Simulating the launching of YSO jets

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Protostellar jets in context   July 7th – 11th 2008   Rhodes - Greece

Outline

- Possible (MHD) mechanisms to explain YSO jet origin

  - Dynamical characteristics

- Numerical MHD simulations of jet launching:

  - Extended disk-winds

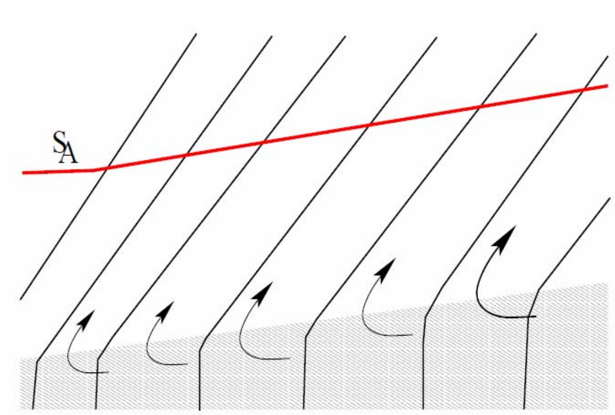
  - Star-disk magnetic interaction and related outflows (stellar winds, episodic ejections)

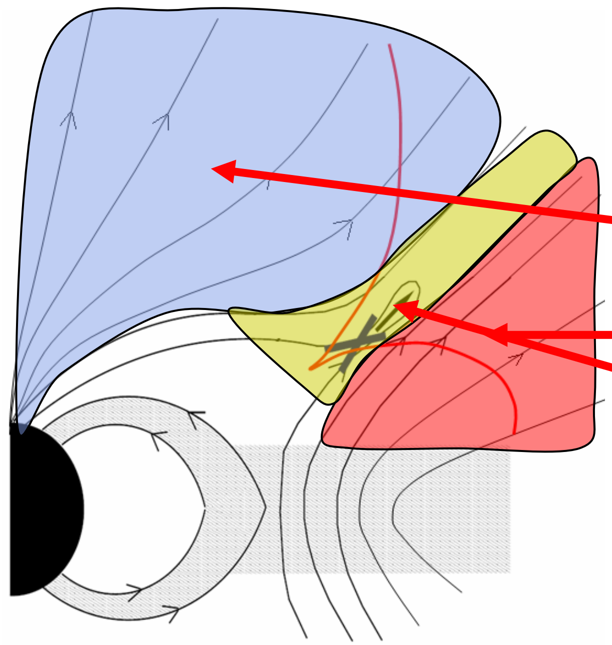
- Summary and conclusions

Possible (MHD) scenarios

- Extended disk-winds:

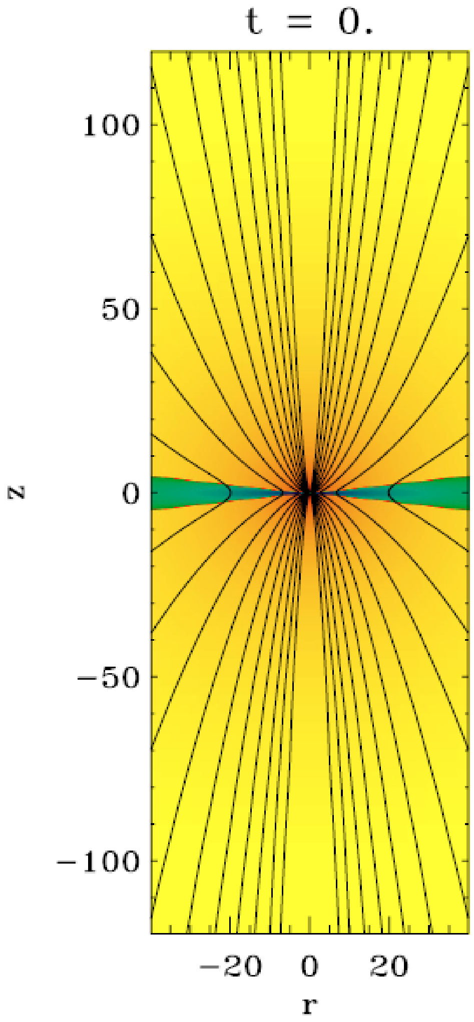
  Plasma flowing along large scale magnetic field distributed on large radial extension of the accretion disk.





- Magnetospheric ejections:
  - Stellar winds
  - X-Winds
  - Episodic magnetospheric ejections (CME-like)

Disk-winds: initial conditions



Self-similar Keplerian disk in equilibrium with gravity, pressure gradients and Lorentz forces.

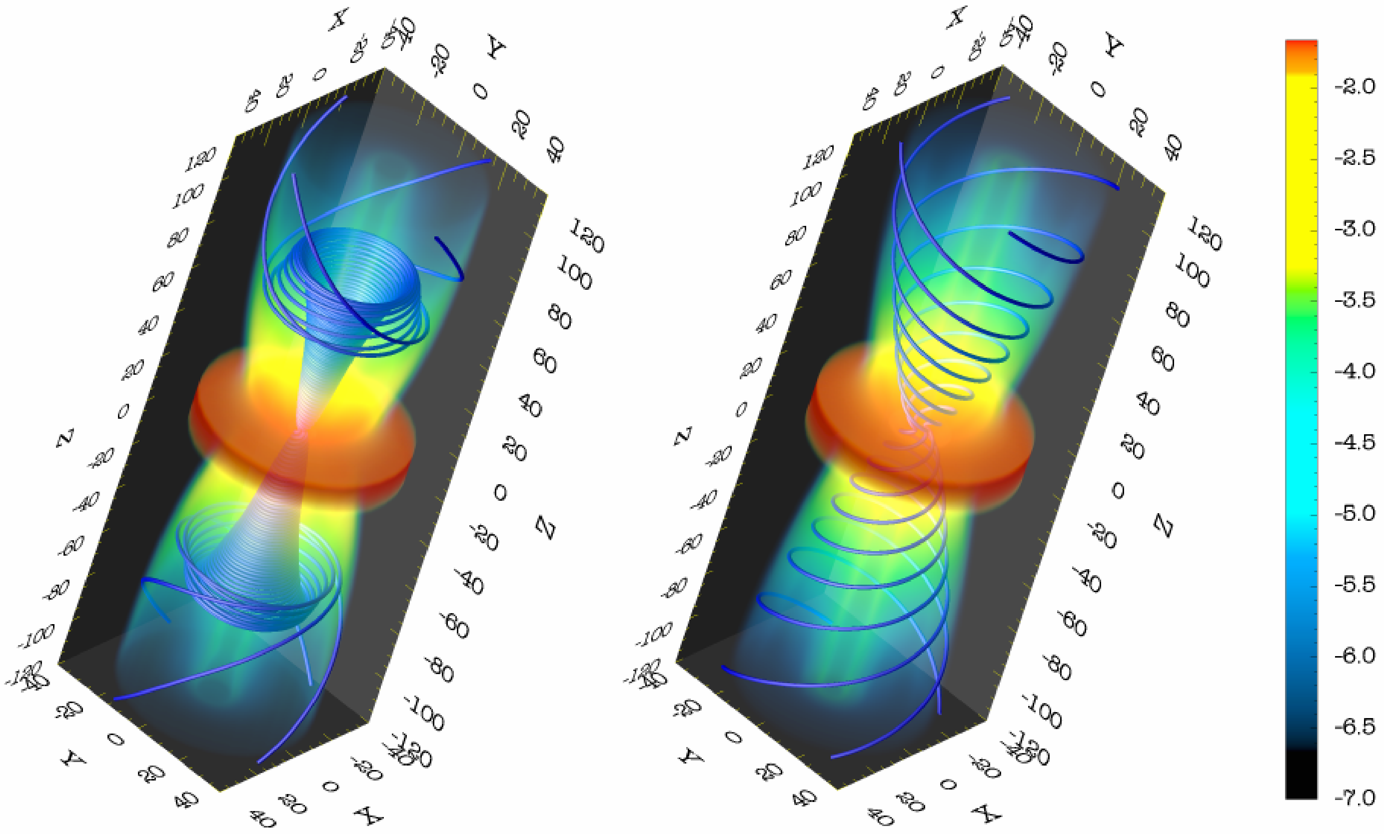
Disk parameters:

$\mu = B^2/P = 0.6$	$H = 0.1r$	$\eta = \alpha_m V_a H \exp[-2(z/H)^2]$
magnetization	thermal heightscale	magnetic resistivity

Resolution:

FLASH – AMR / 7 levels of refinement / 512x1536 eq. resolution

Disk-wind solutions

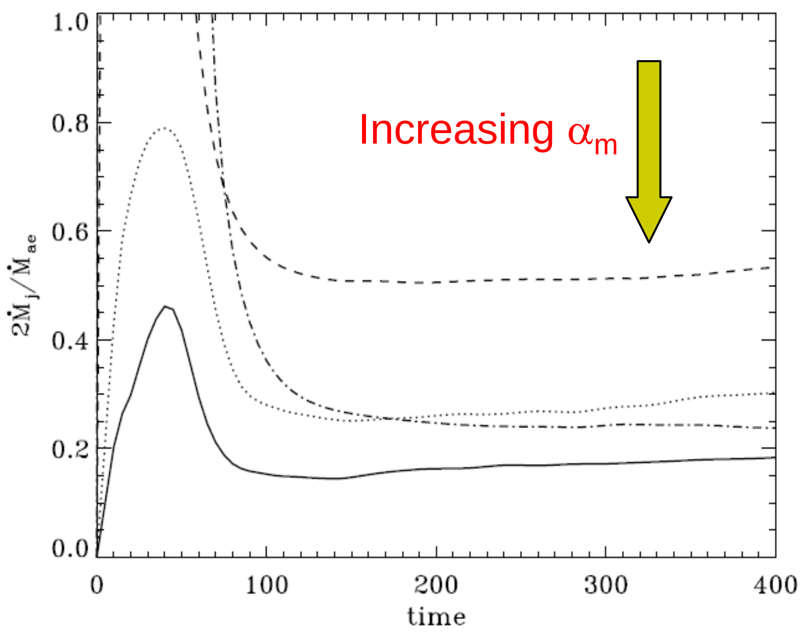


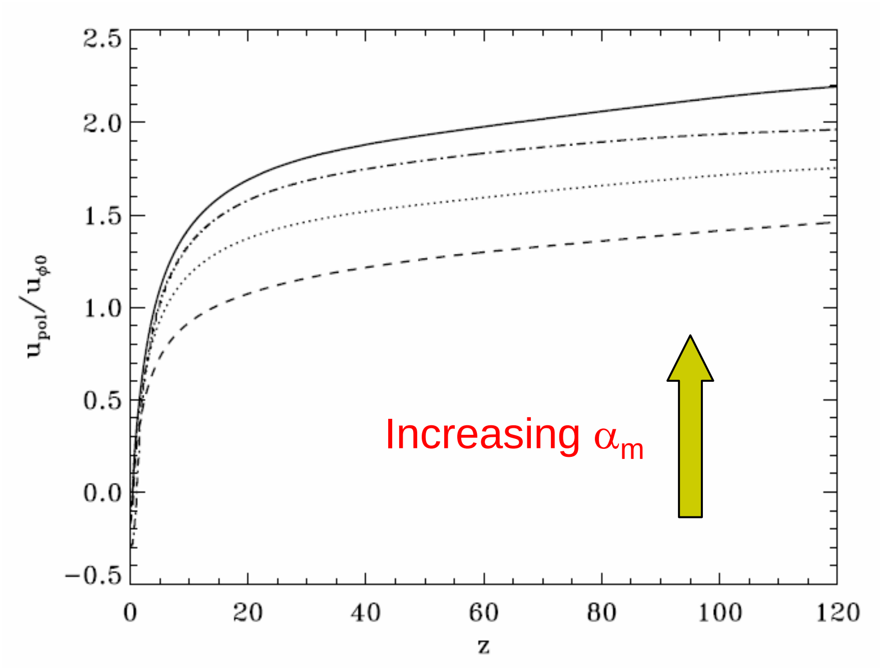
Zanni et al. (2007)

- Confirm analytical models: need $\mu = 1$ and $\alpha_m = 1$ to have a stationary solution

- Unsteady ejection still possible for smaller $\alpha_m = 0.1$: field advection dominates

Disk-wind dynamics

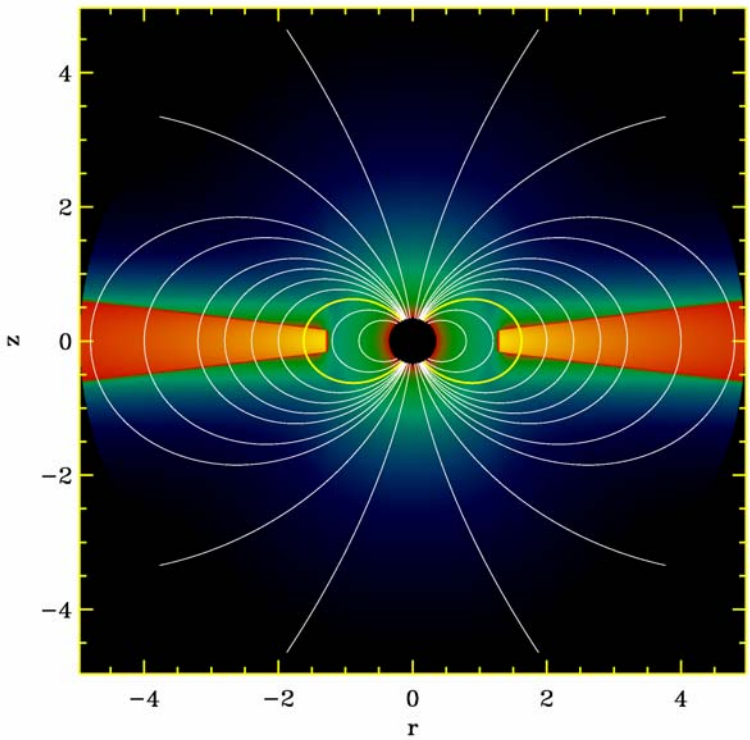




- Ejection efficiencies consistent with observations (Cabrit 2002)
- Terminal speeds around 1-2 times the escape velocity

! Simulated spatial scale too small to check rotation !
But specific angular momentum (λ = 9) appropriate to reproduce rotation measurements (see Ferreira et al. 2006)

Magnetospheric ejections: initial conditions



- Dipolar field aligned with the rotation axis of the star ($B^* = 800$ G)

- Resistive and viscous Keplerian accretion disk

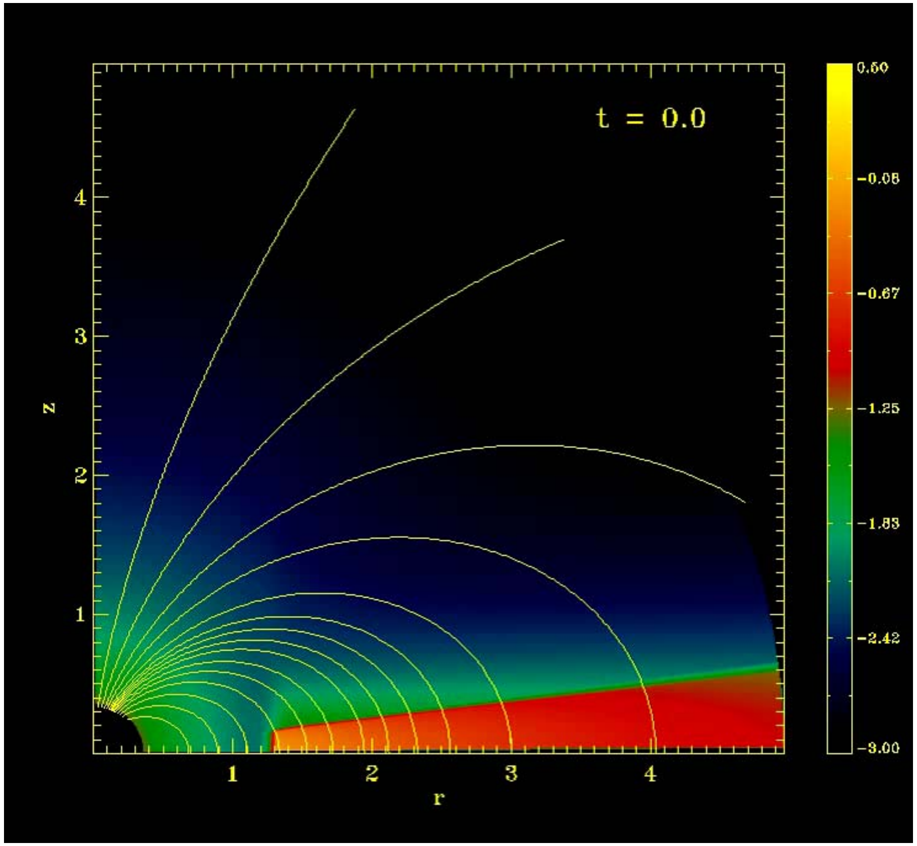
Resistivity $\eta = \alpha_m \, c_s \, \frac{c_s}{\Omega_k}$

Viscosity $\nu = \alpha_v \, c_s \, \frac{c_s}{\Omega_k}$

- “star” ($M_* = 0.5 M_{sun}$, $R_* = 2 R_{sun}$) modeled as perfect conductor rotating with a 4.5 days period ($\Omega_* = 0.1 \Omega_k$, $R_{co} = 4.6\, R_*$)

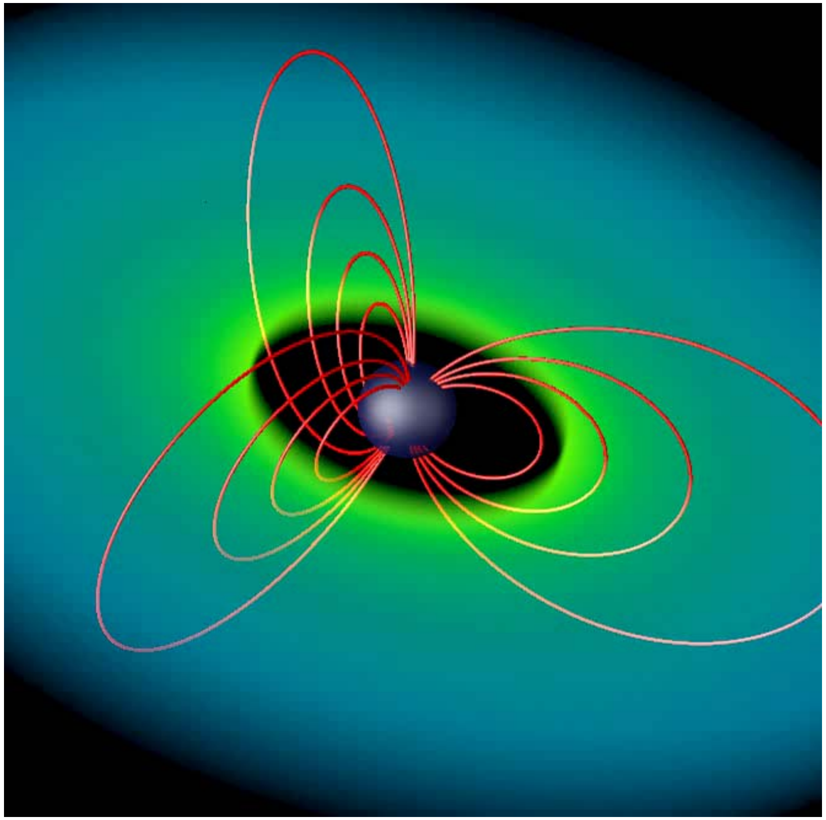
- MHD fluid equations solved with the PLUTO code (Godunov + CT method)

Movies…



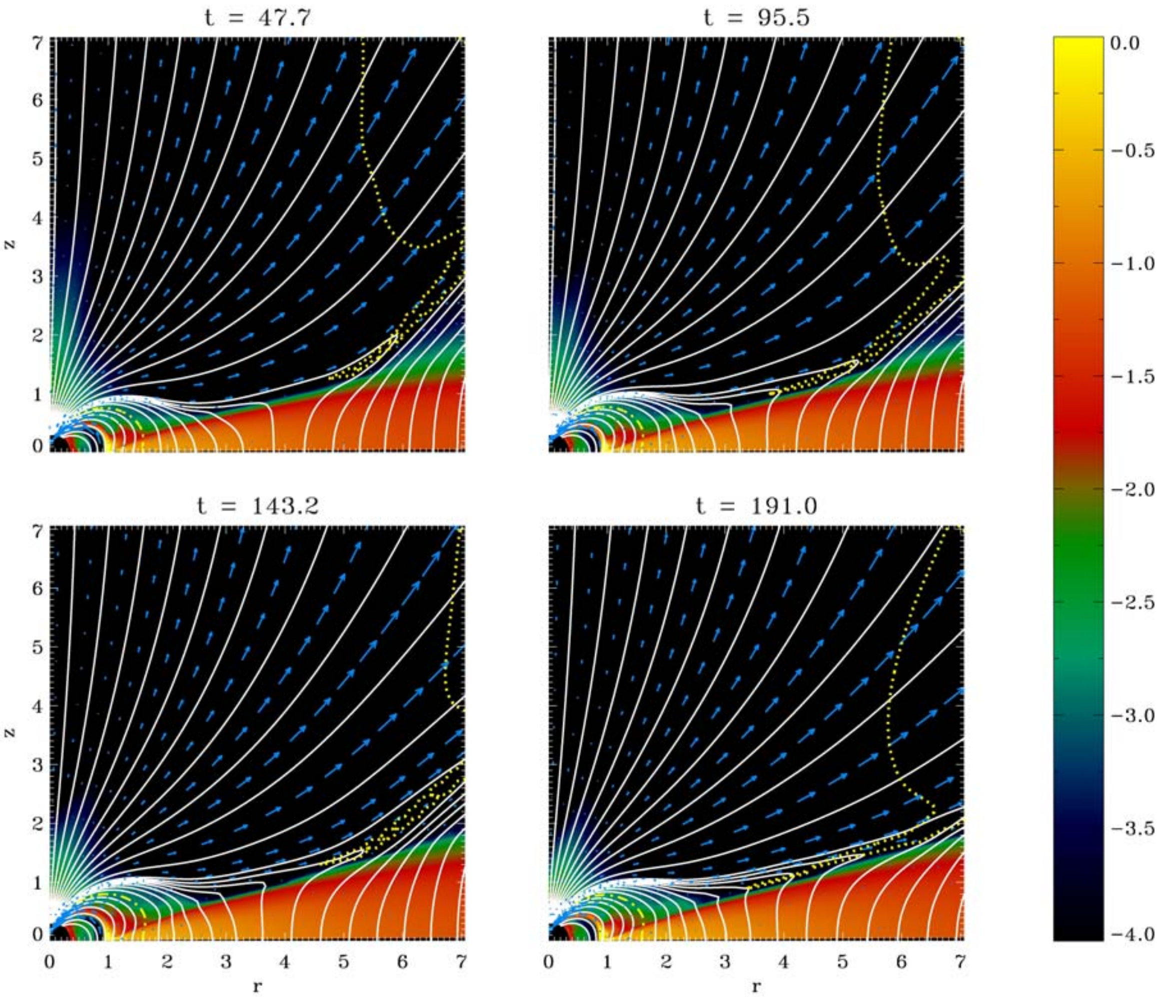
In 2D…

As seen in 3D…



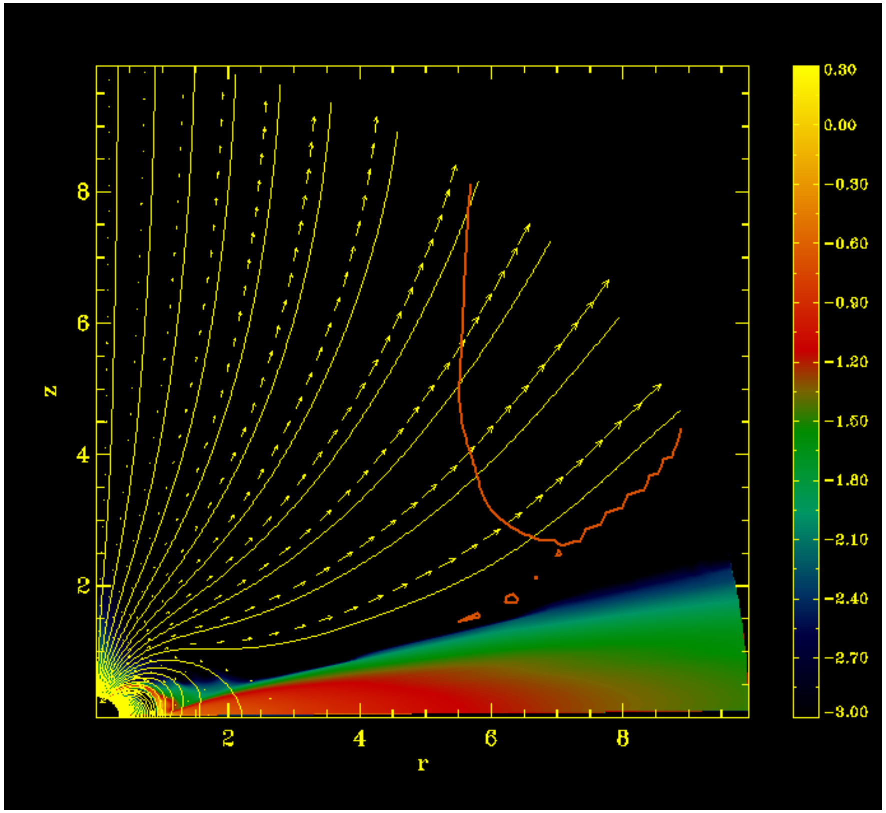
Stellar wind + extended magnetosphere

($\alpha_m = 1$ $\alpha_v = 1$ $\nu/\eta = 1$)



- Magnetosphere stays connected up to a radius = 3 (R_{co} = 1.6)
- The opened stellar and disk fieldlines are separated by a current sheet located far from the star
- The disk viscosity is efficient enough in the connected region in order to remove radially both the disk and the stellar angular momentum

Stellar wind: magnetic braking



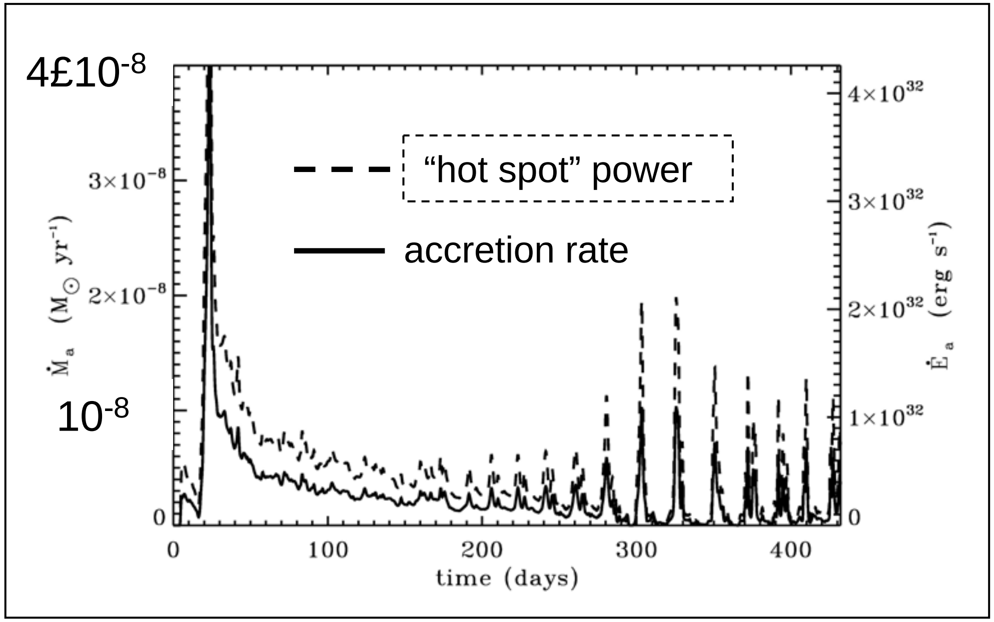
- $\dot{M}_{wind} = 10^{-10} M_{sun}\ yr^{-1}$
- Lever arm $R_A/R_* = 16$
- Slowly rotating star: no centrifugal thrust

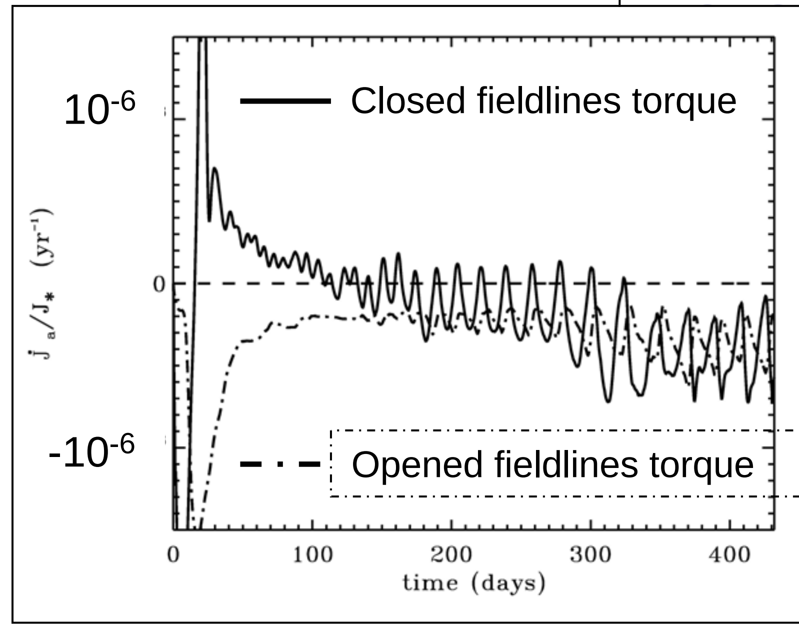
  Thermal driving: P_{th} = 4% P_{acc}
- Energy and angular momentum transport dominated by the Poynting flux:

$$\frac{E}{GM_\star/R_\star} = \frac{R_A^2}{R_\star^2} f^2 - 0.5 \sin\theta^2 f^2 + h - 1 \sim 2.5 \quad \text{where} \quad f = \frac{\Omega_\star}{\sqrt{GM_\star/R_\star^3}} = 0.1$$

Magnetospheric ejections II

($\alpha_m = 0.1 \quad \alpha_v = 0.1 \quad \nu/\eta = 1$)





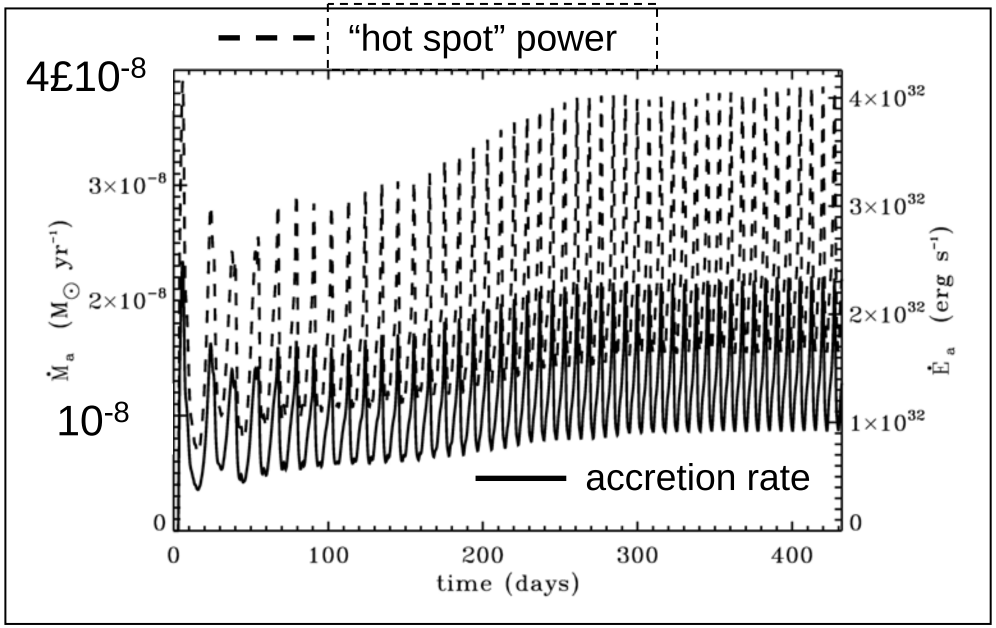
- Low accretion rate (lower viscosity) shows oscillations on longer timescale

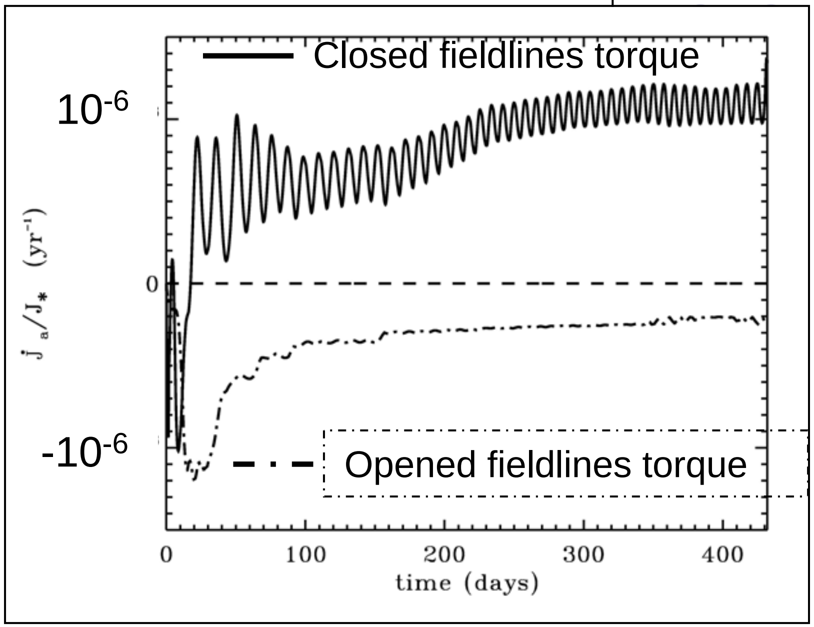
- The torque associated with the closed magnetosphere spins-down the star!!!!
  (combination of CME-like ejections and substellar disk rotation)

- Stellar wind braking

Extended magnetosphere

($\alpha_m = 1 \quad \alpha_v = 1 \quad \nu/\eta = 1$)

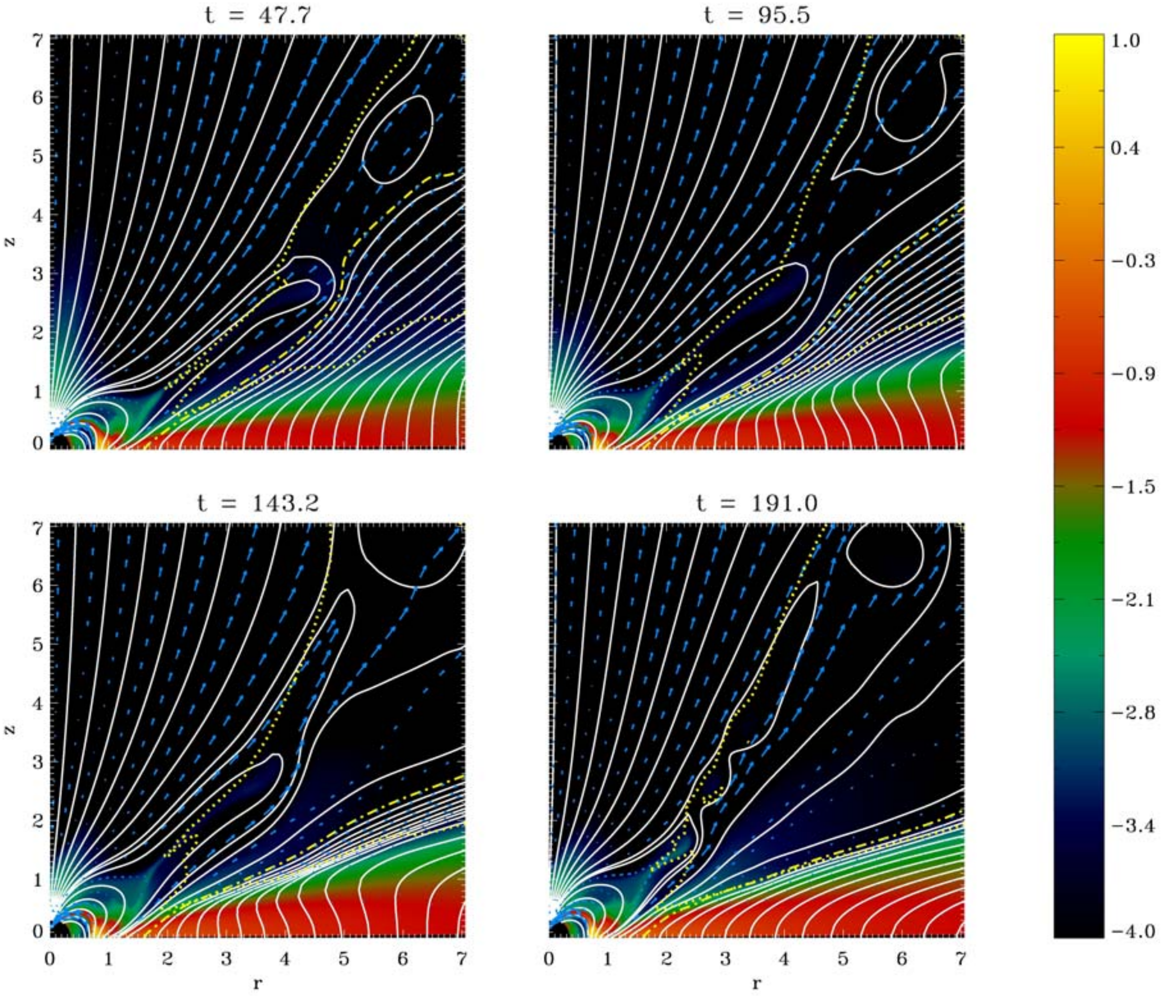




- Accretion rate (and “hot spot luminosity”) regularly oscillates with a 1.5-2 P_* period (mismatch between magnetospheric and viscous torque)
- Even if part of the disk magnetically connected to the star beyond R_{co} the disk-locked torque always spins up the star
- The star is always braked along the opened field lines: stellar wind

Magnetospheric ejections

($\alpha_m = 0.1 \quad \alpha_v = 1 \quad \nu/\eta = 10$)



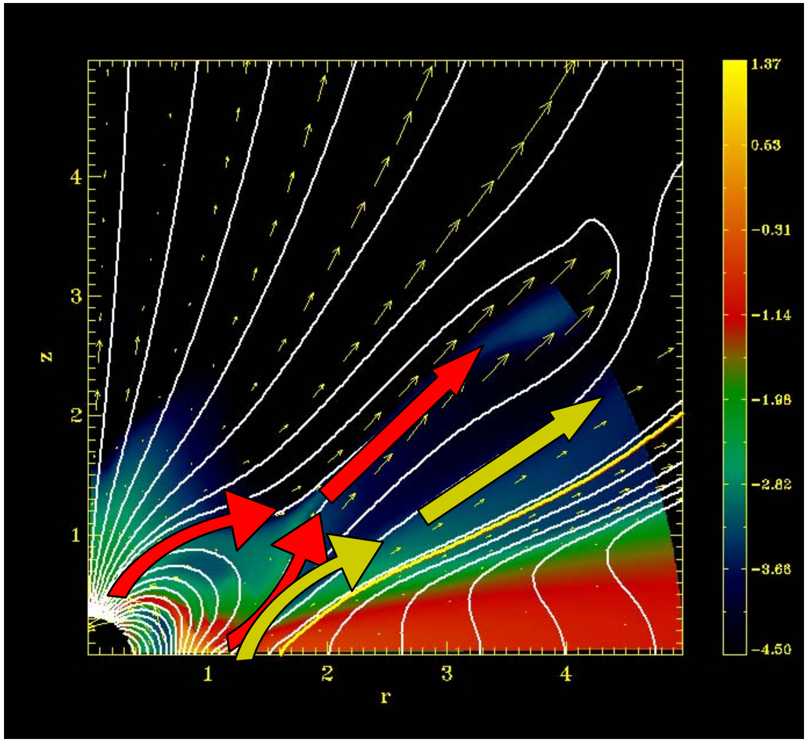
All fieldlines beyond corotation magnetic surface (yellow line) are opened

The current sheet is strong and reconnection phenomena can occur as well as episodic mass outflows

CME-like ejection site close to the base of the accretion column

Magnetospheric ejections

(α_m = 0.1 α_v = 1 ν/η = 10)



- Two types of outflows (beside the stellar wind):

  - CME-like ejections: extract angular momentum both from the disk and the star

  - Disk outflows (X-wind?): extract mass and angular momentum from the disk

- CME-like ejection is mass dominated
- Disk outflow is Poynting-flux dominated

Summary

- Simulations of extended disk-winds:

  - Confirmation of stationary models: equipartition field and strong ($\alpha = 1$) resistivity needed to obtain stationary state. Still problems with numerical dissipation and boundary effects

  - Non-stationary solutions: accretion-ejection still possible for smaller α values. Redistribution of the magnetic flux, magnetic towers.

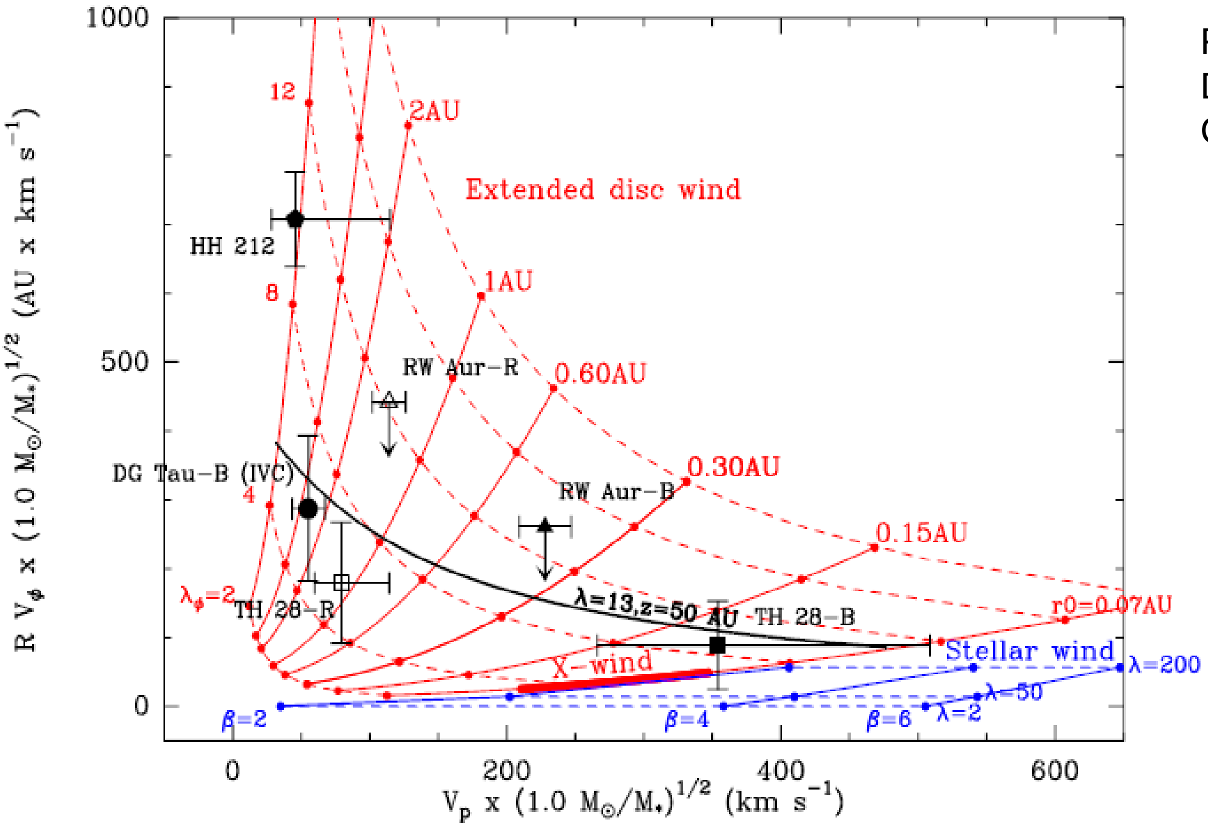
- Magnetic star-disk interaction – braking of the star rotation:

  - Extended magnetosphere: highly inefficient

  - Stellar winds: can provide a spin-down mechanism. Energy source?.

  - CME-like ejections: can efficiently brake the star. Minimize viscous effects and maximize the magnetic effects.

Dynamical characteristics



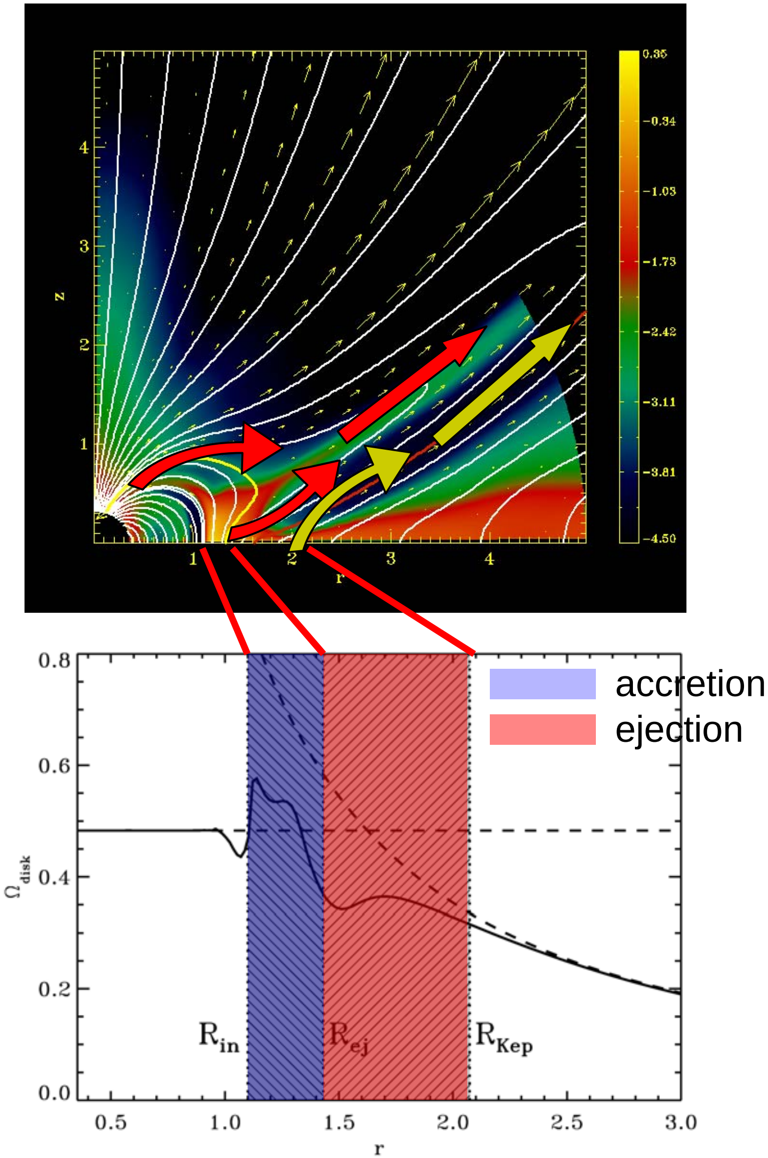
Ferreira, Dougados, Cabrit (2006)

For a given footpoint r_0 relation between toroidal and poloidal speed:

$$2rV_\phi\Omega_0 = V_p^2 + 3\Omega_0^2 r_0^2$$

- Extended disc winds, X-winds, and stellar winds occupy distinct regions in the (V_p – R V_ϕ) plane.

Magnetospheric ejections II
($\alpha_m = 0.1$ $\alpha_v = 0.1$ $\nu/\eta = 1$)



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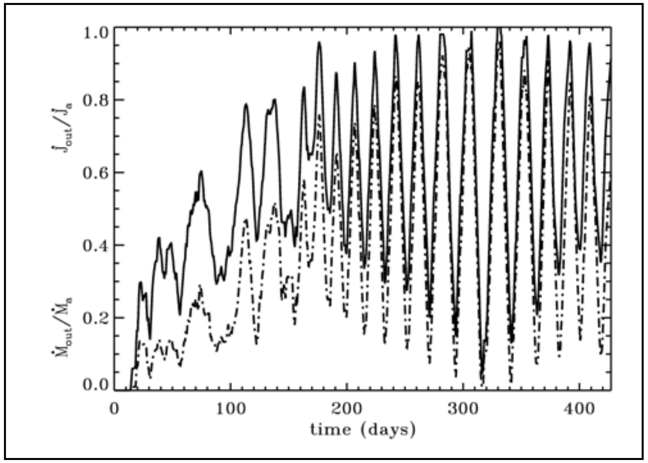

Is everything ok?

Despite having the same disk parameters (μ » 0.6, α_m » 1, ε » 0.1), analytical (Casse & Ferreira 2000) and numerical solutions have different jet parameters

Analytical:

- k » 2£ 10^{-2}
- λ » 35
- ξ » 0.01

Numerical:

- k » 0.1 - 0.3
- λ » 4 - 9
- ξ » 0.09

Analytical solution less mass loaded and faster ($v_{p,\infty} = r_0 \Omega_0 \sqrt{2\lambda - 3}$)

Problem of numerical diffusion at the disk surface ?