Magnetospheric accretion and protostellar outflows in YSOs: a theoretical perspective

Claudio ZANNI
INAF – Osservatorio Astrofisico di Torino

INAF

ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI TORINO

The accretion/outflow connection in young stellar objects – ESA/ESTEC

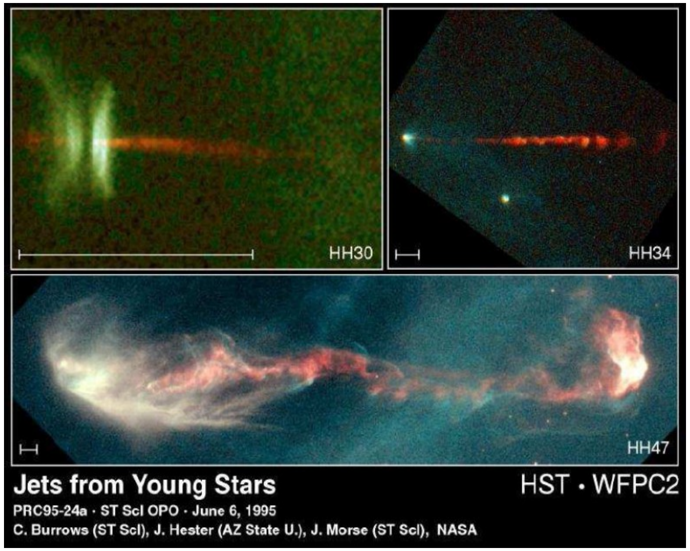
October 27th 2015

Magnetospheric outflows

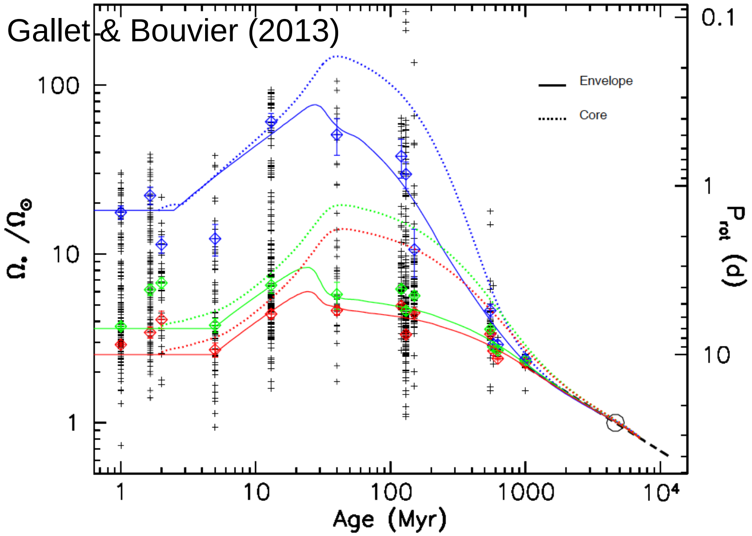
- Outflows are likely associated with magnetospheric accretion
- Magnetically driven outflows need two basic ingredients:
  - rotation (star, disk)
  - large scale magnetic field (measured, both intensity and topology)
- Combination of rotation and ordered magnetic field generates toroidal field B_ϕ
- B_ϕ provides:

- Poynting flux	$E_\perp B_\phi/4\pi$	- Magnetic torque	$- B_\phi B_p/4\pi$
- Poloidal force	$-\nabla_{//} (rB_\phi)^2/8\pi r^2$	- Confinement tension	$- B_\phi^2/4\pi r$

Why bother?



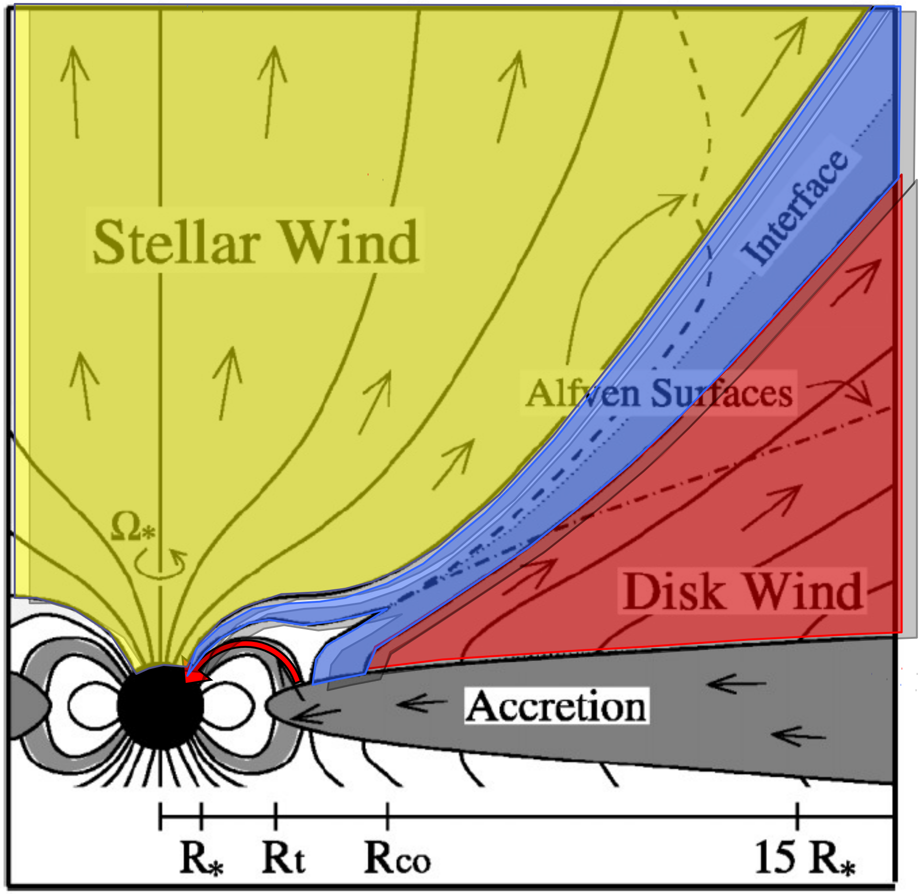
- Jets and outflows are clearly observed, showing strong correlation with accretion signatures, but not close enough to the source to give precise hints about their origin.



Gallet & Bouvier (2013)

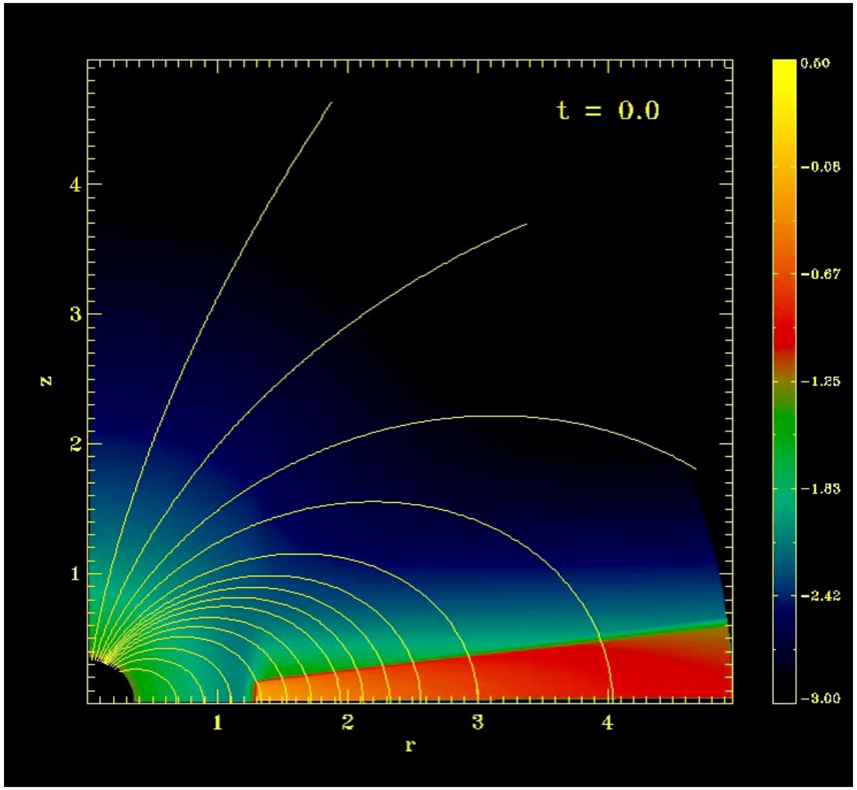
- CTTs show slow rotation periods, well below breakup (3-10 d Bouvier et al. 1993), that appear to be rather constant during the TTauri phase (Irwin et al. 2007). Can magnetospheric outflows extract the excess angular momentum?

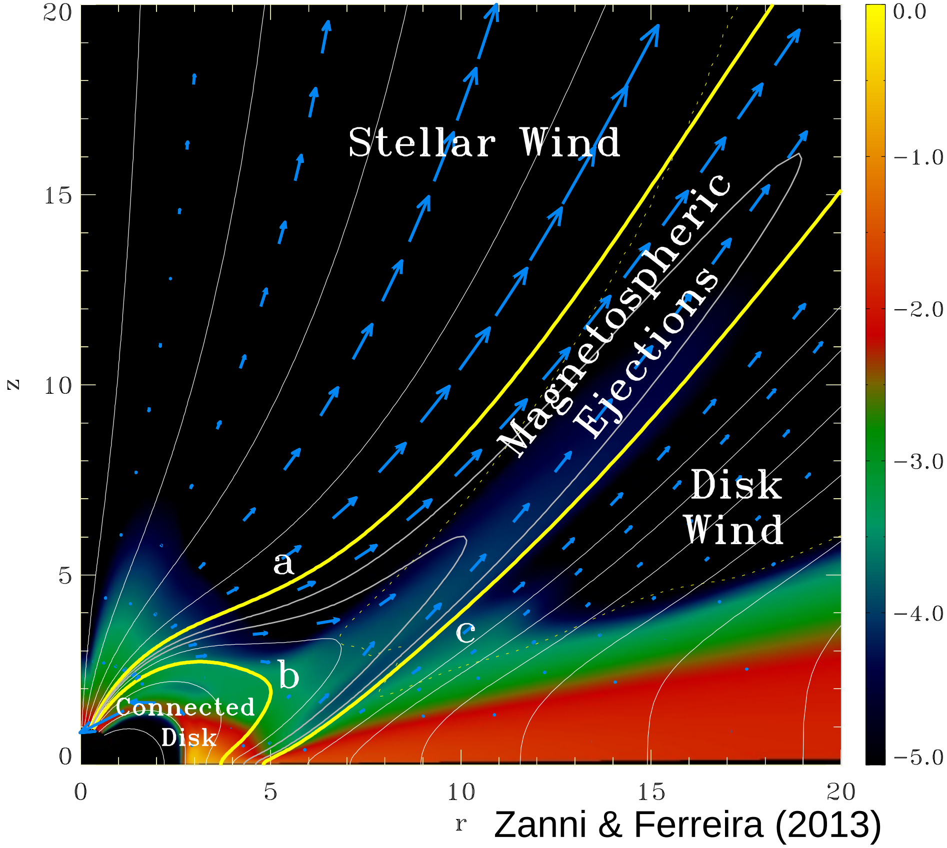
Magnetospheric outflows



- Stellar winds extracting angular momentum from the star (Matt & Pudritz 2005)
- Disk-winds extracting disk angular momentum before it is accreted (e.g. X-wind, Shu et al. 1994)
- Magnetospheric ejections extracting angular momentum from the disk AND the star (Zanni & Ferreira 2013)

A numerical model

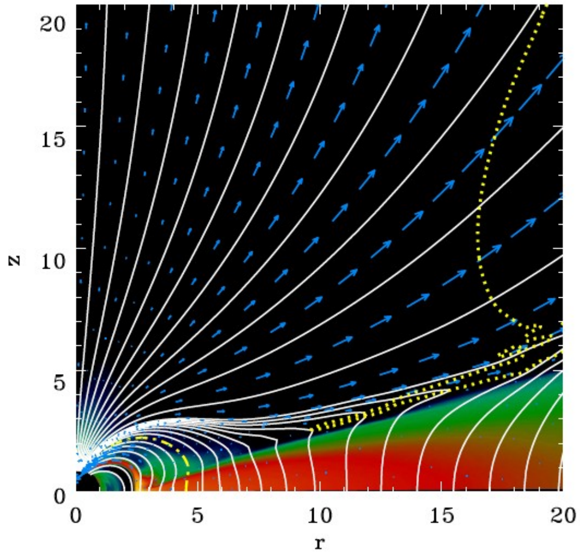




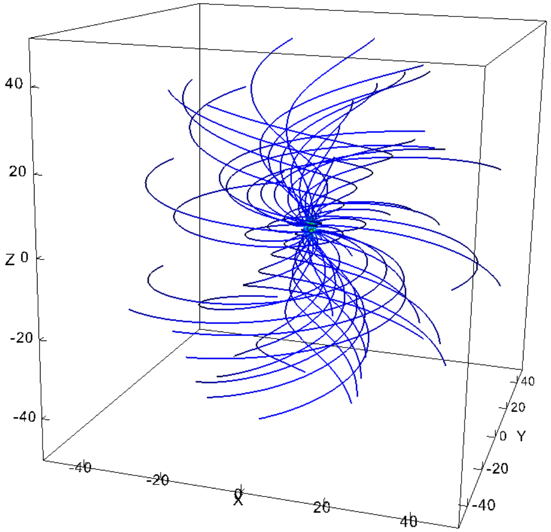
Zanni & Ferreira (2013)

- Dipolar field aligned with the rotation axis of the star ($B_* = 800$ G)
- Star ($M_* = 0.5M_{sun}$, $R_* = 2R_{sun}$) rotating with a 4.6 days period ($\Omega_* = 0.1\Omega_k$)
- Viscous and resistive “alpha” (Shakura & Sunyaev) disk with $M_{acc} = 6\times10^{-9}$ M_{sun}/yr

Stellar winds



Zanni & Ferreira (2009)



- Slowly rotating star:
  - no centrifugal thrust
  - thermal driving ruled out (Matt & Pudritz 2007)

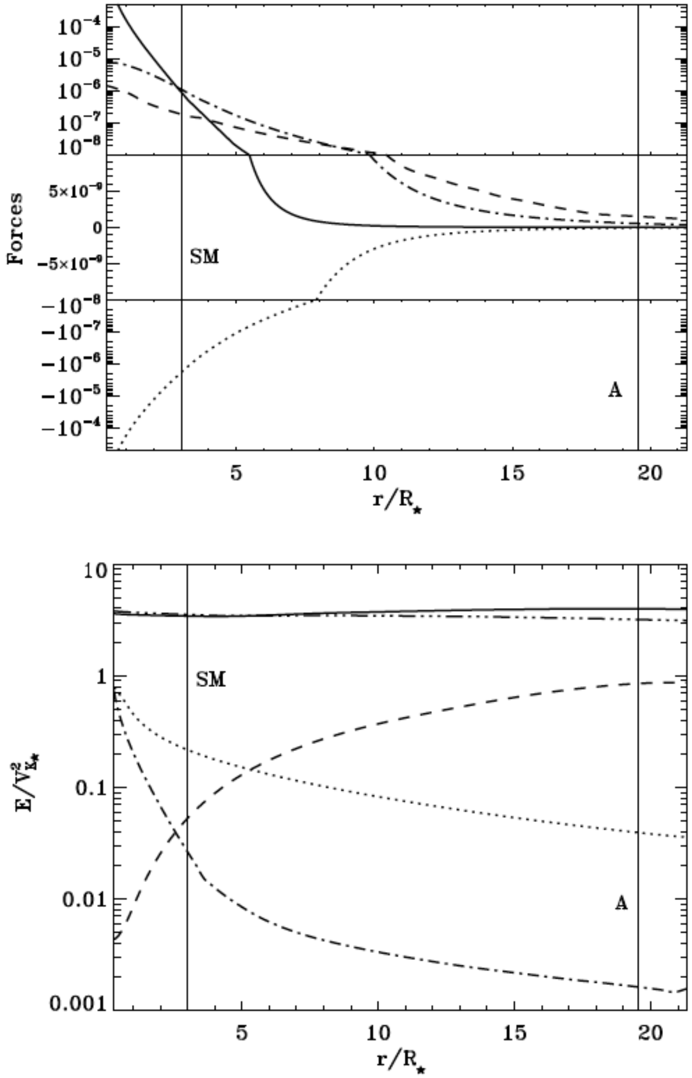
    Virial temperature $\sim 10^6\mathrm{K}$, no HeI or HI features

    Too strong X-ray emission

  - Turbulent Alfven waves (DeCampli 1981) driven by the accretion power? (Matt & Pudritz 2005)

- Ejection rate likely low
  - $M_{wind} < 1\%$ M_{acc} (Cranmer 2009)

Stellar winds



- An example (Zanni & Ferreira 2009):
  - $M_{wind} \approx 1\%\ M_{acc}$
  - Lever arm $R_A/R_* \approx 19$
  - Braking torque: $M_{wind} R_A^2 \Omega_*$
  - $P_{wind} \approx 2\%\ P_{acc}$
- Potentially very fast component (~400 Km s^{-1}), but most of the energy still in Poynting flux
- Poor (self)collimation
- Despite large lever arm only 20% of the accretion torque is extracted

Stellar winds and spin-down

- Is the stellar wind capable of balancing the accretion torque and brake the stellar rotation? (Matt & Pudritz 2005)

$$r_A = 2.11 \left(\frac{B_\star^2 R_\star^2}{\dot{M}_{\rm wind} v_{\rm esc}} \right)^{0.22} R_\star \quad \text{and} \quad \dot{M}_{\rm acc}\sqrt{GM_\star R_{\rm t}} = \dot{M}_{\rm wind} r_A^2 \Omega_\star$$

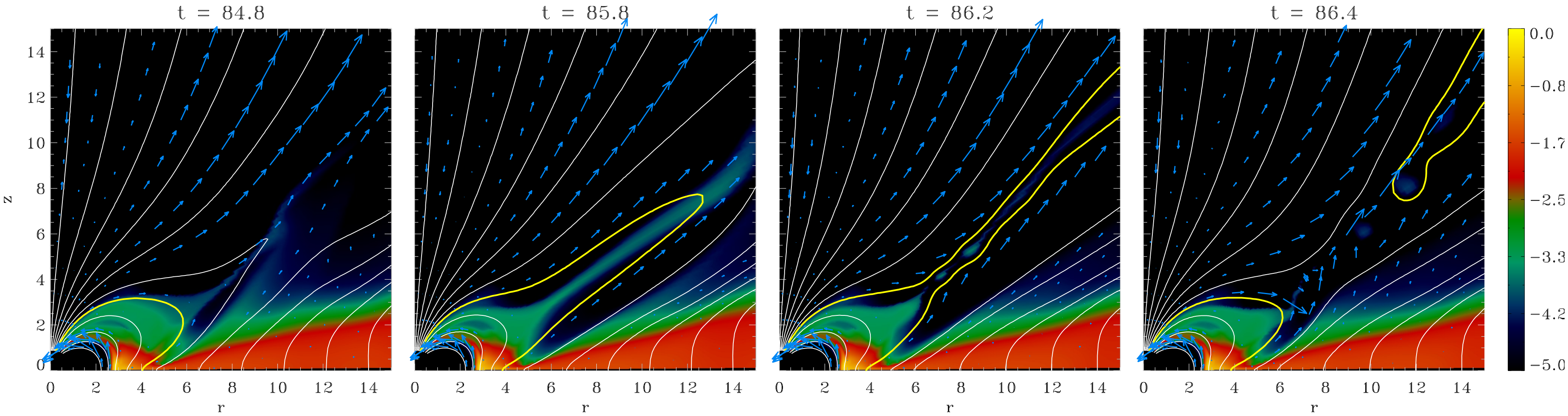
Matt & Pudritz (2008, 2012)

- In order to balance a “Keplerian” accretion torque ($\dot{M}_{\rm acc}\sqrt{GM_\star R_{\rm t}}$) of a star rotating at a small fraction of breakup (less than 10%) even assuming a kG dipolar component, a more massive and powerful wind is required

$M_{wind} > 10\%\ M_{acc}$ $\qquad$ $P_{wind} > 10\%\ P_{acc}$

- For $M_{acc} \leq 10^{-8}$ M_{sun}/yr the contraction timescale (Kelvin-Hemholtz ≈ 10^6 years) becomes comparable to the accretion spin-up timescale. The mass and energy requirement becomes even more important

Magnetospheric ejections



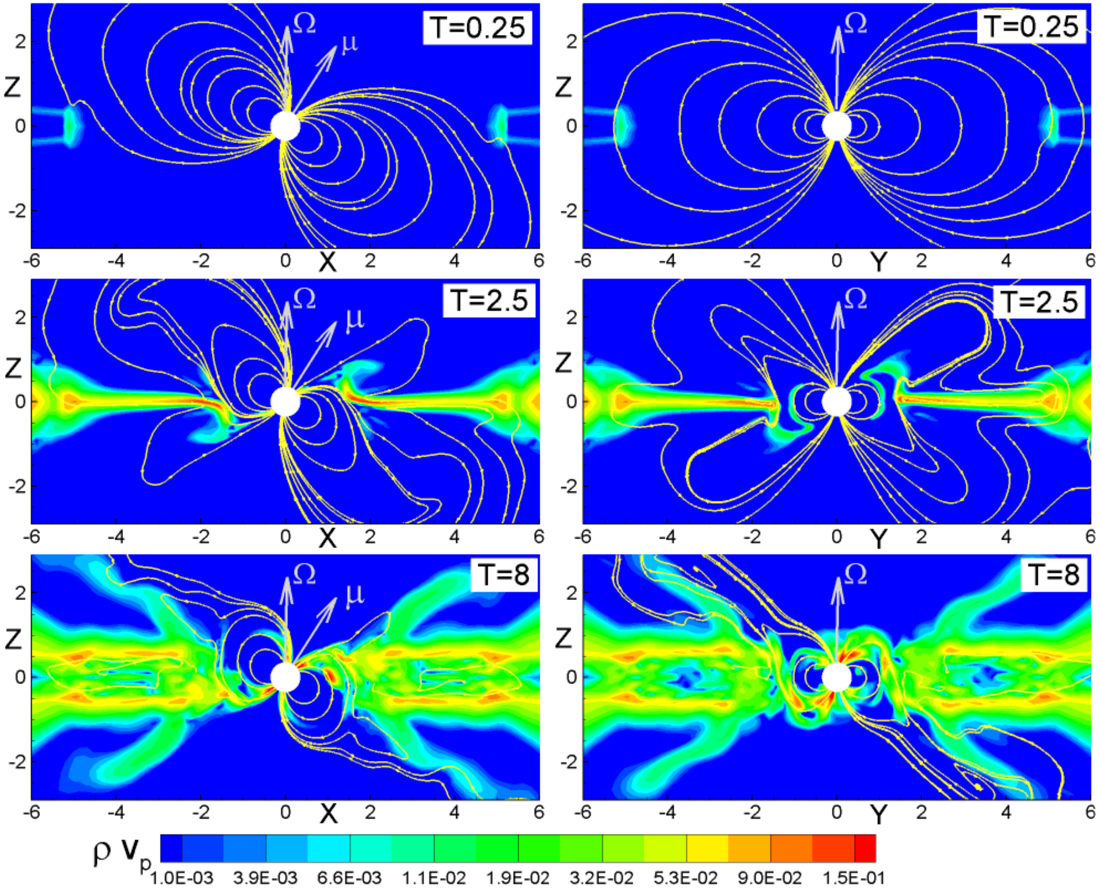
- Star-disk differential rotation builds up toroidal field component

- Due to the B_Φ pressure, initial potential structure (dipole) relaxes by inflating and opening

- Magnetospheric ejections flow along the interface between the disk and the stellar open field lines

- On a spatial scale around 10-20 stellar radii the ejection disconnects in a reconnection event (plasmoids)

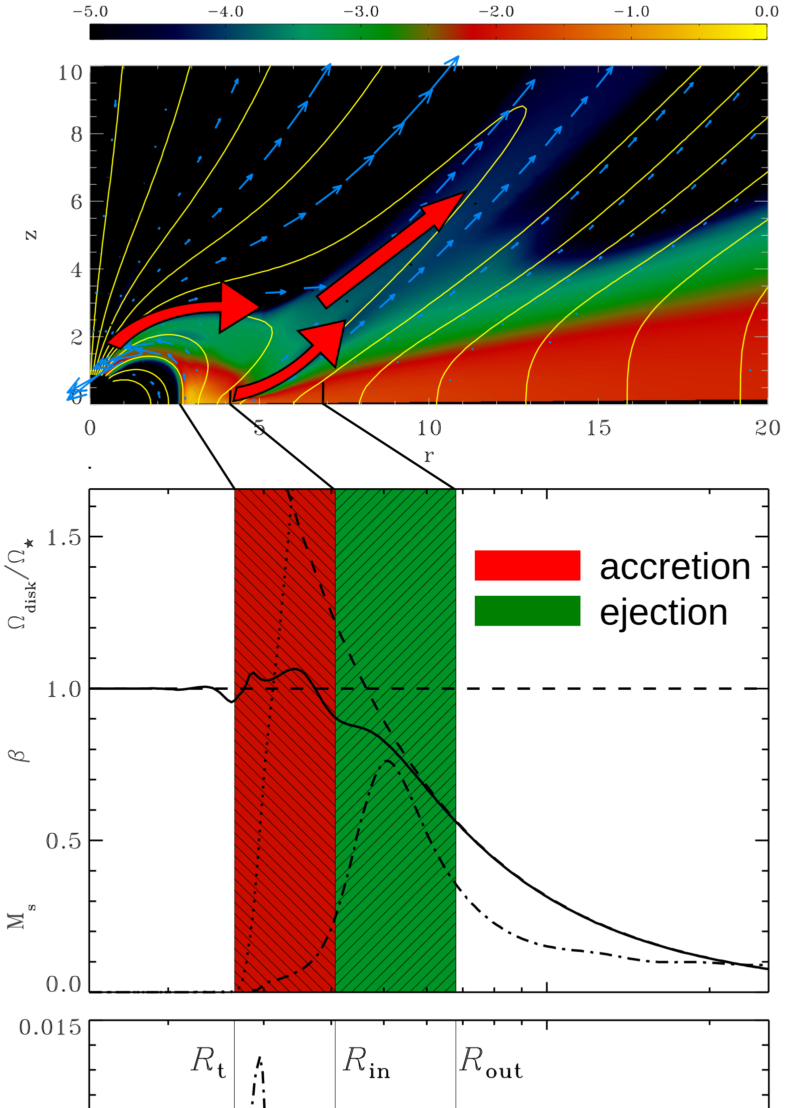
Conical winds (Romanova et al. 2009)



- Magnetospheric ejection phenomenon closely related to “conical winds” (Romanova et al. 2009)

- Observable even in 3D models with misaligned dipole!

Magnetospheric ejections



- Magnetospheric ejections exchange angular momentum both with the disk and the star

- From the disk:

$$\dot{M}_{ej}/\dot{M}_{acc} \approx 0.1$$

$$\dot{J}_{ej}/\dot{J}_{acc} \approx 0.5$$ (“Keplerian” torque ≈ 0.34)

- The torque is strong enough so that the disk rotate slower than the star

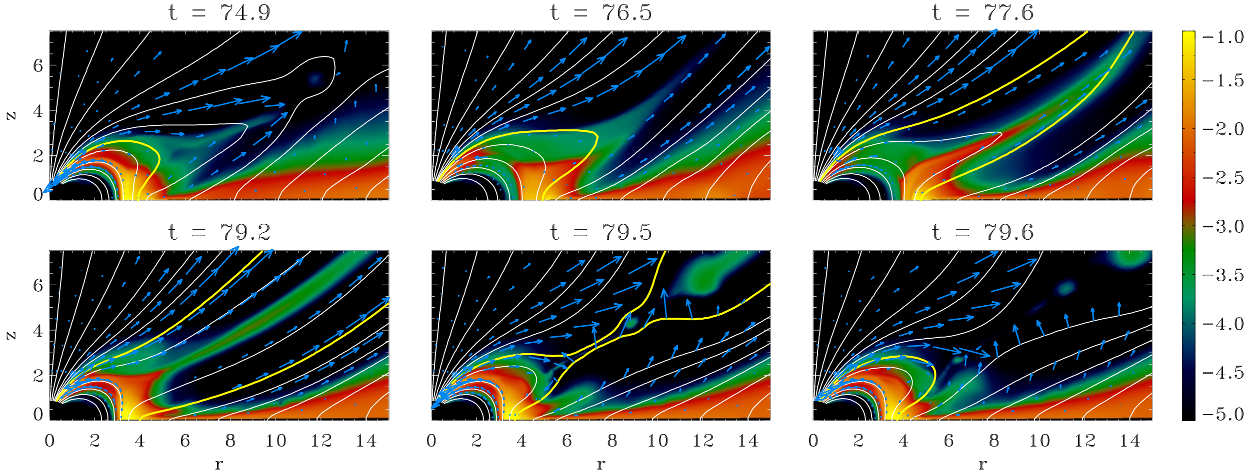
- If also the MEs rotate slower than the star it is possible to extract energy and angular momentum directly from it .

- Energy extracted from the disk and the star can not push this rather massive ejection beyond 100 Km s^{-1}

MEs and spin-down

- Extracting stellar angular AM and a sizeable fraction of the disk AM before it is accreted, MEs (with some light SW) can balance the accretion torque for $R_t \sim 0.6\ R_{co}$ already.

- It has been shown (Zanni & Ferreira 2013) that in a “propeller” regime the MEs are able to balance the contraction spin-up too

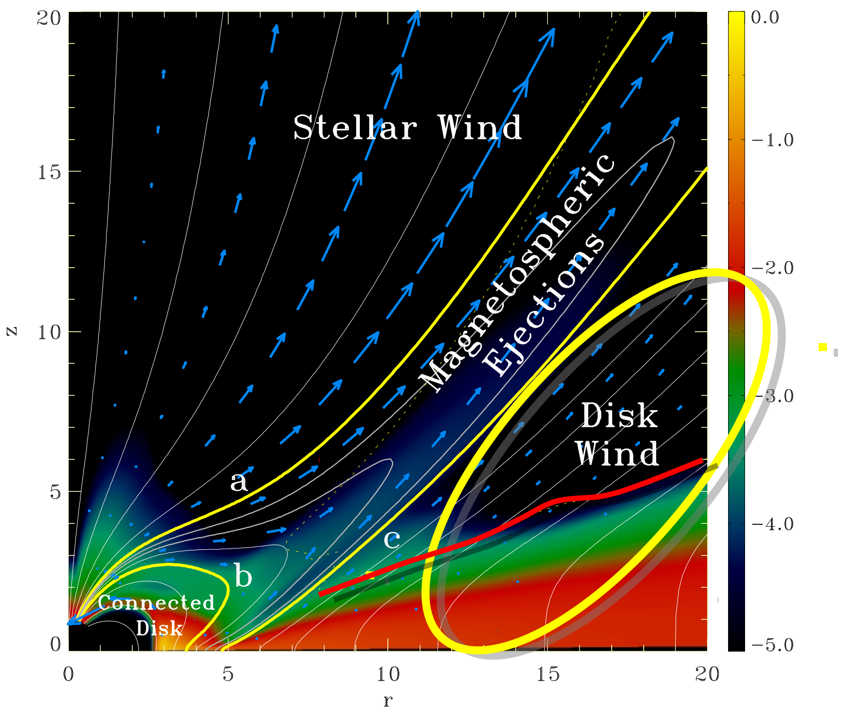


- As the truncation radius gets closer to corotation ($R_t \sim 0.75\ R_{co}$ in the simulation shown), the stellar centrifugal barrier makes accretion difficult

- When the disk is pushed outwards fieldlines open up and strong outflow extracts angular momentum and pushes disk back in

- When the disk gets closer to the star accretion is possible but the magnetosphere closes again and disk is pushed out → accretion-ejection cycles

… and the disk-winds?



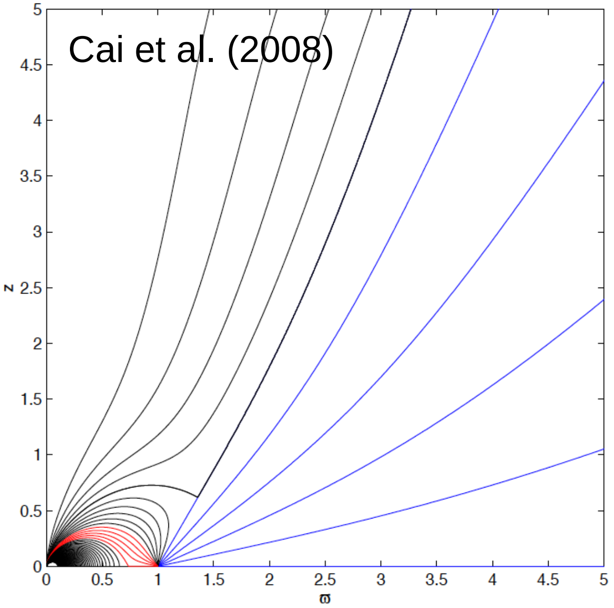
- Simulations display very weak disk winds, with a ≈ 1% mass ejection rate and Alfven surface lying close to the disk surface

- A powerful extended disk wind seems to require a proper disk magnetic field

- Wide angle, fan-shaped powerful X-winds (Shu et al. 1994) are not observed in star-disk interaction numerical experiments.
  - wrong range of parameter space?
  - resolution limits in the launching region around corotation?

X-Winds

- An X-Wind (Shu et al. 1994) is a wide angle, fan shaped disk-wind launched from a small disk region around corotation where the open magnetospheric flux is trapped. It extracts a sizeable fraction of disk mass ($M_{xwind} > 10\% \ M_{acc}$) and ALL the disk angular momentum before it is accreted onto the star.

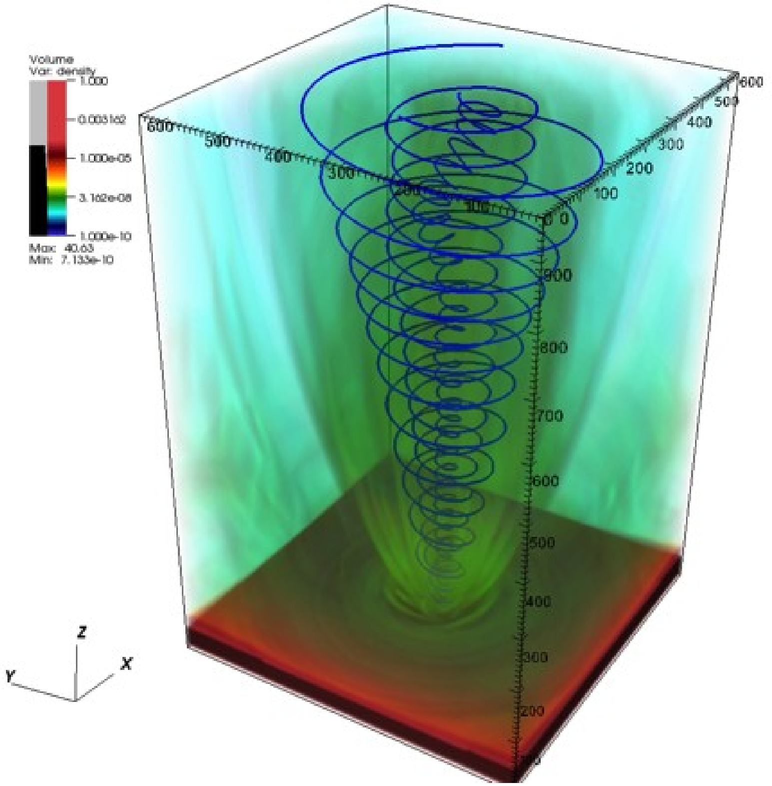

Cai et al. (2008)

- It is actually possible to calculate an outflow solution (Cai et al. 2008, Anderson et al. 2005)

- Coupling with the disk is critical.
  - Can the disk support this magnetic topology?
  - Is it possible to extract a high amount of mass and energy from such a tiny region?

  (Ferreira & Casse 2013)

Extended disk-winds



- Powerful disk-winds (i.e. extracting all the accretion power vs. local turbulent dissipation) require large scale field close to equipartition ($\beta < 10$)

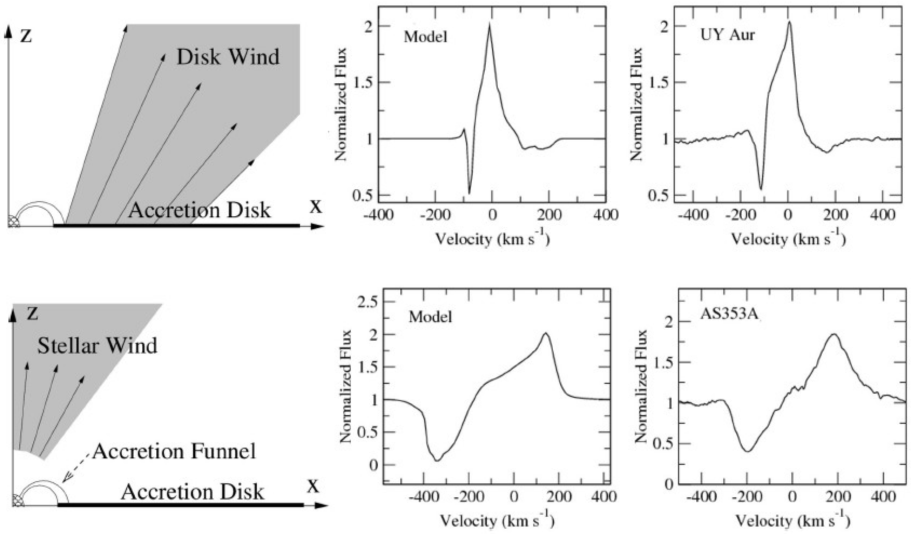
- It is possible to compute solutions:

  - Very fast ($V > 300$ Km s^{-1}), less collimated, light ($M_{wind} \approx 1\%\ M_{acc}$)

  - Slower ($V < 300$ Km s^{-1}), more collimated with $M_{wind} \approx 10\%\ M_{acc}$

- Launched from a distance from the central star disk-winds are unlikely to contribute to the stellar spin evolution problem

Magnetospheric outflows: synthetic observations



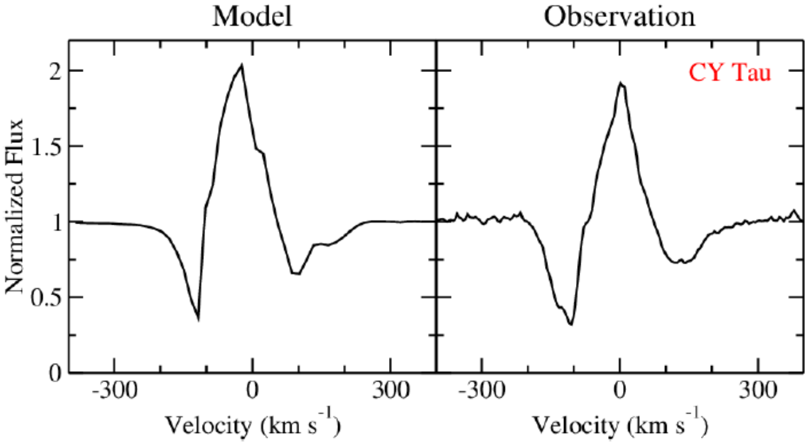
- He I λ10830 line profiles

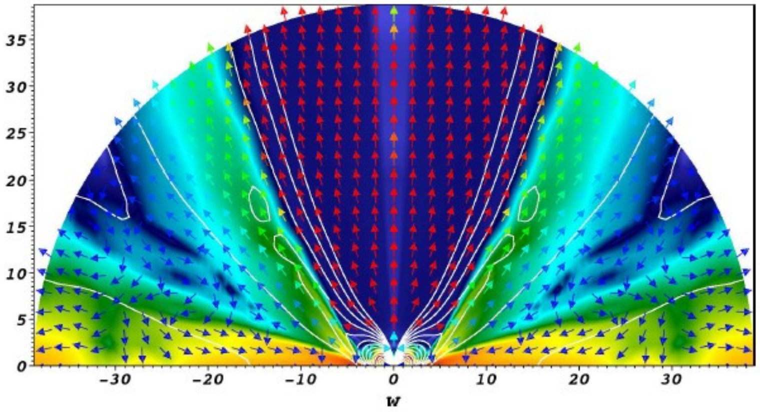
 - DW (edge-on) shows slow and narrow blue-shifted absorption

 - SW (pole-one) shows wide and fast blue-shifted absorption

- Conical winds (MEs?) similar to DW

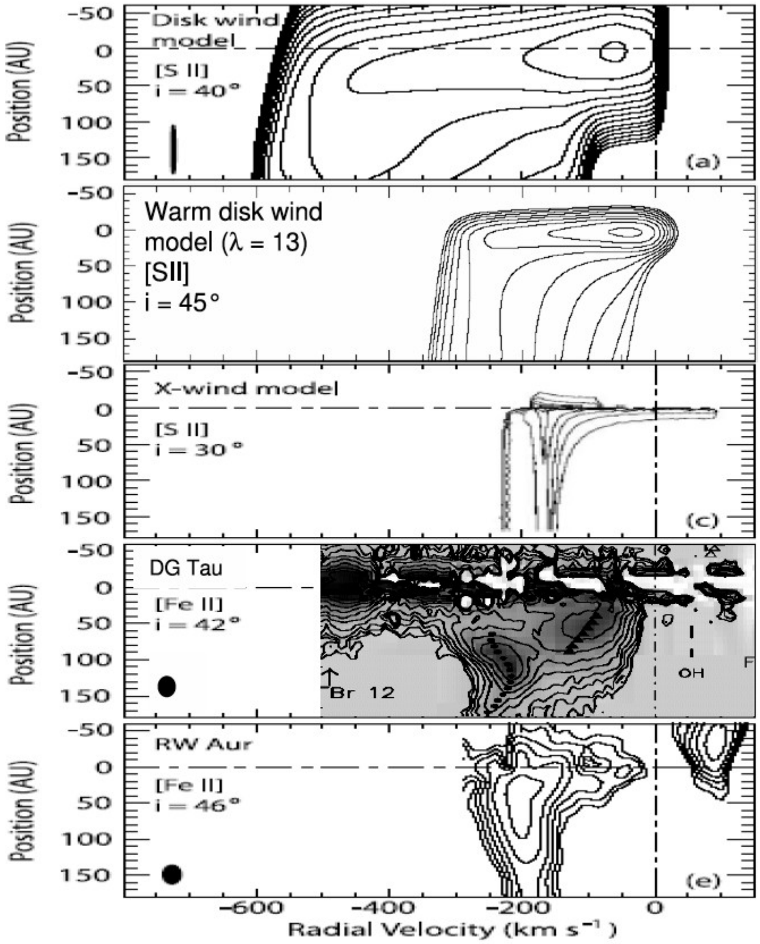
Kurosawa et al. (2011)





Kurosawa & Romanova (2012)

PV diagrams



- Cold disk wind model, $\lambda = 50$
  r_0 = 0.07 - 1 AU (Garcia et al. 2000)
- Warm disk wind model, $\lambda = 13$
  r_0 = 0.07 - 3 AU
- X-wind model, $\lambda = 3.5$
  r_0 = 0.06 AU (Shang et al. 1998)
- Pyo et al. 2003
- Pyo et al. 2006

Cabrit (2007)

Summary

- Stellar winds:
  - Loosely self-collimated, likely low ejection rates and high terminal speeds
  - Can significantly contribute to stellar spin evolution problem, specially for higher ejection rates ➔ driving power problem.

- Magnetospheric ejections:
  - Ballistic propagation (“conical winds”), rather high ejection rates and lower (< 100 Km s^{-1}) propagation speed
  - Significantly contribute to the stellar spin evolution, but can balance stellar contraction during propeller phases ➔ extreme variability not observed.

- Disk-winds:
  - X-winds: support from numerical simulations controversial. Driving power issues.
  - Powerful extended disk winds require proper disk magnetic field

- Line profile fitting extremely useful but ambiguous. Spectro-interferometry?

- Combine with larger scale disgnostics

- Be brave and produce more synthetic observations from simulations