Physics of AGN Jets

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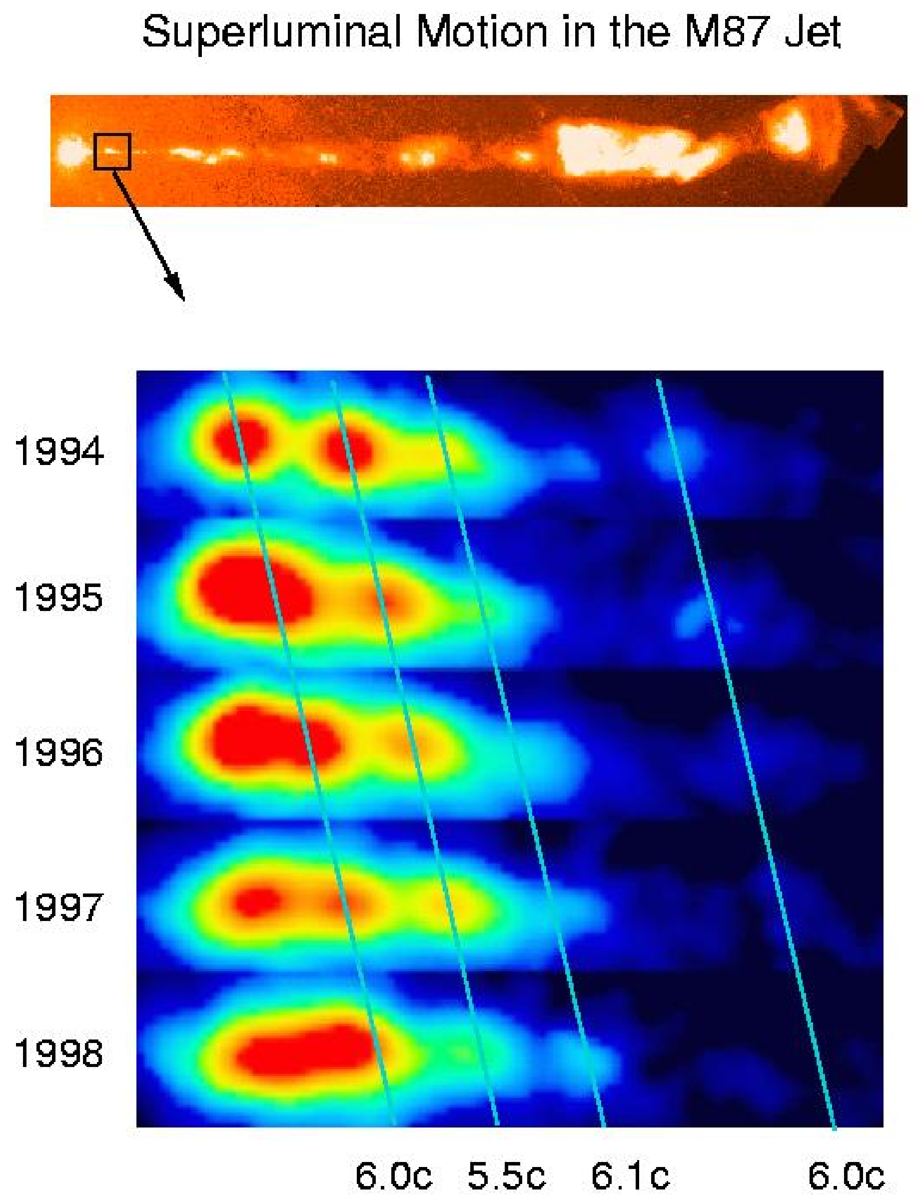
Outline

- observations and their implications
- the role of the magnetic field
  MHD models (semi-analytical – simulations)

Observations: jet speed



- Superluminal apparent motion: $\beta_{\rm app}$ is a lower limit of real γ
- **If** we know both $\beta_{\rm app} = \dfrac{\beta \sin\theta_n}{1-\beta\cos\theta_n}$ and $\delta \equiv \dfrac{1}{\gamma\,(1-\beta\cos\theta_n)}$
  we find $\beta(t_{\rm obs})$, $\gamma(t_{\rm obs})$, $\theta_n(t_{\rm obs})$
  Rough estimates of δ from:
  - comparison of radio and high energy emission (SSC)
    e.g., for the C7 component of 3C 345 Unwin et al 1997 argue that δ changes from ≈ 12 to ≈ 4 ($t_{\rm obs} =$ 1992 – 1993) $\Longrightarrow$ acceleration from $\gamma \sim 5$ to $\gamma \sim 10$ over $\sim 3 - 20$ pc from the core (θ_n changes from ≈ 2 to $\approx 10^o$)
    Similarly Piner et al (2003) inferred an acceleration from $\gamma = 8$ at $R < 5.8$pc to $\gamma = 13$ at $R \approx 17.4$pc in 3C 279
  - variability timescale (compared to the light crossing time), Jorstad, Marscher et al. $\Delta t_{var} = \Delta t_{cross}/\delta$, $\Delta t_{cross} = sD/c$

On the bulk acceleration

- More distant components have higher apparent speeds

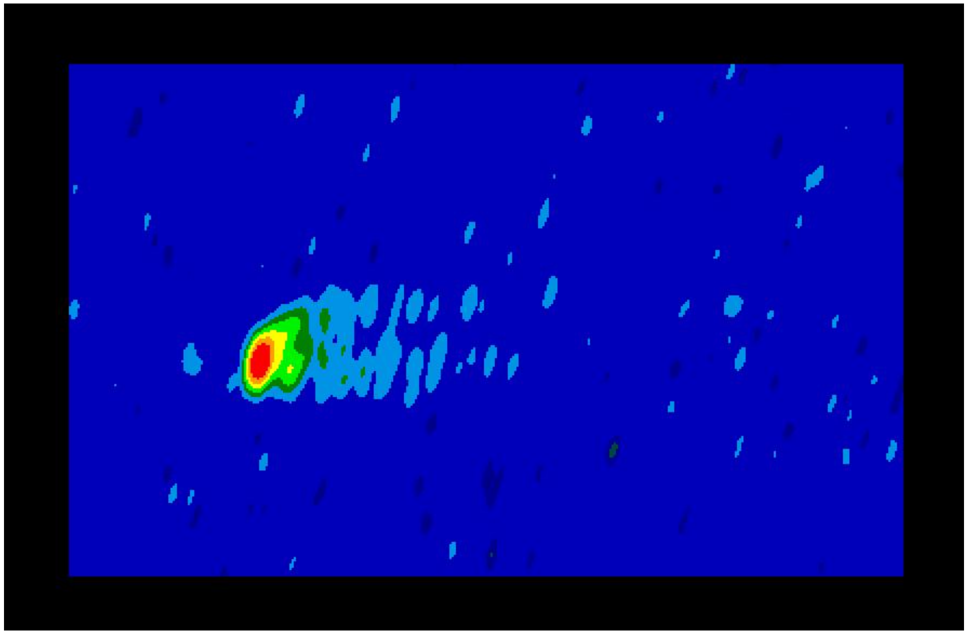
- A more general argument on the acceleration (Sikora et al 2005):

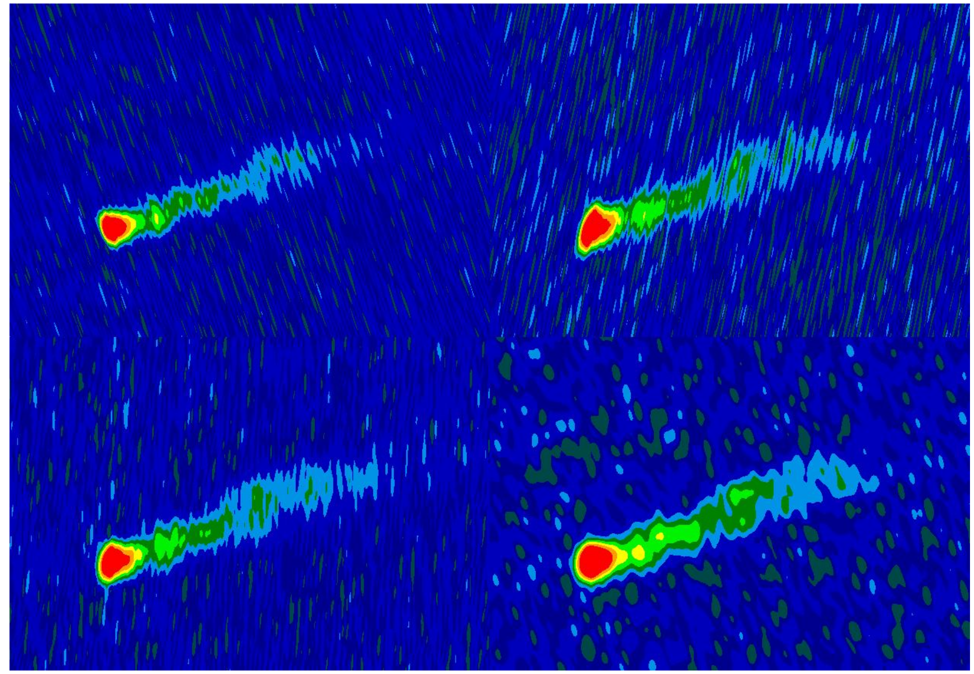
  ⋆ lack of bulk-Compton features $\rightarrow$ small ($\gamma < 5$) bulk Lorentz factor at $\lesssim 10^3 r_g$
  ⋆ the γ saturates at values $\sim$ a few 10 around the blazar zone $(10^3 - 10^4 r_g)$

  So, relativistic AGN jets undergo the bulk of their acceleration on parsec scales ($\gg$ size of the central black hole)

- Sikora et al 2005 also argue that the protons are the dynamically important component in the outflow.

On the collimation

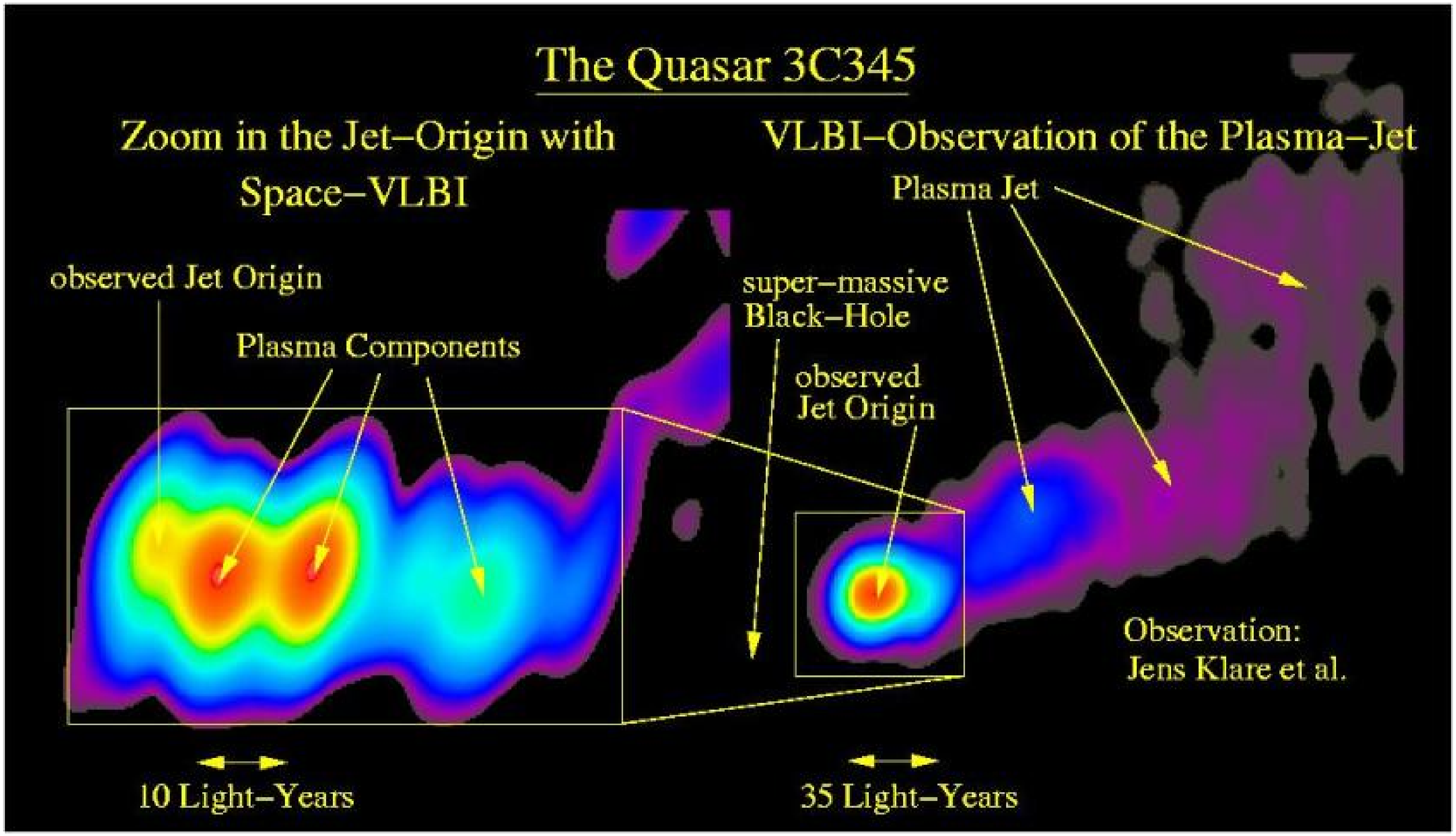




(left Global VLBI + VSOP, right Global VLBI)

Collimation in action (at approximately $100r_g$) in M87. In the formation region, the jet is seen opening widely, at an angle of about 60 degrees, nearest the black hole, but is squeezed down to only 6 degrees a few light-years away (Junor, Biretta, & Livio 1999; see also Krichbaum et al 2006).

Curved trajectories

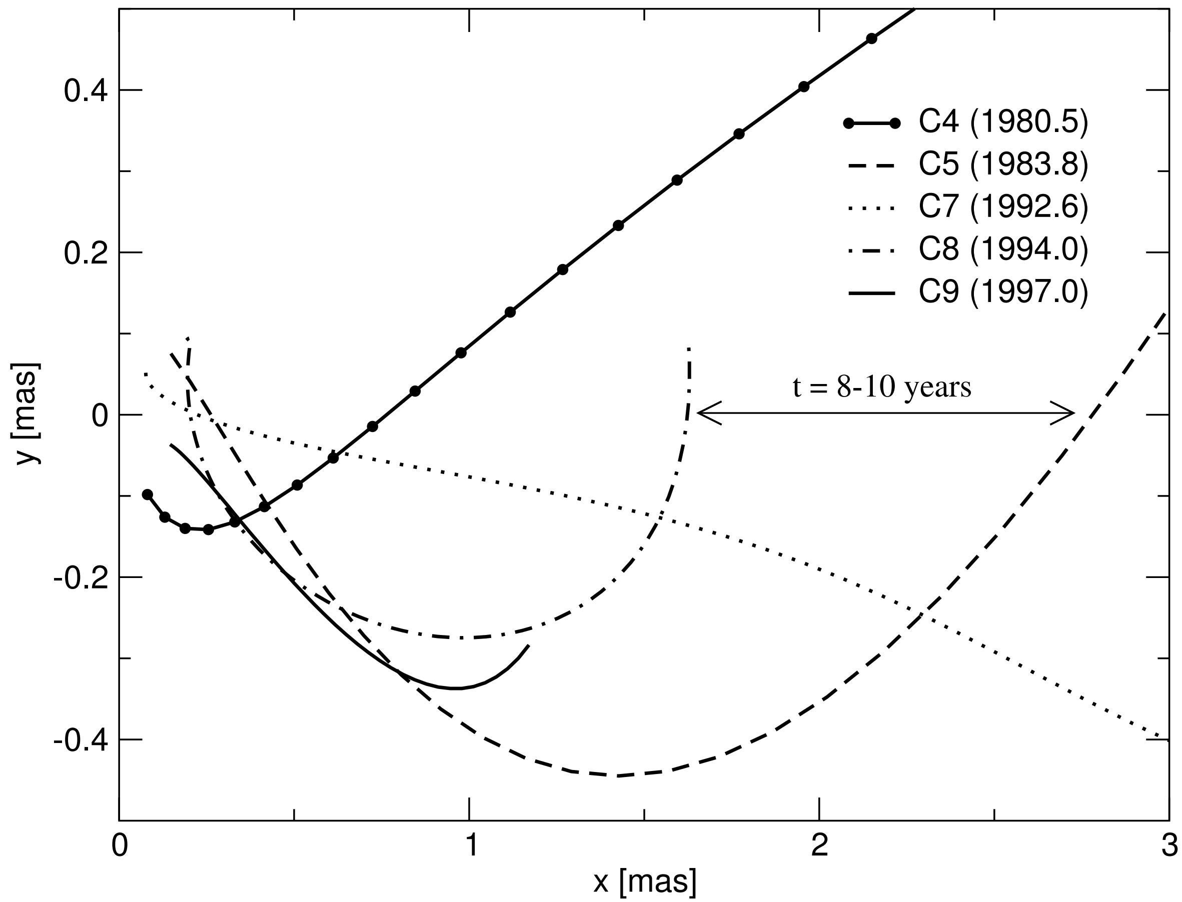


(credit: Klare et al)

The plasma components travel on curved trajectories.

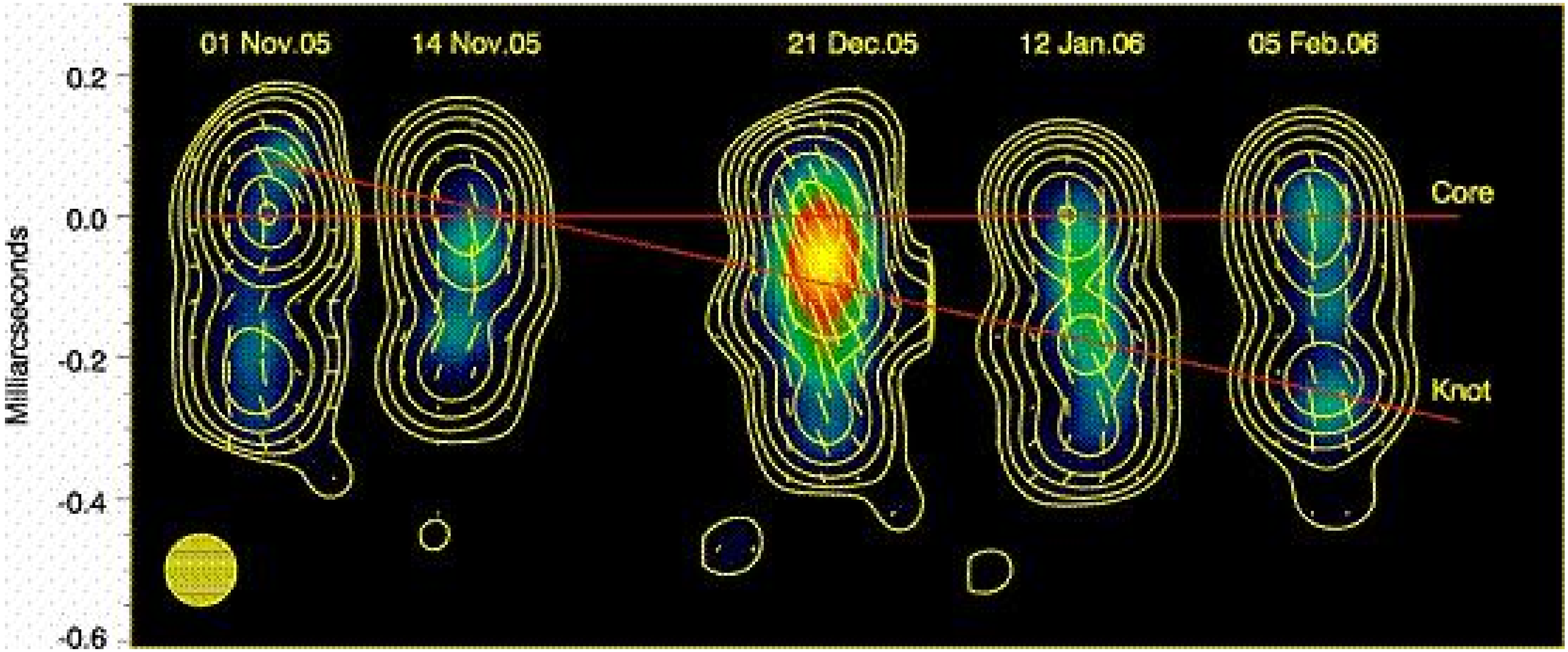
The trajectories differ from one component to the other.

They change their strength.



(credit Klare et al)

Polarization



(Marscher et al 2008, Nature)

helical motion and field rotate the EVPA as the blob moves

observed $\boldsymbol{E}_{rad} \perp \boldsymbol{B}_{rad}$ and $\boldsymbol{B}_{rad}$ is $\parallel$ $\boldsymbol{B}_{\perp los}$
(modified if the jet is relativistic)

Faraday rotation

Faraday rotation – the plane of LP rotates when polarized EM wave passes through a magnetized plasma, due to different propagation velocities of the RCP and LCP components of the EM wave in the plasma.

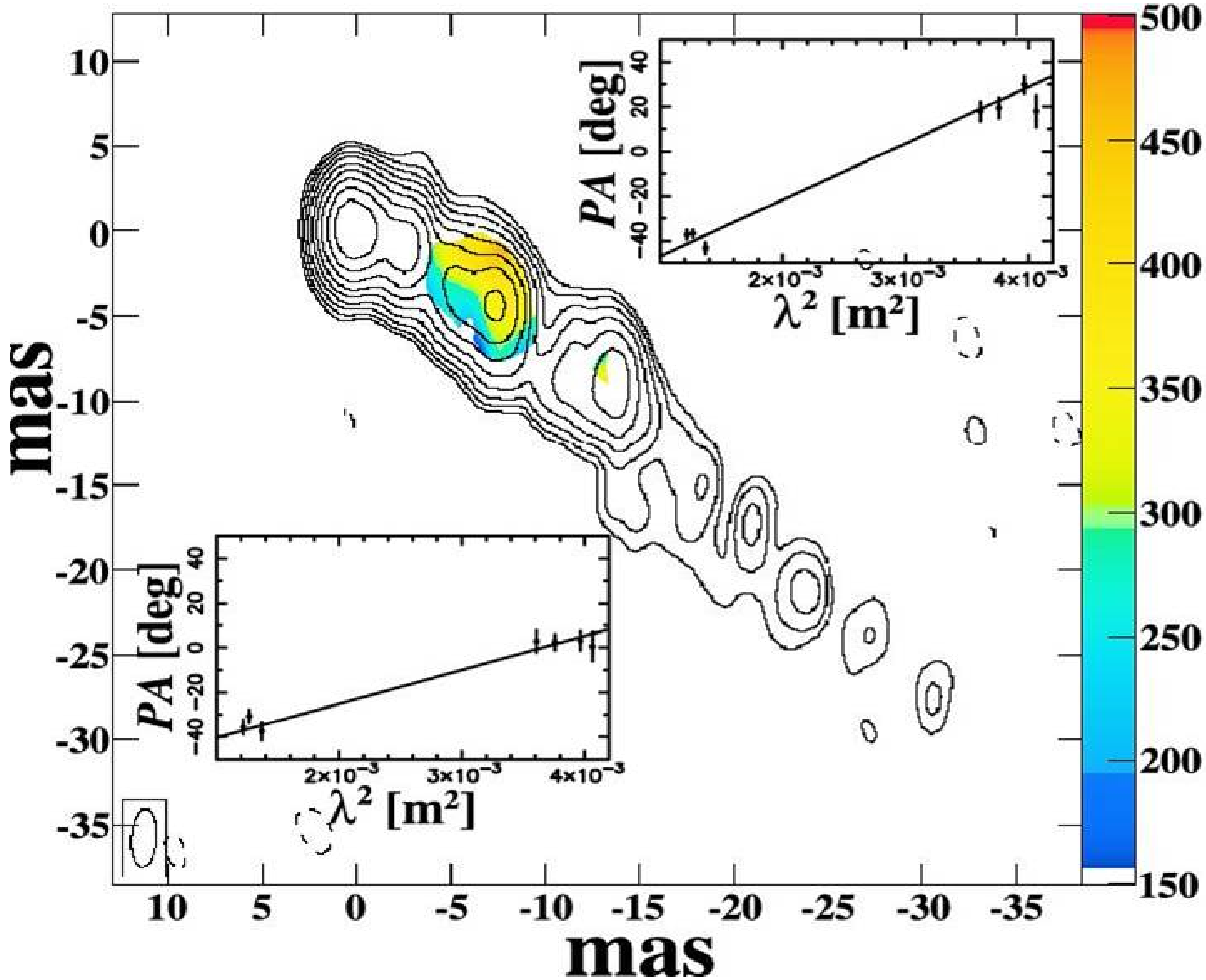
If internal, there is also depolarization (fractional polarization depends on λ).

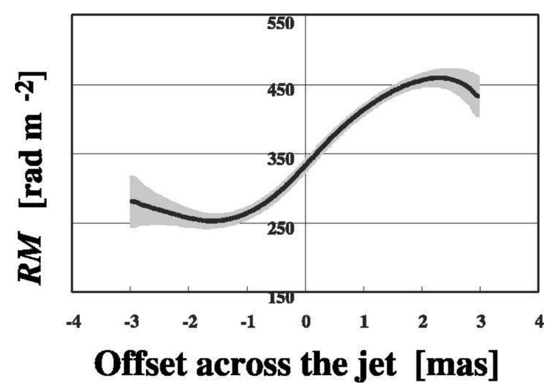
If external, the amount of rotation is proportional to the square of the observing wavelength, and the sign of the rotation is determined by the direction of the line of sight B field:

$$\chi = \chi_0 + (RM)\lambda^2$$

$$(RM) \propto \int n_e B_{\| los} d\ell$$

Faraday RM gradients across the jet





(from Asada et al)

helical field surrounding the emitting region

Theory: Hydro-Dynamics

- In case $n_e \sim n_p$, $\gamma_{\max} \sim kT_i/m_p c^2 \sim 1$ even with $T_i \sim 10^{12} K$
- If $n_e \neq n_p$, $\gamma_{\max} \sim (n_e/n_p) \times (kT_i/m_p c^2)$ could be $\gg 1$
- With some heating source, $\gamma_{\max} \gg 1$ is in principle possible

However, even in the last two cases, HD is unlikely to work because the HD acceleration saturates at distances comparable to the sonic surface where gravity is still important, i.e., very close to the disk surface (certainly at $\ll 10^3 r_g$)

Collimation is another problem for HD

We need magnetic fields

- ⋆ They extract energy (Poynting flux)
- ⋆ extract angular momentum
- ⋆ transfer energy and angular momentum to matter
- ⋆ explain relatively large-scale acceleration
- ⋆ collimate outflows and produce jets
- ⋆ needed for synchrotron emission
- ⋆ explain polarization and RM maps

How to model magnetized outflows?

⋆ as pure electromagnetic energy (force-free, magnetodynamics, electromagnetic outflows, Blandford & Znajek):
– ignore matter inertia (reasonable near the origin)
– this by assumption does not allow to study the transfer of energy form Poynting to kinetic

⋆ as magneto-hydro-dynamic flow ("Blandford & Payne"–type)
– the force-free limit is included (low inertia limit of the MHD theory)
– MHD can also describe the back reaction from the matter to the field (this is important even in the superfast part of the regime where $\sigma \gg 1$)

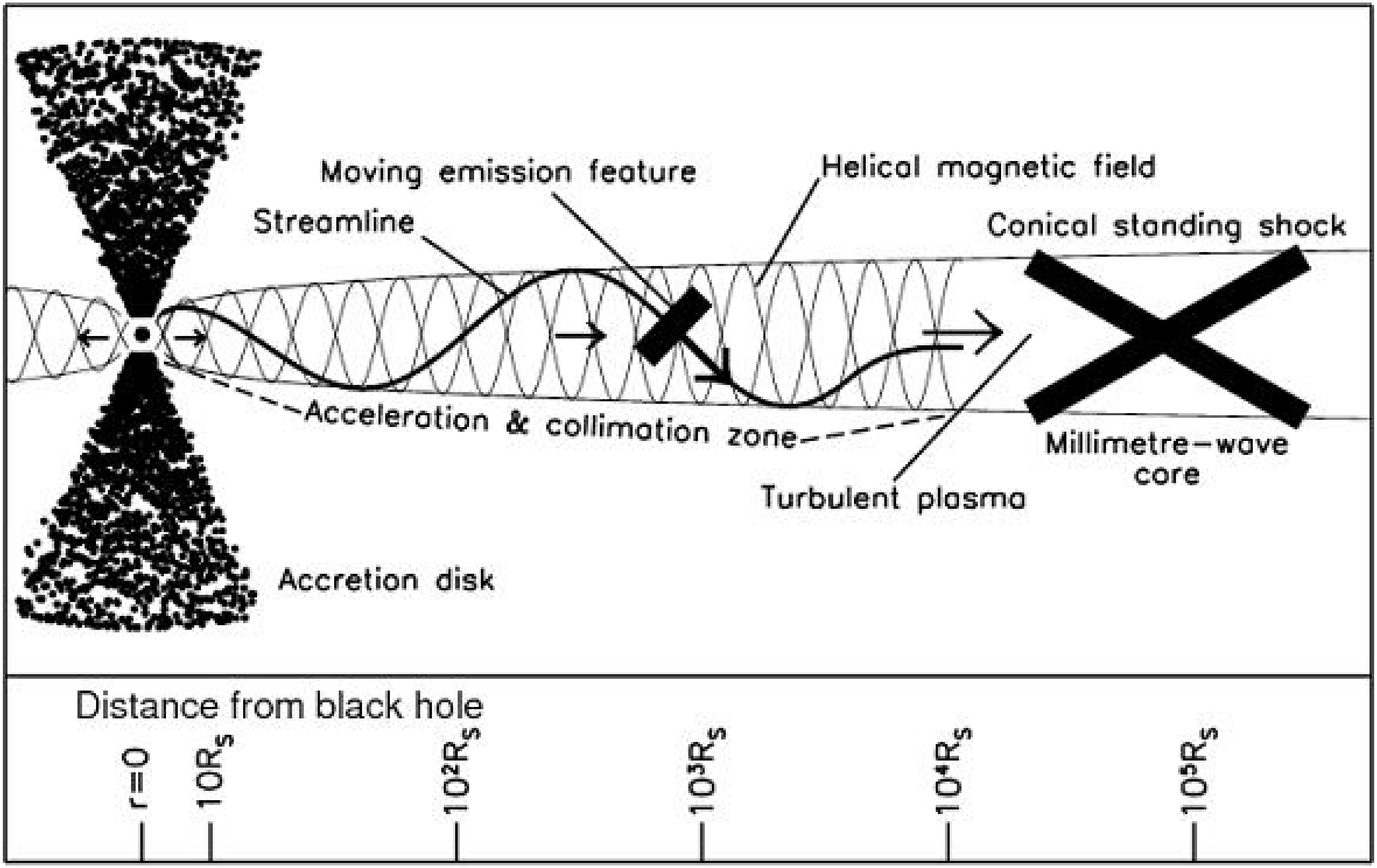
It doesn't matter if the flow is disk-driven or BH-driven. What matters is $\mathcal{E}/Mc^2$ and the field distribution.

Relativistic Magneto-Hydro-Dynamics

- Outflowing matter
- large scale electromagnetic field
- thermal pressure

We need to solve:

- Maxwell + Ohm equations
- mass + entropy conservation
- momentum equation



(from Marscher et al)

Basic questions: bulk acceleration

- thermal (due to ∇P) $\rightarrow$ velocities up to C_s
- magnetocentrifugal (beads on wire - Blandford & Payne)
  - initial half-opening angle $\vartheta > 30^o$
  - the $\vartheta > 30^o$ not necessary for nonnegligible P
  - velocities up to $r_0\Omega$
- relativistic thermal (thermal fireball) gives $\gamma \sim \xi_i$, where $\xi = \frac{\text{enthalpy}}{\text{mass} \times c^2}$.
- magnetic

All acceleration mechanisms can be seen in the energry conservation equation

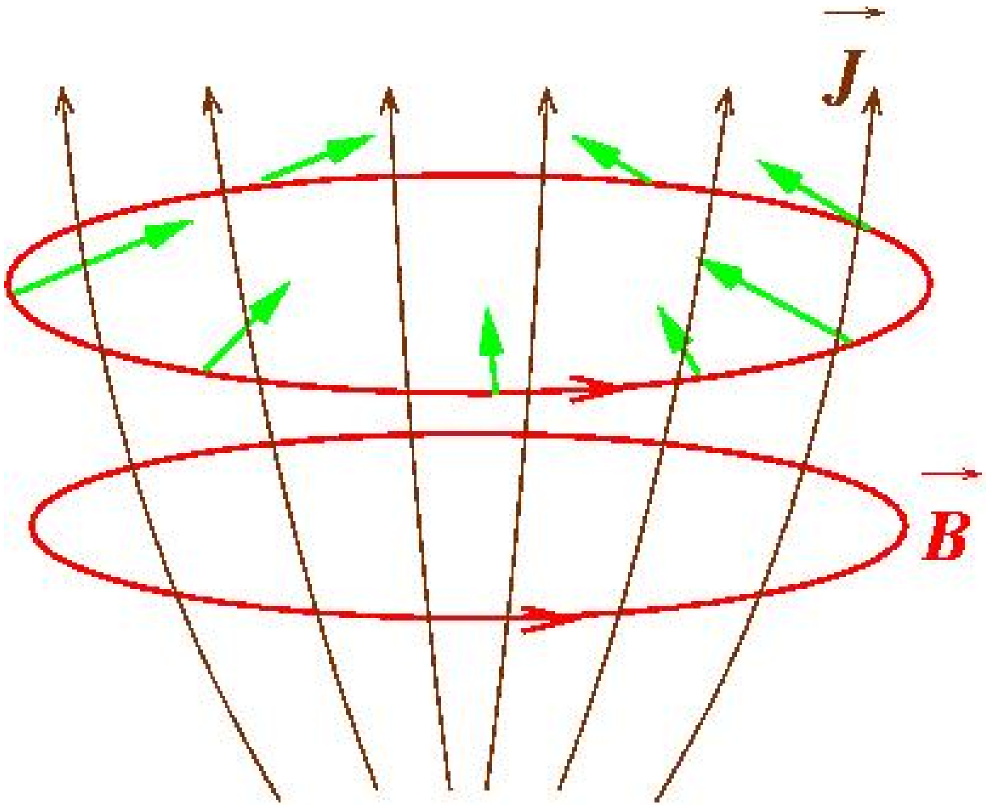
$$\mu = \xi\gamma + \frac{\Omega}{\Psi_A c^2} r|B_\phi| \left(\text{where } \mu = \frac{\frac{dE}{dSdt}}{\frac{dM}{dSdt}c^2} \right)$$

So $\gamma \uparrow$ when $\xi \downarrow$ (thermal, relativistic thermal), or, $r|B_\phi| \downarrow \Leftrightarrow I_p \downarrow$ (magnetocentrifugal, magnetic).

acceleration efficiency $\gamma_\infty/\mu =$?

Basic questions: collimation

hoop-stress:



+ electric force

degree of collimation ?

Role of environment?

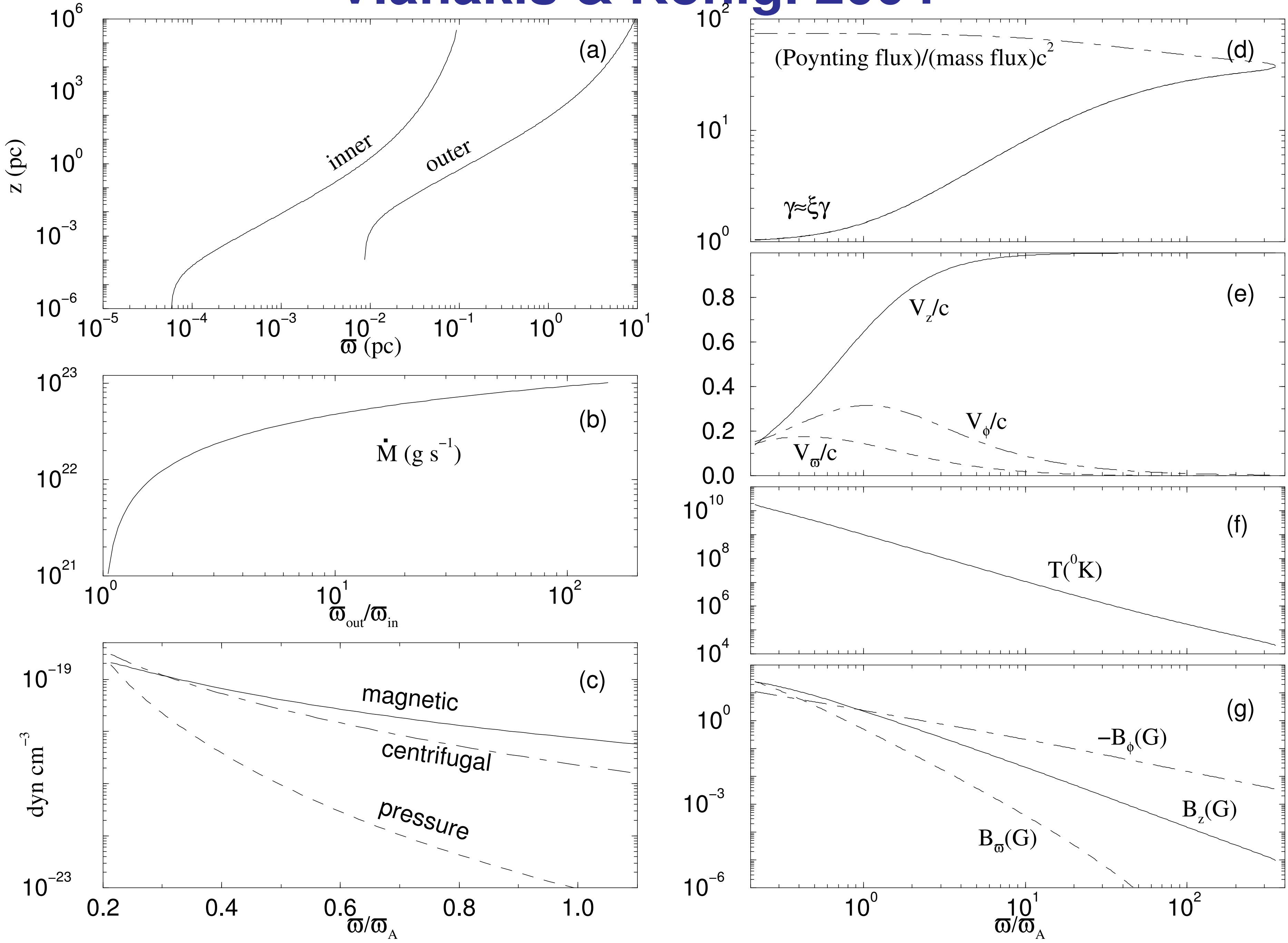
Self-similar relativistic models

- axisymmetry
- steady-state
- ideal MHD (zero resistivity)
- special relativity

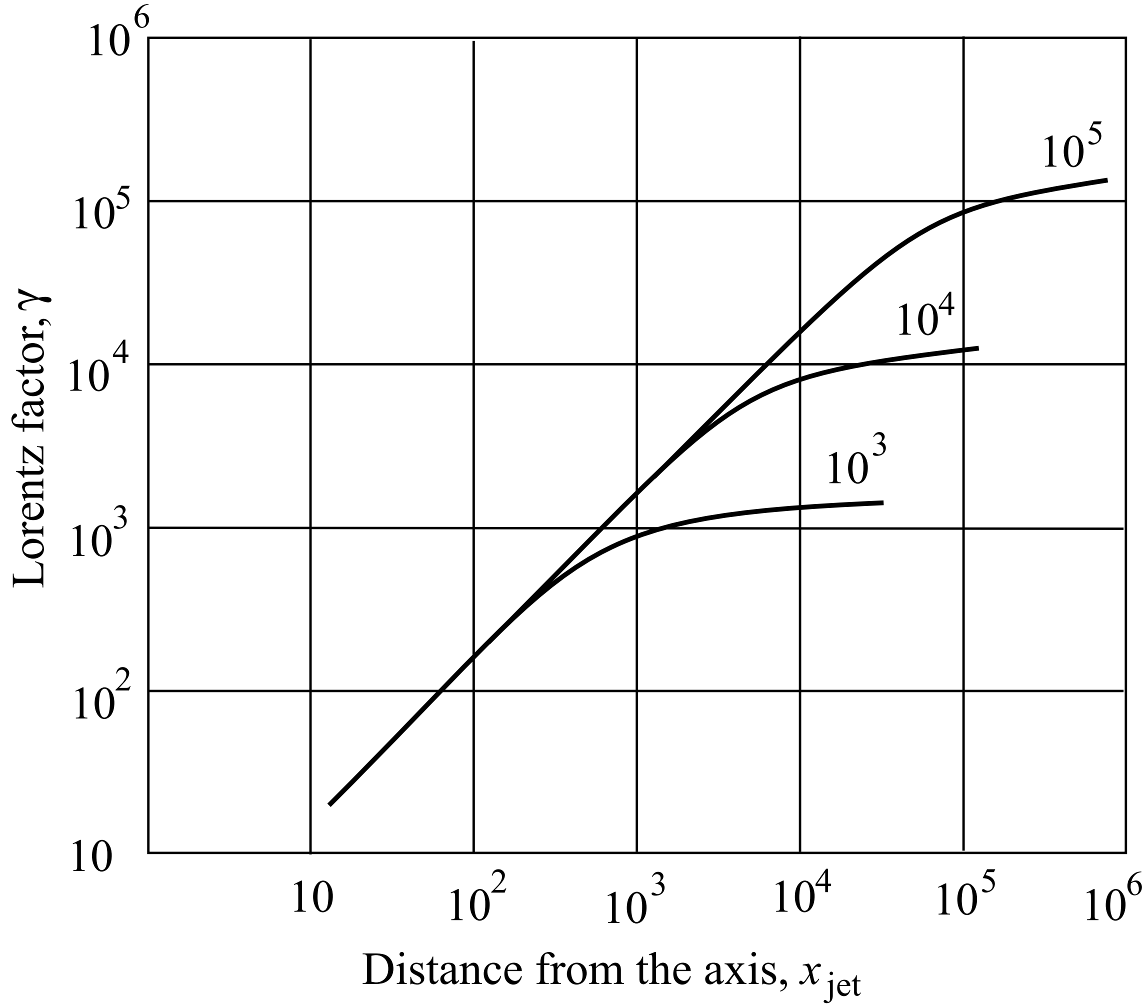
The problem reduces to the two components of the momentum equation: one along the flow (gives γ) and one in the transfield direction (gives the field- and stream-line shape).

- boundary conditions of the form $r^x \times f(\theta)$ lead to separation of variables (radial self-similarity)
  - similar to the nonrelativistic model of Blandford & Payne 1982
  - cold versions of the model: Li et al 1992, Contopoulos 1994

Vlahakis & Königl 2004



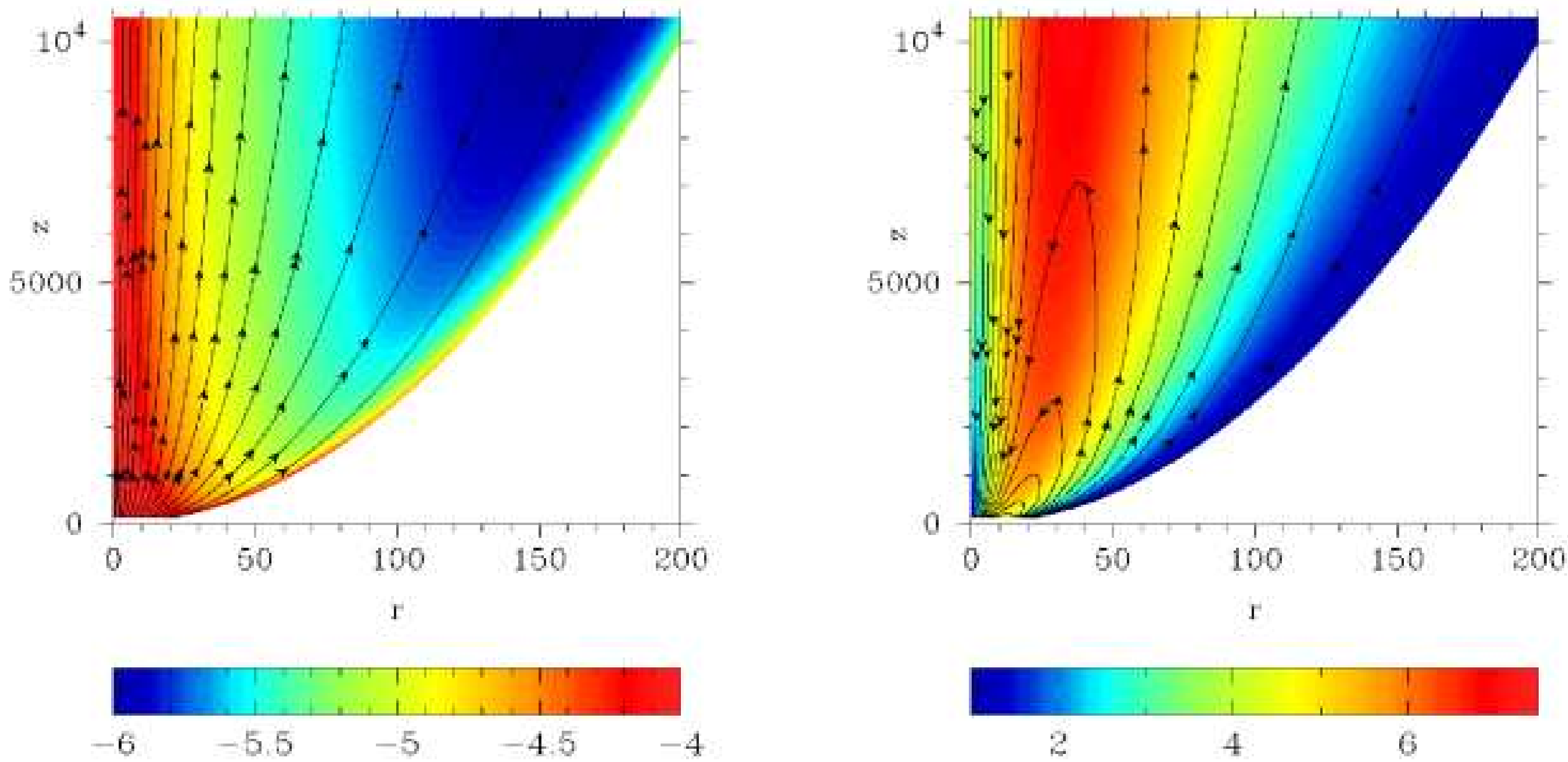
Beskin & Nokhrina 2006



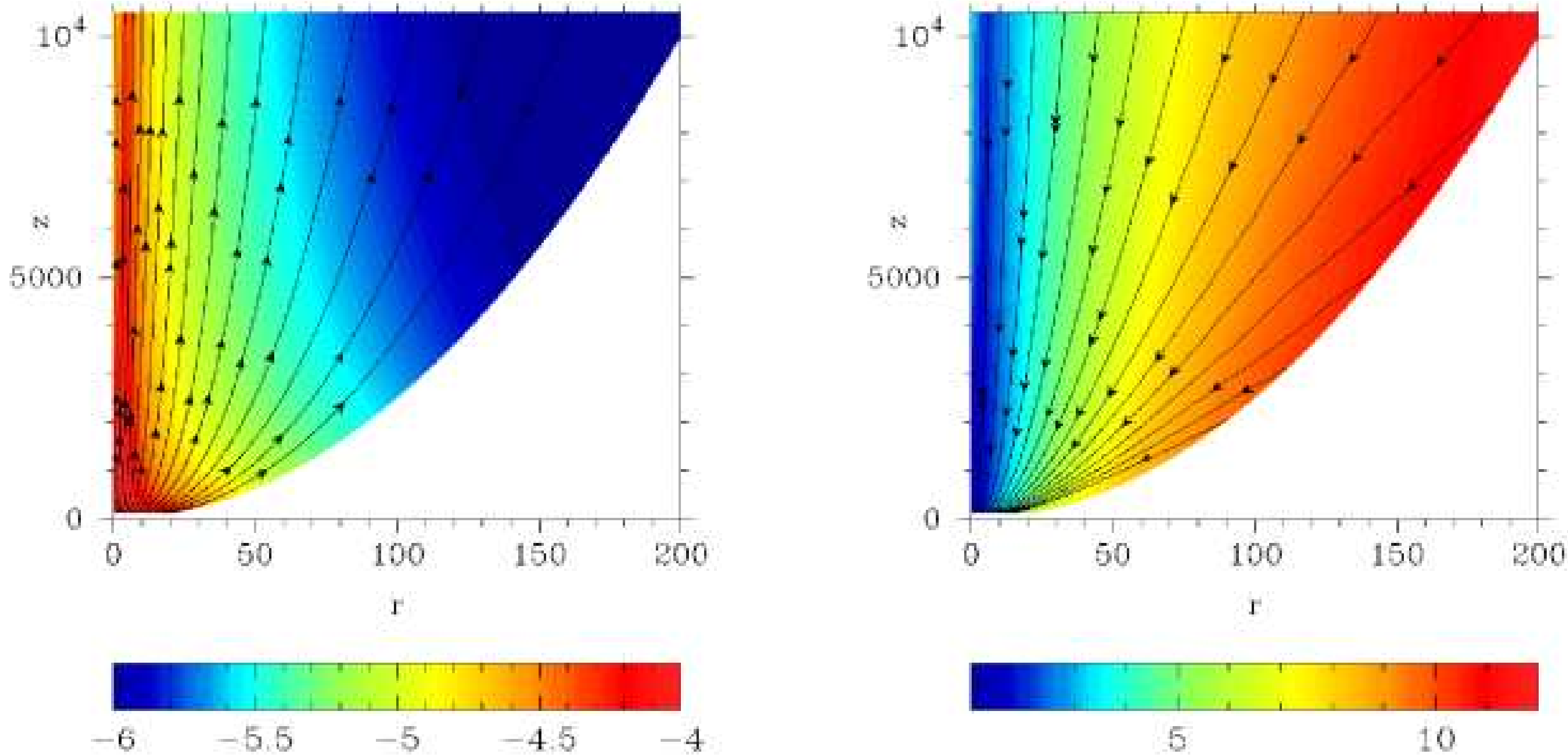
Approximate solutions (based on expansion wrt $2/\mu$ around a flow with parabolic shape). The acceleration is efficient, reaching $\gamma_\infty \sim \mu$.

Simulations of relativistic jets

Komissarov, Barkov, Vlahakis, & Königl (2007)

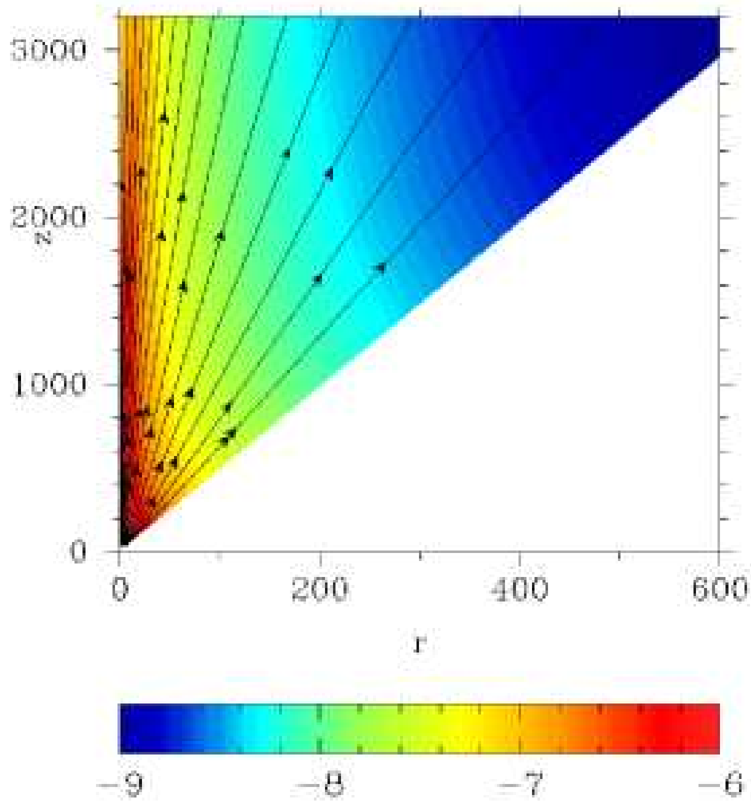


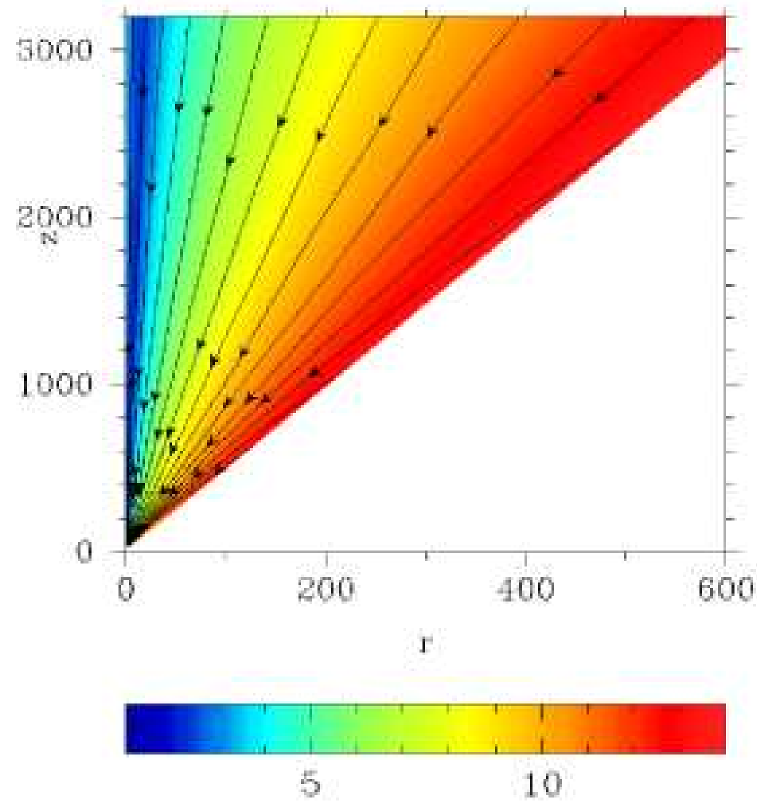
Left panel shows density (colour) and magnetic field lines.
Right panel shows the Lorentz factor (colour) and the current lines.

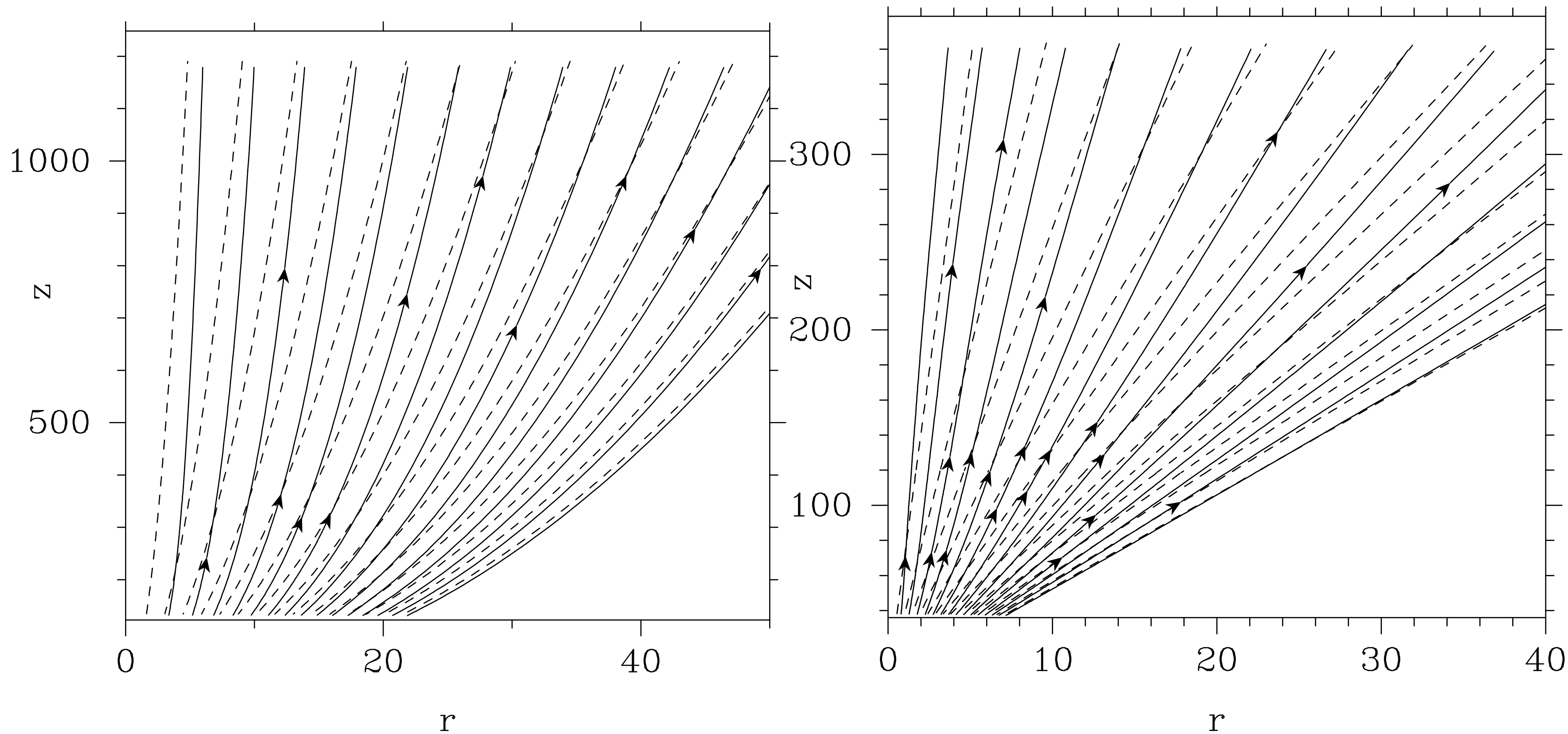


Note the difference in $\gamma(r)$ for constant z.

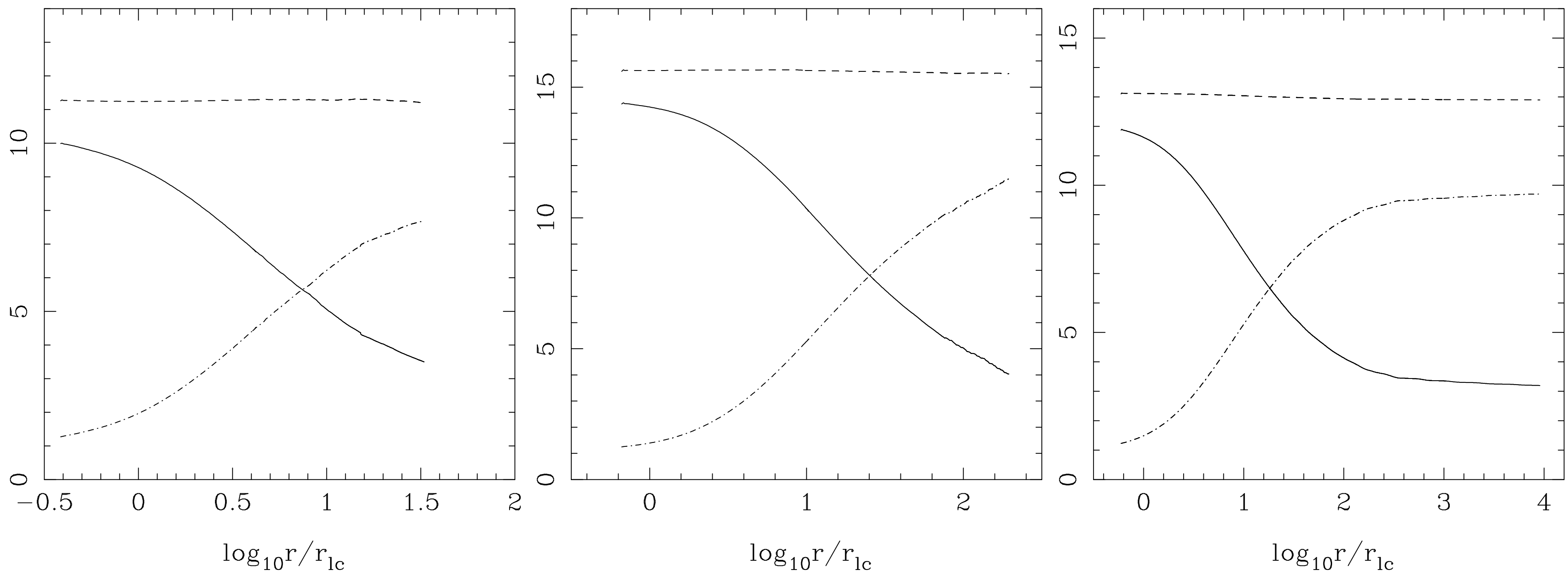
It depends on the current I, which is related to Ω: $$I \approx r^2 B_p \Omega / 2$$


3000
2000
z
1000
0
0
200
400
600
r
−9
−8
−7
−6

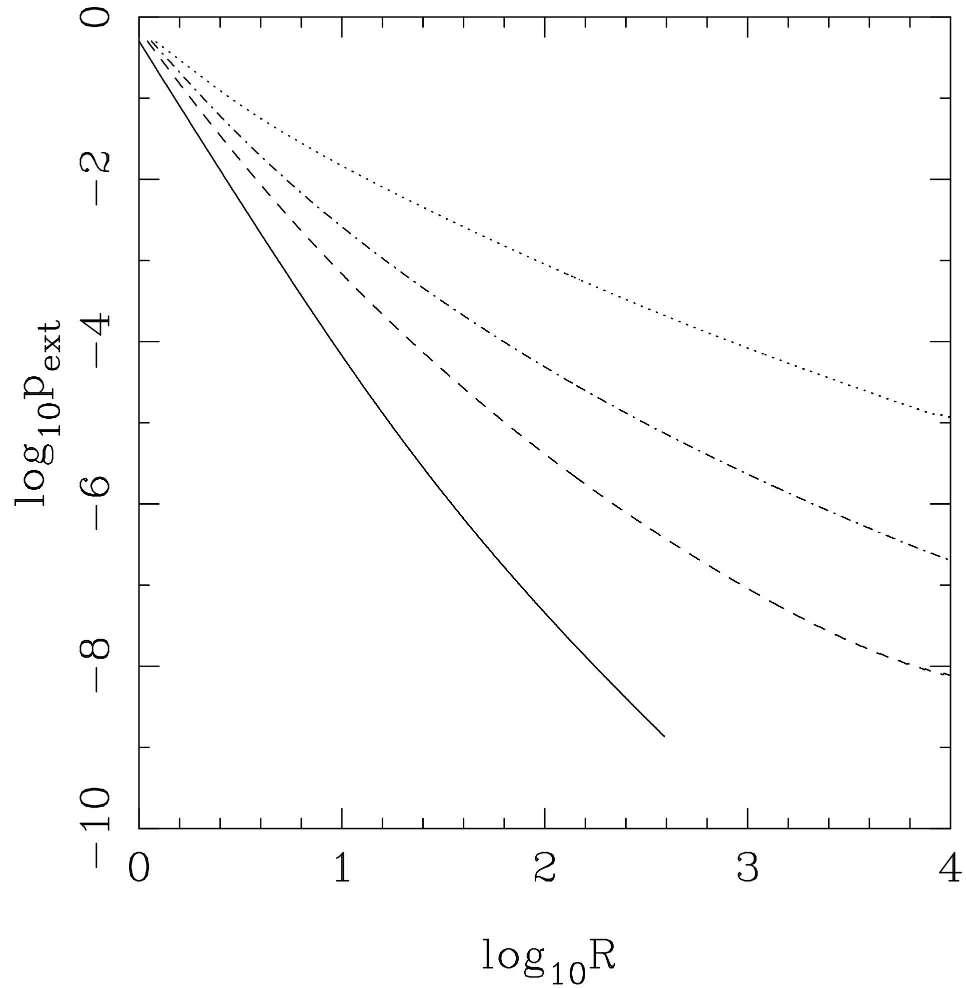

3000
2000
z
1000
0
0
200
400
600
r
5
10



1000
500
z
0
20
40
r
300
200
100
z
0
10
20
30
40
r



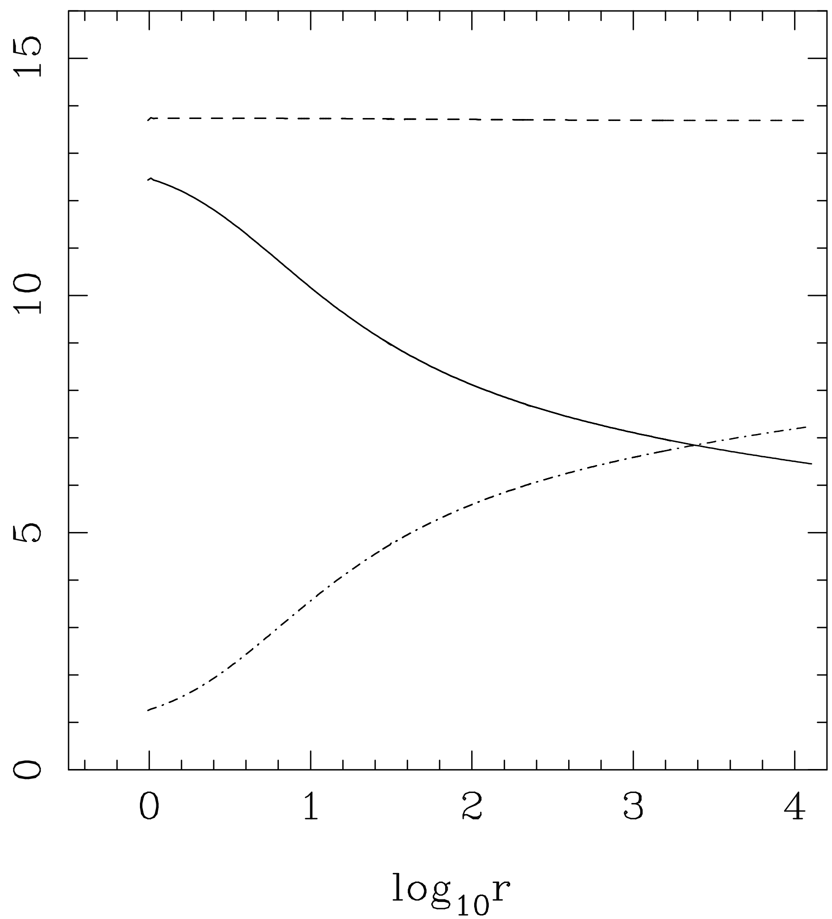
$\gamma\sigma$ (solid line), μ (dashed line) and γ (dash-dotted line) along a magnetic field line as a function of cylindrical radius for models C1 (left panel), C2 (middle panel) and A2 (right panel).

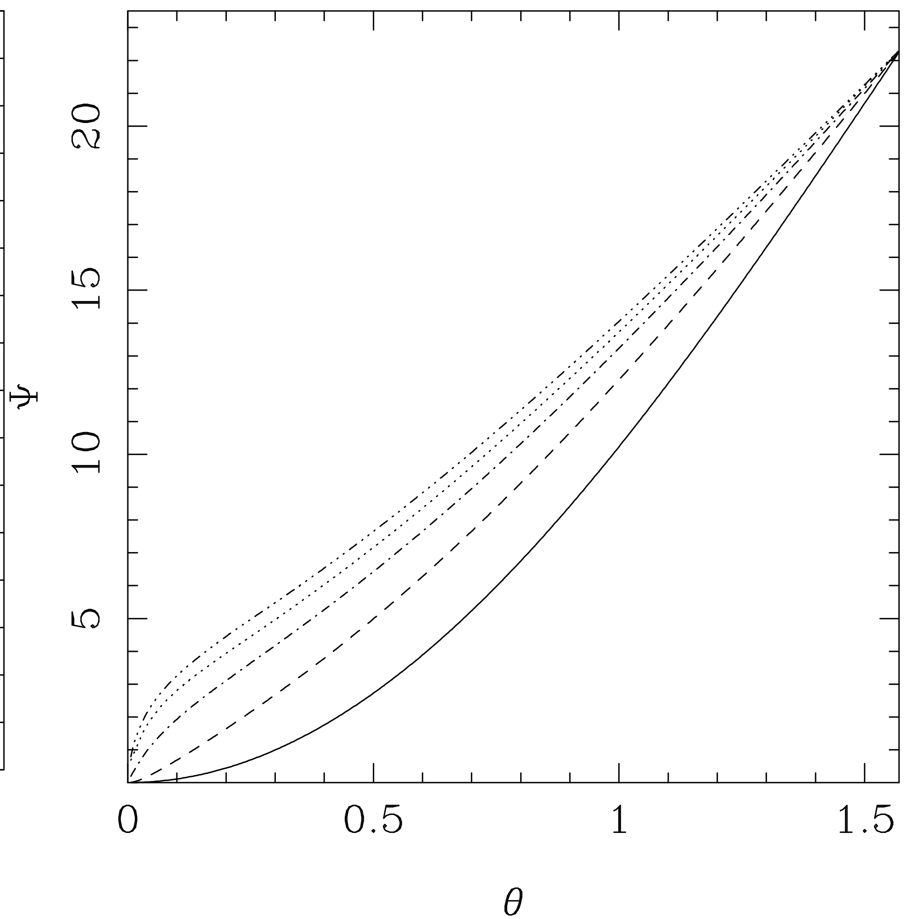


external pressure $P_{ext} = (B^2 - E^2)/8\pi$

solid line: $p_{\rm ext} \propto R^{-3.5}$ for $z \propto r$, dashed line: $p_{\rm ext} \propto R^{-2}$ for $z \propto r^{3/2}$, dash-dotted line: $p_{\rm ext} \propto R^{-1.6}$ for $z \propto r^2$, dotted line: $p_{\rm ext} \propto R^{-1.1}$ for $z \propto r^3$

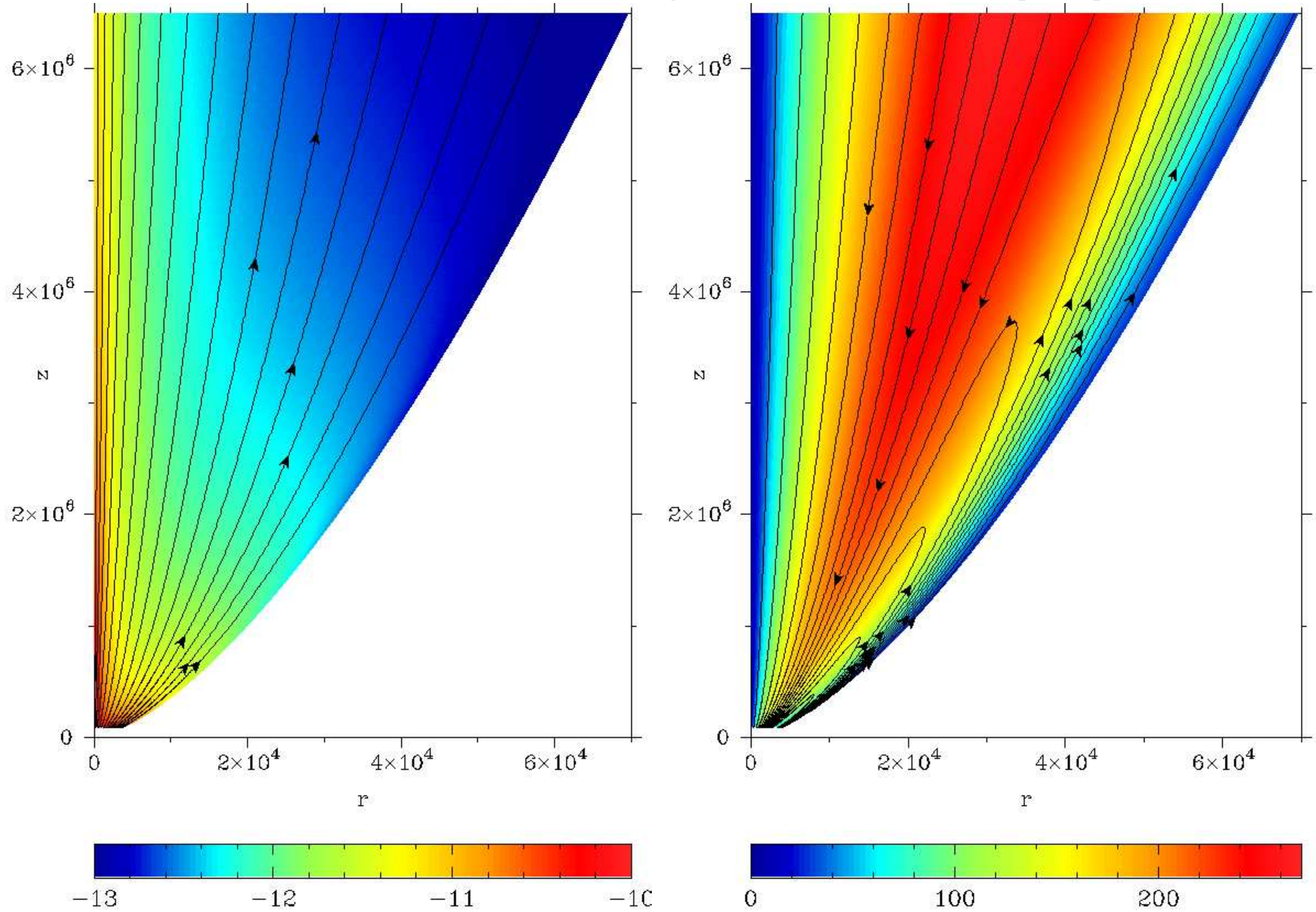
(without a wall)





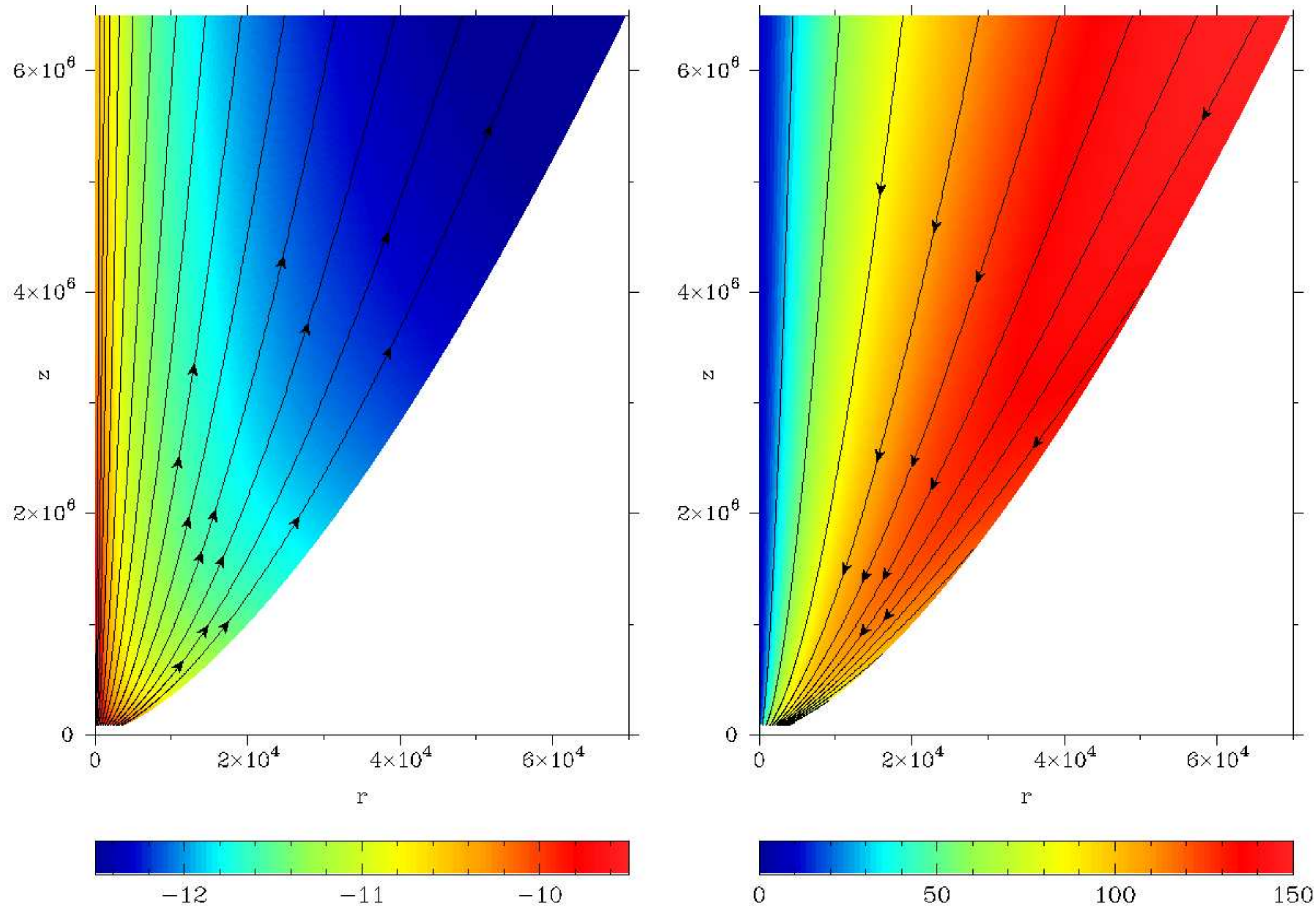
e.g. for $\Psi = 10$, $\vartheta = 57^{\rm o} \rightarrow 40^{\rm o}$
while for $\Psi = 5$, $\vartheta = 40^{\rm o} \rightarrow 15^{\rm o}$

Komissarov, Vlahakis, Königl, & Barkov, in preparation

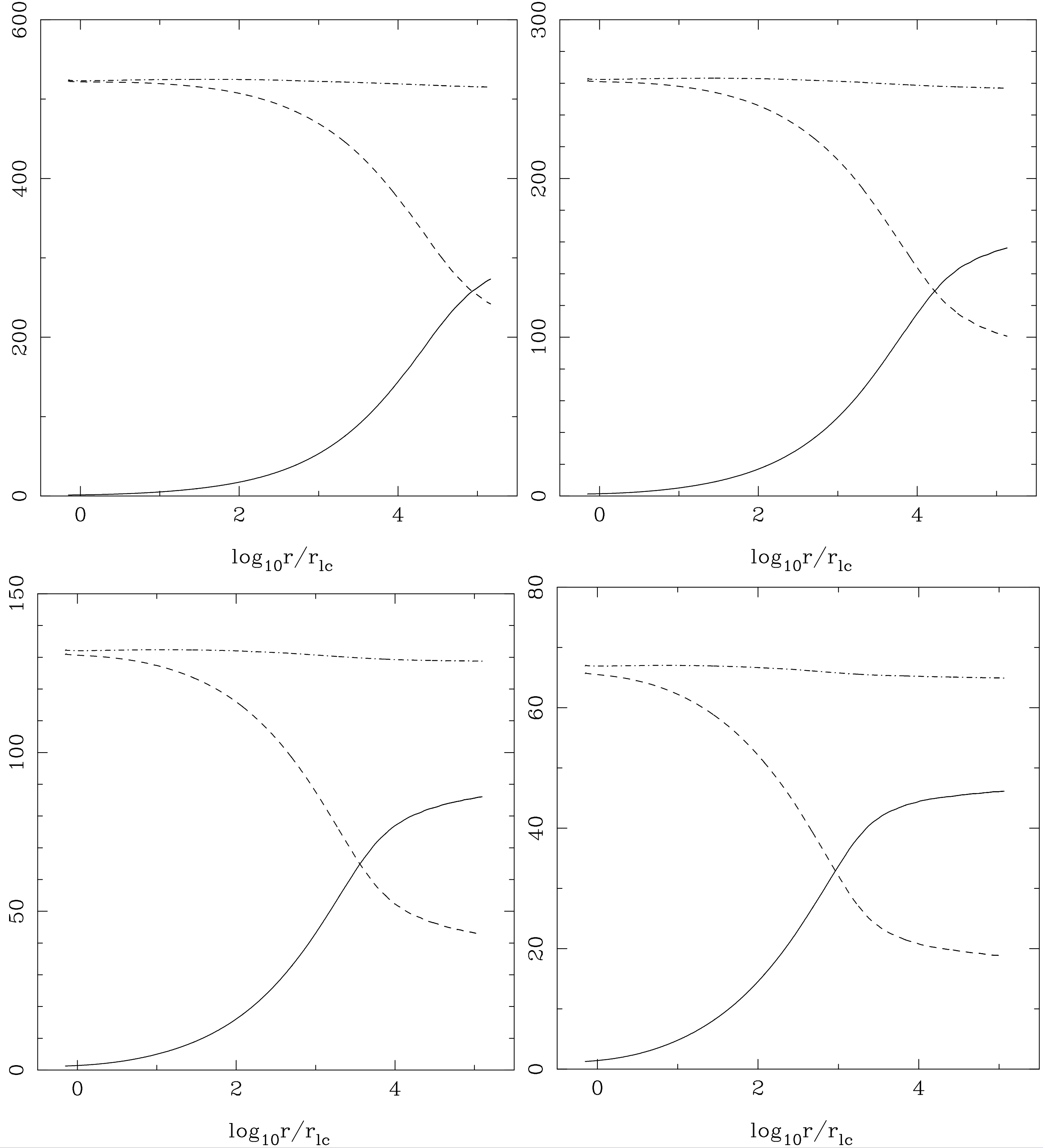


left: density/field lines, right: Lorentz factor/current lines (wall shape $z \propto r^{1.5}$)

Differential rotation → slow envelope



Uniform rotation $\rightarrow \gamma$ increases with r


0
200
400
600
0
2
4
log10r/rlc
0
100
200
300
0
2
4
log10r/rlc
0
50
100
150
0
2
4
log10r/rlc
0
20
40
60
80
0
2
4
log10r/rlc

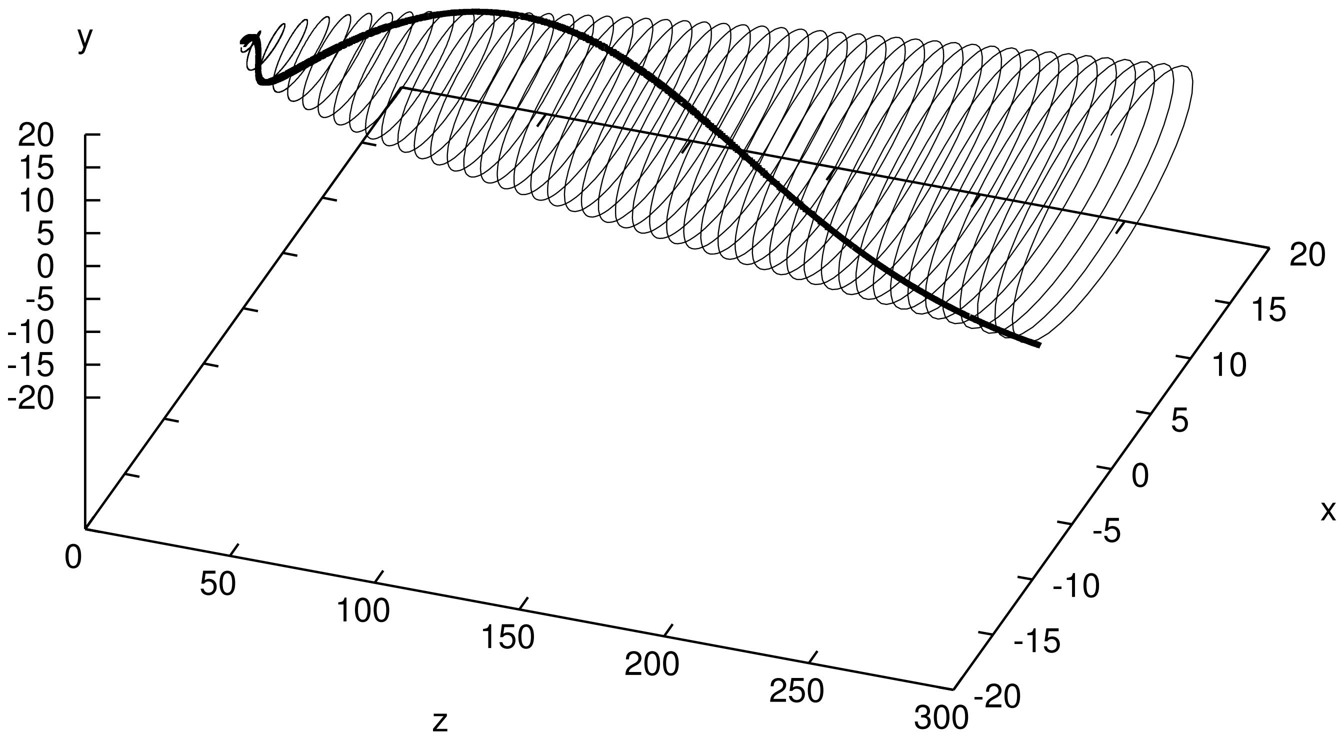
Jet kinematics

- due to precession? (e.g., Lobanov & Roland)
- instabilities? (e.g., Hardee, Meier)

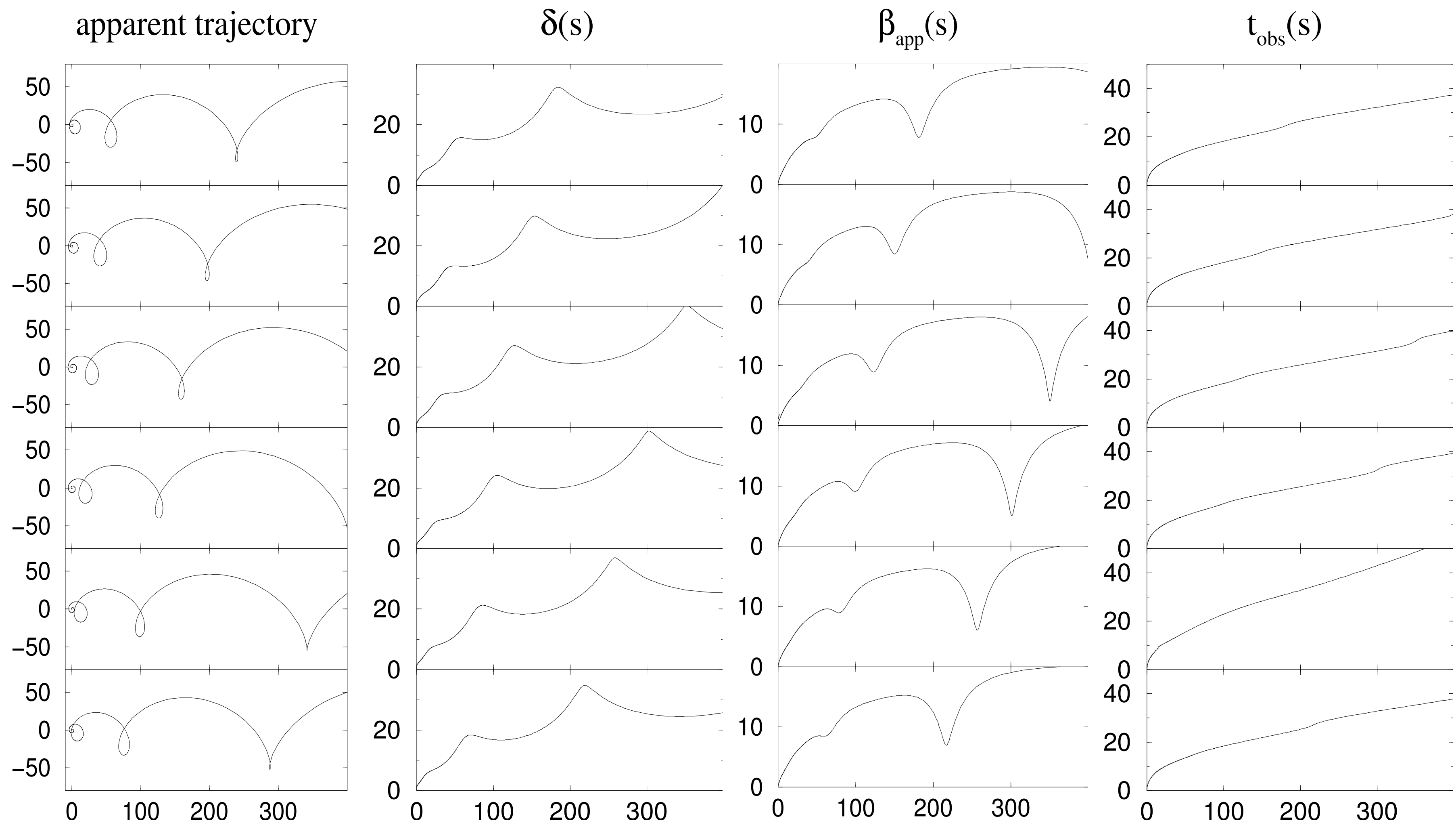
bulk jet flow may play at least a partial role

to explore this possibility, we used the relativistic self-similar model (Vlahakis & Königl 2004)

since the model gives the velocity (3D) field, we can follow the motion of a part of the flow

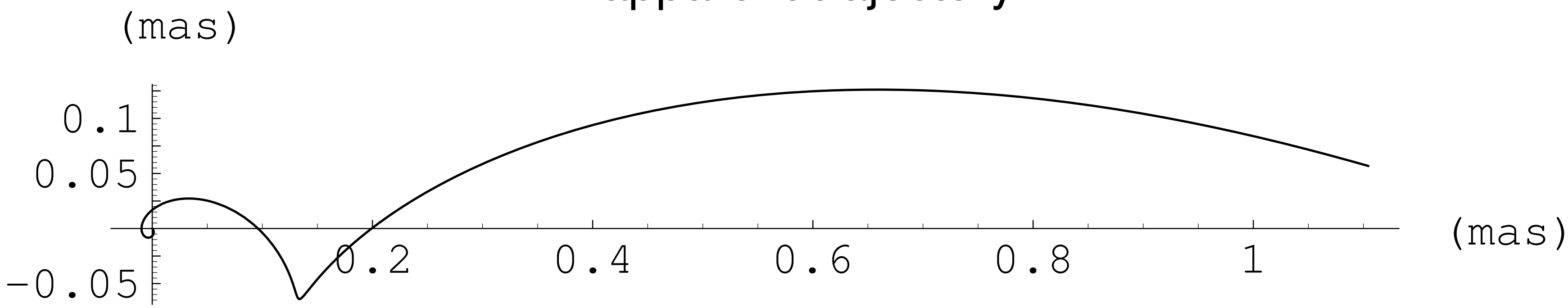

y
20
15
10
5
0
-5
-10
-15
-20
0
50
100
150
200
250
300
z
-20
-15
-10
-5
0
5
10
15
20
x

For $\theta_{\rm obs} = 1^{\rm o}$ and $\phi_o = 0^{\rm o}$, $60^{\rm o}$, $120^{\rm o}$, $180^{\rm o}$, $240^{\rm o}$, $300^{\rm o}$ (from top to bottom):

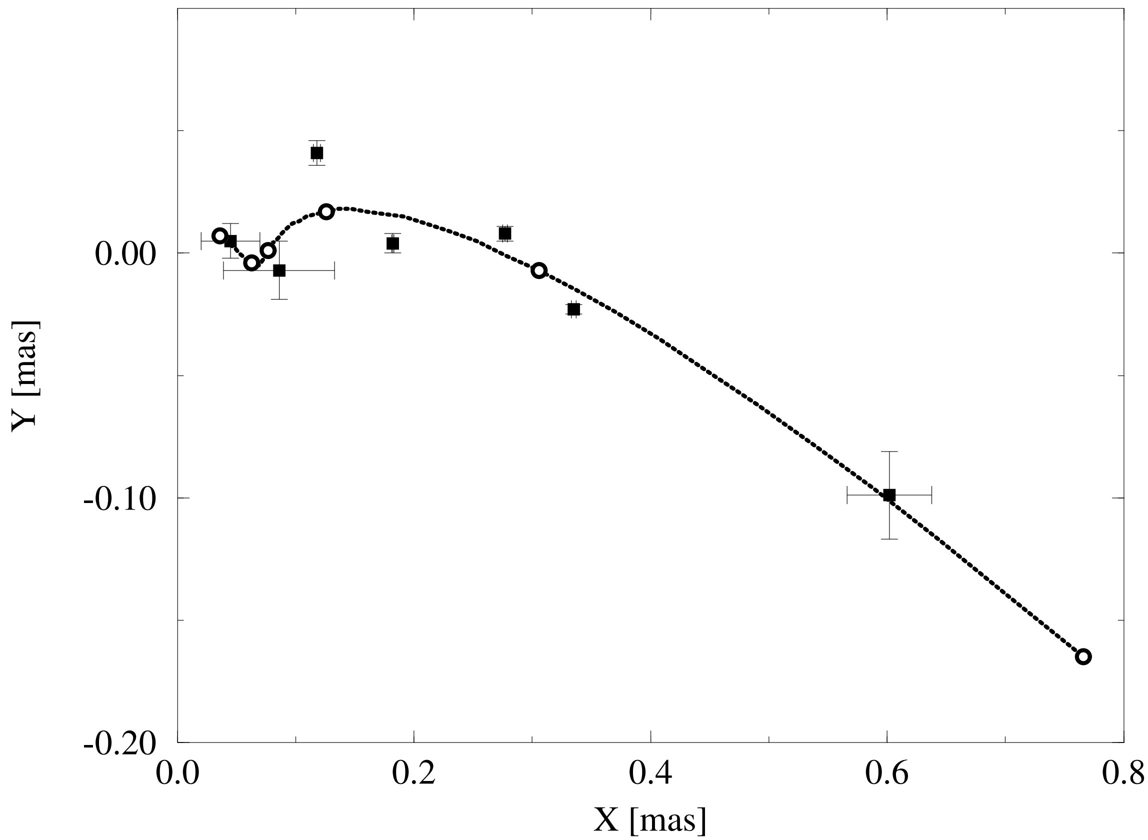


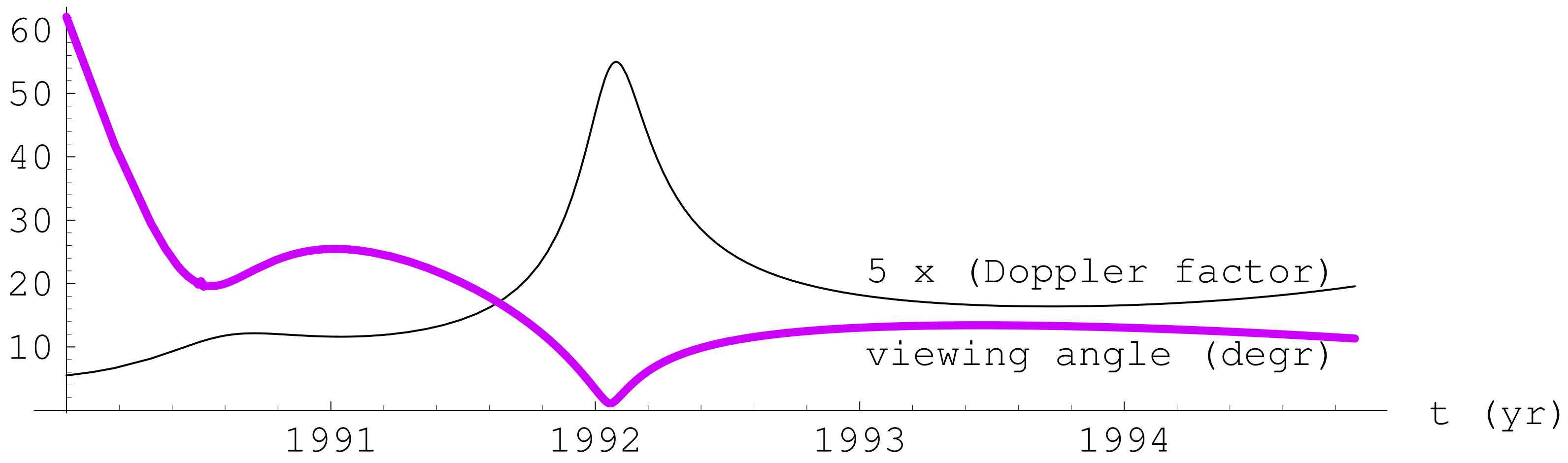
best-fit to Unwin et al results: $r_o \approx 2 \times 10^{16}$cm, ϕ_o=180^o, $\theta_{\rm obs}$=9^o

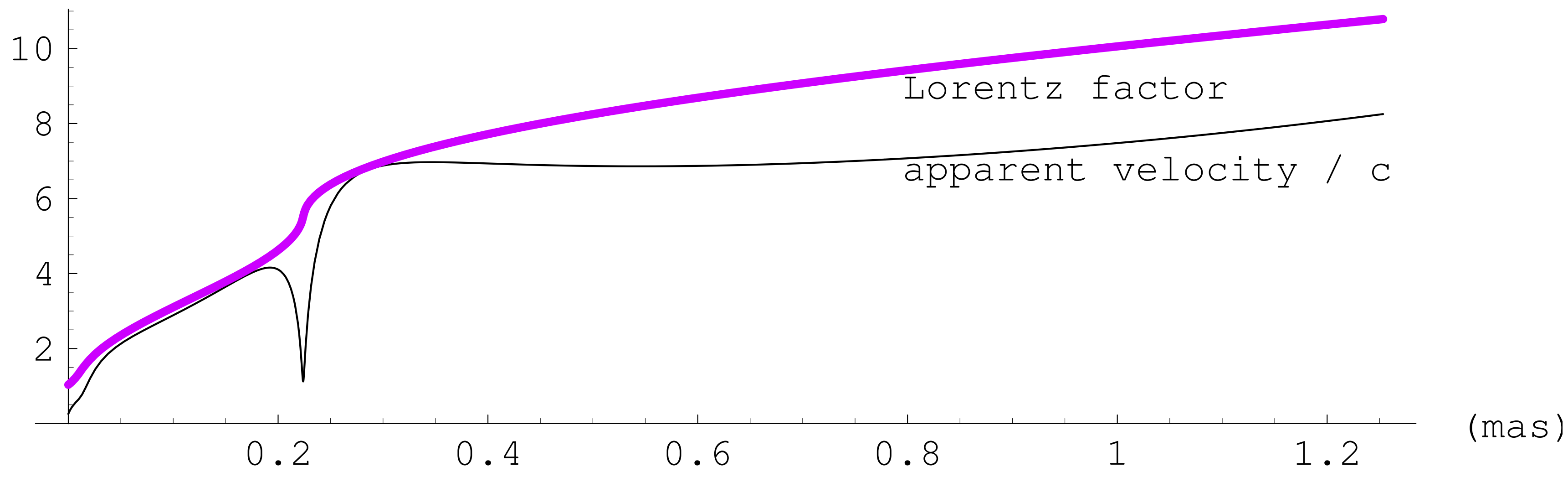
apparent trajectory



Trajectory of C7




60
50
40
30
20
10
5 x (Doppler factor)
viewing angle (degr)
t (yr)
1991
1992
1993
1994


10
8
6
4
2
Lorentz factor
apparent velocity / c
(mas)
0.2
0.4
0.6
0.8
1
1.2

Angular momentum extraction

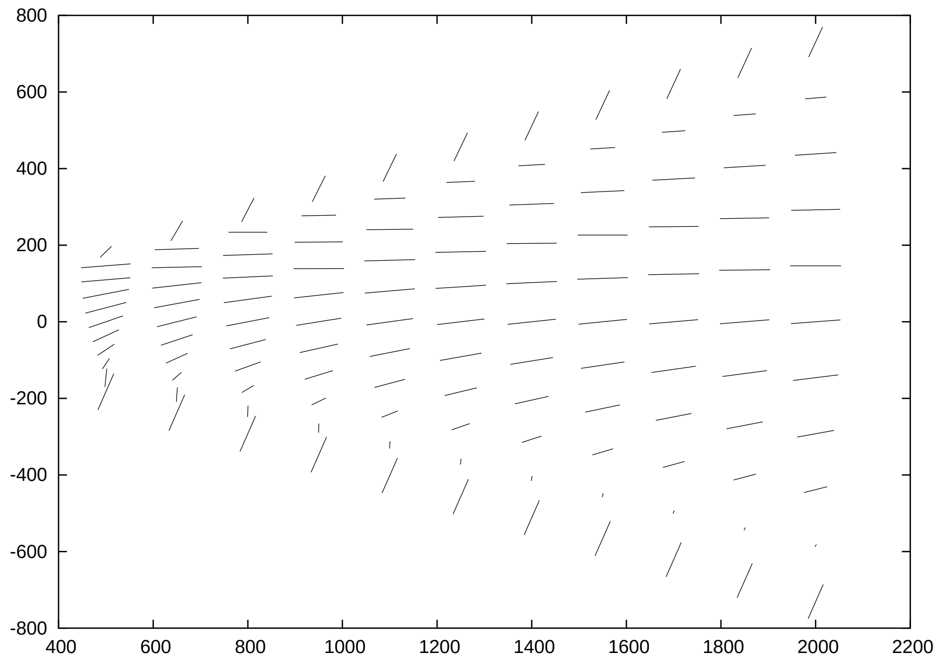
$L = \mu \Omega r_{\rm A}^2$ where $\mu = \dfrac{\dfrac{dE}{dSdt}}{\dfrac{dM}{dSdt}c^2}$ = maximum Lorentz factor

So rate of angular momentum $= \mu \Omega r_{\rm A}^2 \dot{M}_j$
(initially carried by the field).

In the disk, rate $= \Omega_{\rm K} r_0^2 \dot{M}_a$.
If these are equal, $\dfrac{\dot{M}_j}{\dot{M}_a} = \dfrac{r_0^2}{\mu r_{\rm A}^2} \dfrac{\Omega_{\rm K}}{\Omega}$.
(This is equivalent to $\dfrac{dE}{dt} \equiv \mu \dot{M}_j c^2 = \dfrac{GM\dot{M}_a}{r_0} \dfrac{\Omega_{\rm K}}{\Omega}$.)

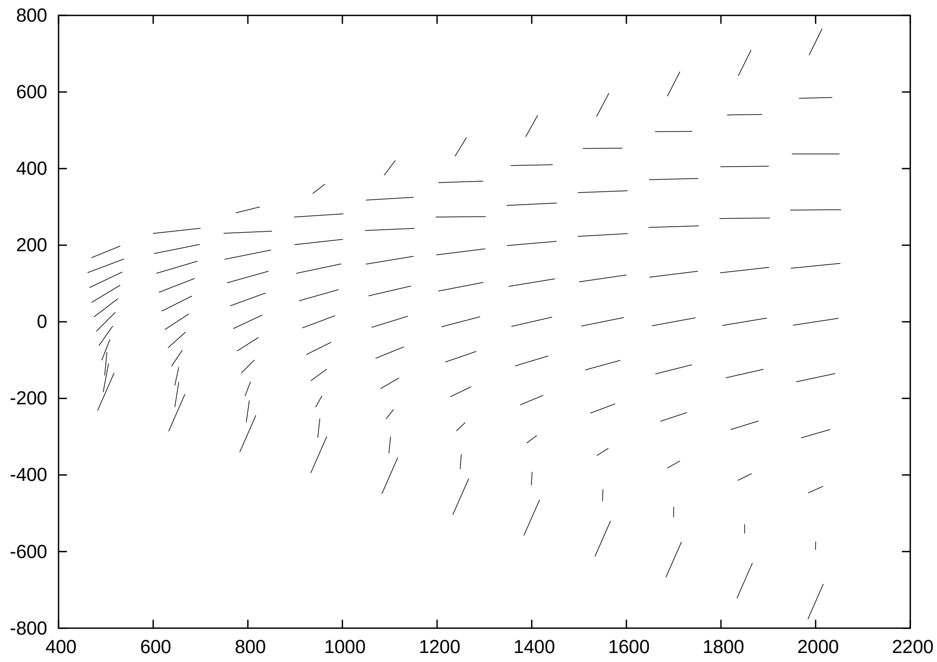
- in YSO confirmed by HST observations! (Woitas et al 2005)

Polarization maps



$\gamma = 10$, $\theta_{obs} = 1/2\gamma$, jet half-opening=1 degree, pitch angle at a reference diastance = 0.1 degrees
electron's energy spectrum $\propto \gamma_e^{-2.4}$

Polarization maps



$\gamma = 10$, $\theta_{obs} = 1/2\gamma$, jet half-opening=1 degree, pitch angle at a reference diastance = 0.05 degrees
electron's energy spectrum $\propto \gamma_e^{-2.4}$

Summary

⋆ Magnetic driving provides a viable explanation of the dynamics of relativistic jets:

- bulk acceleration up to Lorentz factors corresponding to rough equipartition between kinetic and Poynting fluxes
  $\gamma_\infty \approx 0.5 \frac{\mathcal{E}}{Mc^2}$
- collimation
- the intrinsic rotation of jets could be related to the observed kinematics and to the rotation of EVPA (Marscher et al 2008, Nature)

⋆ The paradigm of MHD jets works in a similar way in all astrophysical jets

The ideal MHD equations

Maxwell:

$$\nabla \cdot \mathbf{B} = 0\,, \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{c\partial t}\,, \nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{\partial \mathbf{E}}{c\partial t}\,, \nabla \cdot \mathbf{E} = \frac{4\pi}{c}J^0$$

Ohm: $\mathbf{E} + \frac{\mathbf{V}}{c} \times \mathbf{B} = 0$

mass conservation: $\left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right)(\gamma\rho_0) + \gamma\rho_0 \nabla \cdot \mathbf{V} = 0\,,$

energy $U_\mu T^{\mu\nu}_{,\nu} = 0$: $\left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right)\left(\frac{P}{\rho_0^\Gamma}\right) dt = 0$

momentum $T^{\nu i}_{,\nu} = 0$:

$$\gamma\rho_0 \left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right)(\xi\gamma\mathbf{V}) = -\nabla P + \frac{J^0\mathbf{E} + \mathbf{J} \times \mathbf{B}}{c}$$

The ideal, steady, GRMHD equations

Maxwell:

$$\nabla \cdot \boldsymbol{B} = 0\,, \nabla \times (h\boldsymbol{E}) = 0\,, \nabla \times (h\boldsymbol{B}) = \frac{4\pi h}{c}\boldsymbol{J}\,, \nabla \cdot \boldsymbol{E} = \frac{4\pi}{c}J^0$$

Ohm: $\boldsymbol{E} + \frac{\boldsymbol{V}}{c} \times \boldsymbol{B} = 0$

mass conservation: $\nabla \cdot (h\gamma n\boldsymbol{V}) = 0\,,$

energy $U_\mu T^{\mu\nu}_{;\nu} = 0$: $n\boldsymbol{V} \cdot \nabla w = \boldsymbol{V} \cdot \nabla P$

momentum $T^{\nu i}_{;\nu} = 0$:

$$\gamma n(\boldsymbol{V} \cdot \nabla)\left(\frac{\gamma w\boldsymbol{V}}{c^2}\right) = -\gamma^2 nw\nabla \ln h - \nabla P + \frac{J^0\boldsymbol{E} + \boldsymbol{J} \times \boldsymbol{B}}{c}$$