Discs Winds

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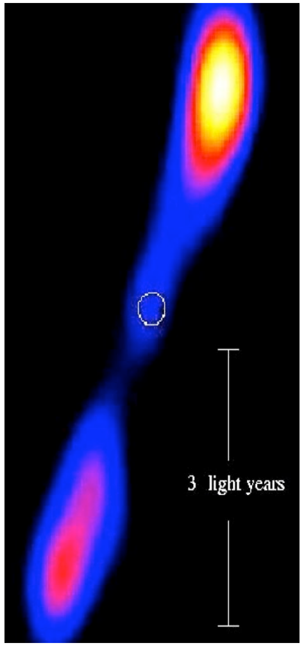
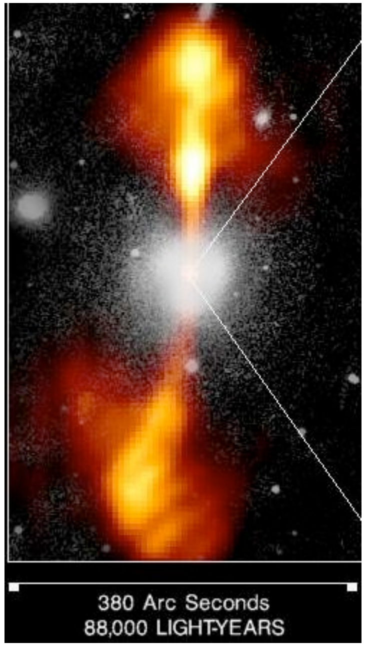
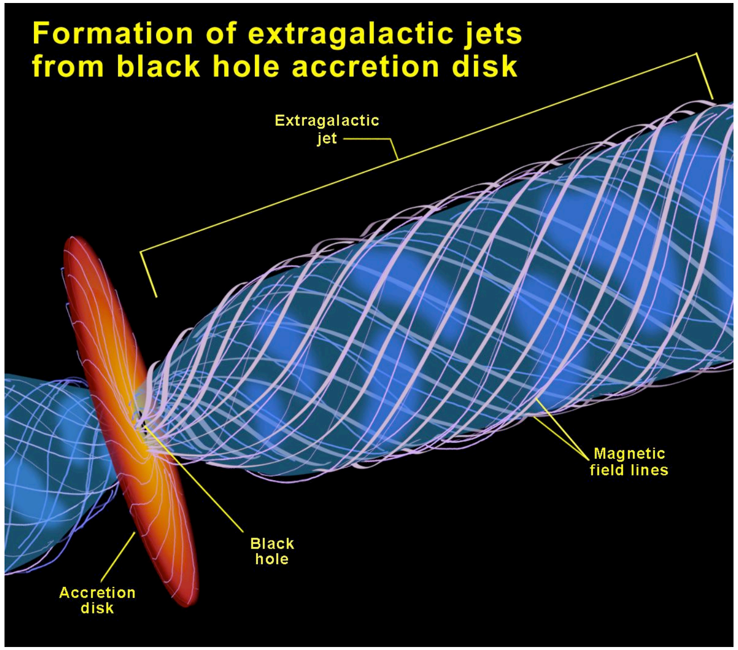


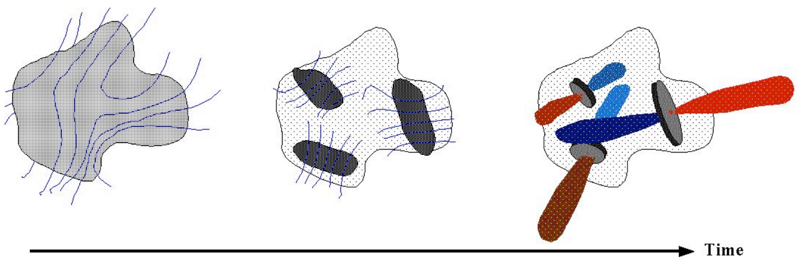


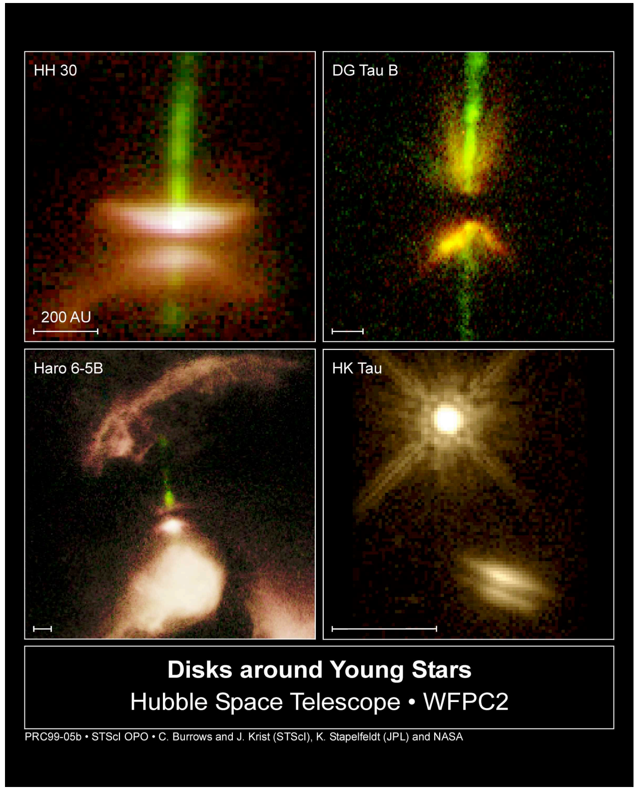


Collaborators:

F. Casse, G. Pelletier, S. Cabrit, P. Garcia, C. Dougados, C. Combet, G. Murphy, C. Zanni

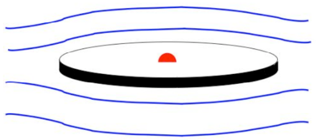
Large scale B_z in YSO discs ?





CTTs discs are randomly oriented / B_z

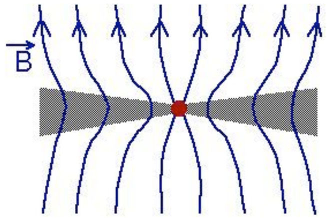
(Ménard & Duchêne 04)

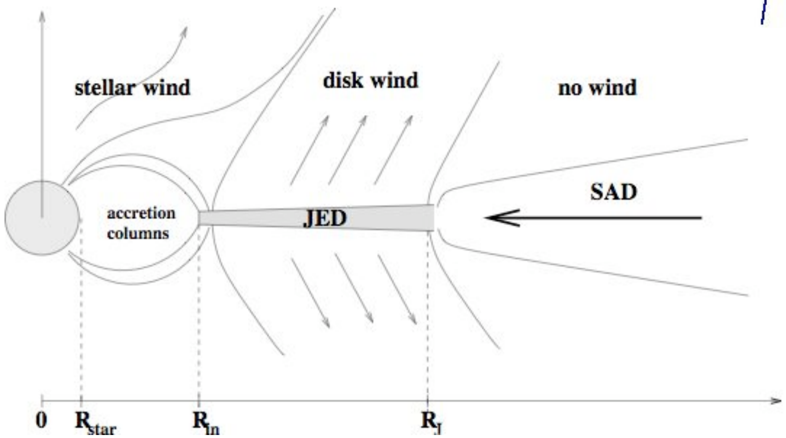


BUT

- sources without jets: parallel
- sources with jets: perpendicular

(Strom et al 86)



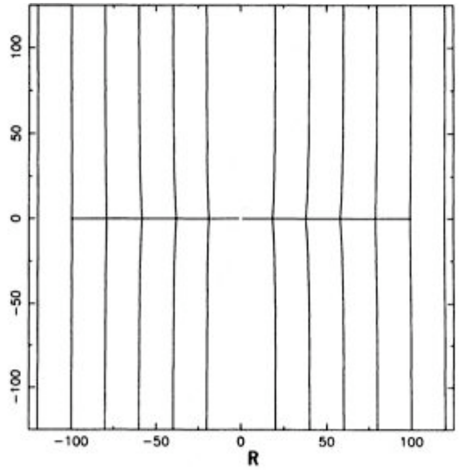


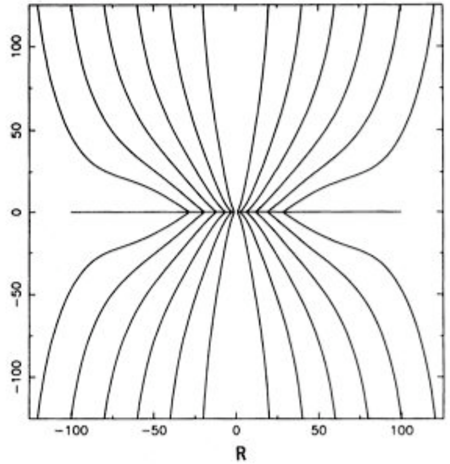
Jet Emitting Discs (JED) vs Standard Accretion Discs (SAD)

=> Disc magnetization $\mu = \frac{B_z^2}{\mu_o P_{tot}} \leq 1$

Ferreira & Pelletier 95

Magnetic field advection in SADs





Lubow *et al*. 94a, Heyvaerts et a 96
Ogilvie & Livio 98, Shu et al 07
Rothstein & Lovelace 08

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

SAD, by def $\mathcal{R}_e = \frac{r u_r}{\nu_v} \simeq 1$

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 $\varepsilon \sim 1$ for typical values for δ

Ferreira et al 06a, A&A

G. Murphy's talk

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

Disc-winds - analytics (1/4)

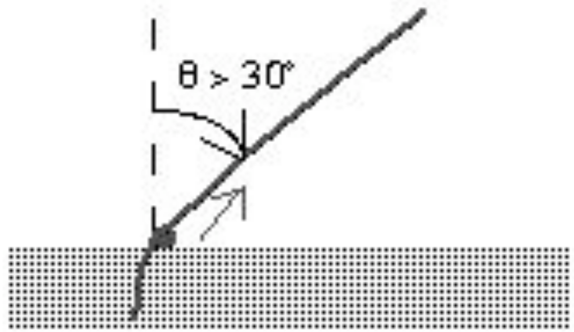
Disc vertical equilibrium quasi MHS balance $\dfrac{\partial P}{\partial z} = -\rho \Omega_K^2 z + F_z$

magnetic shear $q = -\dfrac{B_\phi^+}{B_z}$

magnetic bending $p = \dfrac{B_r^+}{B_z}$

$\mu = \dfrac{B_o^2}{\mu_o P}$

MHS requires $\mu (q^2 + p^2) < 2$



@ surface: Blandford & Payne criterion (cold)

⇒ p ~ unity => μ < about unity

Jet acceleration must take place… in the poloidal direction

$$u_p \cdot \nabla u_z = -\Omega_K^2 z - \frac{\partial P/\partial z}{\rho} + \frac{F_z}{\rho}$$ => super-sonic flow

Disc-winds - analytics (2/4)

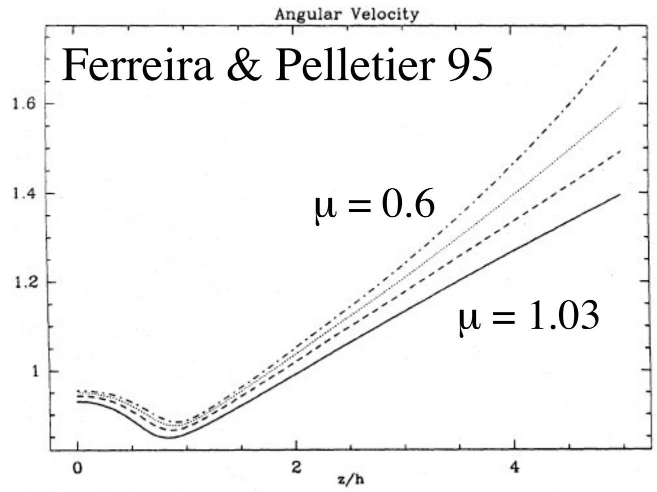
Radial MHS equilibrium $$\Omega^2 = \Omega_K^2 \left(1 + \frac{\partial P/\partial r}{\rho \Omega_K^2 r} - \frac{F_r}{\rho \Omega_K^2 r}\right)$$

- pressure deviation ~ $(h/r)^2$
- magnetic radial tension ~ p μ (h/r)

BUT estimate valid only @ z=0

Magnetic effect increases with height

⇒ Ω(z) decreases within the disc



However, @ disc surface, no static equilibrium anymore: unavoidable acceleration

$$u_p \cdot \nabla u_r = (\Omega^2 - \Omega_K^2) r - \frac{\partial P/\partial r}{\rho} + \frac{F_r}{\rho}$$

Caveat for averaging procedures (e.g. Shu et al 08, ApJL)

Disc-winds - analytics (3/4)

Angular momentum

$$\frac{1}{r}\rho\vec{u}_p \cdot \nabla\Omega r^2 = F_\phi + \frac{1}{r^2}\frac{\partial}{\partial r}\eta_v r^3 \frac{\partial\Omega}{\partial r}$$

where jet torque is

$$F_\phi = J_z B_r - J_r B_z \simeq \frac{B_\phi^+ B_z}{\mu_o h}$$

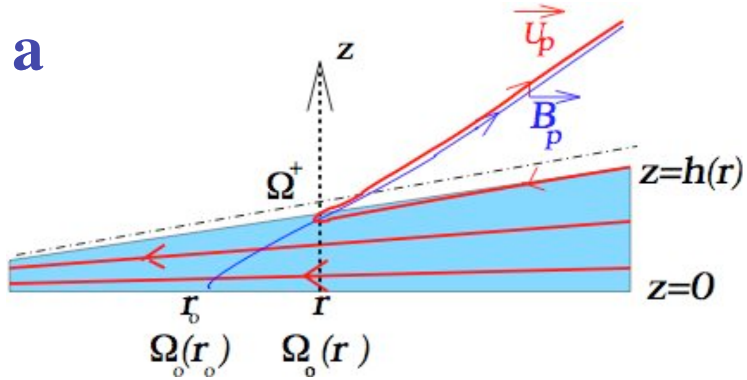
@ z=0, translates into

$$m_s = \frac{u_o}{C_s} = 2q\mu + \alpha_v \frac{h}{r} = 2q\mu\left(1 + \Lambda^{-1}\right)$$

Steady-state diffusion: $m_s = \frac{r u_o}{\nu_m}\frac{\nu_m}{C_s r} = \alpha_v p \frac{\nu_m}{\nu_v} \sim \alpha_v$

⇒ Accretion velocity determined by large scale field (Λ >>1)

A necessary condition for jet production is **a magnetic azimuthal acceleration**



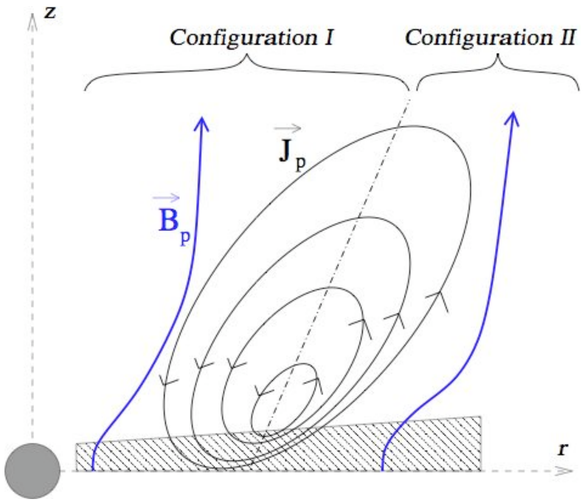
@ z= 0, F_ϕ< 0 (disc material spun down)

@ z= h, F_ϕ > 0 (jet material spun up)

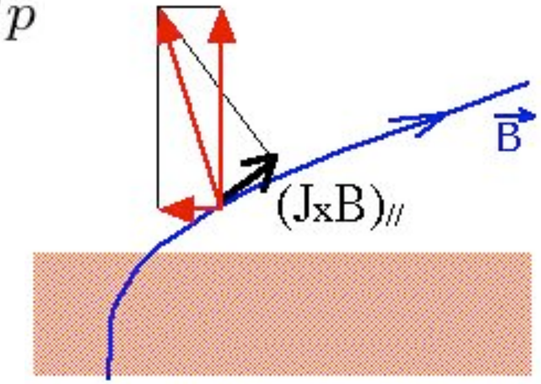
Jr decrease on h, requires q ~ p ~ unity (Ferreira & Casse 08, sub to MNRAS)

EMF: disc and/or central source?

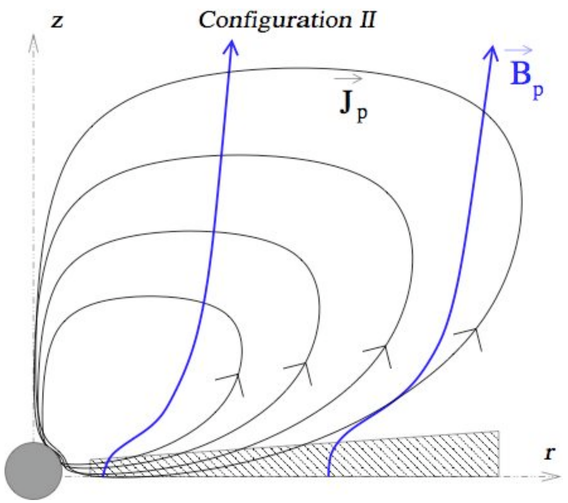
Two possible electric current configurations, associated with different vertical forces and mass fluxes:

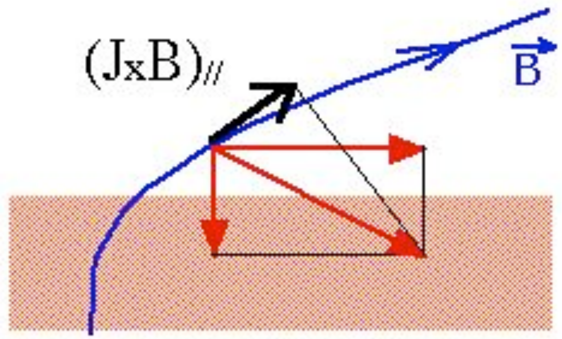


$$F_{\|} = (\vec{J} \cdot \vec{B}) \cdot \vec{B}_p / B_p$$
$$= -\frac{B_\phi}{2\pi r} \nabla_{\|} I$$



Large mass flux =>
(unsteady for cold)



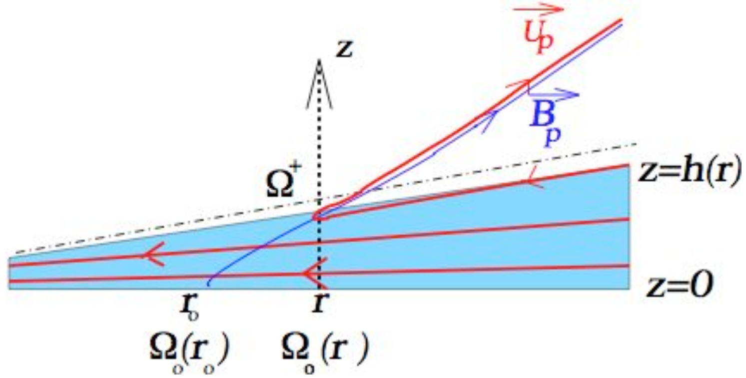


Small mass flux =>

Ferreira 97, Ferreira & Casse 08, MNRAS

Disc-winds - analytics (4/4)

Why near equipartition fields ?



@ disc surface, resistive-ideal MHD transition, $u_r = 0$

Ohm's law gives: $\eta J_\phi = u_z B_r - u_r B_z$

$$u_z^+ = \frac{\nu_m^+}{h} \left. \frac{\partial B_r/\partial z}{B_r/h} \right|^+ \sim \frac{\nu_m^+}{h} \simeq m_s \frac{\nu_m^+}{\nu_o} C_s$$

=> within **cold** approx, deviation by B requires $m_s \sim 1$, thus $\mu \sim 0.5$

$$m_s = \frac{u_o}{C_s} = 2q\mu + \alpha_v \frac{h}{r} = 2q\mu \left(1 + \Lambda^{-1}\right)$$

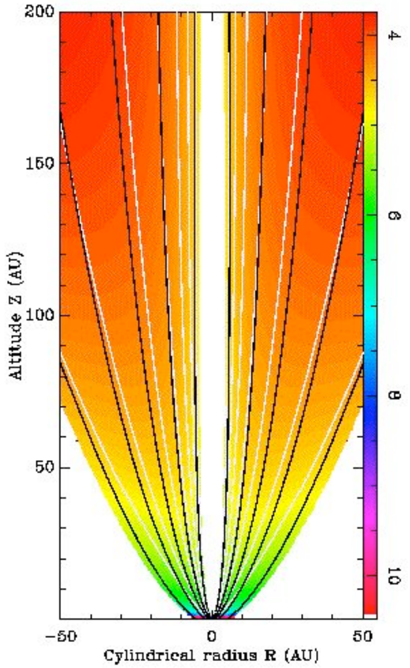
It implies: - dominant jet torque (regardless of Prandtl)

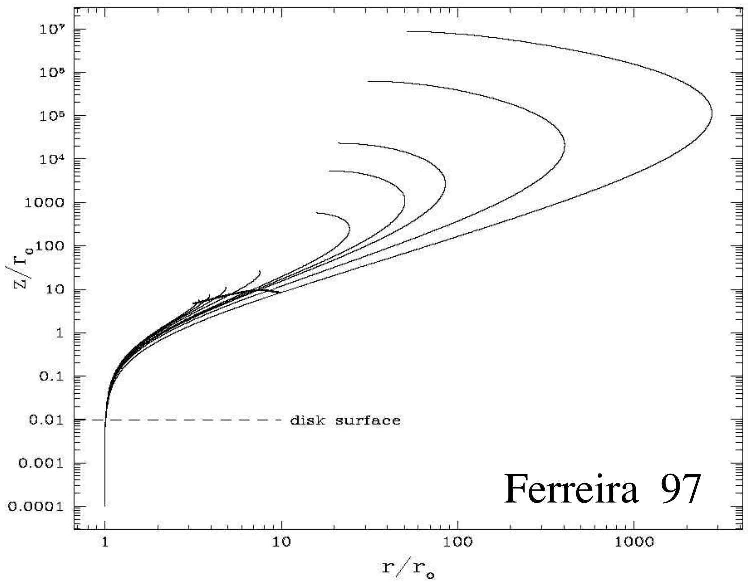
- most of accretion power feeds jets

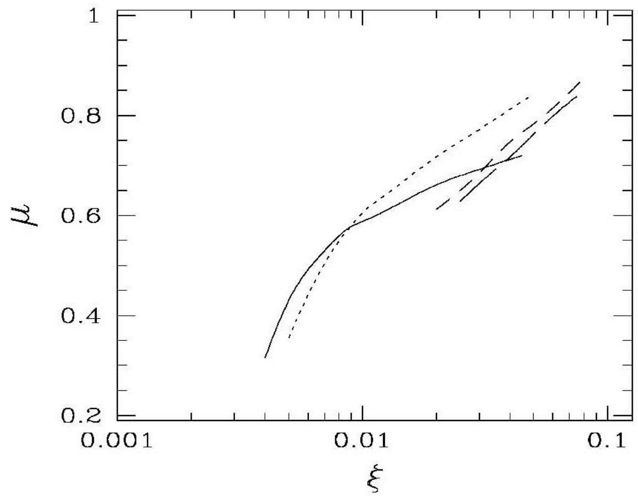
Ferreira & Pelletier 93,95

Self-similar models

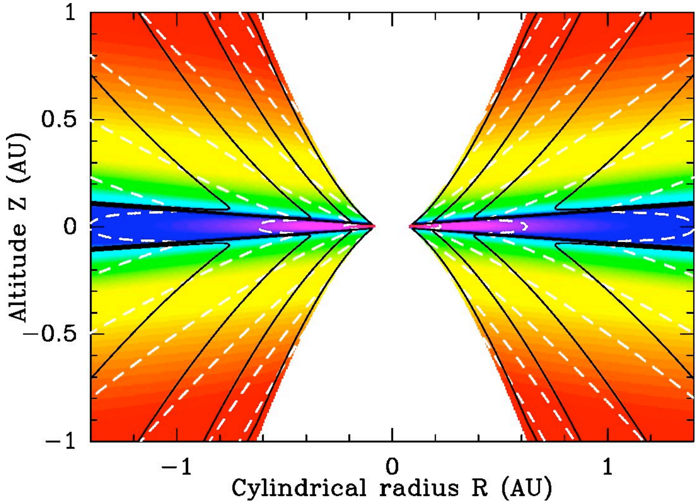
Ferreira & Pelletier 93,95
Ferreira 97,
Casse & Ferreira 00,04







$$\dot{M}_{acc} \propto r^{\xi}$$

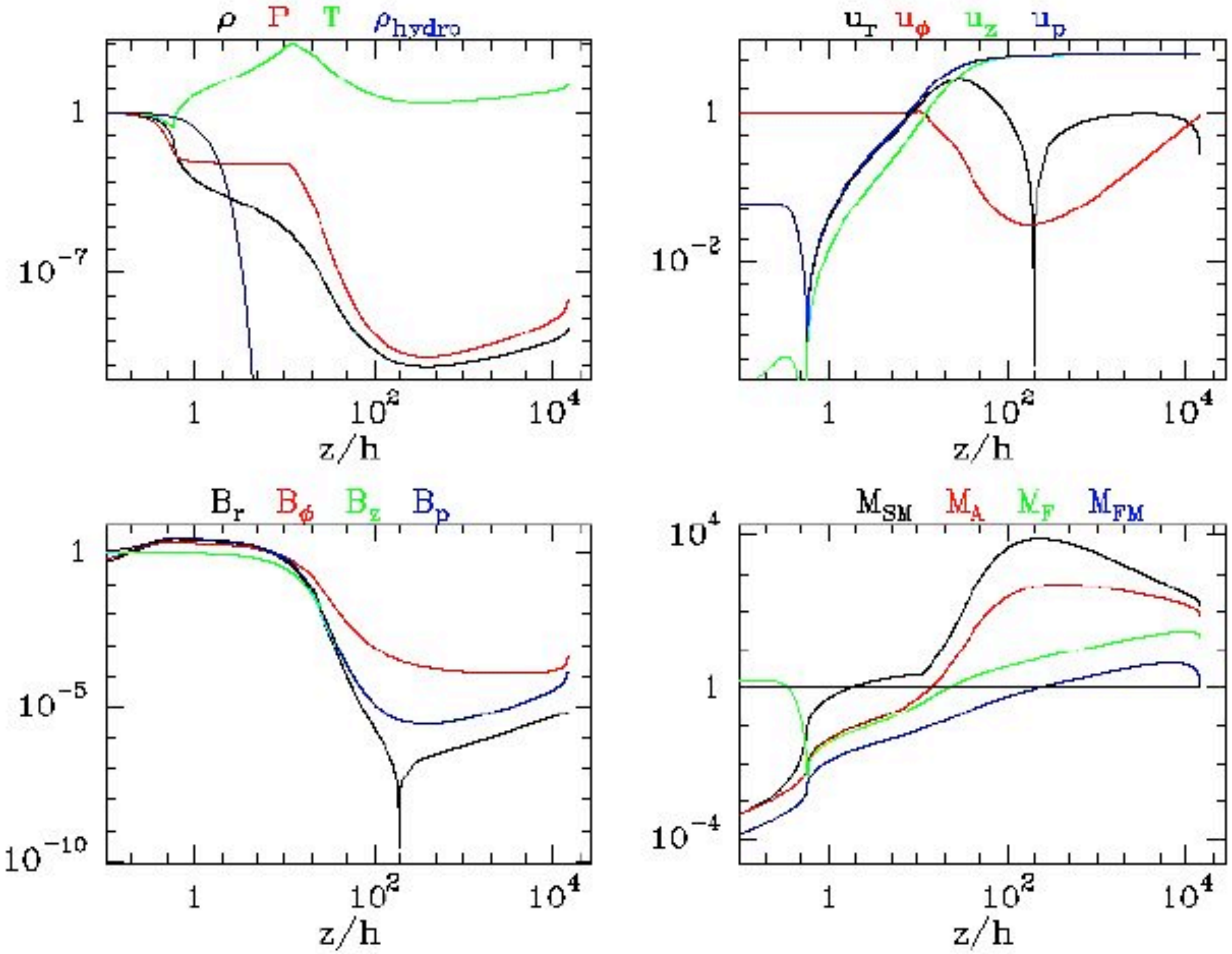


- All dynamical terms included
- resistive -> ideal MHD transition
- Thermodynamics: ad-hoc energy equation

$0.1 < \mu < 1$ narrow parameter range

$\xi \sim 0.01$ for cold solutions, up to **$\xi \sim 0.5$** for warm solutions

A typical super-FM (very warm) solution



$\xi = 0.03$

$\varepsilon = h/r = 0.03$

$\alpha_m = 1$

$\kappa_{BP} = 0.12$

$\lambda_{BP} = 23$

$$\frac{2P_{jet}}{P_{acc}} = 0.84$$

$$\frac{P_{diss}}{P_{acc}} = 0.16$$

Ferreira & Casse 04, ApJL

Some interesting consequences of JEDs

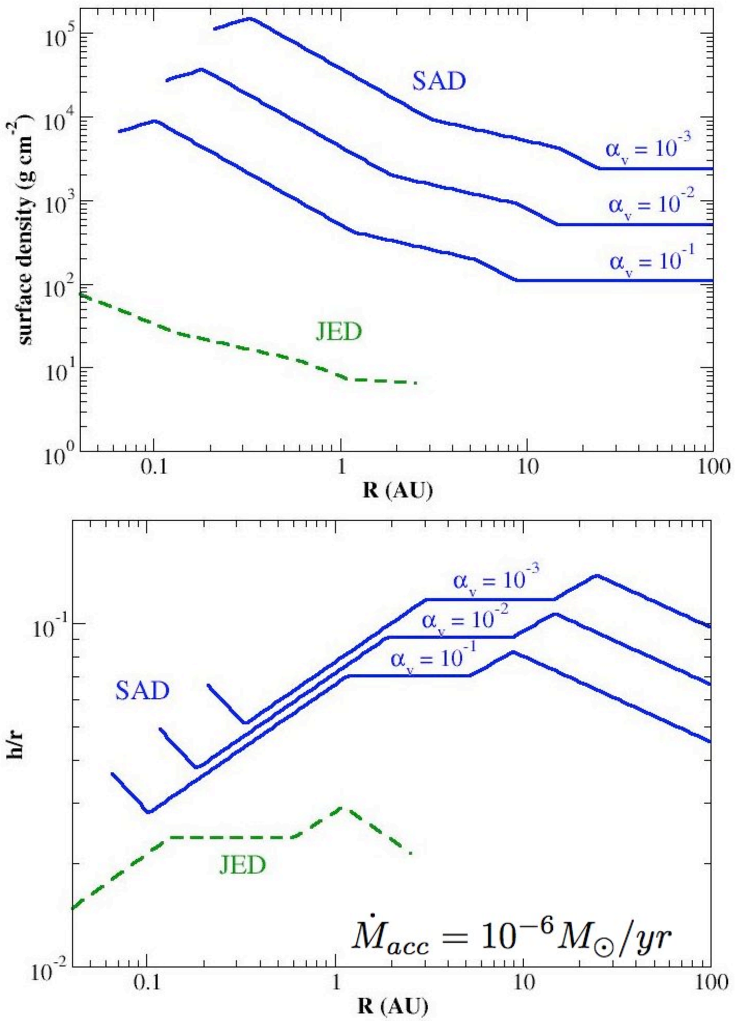
A JED fed with same Mdot as a SAD:

- ✓ Different radial structure than a SAD (colder, less dense, faster accretion), different SEDs

  See Combet's poster

- ✓ The SAD/JED transition provides a trap stopping migration of protoplanetary cores (Masset et al 06)

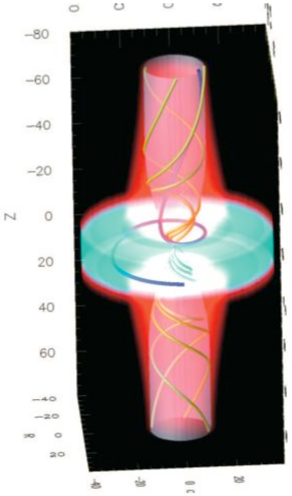
- ✓ Accretion time scale issue: unsteady accretion ?

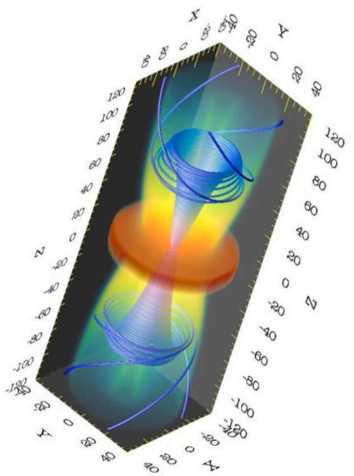


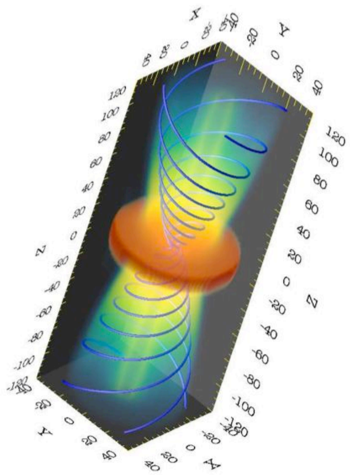
Combet & Ferreira 08

Related works

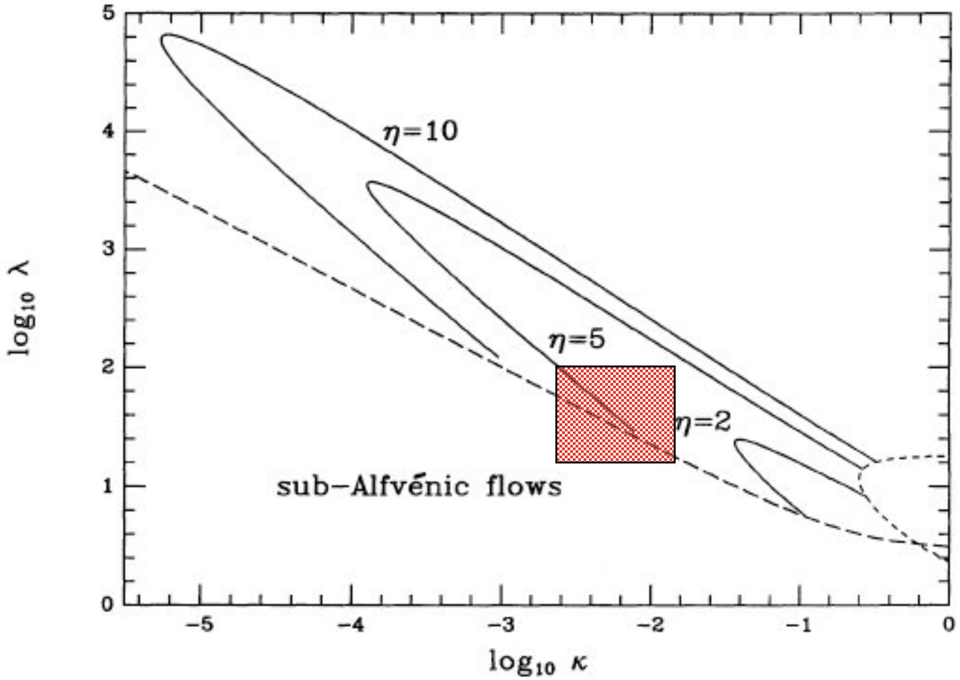
=> Main results from self-similar calculations are confirmed by MHD simulations where the disc is also computed: Casse & Keppens 02, 04, Zanni et al 07,   see P. Tzeferakos's poster





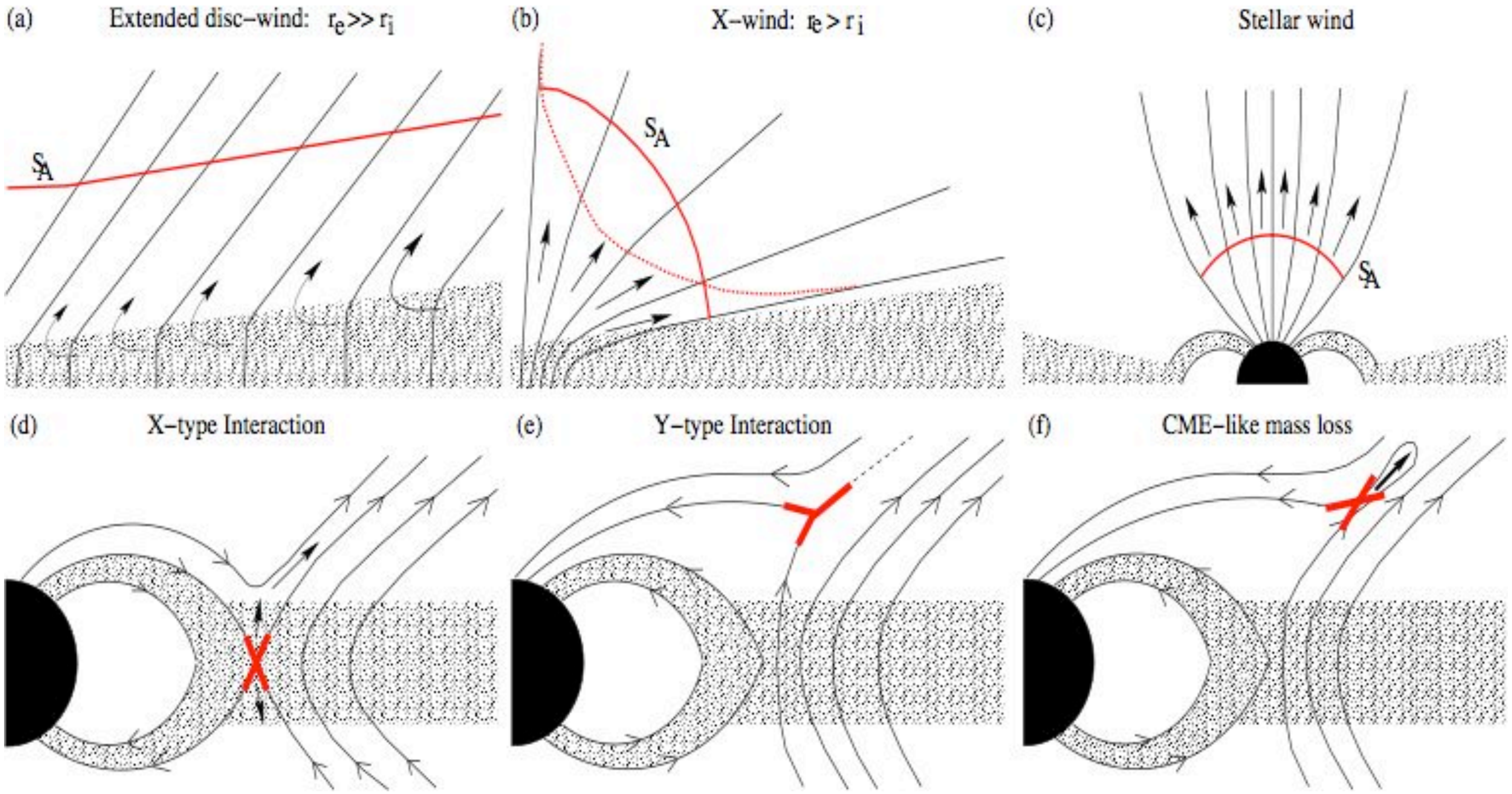


Wardle & Konigl 93



-> Modelling objects: warm winds (heating source, disc ionization…?)

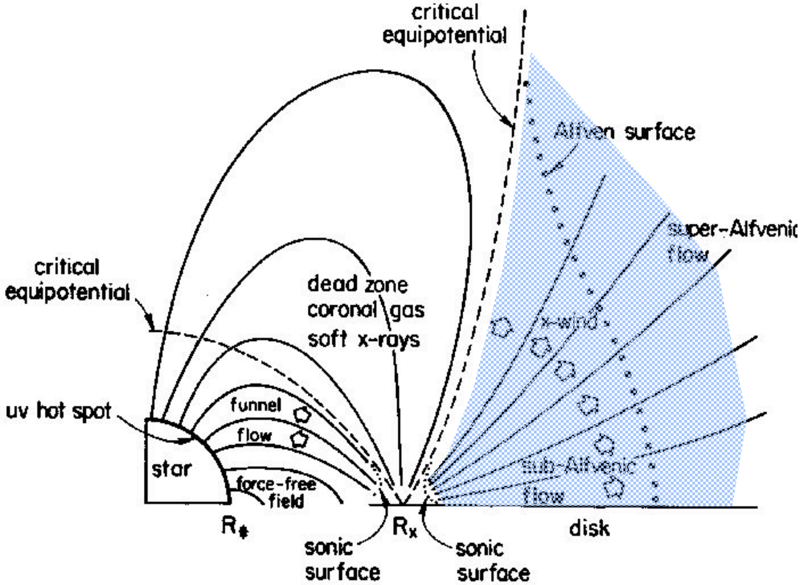
Wind models and star-disc interaction



Ferreira, Dougados, Cabrit, 06

X-winds

Shu et al 94a,b Najita et al 94
Shang et al 98, Cai et al 08



$$f = 2\dot{M}_X/\dot{M}_a \sim 1/3$$

Is this achievable from $\Delta r_X/r_X = \varepsilon$?

$$\dot{M}_a = -2\int_0^h 2\pi r\rho u_r dz \simeq 4\pi\rho_o u_o r h = 4\pi\rho_o\Omega_K r h^2 m_s$$

$$\rho_X = \dot{M}_X/2\pi r_X^3\Omega_X$$

$$B_X = (\mu_o\Omega_X\dot{M}_X/2\pi r_X)^{1/2}$$

$\mathbf{B} = \beta(\psi)\rho\mathbf{u}$ with β ~ unity

$$2P_{jet,X} = 2\int E(\Psi)\rho\vec{u}_p\cdot d\vec{S} = 2P_{MHD} + 2P_{kin} = 2\int \vec{S}_{MHD}\cdot d\vec{S} + 2\int\left(\frac{u^2}{2} + \Phi_G + H\right)\rho\vec{u}_p\cdot d\vec{S}$$

$$= 2P_{MHD}\left(1 + \frac{\tilde{H}-1}{2(\lambda-1)}\right)$$

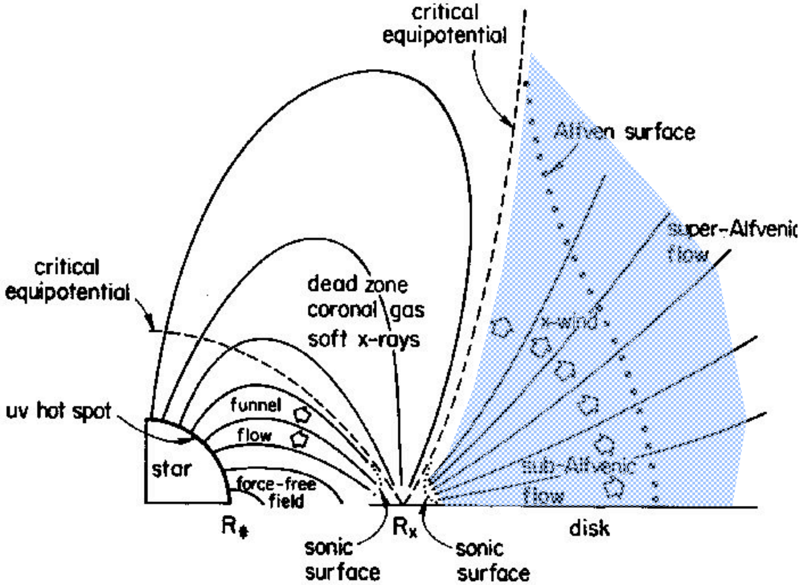
with $2P_{MHD} \simeq -2\Omega_X r_X \frac{B_\phi^+ B_o}{\mu_o} 2\pi r_X \Delta r_X$

$$\frac{2P_{jet,X}}{GM\dot{M}_a/2r_X} \simeq \left(\frac{2q\mu}{m_s}\right)\frac{\Delta r_X}{r_X} = \frac{\Lambda}{1+\Lambda}\frac{\Delta r_X}{r_X}$$

~ ε **not enough power to explain YSO jets !**

X-winds

Shu et al 94a,b Najita et al 94
Shang et al 98, Cai et al 08



$$\Phi_X \simeq 2\pi\bar{\beta}B_X r_X^2 = 2\pi B_o r_X \Delta r_X$$

Large mass loss => large magnetic flux (β ~ unity)

Small extent => large field $B_z = B_o$

Disc magnetization defines the importance of the magnetic torque

$$\mu = \frac{B_o^2}{\mu_o P_o} = m_s f \frac{\bar{\beta}^2}{\varepsilon^2} = 2q\mu f \frac{\bar{\beta}^2}{\varepsilon^2}(1+\Lambda^{-1})$$

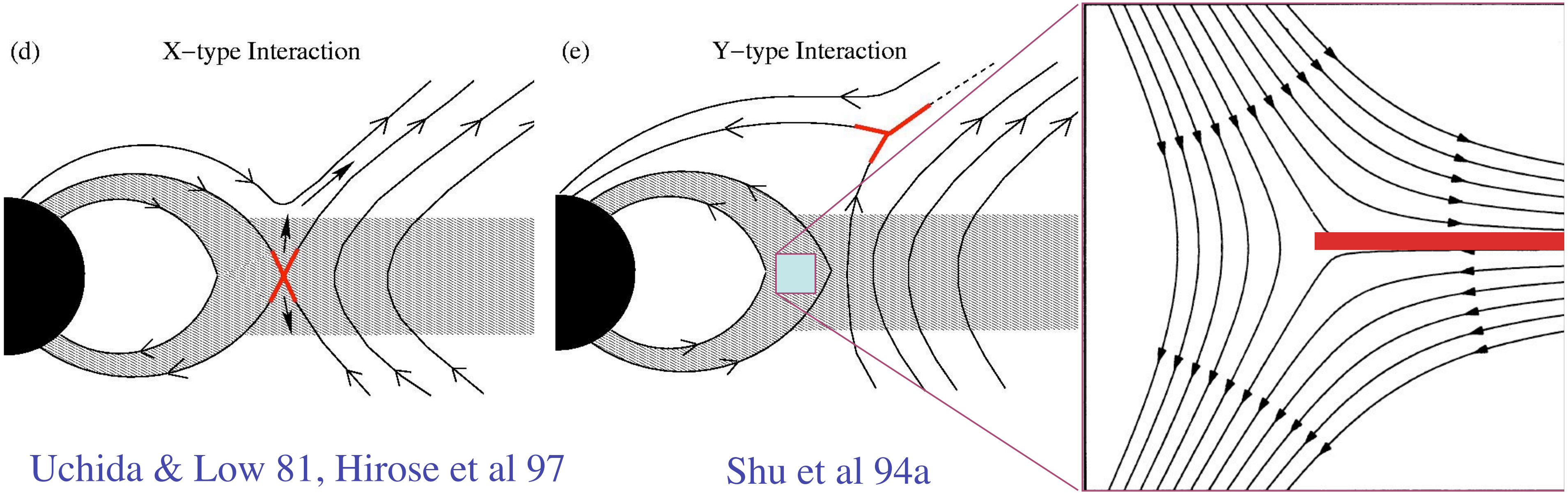
Most favourable X-wind case: Λ>>1 $q = \varepsilon^2/2f\bar{\beta}^2 < \varepsilon^2$

whereas values adopted are around ε (only Alfvenic constraint)…

Cold, fan-like wind can only provide $f \sim \varepsilon^2/2\bar{\beta}^2$

Ferreira & Casse 08, subm to ApJL

Two (over-)simple configurations



Uchida & Low 81, Hirose et al 97

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 : good for chondrules (Gounelle et al 06)

- X-wind: unspecified origin (requirement for cold mass loading)

- Reconnection X-winds: due to oppositely directed fields

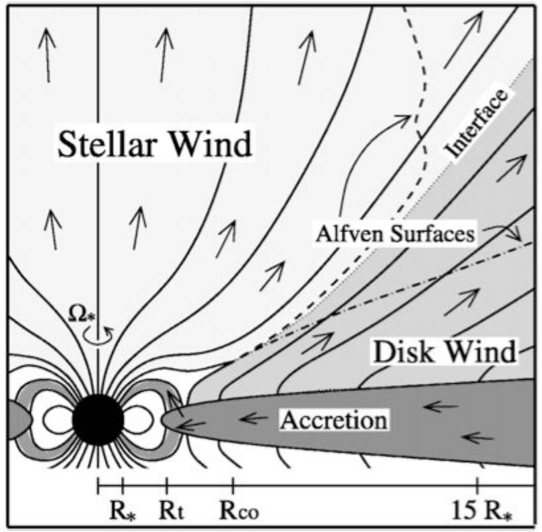
Concluding remarks

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

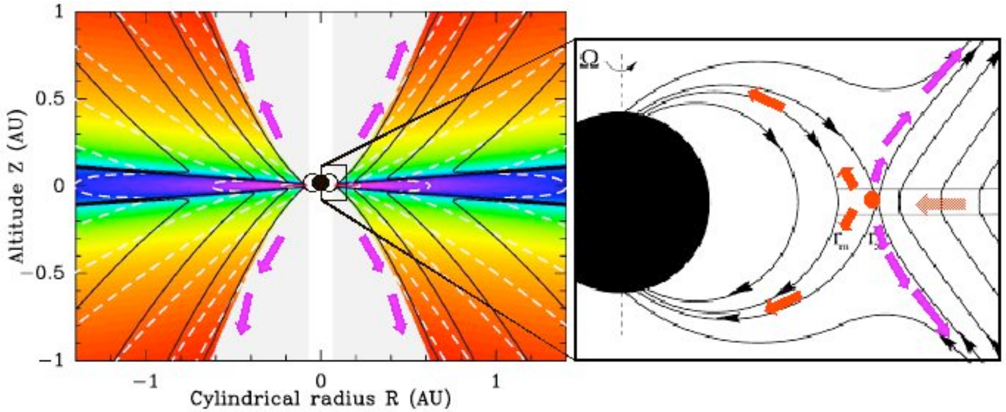
⇒ X-winds ? mass loss issue…

⇒ Accretion-powered stellard winds ?

⇒ Reconnection X-winds ?



Matt & Pudritz 05, 08



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 (multi-fluid approach for YSOs)