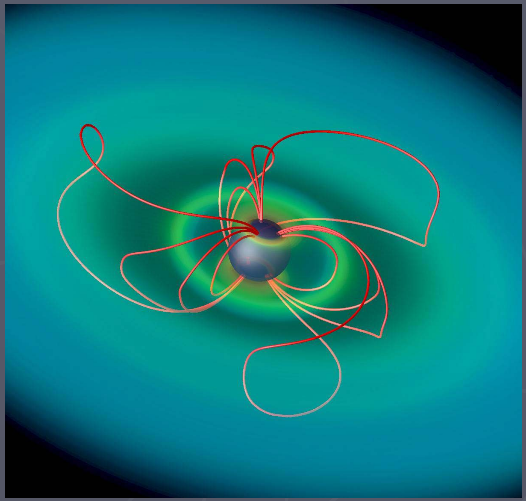
# On some MHD aspects of Star-Disc-Jet systems

Jonathan Ferreira



Collaborators:

N. Bessolaz, C. Zanni, C. Dougados, S. Cabrit, P. Garcia, J. Bouvier, PO Petrucci, G Henri, G. Pelletier

I- Why should accretion discs host large scale $B_z$ field ?

II- Constraints from TTauri jets on accretion-ejection flows

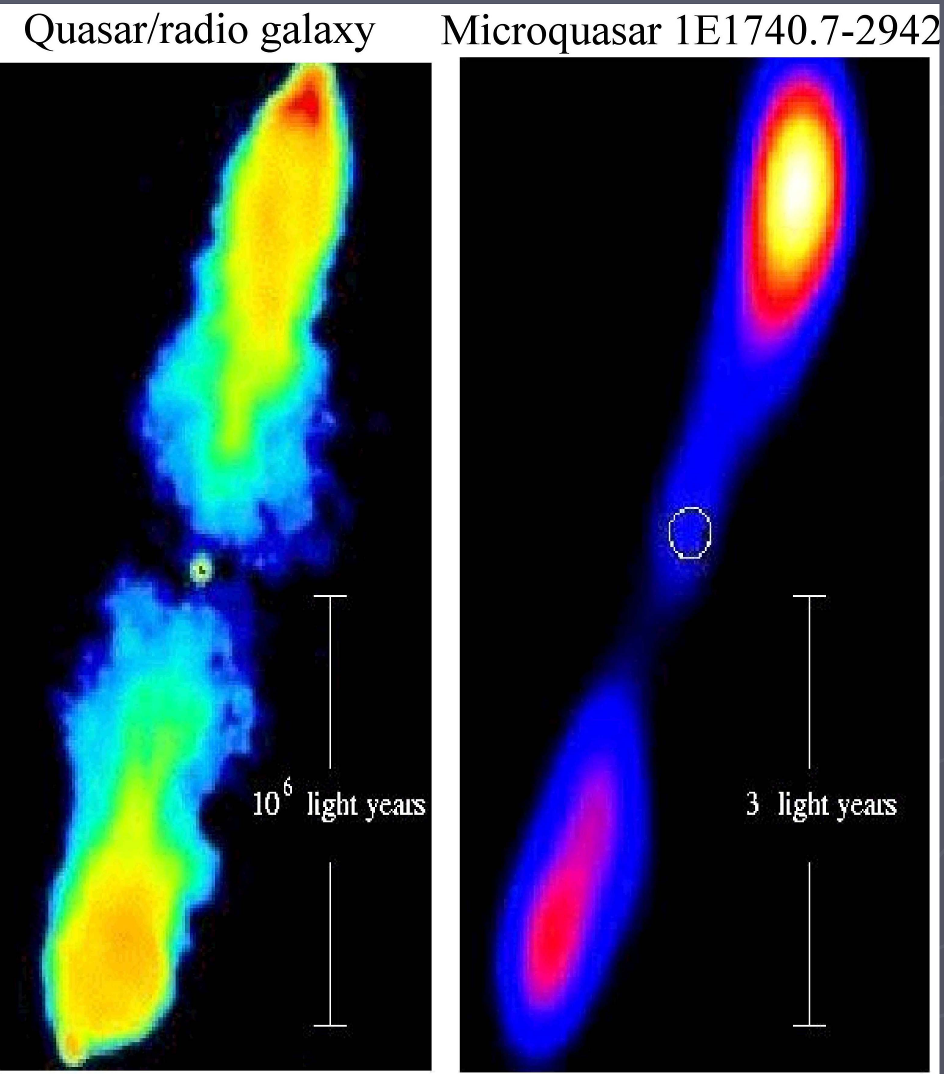
III- Naive views on star-disc interactions

Laboratoire d'AstrOphysique de Grenoble SHERPAS

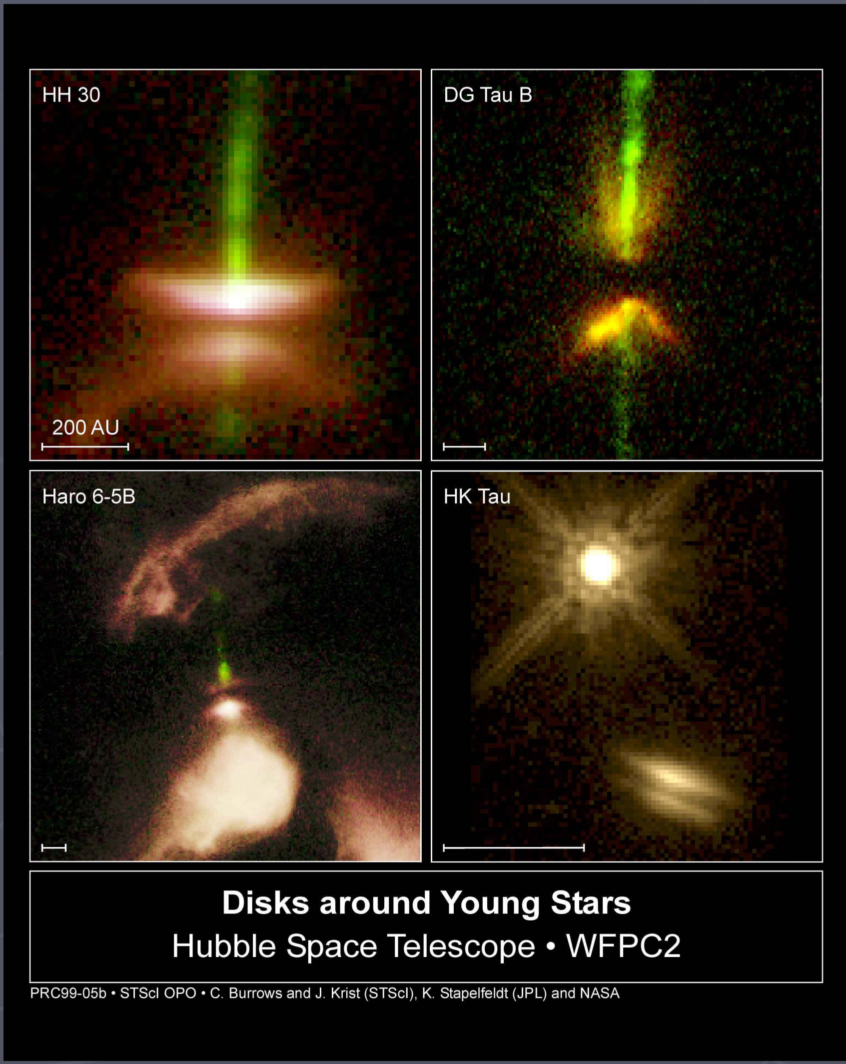
LAOG

# I-1 Astrophysical jets as disc winds

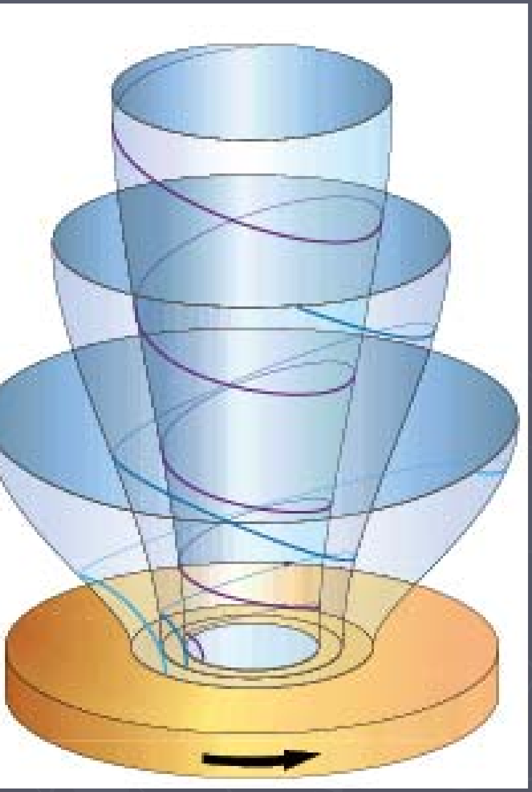
## 1- A « universal » model




## 2- Jets not always present



# I-2 Accretion-Ejection Systems



Axisymmetric jets are nested magnetic surfaces of constant magnetic flux: a(r,z) = Cst

Blandford & Payne 82

- Single fluid MHD description
- Non-relativistic equations (no light-cylinder)
- Steady-state
- Usually: polytropic energy equation
- Ideal MHD (no viscosity, no diffusivity)

A complex interplay between disc and jets

=> **M**agnetized **A**ccretion-**E**jection **S**tructure (MAES)

# I-3 Some Ideas heard in conferences (and written too)

« Jets cannot be described by the Blandford & Payne picture »
Because:

(1) There is never the correct bending at the disc surface

(2) No large scale $B_z$ can be maintained in the disc

(3) In any case, accretion-ejection is by essence unstable

Jets may indeed be something else than what the accretion-ejection model depicts…but these ideas are wrong.

# (1) « There is never the correct bending at the disc surface »

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Lubow *et al*. 94a
Heyvaerts, Priest & Bardou 96
Ogilvie & Livio 98

BP criterion for cold jets: $\theta > 30°$ ($B_r > B_z$) at the disc surface.

This is never achieved in a Standard Accretion Disc (SAD). BP criterion requires a magn Reynolds number

$$\mathcal{R}_m = \frac{r u_r}{\nu_m} \geq \frac{r}{h}$$

In a SAD, « viscous » accretion gives

$$\mathcal{R}_e = \frac{r u_r}{\nu_v} \simeq 1$$

and in turbulent media $\nu_v \sim \nu_m$ …

BUT the jet torque has been forgotten !
And it is dominant in a Jet Emitting Disc (JED)…

# (2) « No large scale $B_z$ can be maintained in the disc »


Argument mainly based on previous calculations: with $R_m$~1, mass accretes whereas $B_z$ stays behind… but because of imposed rigid BC!

Actually, a SAD can transport $B_z$ such as to increase the disc magnetization towards the center :

Diffusion equation $\nu_m \frac{\partial B_z}{\partial r} \simeq u_r B_z$ leads to $B_z \propto r^{-\mathcal{R}_m}$

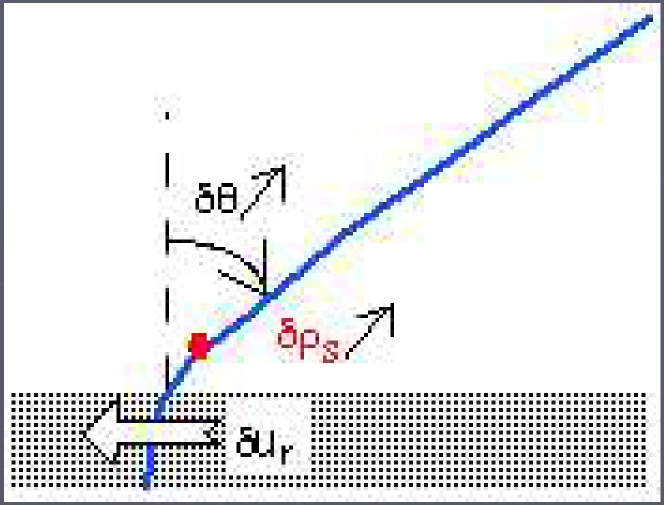
Since $P_{tot} = \frac{\dot{M}_a \Omega_k^2 h}{6\pi \nu_v} \propto r^{-3/2-\delta}$ where $h(r) \propto r^{\delta}$

one gets $\mu = \frac{B_z^2}{\mu_o P_{tot}} \propto r^{-\varepsilon}$ with ε~1 for typical values for δ

Ferreira et al 06a, A&A

Note: the only real issue is ionization and B/plasma coupling

# (3) « In any case, accretion-ejection is by essence unstable »




Lubow *et al*. 94b
Ogilvie & Livio 01
Cao & Spruit 02

Calculations assumed a hydrostatic density profile.

This is a description far too crude : MHS quasi-equilibrium

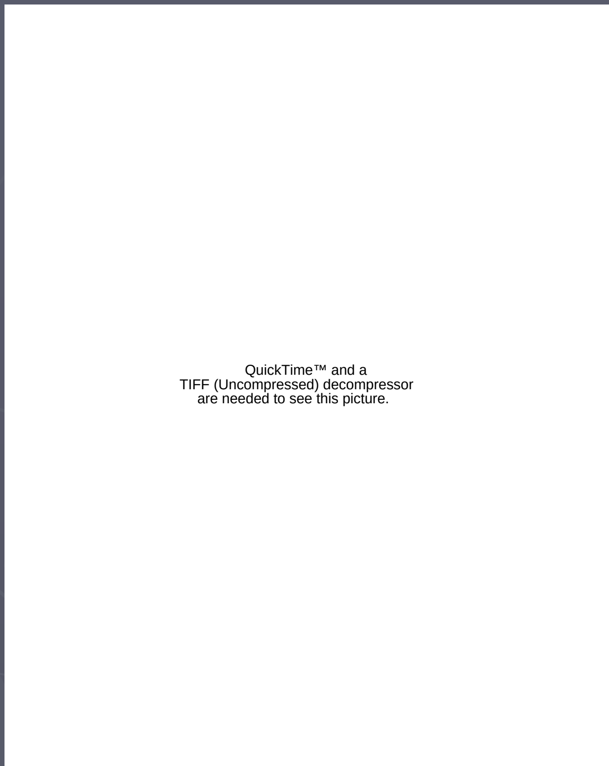
- Disc rotation produces **larger $B_\phi$** if $B_r$ becomes larger
- The magnetic field produces a strong vertical compression
- The SM point lies **below** the Sonic point (wrong mass flux)

=> as θ increases **less** mass ejected, not more!

Accretion-Ejection are stable (against this particular effect)

Königl & Wardle 96, Königl 04

# I-4 Semi-analytical studies of Accretion-Ejection systems




Casse & Ferreira 00

Wardle & Konigl 93, Ferreira & Pelletier 93,95
Ferreira 97, Vlahakis et al 00, Casse & Ferreira 00,0
Ferro-Fontan & Gomez 03, Campbell 99->05

These studies address the mass load issue and the physical conditions within the disc required to drive super-fast jets.

=> The disc radial + vertical structures must be solved for.

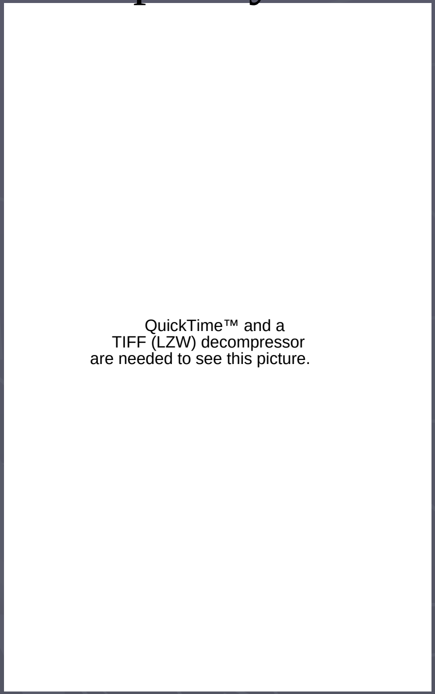
Major results:

1- magnetic $B_z$ field close to equipartition ($\mu$~1)

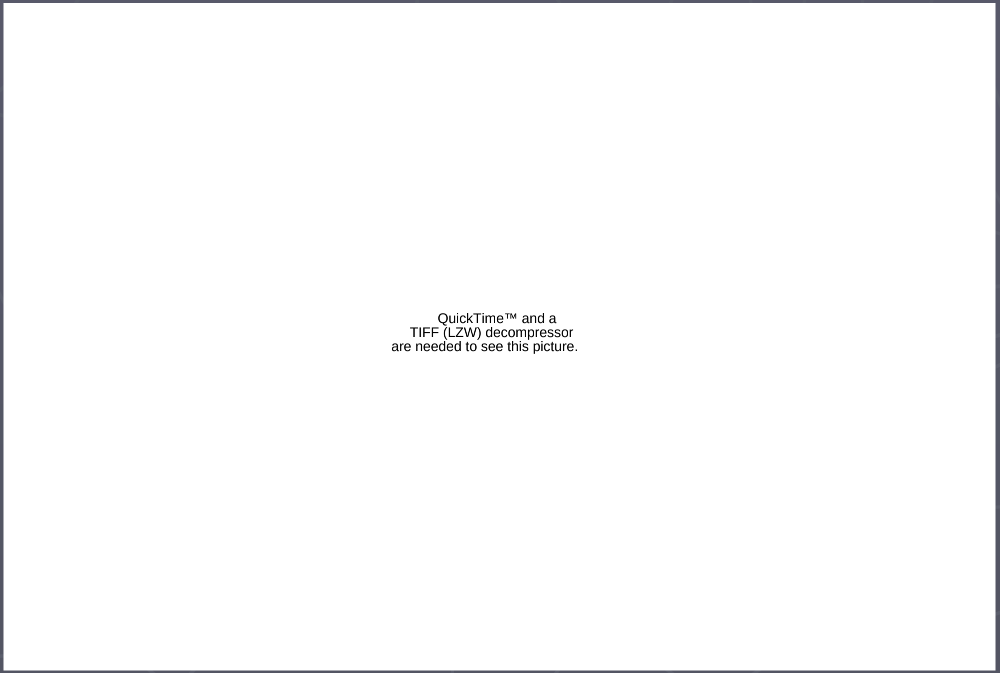
2- high level of turbulence ($\alpha_m$~1) required for stationarity

# I-5 Numerical studies of Accretion-Ejection systems

Many numerical simulations where the disc is a boundary condition and mass loss imposed (eg. Ouyed & Pudritz 97,99,03, Ustyugova 99, Krasnopolsky et al 99, 03, Anderson et al 05…)



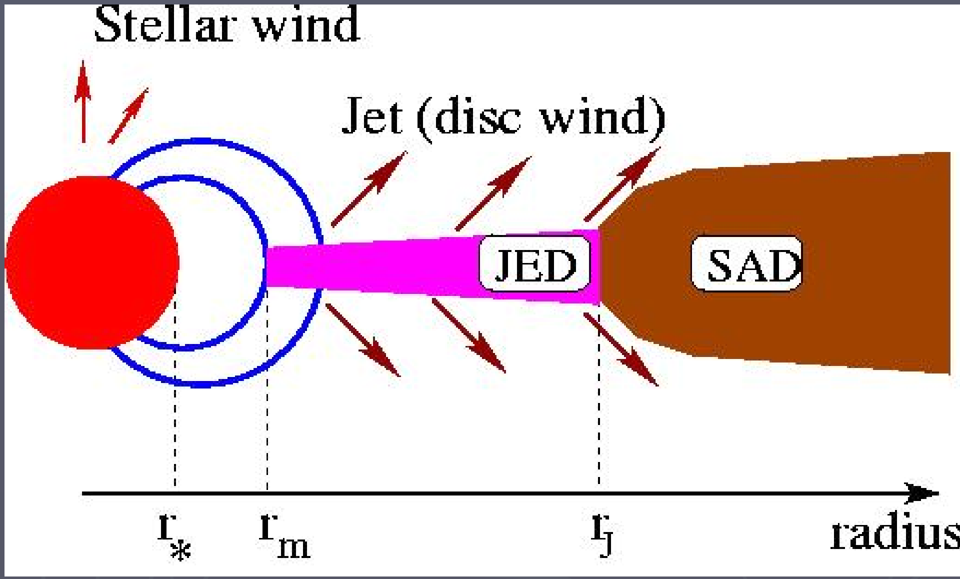

Casse & Keppens 02, 04

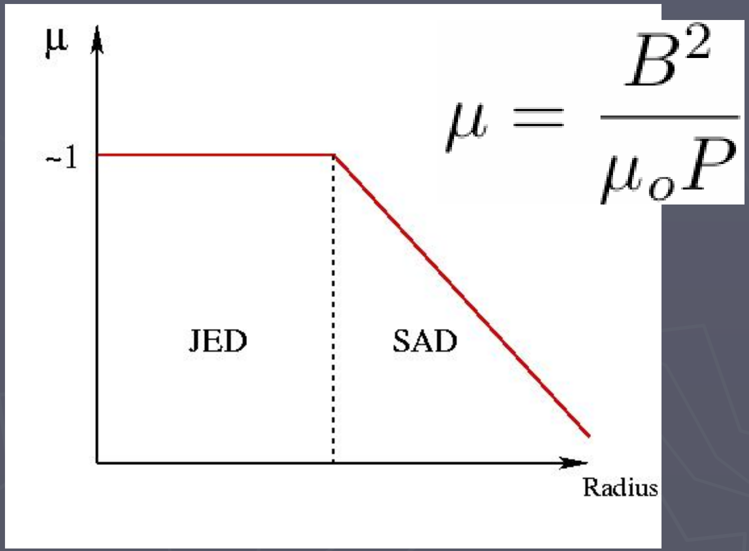



Zanni et al 07

=> Main results from self-similar calculations are confirmed by MHD simulations where the disc is also computed.

# I-6 A picture for the innermost disc regions



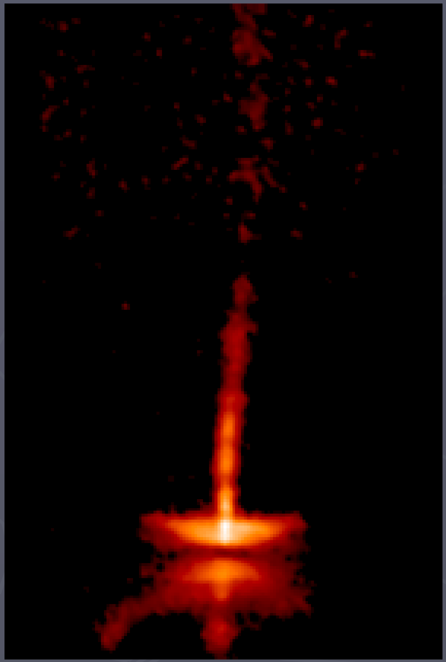

Jet Emitting Disc with ~ equipartition large scale $B_z$ field

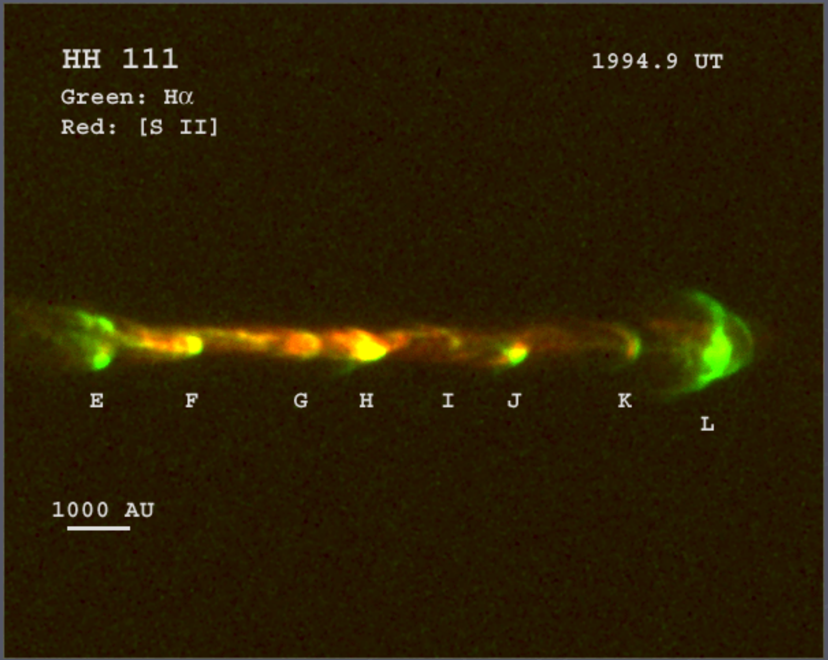
$$B_z \simeq 0.2 \left(\frac{M}{M_\odot}\right)^{1/4} \left(\frac{\dot{M}_a}{10^{-7} M_\odot/yr}\right)^{1/2} \left(\frac{r_o}{1\ \mathrm{AU}}\right)^{-5/4+\xi/2} \ \mathrm{Gauss}$$

Ferreira & Pelletier 95

=> Existence of such $B_z$ recently confirmed by spectro-polarimetric observations around FU Or (~ kG @ 0.05 AU) Donati et al 05, Nature

# II-1 Constraints from Ttauri Jets



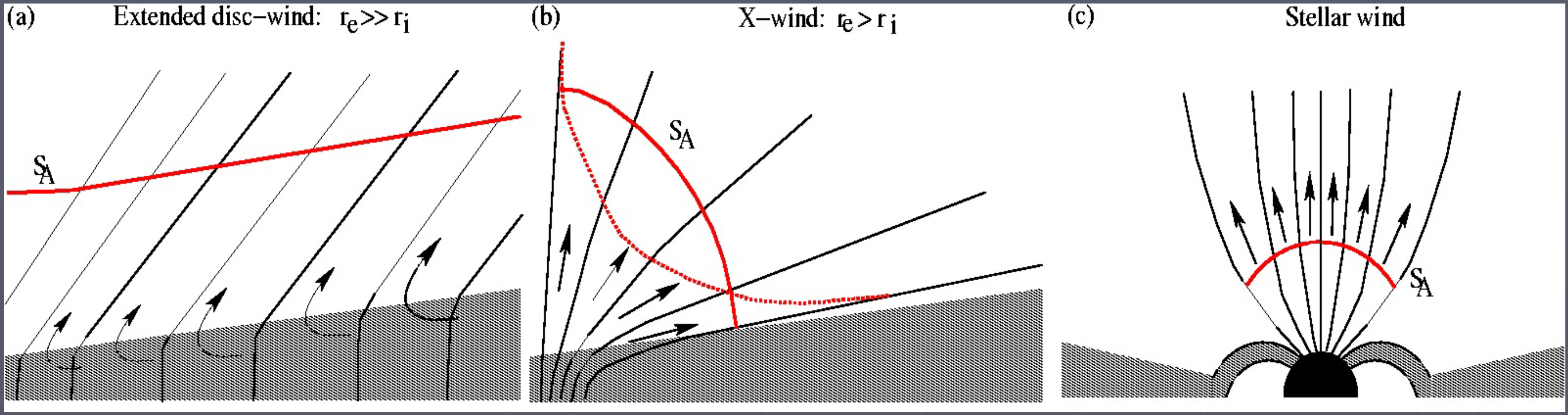



Images: degree of collimation, evolution (HH objects)

Spectroscopy: jet kinematics (line profiles, PV diagrams) and physical conditions such as density and temperature (line ratios).

=> Strong contrainsts on all MHD models

# II-2 The 3 basic steady-state jet models




| | | |
|---|---|---|
| Blandford & Payne 82 | Shu et al 94, 95 | Weber & Davis 68 |
| Ferreira & Pelletier 93,95,97 | Fendt 9, 00 | Hartmann & McGregor 80 |
| Wardle & Königl 93 | Shang et al 98, 02 | DeCampli 82 |
| Casse & Ferreira 00, 04 | | Sauty & Tsinganos 94, 02 |

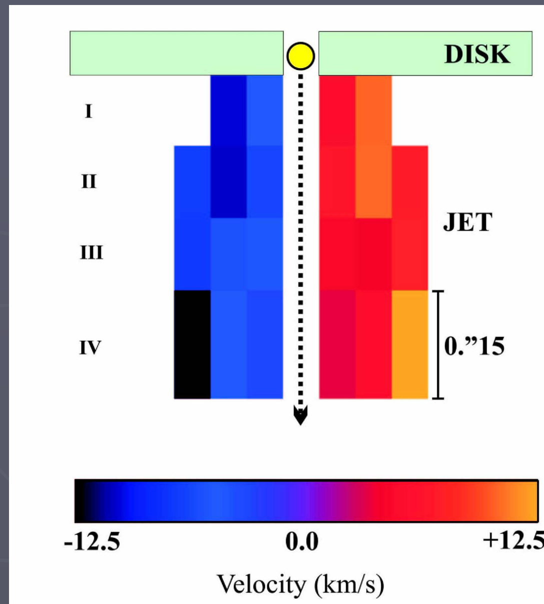
- share the same physics: rotating body + large scale $B_z$
- Governed by the same set of MHD equations
- Apart the « extended disc wind » model, mass flux is imposed

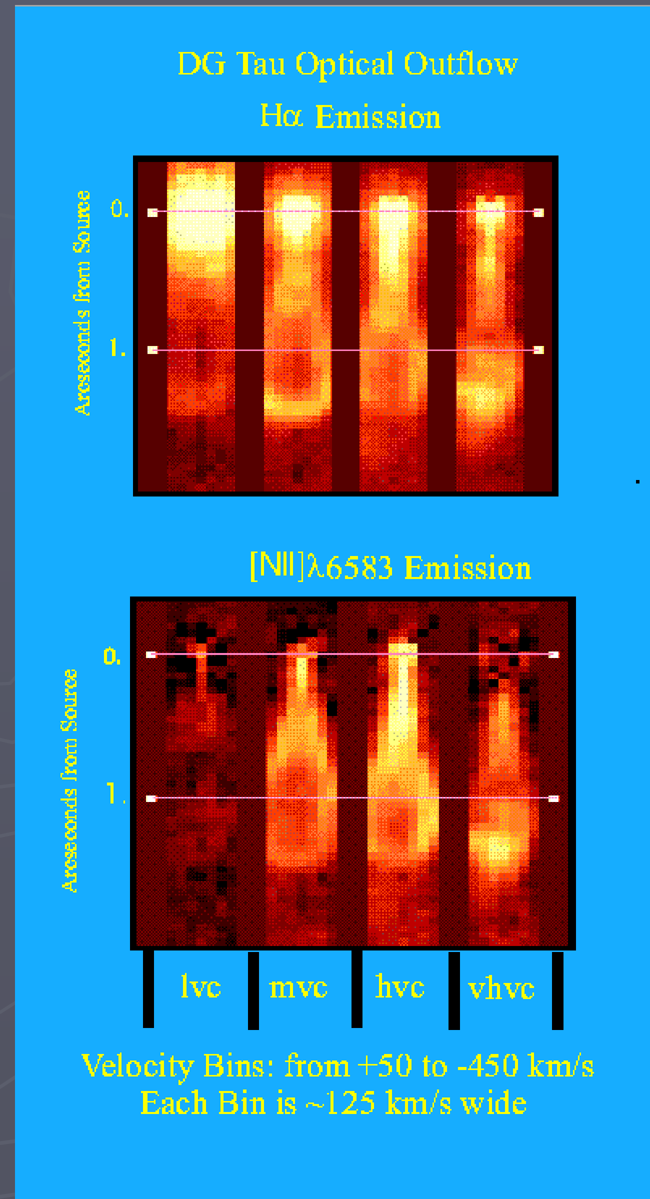
=> Can observations discriminate between these models ?

# II-3 First: are jets indeed rotating?

DG Tau
Observations
HST/STIS

Bacciotti et al 00



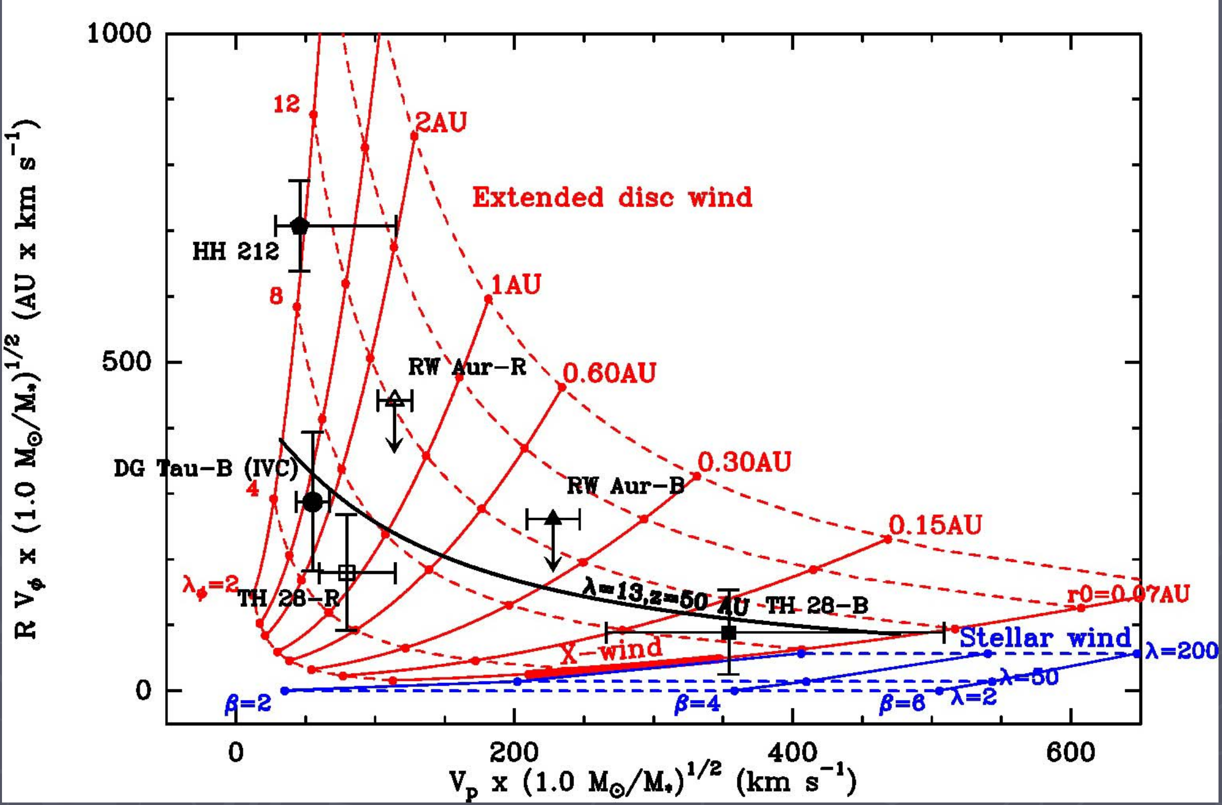




1. The collimation degree increases with the jet speed (higher closer to the axis)
2. Unresolved acceleration scale <20 au

**=> MHD: launching radius at 2-3 au**
(Anderson et al 03, Pesenti et al 04)

# II-4 Putting all constraints together

Ferreira *et al.* 06b




Observations:

- jet radius r
- velocity Vphi
- velocity Vp

Models:

-anchoring radius $r_o$

- magnetic lever arm

$$\lambda \simeq \frac{r_A^2}{r_o^2}$$

=> $\lambda \sim 10$ needed

- Jet velocity gradients incompatible with current X-wind models
- Observed mass fluxes incompatible with stellar winds only.
- IF velocity shifts are rotation: launching radius from 0.2 to 3 AU

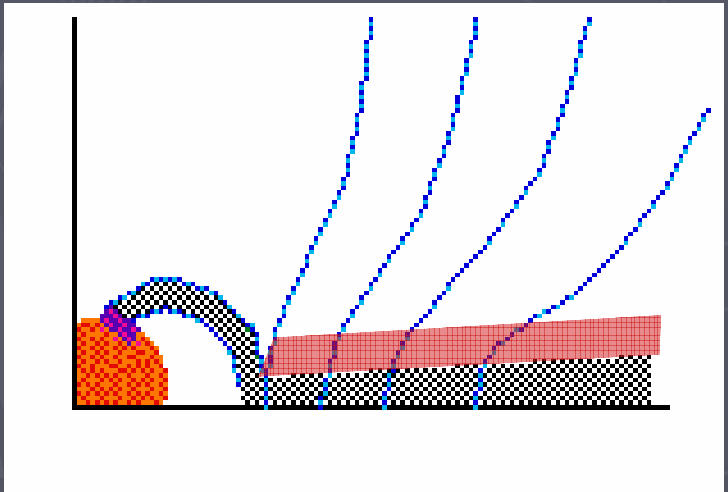
# II-5 The need for a warm « corona »

Thin discs => enthalpy negligible in jets: « cold jet » models

In that case, λ~ 50-100 (Ferreira 97, Casse & Ferreira 00a)

- Mass fluxes too low $\frac{2\dot{M}_{jet}}{\dot{M}_{acc}} \simeq 1/\lambda$ < 10% observed
- Velocities too high

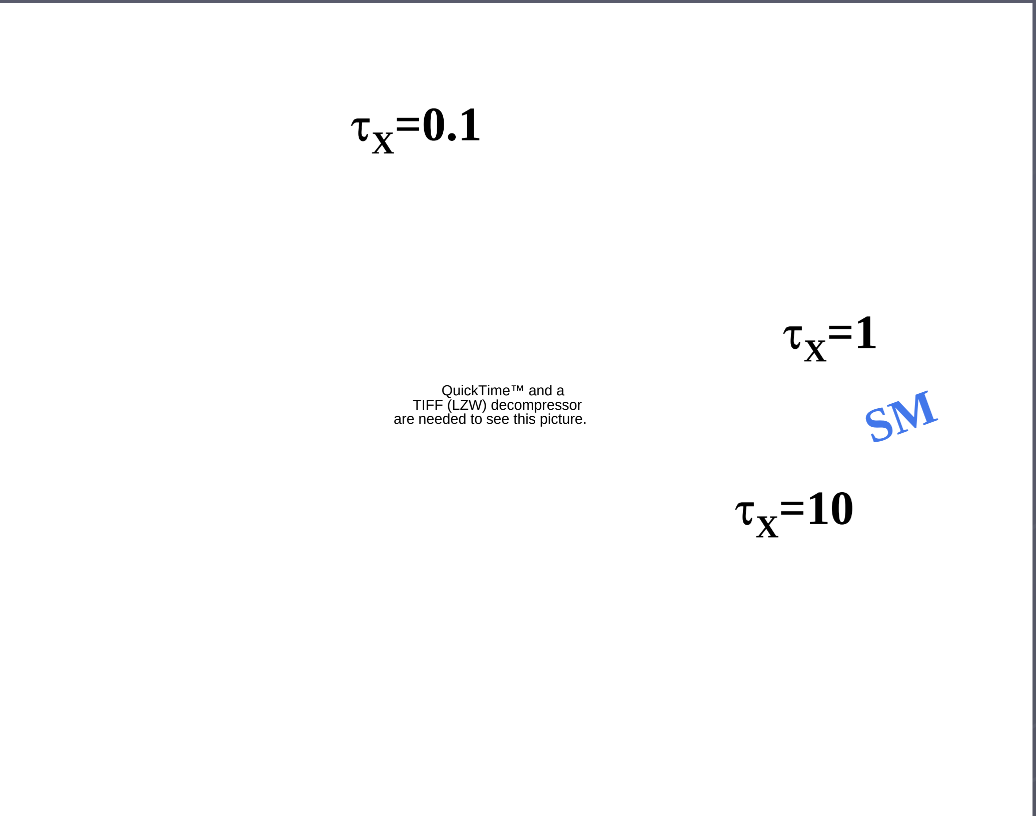
Higher mass fluxes with λ~ 10 can only be done if some energy is deposited at the disc surface (Casse & Ferreira 00b).

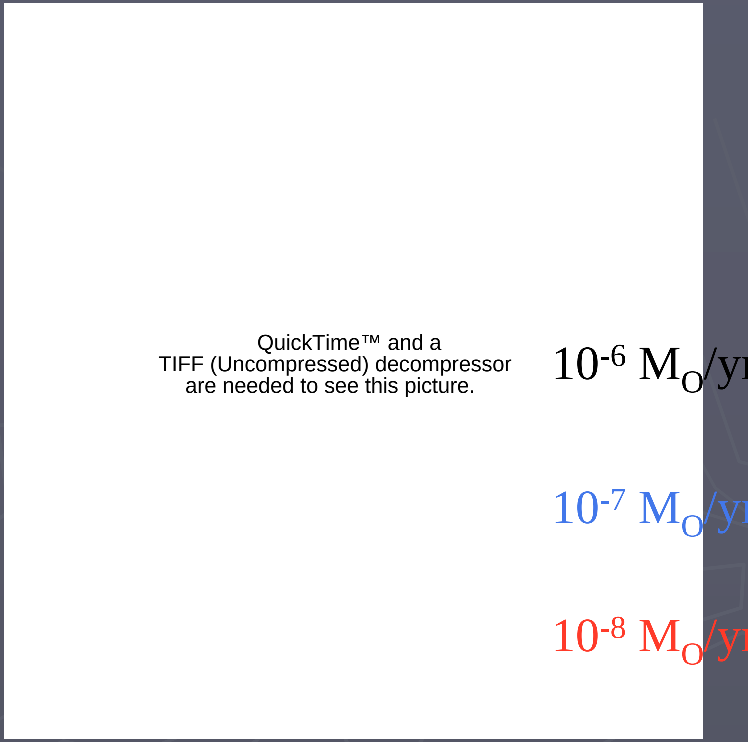


**Warm jets** from thin discs can arise if

1. **Stellar UV/X illumination** (accretion shock)
2. **Local dissipation of accretion energy** (coronal heating, Galeev 79, Heyvaerts & Priest 89)

# II-6 Can X-rays do the job?



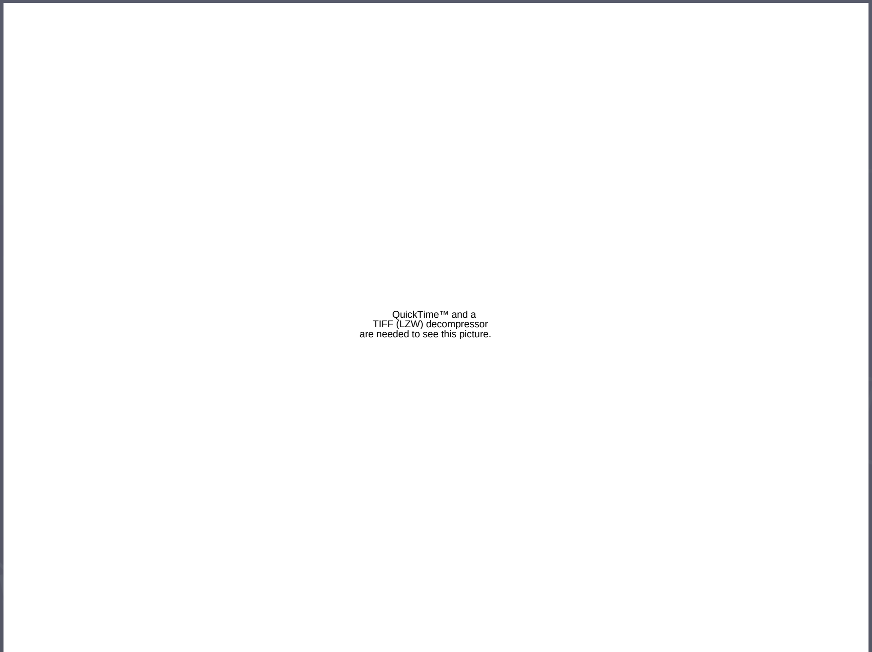




For relevant T Tauri star parameters (Macc, X-ray flux and spectrum, Imanishi et al 03, Wolk et al 05, Guedel 05) X-rays are unable to heat the base of the jet to the level required to enhance the mass flux.

Garcia et al, to be subm.

=> *heating must be of turbulent origin*

# II-7 Black Hole XrBs: a similar situation?

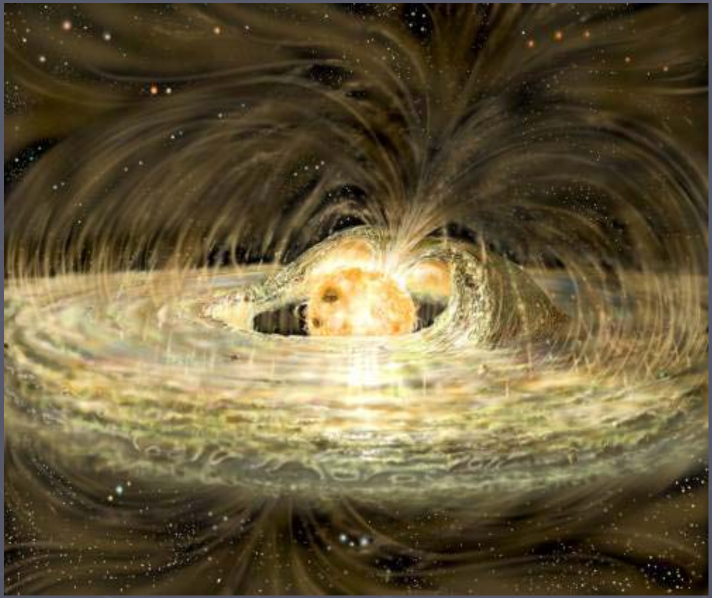



Ferreira et al 06a, A&A

Here, a corona is needed in order to account for the hard X-ray spectrum when the disc emission is lacking *and jets observed*.

=> Consistent with JEDs

# III-1 The star-disc magnetic interaction



See review in PPV Alencar et al

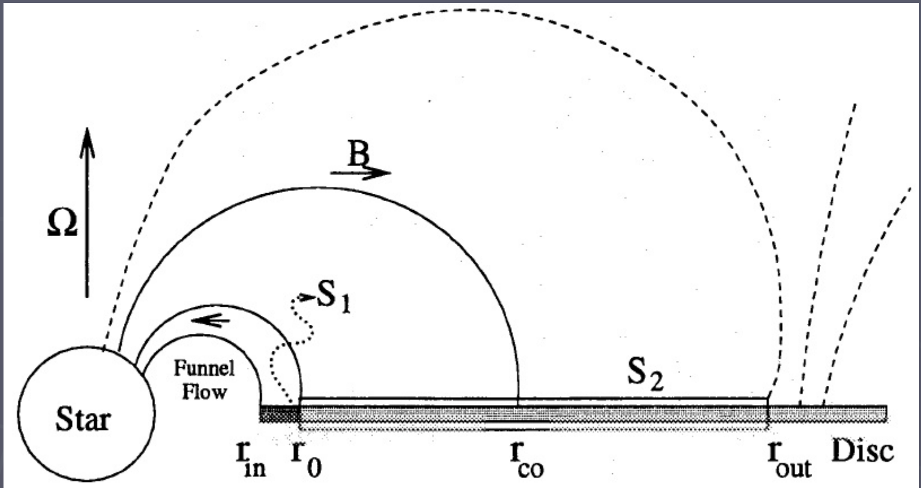
T Tauri stars are slow rotators despite contraction+accretion (Bertout et al 89, Bouvier et al 97, Rebull et al 02)

=> Accretion must help to remove stellar angular momentum

Evidences of a magnetospheric interaction (Edwards *et al.* 94, 98, Calvet 04, Muzerolle et al 01, Bouvier *et al.* 99, Günther et al 99, Johns-Krull et al 99,01, Feigelson & Montmerle 99)

=> What kind of magnetic configuration?

# III-2 Two contradictory requirements




(1) The disc-locking paradigm

(2) Accretion must still proceed

Gosh & Lamb 79

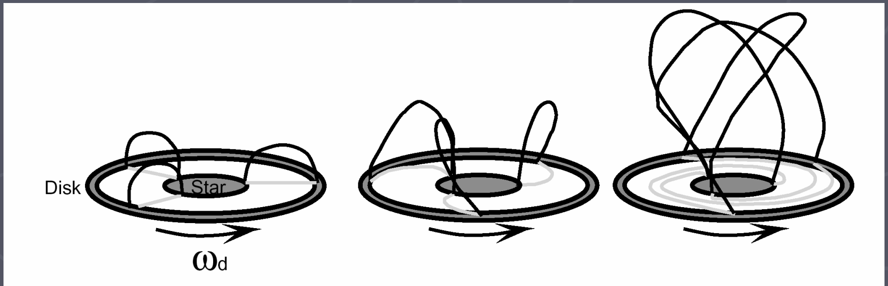
Cameron & Campbell 93, Li 96

Matt & Pudritz 04

-$r_{in} > r_{co}$: star is spun down => accretion is prevented

-$r_{in} < r_{co}$: star is spun up => accretion is allowed

=> Efficiency of disc viscosity??



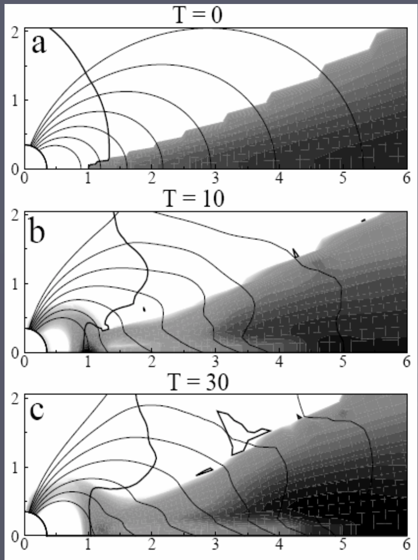

Second process: reconnection

=> Efficiency of disc magnetic diffusivity??

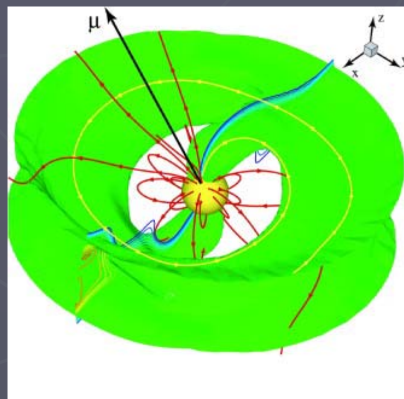
Lovelace et al 95, 99, Bardou & Heyvaerts 96

Uzdensky et al 02, Matt & Pudritz 05

# III-3 Heavy numerical simulations

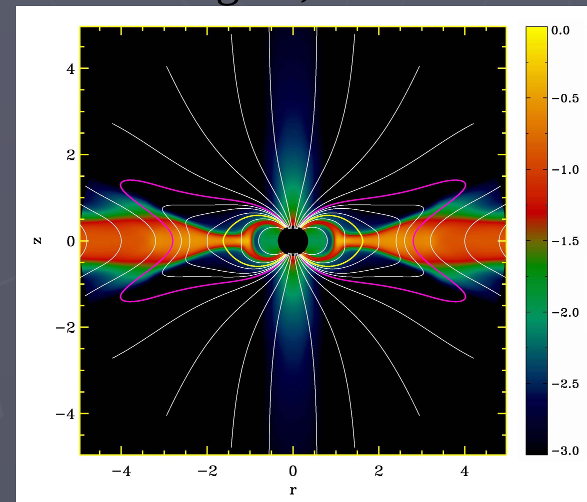



QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.




Hayashi et al 96, Miller & Stone 97, Hirose et al 97, Goodson et al 97,99, Kueker et al 03, Romanova et al 02,03,04,05, Long et al 05, 06 von Rekowski & Brandenburg 04,05

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.



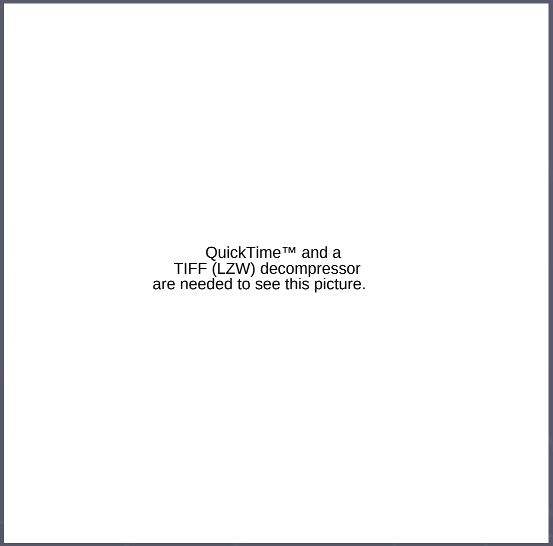

Zanni et al, in pre

Funnel flows are a natural feature in a non force-free magnetosphere, BUT **stellar spin up**.

Main difficulties (and differences):

- -Treatment of disc physics (mass, $\nu_v$ and $\nu_m$)
- -Boundary conditions at the star (!!)
- -Numerical resolution

# Concluding remarks

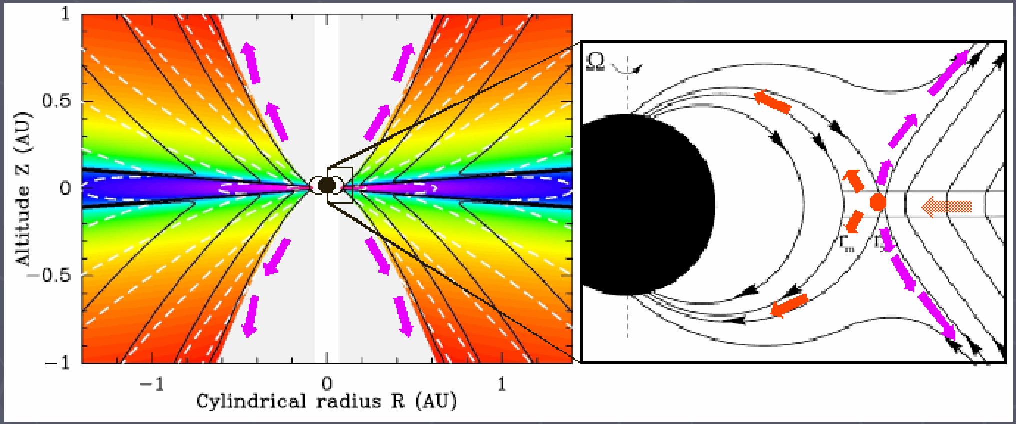



Matt & Pudritz 05

The « stellar angular momentum problem » requires a wind as a sink:

⇒ Accretion-powered stellard winds ?

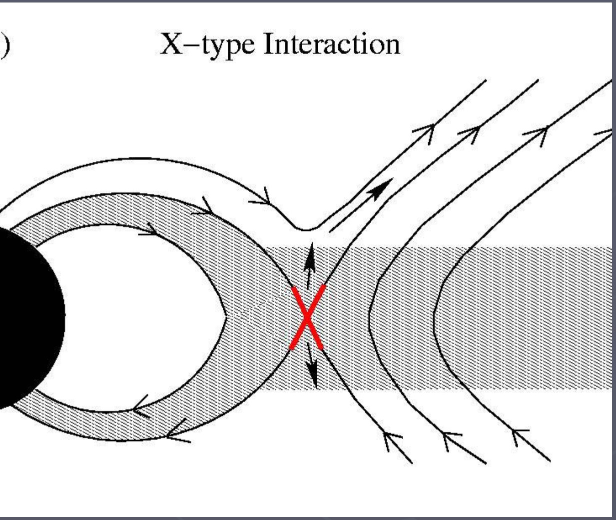
⇒ Reconnection X-winds ?

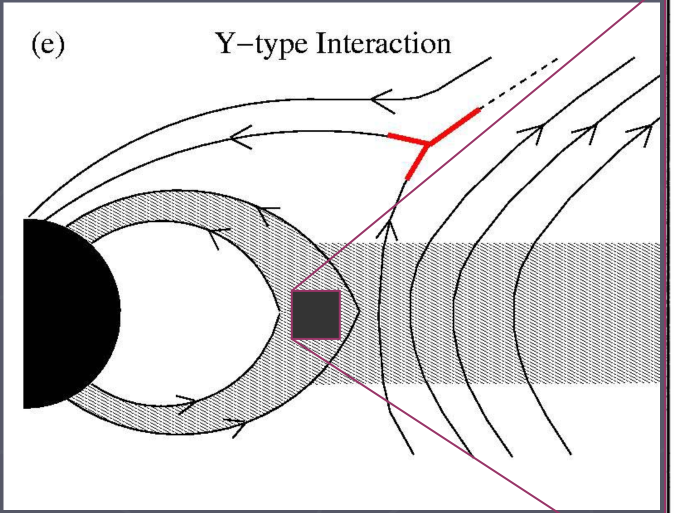


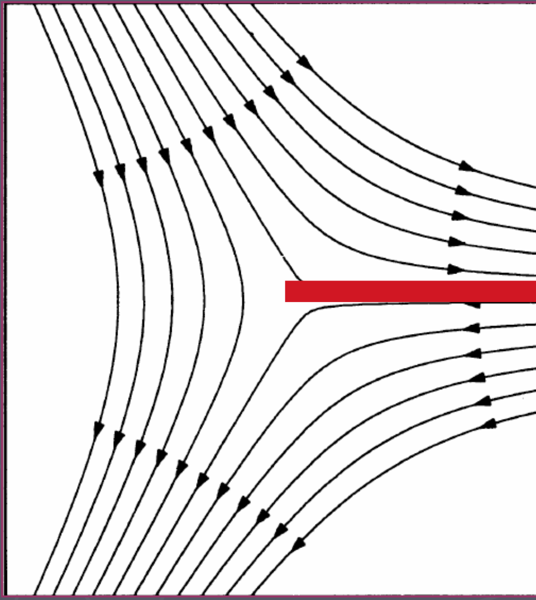

Ferreira, Pelletier & Appl 00

The answer probably relies on MHD experiments:
- Quality is greatly and rapidly improving over the years
- BUT the outcome is strongly dependent on the disc microphysics and turbulence (transport coefficients, corona)

# Two (over-)simple configurations



Ferreira, Pelletier, Appl 00

Shu et al 94a

Camenzind 90

Matt & Pudritz 05

Ostriker & Shu 95

Both configurations give birth to a magnetic neutral line at the equator : chondrules (Gounelle et al 06)

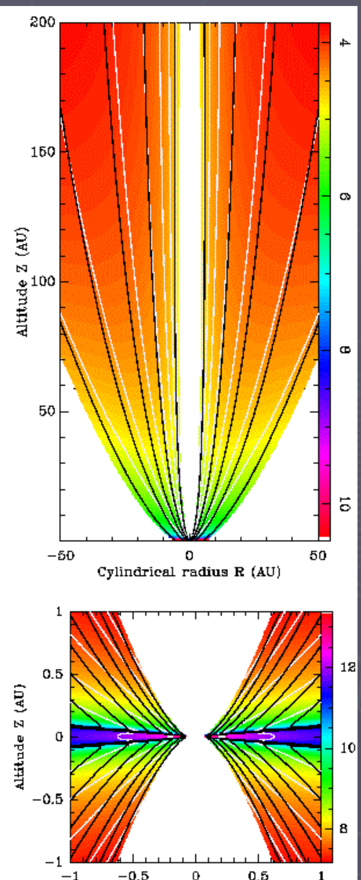
-Reconnection X-winds: due to oppositely directed fields

-X-wind: unspecified origin

# II-5 Testing models against observations

MHD model
V,ρ,B

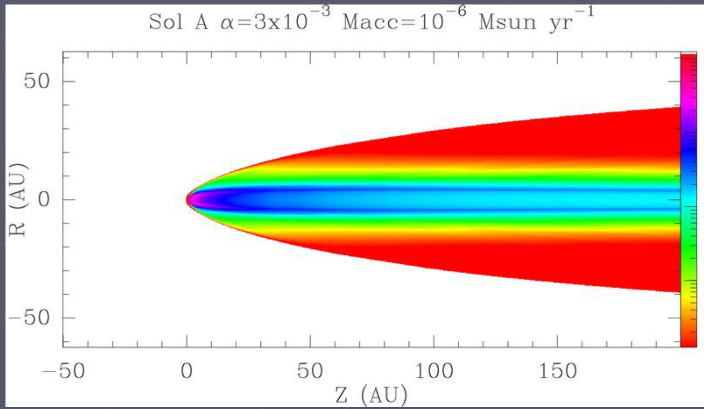
+




Thermal and Ionization Structures
$T, n_H, xe$

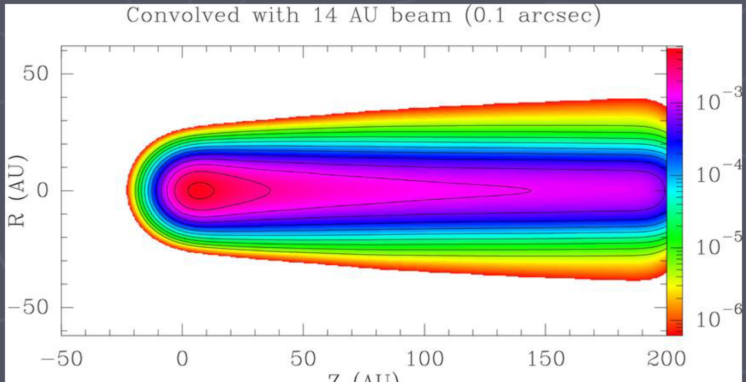
Projection

Emissivity map




Convolution

Synthetic image



QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.