The star-jet-disk system and angular momentum transfer

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why did God make such a complicated star-disk interface?

The angular momentum (and energy!) problem

If stars accrete most of their mass from disks, they should be rotating rapidly

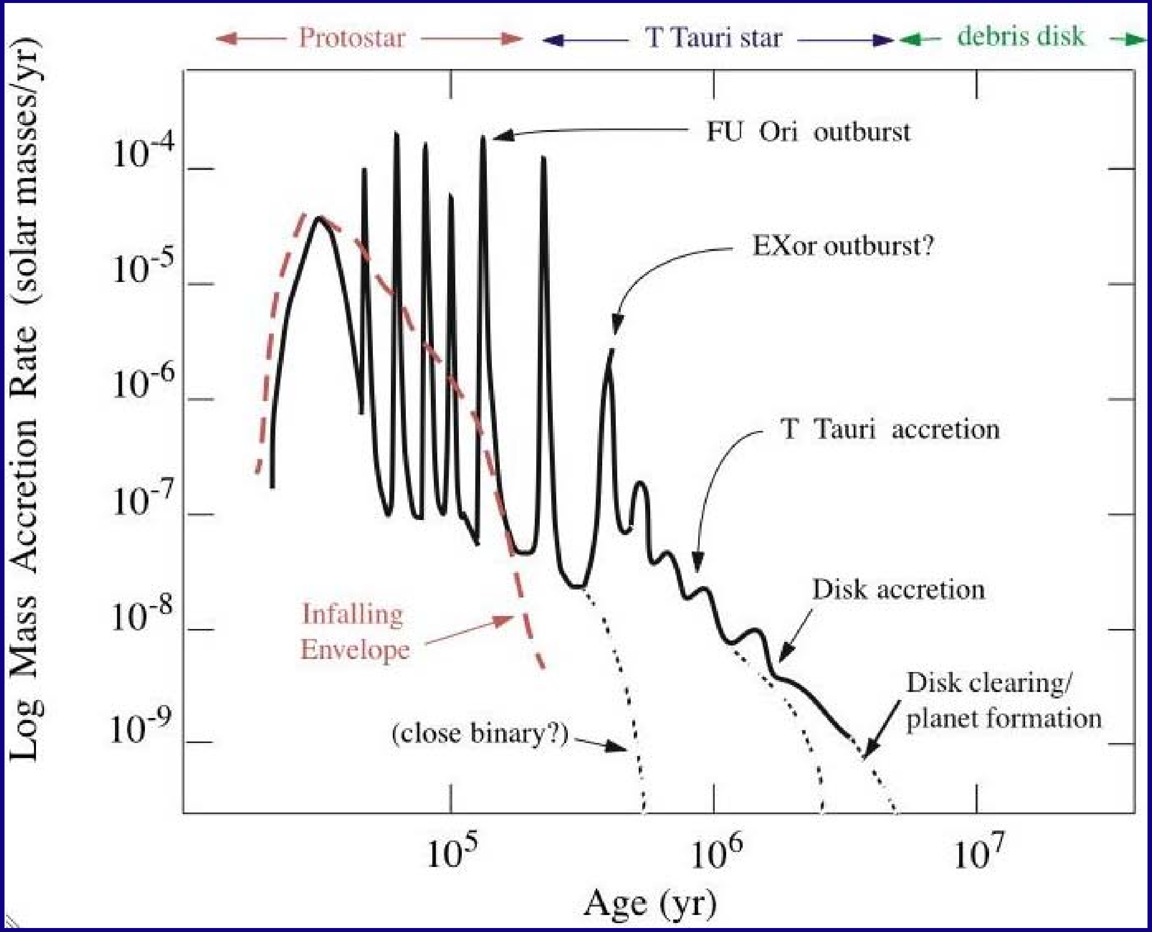
But they don't (~ 10% breakup for low-mass stars...)

This implies that a LARGE fraction of the accretion energy goes into whatever causes spindown ------- winds/jets! ($J = v_K r$; $KE = (1/2)\ v_K^2$)

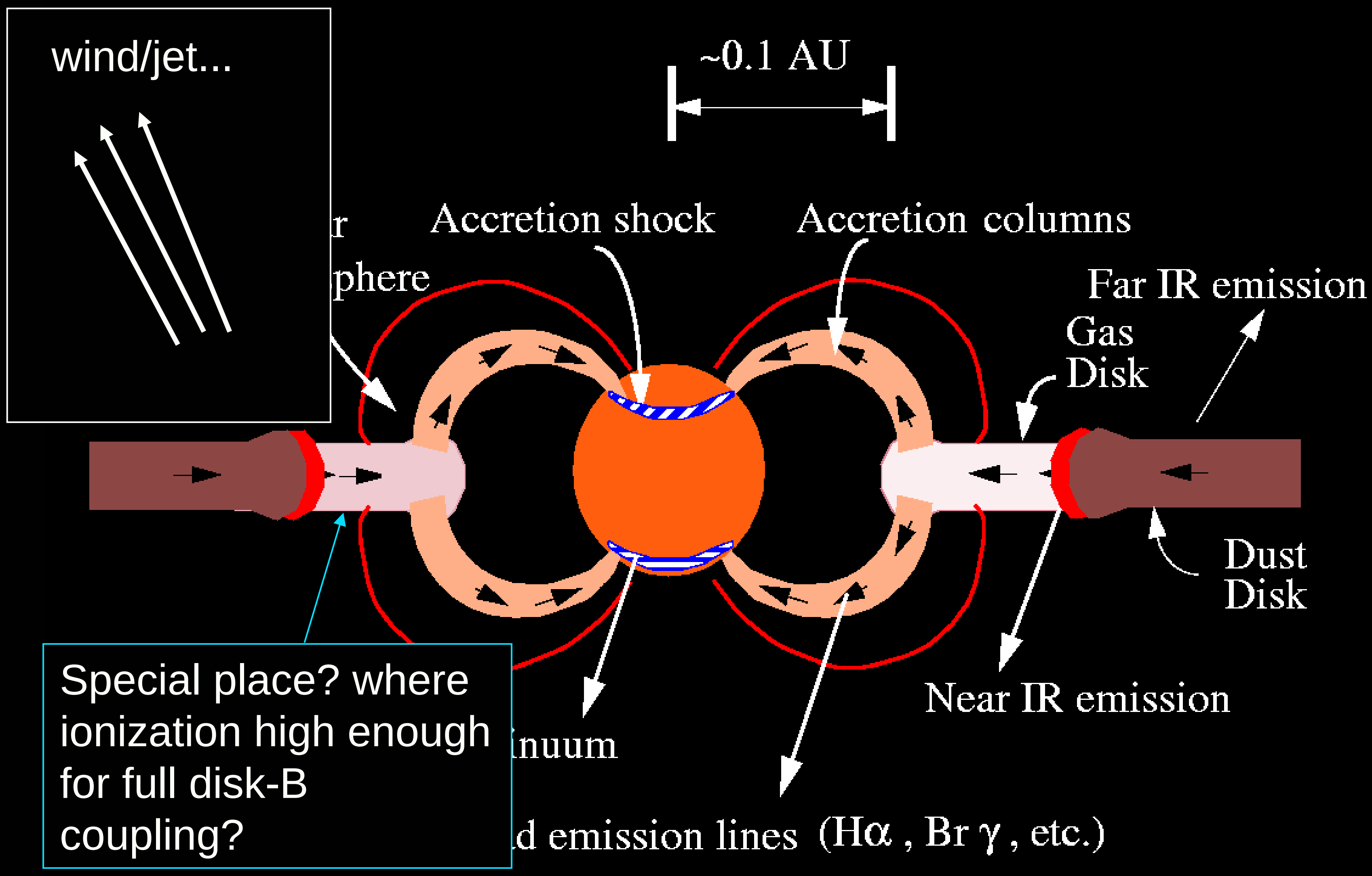
Magnetosphere-disk spindown (?)

Most of the stellar mass and (therefore) J is accreted in the protostellar phase - dM/dt may be high enough to crush magnetospheres.

- Here I assume that the protostellar “in between” times of slow accretion is where spindown occurs.

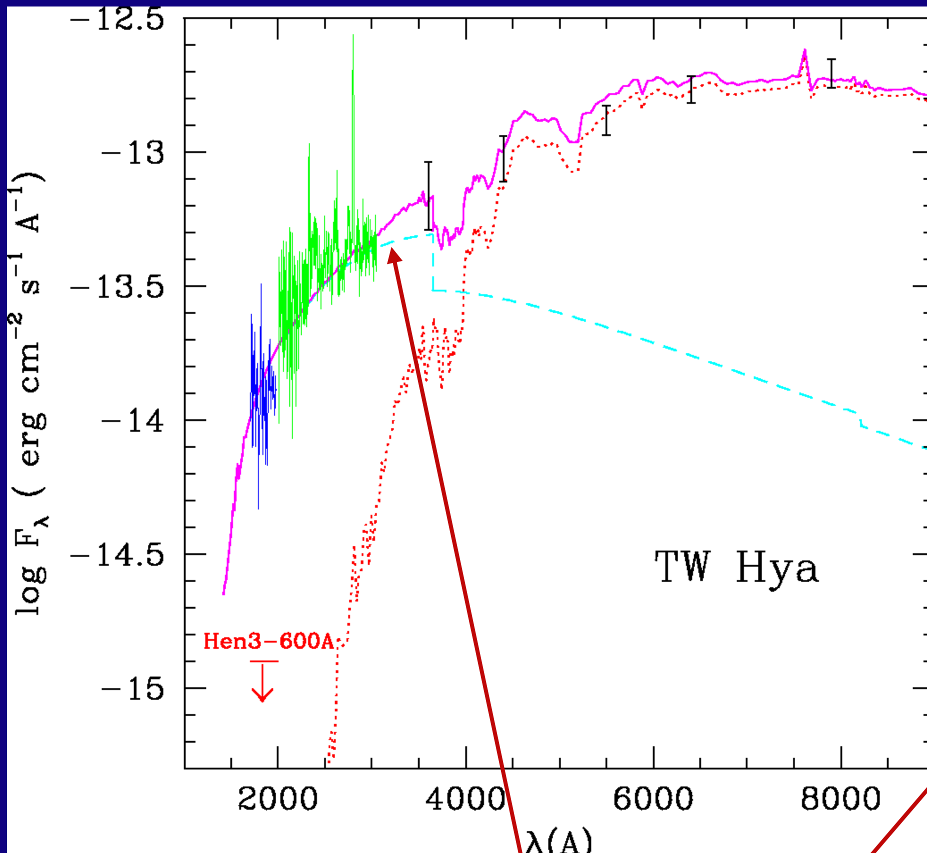


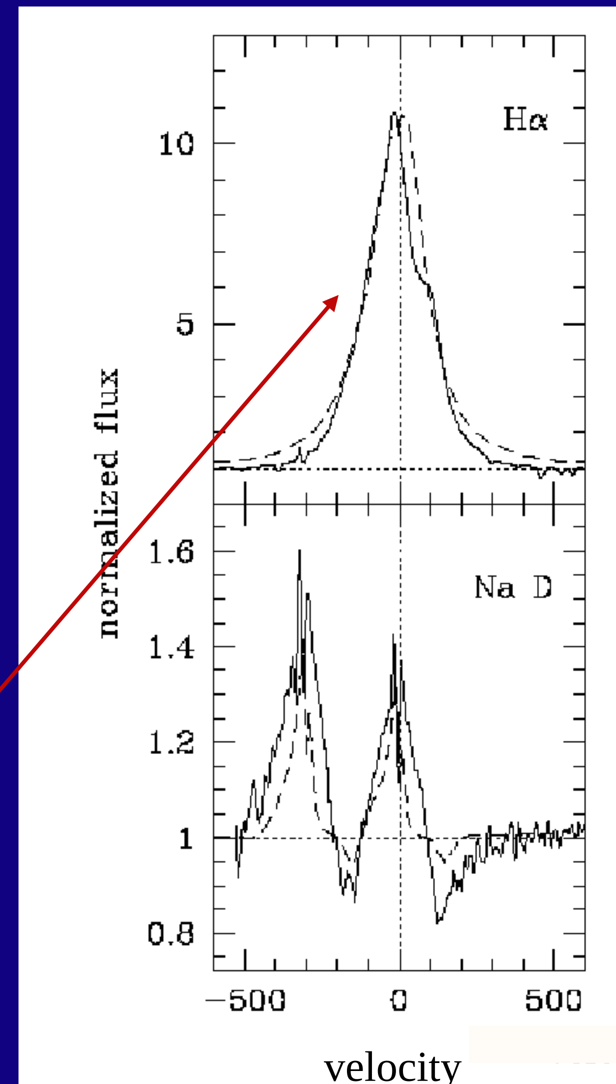
T Tauri star - magnetospheric accretion



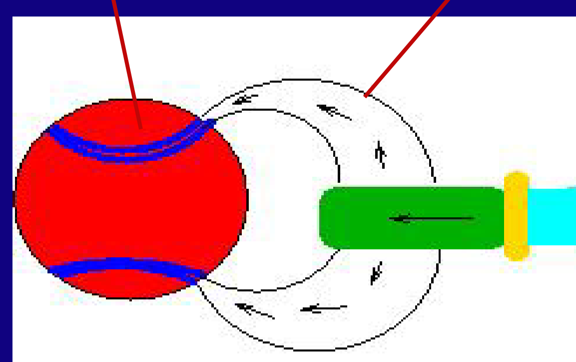
Excess emission/veiling

Broad emission lines   v ~ 250 km/s



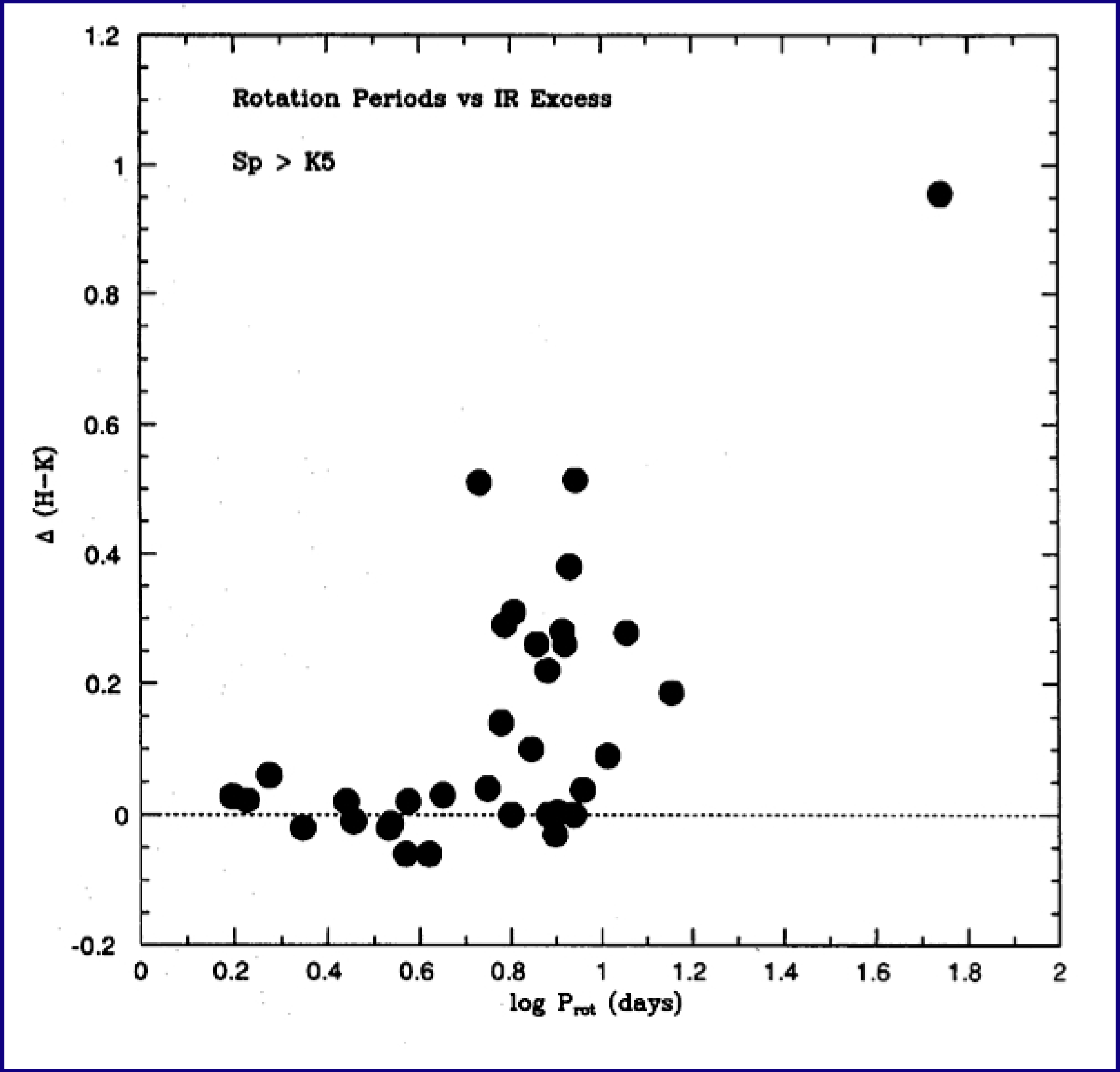


Calvet et al.



Muzerolle et al.

slow rotation (narrow distribution) for K7-M4 CTTS

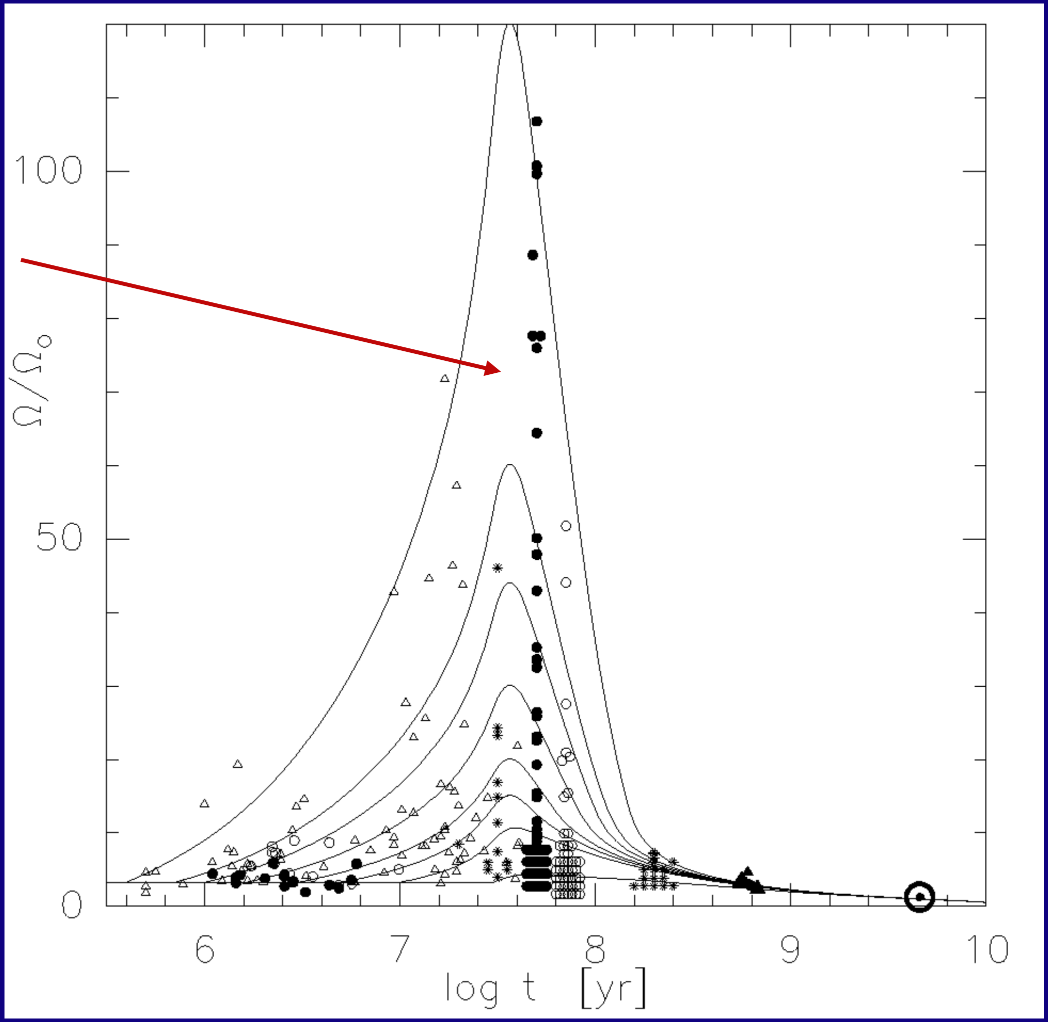


Edwards et al. 1993

Stellar wind spindown? but fast rotators in Pleiades require spinup during contraction to main sequence - stellar wind can't be TOO effective

(spinup due to contraction toward MS

Stauffer et al. 1986
Bouvier et al. 1997



The angular momentum problem

Solution (?): some stars spin down by coupling magnetically to their disks (Königl 1991); stellar wind spindown is slower, only effective at later times.

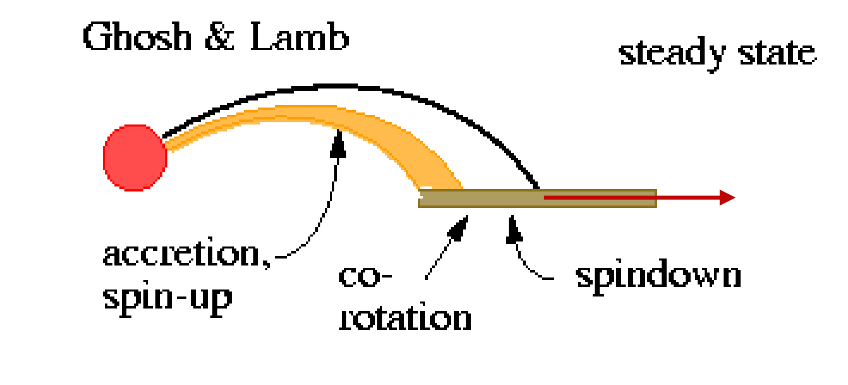
Explains why CTTS (stars with disks) rotate more slowly than WTTS (stars without disks)...

except that the stars with disks are ACCRETING, both mass AND angular momentum - we are having our cake and eating it too

The angular momentum problem

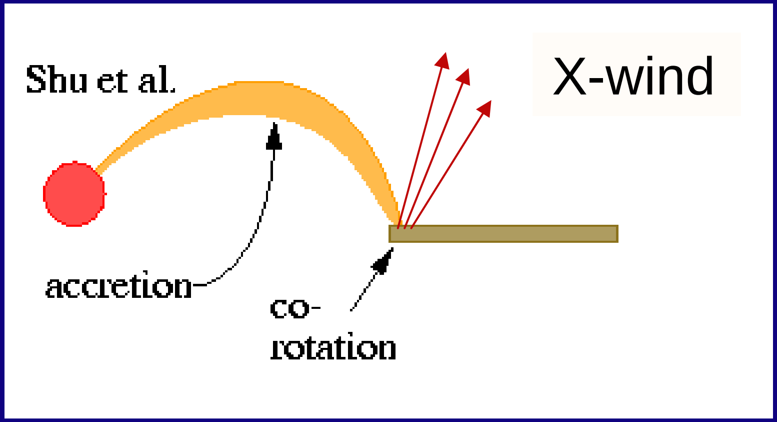
Accretion implies J(disk) $\Rightarrow$ J(star); how to get rid of it?

Solution 1: different field lines
problem: field lines wind up unless perfect "slippage"



(Konigl, Collier Cameron & Campbell)

Solution 2: exact co-rotation, no winding
problem: unrealistic (axisymmetric, etc.)
detailed assumptions of angular momentum transfer?



Does disk braking really work?

(at least in the simplest ways)

Disks may be truncated INSIDE corotation:

• Near-IR excess: T ~ dust sublimation temperature (Muzerolle et al. 2003; Natta et al. 2001 for HAe/Be)$\Rightarrow$ disk truncation can be closer to the star than previously assumed

• Eisner et al. 2005, 2007 - may be gas interior to dust sublimation radius

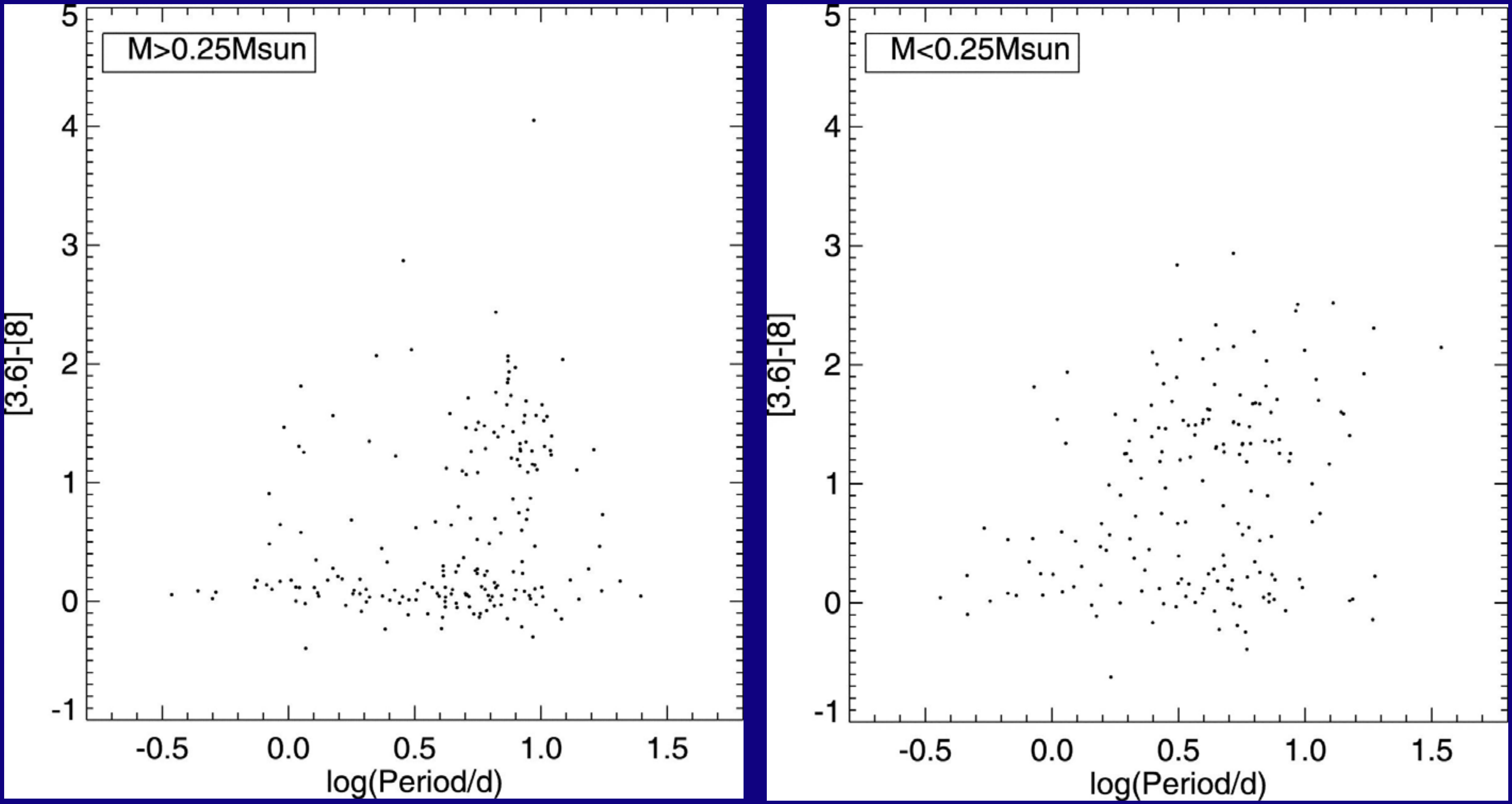
More generally, steady state is implausible:

• field lines not plausibly smoothly slipping through disk (G&L)

• exact truncation at corotation is implausible (Shu) because magnetic fields and accretion are unsteady on short timescales; fields are non-axisymmetric

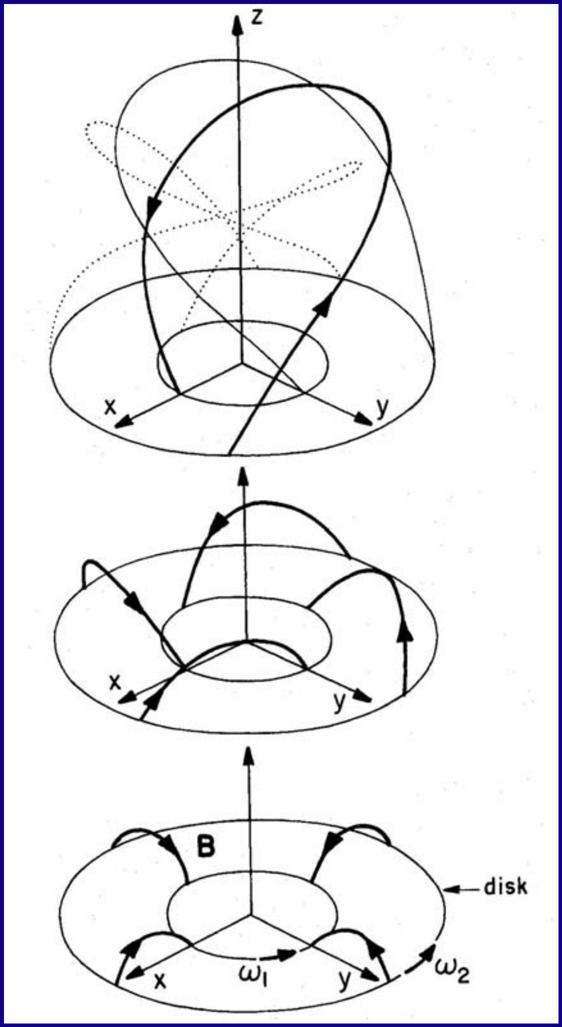
• observationally, complete disk locking of rotation less clear, especially for low-mass stars...

larger samples of stars suggest broader range of CTTS rotation



Rebull et al. 2006

General case: magnetic field lines twist up, balloon out as they are twisted - then reconnect



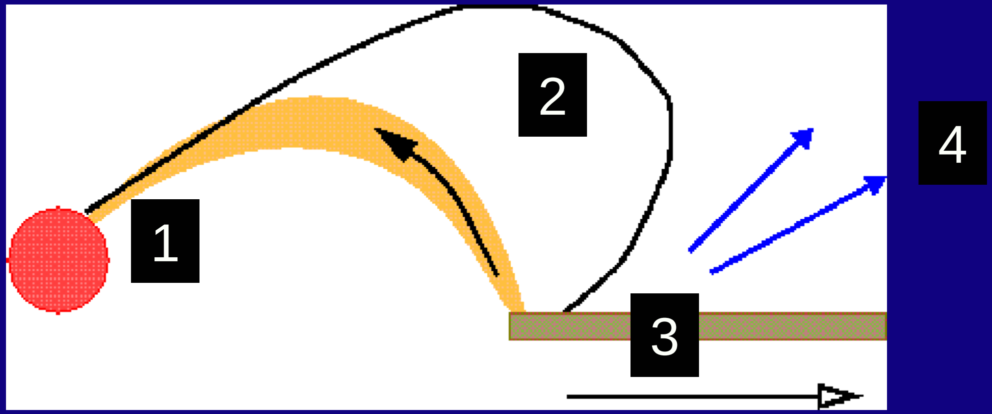
reconnection-

$\Rightarrow$ limits spindown (too much?)

(Matt & Pudritz 2004)

Lovelace, Romanova, & Bisnovatyi-Kogan 1995

Alternating cycles of accretion and disk braking?



1. accretion

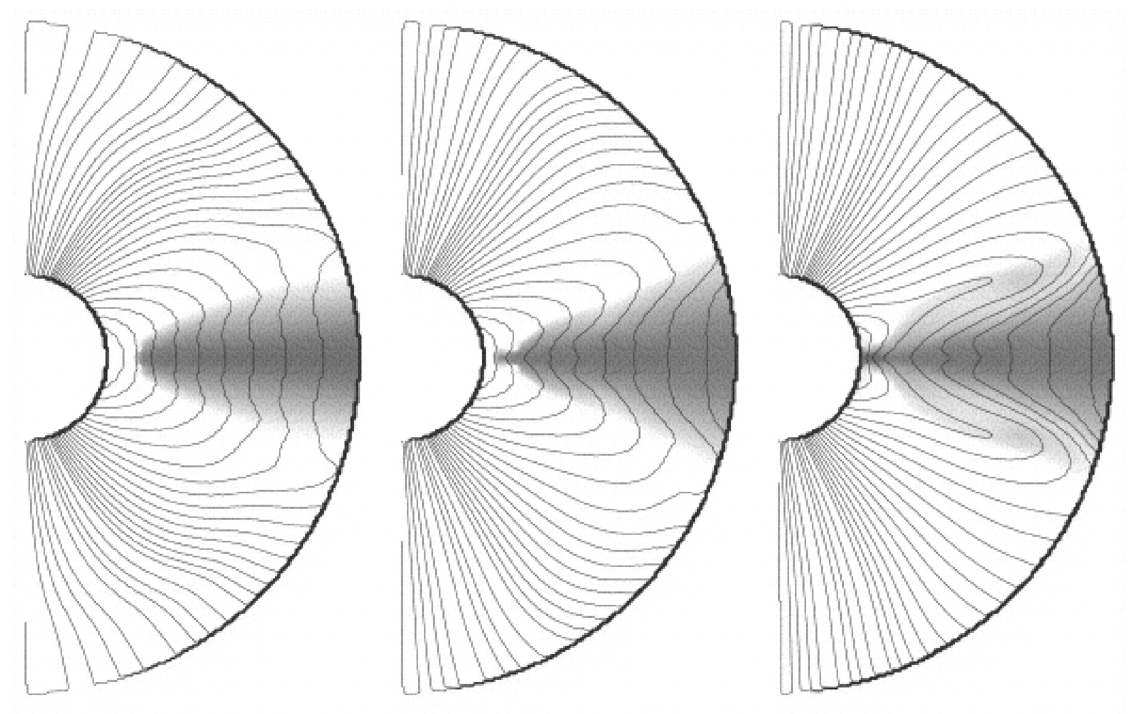
2. bulging field lines - material drains out onto star AND disk

3. accretion stops, field lines might move outside of corotation - disk braking

4. field configuration might assist disk outflow

pure “propeller mode” (i.e., magnetospheric boundary > corotation) - doesn’t work if disk is accreting; material piles up until it pushes the magnetosphere inward and then accretes

(don’t observe this anyway -not even alternating cycles



Miller & Stone 1997

Matt & Pudritz (2008a,b) suggest-
STELLAR WINDS!

Advantages:

- field lines connect to star, so star is directly spun down
- don’t need star to be spinning at breakup!

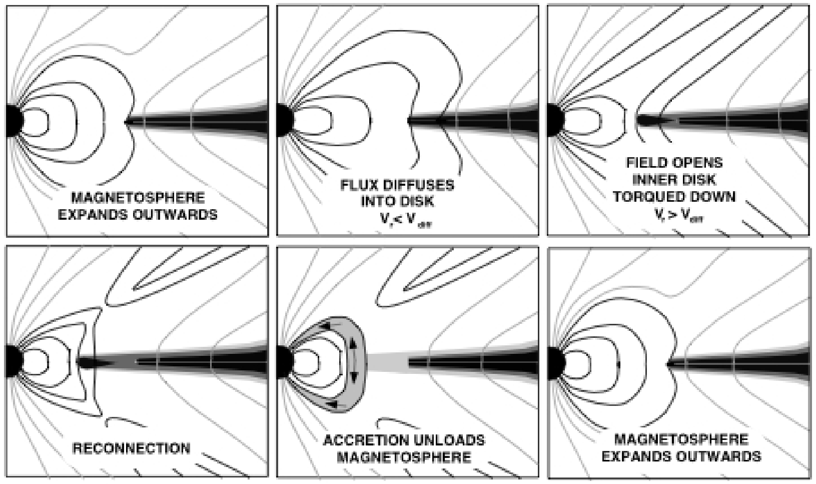
Disadvantages:

- stellar (magnetic activity) winds not powerful enough (otherwise, spindown to main sequence)
- therefore need other, very large energy source

Solution: tap into accretion energy! (need to differentiate CTTS from WTTS)

problem: how?

Wind driven by magnetic field inflation

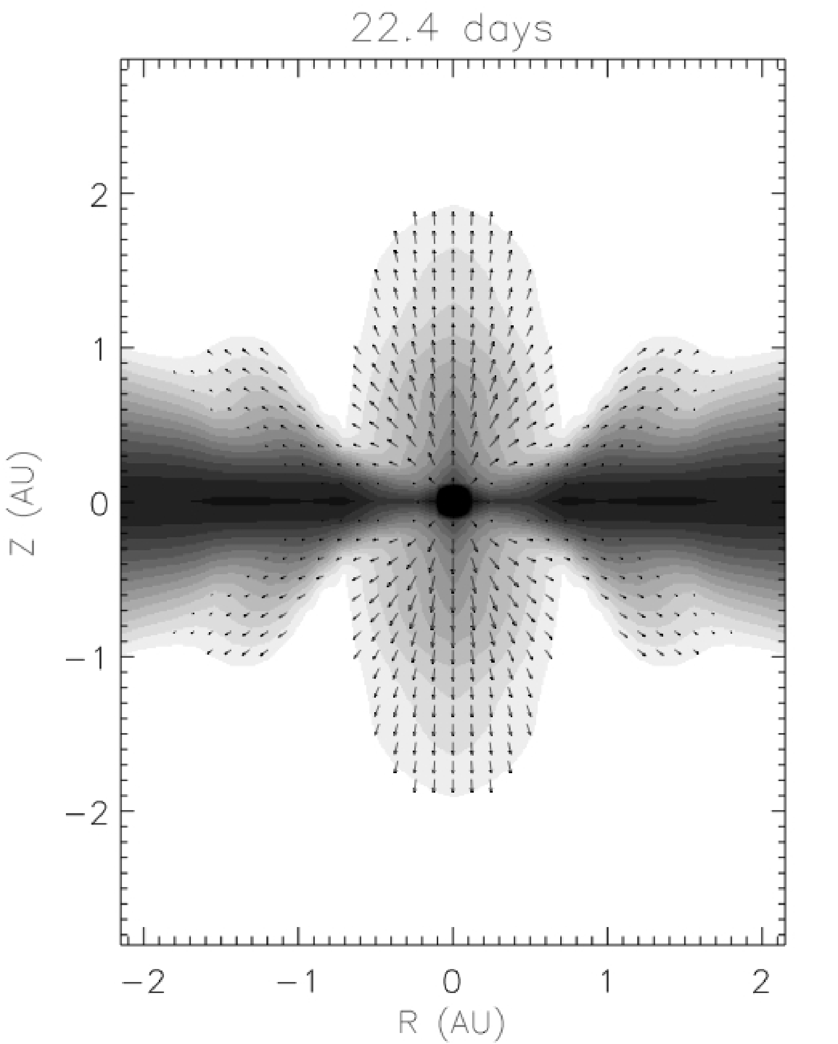


Goodson, Winglee, Böhm 1997; Goodson, Winglee 1999; Matt et al. 2002

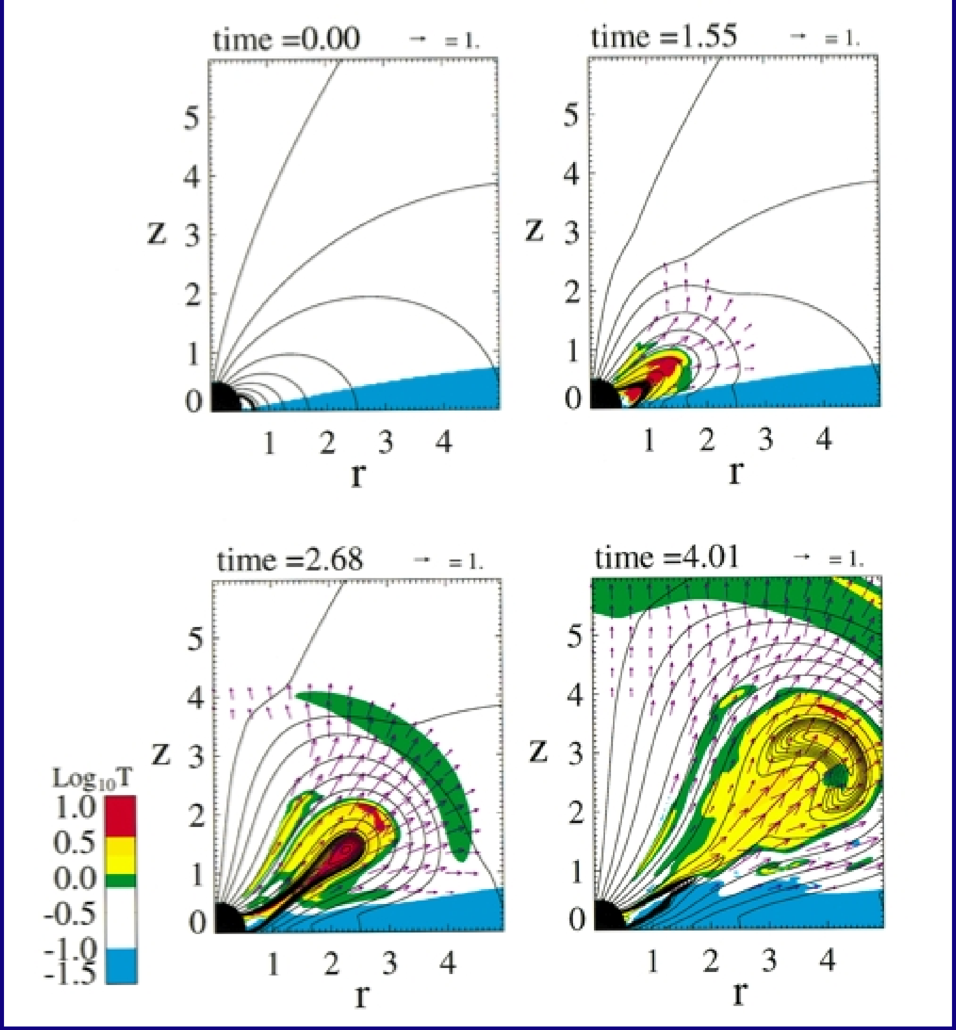
⇒mass ejection during inflation/reconnection of twisting field lines

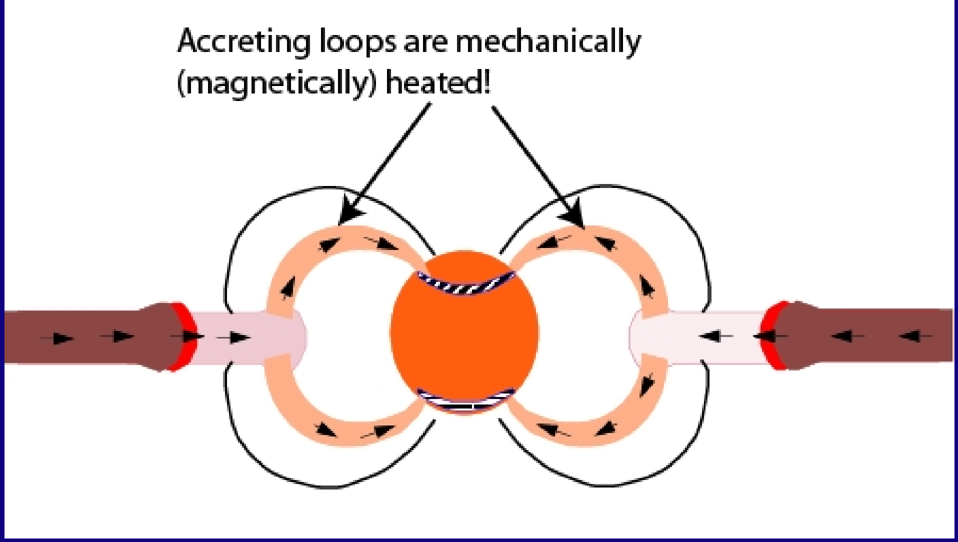
⇒ angular momentum loss from B connected with both the disk AND the star

⇒taps into twisting energy (which is driven by accretion!)



Hayashi et al. 1996; coronal gas in twisted loop - heating to 10^8 K - outflow, flare...



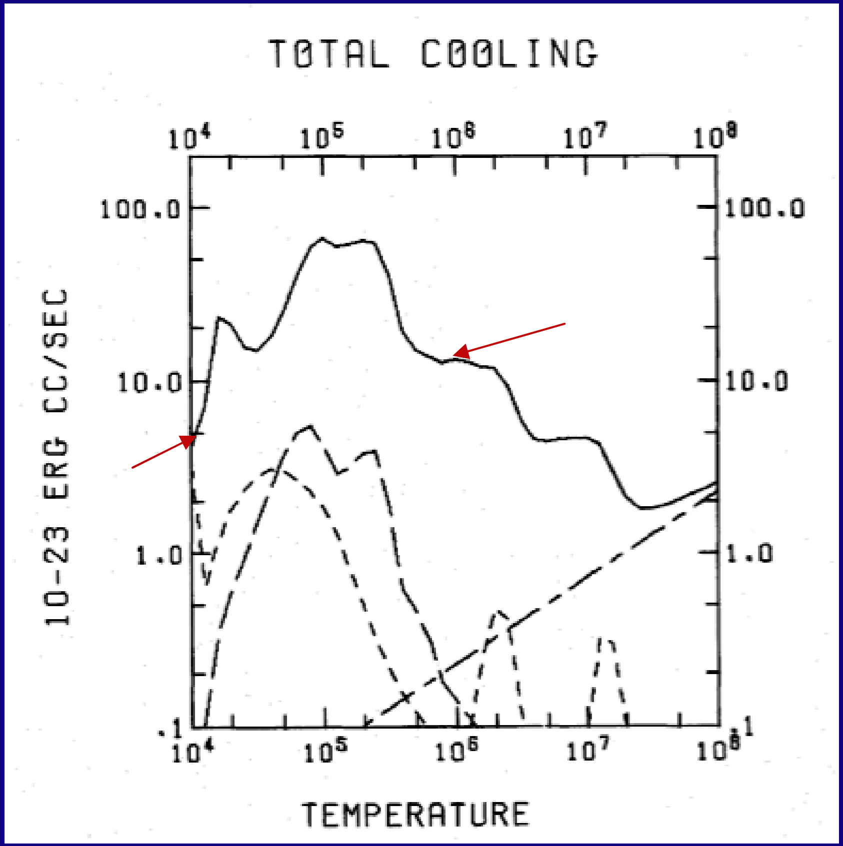


radiative energy loss ~ 1-10% L_{acc}

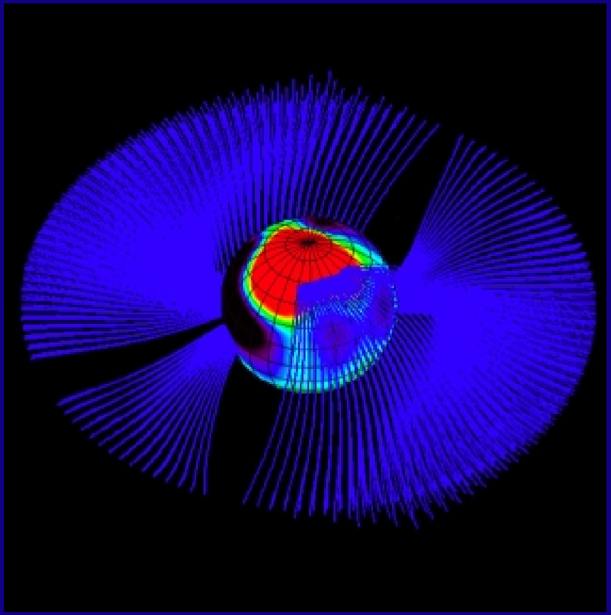
Loops are heated to ~ 10^4 K

⇒ at SLIGHTLY lower density, can be heated to 10^6 K!

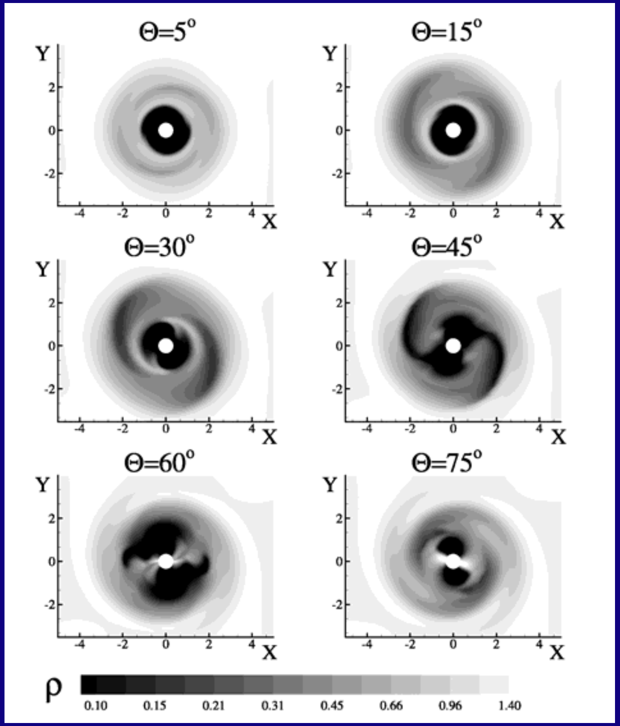
• Why not higher T (coronal) loops *filled with disk material*?



Magnetospheres are complex



Jardine, Donati et al.

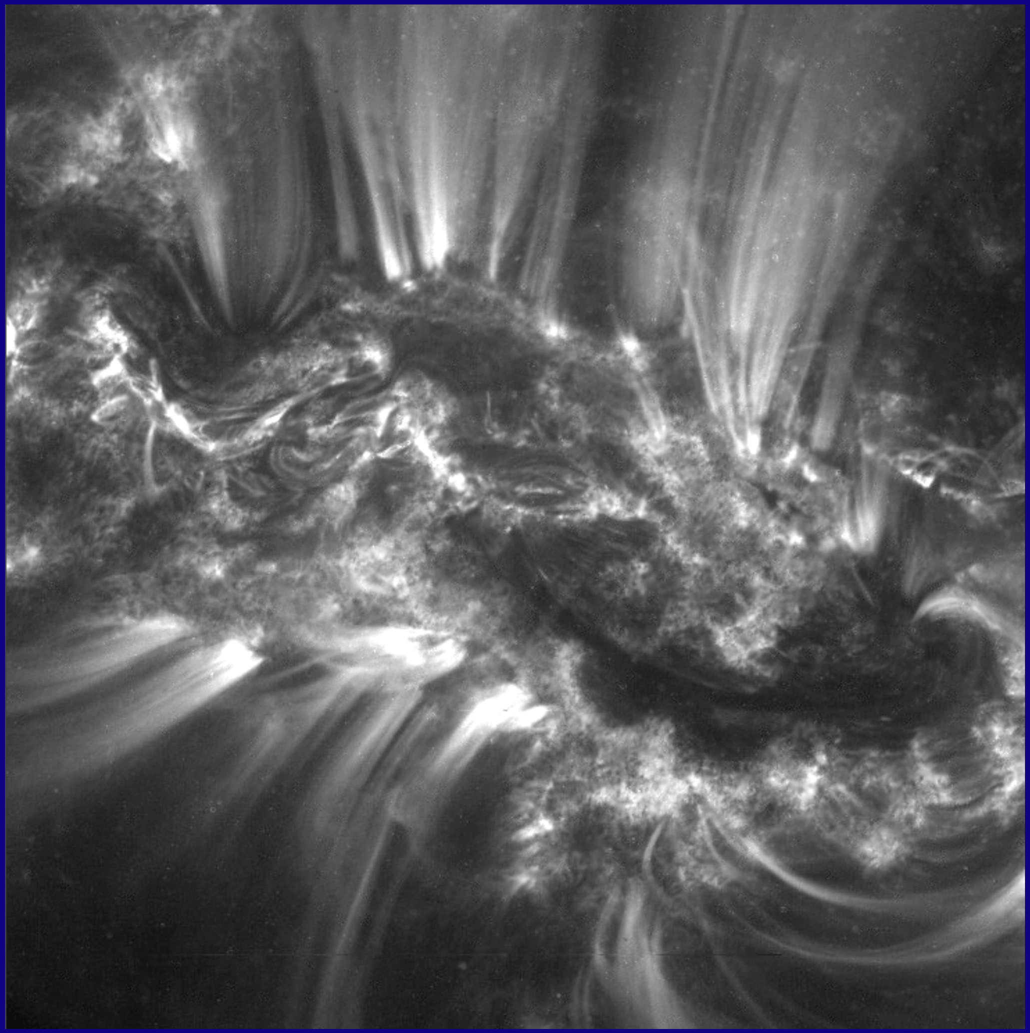


Romanova et al. 2003, 2004

Continuum emission: (Calvet & Gullbring 1998)

- very small (~ 1%) covering factors
- Ingleby & Calvet (in prep); lower-mass flux tubes, f ~ 10%

⇒ ***accretion through many individual flux tubes*** should think of accretion through a multitude of flux tubes with differing densities- and therefore a wide range of temperatures



Implications? Should be warm/hot loops: either

- magnetospheric infall @ 10^5 K (e.g., $c_s << v_{ff}$)
- outflow (T > 10^6 K and/or magnetic propulsion)

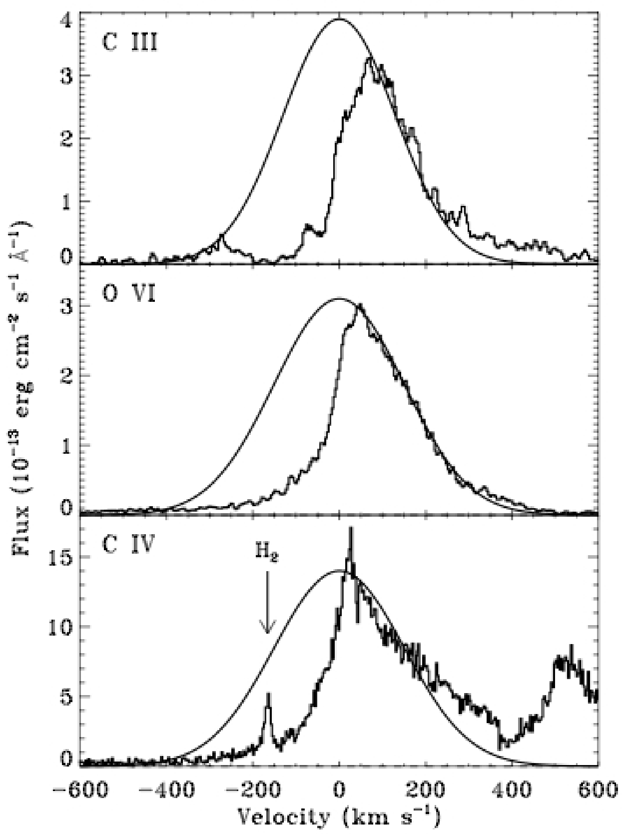
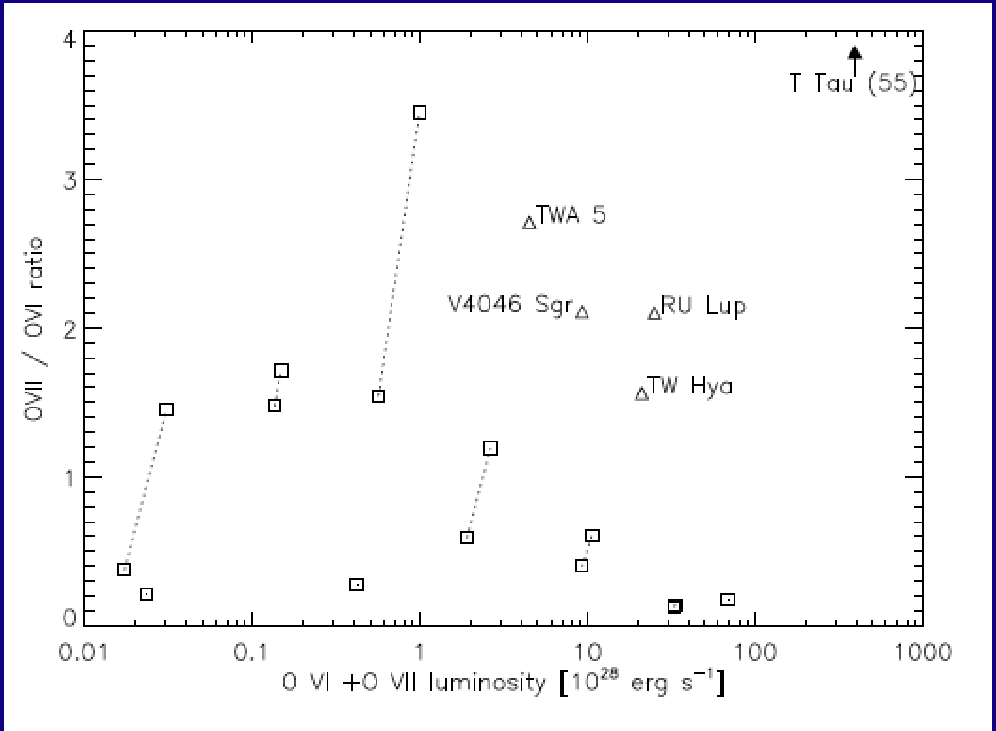


FIG. 2.—Line profiles of C III λ977, O VI λ1032, and C IV λ1548. Shown with each line is a Gaussian fit to the red side of the profile.

Line profiles too wide to be explained by accretion shocks

Dupree et al. 2005, Herczeg & Johns-Krull 2007, Gunther & Schmitt 2008, Lamzin et al. 2007



Hot (closed AND expanding) loops:

• May explain OVII excess in CTTS (Gunther & Schmitt) (higher density loops due to mass accretion, lower T; also gas pressure?)

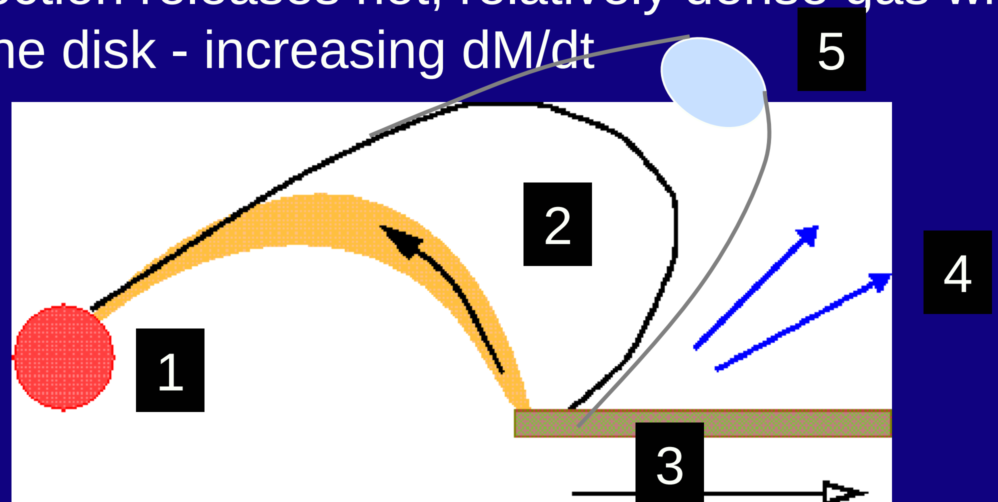
• Some stellar mechanical energy into accreting loops might explain slightly lower L_X in CTTS

• May explain hot winds/accretion (Dupree et al.)

Alternating cycles of accretion and disk braking

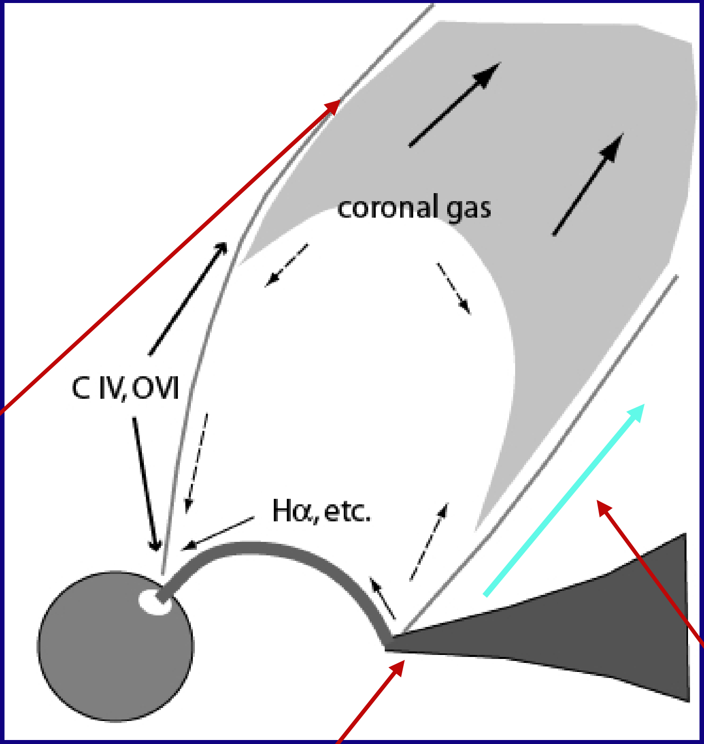
Modifications:

- many independent field lines, doing different things at same time
- during (2), mass drains out - density drops UNTIL magnetic heating creates enough gas pressure to support material...
- then reconnection releases hot, relatively dense gas which originated in the disk - increasing dM/dt



1. accretion
2. bulging field lines - material drains out onto star AND disk
3. accretion stops, field lines might move outside of corotation - disk braking
4. field configuration might assist disk outflow
5. mass ejection of hot trapped disk gas - spin down BOTH star and disk

How ugly can it get? several mechanisms operating at once?



"Accretion-powered" stellar wind- not enough by itself(?)

Some disk braking from field lines tied to the disk outside of corotation?

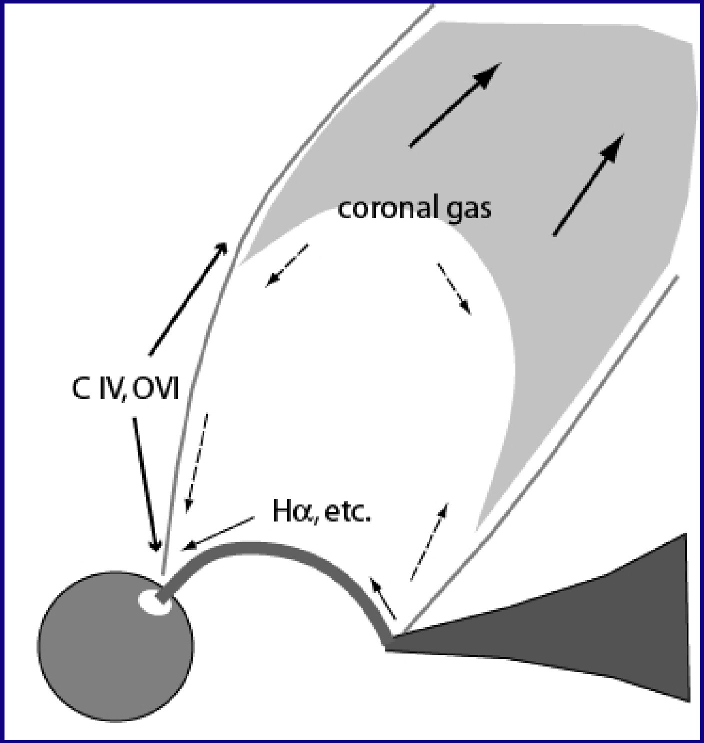
Some disk wind angular momentum loss from inner disk?

“Twister” scenario

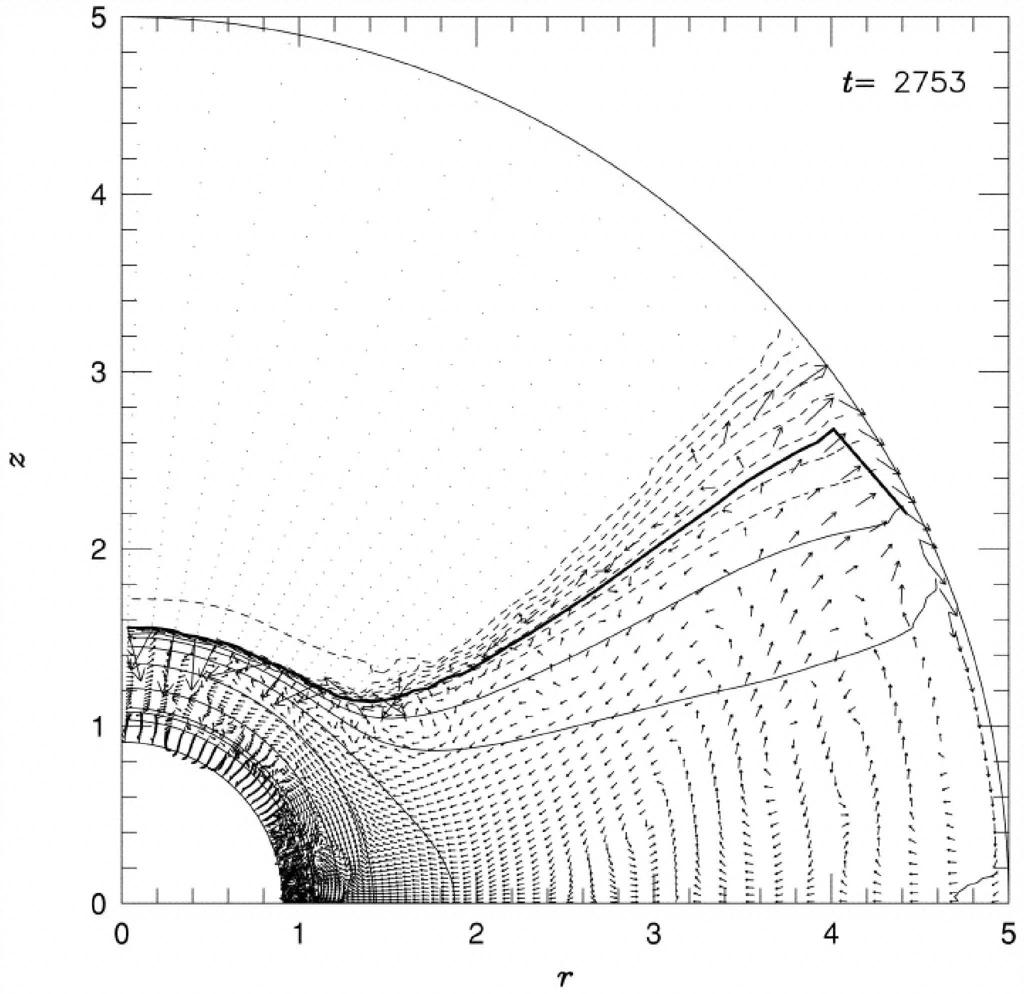
- Most general case - no requirement of smooth field drift or interaction exactly at corotation
- May explain evidence for hot (stellar) winds connected with accretion
- Predicts some magnetospheric infall in transition-region (C IV, O VI) lines- maybe also outflows
- Helps explain OVII excess in CTTS

Twister implications for jets?

- INNER disk outflows required to limit stellar J
  - note: jets from ~ 0.05 AU, not 0.5 AU
- Likely to be HOT (> 10^6 K) inner flows within colder jets
- Jets likely to have non-axisymmetric disturbances at their base (if more like X-wind than disk wind)
- Inner jets likely to be non-axisymmetric if stellar B is non-axisymmetric
  - creates difficulties for measuring jet rotation?
- Significant part of accretion energy!


coronal gas
C IV, OVI
Hα, etc.

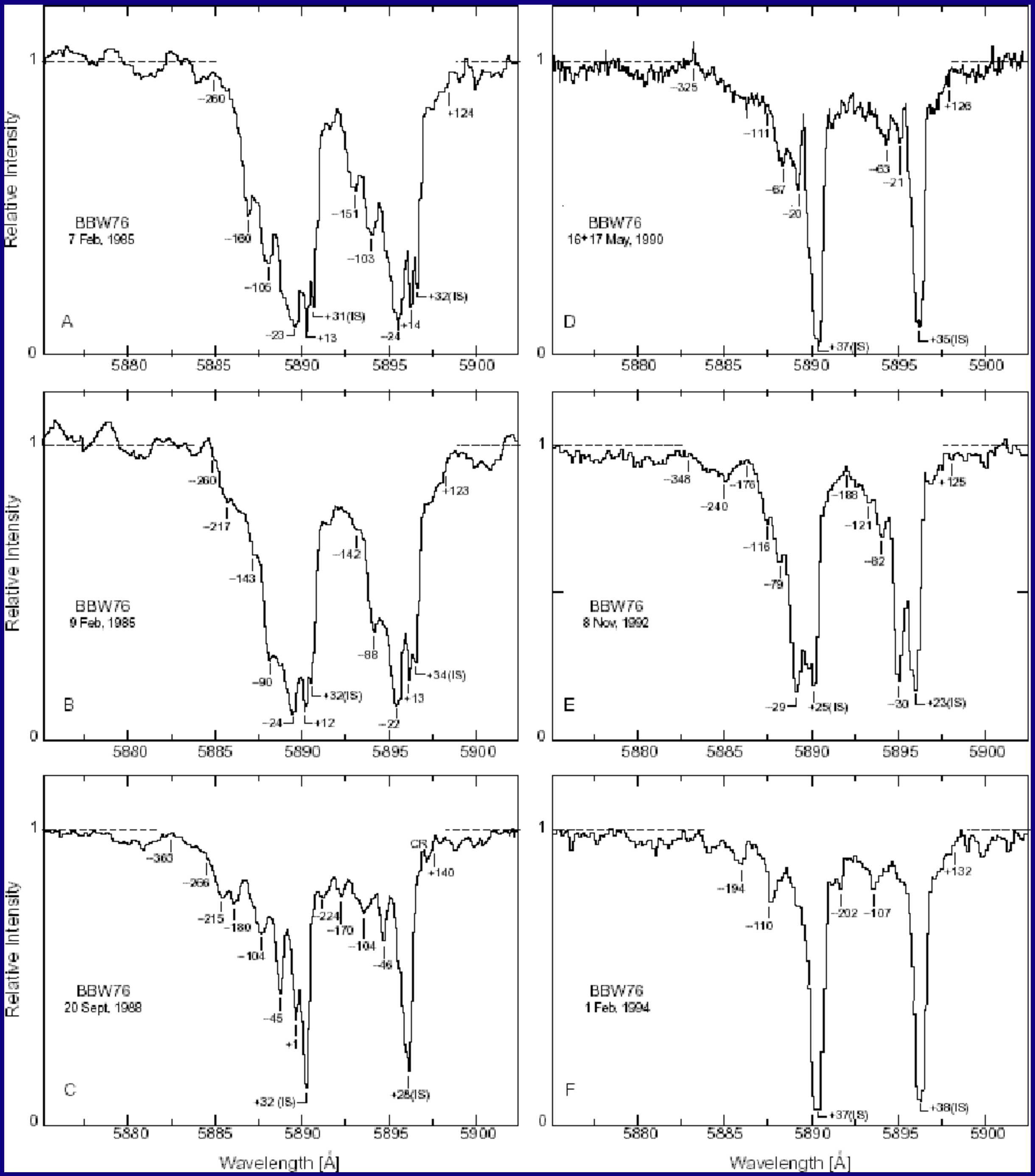
high dM/dt? end of outburst might lead to enhanced stellar wind due to shears induced in the star by rapid accretion of material



Kley & Lin 1996

Variability

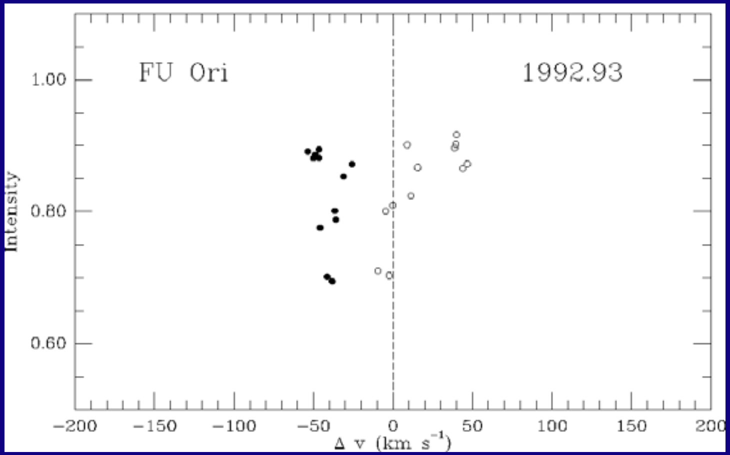
FU Ori winds are extremely time-variable, as seen in, e.g. Na I



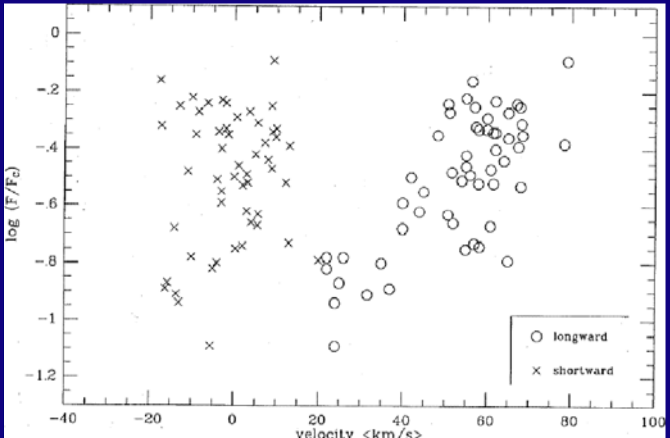
Reipurth et al. 2002

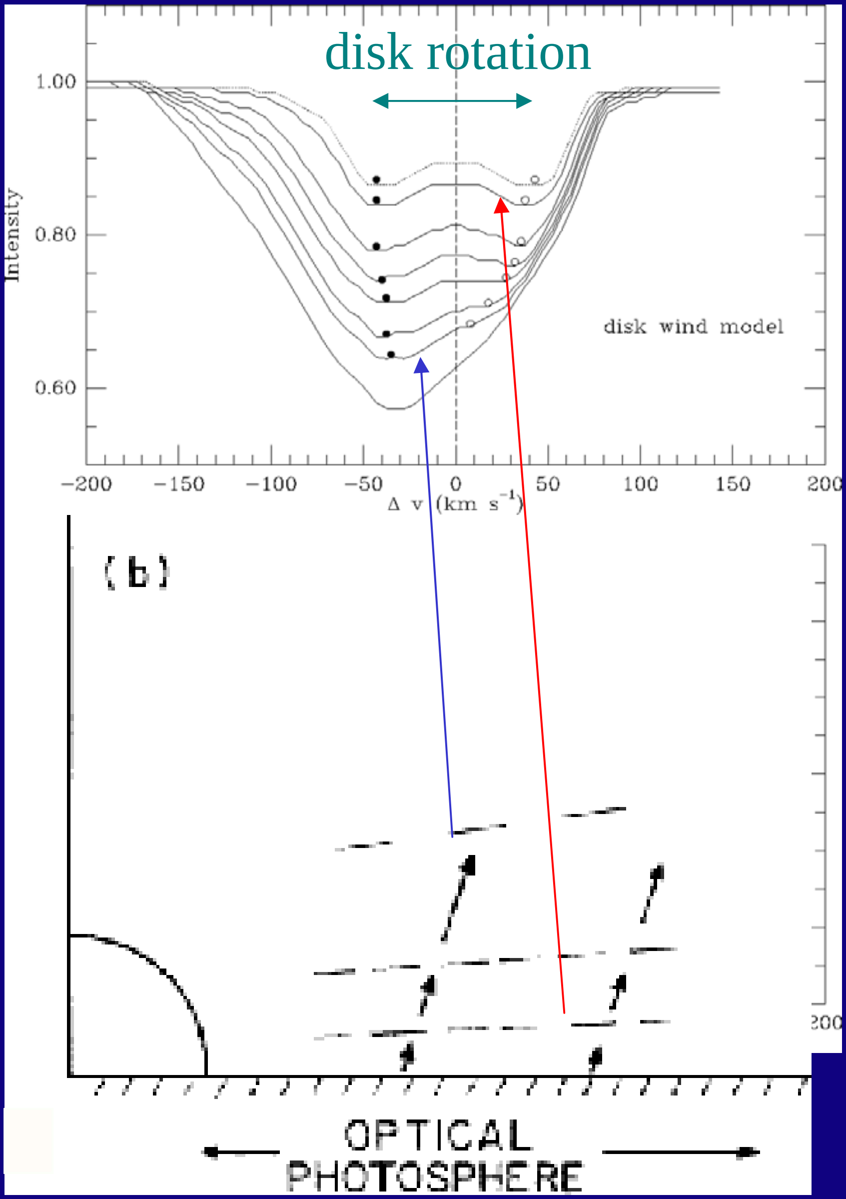
FU Ori disk winds

Hartmann & Calvet (1995); accelerating disk wind results in shifts increasing with increasing strength (upper levels)



Petrov & Herbig 1992

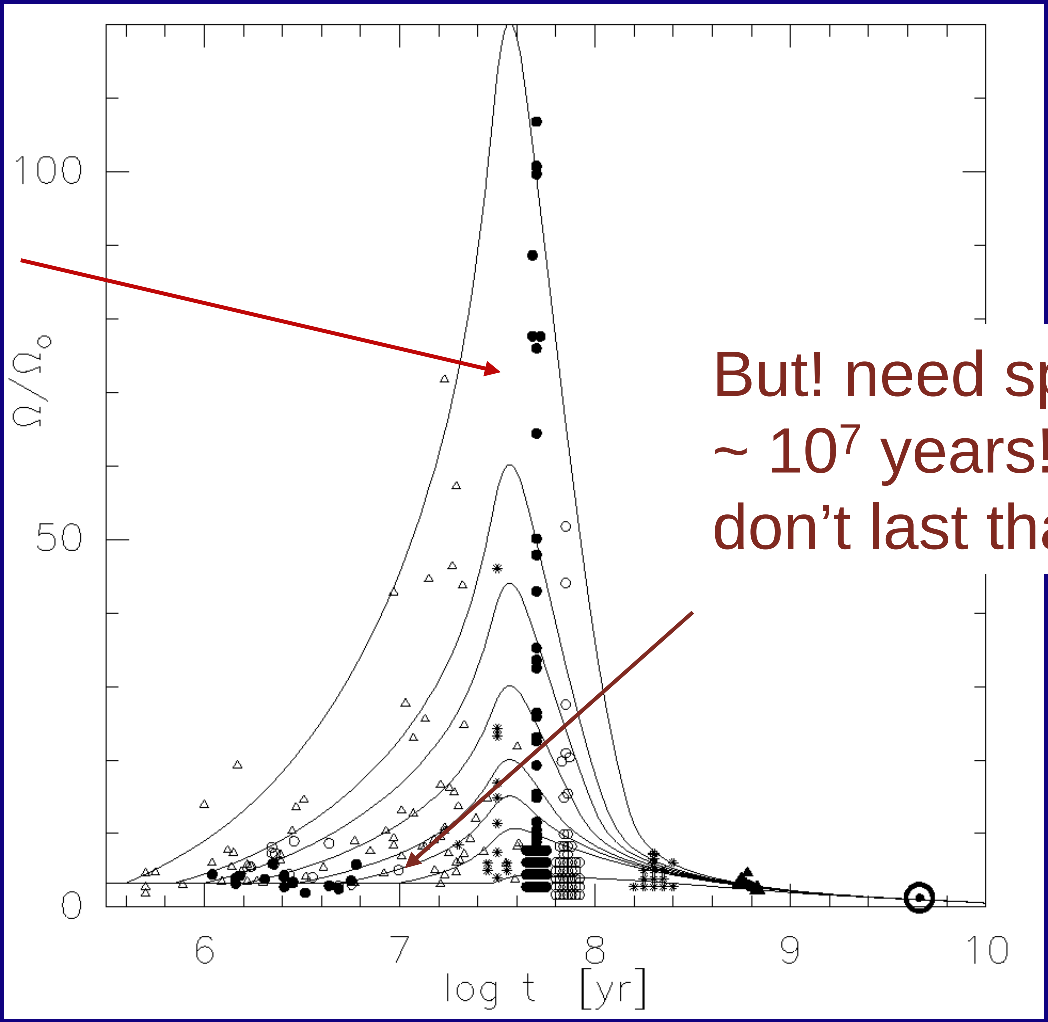




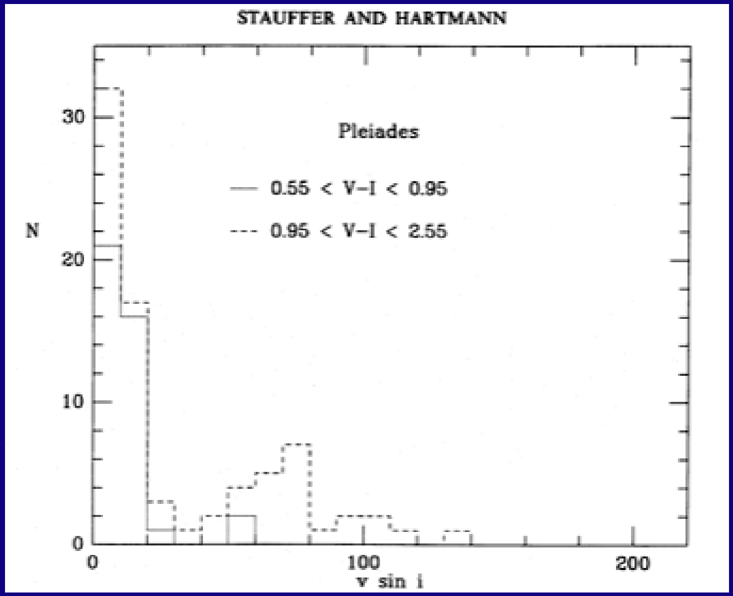
Need ~ no angular momentum loss to explain fast rotators in Pleiades - stellar wind can't be TOO effective

(spinup due to contraction toward MS

Stauffer et al., Bouvier et al. 1997



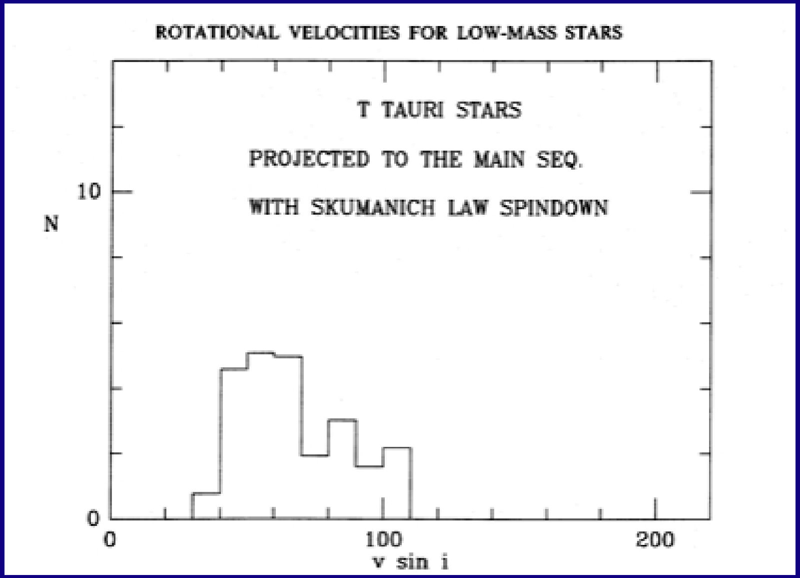
But! need spindown to ~ 10^7 years! disks don't last that long...

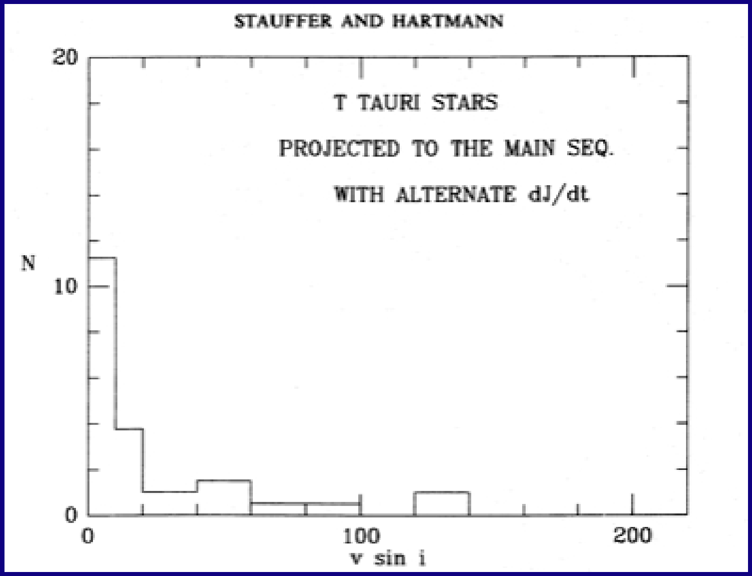


Disks don't last for 10 Myr - disk locking can't account for slow Pleiades rotators!

But: if dJ(wind)/dt ~ independent of rotation for fast rotators (as indicated by "saturation" of magnetic activity), then can retain fast rotators while spinning down initially slow rotators (Stauffer & Hartmann 1987)

as long as there is no more accretion...





- Calvet & Gullbring 1998; Gullbring & Calvet 2000; fraction of surface coverage of accretion shock ~ 0.5 - 5%
- Ingleby & Calvet (in prep); red-optical veiling implies lower mass flux regions with f ~ 5-10%

$\Longrightarrow$ complex accretion structure with many differing flux tubes of small area (as in TRACE images)

Using data from Herczeg et al., I estimate that TW Hya accretion column has radiative losses ~ 1-10% of the accretion luminosity (Lyα)

$\Rightarrow$ mechanical (magnetic) heating!

why aren't these loops emitting X-rays?

$\Rightarrow$ high densities due to accretion

$\Rightarrow$ LOWER density loops - why not same heating? in which case they WILL be coronal!

$\Rightarrow$ UV transition region lines - magnetospheric infall at $T < 3 \times 10^5$ K

$\Rightarrow$ O VII excess - trapped accreting gas @ 10^6 K (at this temperature, gas can't fall in easily)

N.B.: if most of the angular momentum of accretion is carried off - requires a large fraction of the accretion energy to be carried off as well!

Angular momentum in: $dJ/dt = dM/dt\ \Omega_K\ R_T^2$

out: $dJ/dt = dM_w/dt\ \Omega_K\ R_A^2$

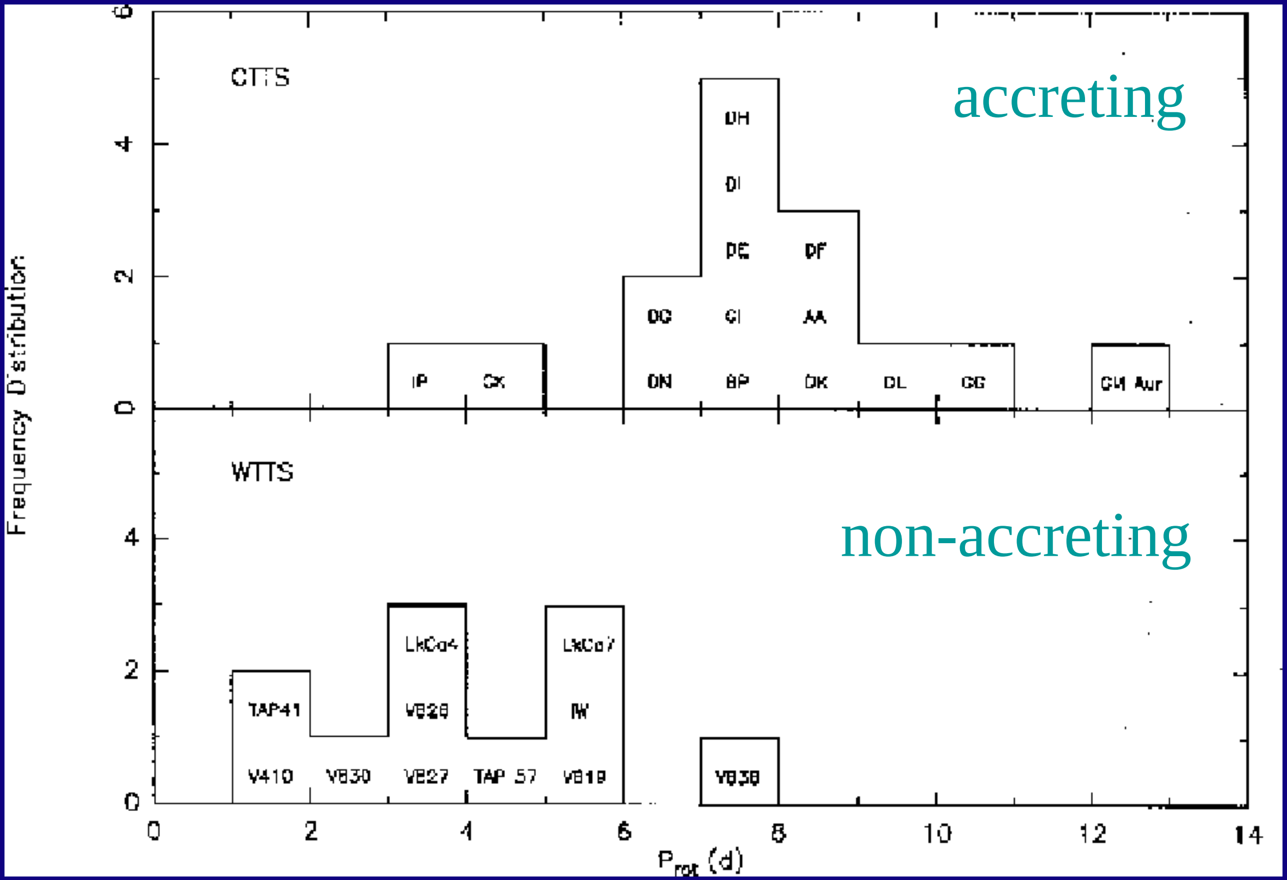
thus $dM_w/dt = dM/dt\ (R_T/R_A)^2$

Energy out = $\Omega_K\ dJ/dt = (G\ M\ dM_w/dt\ /R_T)\ (R_T/R_A)^2 = L_{acc}$!

Same analysis for "stellar wind":

Energy out $\approx L_{acc}\ (\Omega_*/\Omega_K)$

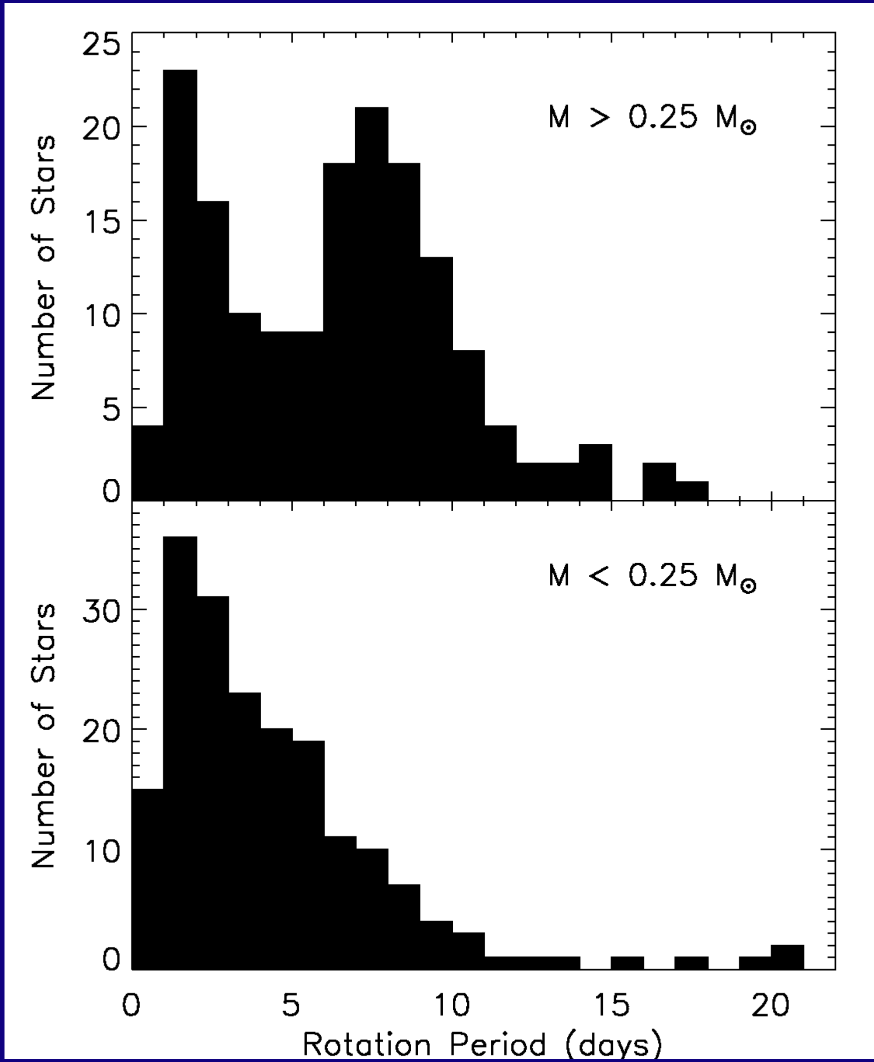
Disk-star magnetic coupling: does it work?



Taurus: accreting stars (stars with disks) rotate more slowly (Bouvier et al. 1993)

Why do young stars rotate so slowly if they are formed from disk accretion?

Bimodal at higher masses
(Herbst et al. 2002)



Why do young stars rotate so slowly if they are formed from disk accretion?

And why faster for lower-mass stars??

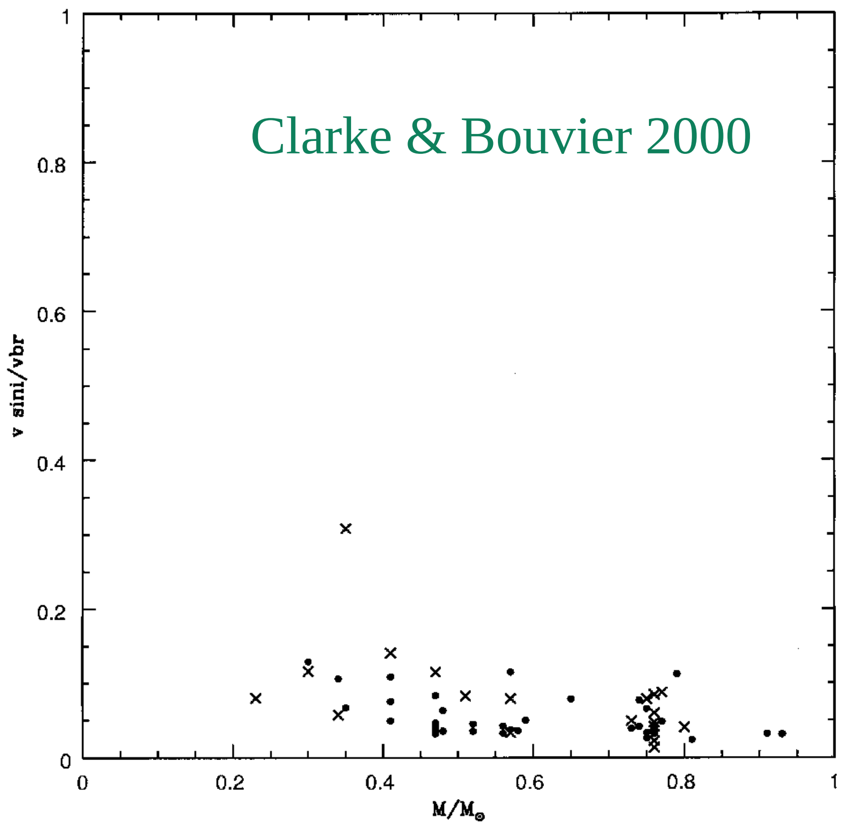


Figure 2. Projected velocity normalized to breakup velocity is plotted as a function of mass for the 55 stars in Taurus with masses <1 $M_\odot$. Filled circles are CTTs, crosses WTTs.

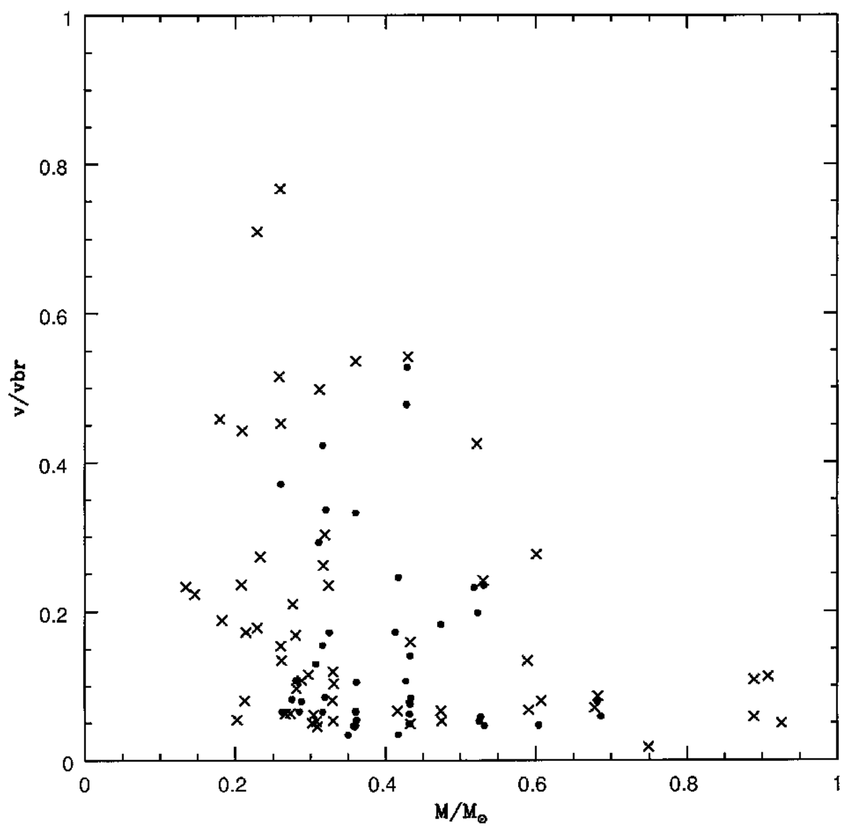
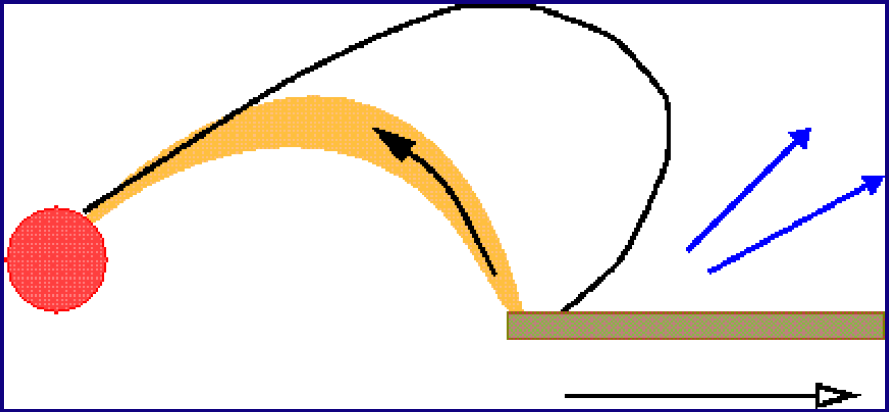


Figure 3. Equatorial velocity normalized to breakup velocity is plotted as a function of mass for the 102 stars in the Orion sample with masses <1 $M_\odot$. Filled circles are CTTs, crosses WTTs.

Disk-star magnetic coupling: does it work?

To spin down star, either wind or disk must carry away the stellar J!



Disk: to accrete at dM/dt, inner disk must carry away this angular momentum; assume co-rotation (Keplerian)

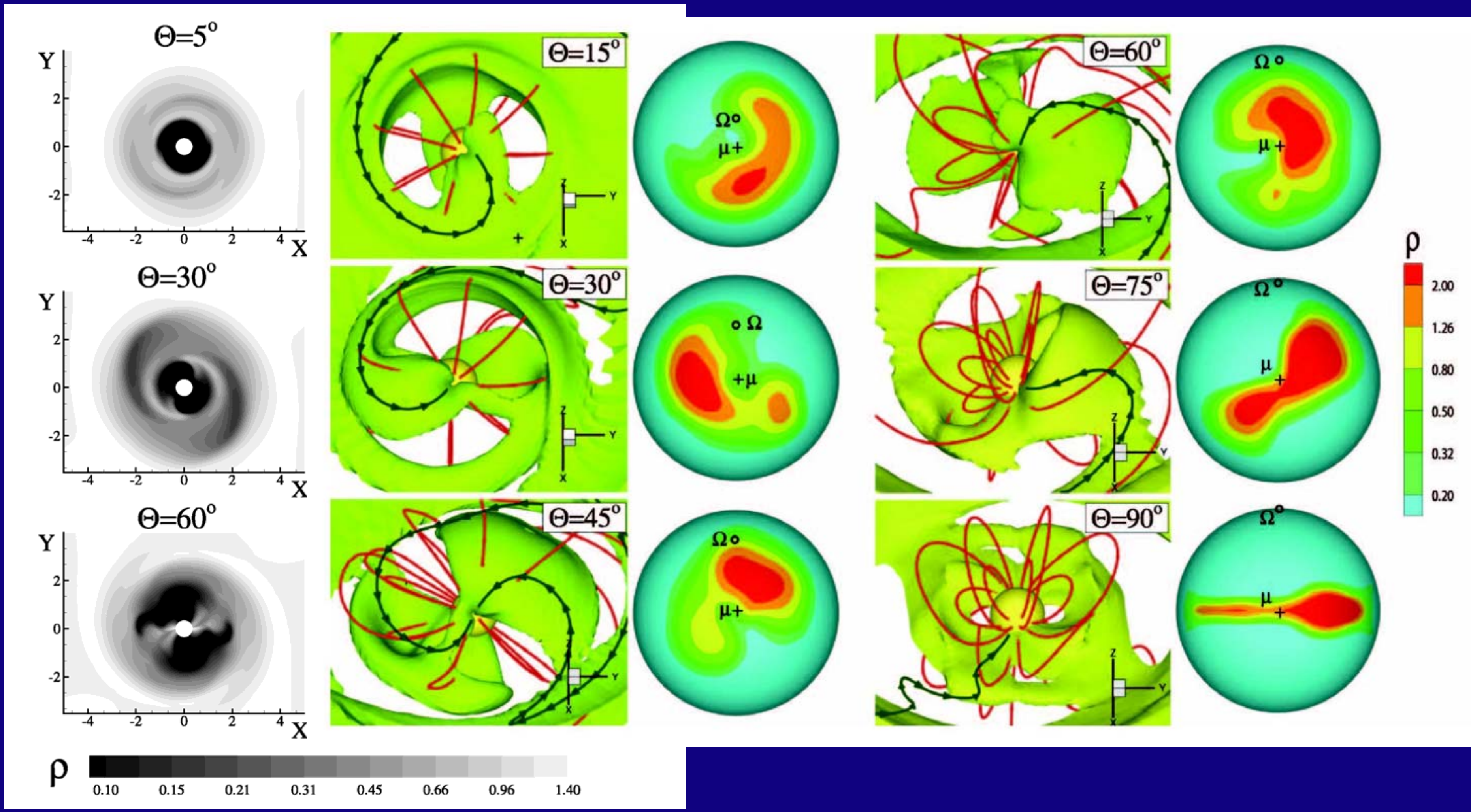
$$\tau_s = I_* \Omega_*/(dJ/dt) = \frac{k^2 M_* \quad \Omega_* R_*^2}{dM/dt \;\; \Omega_d R_d^2}$$

$$\approx k^2 \;(M_*/dM/dt)\;(\Omega_*/\Omega_K)\;(R_*/R_{co})^{1/2}$$

$$\approx 0.2 \times 10^8 \text{ yr} \times (\Omega_*/\Omega_K) / 2$$

so either slow rotation or need very high dM/dt to spin down in 10^6 yr

Tilted dipole $\Rightarrow$ asymmetric streams of accretion:
But: we don't see implied strong variations of line profiles. Geometry must be more complicated.



Romanova et al. 2003, 2004

The angular momentum problem

Shu et al. “funnel” flow + x-wind

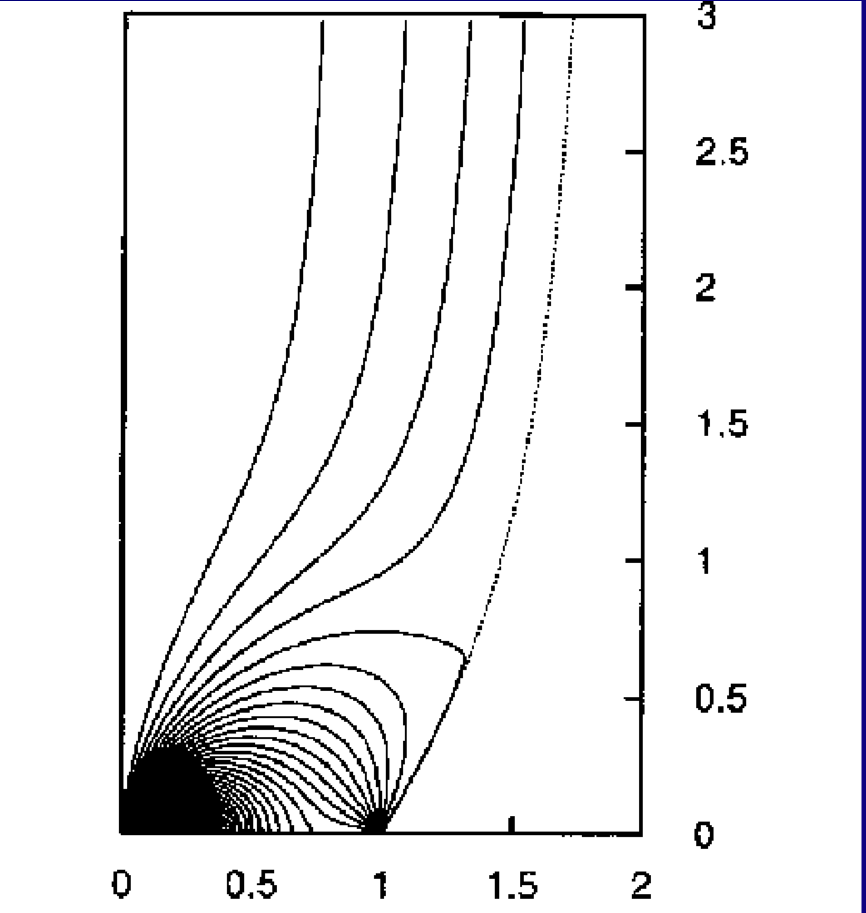


FIG. 3.—Magnetic field structure inside the wind (*solid curves*). Dotted curve shows the outer boundary of the calculation (the upper wind surface). Spacing between contours is 0.1. Same parameters as Fig. 2c.

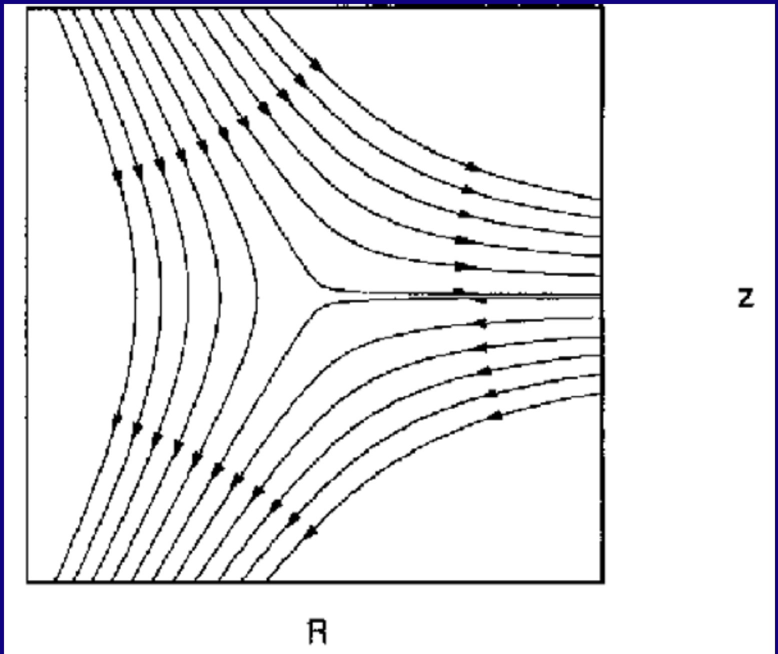
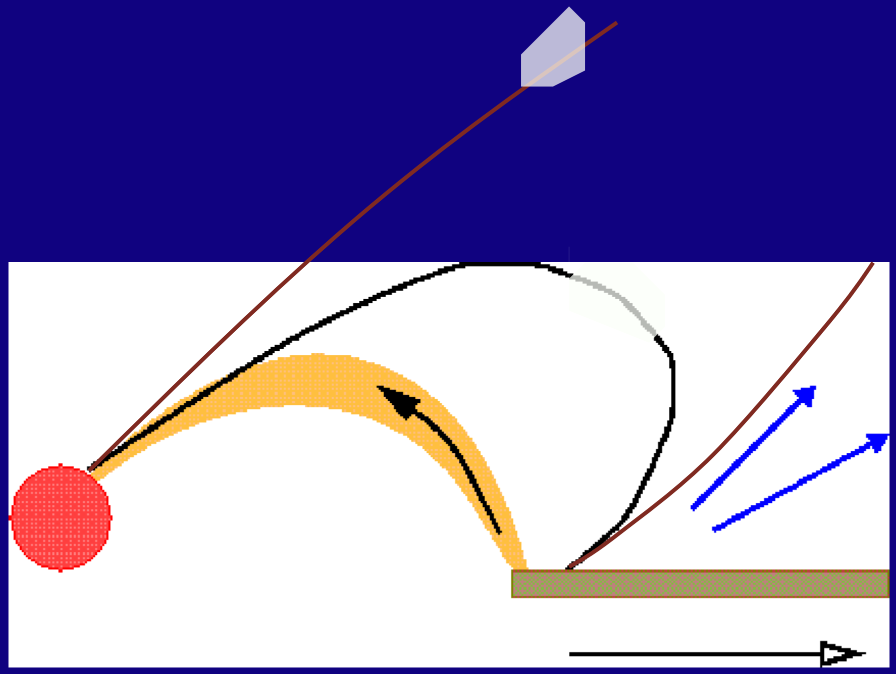


FIG. 1.—Magnetic field lines in the meridional plane near an ideal kink point given by eq. (3.8), with arrowheads indicating the local field direction. Note the three-way even split of angles and the oppositely directed field lines that lead toward and emanate from the centrifugal X-point far to the right of this diagram.

Disk-star magnetic coupling: does it work?

or?? coronal mass ejection-type loss, except using disk material??



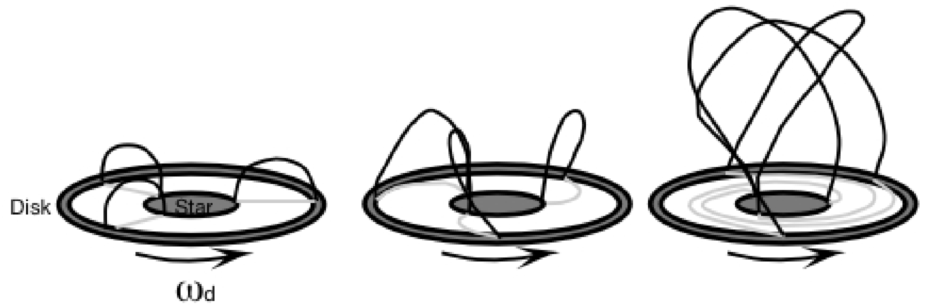
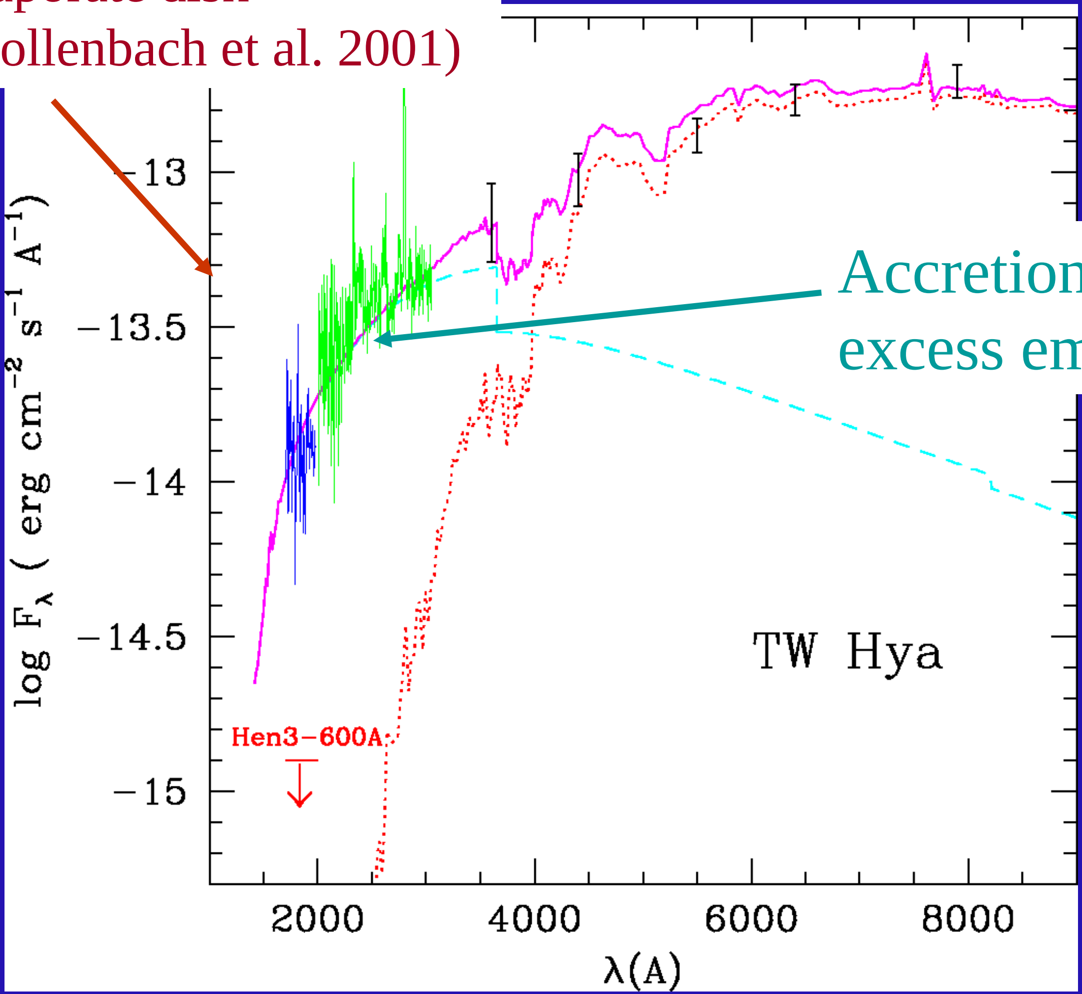


FIG. 2.—After LRBK; poloidal field that initially connects the star to a region of the accretion disk that is rotating at a different rate is wrapped up, inducing a B_ϕ component that increases the total B field. This increase in magnetic energy density causes the loops that connect the star to the disk to inflate rapidly.

Photoevaporative fluxes?

$\Phi \approx 10^{41}\ s^{-1}$ (typical EUV flux needed to evaporate disk in 10 Myr; Hollenbach et al. 2001)



Accretion-produced excess emission

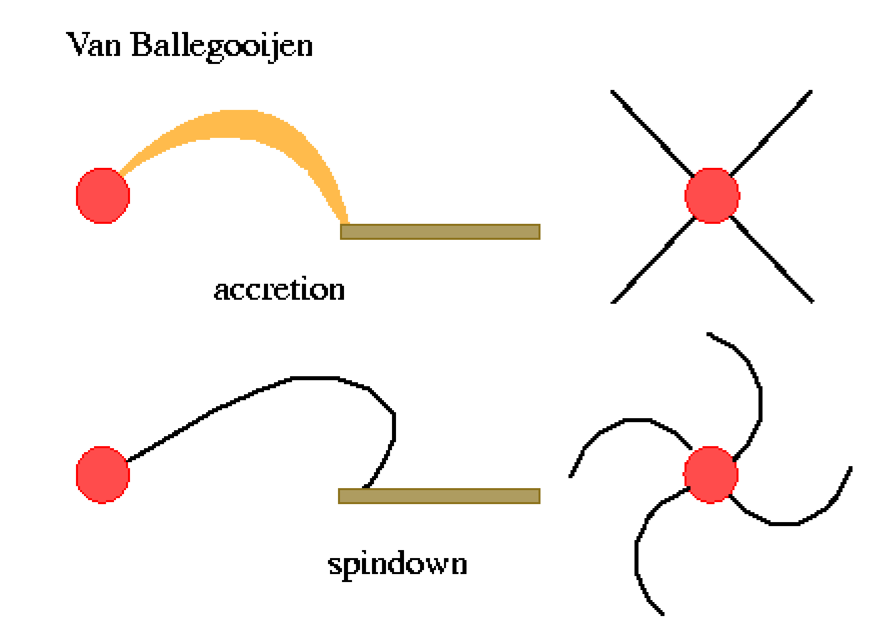
Muzerolle, Calvet et al. 2000

non-steady disk-star magnetic coupling

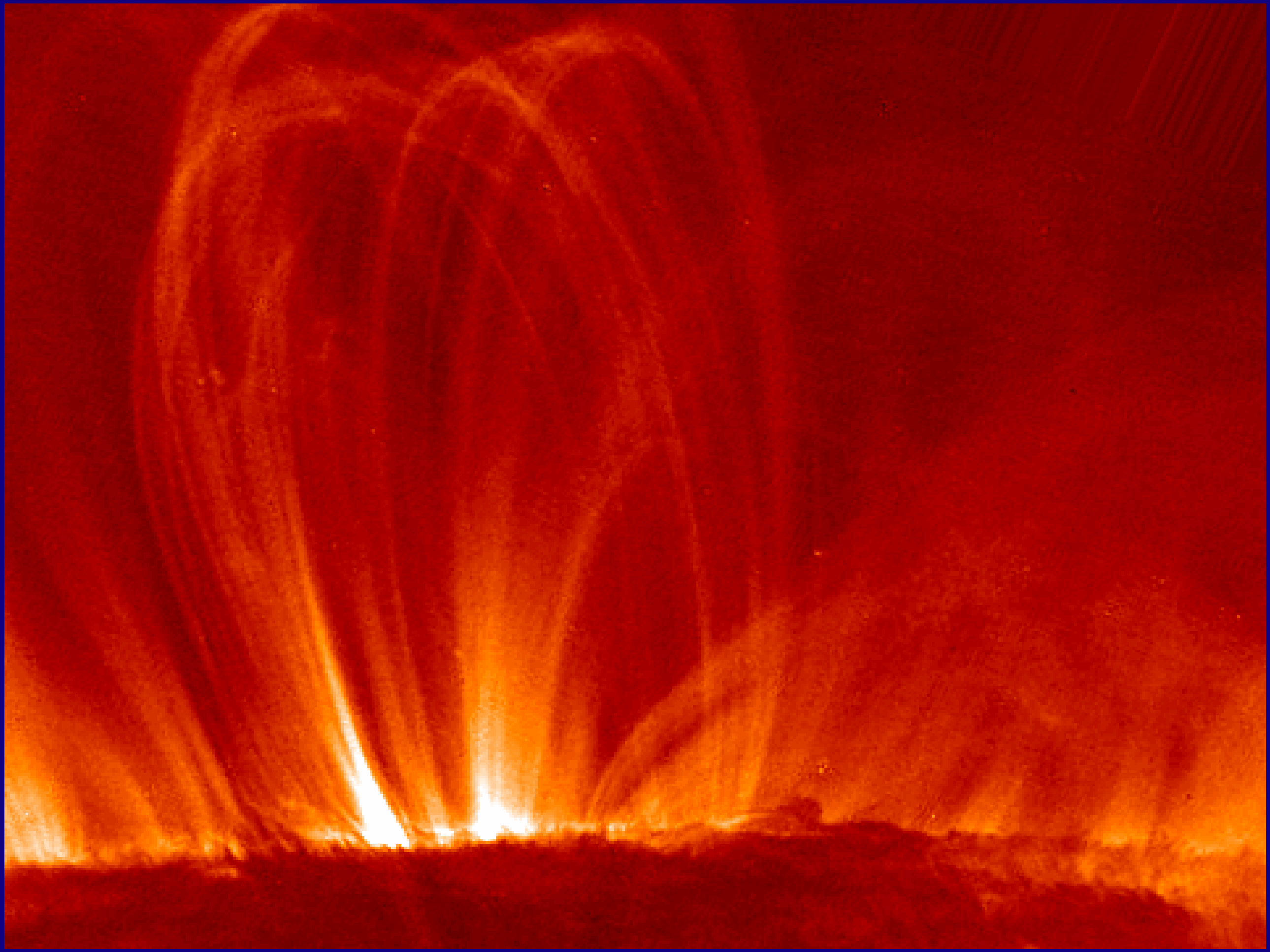
reconnection-

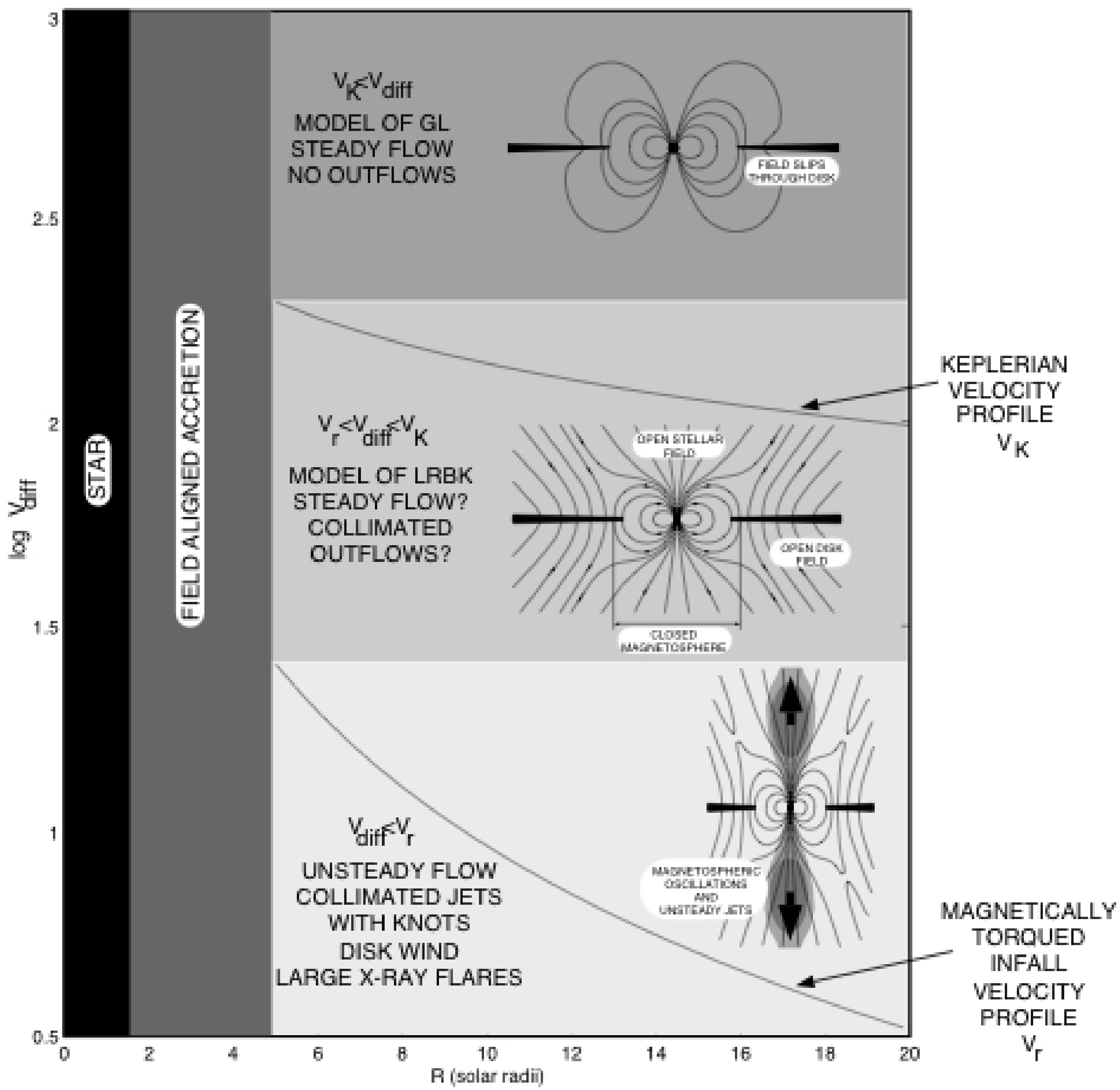
⇒ limits spindown too much?

(Matt & Pudritz 2004)



Class I (protostars) rotate at ~ 2 x TTS values
(Covey et al. 2005)

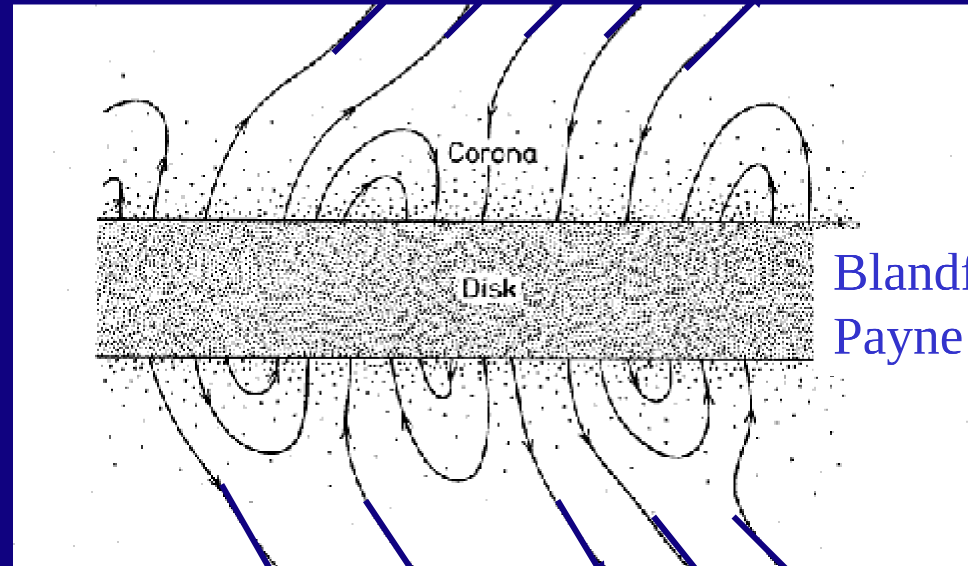




log V_{diff}
STAR
FIELD ALIGNED ACCRETION
$V_K < V_{diff}$
MODEL OF GL
STEADY FLOW
NO OUTFLOWS
FIELD SLIPS THROUGH DISK
$V_r < V_{diff} < V_K$
MODEL OF LRBK
STEADY FLOW?
COLLIMATED
OUTFLOWS?
OPEN STELLAR FIELD
OPEN DISK FIELD
CLOSED MAGNETOSPHERE
$V_{diff} < V_r$
UNSTEADY FLOW
COLLIMATED JETS
WITH KNOTS
DISK WIND
LARGE X-RAY FLARES
MAGNETOSPHERIC OSCILLATIONS AND UNSTEADY JETS
KEPLERIAN
VELOCITY
PROFILE
V_K
MAGNETICALLY
TORQUED
INFALL
VELOCITY
PROFILE
V_r
R (solar radii)

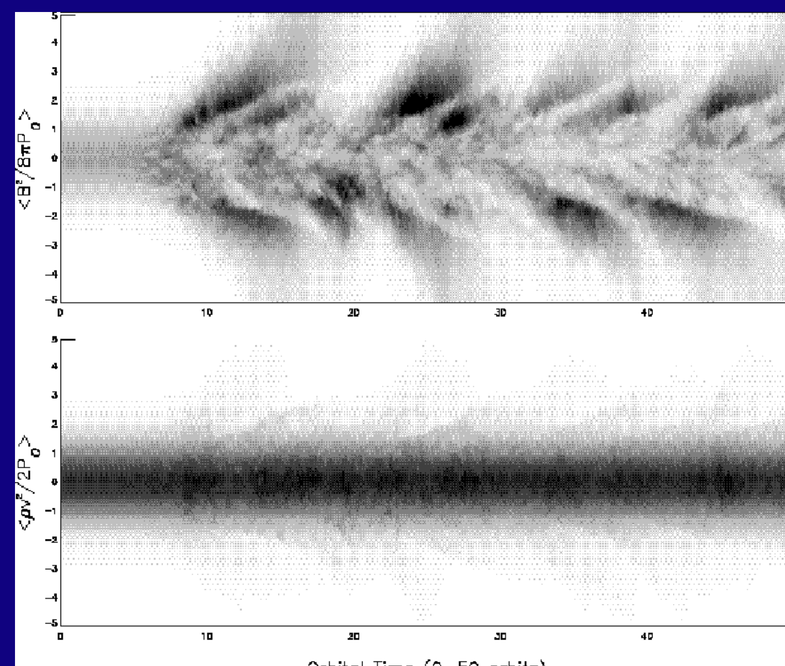
Variability

FU Ori winds are extremely time-variable; consistent with complex disk magnetic field geometry



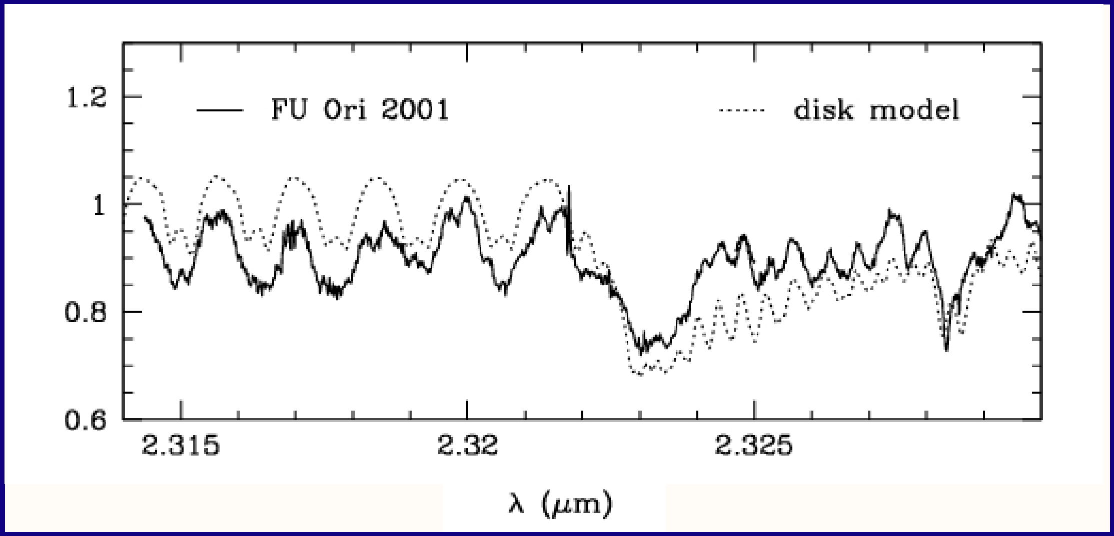
Blandford & Payne 1982

FU Ori winds must be heated to explain Hα, etc; numerical simulations of MRI show waves propagating upward and shocking



Miller & Stone 2002

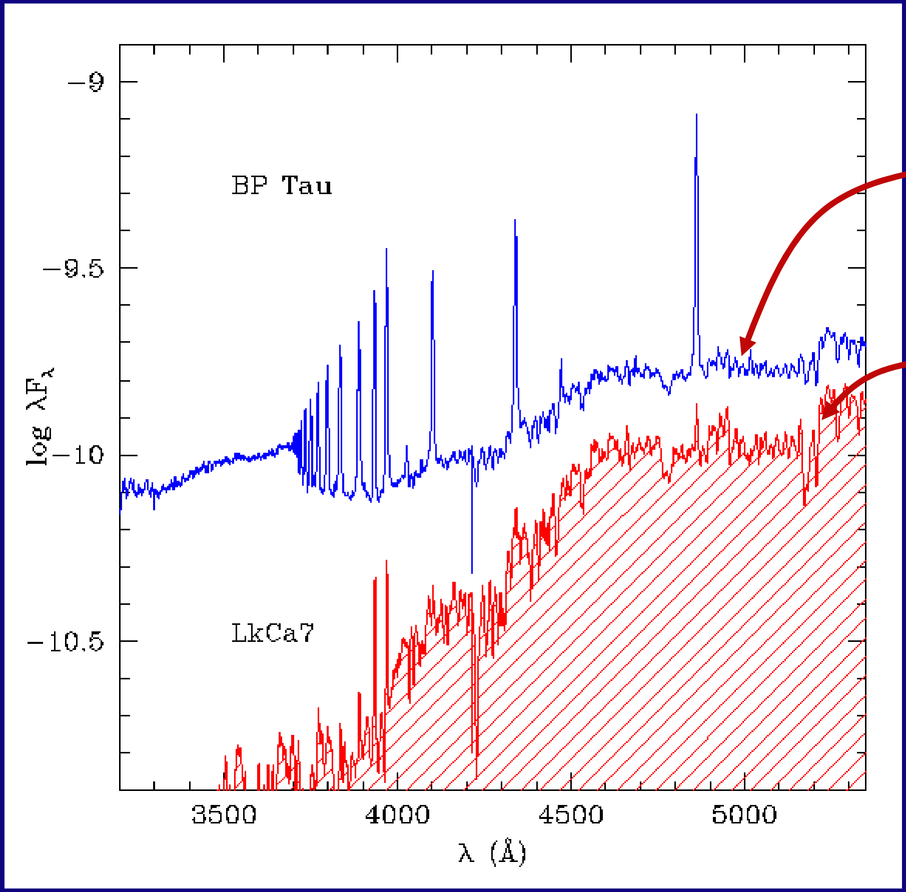
Line profile modeling of CO first-overtone; suggests turbulent velocities ~ 1.5 c_s



Hartmann, Hinkle, & Calvet 2004

Accretion power in T Tauri Stars

Bertout et al. 88;
Kenyon & Hartmann 87;
Hartigan et al. 90,91;
Valenti et al. 93



Classical TTS

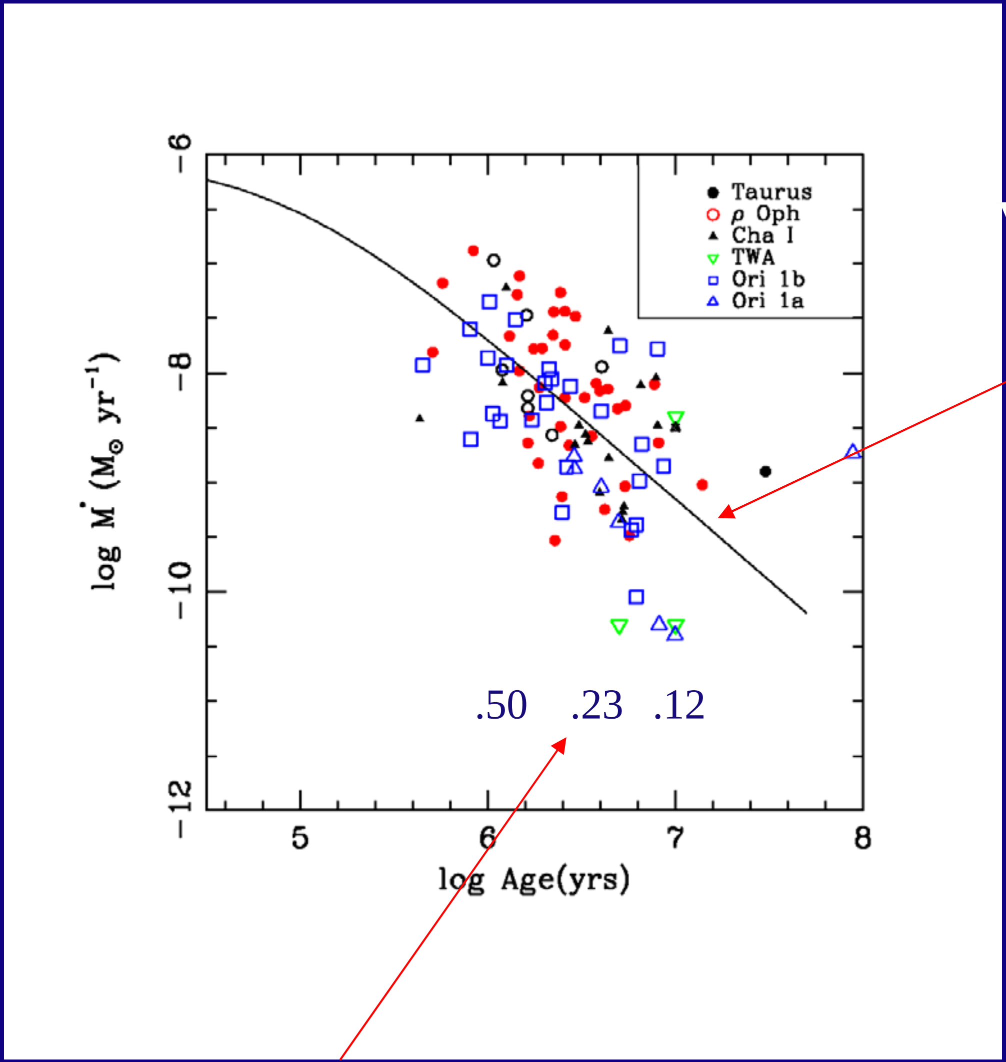
Weak TTS

Blue excess (veiling) continuum can be > L_*;

$\Rightarrow$ not stellar magnetic activity, but accretion powered;

inner disks (IR emission) $\Longleftrightarrow$ veiling $\Rightarrow$ accretion

Mass accretion rate decreases with time

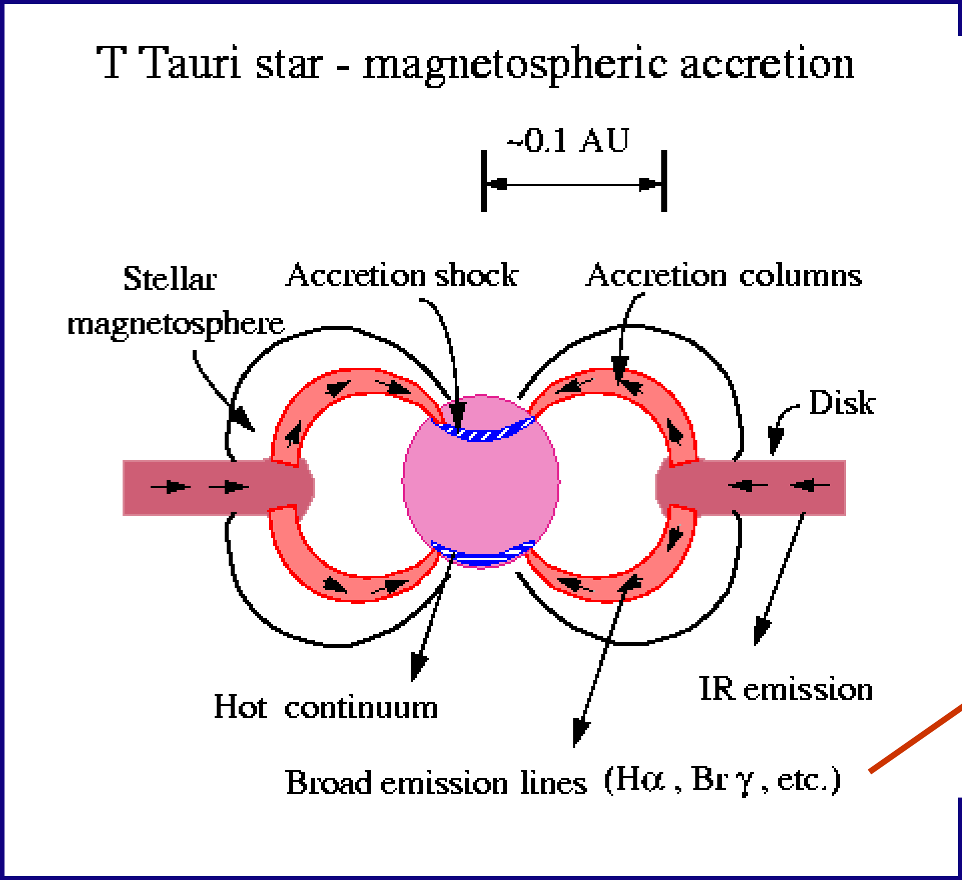


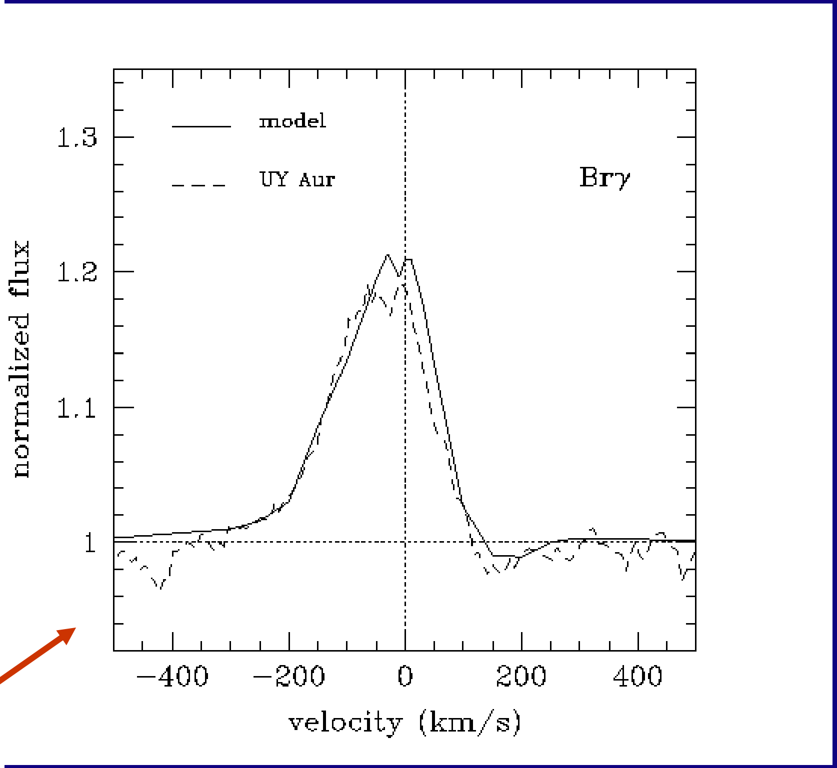
Viscous evolution - Gas

Hartmann et al. (1998), Muzerolle et al. (2001), Calvet et al. (2005)

Fraction of accreting objects decreases with time

Magnetospheric accretion: line profiles





Königl 1991

(Muzerolle et al. 1998):

line width ≈ $(2GM_*/R_*)^{1/2}$