Magnetic Driving of AGN Jets

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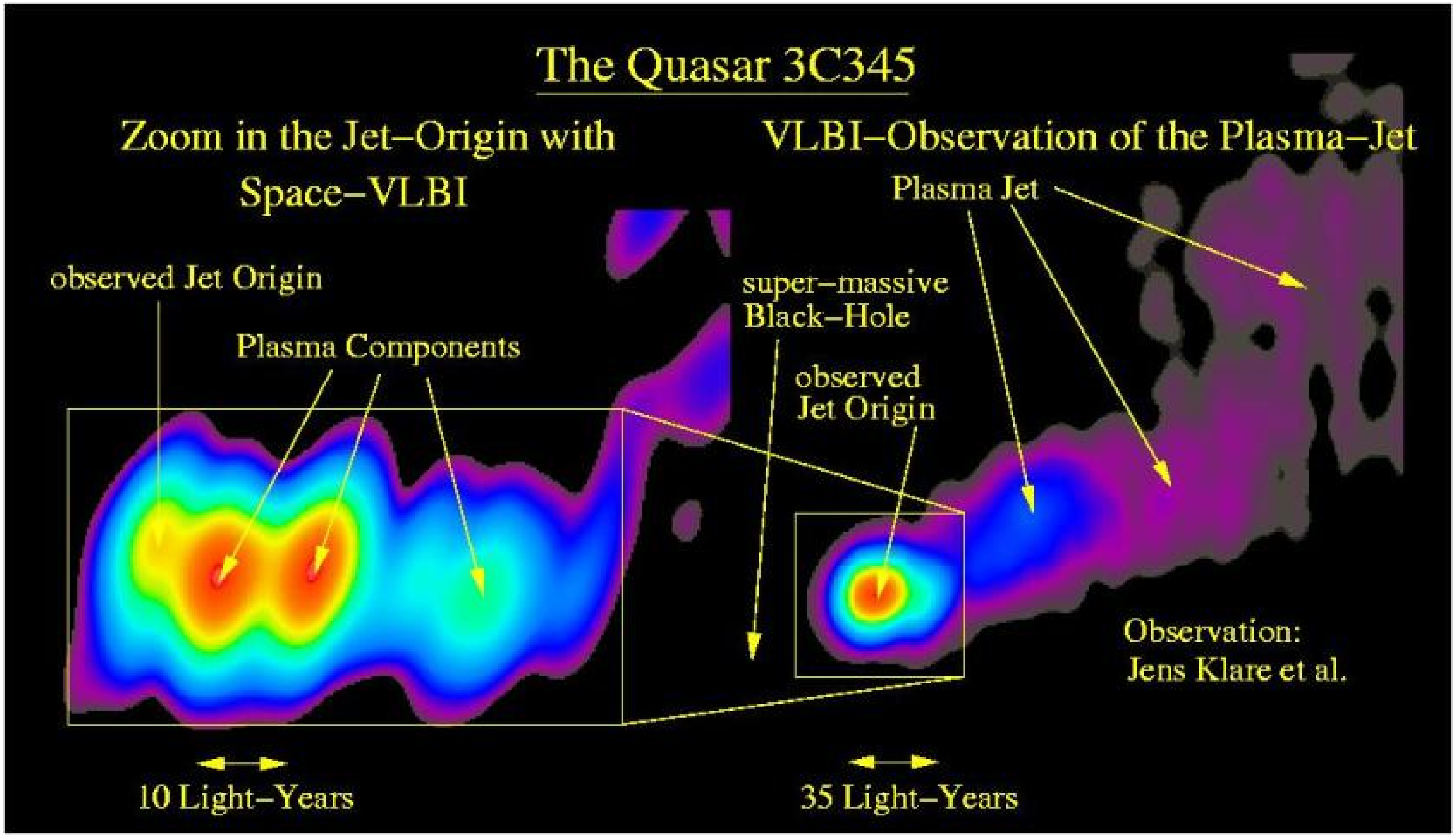
Outline

- observations
- inner jet magneto-hydro-dynamics
  - acceleration and collimation
  - jet kinematics

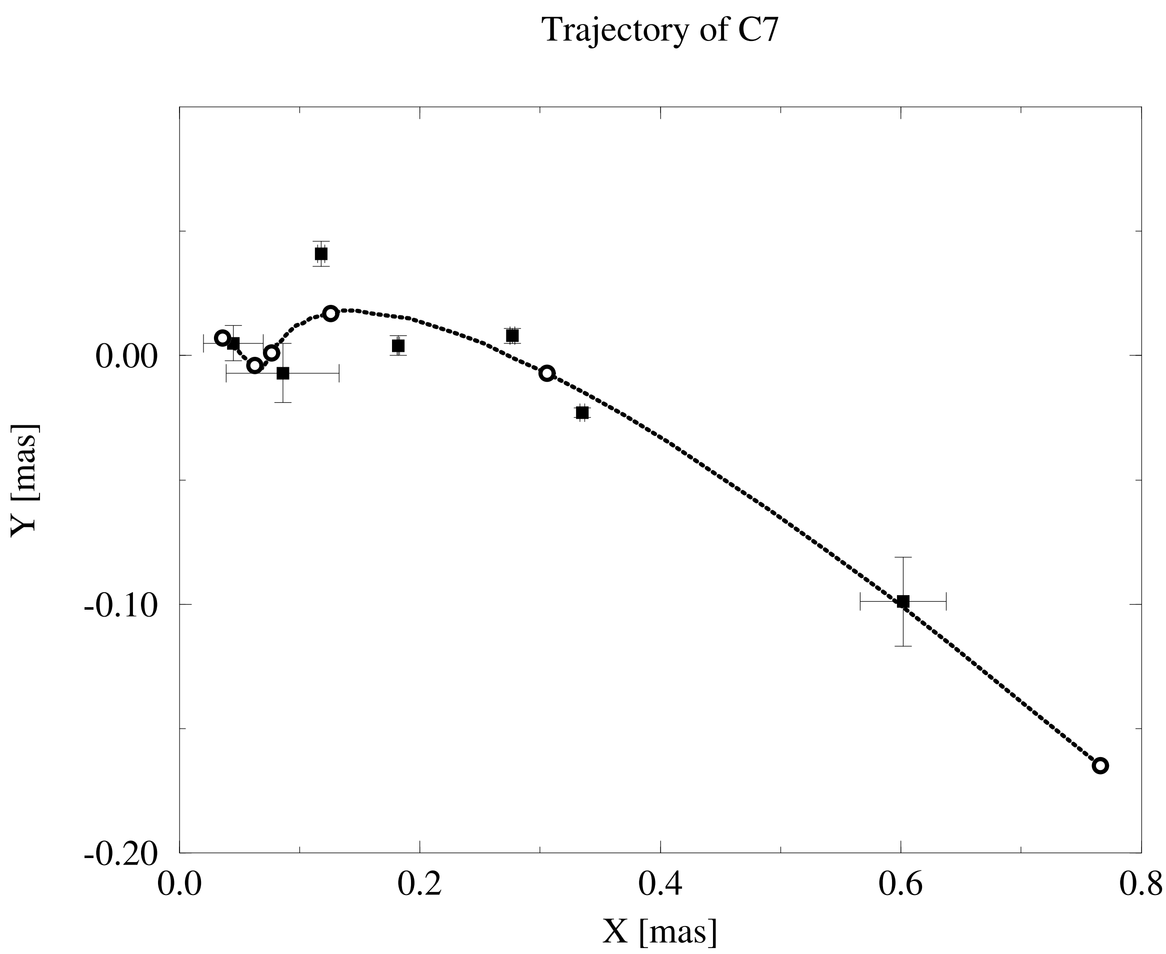


(credit: Klare et al)

The plasma components move with superluminal apparent speeds

They travel on curved trajectories

The trajectories differ from one component to the other



(from Lobanov's PhD thesis)

Implications on the dynamics

- Superluminal apparent motion $\Rightarrow \beta_{\rm app}(t_{\rm obs}) = \dfrac{\beta \sin\theta_V}{1-\beta\cos\theta_V}$
  (small θ_V, β close to 1)

- **If** we know $\delta(t_{\rm obs}) \equiv \dfrac{1}{\gamma\,(1-\beta\cos\theta_V)}$
  we find $\beta(t_{\rm obs})$, $\gamma(t_{\rm obs})$, $\theta_V(t_{\rm obs})$

- Compare radio- and high energy emission (SSC) $\Rightarrow \delta$ (e.g., Unwin et al 1997)

- For the C7 component of 3C 345 Unwin et al (1997) inferred that the Doppler factor 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_V changes from ≈ 2 to $\approx 10^o$)

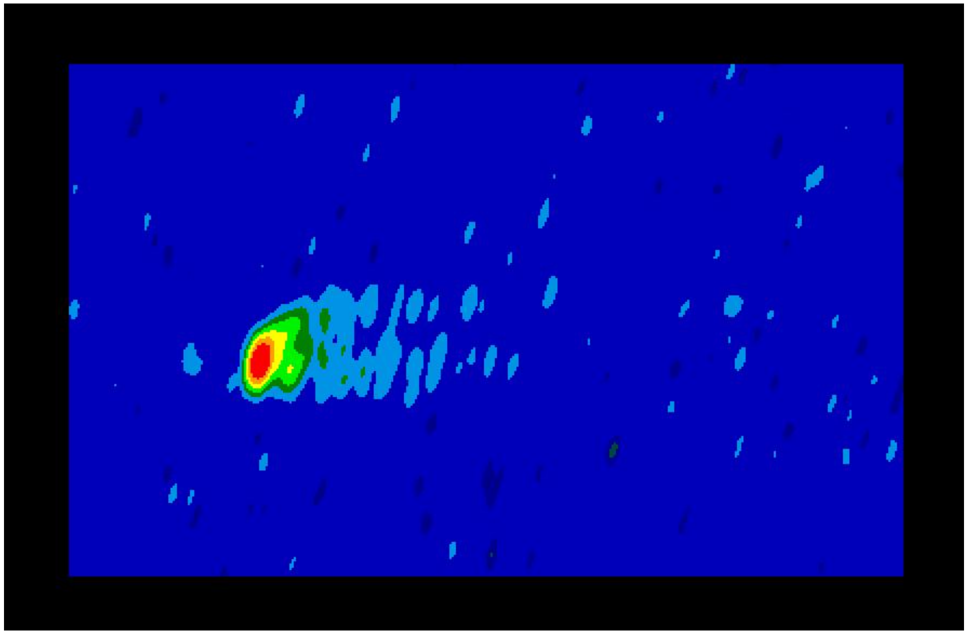
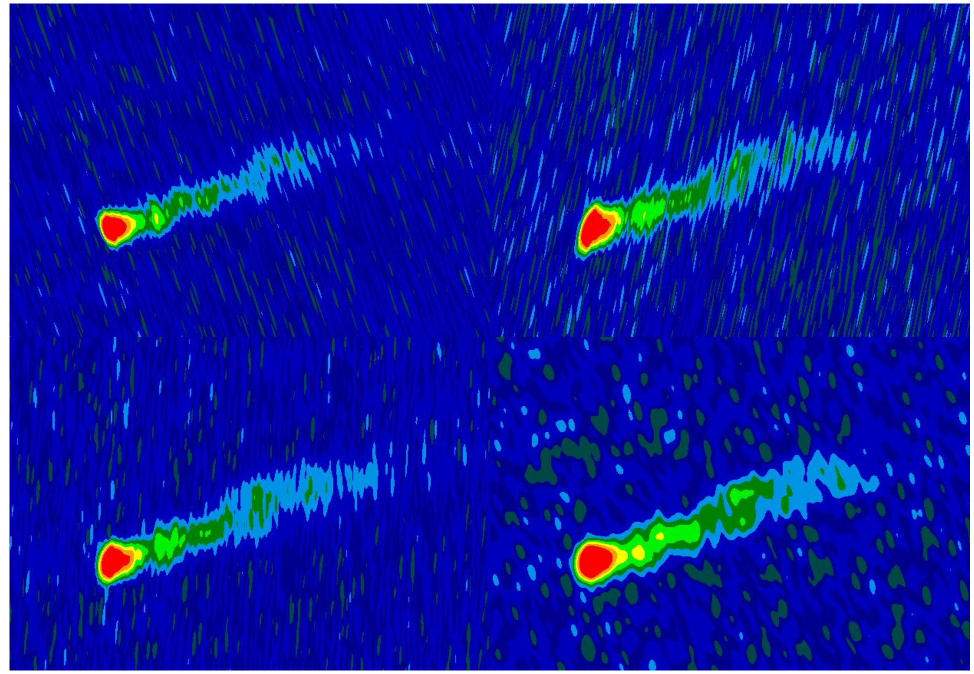
- Piner et al (2003) inferred an acceleration from $\gamma = 8$ at $r < 5.8$pc to $\gamma = 13$ at $r \approx 17.4$pc in 3C 279 using a similar approach

- A more general argument (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)

(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.

(from Junor, Biretta, & Livio 1999)

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

Relativistic Magneto-Hydro-Dynamics

- Outflowing matter
- large scale electromagnetic field
- thermal pressure

We need to solve:

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

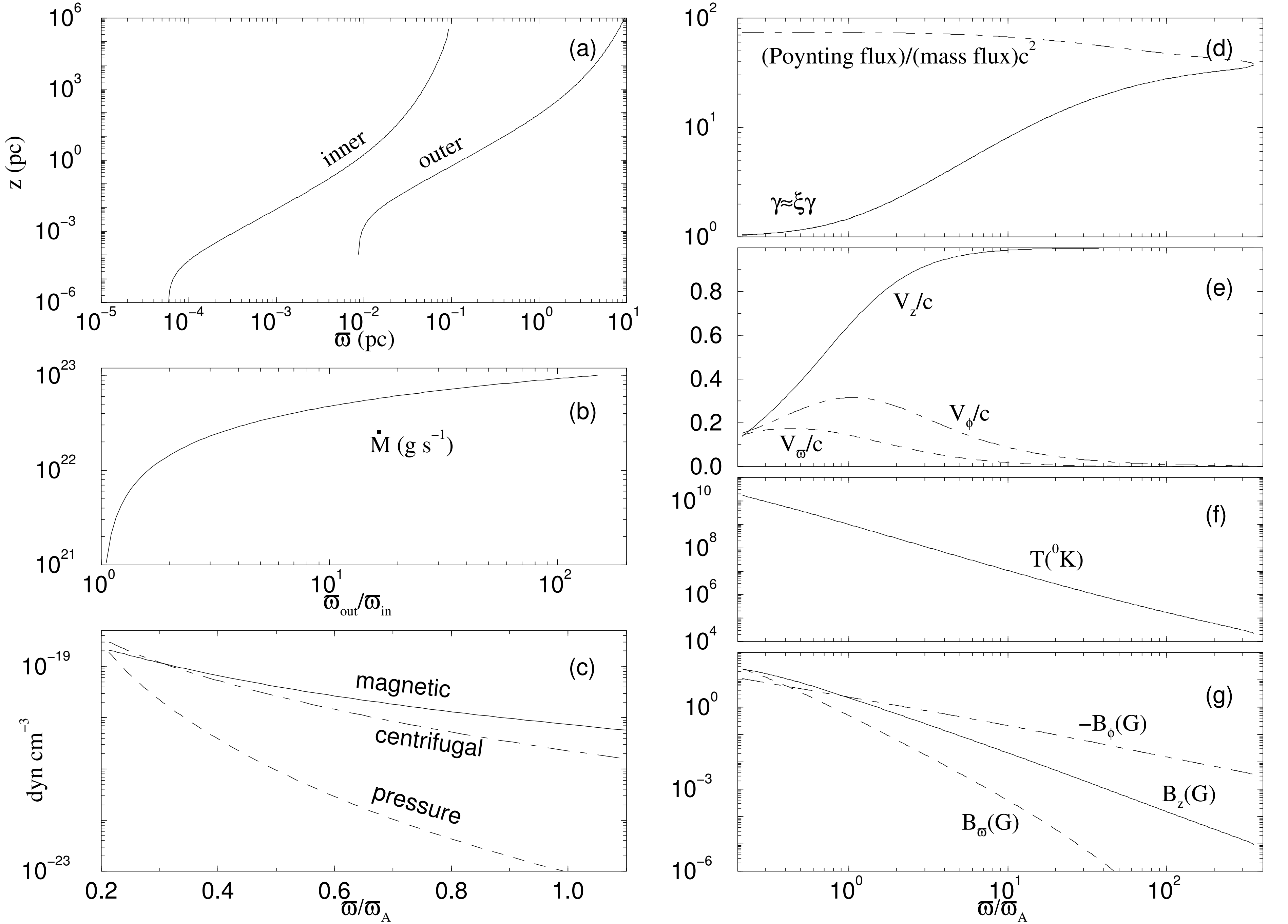
Self-similar, relativistic, disk-wind models

- axisymmetry
- steady-state
- ideal MHD (no 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, ApJ (2004) – application to 3C345



Jet kinematics

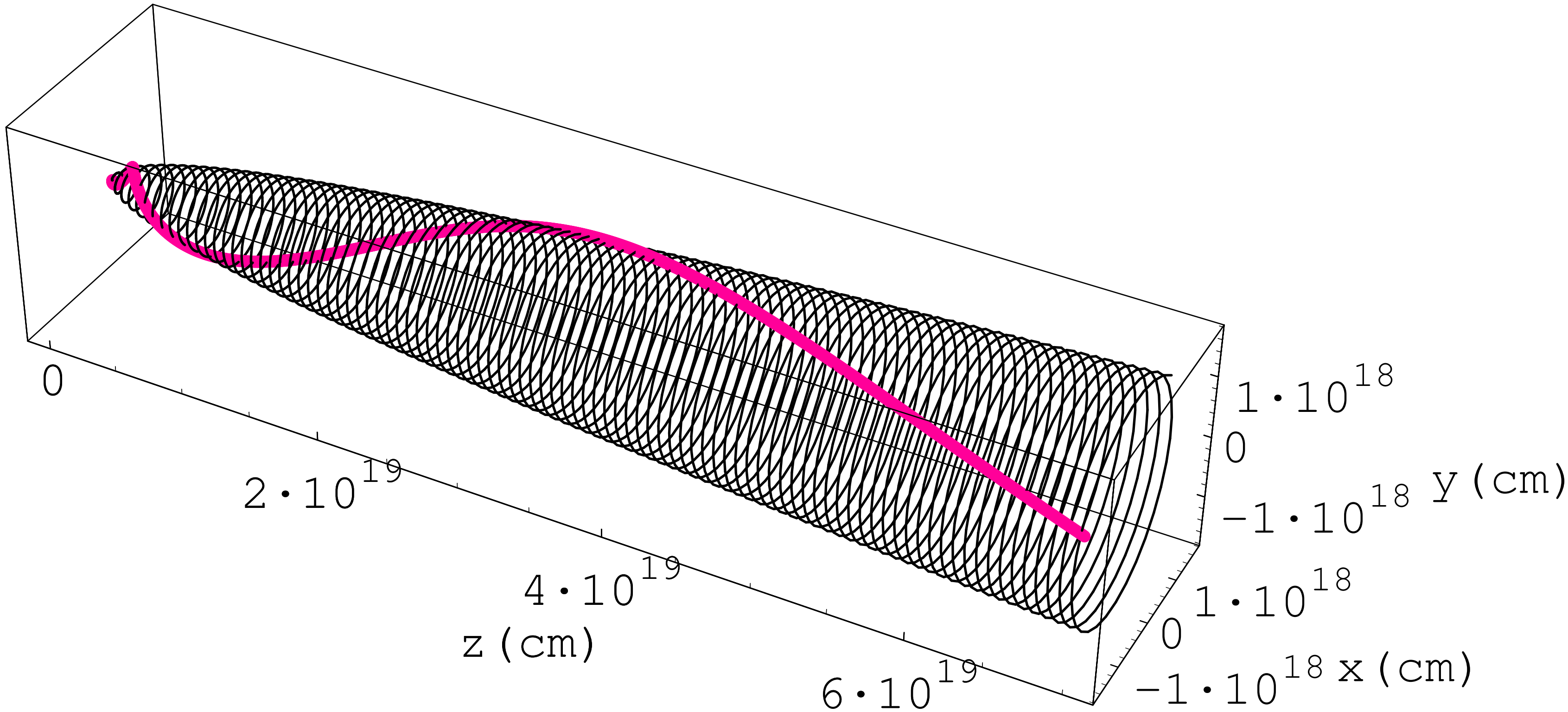
- due to precession? (e.g., Caproni & Abraham)
- instabilities? (e.g., Hardee, Meier)

bulk jet flow may play at least a partial role

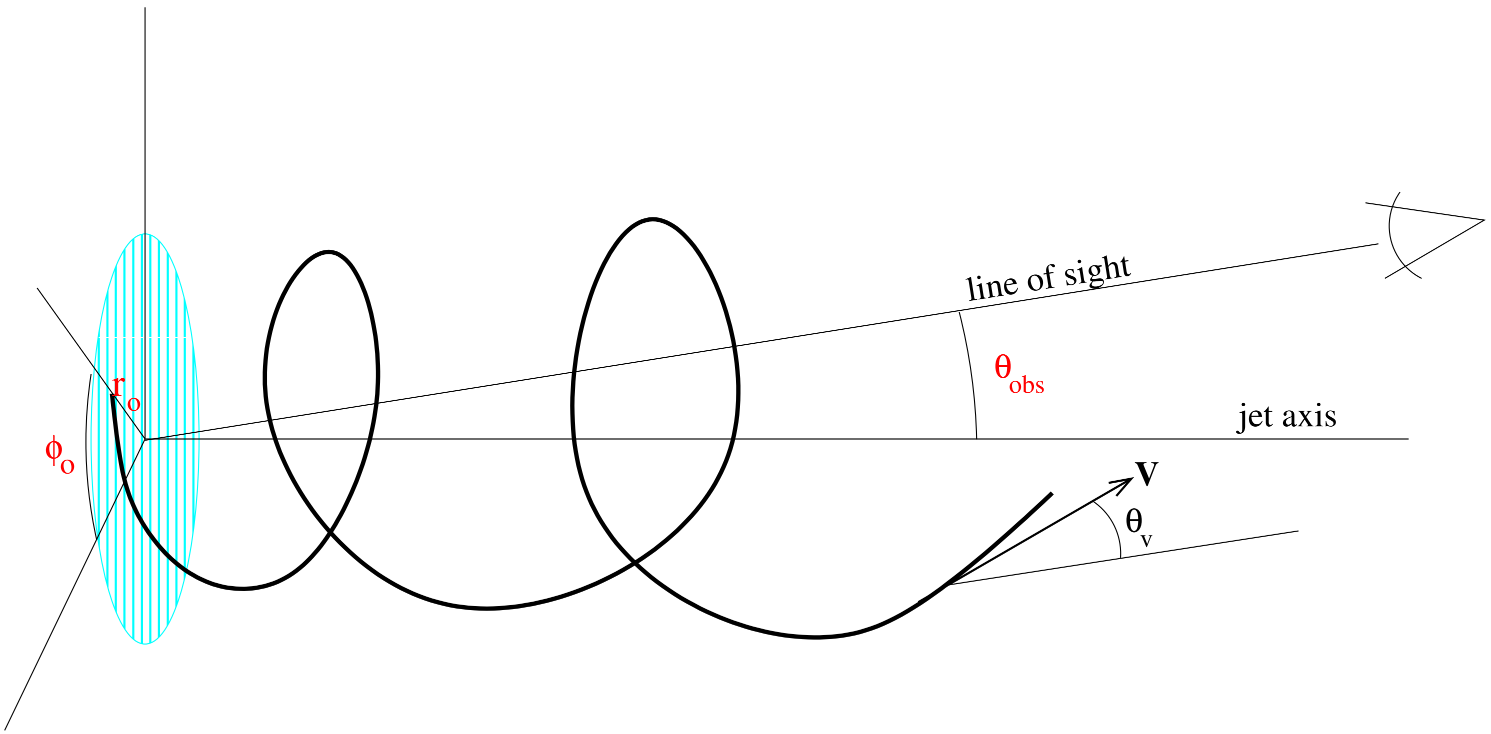
to explore this possibility, we used the relativistic self-similar model (Vlahakis & Königl 2004)

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

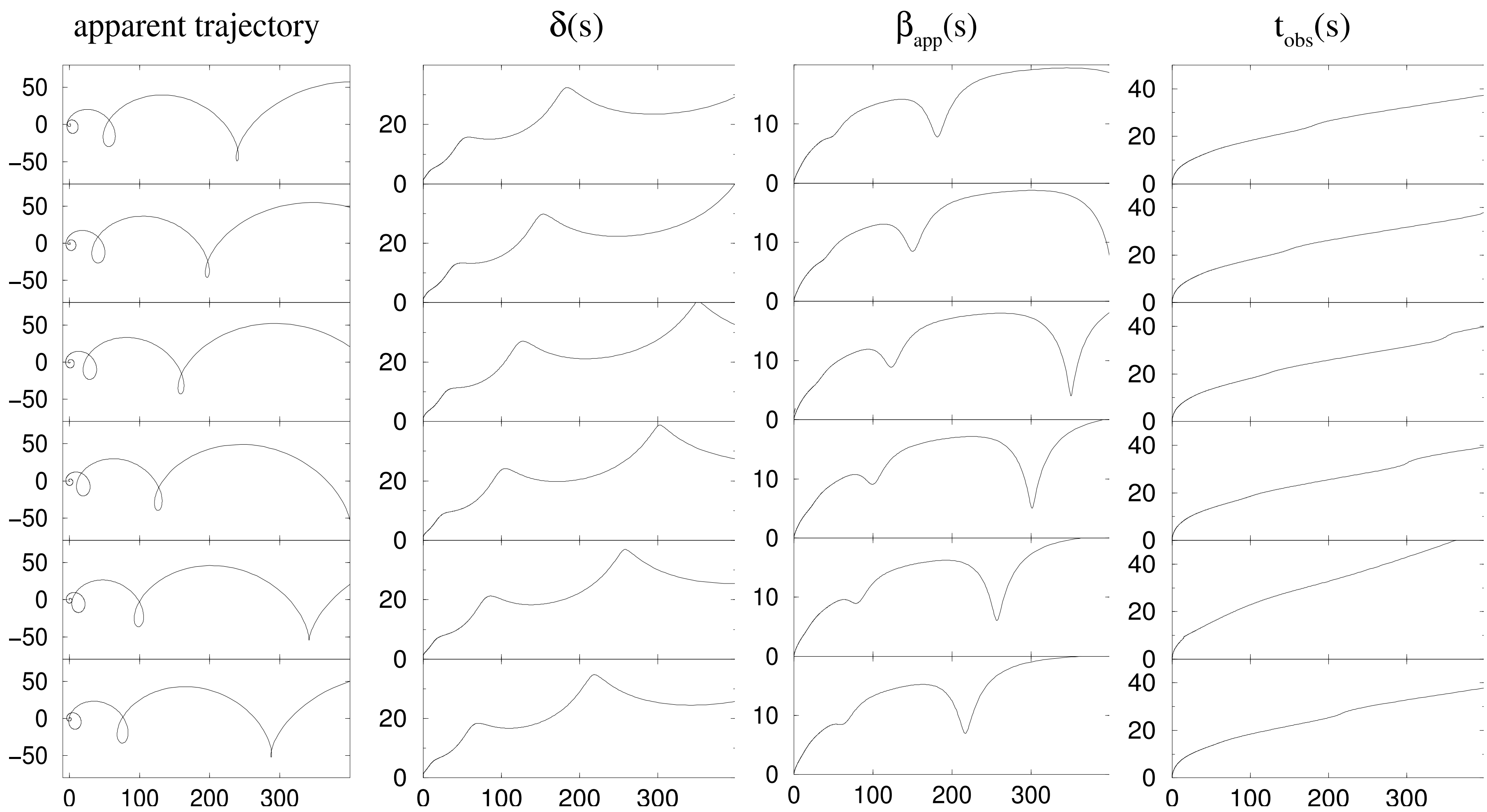
Vlahakis, Marin, & Königl, in preparation



For given $\theta_{\rm obs}$ (angle between jet axis and line of sight) and ejection area on the disk (r_o, ϕ_o), we project the trajectory on the plane of sky and compare with observations. Find the best-fit parameters r_o, $\theta_{\rm obs}$, ϕ_o.

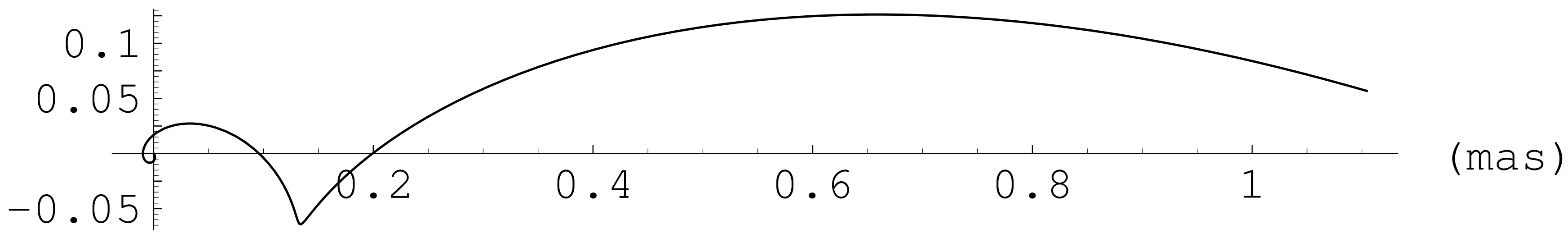


For $\theta_{\rm obs} = 1^{\rm o}$ and $\phi_o = 0^{\rm o}, 60^{\rm o}, 120^{\rm o}, 180^{\rm o}, 240^{\rm o}, 300^{\rm o}$ (from top to bottom):

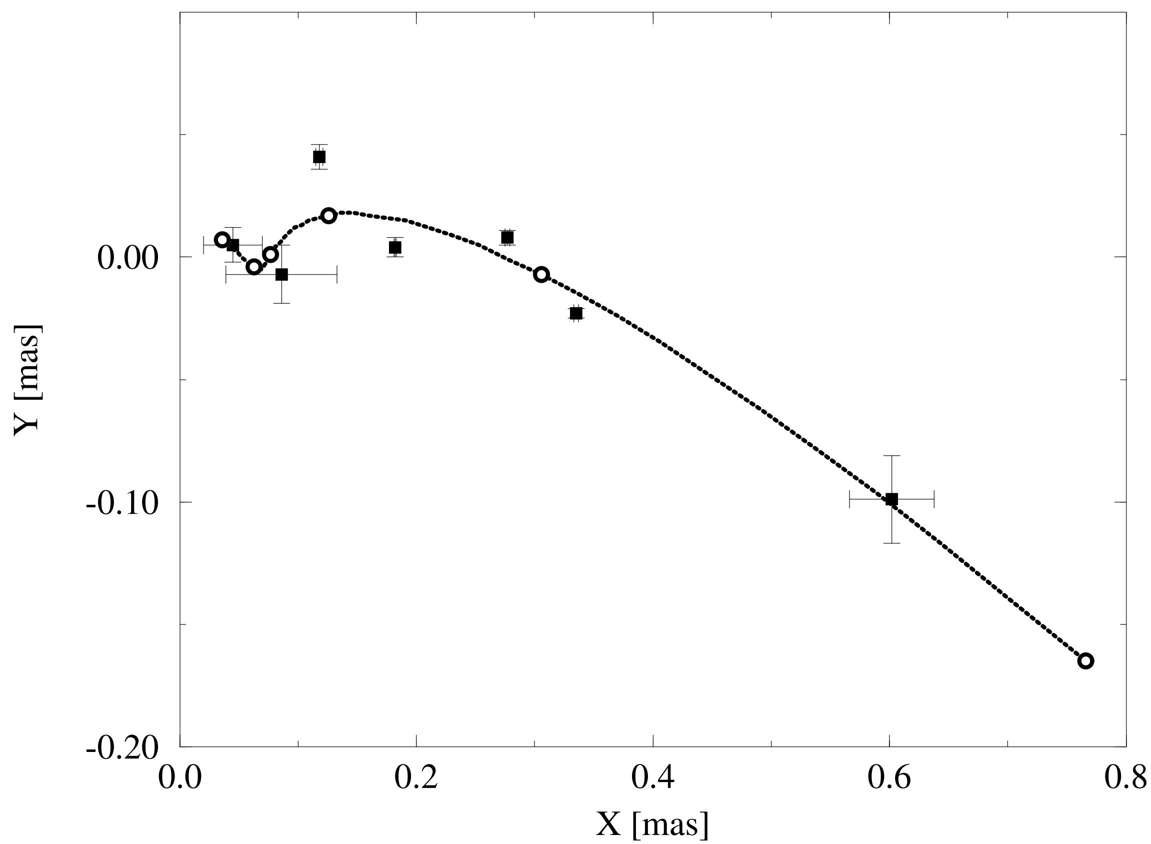


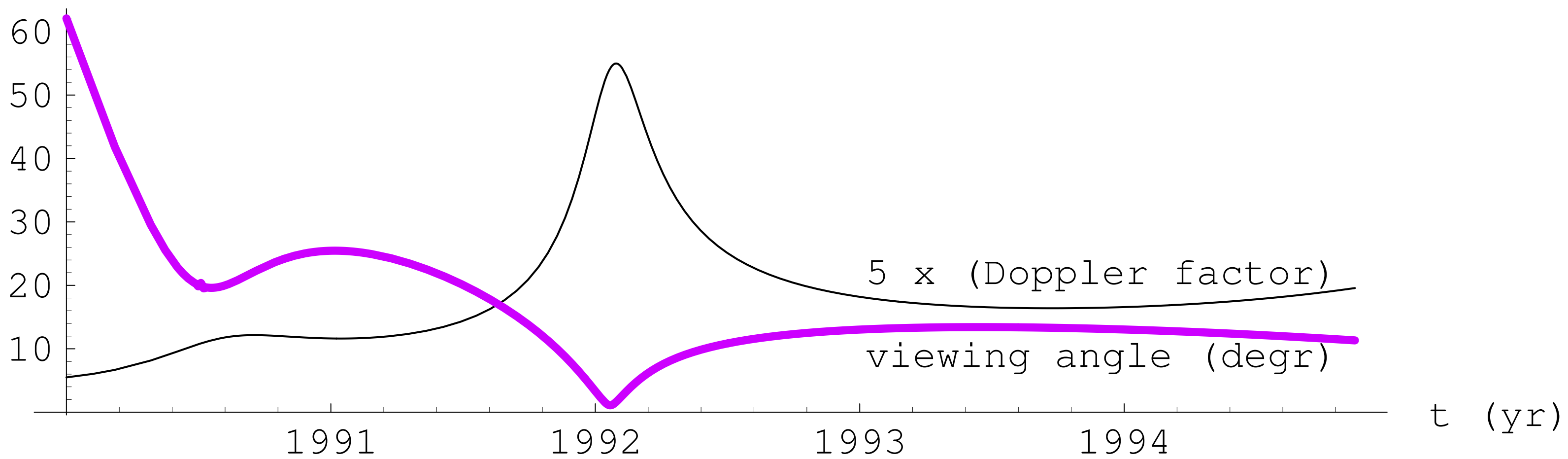
best-fit to Unwin et al results: $r_o \approx 2 \times 10^{16}$cm, ϕ_o=180^o, $\theta_{\rm obs}$=9^o

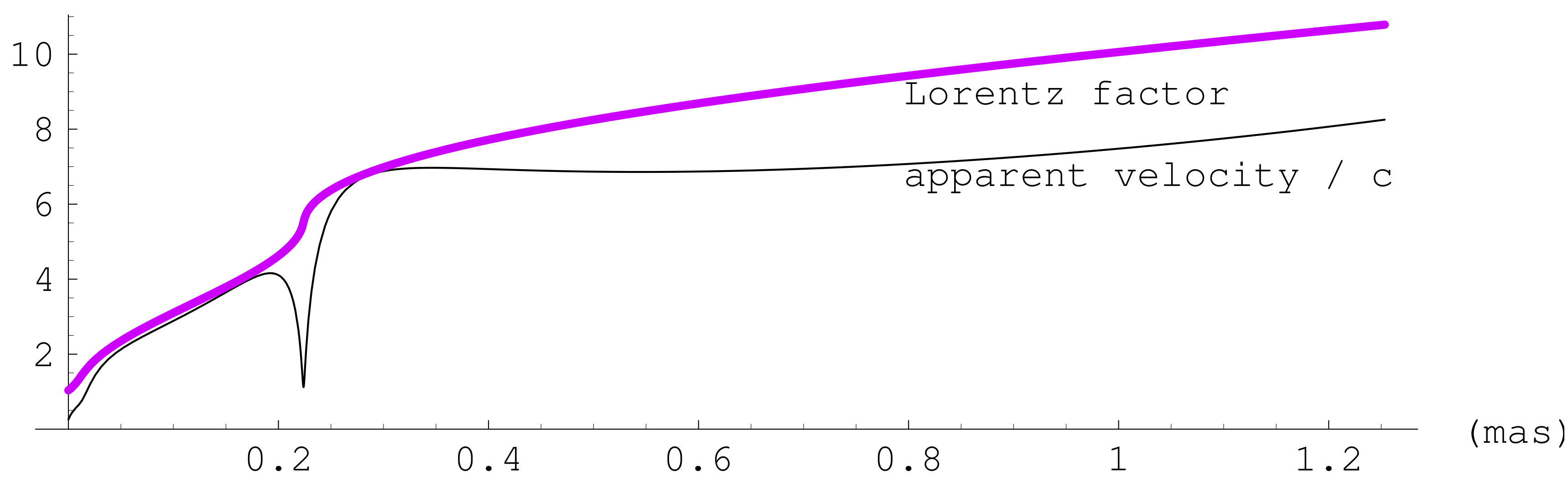
apparent trajectory



Trajectory of C7




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


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

Summary

⋆ Blazar jets are likely accelerated at relatively large distances from the disk ($\gg r_g$)

⋆ Magnetic driving provides a viable explanation of the jet bulk acceleration (with efficiencies $\sim 50\%$)

⋆ Collimated flows are naturally produced

⋆ The intrinsic rotation of the jets could explain the observed apparent motion

– We get information on many source characteristics (e.g., size of disk and mass of central black hole, magnetic field in relation to the mass-loss rate)

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

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

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

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

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