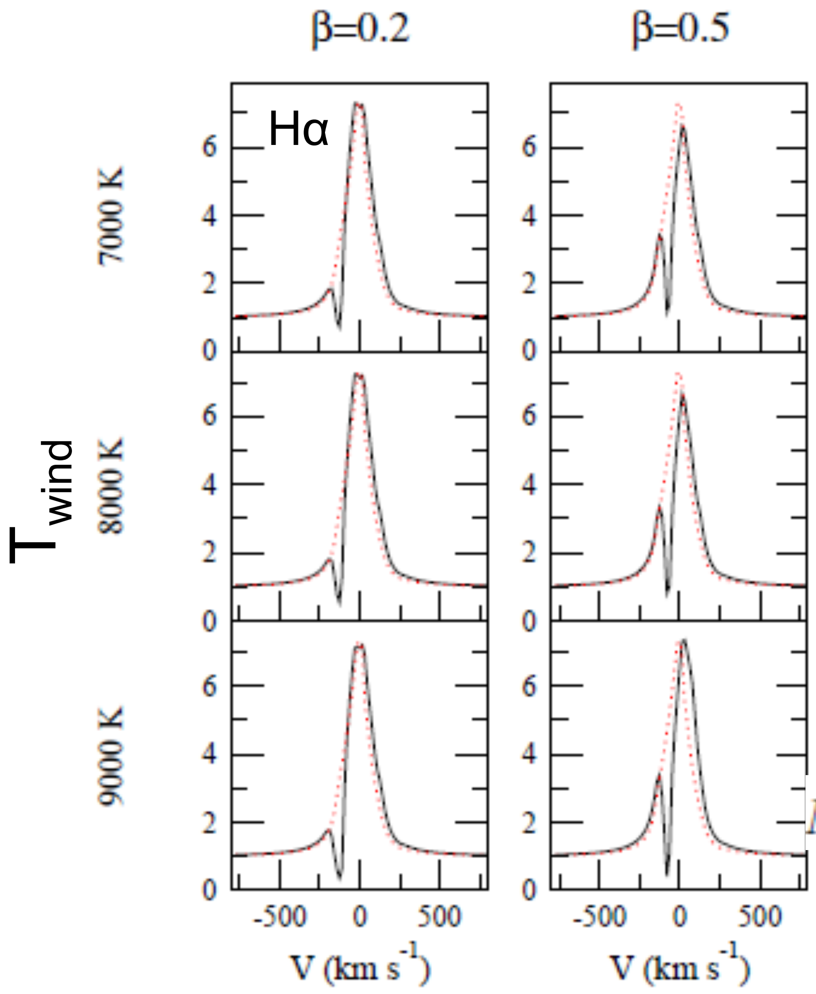
Hybrid line profile models : funnel flows + disk wind





Kurosawa et al. 2006

Hybrid Hα line profile models : funnel flows + disk wind



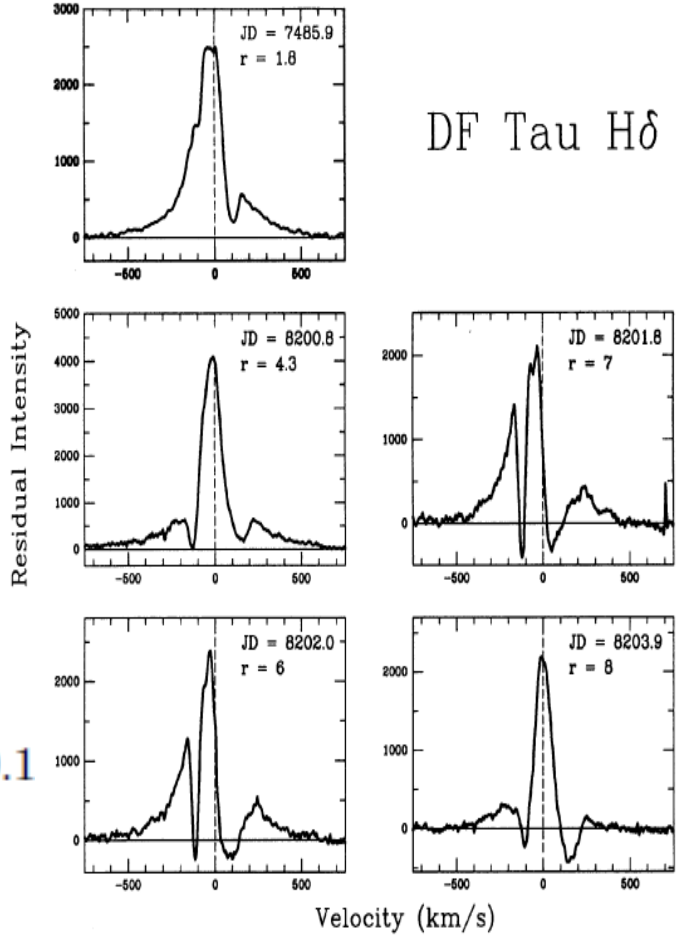
β : wind velocity law

Isothermal wind

T_{funnel} = 7500K

$$\dot{M}_{\rm wind}/\dot{M}_{\rm acc} = 0.1$$

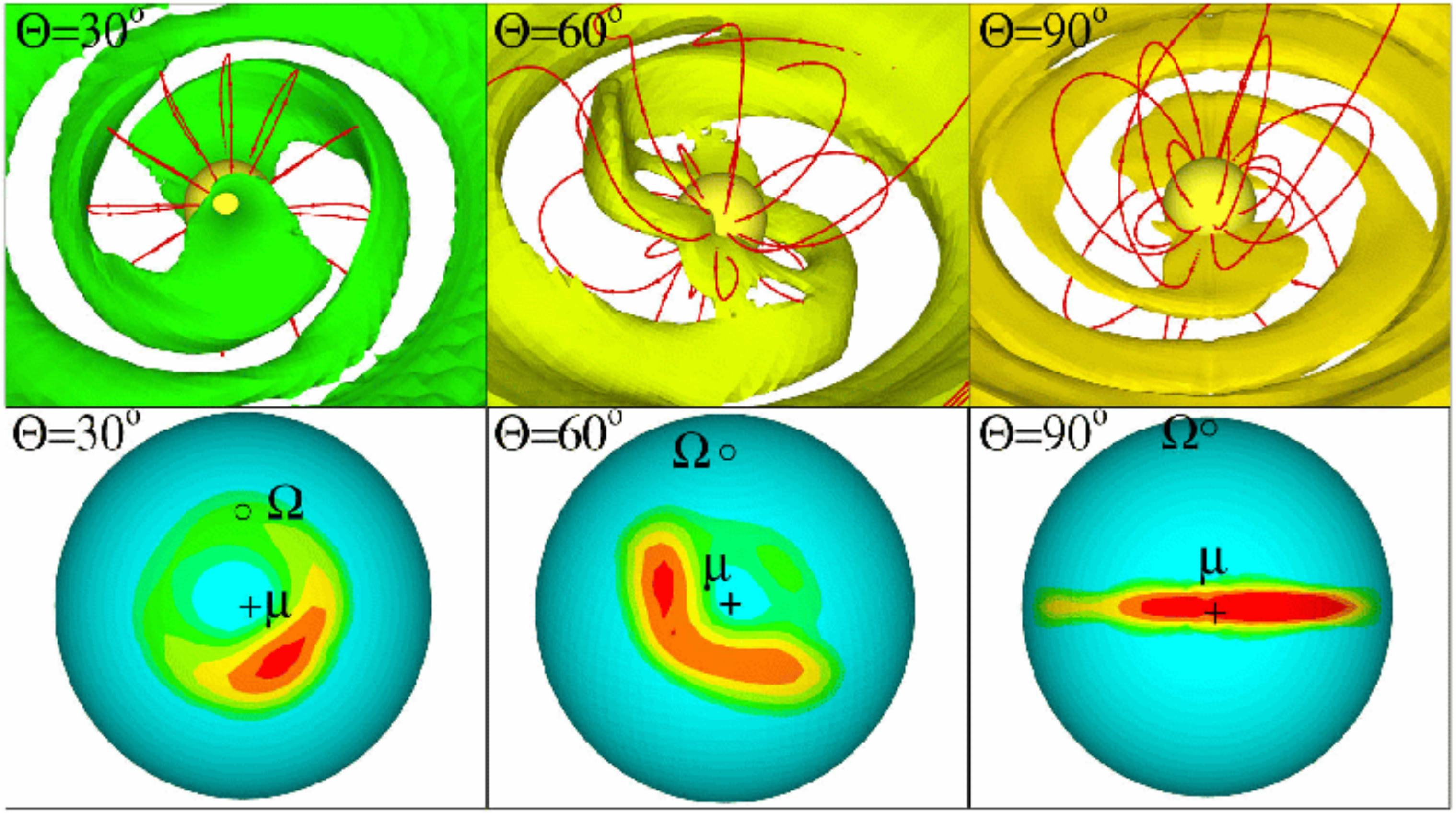
Kurosawa et al. 2006



Edwards et al. 1994

Accretion shocks

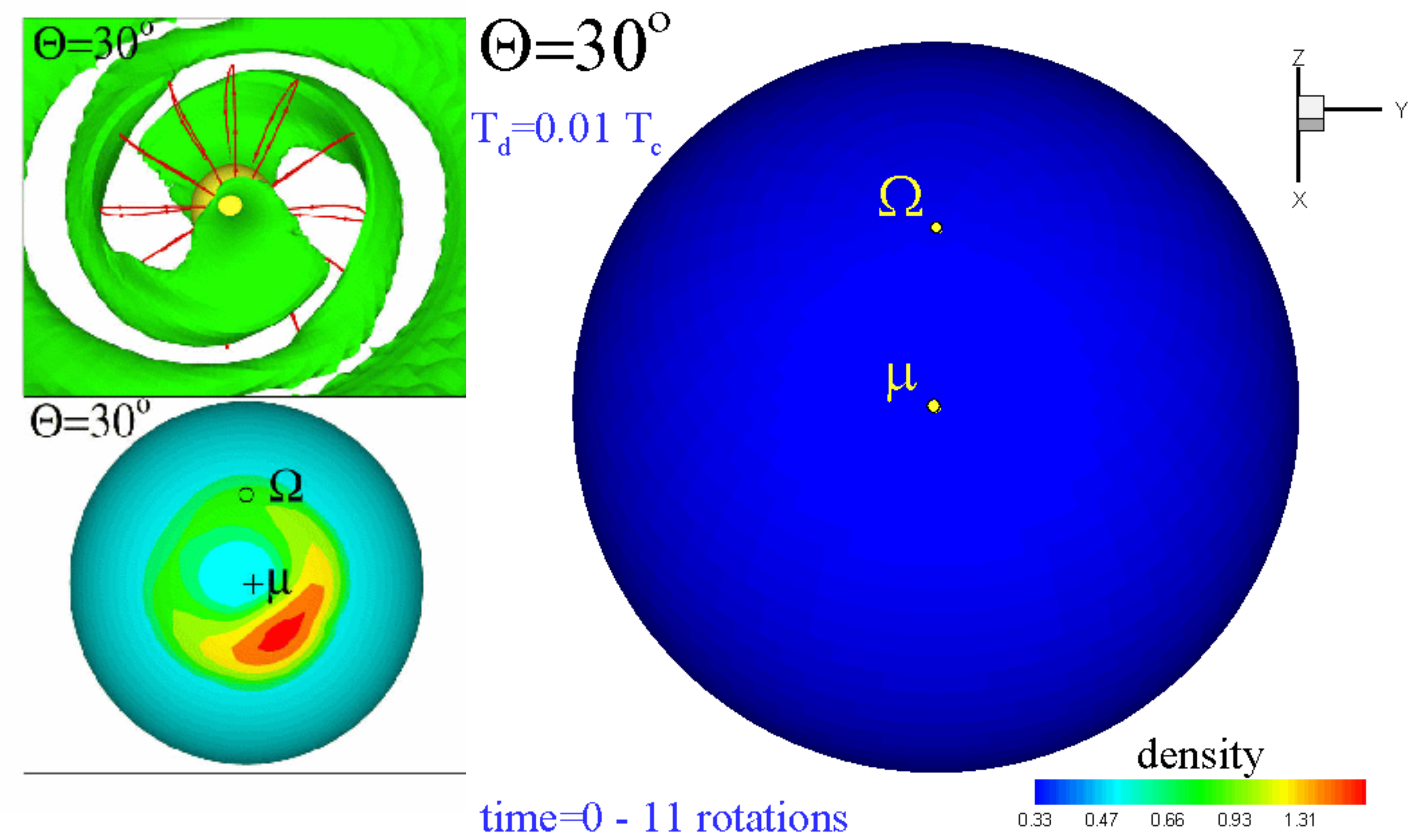
Rotational modulation by hot spots



Accretion onto an inclined dipole (θ=30, 60, 90 deg)

Romanova et al. 2004

Rotational modulation by hot spots

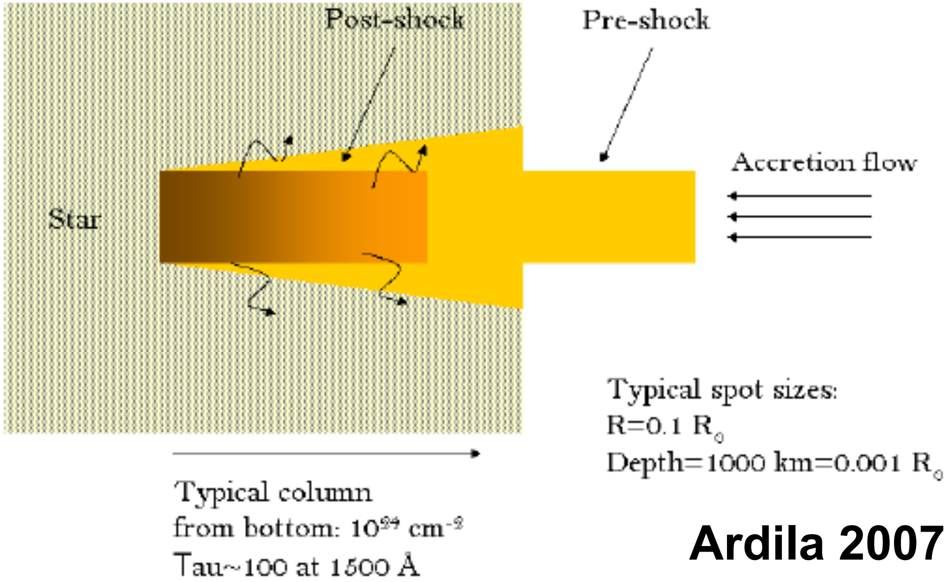


Accretion onto an inclined dipole (θ=30, 60, 90 deg)

Romanova et al. 2004

UV spectrum from accretion shock

- Accretion shock models reproduce the continuum UV excess spectrum

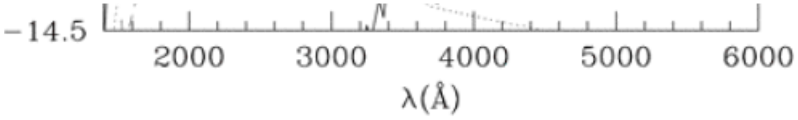


Ardila 2007

$$\dot{M} = 10^{-8}\ \mathrm{M_\odot yr^{-1}}$$

$$f \sim 0.001 - 0.01$$

$$T_s = \frac{3}{16}\frac{\mu m_H}{k} v_{ps}^2 = 8.6 \times 10^5 K (\frac{M}{0.5 M_\odot})(\frac{R}{2R_\odot})^{-1}$$

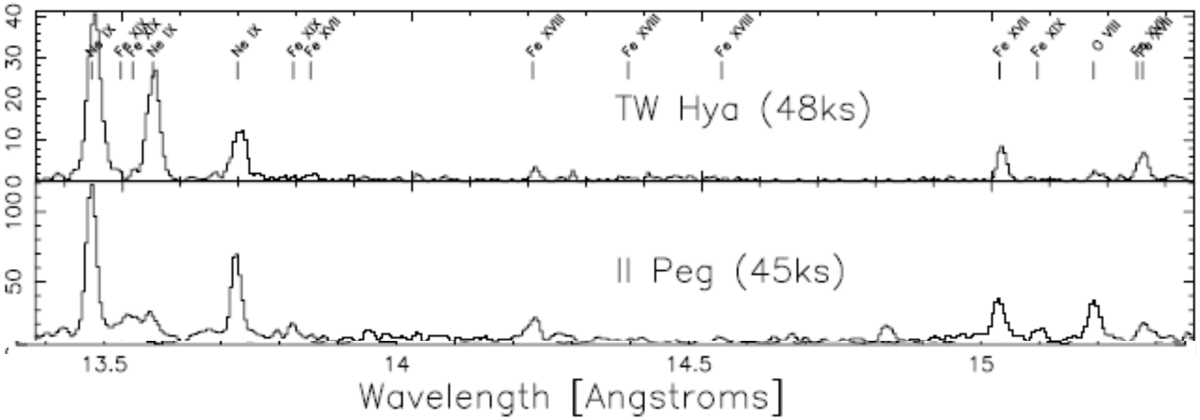


$$n_{pre} = \frac{\dot{M}}{\mu m_H f 4\pi R_*^2} = 5.8 \times 10^{12} cm^{-3} (\frac{\dot{M}}{10^{-8} M_\odot / yr})(\frac{M}{0.5 M_\odot})^{1/2}(\frac{R}{2R_\odot})^{-3/2}(\frac{f}{0.01})^{-1}$$

Gullbring et al. 2000

X-ray spectroscopy

- In most T Tauri stars, X-ray comes from coronal emission
- However, in a handful of them, X-ray emission seems to originate from the accretion shock at the stellar surface



Accreting TTS

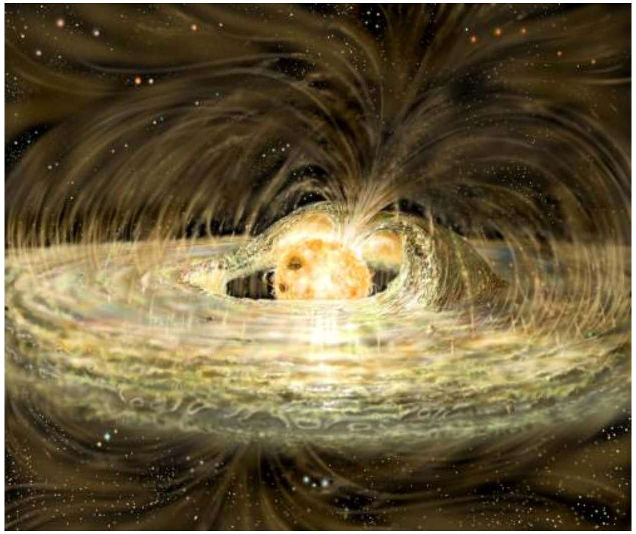
Coronal RS CVn

•Chandra X-ray spectrum reveals unusually high plasma density ($n_e \sim 10^{12}$ cm^{-3}) and a soft spectrum ($T \sim 10^6$K)

•Consistent with an accretion shock near the stellar surface at the free-fall velocity of the gas ($V_{ff} \sim 200$ km/s)

Kastner et al. 2002

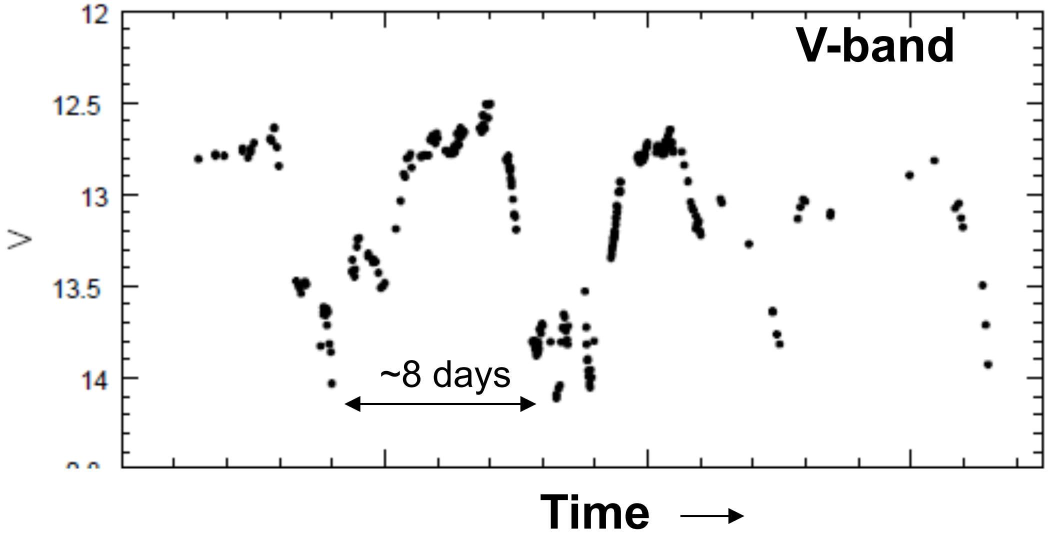
The time domain : rotational modulation and intrinsic time variability of the accretion/ ejection process

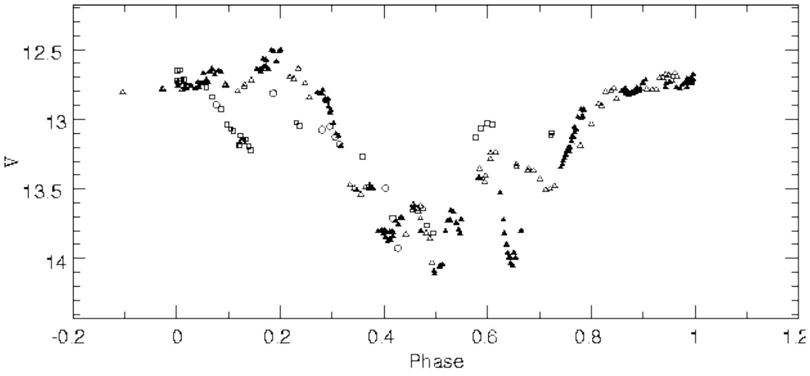


Inner disk warps : AA Tau

Best seen in high inclination system : AA Tau; *i* ~ 75 deg.; Prot = 8.2 days

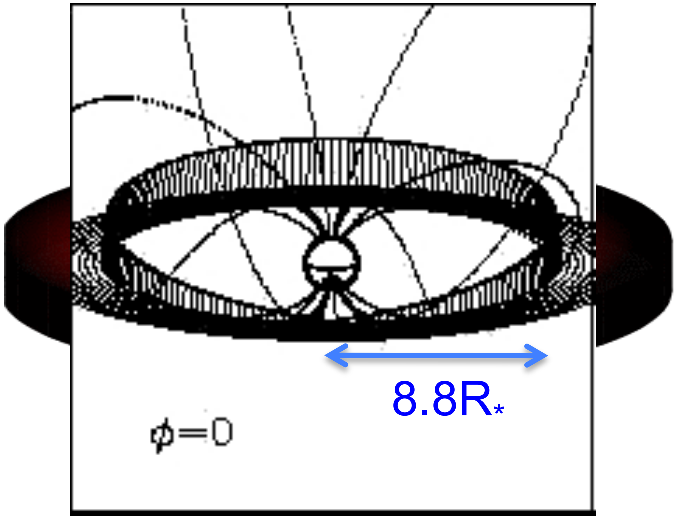
Recurrent luminosity dips in the optical





→ **Periodic occultations of the star by the rotating inner disk warp**

Inner disk warp resulting from a tilted large scale magnetic field ?



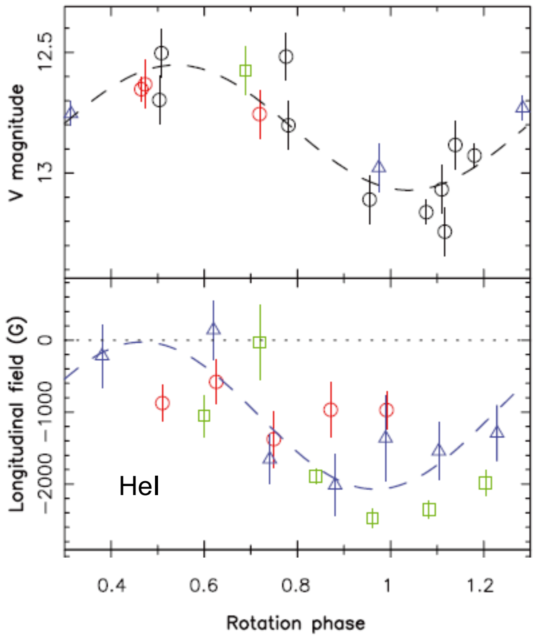
Bouvier et al. 2007

AA Tau spectro-polarimetry

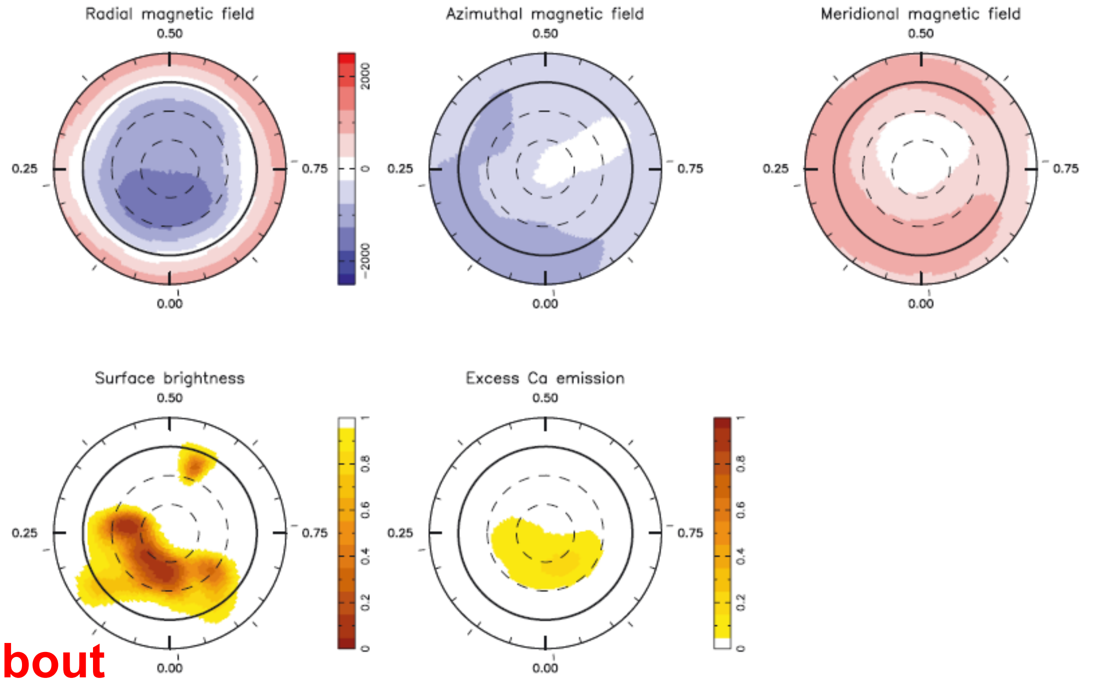
2-3kG dipole, tilted at ~20 deg onto the rotation axis

AA Tau : M~0.7Mo, log(Macc) = -9.2

Donati et al. 2010



Magnetospheric accretion and spin-down of AA Tau 1357



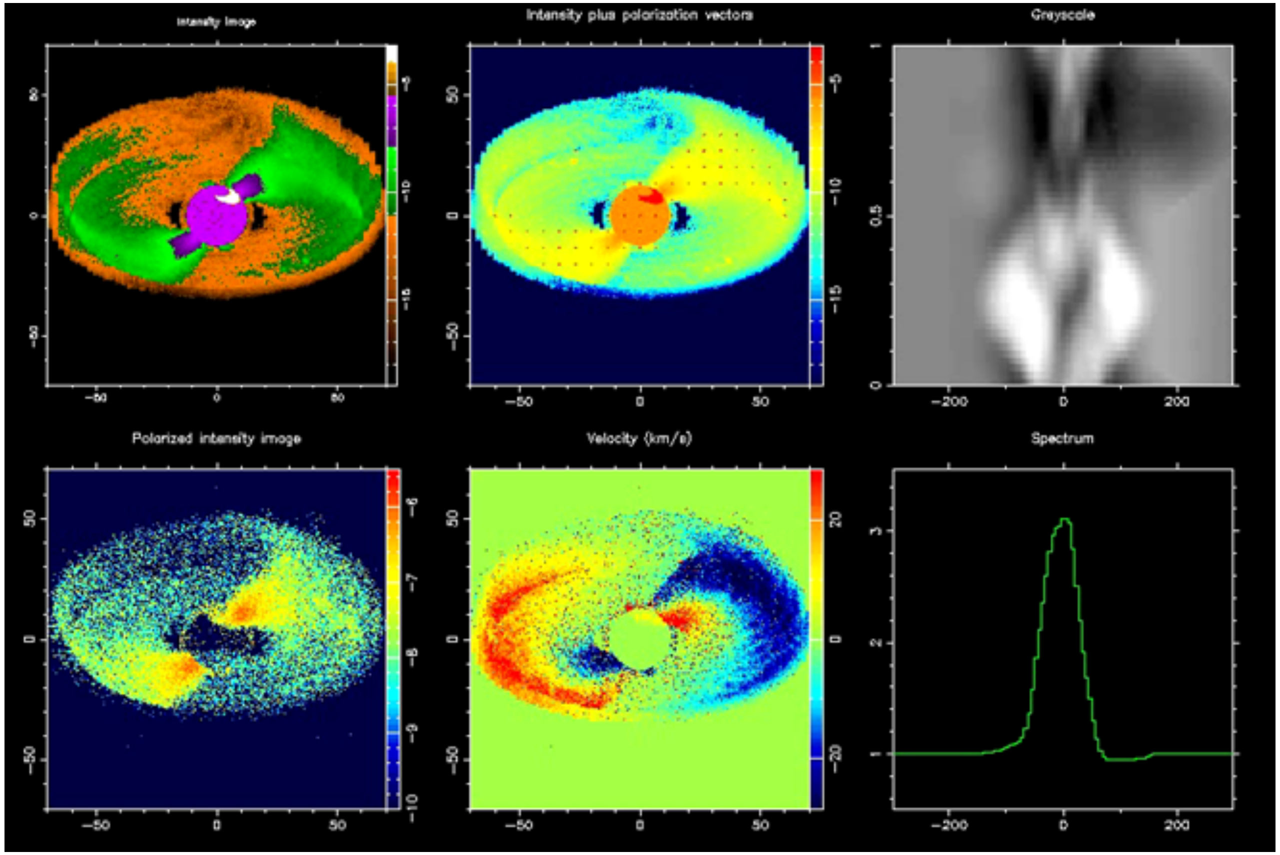
The magnetic pole is located at about the same azimuth as the disk warp that produces the eclipse

Both a cold (magnetic) spot and a hot (accretion) spot are found close to the magnetic pole

Line profile variability from inclined magnetospheres

Kurosawa, Romanova, Harries 2008

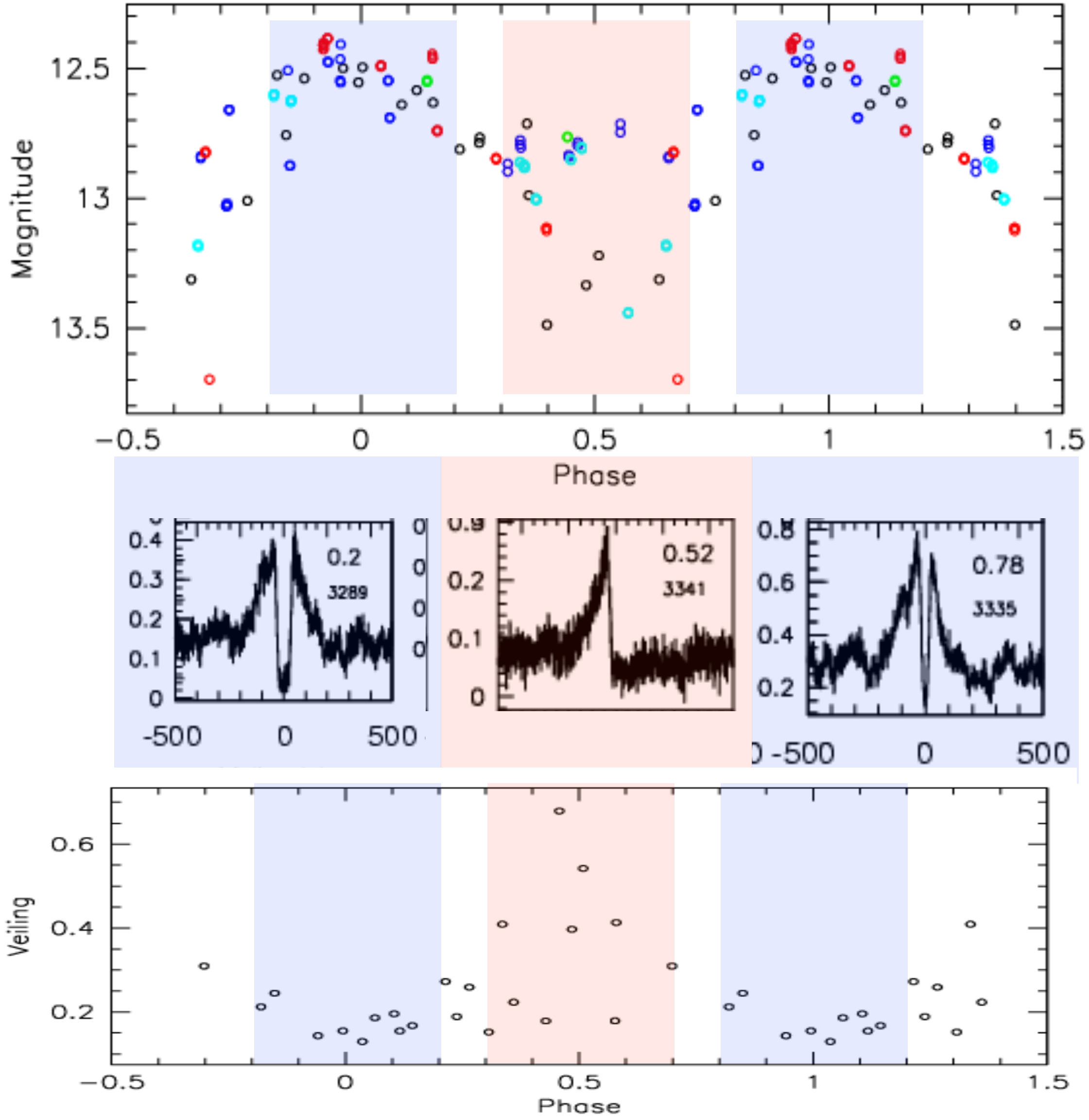
3D MHD simulations of accretion onto an inclined dipole
3D radiative transfer of rotationally-induced line variability (e.g. Paβ)



(.avi)

Inclined magnetospheres : AA Tau

Bouvier et al. 2007



Periodic eclipses

(disk warp)

(P=8.22d)

Balmer lines

(accretion funnel)

Veiling

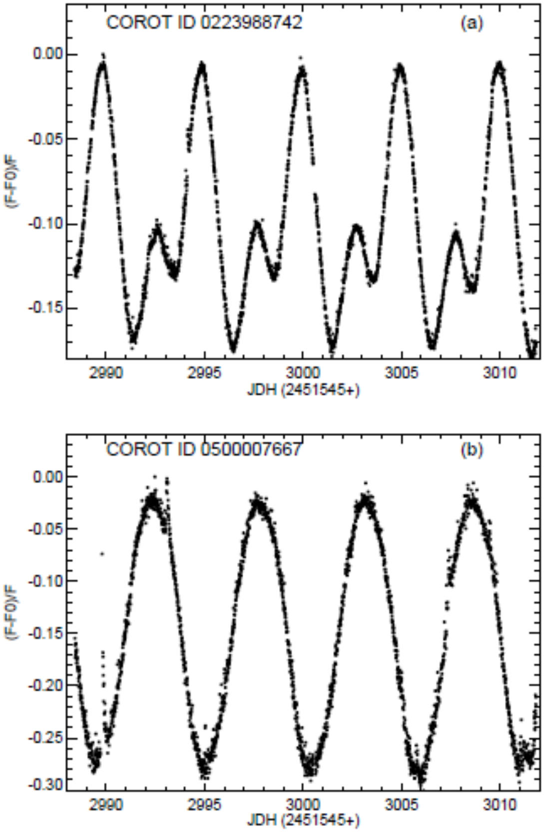
(accretion shock)

Is AA Tau a unique object ?

COROT light curves : NGC 2264

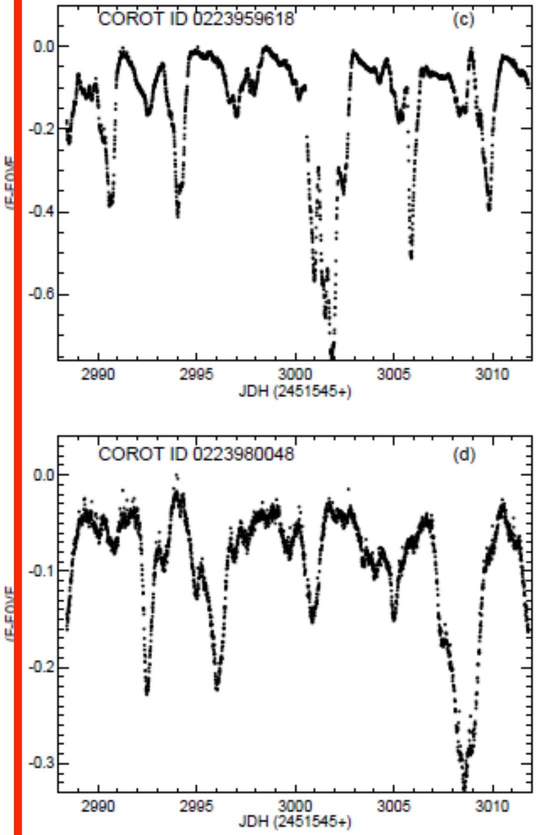
Alencar et al. 2010

Periodic; sinusoidal



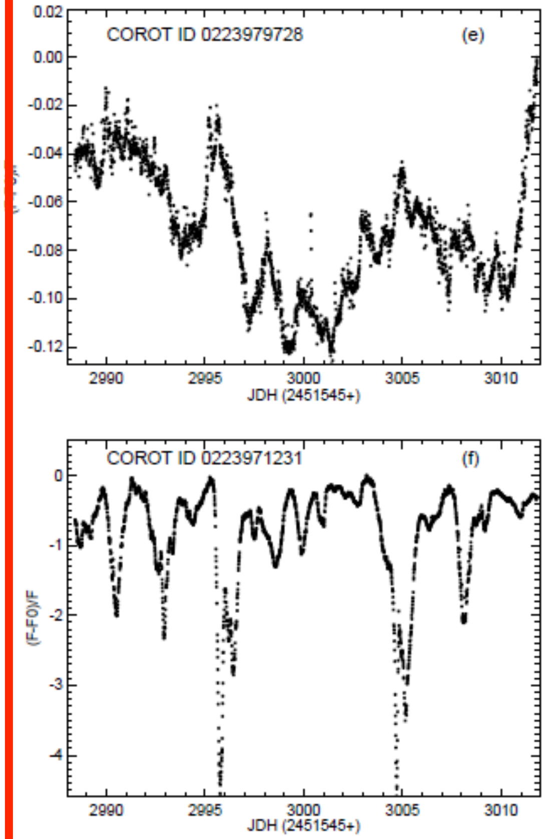
SPOTS

Quasi-Periodic
AA Tau-like



OBSCURATION

Irregular

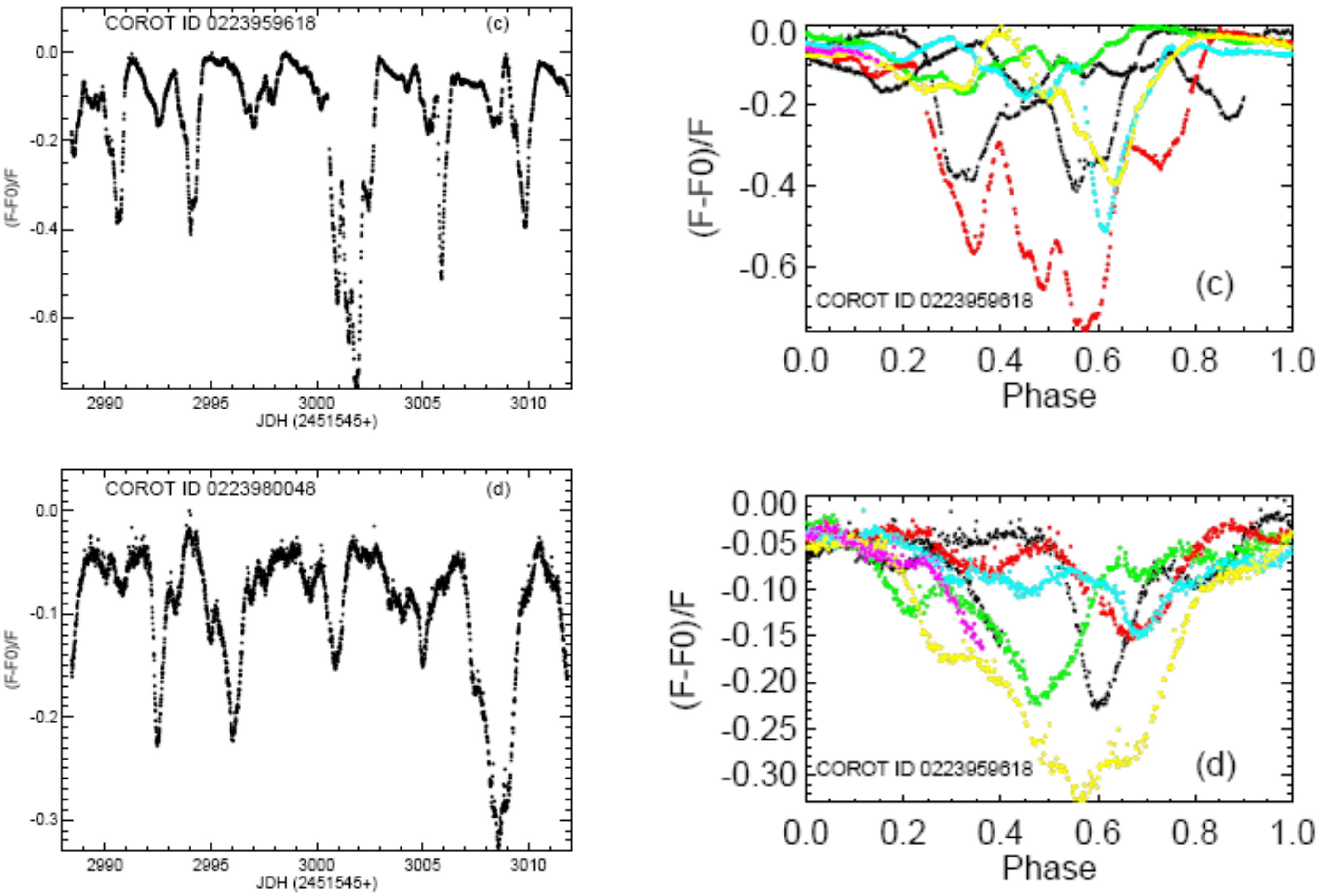


Accretion+obscuration?

AA Tau-like COROT light curves

Periods between 4 and 10 days

Alencar et al. 2010

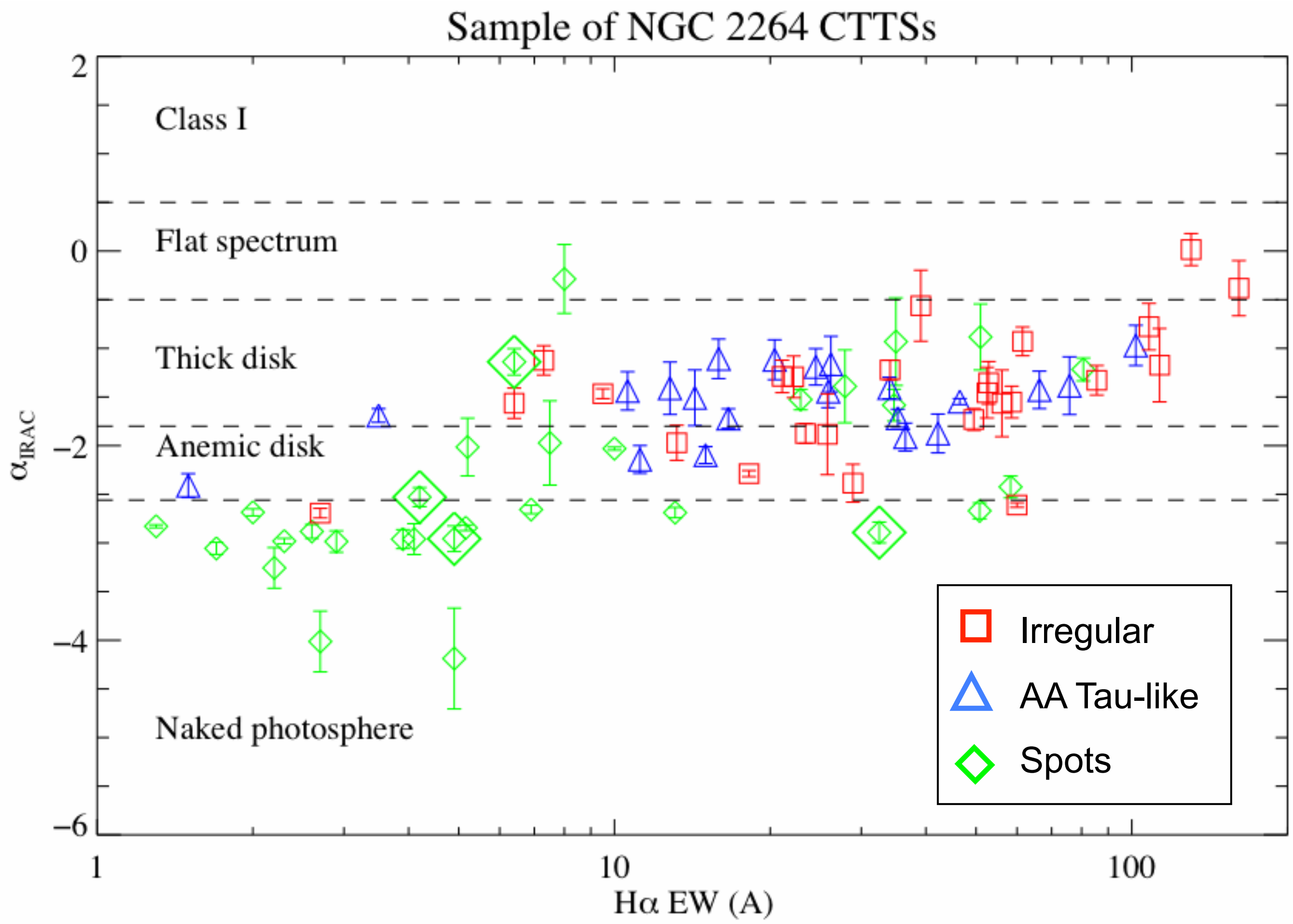


Rapid (~rotation cycle) and significant variations of the occulting material.

Corot light curves vs. disc evolution

Alencar et al. 2010

97 CTTS with IRAC [3.6-8]µm color



The Corot light curve morphology reflects the evolution of the disk

25% of CTTS exhibit AA Tau-like light-curves

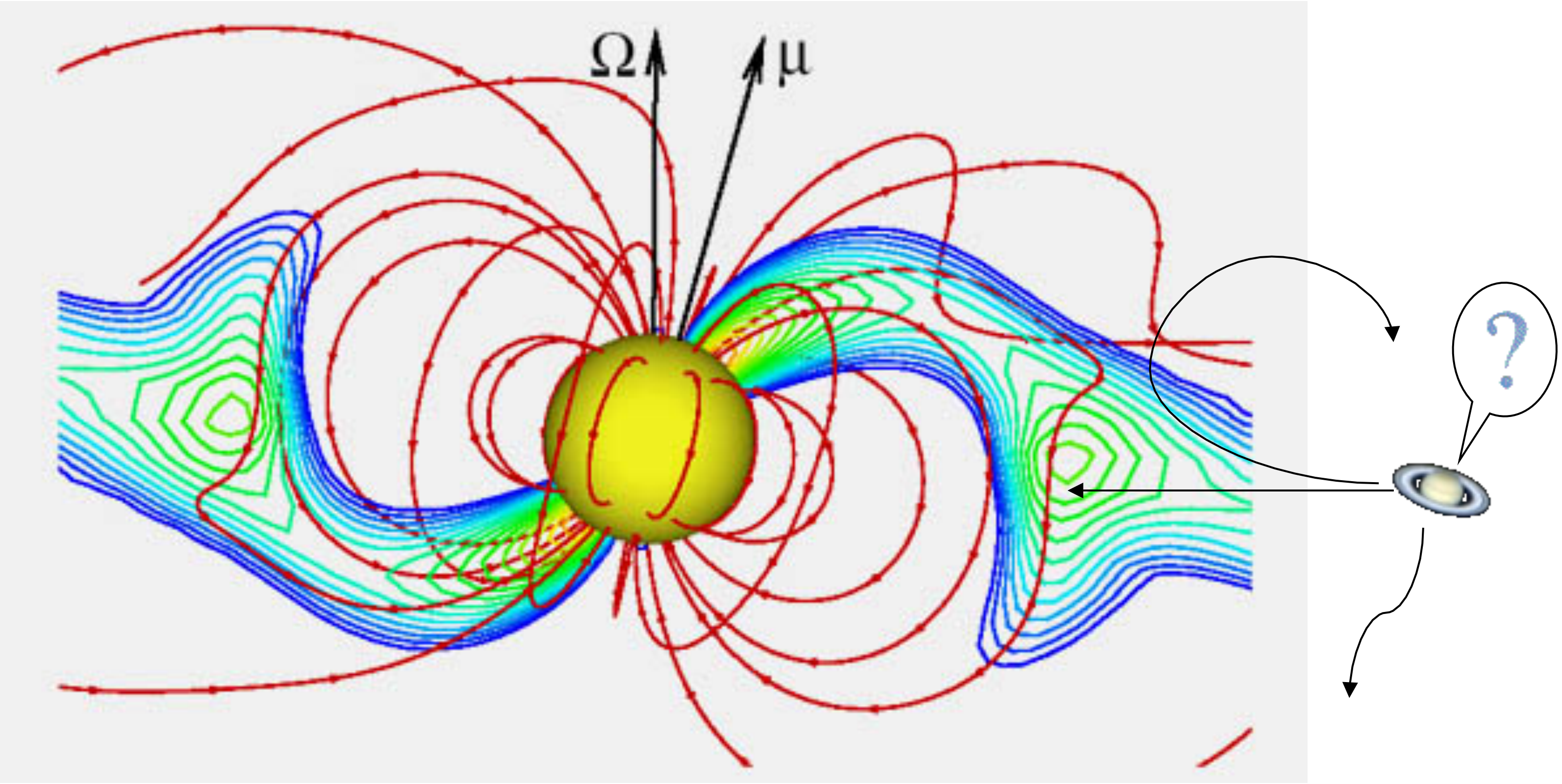
Assuming random inclinations, this fraction yields : **h/R~0.3 at the inner disk edge**

(while flared α-disks have h/R≤0.1)

Implications for planet formation and migration

Inner disk warps

induced by the interaction with an inclined magnetosphere

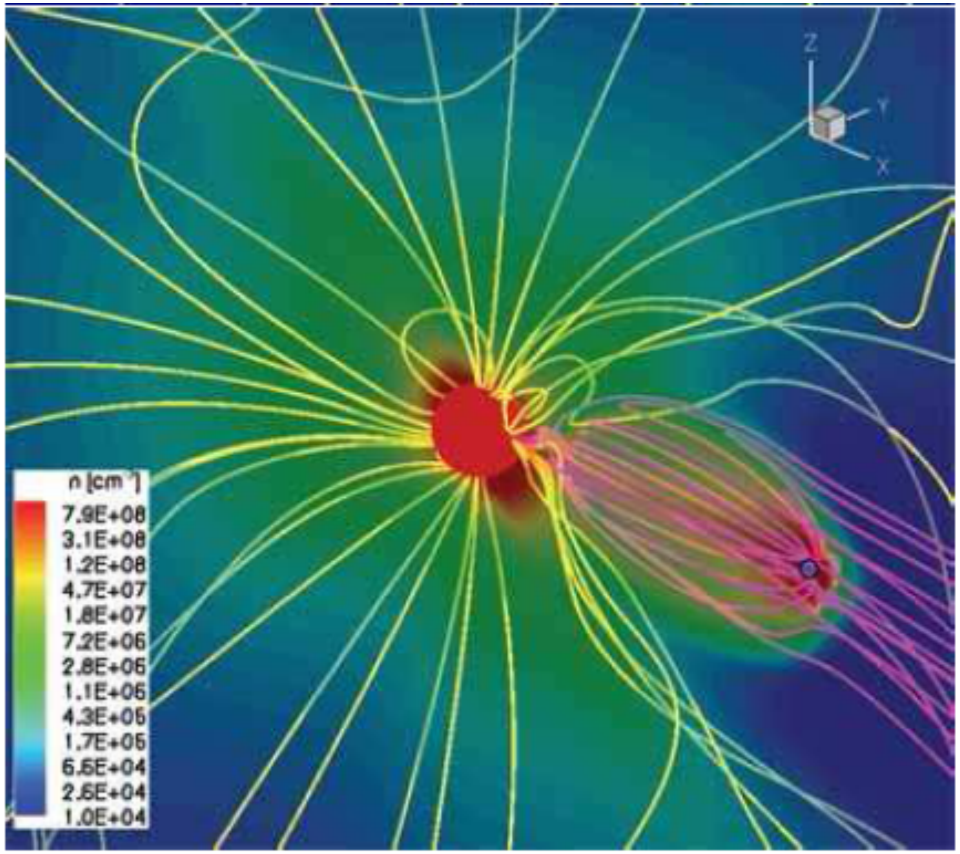


Halting the planet migration ?

“Hot Jupiters” (or Saturns…)?

Star-planet interacting magnetospheres ?

MHD simulations of the star-planet magnetospheric interaction



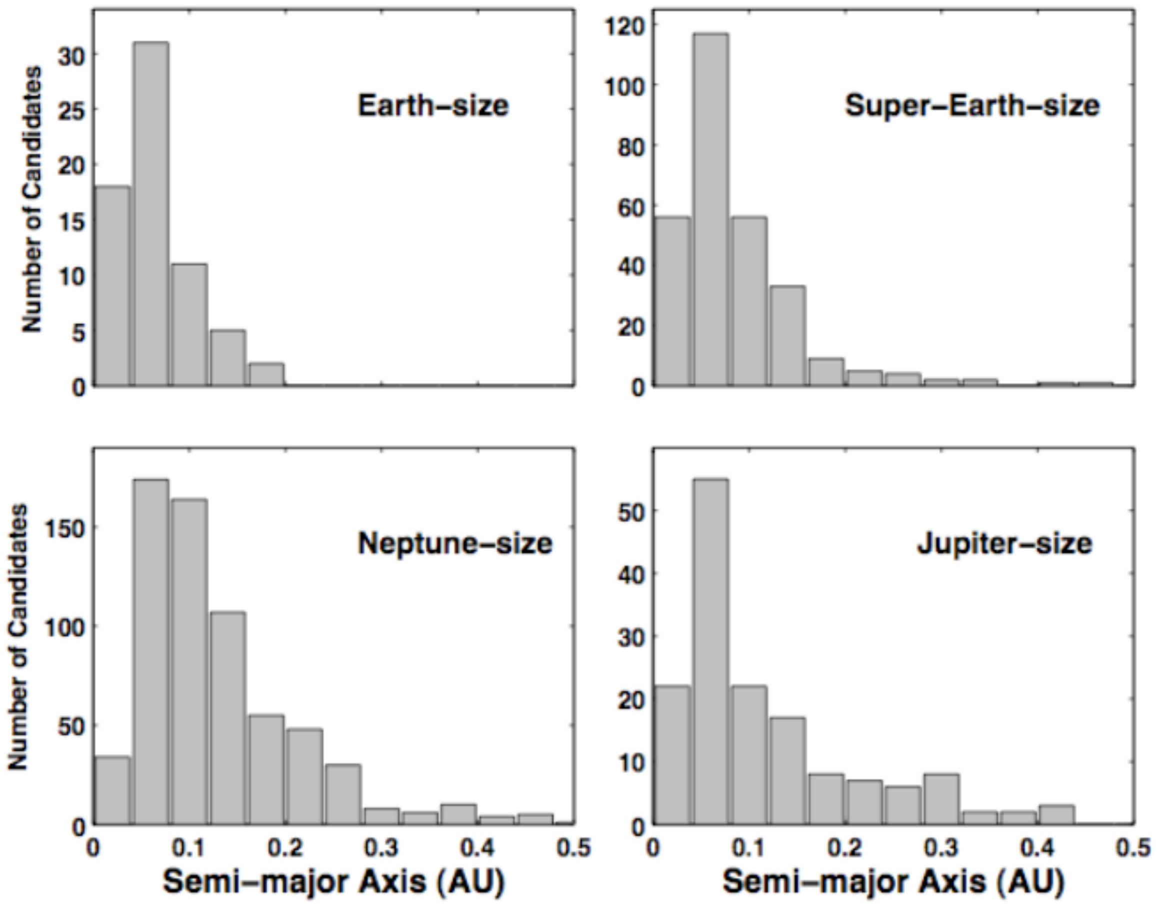
Cohen et al. 2009

Main sequence system:
B(star) = 5 G
B(planet) = 2 G

Much stronger fields to be expected at 1-10 Myr (~ 0.1-1.0 kG)

Impact on planet formation ?

1235 planetary candidates from Kepler



Semi-major axis distribution of transiting planetary candidates peaks at : **a ≤ 0.1 AU**

Is there a link between the orbital radius of planetary orbits and the magnetospheric truncation radius :
Rm~0.05-0.1 AU ?

Borucki et al. 2011

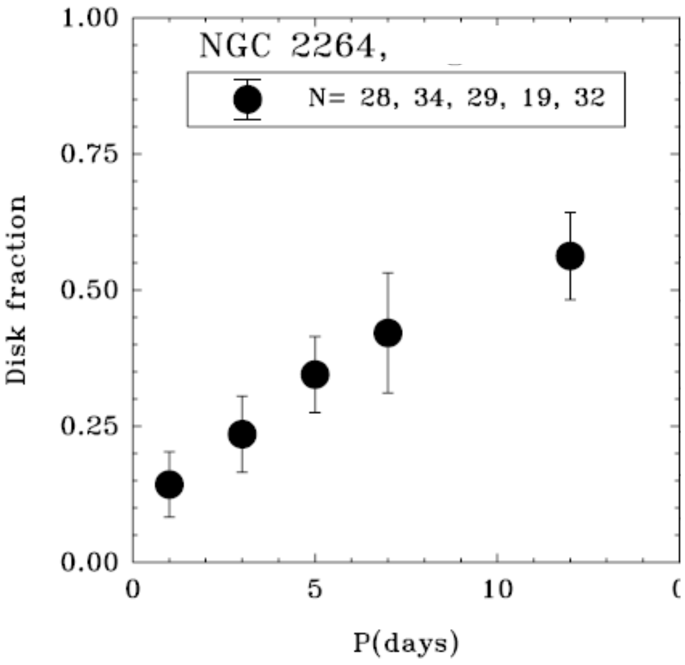
Angular momentum evolution, disc lifetimes and planet formation timescale

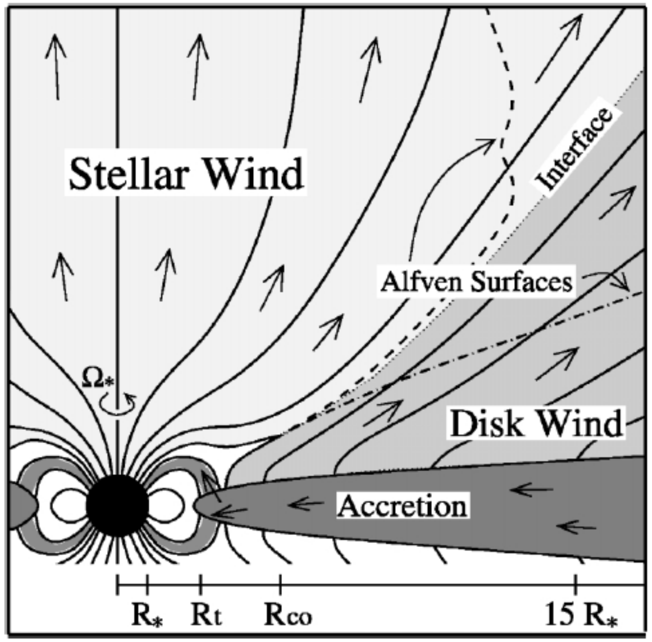
Angular momentum regulation

The magnetic star-disc interaction regulates the angular momentum of the star.

e.g., **accretion-powered magnetic winds** carry away angular momentum, thus braking the star

Cieza & Baliber 2007



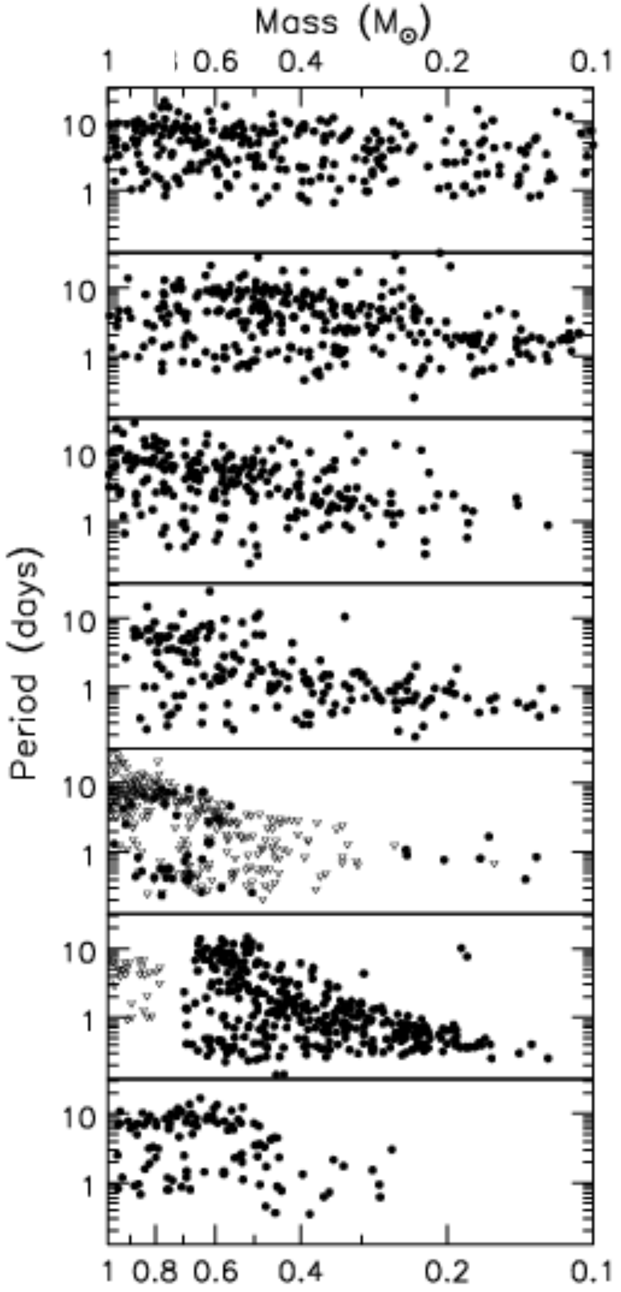


Matt & Pudritz 2005

Observational evidence for **« Disc locking » :** as long as the star accretes from its disc, it evolves at a constant angular velocity

The rotational distributions of young stars

Monitor Project (Aigrain et al.)



ONC
1 Myr
(Herbst et al. 2002)

NGC 2264
2 Myr
(Lamm et al. 2005)

NGC 2362
5 Myr

NGC 2547
40 Myr

Pleiades
100 Myr
(compilation)

NGC2516
150 Myr

M34
200 Myr

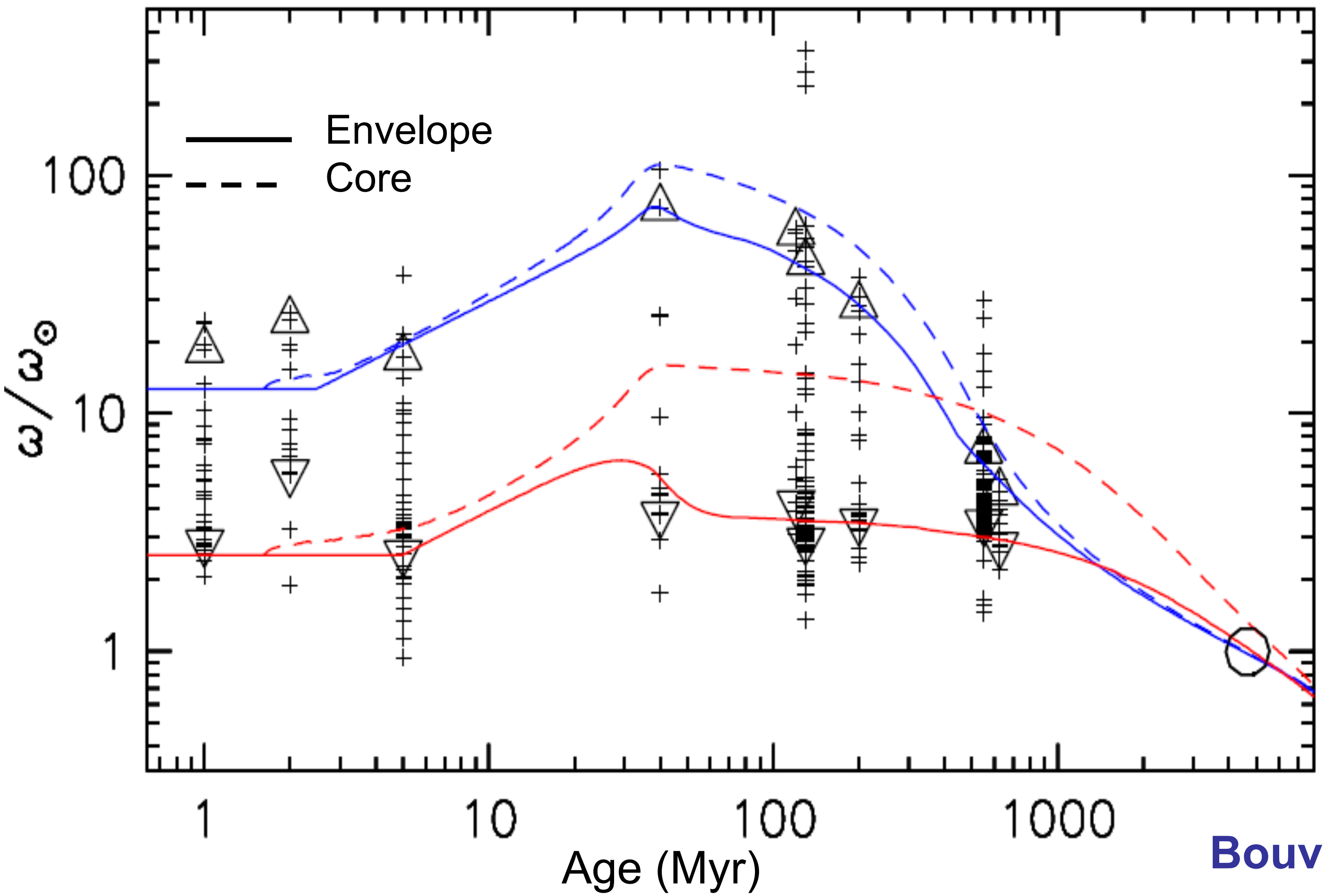
Rotation period measurements for hundreds of stars in the mass range 0.1-1.0Mo in PMS and ZAMS clusters over the age range 1-200 Myr

Provides unique constraints on PMS and early ZAMS angular momentum evolution

Irwin & Bouvier 2009

The rotational evolution of solar-type stars

Rotational evolution from 1 Myr to 10 Gyr : observations vs. models



Bouvier 2008

Lithium in exoplanet hosts

Solar-type stars with massive planets have lower Li abundances than solar-type stars without massive planets

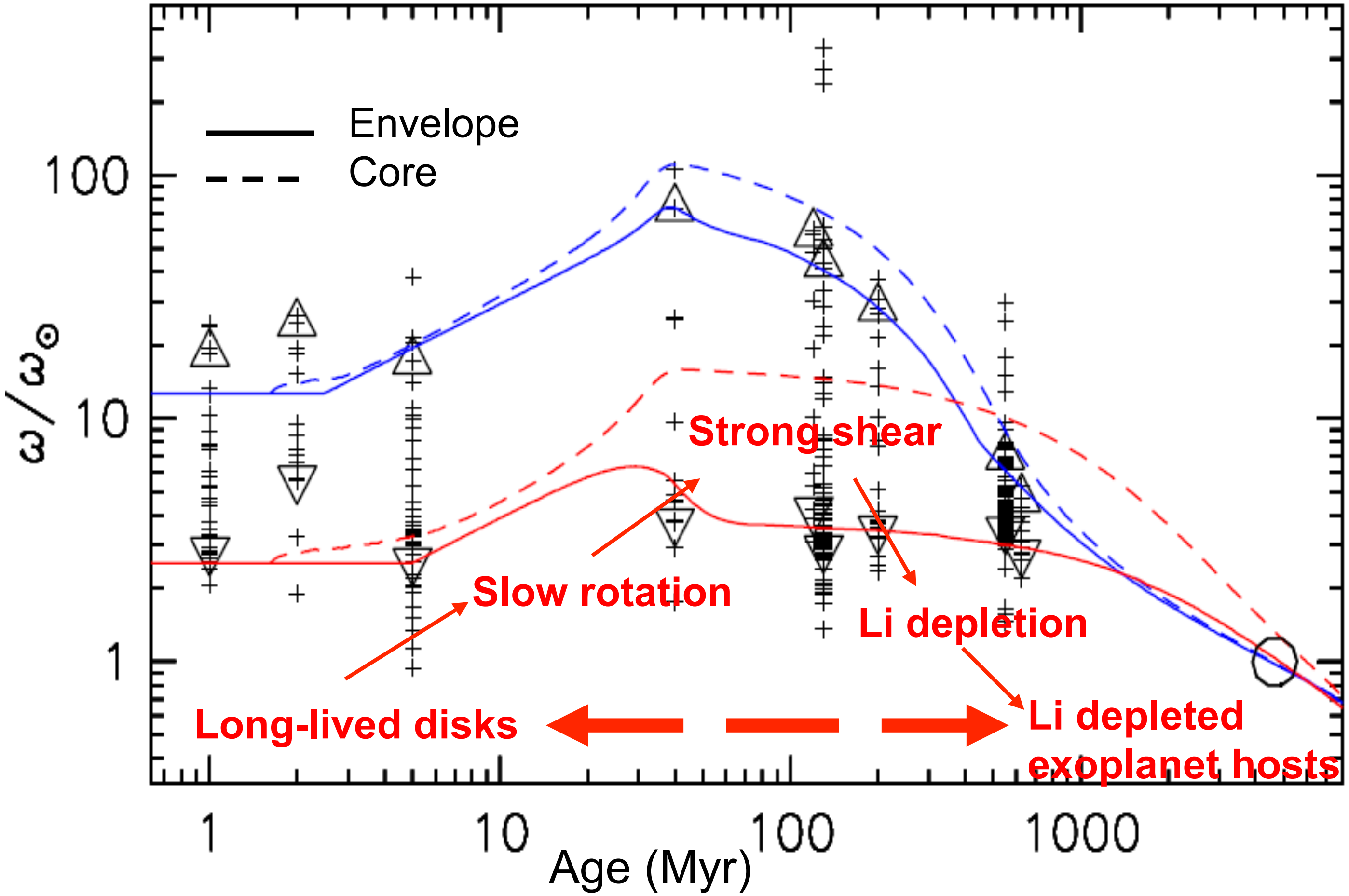
Israelian et al. 2009; Gonzalez 2008

Enhanced Li depletion in exoplanet hosts

A signature of the early rotational evolution of exoplanet hosts ?

Rotation, lithium, and planet formation

Why are exoplanet hosts lithium over-depleted ?



Suggests that long lived disks (≥ 5 Myr) are required for planet formation

Conclusions

The **magnetic star-disc interaction** seems to be **ubiquitous** in young stars, and impacts on :

- The structure of the inner disk, producing a non-axisymmetric warp (with consequences on radiative transfer, chemical evolution, disk dissipation, etc.)
- Planetary migration via the development of a magnetospheric cavity (size ~ a few stellar radii)
- Angular momentum transfer that dictates the rotational evolution of young stars
- Different PMS rotational histories may result in lithium dispersion on the main sequence