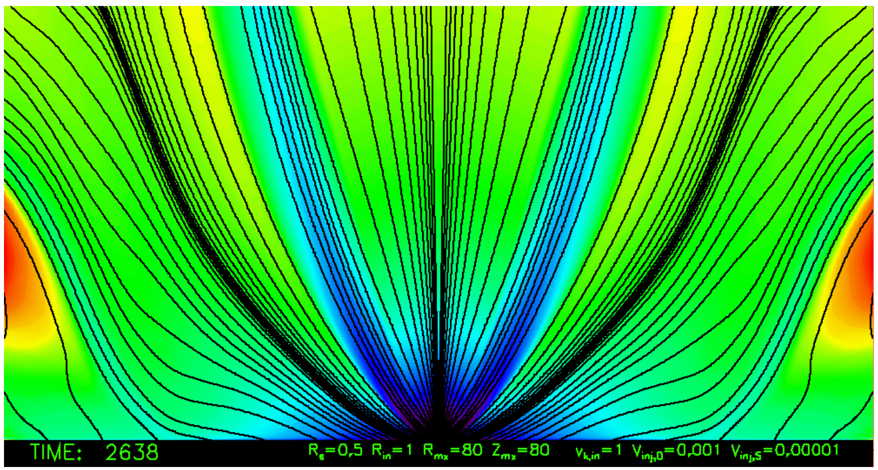
MHD jets from different field configurations



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Contents:

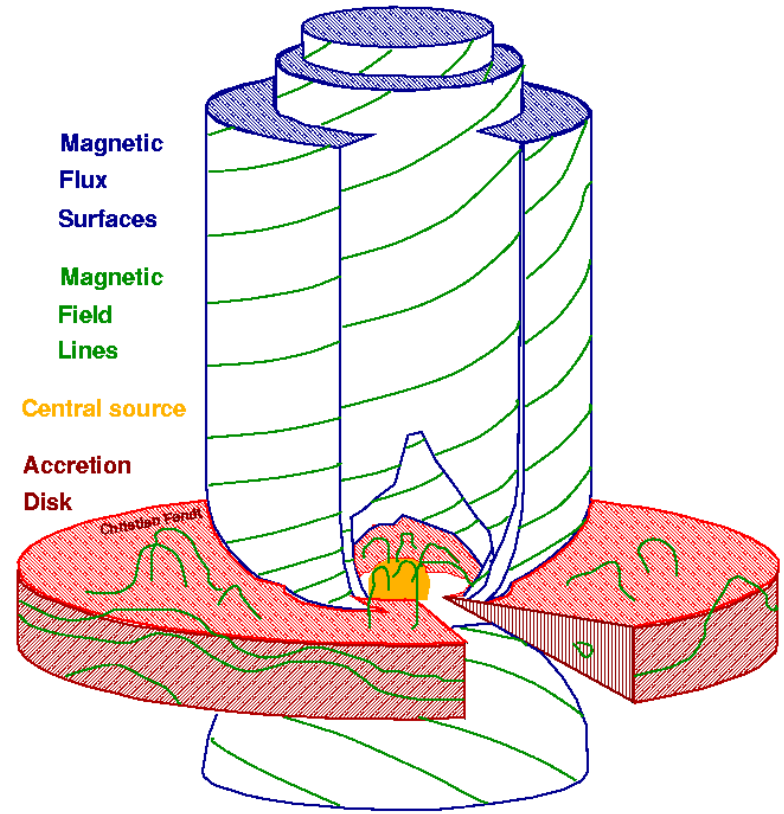
MHD simulations of jet formation:

- Jet collimation & disk magnetic flux / mass flux profiles
- Outflow formation from star + disk magnetic field configuration

Motivation:

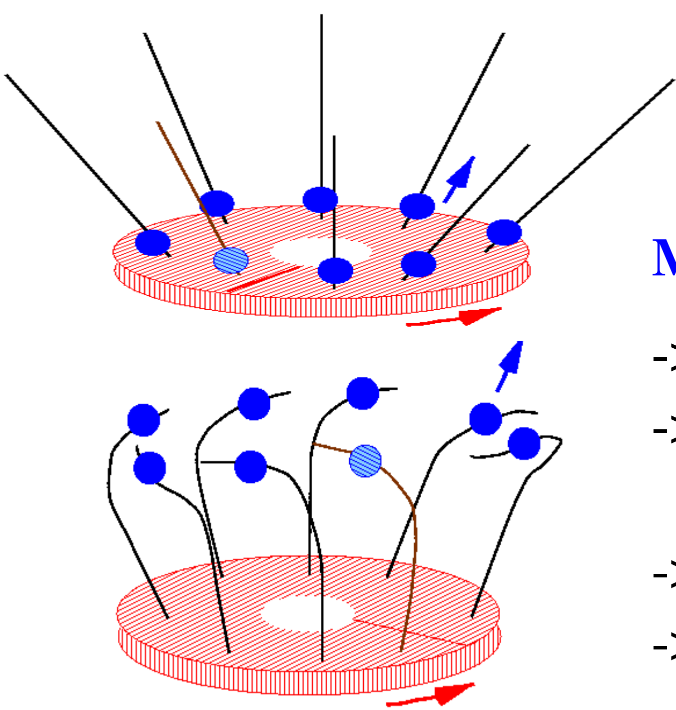
to constrain the underlying magnetic field & mass flux distribution for jet formation

Astrophysical jets:
Standard model



MHD model of jet formation:

Jets are collimated disk/stellar winds,
launched,
accelerated,
collimated
by magnetic forces



Magneto-centrifugal acceleration: (Blandford & Payne 1982)

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

-> strong poloidal field, field line inclination < 60 deg

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

-> induced toroidal field hoop stress collimates outflow

-> further acceleration by Lorentz forces: magnetic acceleration

MHD jet formation
Jet simulations

Proof of jet MHD acceleration & self-collimation by simulations

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

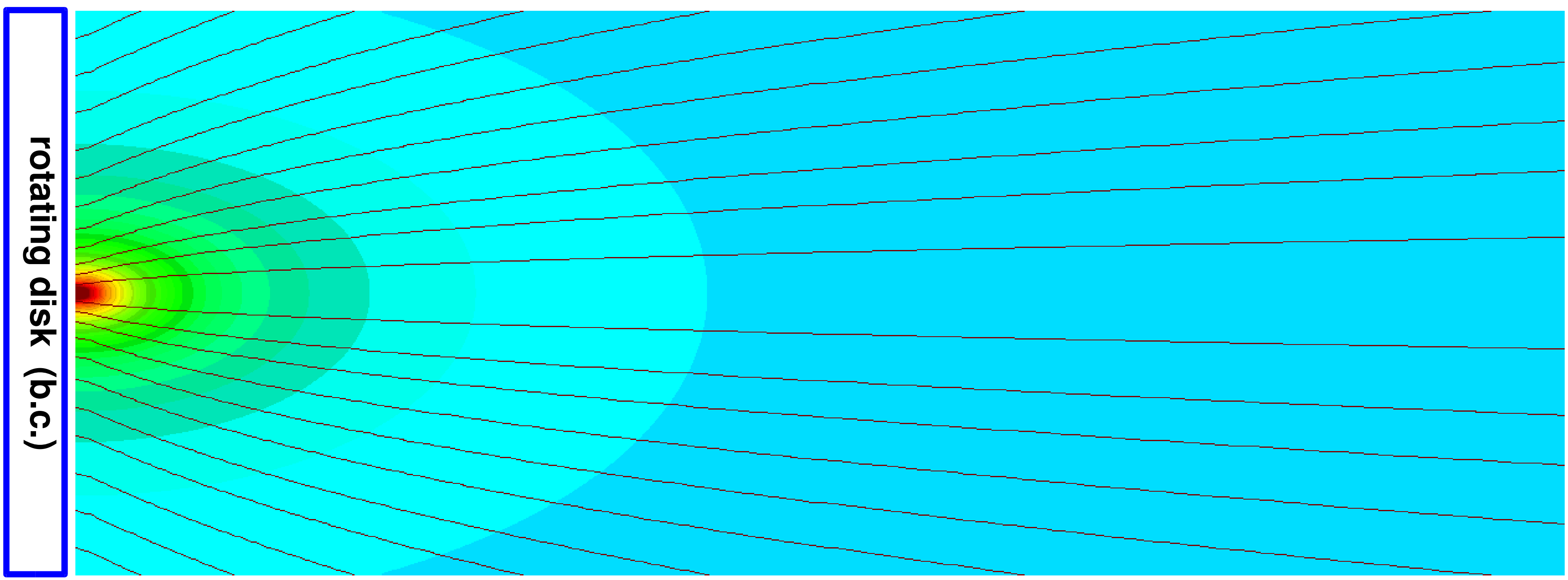
Model assumptions:

-> ideal MHD, axisymmetry, polytropic gas + turb. Alfvenic pressure

-> Keplerian disk as boundary condition, prescribed mass loss rate, inner disk radius

-> steady state initial condition (f-f field, hydrostatic corona) to avoid dynamical artifacts

-> allows for long-term evolution, parameter runs of different b.c.

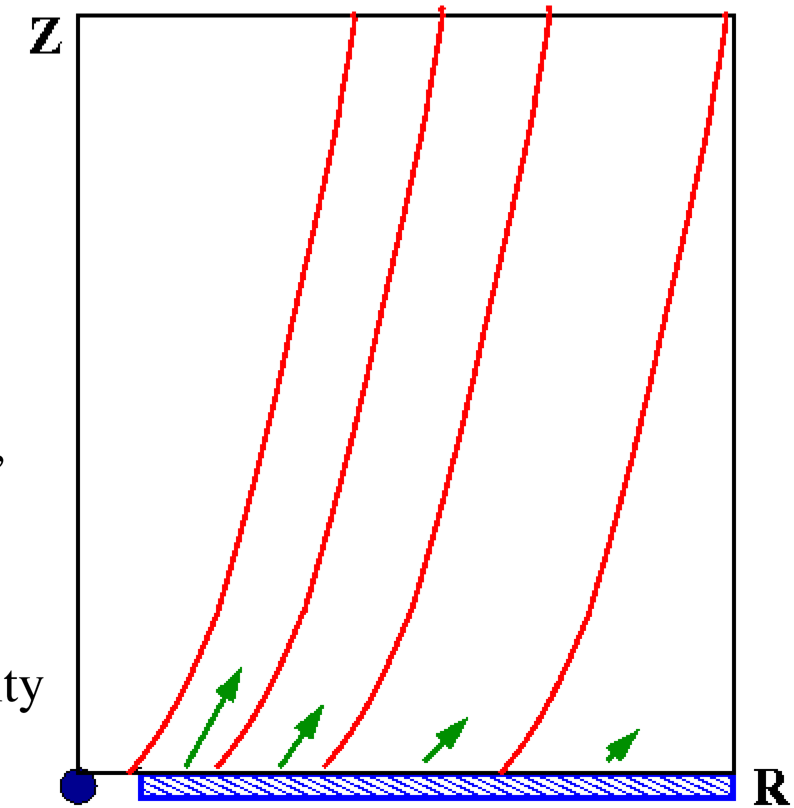


colors: gas density, lines: poloidal magnetic field lines

MHD jet formation simulations

Aim: Investigate jet formation process in more “detail”:

Model setup (Fendt):



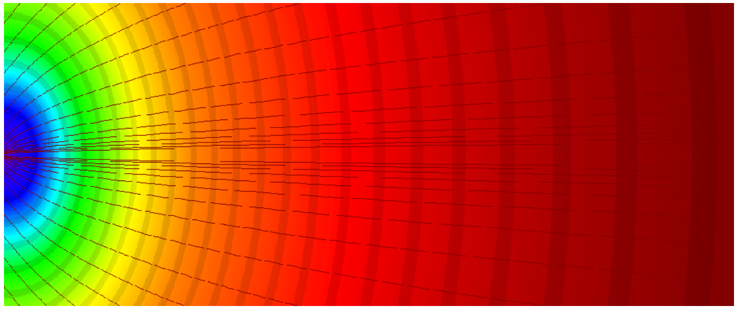
- Keplerian disk as B.C. (disk evolution not taken into acount)
- Initial hydrostatic corona / force-free magnetic field
- Turbulent magnetic diffusivity / pressure model
- Rotating star, R_cor = R_in, gap
- Mass flux from star & disk, with v_inj ~ 0.001 v_K, gap with no/low mass flux

Questions:

1) Jet self-collimation & turbulent magnetic diffusivity
   -> de-collimation of resistive jets: critical level of resistivity (Fendt & Cemeljic 2002)
2) Jet collimation & disk magnetic / mass flux profile
   -> pure disk wind / magnetic field: steep profiles give less collimation (Fendt 2006)
3) Jet formation in two-component magnetic field configuration:
   -> stellar + disk wind, stellar + disk magnetic field

MHD jet collimation &

Disk magnetic flux profile



Self-collimation <---> mass flux profile / disk magnetic field profile (Fendt 2006)

-> disk magnetic field profile: $B_p \sim r^{-\mu}$ wind density: $\rho_0 \sim r^{-\mu_\rho}$

-> construct force-free initial field from disk B.C. (finite element code)

-> disk wind magnetization: $\sigma \equiv \frac{B_{\rm p}^2 r^4 \Omega_{\rm F}^2}{4\dot{M} c^3}$

-> degree of collimation: $\zeta \equiv \frac{\dot{M}_{\rm z}}{\dot{M}_{\rm r}} = \frac{2\pi \int_0^{r_{\rm max}} r\rho v_z dr}{2\pi r_{\rm max} \int_0^{z_{\rm max}} \rho v_r dz.}$

--> mass flux in axial & lateral direction

-> grid size: (150x300) R_i <--> (7x14) AU ~ observational resolution

-> parameter runs: μ, |B|, dM(r)/dt

$\delta_i = 100,\ \beta_p = \beta_\phi = 1,\ \beta_T = 0.03,\ v_{inj}(r) = 10^{-3} v_K(r),\ \rho_{inj} = 100\,\rho_{cor},\ r_{max} = 150,\ z_{max} = 300$

MHD jet collimation &

Disk magnetic flux profile

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

(note different mass flux profile)

-> μ=1.25 is Blandford &Payne

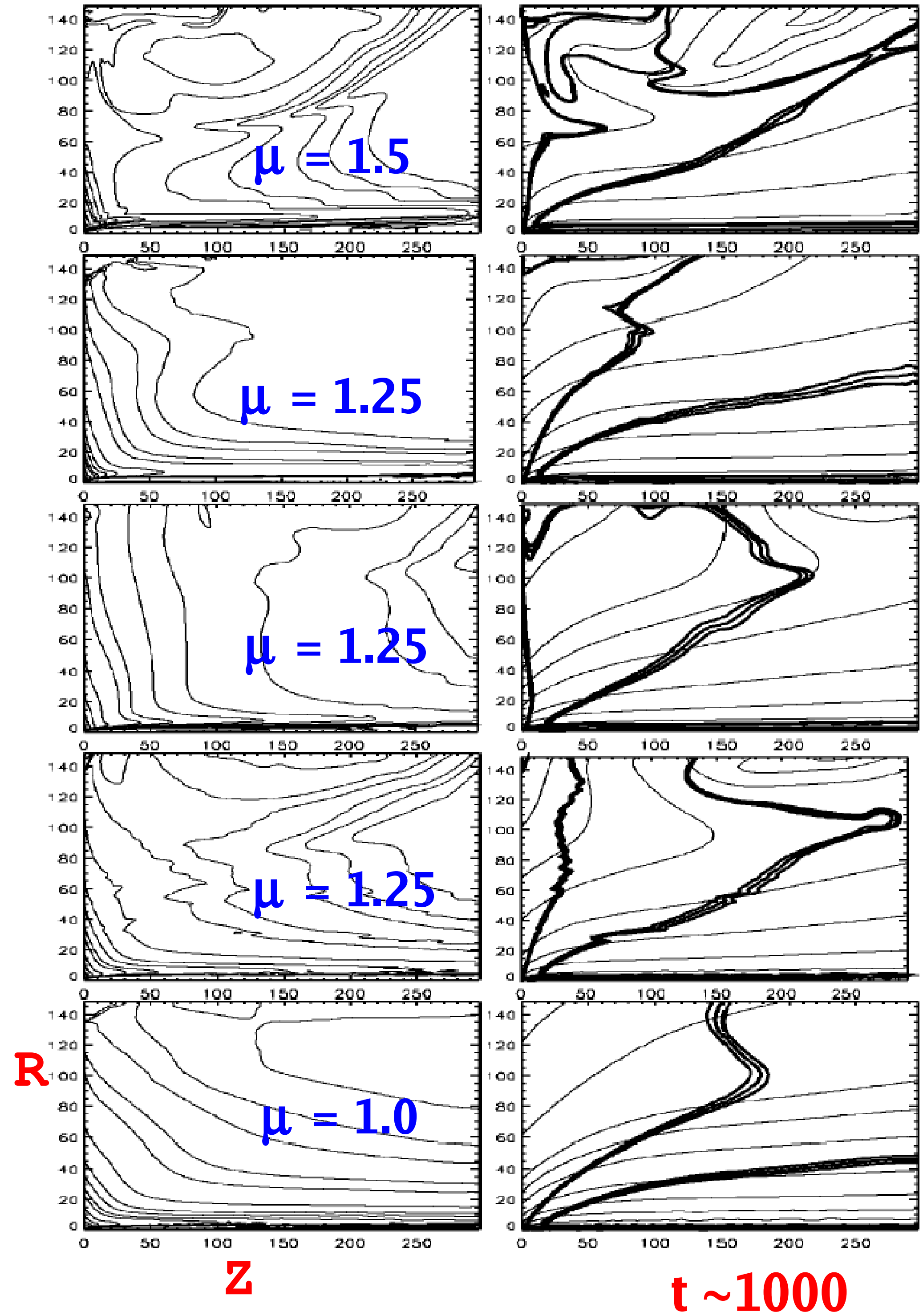
-> μ=1.0 is Ouyed & Pudritz

-> density contours,
poloidal magnetic field lines
at t = 1000

-> note: shape of critical surfaces
|| disk or || axis

-> run simulation as long as possible,
or find stationary state

-> collimation degree, velocity profiles, asymptotic speed, ...



MHD jet collimation & Disk magnetic flux profile

- systematic parameter study: $\mu = 0.2 \ldots 2.0$

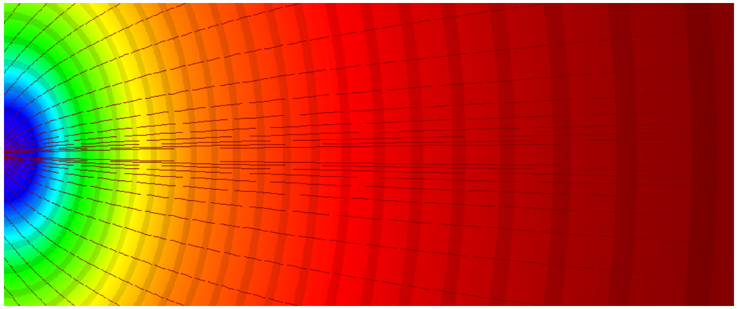
$$B_p \sim r^{-\mu}$$

- one year of CPU time (workstation)
- steep B(r) profiles (stellar dipole, "X-winds")
- flat B(r) profiles (disk winds)

run	μ	μ_ρ	μ_σ	$B_{\rm p,i}$	τ	$\dot M_{z,1}, \dot M_{r,1}$	$\dot M_{z,2}, \dot M_{r,2}$	$\dot M_{z,3}, \dot M_{r,3}$	$\hat\zeta_1, \hat\zeta_2, \hat\zeta_3$	$v_{\rm mx}$	$<\zeta>$
p21	1.5	2.0	-1.5	0.214	2010	0.25, 0.16	0.40, 0.07	0.42, 0.16	9.6, 22.8, 13.0	1.25	15
i9	1.5	2.0	-1.5	0.667	840	0.14, 0.28	0.37, 0.10	0.42, 0.16	3.0, 14.8, 13.0	3.08	15
c3	1.5	1.5	[illegible]	0.214	1940	0.49, 0.36	0.78, 0.29	0.85, 0.30	8.4,10.8,14.0	1.07	15
p4	1.5	1.5	-2.0	0.321	2370	0.40,0.46	0.72,0.33	0.87, 0.41	5.2, 8.8, 11.0	1.74	10
i16	1.5	1.0	-2.5	0.321	2040	0.56,1.51	1.21,1.84	1.73,2.12	2.2, 2.6, 4.0	2.50	5
i4,⋆	1.5	0.5	-3.0	0.40	550	0.93, 2.10	1.8[illegible], 4.07	1.30, 7.07	2.7, 1.9, 0.92	1.47	2
i8	1.5	0.5	-3.0	2.67	290	0.11,5.78			sup.-Alf. inflow		?
i14	1.25	1.5	-1.5	0.355	610	0.63,0.49	1.01,0.46	1.09,1.40	7.8, 8.8, 4.0	1.53	10
i15,⋆	1.25	1.5	-1.5	0.177	5000	0.25,0.28	0.42,0.24	0.52,0.22	5.4, 7.2, 12.0	1.22	10
p20	1.25	1.0	-2.0	0.355	1810	1.07,1.58	1.98,2.00	2.31,2.69	4.2, 4.0, 4.5	1.47	5
a2	1.25	0.5	-2.5	0.177	2350	0.56, 0.51	0.89, 0.69	1.03, 0.58	6.6, 5.1, 8.8	0.91	8
p2	1.0	1.5	-1.0	0.155	2550	0.79,0.53	1.21,0.40	1.43,0.38	9.0, 12.0, 18.5	0.87	15
i10	1.0	1.5	-1.0	0.155	3330	0.75,0.49	1.11,0.49	1.32,0.52	9.0, 9.2, 12.5	0.89	10
i11	1.0	1.0	-1.5	0.155	2090	1.60,1.66	2.75, 2.13	3.18, 2.97	5.8, 5.2, 5.5	0.84	5
c9	1.0	0.5	-2.0	0.358	1730	3.14, 6.14	6.64, 11.[illegible]	8.30, 18.5	3.1, 2.3, 2.3		2
p13	0.8	1.5	-0.6	0.922	290	0.93, 0.53	1.87,1.2[illegible]	6.00, 1.90	10.5, 5.8, 15.8	2.33	15
p14	0.8	1.5	-0.6	0.307	1840	0.90, 0.46	1.34, 0.39	1.41, 0.43	12.3, 18.2, 16.5	1.18	20
a1	0.8	1.5	-0.6	0.247	2830	1.02, 0.35	1.39, 0.26	1.55, 0.34	17.5, 20.5, 22.8	1.08	20
i17	0.8	1.0	-1.1	0.247	2790	1.88, 1.49	3.44, 1.89	4.58, 1.59	7.6, 7.3, 14.5	1.05	$\simeq$ 15
p15	0.8	0.6	-1.5	0.310	990	3.34, 4.60	6.95, 7.81	9.13, 11.2	4.4, 3.6, 4.1	1.05	4
c10	0.8	0.5	-1.6	0.247	1400	3.85, 6.08	8.05, 11.8	11.3, 18.8	3.8, 2.7, 3.0	0.93	3
i19	0.65	1.5	-0.3	0.279	1420	0.53, 0.17	0.73, 0.16	0.82, 0.27	18.4, 18.1, 15.5	1.01	20
i18	0.65	0.5	-1.3	0.279	1600	4.93, 5.58	10.8, 10.1	14.2, 16.6	5.3, 4.3, 4.3	1.01	4
a5	0.65	1.0	-0.8	0.279	1700	2.14, 1.51	3.79, 1.75	4.59, 2.22	8.5, 8.6, 10.1	1.05	10
p6	0.5	1.5	0.0	0.112	1800	1.18,0.33	1.65,0.23	1.82, 0.25	21.5, 28.7, 36.4		30
i1	0.5	1.5	0.0	0.112	3600	1.18, 0.04	1.35, -.048	0.92, 0.18	161, (112), 25.6	0.7	30
p7	0.5	1.5	0.0	0.225	1000	1.19, 0.30	1.63, 0.26	2.07, 0.51	23.8, 25.1, 20.3	0.86	20
c5	0.5	1.5	0.0	0.225	430	1.23, 0.39	2.44, 0.35	4.89,-0.22	18.9, 27.9, (111)	0.78	30
c8	0.5	0.8	-0.7	0.112	3800	3.66, 2.08	7.38, 2.40	10.1, 1.77	10.6, 12.3, 28.5	0.7	30
i2	0.5	0.8	-0.7	0.112	3800	3.69, 2.07	7.37, 2.38	10.3, 1.75	10.7, 12.4, 29.4	0.5	30
p8,⋆	0.5	0.5	-1.0	0.112	3500	3.18,2.35	7.19, 3.86	10.5, 5.10	8.1, 7.5, 10.3	0.65	10
i3,⋆	0.5	0.5	-1.0	0.112	3900	3.13, 2.15	7.74, 3.10	11.3, 4.07	8.7, 10.0, 13.9	0.65	15
p18	0.5	0.5	-1.0	0.112	2210	5.60, 5.48	12.5, 9.57	17.6, 15.3	6.1, 5.2, 5.8	0.51	5
p19	0.5	0.5	-1.0	0.225	1640	5.88, 5.14	12.9, 9.09	17.2, 15.1	6.9, 5.7, 5.7	0.95	6
p16	0.5	[illegible]	-1.2	0.225	2790	9.60, 7.87	24.2, 15.2	36.8, 27.0	7.3, 6.4, 6.8	0.58	7
c11	0.35	1.5	0.3	0.366	1250	1.14, 0.25	2.23, 0.55	2.39, 1.20	27.4, 16.3, 10.0		$\simeq$ 10
a4	0.35	1.0	[illegible]	0.255	2000	3.02, 0.70	5.05, 1.04	7.75, -.39	25.9, 19.4, (99)		$\simeq$ 25
a6	0.35	0.5	[illegible]	0.255	1900	8.51, 2.44	18.8, 1.38	23.9, 3.47	20.9, 54.3, 34.3	0.8	$>$ 30
a8	0.2	1.0	0.1	0.296	1950	2.62, 0.67	4.93, 0.61	7.64, -2.5	23.5, 32.3, (-19)		$\simeq$ 30
a7	0.2	0.5	-0.4	0.296	2100	8.89, 2.05	15.7, 3.67	29.9, 5.72	26.0, 17.1, 26.1	0.68	$\simeq$ 25

MHD jet collimation:

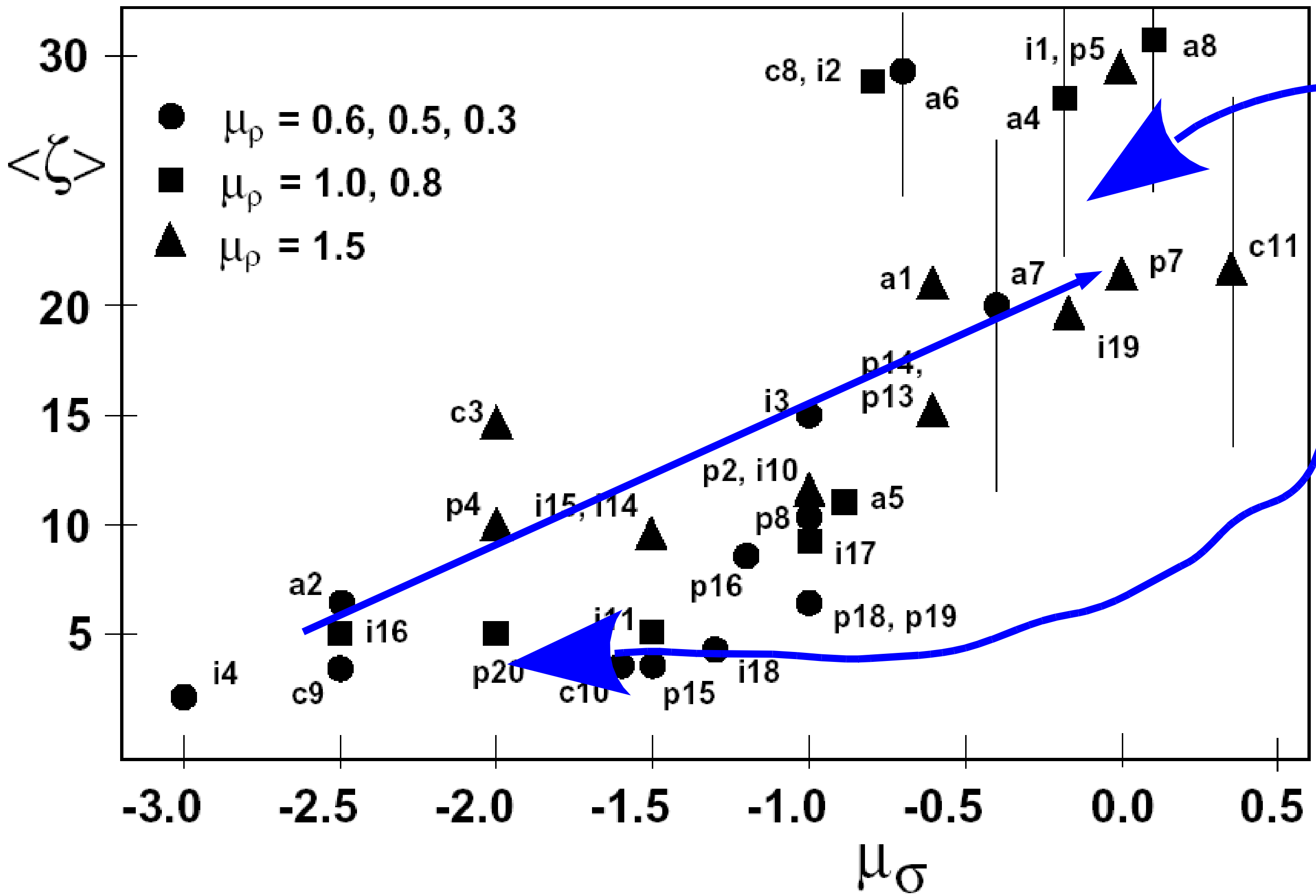
Disk magnetic flux profile



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

-> ”flat” profile (B, σ) -> good 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”

Outflows from disk-star magnetospheres

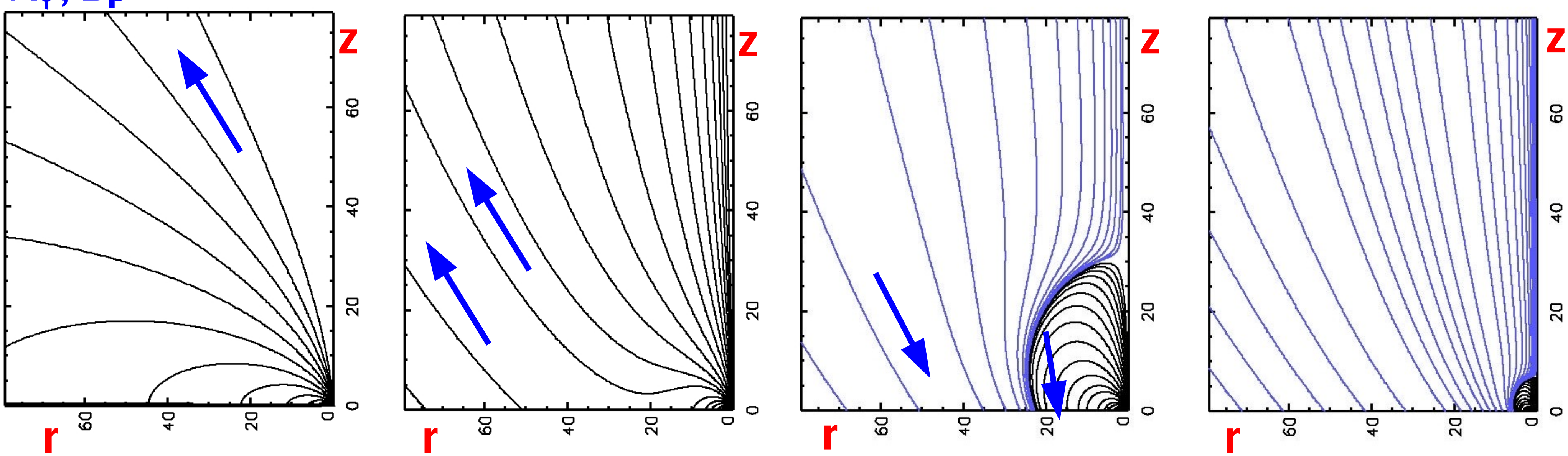
Two-component magnetic field configuration:

-> superposed stellar dipole + disk magnetosphere

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

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

Aϕ, Bp



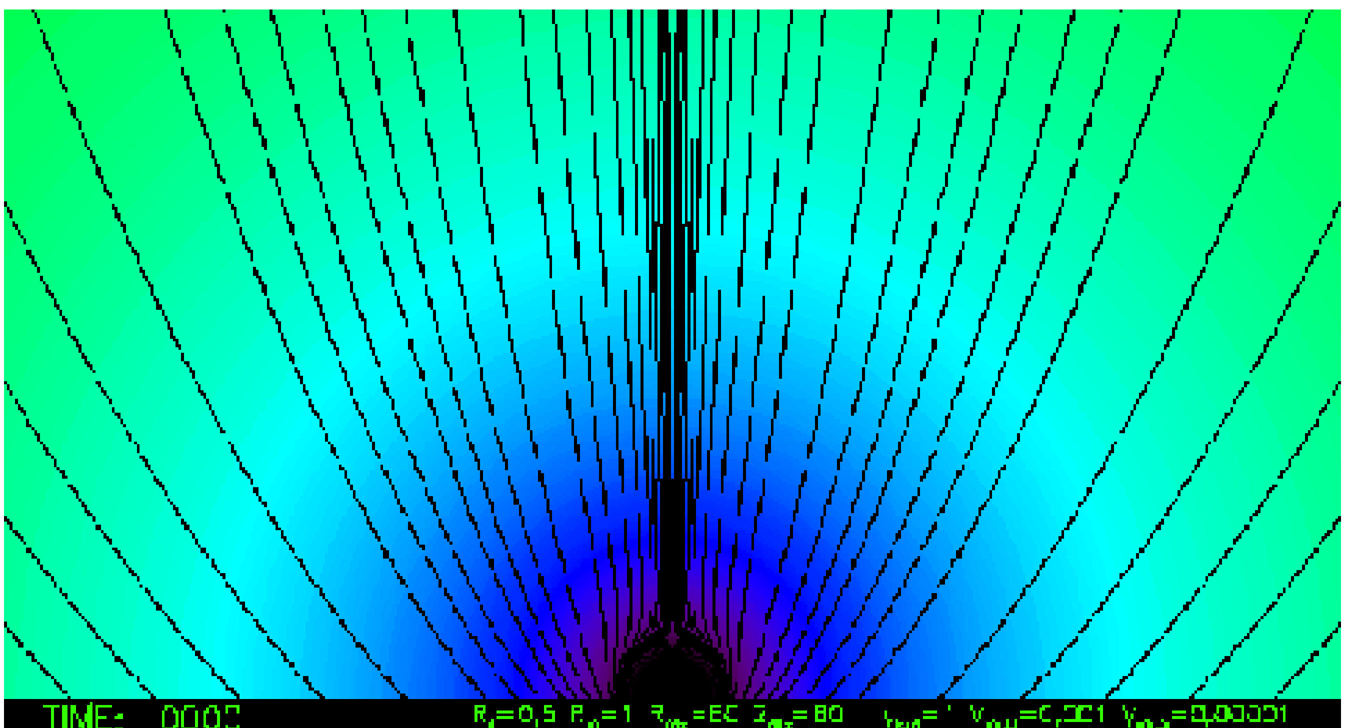
A_d = 0, A_s = 1.0 | A_d = 0.01, A_s = 5.0 | A_d = -0.01, A_s = 1.0 | A_d = -0.1, A_s = 3.0

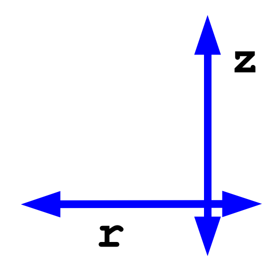
-> other parameters: plasma beta, mass flow rates (from star/disk), turbulent Alfvenic pressure, magnetic diffusivity

Outflows from disk-star magnetospheres

Time evolution of disk-star magnetospheres: (example A_d = -0.1, A_s = 3.0)

- rotating star: corotation radius = inner disk radius
- resistive MHD: consistent model of turbulent Alfvenic diffusivity / pressure
- total run time ~ 3600 inner disk orbits (= 6 outer disk orbits),
  700 (100) inner disk orbits (= 0.15 (1.0) 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 state again -> cyclic behavior on large scale ?
  -> central dipole disturbs large scale structure (Goodson et al. 1999)





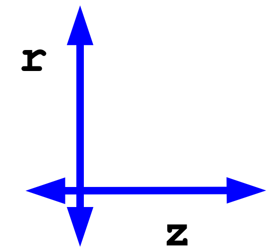
grid: 80x80 inner disk radii
= 160x160 stellar radii

colors: gas density

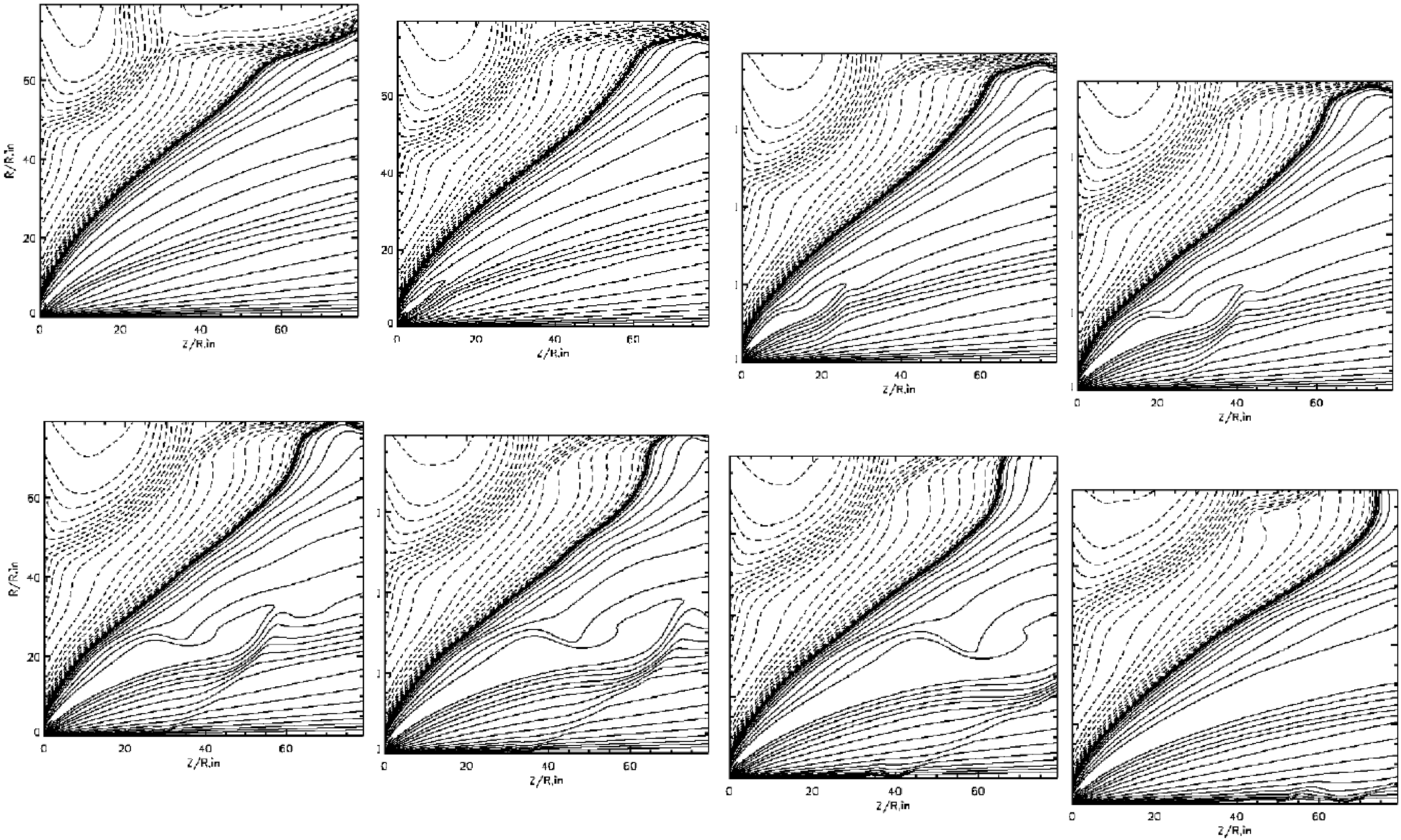
lines: poloidal field lines /
vector potential contours

code: ZEUS

Outflows from disk-star magnetospheres

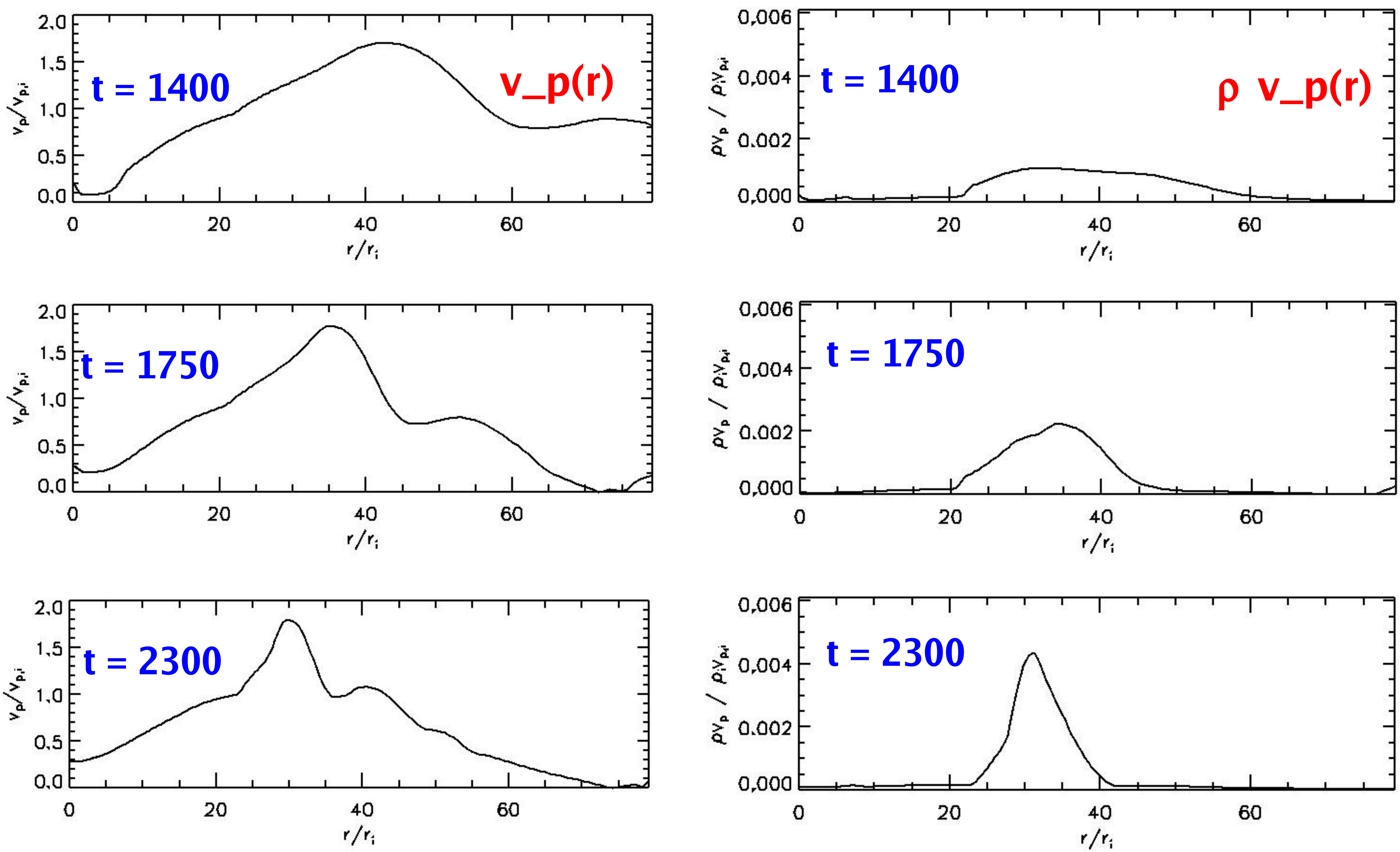


Flare evolution t=1700 - 1860 (lines: poloidal magnetic field lines)



Outflows from disk-star magnetospheres

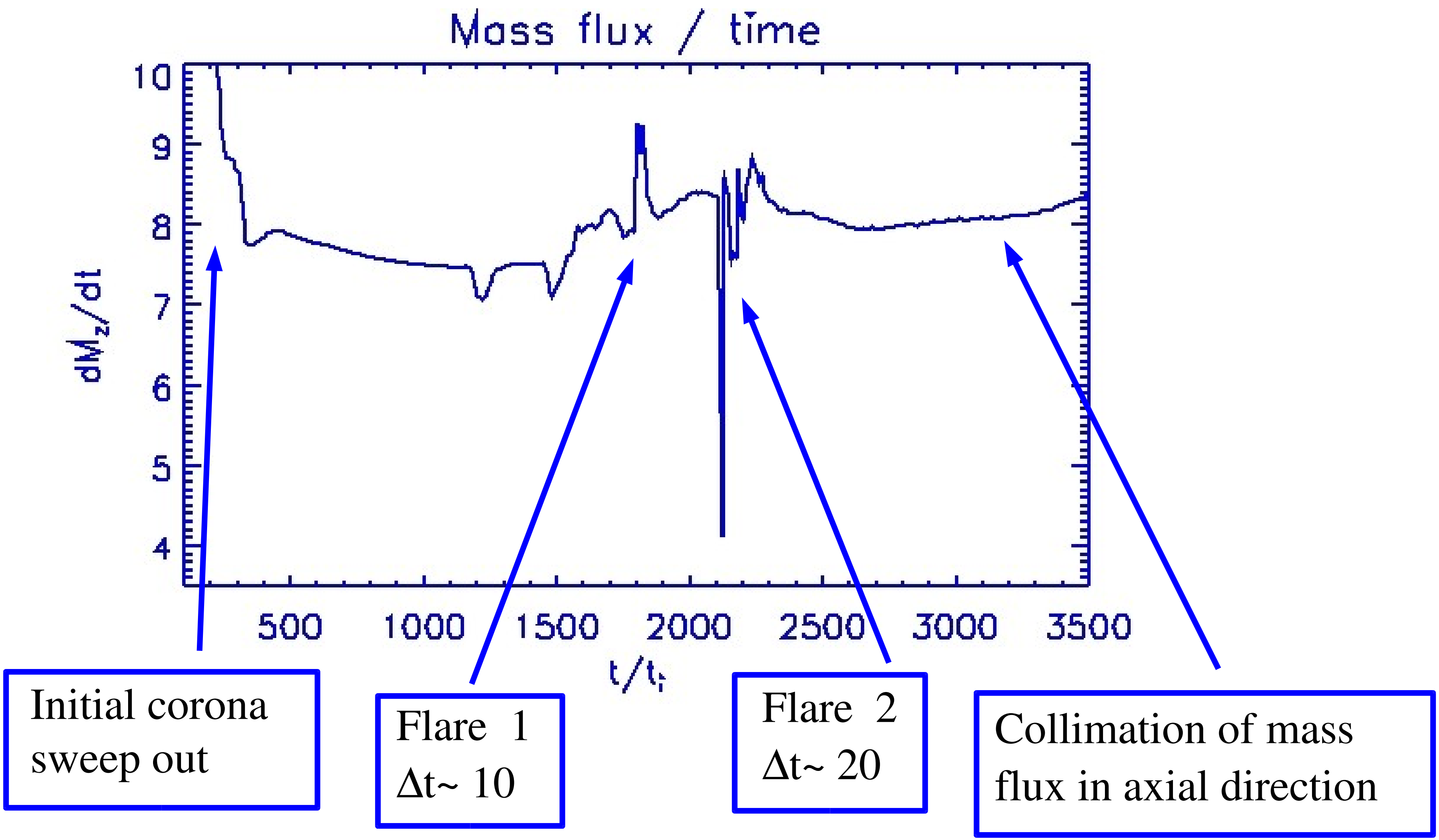
Flare evolution t=1400 - 2300: lateral velocity & momentum re-distribution



Outflows from disk-star magnetospheres

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

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



MHD jets from different field configurations

Summary

(1) Axisymmetric MHD simulations of jet formation (ZEUS)

(2) Disk/star as b.c. allows for long-term evolution (t=3600), parameter runs

(3) "Self-consistent" model of magnetic diffusivity (related to turbulent Alfvenic pressure)

(4) Initial hydrostatic state plus force-free magnetic field

(5) Simulations of diffusive jets: critical diffusivity / collimation, (Fendt & Cemeljic 2002)

(6) Disk jet simulations of different disk magnetic flux & mass flux profiles (Fendt 2006):
unique relation between disk wind magnetisation σ and degree of collimation ζ.
Better collimation for flat disk magnetic field / disk wind magnetization profile
-> origin of field structure??
-> "X-wind" kind models are unlikely to launch collimated outflows
-> disk dynamo provides flat magnetic field profile (?)

(7) (Preliminary) simulations of superposed stellar & disk magnetosphere demonstrate de-collimation of disk wind by stellar wind (Fendt 2008, submitted):
flares (CME) on t=1000 time scale, duration about t=10-20
-> re-configuration of jet velocity & mass flux profile
-> variation of jet mass flux by factor 2- 4
-> may drive jet internal shocks / knots (??)