Formation of MHD jets: flares as triggers of internal shocks

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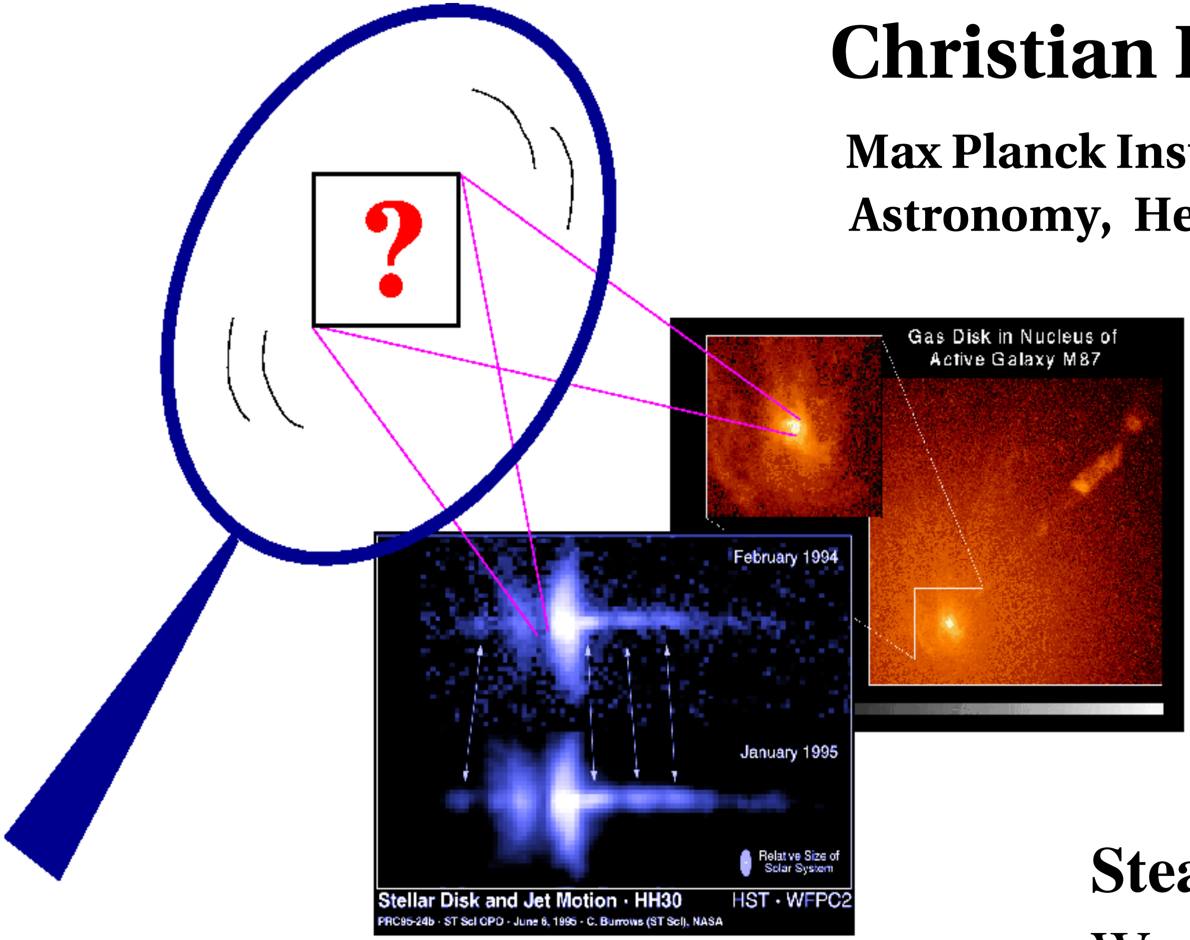


Steady Jets & Transient Jets
Workshop Bonn
April 7/8, 2010

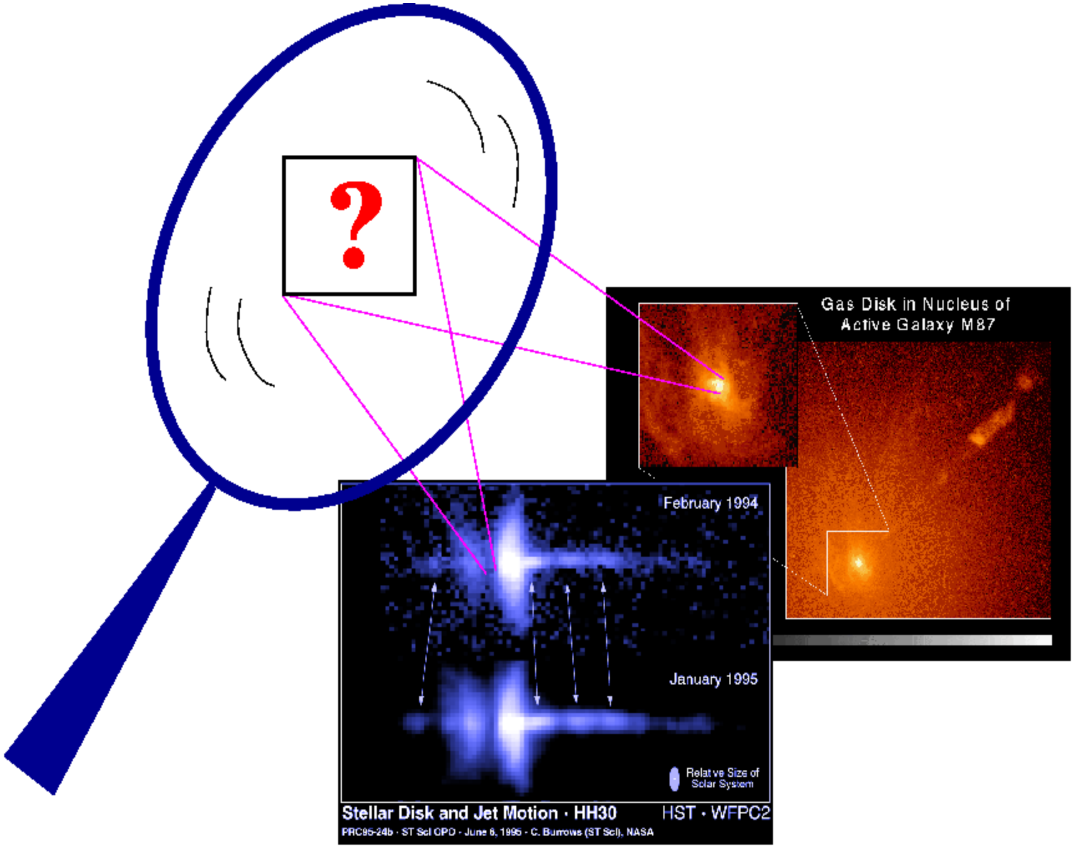
Formation of MHD jets: flares as triggers of internal shocks

Contents:

-> Model scenario: MHD jets

-> Jet formation simulations:

- Disk jets & stellar jets:
  magnetization profile
  & collimation
- Disk jets + central dipole:
  reconnection, flares
- Relativistic jets (Oliver Porth)



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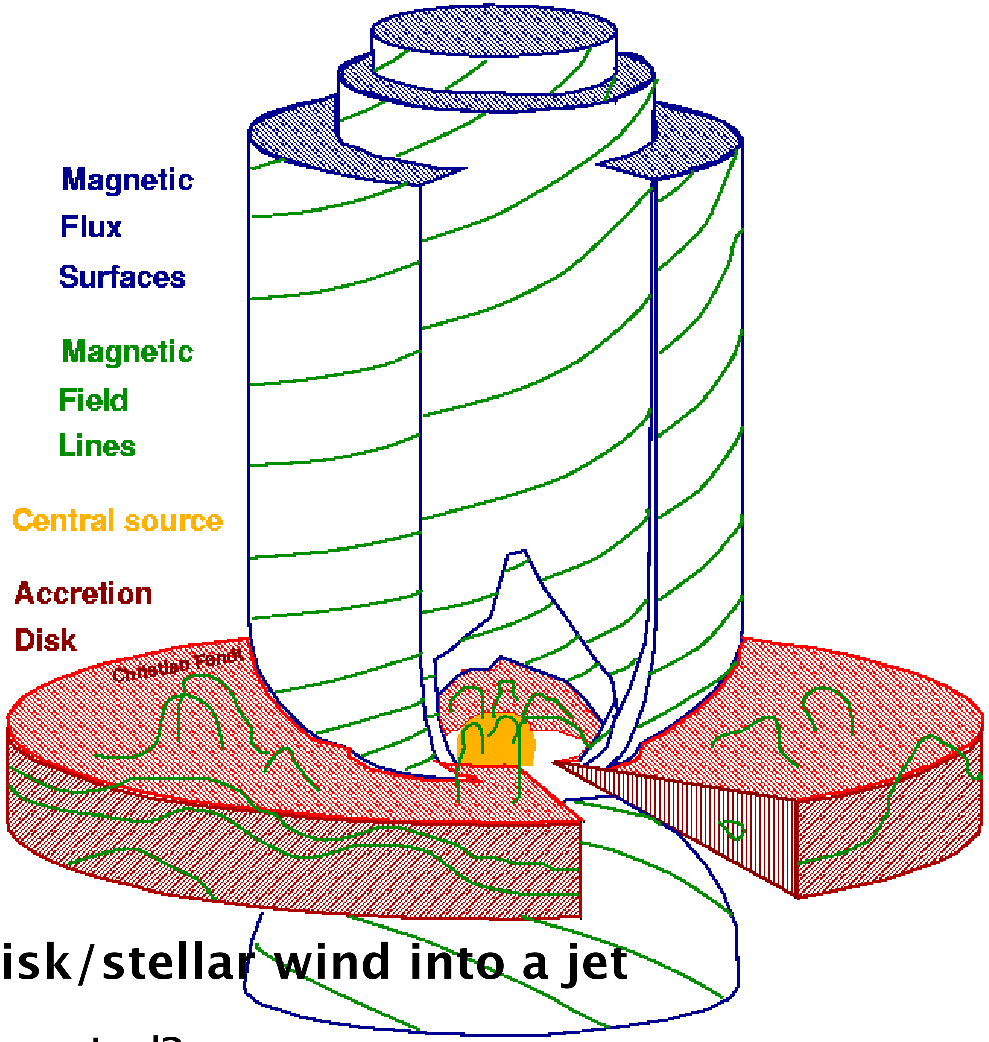
Astrophysical jets:
“Standard model”

MHD model of jet formation:

-> jets are collimated disk/stellar winds,
launched,
accelerated,
collimated
by magnetic forces



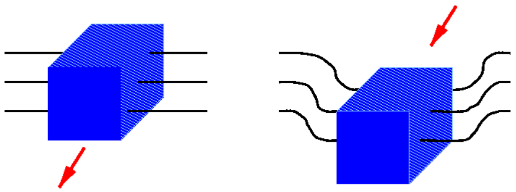
-> 5 basic questions of jet theory:

- **collimation & acceleration of a disk/stellar wind into a jet**
- ejection of disk/stellar material into wind?
- accretion disk structure?
- origin of magnetic field?
- jet propagation / interaction with ambient medium

Astrophysical jets:
Magnetohydrodynamics (MHD)

- MHD concept: ionized, neutral fluid:
  average quantities: $\vec{j} \equiv q_{\rm e}\vec{v}_{\rm e}\rho_{\rm e} + q_{\rm i}\vec{v}_{\rm i}\rho_{\rm i}$

- ideal MHD: infinite conductivity,
  "frozen-in" field lines:



- **MHD Lorentz force:** $\vec{F}_L \sim \vec{j} \times \vec{B}$

- MHD equations (to be solved numerically):

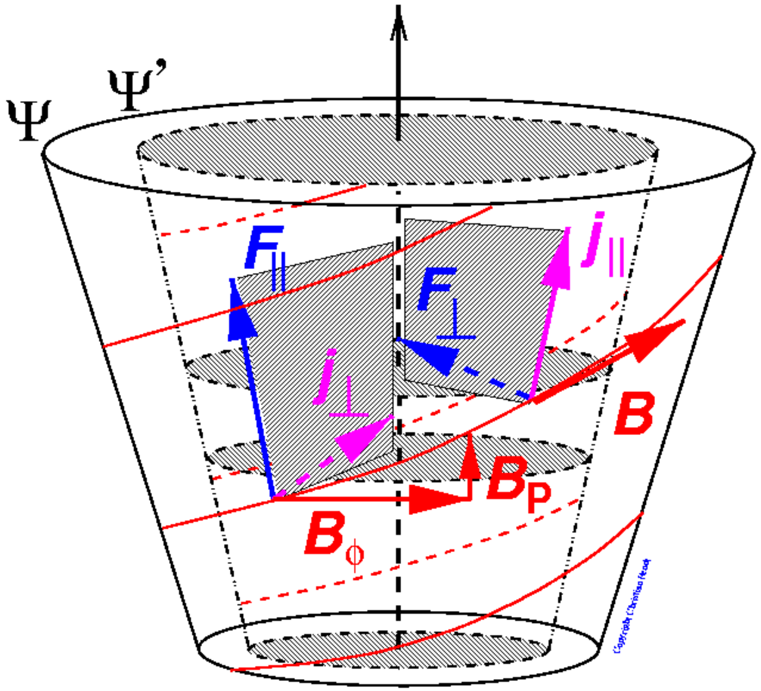
$$\partial_t \rho + \nabla \cdot (\rho \vec{v}) = 0$$

$$\rho\left(\partial_t \vec{v} + (\vec{v} \cdot \nabla)\,\vec{v}\right) + \nabla P + \rho \nabla \Phi - \vec{j} \times \vec{B} = 0$$

$$\rho\left(\partial_t e + (\vec{v} \cdot \nabla)\, e\right) + P(\nabla \cdot \vec{v}) - \eta_{\rm D} |\vec{j}|^2 / c^2 = 0$$

$$\partial_t \vec{B} = \nabla \times \left(\vec{v} \times \vec{B} - \eta_{\rm D} \vec{j} / c\right)$$

$$\nabla \cdot \vec{B} = 0, \quad \nabla \times \vec{B} = 4\pi \vec{j} / c$$



Axisymmetric flows:

-> poloidal, toroidal field: $B = B_p + B_\phi$

-> magnetic flux surfaces:

$$\Psi(R, Z) \sim \int \vec{B}_{\rm P} \cdot d\vec{A}$$

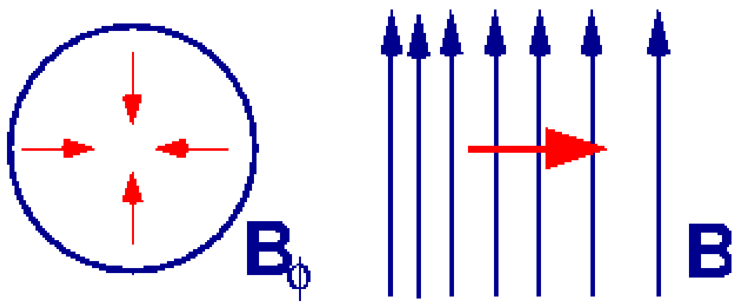
Lorentz force components (1)

-> projected on Ψ : $\vec{F}_L \equiv \vec{F}_{L,||} + \vec{F}_{L,\perp}$

-> (de/) accelerating: $\vec{F}_{L,||} \equiv \vec{j}_{\perp} \times \vec{B}_{\phi}$

-> (de-) collimating: $\vec{F}_{L,\perp} \equiv \vec{j}_{||} \times \vec{B}$

Astrophysical jets:
Magnetohydrodynamics (MHD)



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- ideal MHD: infinite conductivity,
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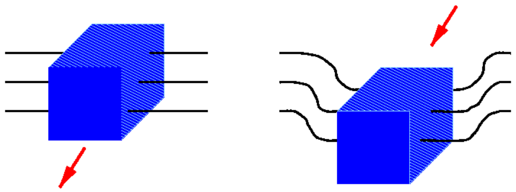

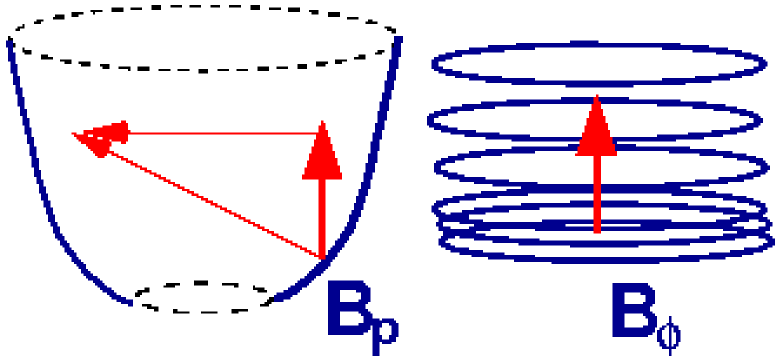

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$$\partial_t \vec{B} = \nabla \times \left(\vec{v} \times \vec{B} - \eta_\mathrm{D} \vec{j} / c \right)$$

$$\nabla \cdot \vec{B} = 0, \qquad \nabla \times \vec{B} = 4\pi \vec{j} / c$$

Lorentz force components (2):

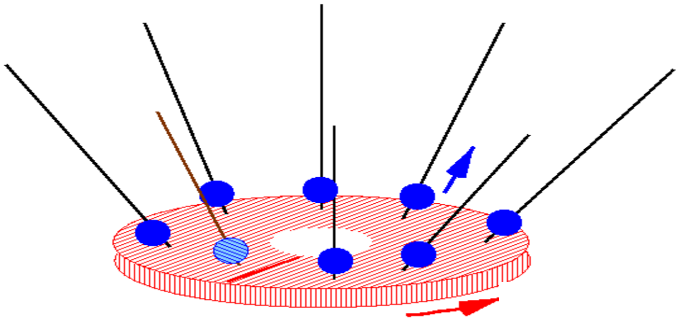
-> magnetic pressure & tension:

$$\vec{F}_L = \nabla \left(\frac{|\vec{B}|^2}{8\pi} \right) + \frac{1}{4\pi} \left(\vec{B} \cdot \nabla \right) \vec{B}$$

-> (de/) accelerating , (de-) collimating

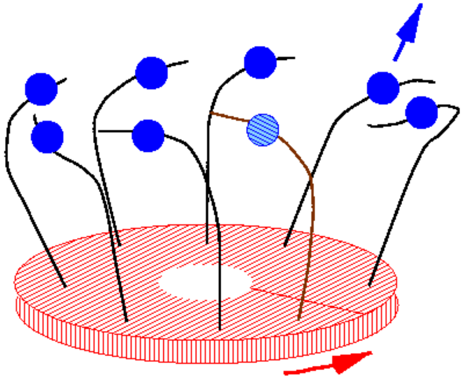
-> e.g.: pure dipole is force-free: $F_L = 0$

Astrophysical jets:
Acceleration & collimation



Magneto-centrifugal acceleration:

(Blandford & Payne 1982)

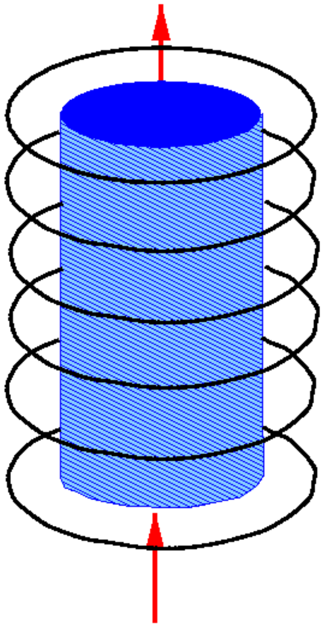


-> field lines corotate w/ disk, ”beads on wire”

-> strong poloidal field

-> field line inclination < 60°

-> unstable equilibrium, (magneto-) centrifugal sling-shot



Self-collimation of MHD jets:

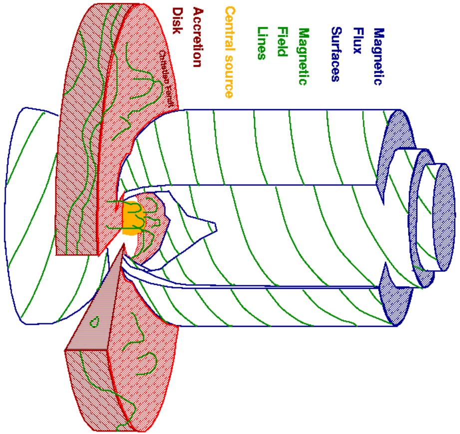
Alfven radius: kinetic ~ magnetic energy:

-> poloidal field twisted by inertia -> toroidal field component

-> collimation by toroidal field tension

MHD acceleration: Lorentz force ~ $j \times B_\phi$

MHD jet simulations

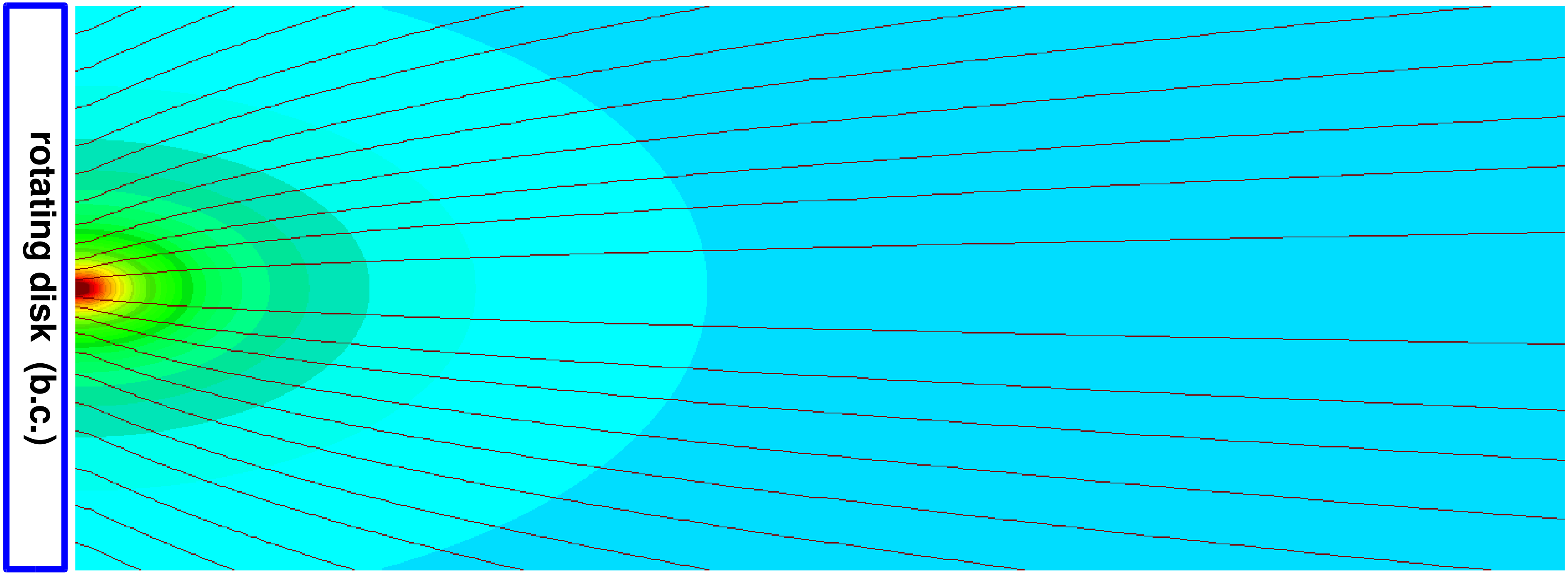


Numerical proof of jet MHD acceleration & self-collimation

(Ouyed & Pudritz 1997; Ustyugova et al. 1996; a.m.m.):

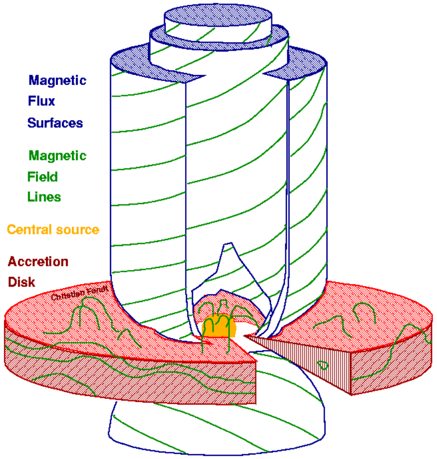
Model assumptions:

-> ideal MHD, axisymmetry, polytropic gas + turb. Alfvenic pressure
-> Keplerian disk = boundary condition: mass flux, inner disk radius
-> steady state initial condition: force-free field, hydrostatic corona
-> allows for long-term evolution, parameter runs of different B.C.



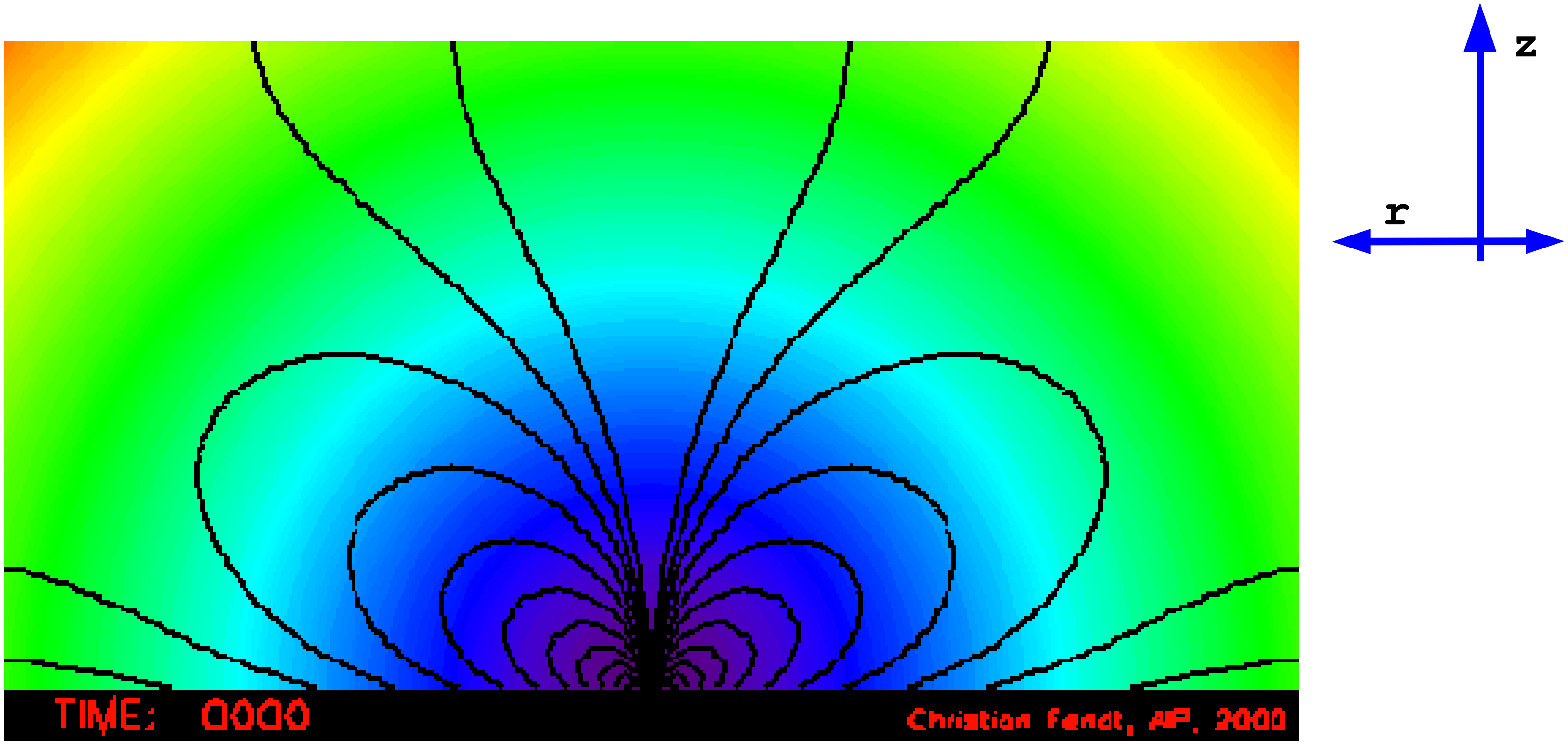
colors: gas density, lines: poloidal magnetic field lines

MHD simulations:
Dipolar magnetosphere



Stellar magnetosphere (Fendt & Elstner, A&A 1999, 2000):

-> quenched stellar dipole anchored in star & Keplerian disk
-> mass injection from disk & star (B.C.), parameter: Ω^*, B, dM/dt
-> stable initial state: force-free magnetic field + hydrostatic corona
-> grid size: 20 x 20 inner disk radii = 40 x 40 stellar radii
-> long-term evolution: ~2500 (20) inner (outer) disk orbital periods



colors: gas density **lines: poloidal field lines / vector potential contours**

MHD simulations:

Dipolar magnetosphere

Long-term evolution (Fendt & Elstner, A&A 1999, 2000):

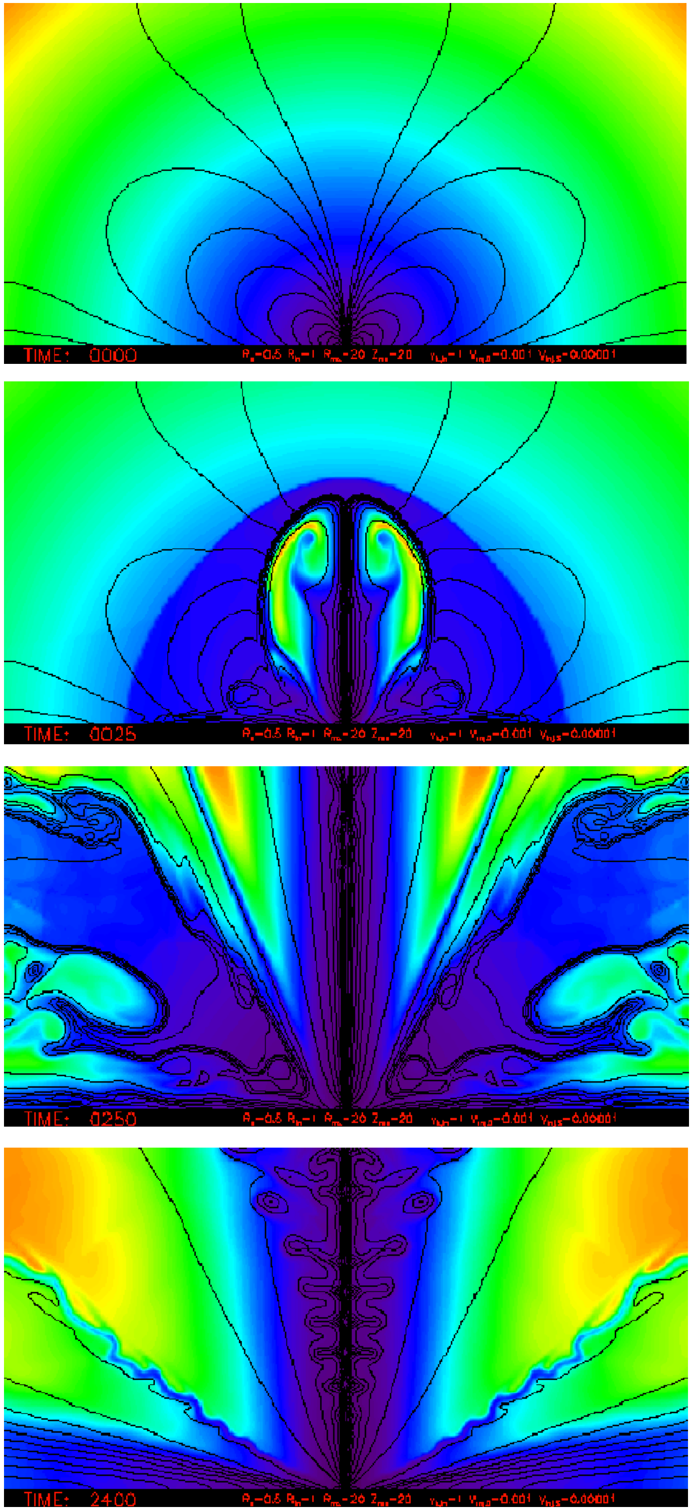
-> differential rotation between star & disk
twists magnetic field
-> magnetic pressure-driven expanding bubble
-> large-scale dipole breaks up, small-scale dipole
remains within disk gap

-> initial "axial jet" disappears on the long-term:
transition from initial magnetohydro-static
to new magnetohydro-dynamic equilibrium

-> quasi steady state reached
-> two-component outflow, v ~ 0.5 – 2 v_Kep:
MHD driven disk wind & stellar wind
-> no collimation !! (zero net electric current)

-> axial knots / "instabilities" for low stellar wind
mass flux

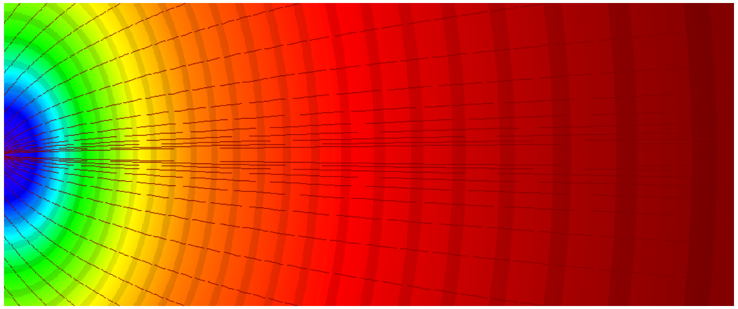
-> no "reconnection", ideal MHD



MHD jet collimation:

Pure disk jets

Collimation & magnetic field profile



Mass flux profile / disk magnetic flux profile and jet self-collimation (Fendt ApJ 2006)

-> disk magnetic field profile: $\boxed{B_p \sim r^{-\mu}}$

-> disk wind magnetization:

$$\sigma \equiv \frac{B_p^2 r^4 \Omega_F^2}{4 \dot{M} c^3} \sim r^{\mu_\sigma}$$

-> degree of collimation:

mass flux in axial & lateral direction

$$\zeta \equiv \frac{\dot{M}_{\mathrm{z}}}{\dot{M}_{\mathrm{r}}} = \frac{2\pi \int_0^{r_{\max}} r \rho v_z dr}{2\pi r_{\max} \int_0^{z_{\max}} \rho v_r dz.}$$

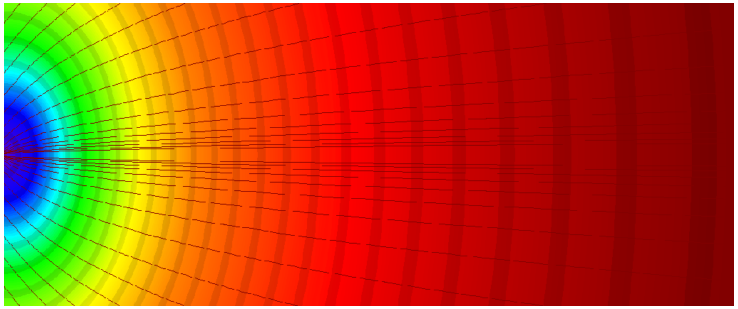
-> grid size: (150x300) r_i ~ (7x14) AU ~ observational resolution for stellar jets

-> parameter runs: μ, |B|, dM(r)/dt

$$\delta_i = 100,\ \beta_p = \beta_\phi = 1,\ \beta_T = 0.03,\ v_{inj}(r) = 10^{-3} v_K(r),\ \rho_{inj} = 100\, \rho_{cor},\ r_{max} = 40,\ z_{max} = 160$$

MHD jet collimation:

Disk magnetic flux profile

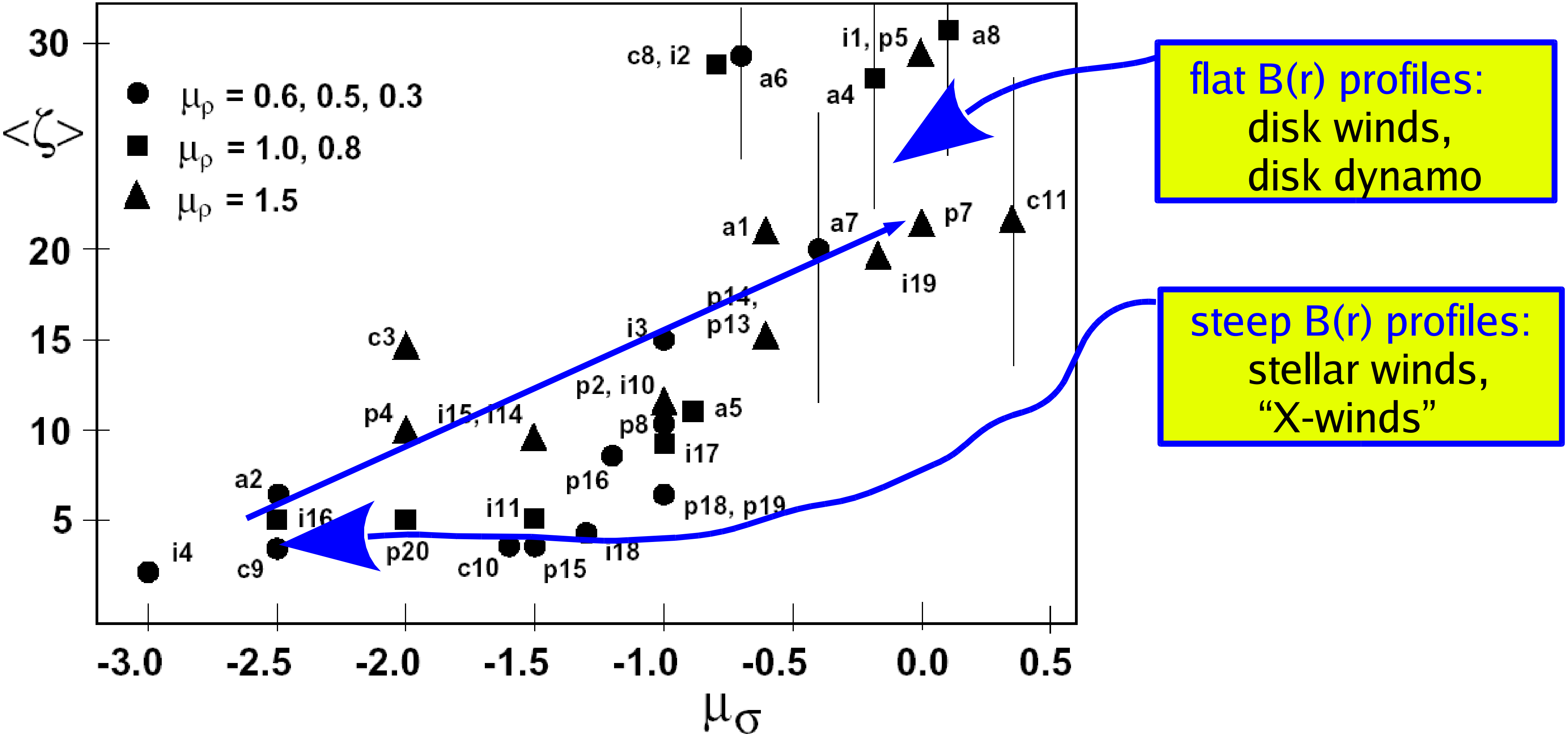


Collimation & magnetic field profile

$$B_p \sim r^{-\mu}, \sigma_0 \sim r^{\mu_\sigma}, \rho_0 \sim r^{-\mu_\rho}$$

-> "flat" profile (B, σ) -> efficient collimation

-> axial "instabilities" for too flat profile (no stationary state)

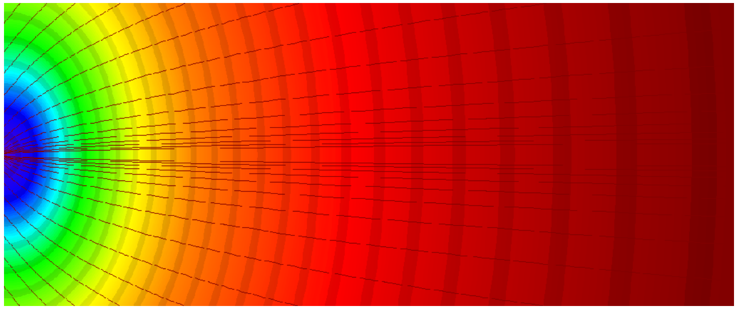


flat B(r) profiles:
disk winds,
disk dynamo

steep B(r) profiles:
stellar winds,
"X-winds"

MHD jet collimation:

Disk magnetic flux profile



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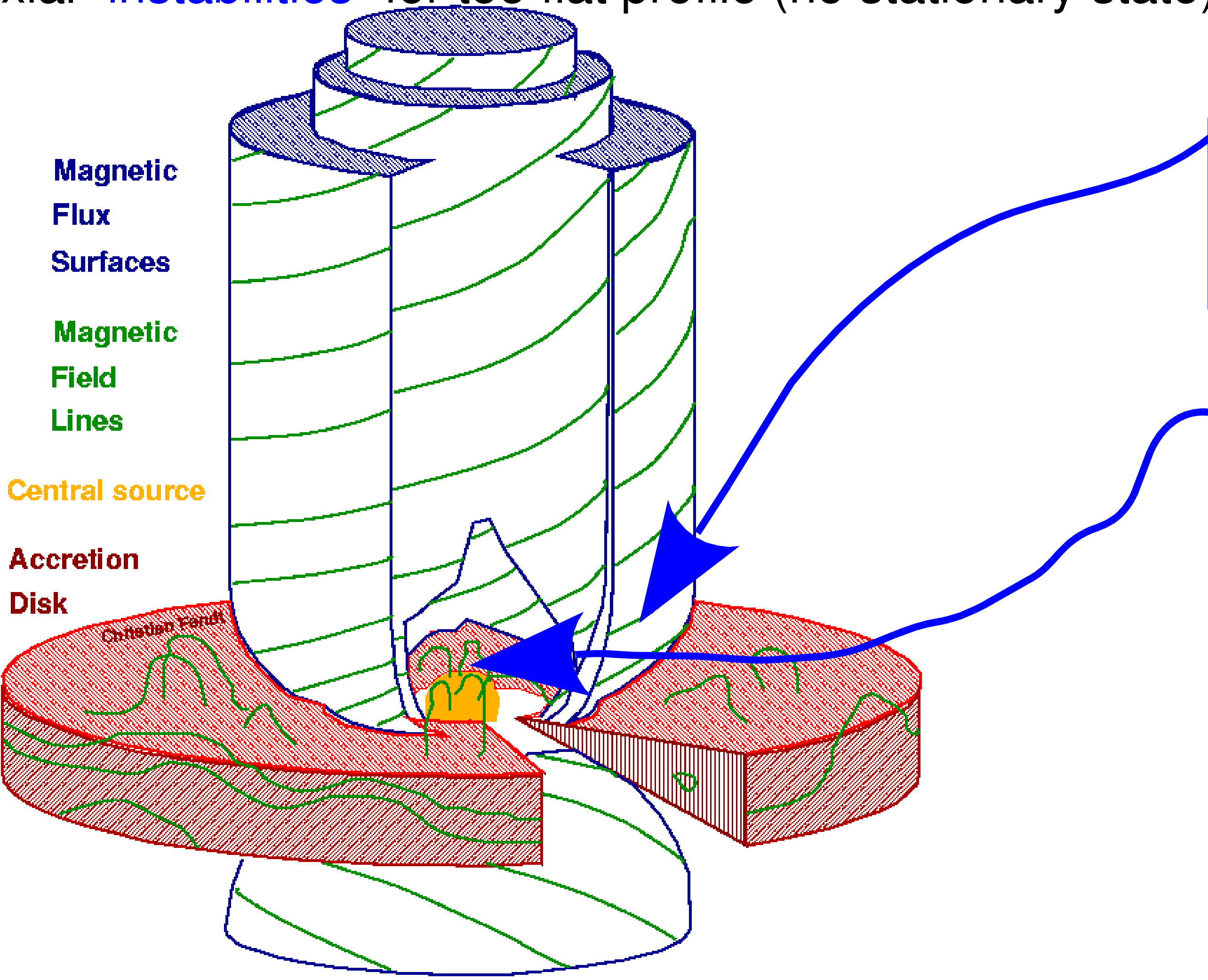


flat B(r) profiles:
disk winds,
disk dynamo

steep B(r) profiles:
stellar winds,
"X-winds"

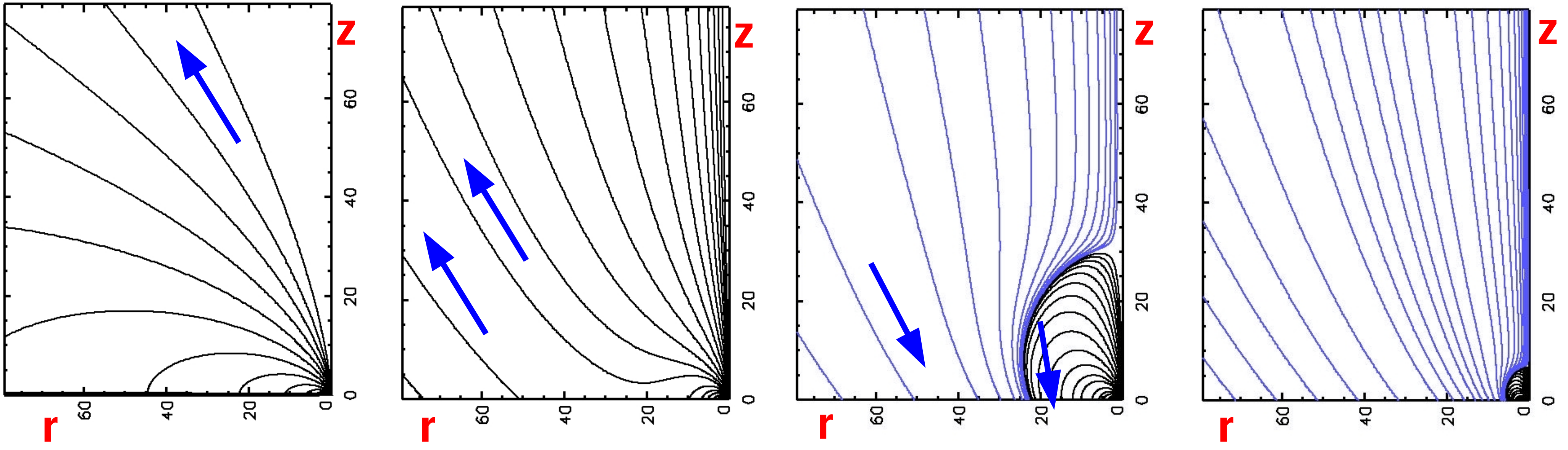
Outflows from disk-star magnetospheres

Two-component magnetic field configuration (Fendt ApJ 2009):

-> superposed stellar dipole + disk magnetosphere
-> mass flux from underlying Keplerian disk (r >1.0) + stellar wind (r <0.5)

$$A_{\Phi}(r,z) = A_{disk}\left(\sqrt{r^2+(z+z_D)^2}-(z+z_D)\right)+A_{star}\,\frac{r^2}{\left(r^2+(z+z_D)^2\right)^{-3/2}}$$

A_ϕ, B_p



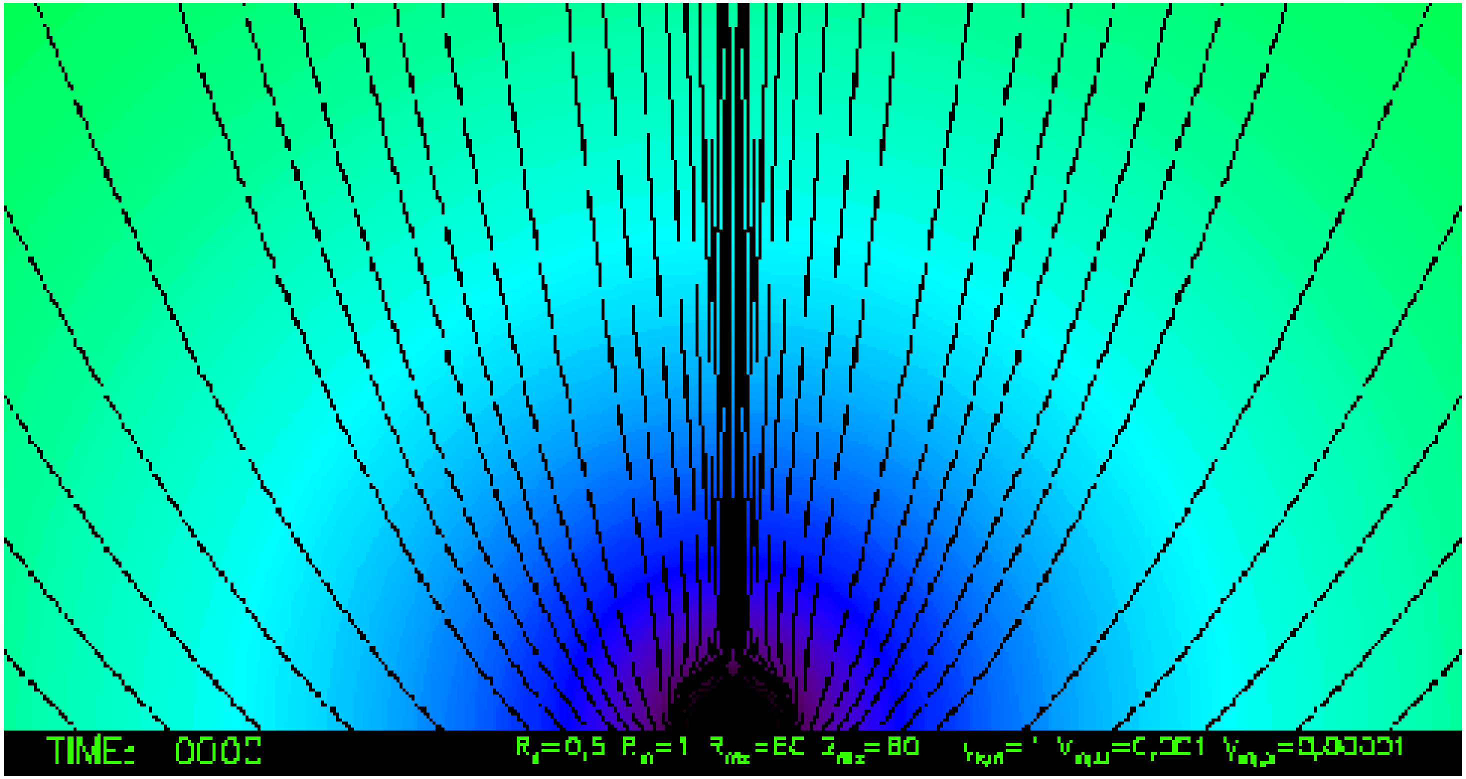
$A_{disk} = 0$, $A_{star} = 1.0$ $A_{disk} = 0.01$, $A_{star} = 5.0$ $A_{disk} = -0.01$, $A_{star} = 1.0$ $Adisk = -0.1$, $A_{star} = 3.0$

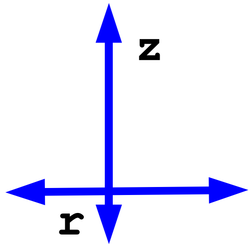
-> other parameter: plasma-β, stellar/disk mass fluxes,
turbulent Alfvenic pressure, magnetic diffusivity

Outflows from disk-star magnetospheres

Time evolution of disk-star magnetospheres: (example $A_{disk} = -0.1$, $A_{star} = 3.0$)

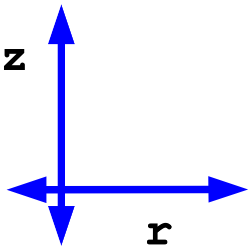
- rotating star: co-rotation radius = inner disk radius
- **resistive MHD:** model of turbulent Alfvenic diffusivity, reconnection (!!)
- run time ~ 3600 inner disk orbits (= 6 outer disk orbits)
- intermediate times: -> quasi stationary state, however transient, **flares (~CME)**
  -> de-collimation of disk wind by central stellar wind
- long-term evolution: -> quasi stationary states -> cyclic behavior @ large scale ?
  -> central dipole disturbs large-scale structure (Goodson 1999)



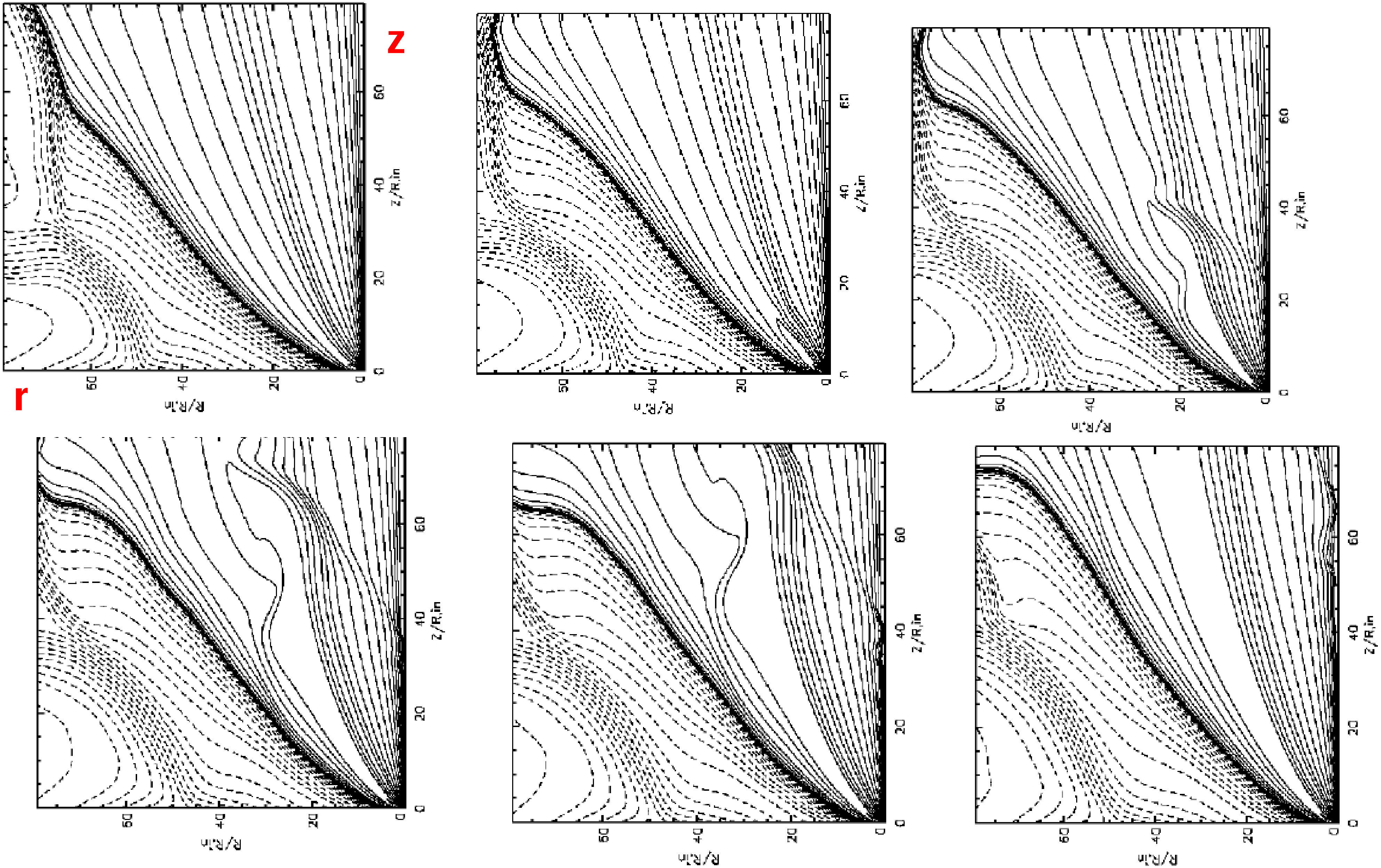


grid: 80x80 inner disk radii
= 160x160 stellar radii
colors: gas density
lines: poloidal field lines /
vector potential contours
code: ZEUS

Outflows from disk-star magnetospheres

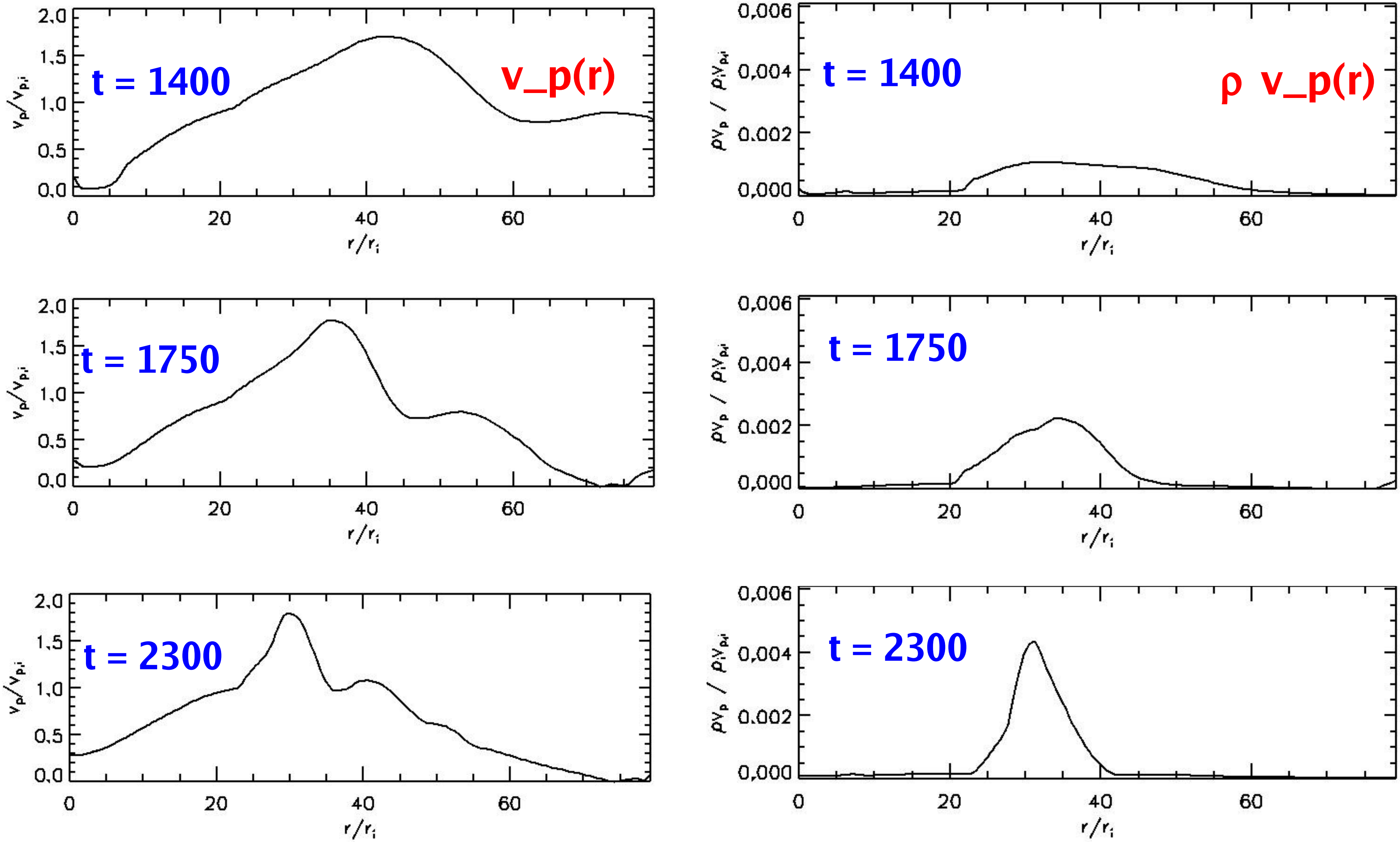


Flare evolution t=1700 - 1860 (lines: poloidal magnetic field lines)



Outflows from disk-star magnetospheres

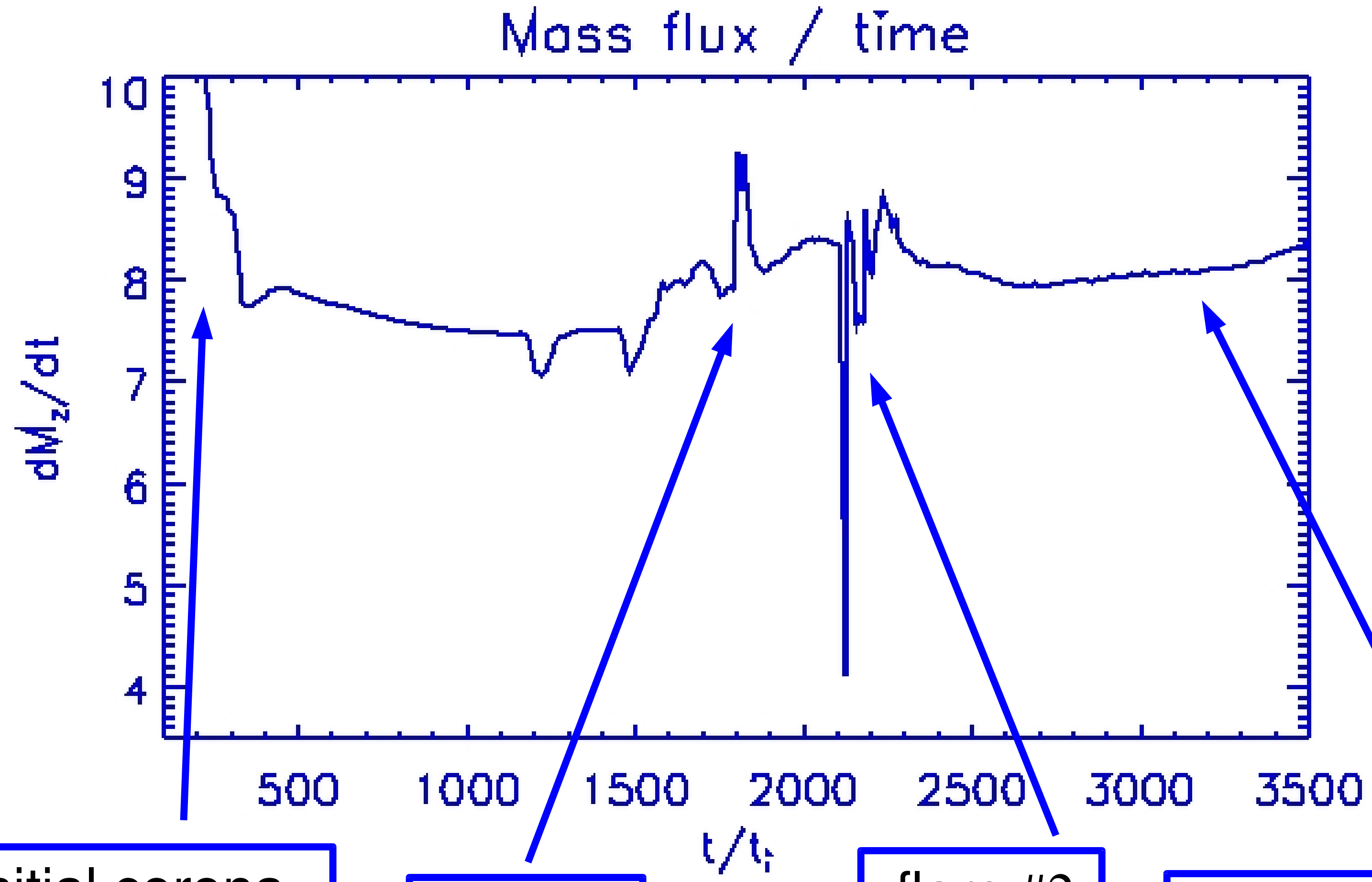
Flare evolution t=1400 - 2300: lateral velocity & momentum re-distribution



Outflows from disk-star magnetospheres

Axial mass flux during flare: **variation by factor 2-4**

-> triggering jet internal shocks / knots (??)



initial corona sweep out

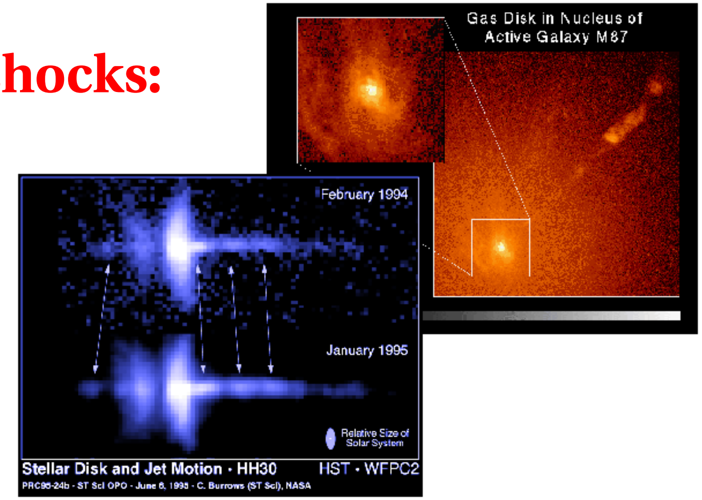
flare #1
Δt~ 10

flare #2
Δt~ 20

collimation of mass flux in axial direction

Formation of MHD jets: flares as triggers of internal shocks:

Summary



(1) Axisymmetric MHD simulations of jet formation:

-> disk/star B.C. allows for long-term evolution (t=3600),
parameter runs
-> iniitial hydrostatic state plus force-free magnetic field

-> "self-consistent" model of magnetic diffusivity ~ turbulent Alfvenic pressure

(2) Disk jet simulations with different disk magnetic flux & mass flux profiles

-> unique relation between disk wind magnetisation σ and degree of collimation ζ.

-> efficient collimation for flat disk magnetic field / disk wind magnetization profile

-> origin of field structure??
-> "X-wind" models are unlikely to launch collimated outflows
-> disk wind/ dynamo provides flat magnetic field profile (?)

(3) Simulations of superposed stellar & disk magnetosphere:

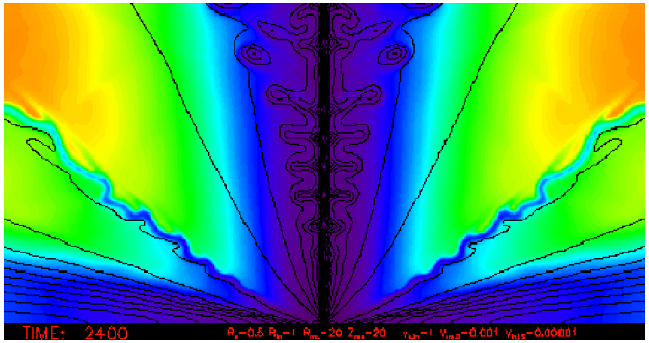
-> de-collimation of disk wind by stellar wind.
-> flares (CME) on t=1000 time scale, duration about t=10-20
-> re-configuration of jet transverse velocity & mass flux profile
-> variation of jet mass flux by factor 2- 4
-> may trigger jet internal shocks / knots (??)

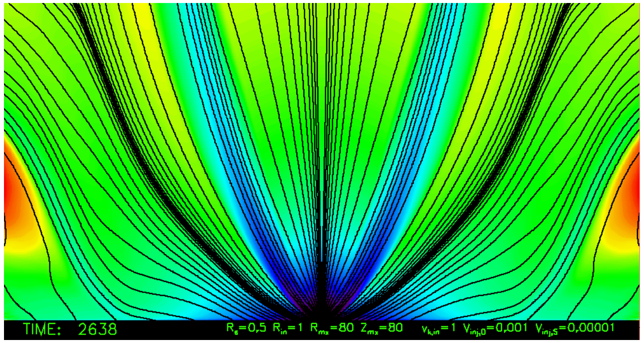
(4) Outlook: relativistic MHD disk jets, radiative forces, disk structure evolution

Appendix

MHD jet collimation:

MHD simulations of magnetospheres





Critical review of disk-as-boundary simulations:

(+) -> powerful tool to investigate the long-term, large-scale evolution of disk / star / star-disk magnetospheres

- -> fast tool: only magnetospheric variables are treated:
  - -> (numerical) time steps in disk & outflow differ largely
  - -> strong gradients between disk & corona not need to be resolved
- -> disk / star boundary condition helps to control simulation
  - -> allows to investigate wide range of parameters & geometries
  - -> ok, as many quantities are not really known: field structure (star / disk), mass loss, disk "physics" (radiative MHD, opacities, turbulence, dynamo)
  - -> interesting for 3D jet formation stability studies (e.g. Ouyed & Pudritz 2003)
- -> option for comparison / fit to observations

(-) -> disk physics not included (provides the launching conditions for outflows):

- -> non-steady mass flux into outflow
- -> time scales set by disk physics
- -> feedback from outflow to disk structure

-> ad hoc prescription for parameters like mass flow rate, field structure