AGN Jets

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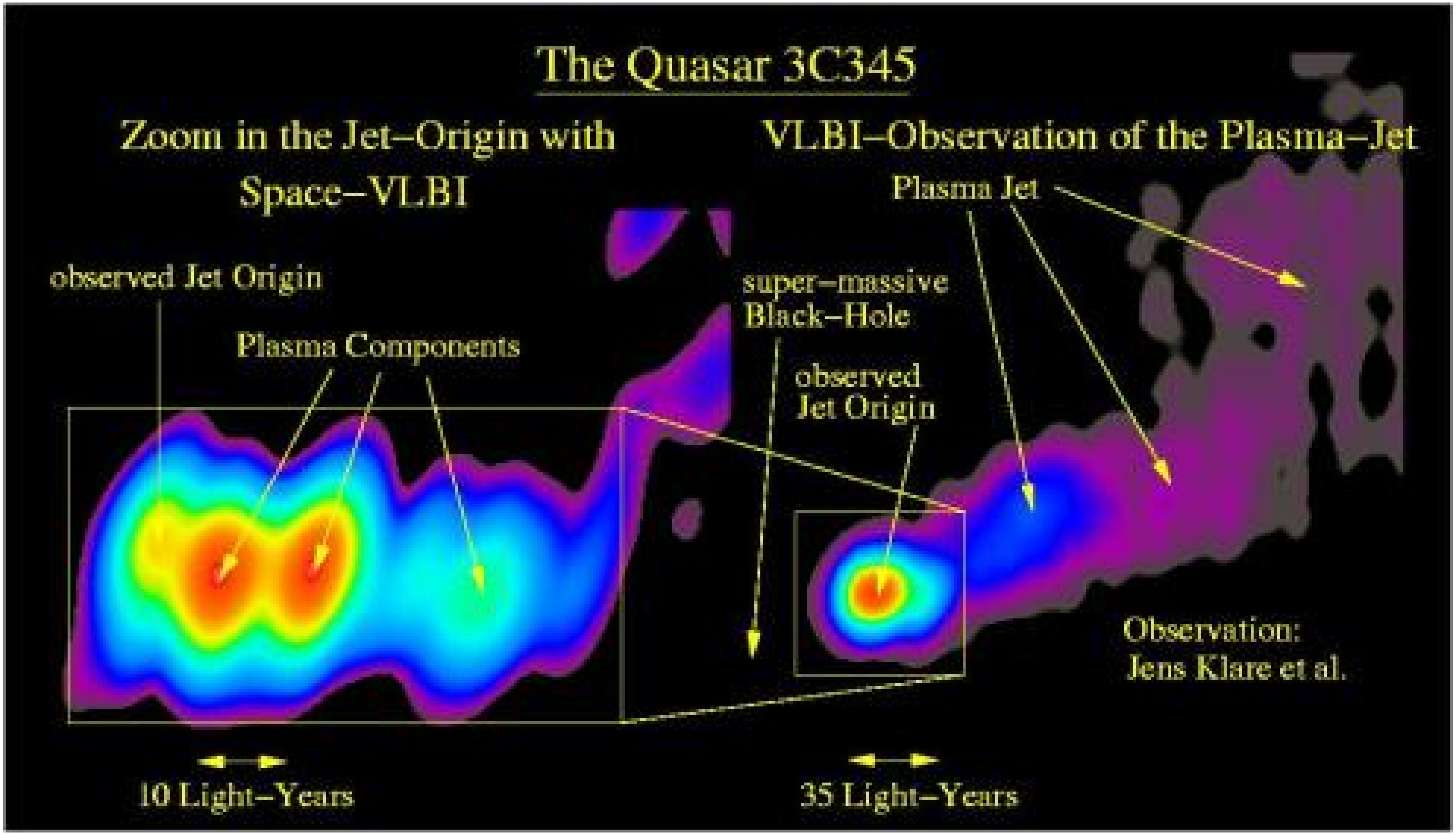
Outline

- What we observe
- MHD description

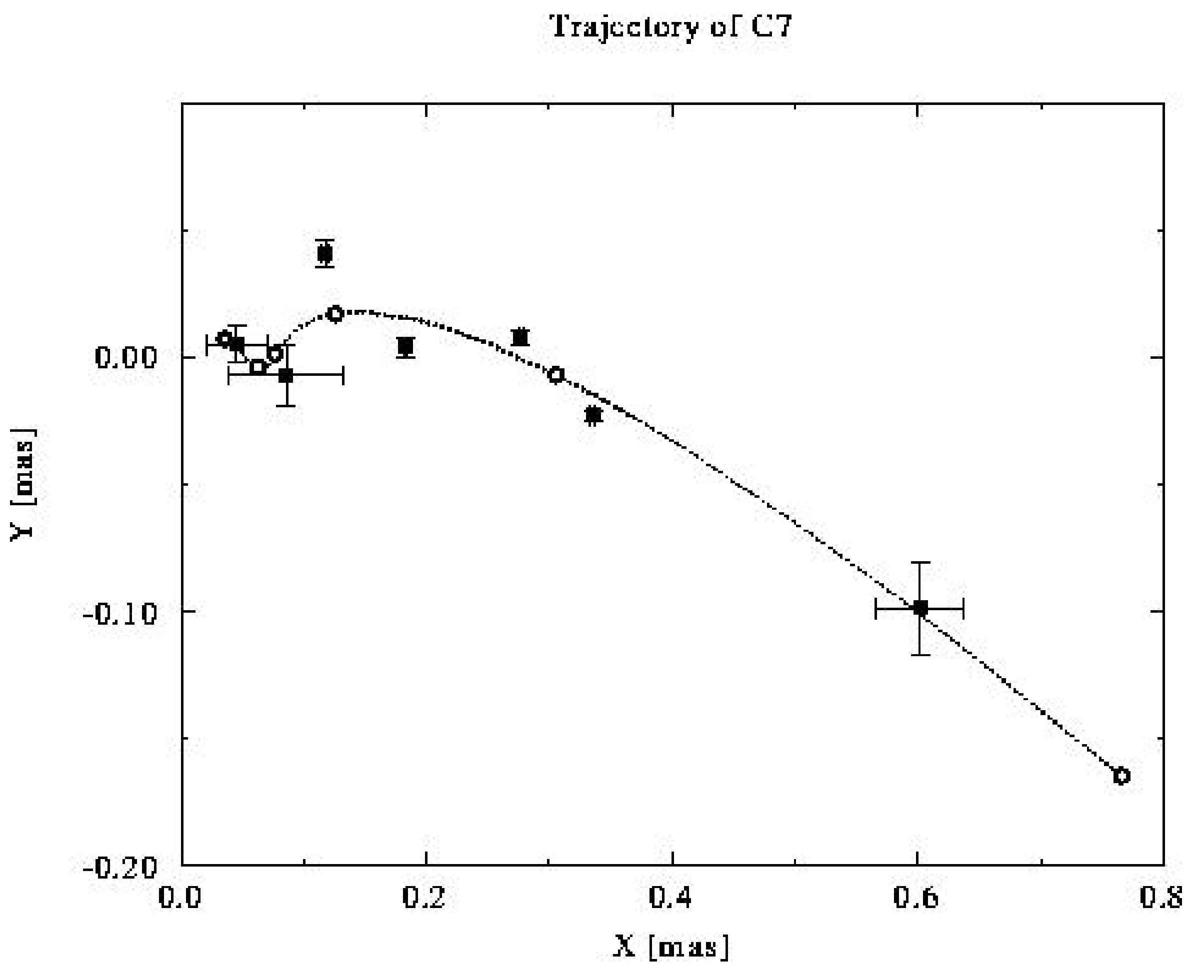


The Quasar 3C345
Zoom in the Jet–Origin with Space–VLBI
VLBI–Observation of the Plasma–Jet
Plasma Jet
observed Jet Origin
super–massive Black–Hole
Plasma Components
observed Jet Origin
Observation: Jens Klare et al.
10 Light–Years
35 Light–Years

The plasma components move with an apparent speed of 3-20c $\rightarrow$ the jet points almost toward us and has $V \approx c$

These plasma components travel on curved trajectories (helix?)

These trajectories differ from one component to the other



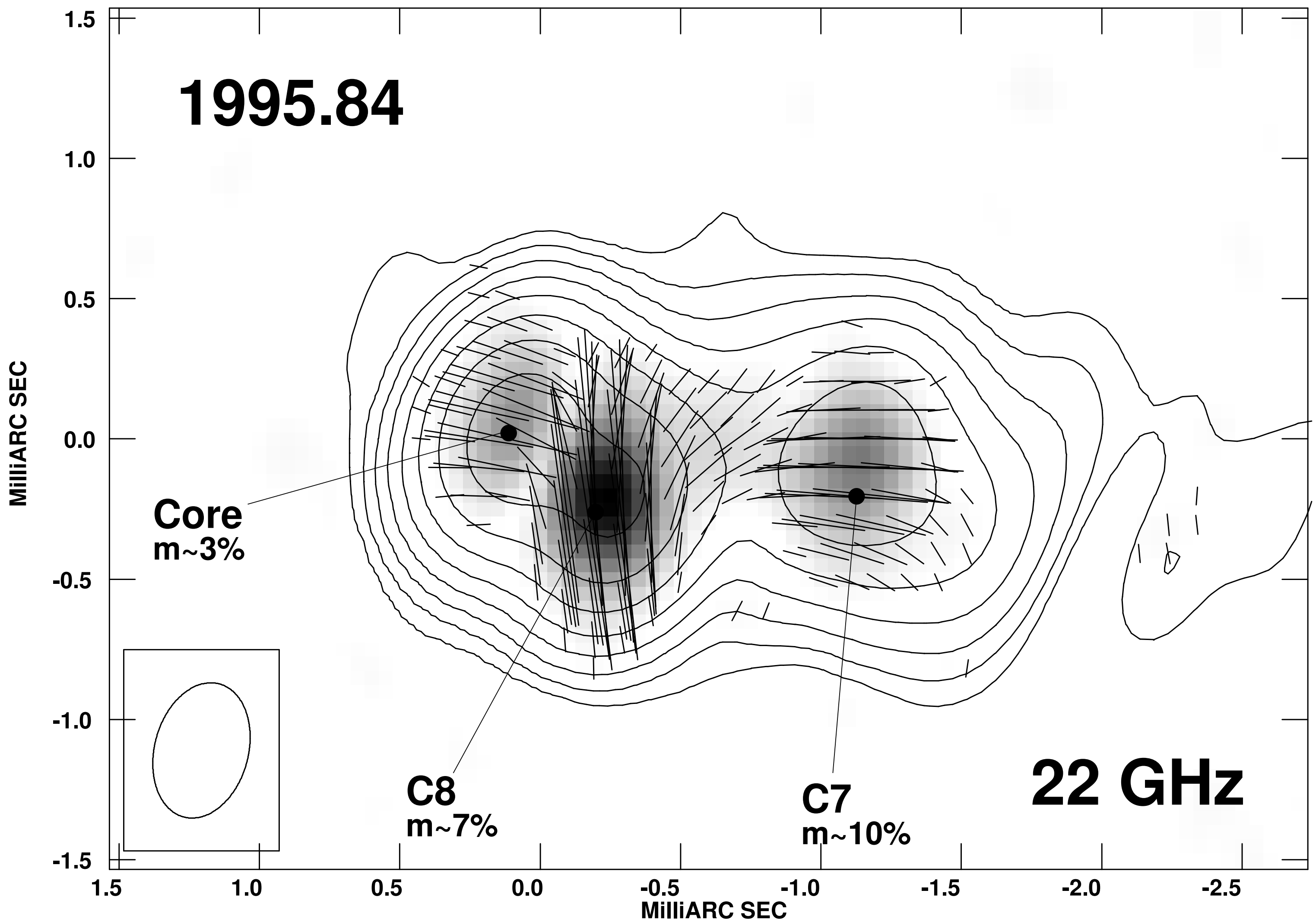
- Compare radio- and X-emission $\Rightarrow \delta$ (Doppler factor)

- Superluminal apparent motion $\Rightarrow \beta_{\rm app}$

From $\delta(t_{\rm obs}) \equiv \dfrac{1}{\gamma\,(1-\beta\cos\theta_v)}$ and $\beta_{\rm app}(t_{\rm obs}) = \dfrac{\beta\sin\theta_v}{1-\beta\cos\theta_v}$
we find $\beta(t_{\rm obs})$, $\gamma(t_{\rm obs})$ and $\theta_v(t_{\rm obs})$.

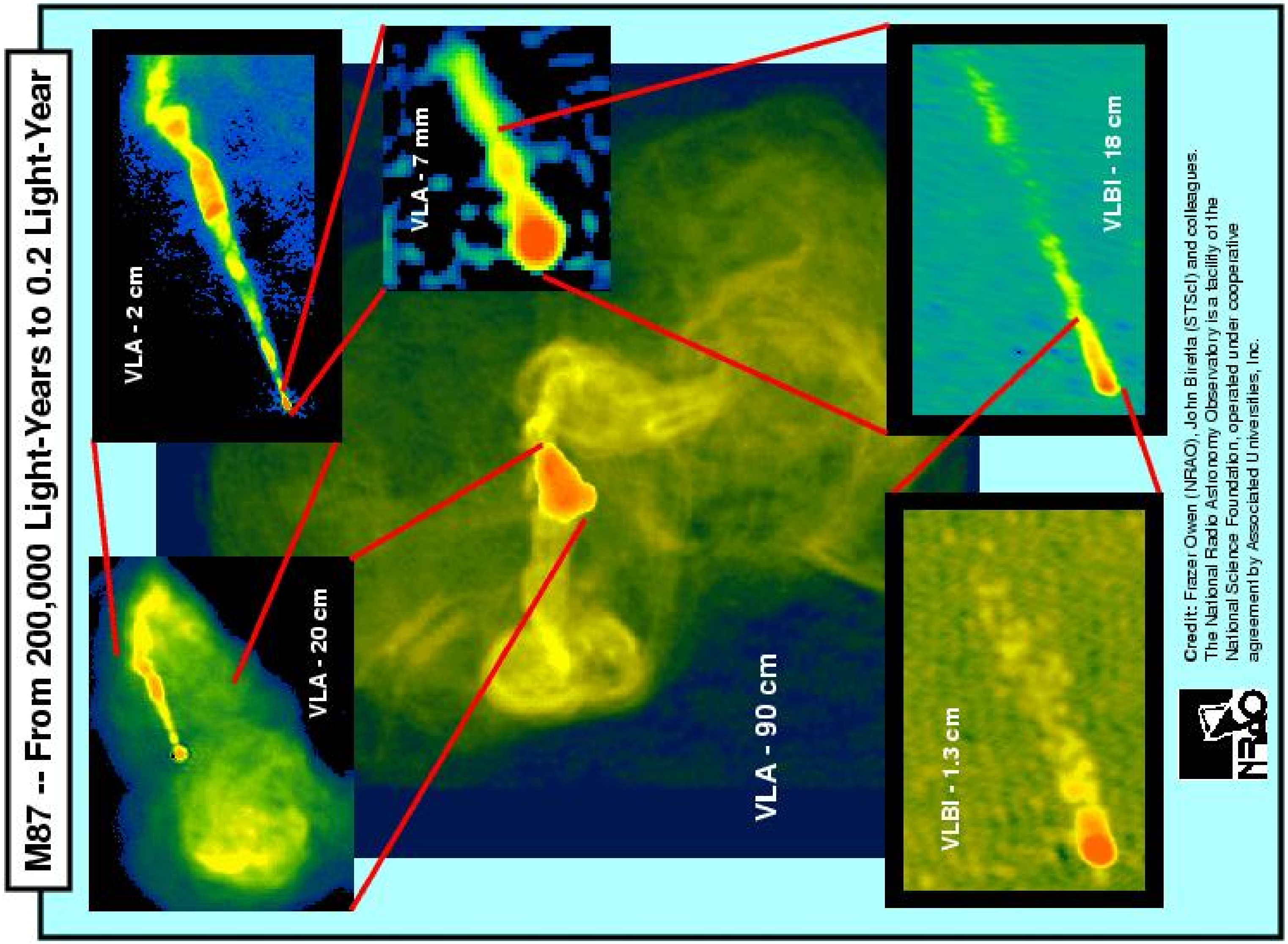
For the C7 component of 3C 345 Unwin et al. (1997) inferred that it accelerates from $\gamma \sim 5$ to $\gamma \sim 10$ over the (deprojected) distance range (measured from the core) $\sim 3 - 20\ {\rm pc}$. Also the angle θ_v changes from ≈ 2 to $\approx 10^o$. ($t_{\rm obs} =$ 1992 – 1993.)

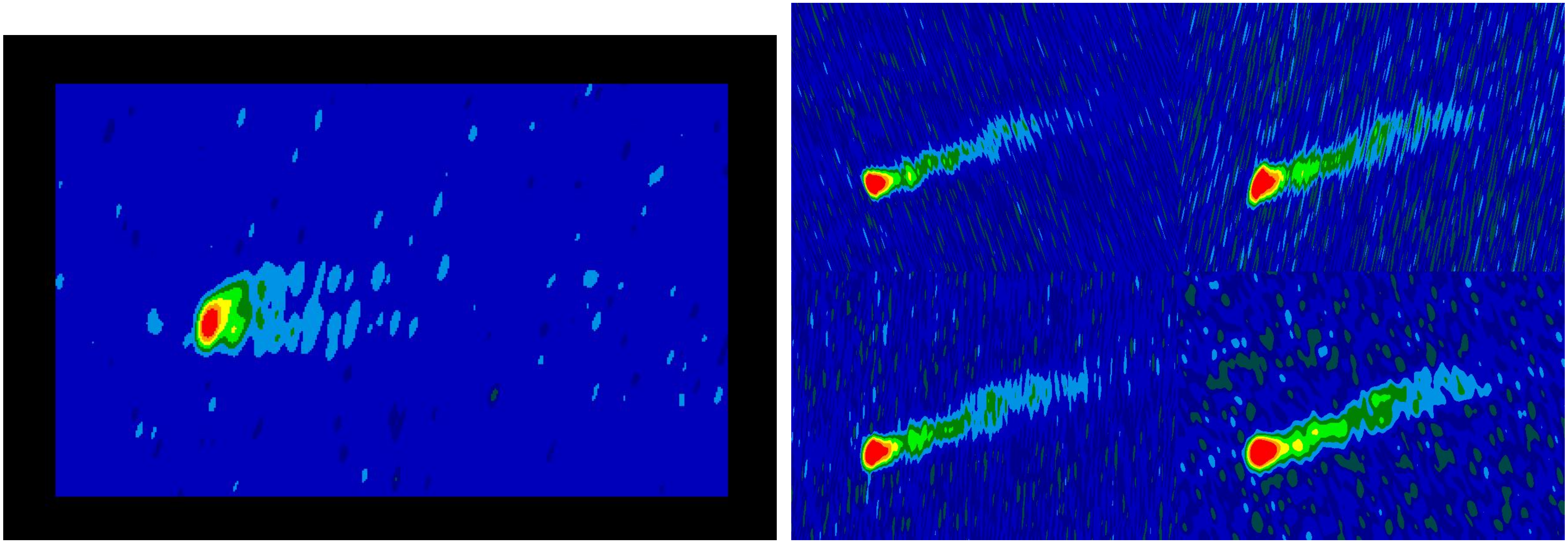
Polarization



(electric vectors)

M87


M87 -- From 200,000 Light-Years to 0.2 Light-Year
VLA - 2 cm
VLA - 7 mm
VLBI - 18 cm
VLA - 20 cm
VLA - 90 cm
VLBI - 1.3 cm
Credit: Frazer Owen (NRAO), John Biretta (STScI) and colleagues.
The National Radio Astronomy Observatory is a facility of the
National Science Foundation, operated under cooperative
agreement by Associated Universities, Inc.
NRAO



(left Global VLBI + VSOP, right Global VLBI)

Collimation in action (at approximately 100 Schwarzschild radii)!

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.

MHD (Magneto-Hydro-Dynamic) description

- How the jet is collimated and accelerated? Need to examine outflows taking into account
  - matter: velocity $\boldsymbol{V}$, rest density ρ_0, pressure P, specific enthalpy ξc^2
  - electromagnetic field: $\boldsymbol{E}$, $\boldsymbol{B}$

- ideal MHD equations in special relativity:
  - Maxwell: $\nabla \cdot \boldsymbol{B} = 0 = \nabla \times \boldsymbol{E} + \dfrac{\partial \boldsymbol{B}}{c \partial t}$, $\nabla \times \boldsymbol{B} = \dfrac{\partial \boldsymbol{E}}{c \partial t} + \dfrac{4\pi}{c} \boldsymbol{J}$, $\nabla \cdot \boldsymbol{E} = \dfrac{4\pi}{c} J^0$
  - Ohm: $\boldsymbol{E} + \dfrac{\boldsymbol{V}}{c} \times \boldsymbol{B} = 0$
  - mass conservation: $\dfrac{\partial (\gamma \rho_0)}{\partial t} + \nabla \cdot (\gamma \rho_0 \boldsymbol{V}) = 0$
  - specific entropy conservation: $\left(\dfrac{\partial}{\partial t} + \boldsymbol{V} \cdot \nabla \right) \left(\dfrac{P}{\rho_0^\Gamma} \right) = 0$
  - momentum: $\gamma \rho_0 \left(\dfrac{\partial}{\partial t} + \boldsymbol{V} \cdot \nabla \right) (\xi \gamma \boldsymbol{V}) = -\nabla P + \dfrac{J^0 \boldsymbol{E} + \boldsymbol{J} \times \boldsymbol{B}}{c}$

- The system gives $\boldsymbol{B}$, $\boldsymbol{V}$, ρ_0, P.

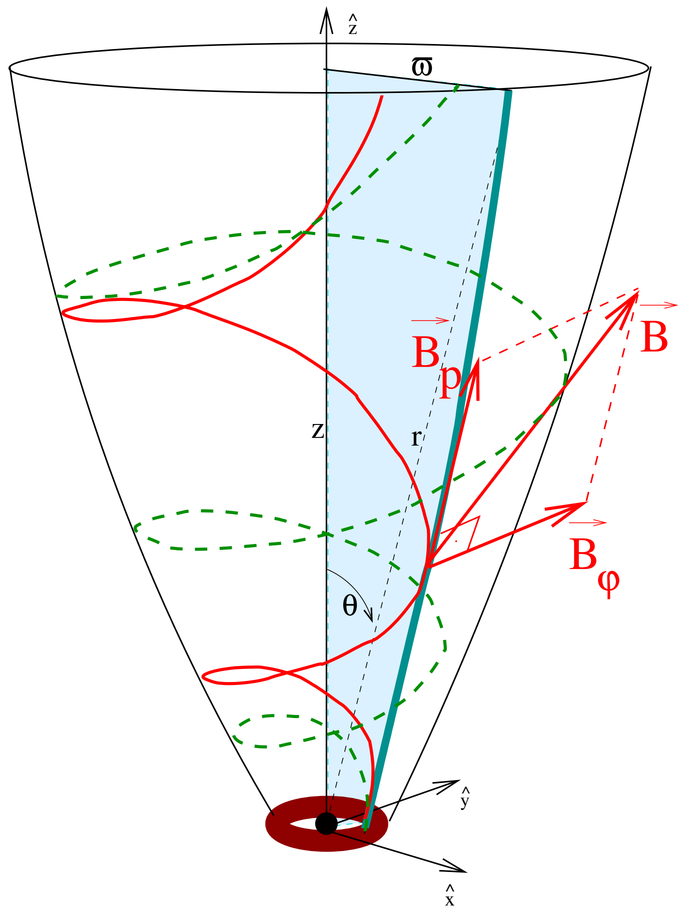
Integrals of motion

under the assumption of steady-state and axisymmetry

From $\nabla \cdot \boldsymbol{B} = 0$

$$\boldsymbol{B}_p = \frac{\nabla A \times \hat{\boldsymbol{\phi}}}{\varpi}\,, \text{ or, } \boldsymbol{B}_p = \nabla \times \left(\frac{A\,\hat{\boldsymbol{\phi}}}{\varpi} \right)$$

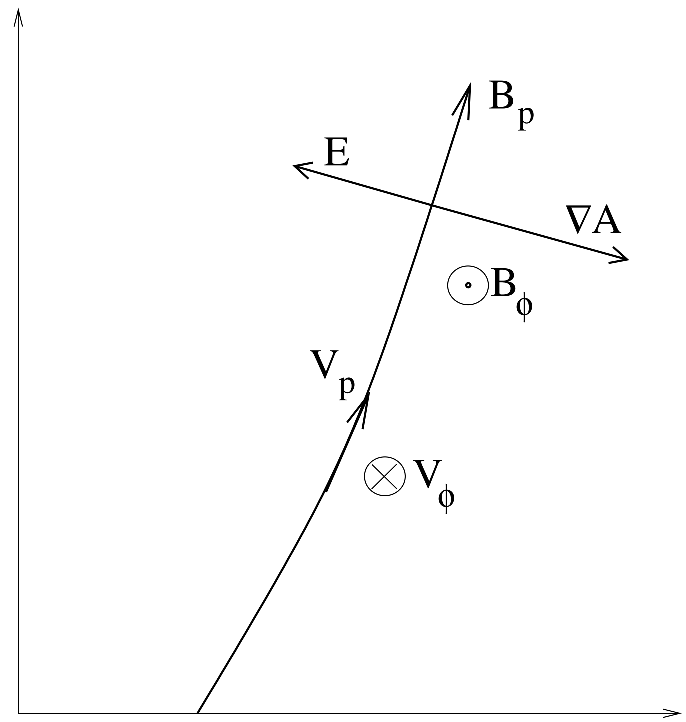
$$A = \frac{1}{2\pi} \iint \boldsymbol{B}_p \cdot d\boldsymbol{S}$$



From $\nabla \times \boldsymbol{E} = 0$, $\boldsymbol{E} = -\nabla \Phi$
Because of axisymmetry $E_\phi = 0$.
Combining with Ohm's law
$(\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}/c)$ we find $\boldsymbol{V}_p \parallel \boldsymbol{B}_p$.

Because $\boldsymbol{V}_p \parallel \boldsymbol{B}_p$ we can write

$$\boldsymbol{V} = \frac{\Psi_A}{4\pi\gamma\rho_0}\boldsymbol{B} + \varpi\Omega\hat{\boldsymbol{\phi}}\,, \quad \frac{\Psi_A}{4\pi\gamma\rho_0} = \frac{V_p}{B_p}\,.$$



The Ω and Ψ_A are constants of motion, $\Omega = \Omega(A)$, $\Psi_A = \Psi_A(A)$.

- $\Omega =$ angular velocity at the base

- $\Psi_A =$ mass-to-magnetic flux ratio

The electric field $\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}/c = -(\varpi\Omega/c)\hat{\boldsymbol{\phi}} \times \boldsymbol{B}_p$ is a poloidal vector, normal to $\boldsymbol{B}_p$. Its magnitude is $E = \frac{\varpi\Omega}{c} B_p$.

So far, we've used Maxwell's eqs, Ohm's law and the continuity.

The entropy eq gives $P/\rho_0^\Gamma =$ constant of motion (entropy).

We are left with the momentum equation

$$\gamma\rho_0 \left(\boldsymbol{V}\cdot\nabla\right)\left(\xi\gamma\boldsymbol{V}\right) = -\nabla P + \frac{J^0\boldsymbol{E} + \boldsymbol{J}\times\boldsymbol{B}}{c}, \text{ or,}$$

$$\gamma\rho_0 \left(\boldsymbol{V}\cdot\nabla\right)\left(\xi\gamma\boldsymbol{V}\right) = -\nabla P + \frac{(\nabla\cdot\boldsymbol{E})\boldsymbol{E} + (\nabla\times\boldsymbol{B})\times\boldsymbol{B}}{4\pi}$$

Due to axisymmetry, the toroidal component can be integrated to give the total angular momentum-to-mass flux ratio:

$$\xi\gamma\varpi V_\phi - \frac{\varpi B_\phi}{\Psi_A} = L(A)$$

Poloidal components of the momentum eq

$$\gamma\rho_0 \left(\boldsymbol{V}\cdot\nabla\right)\left(\xi\gamma\boldsymbol{V}\right) = -\nabla P + \frac{(\nabla\cdot\boldsymbol{E})\boldsymbol{E} + (\nabla\times\boldsymbol{B})\times\boldsymbol{B}}{4\pi} \Leftrightarrow$$

$$\boldsymbol{f}_G + \boldsymbol{f}_T + \boldsymbol{f}_C + \boldsymbol{f}_I + \boldsymbol{f}_P + \boldsymbol{f}_E + \boldsymbol{f}_B = 0$$

$$\left.\begin{array}{lcl} \boldsymbol{f}_G = -\gamma\rho_0\xi\left(\boldsymbol{V}\cdot\nabla\gamma\right)\boldsymbol{V} & & \\ \boldsymbol{f}_T = -\gamma^2\rho_0\left(\boldsymbol{V}\cdot\nabla\xi\right)\boldsymbol{V} & : & \text{“temperature” force} \\ \boldsymbol{f}_C = \hat{\boldsymbol{\varpi}}\gamma^2\rho_0\xi V_\phi^2/\varpi & : & \text{centrifugal force} \\ \boldsymbol{f}_I = -\gamma^2\rho_0\xi\left(\boldsymbol{V}\cdot\nabla\right)\boldsymbol{V} - \boldsymbol{f}_C & & \end{array}\right\} \text{inertial force}$$

$$\begin{array}{lcl} \boldsymbol{f}_P = -\nabla P & : & \text{pressure force} \\ \boldsymbol{f}_E = \left(\nabla\cdot\boldsymbol{E}\right)\boldsymbol{E}/4\pi & : & \text{electric force} \\ \boldsymbol{f}_B = \left(\nabla\times\boldsymbol{B}\right)\times\boldsymbol{B}/4\pi & : & \text{magnetic force} \end{array}$$

Acceleration mechanisms

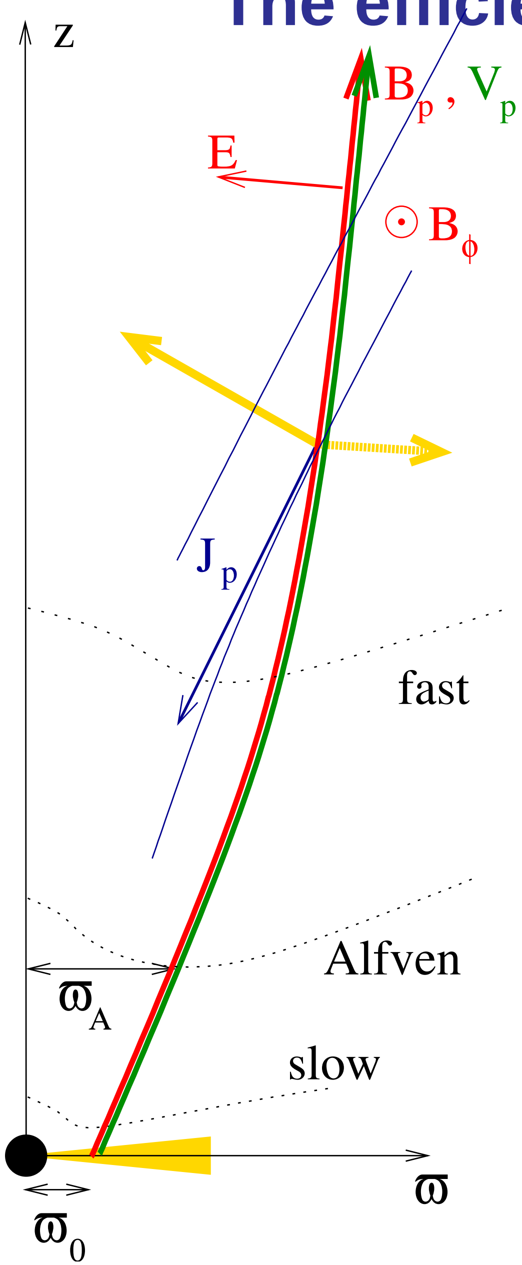
- thermal (due to ∇P) $\longrightarrow$ velocities up to C_s
- magnetocentrifugal (beads on wire - Blandford & Payne)
  - in reality due to magnetic pressure
  - initial half-opening angle $\vartheta > 30^o$
  - the $\vartheta > 30^o$ not necessary for nonnegligible P
  - velocities up to $\varpi_0 \Omega$
- relativistic thermal (thermal fireball) gives $\gamma \sim \xi_i$,
  where $\xi = \dfrac{\text{enthalpy}}{\text{mass} \times c^2}$.
- magnetic

All acceleration mechanisms can be seen in the energry conservation equation

$$\mu = \xi \gamma + \frac{\Omega}{\Psi_A c^2} \varpi B_\phi$$

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

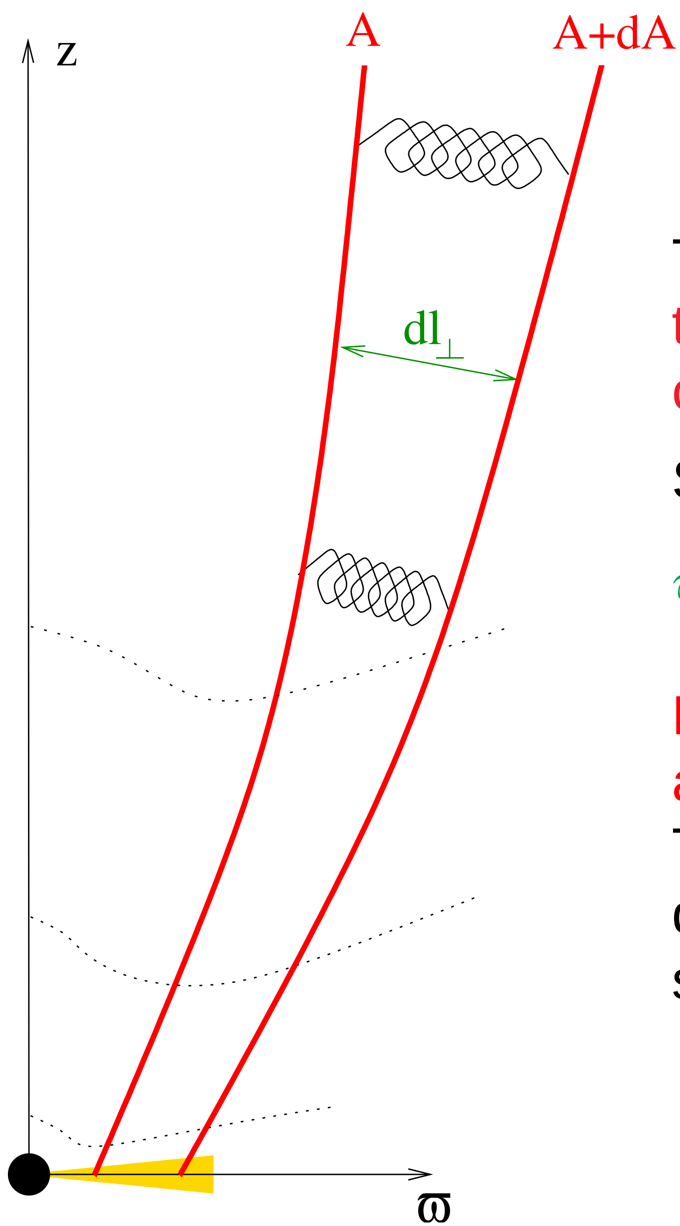
The efficiency of the magnetic acceleration



The $\boldsymbol{J}_p \times \boldsymbol{B}_\phi$ force strongly depends on the angle between field-lines and current-lines.

Are we free to choose these two lines? NO! All MHD quantities are related to each other and should be found by solving the full system of equations.

From Ferraro's law ($V_\phi = \varpi\Omega + V_p B_\phi / B_p$) we get $\varpi B_\phi \approx \varpi^2 B_p \Omega / V_p$. So, the transfield force-balance determines the acceleration.



The magnetic field minimizes its energy under the condition of keeping the magentic flux constant.

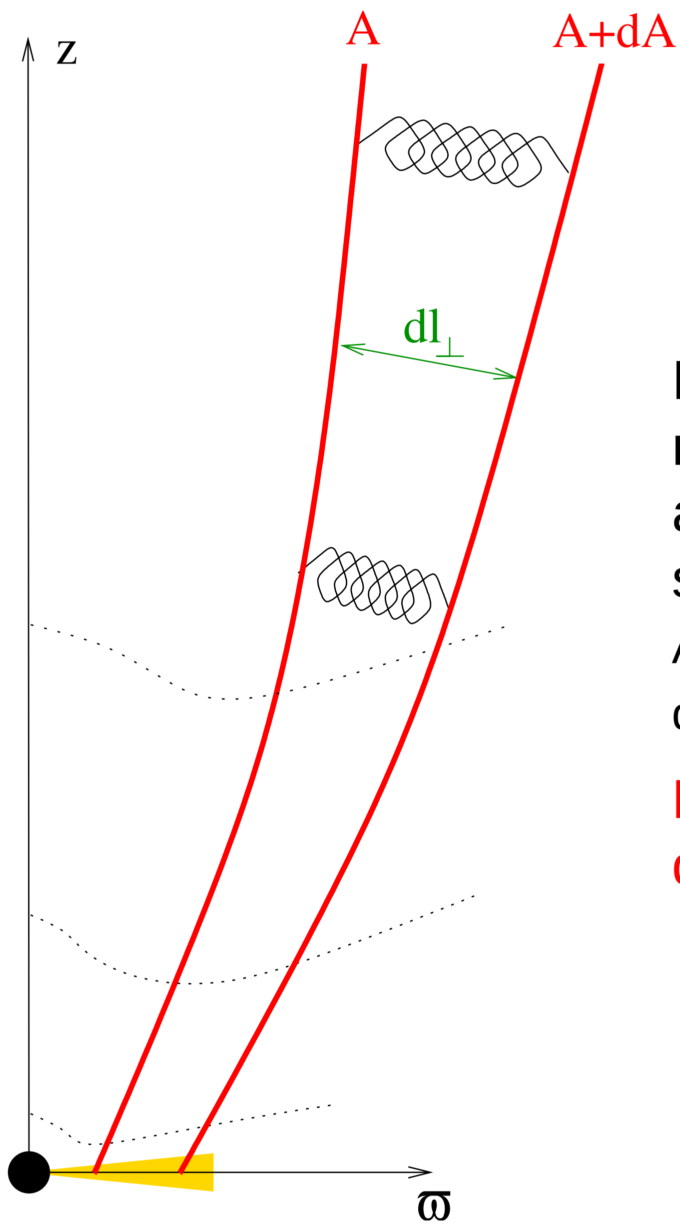
So, $\varpi B_\phi \downarrow$ for decreasing

$$\varpi^2 B_p = \frac{\varpi^2}{2\pi\varpi dl_\perp}\underbrace{(B_p dS)}_{dA} \propto \frac{\varpi}{dl_\perp}.$$

Expansion with increasing $dl_\perp/\varpi$ leads to acceleration

The expansion ends in a more-or-less uniform distribution $\varpi^2 B_p \approx A$ (in a quasi-monopolar shape).

Conclusions on the magnetic acceleration

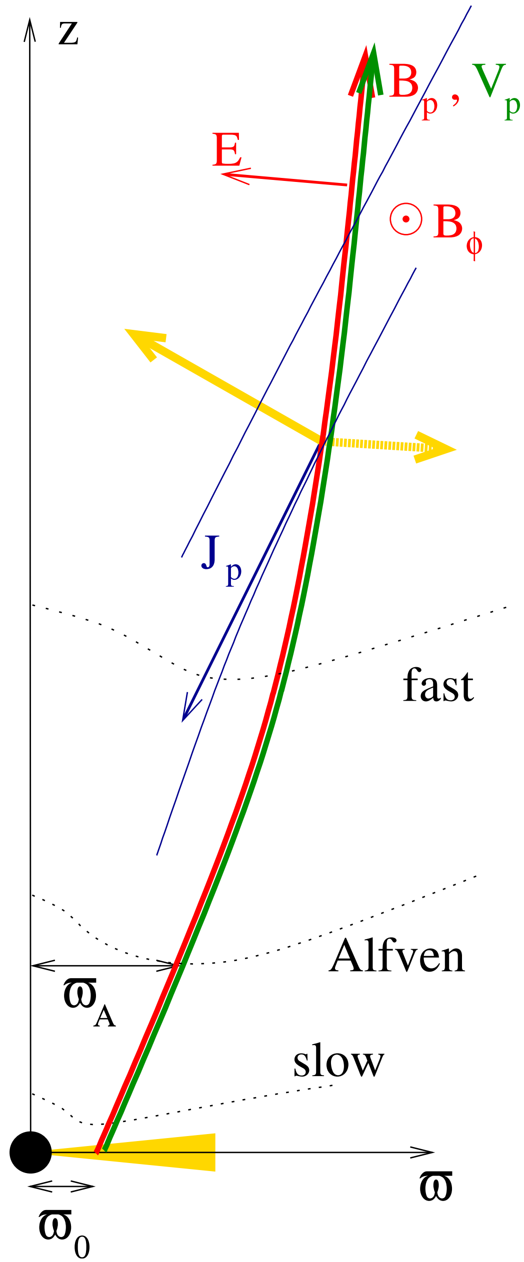


If we <u>start</u> with a uniform distribution the magnetic energy is already minimum $\longrightarrow$ no acceleration. Example: Michel's (1969) solution which gives $\gamma_\infty \approx \mu^{1/3} \ll \mu$.

Also Beskin et al (1998); Bogovalov (2001) who found quasi-monopolar solutions.

For any other (more realistic) initial field distribution we have efficient acceleration!

On the collimation



The $\boldsymbol{J}_p \times \boldsymbol{B}_\phi$ force contributes to the collimation (hoop-stress paradigm).
In relativistic flows the electric force plays an opposite role (a manifestation of the high inertia of the flow).

- collimation by an external wind (Bogovalov & Tsinganos 2005)
- surrounding medium may play a role
- self-collimation mainly works at small distances where the velocities are mildly relativistic (Vlahakis & Königl 2003)

For $\gamma \gg 1$, curvature radius $\mathcal{R} \sim \gamma^2 \varpi \ (\gg \varpi)$.

Collimation more difficult, but not impossible!

$$\frac{\varpi}{\mathcal{R}} = -\varpi \frac{\partial^2 \varpi}{\partial z^2} \left(\frac{B_z}{B_p} \right)^3 \sim \left(\frac{\varpi}{z} \right)^2$$

Combining the above, we get

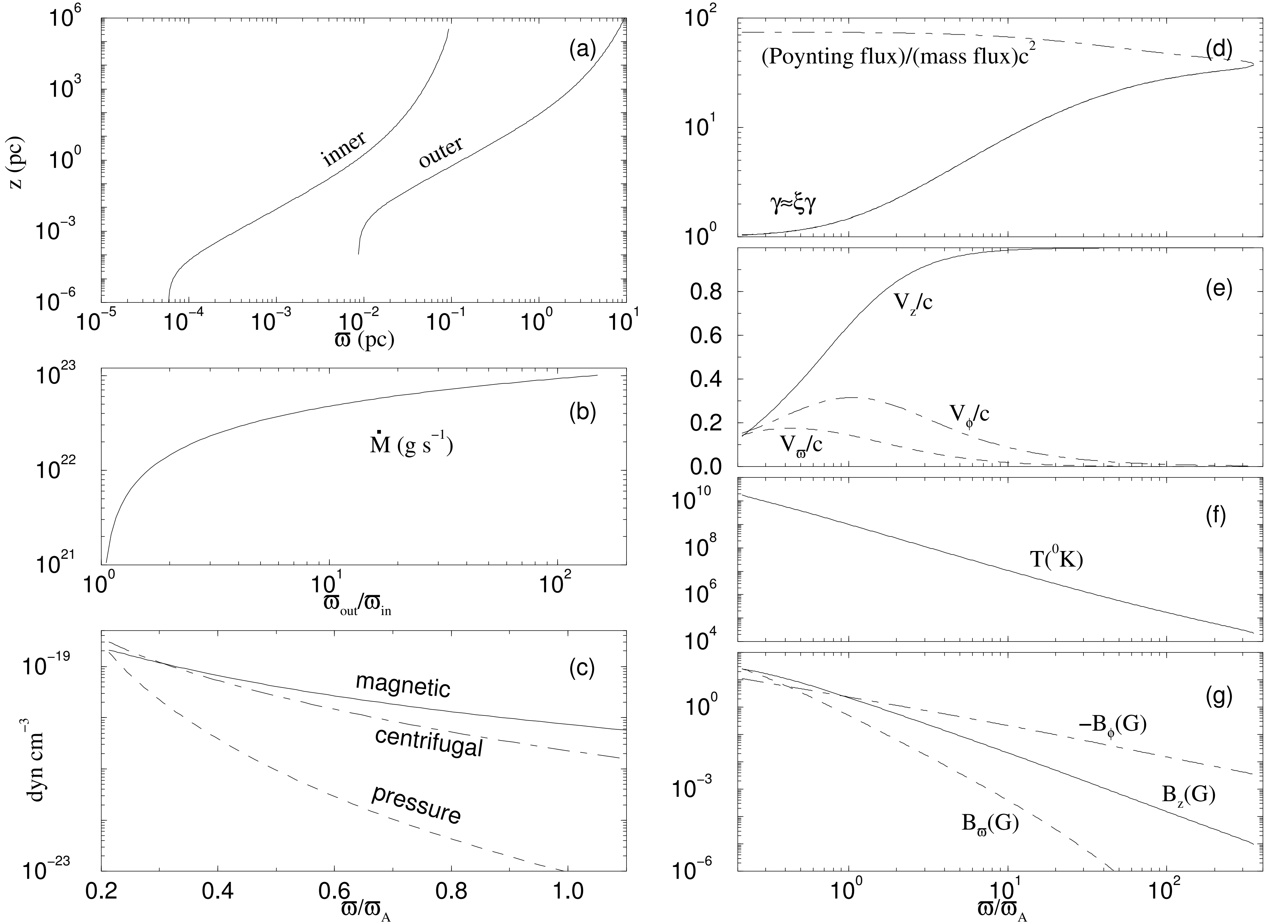
$$\gamma \sim \frac{z}{\varpi}$$

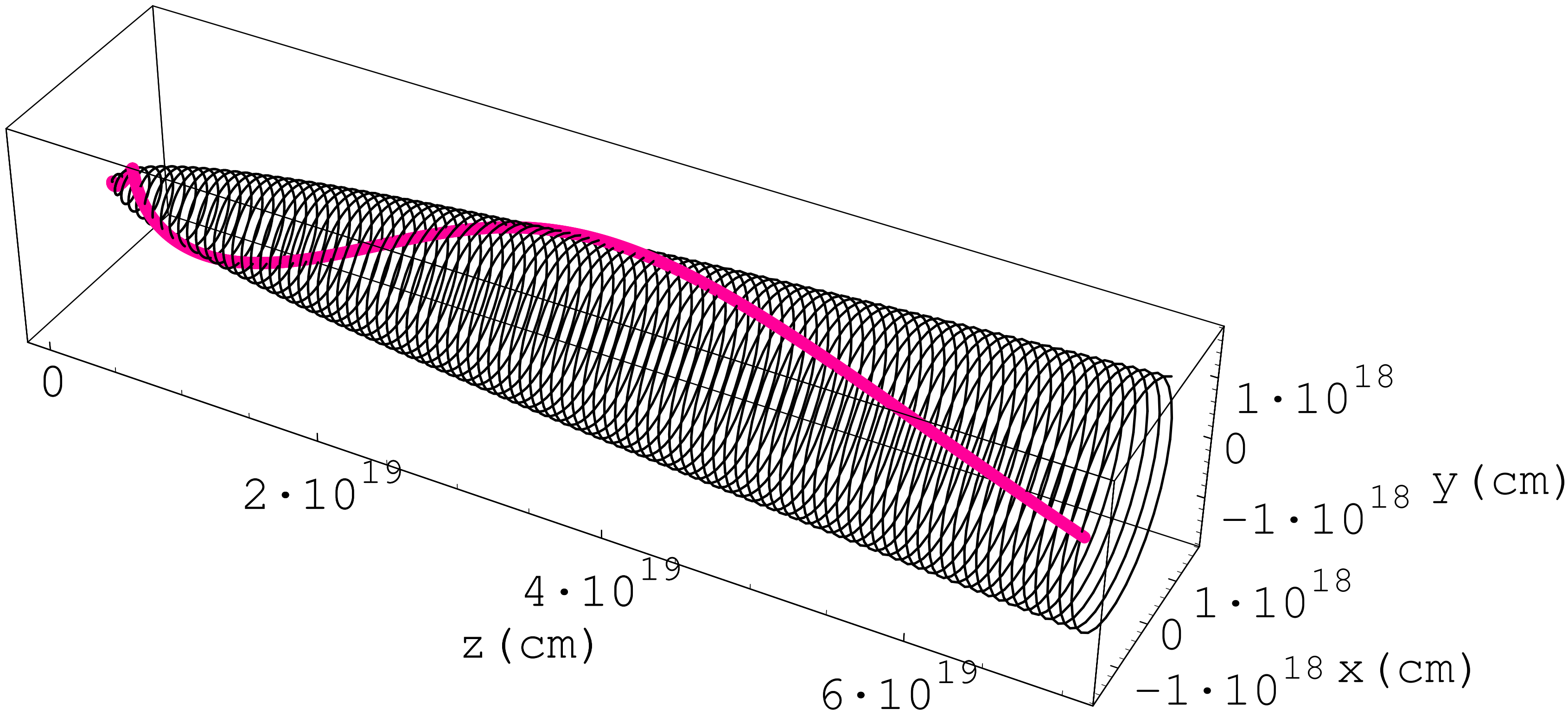
The same from

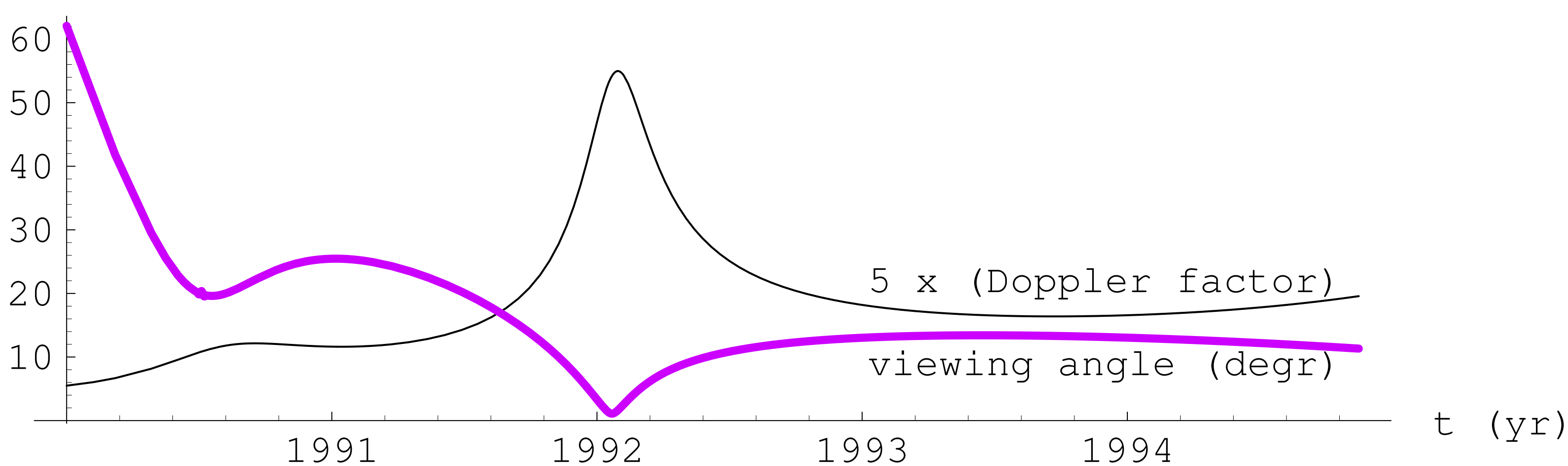
$$(t =) \ \frac{z}{V_z} = \frac{\varpi}{V_\varpi} \Leftrightarrow \frac{z}{c} = \frac{\varpi}{\sqrt{c^2 - V_z^2}} \approx \frac{\varpi}{c/\gamma}$$

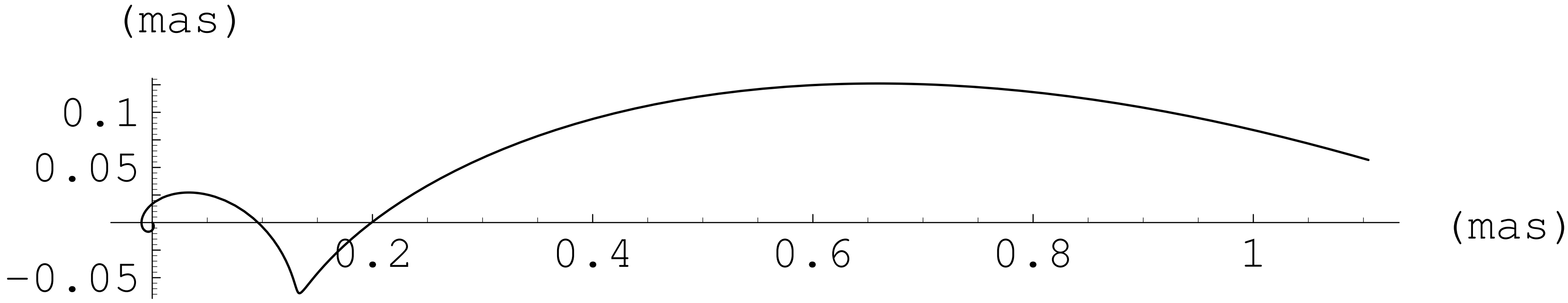
Summary

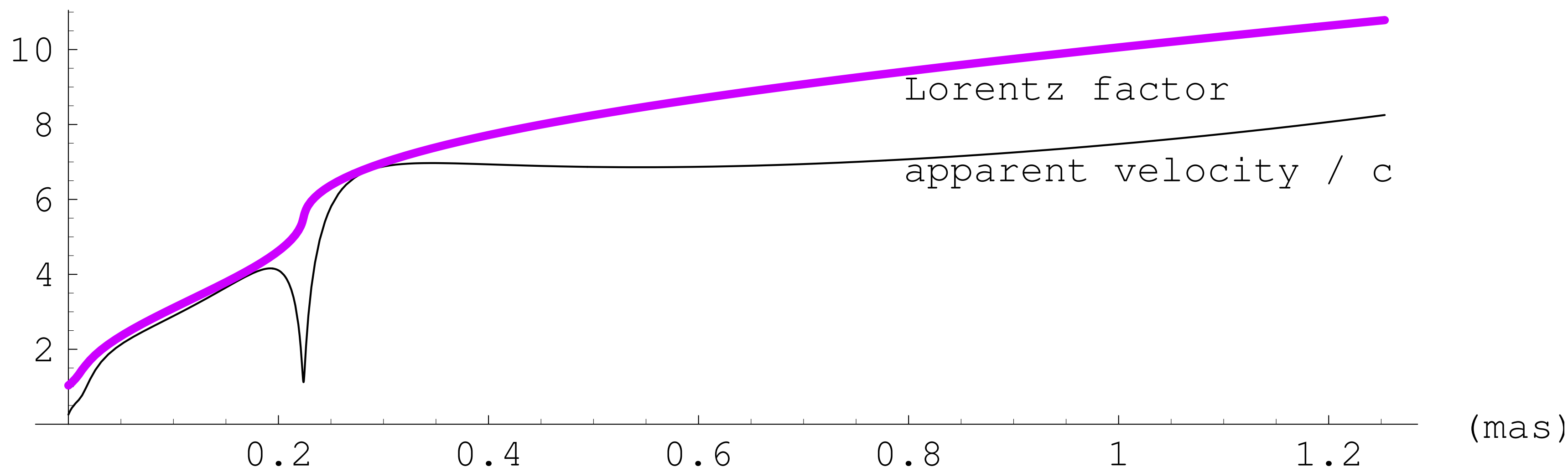
- assume
  - axisymmetry $(\partial/\partial\phi = 0\,,\ E_\phi = 0)$
  - steady state $(\partial/\partial t = 0)$
- introduce the magnetic flux function $A(\varpi\,, z)$
  ($A = const$ is a poloidal field-streamline)
- the full set of ideal MHD equations can be partially integrated to yield five fieldline constants:
  ① the mass-to-magnetic flux ratio $\Psi_A(A) = \frac{4\pi\rho_0\gamma V_p}{B_p}$
  (continuity equation)
  ② the field angular velocity $\Omega(A) = \frac{V_\phi}{\varpi} - \frac{\Psi_A}{4\pi\gamma\rho_0}\frac{B_\phi}{\varpi}$
  (Faraday + Ohm)
  ③ the specific angular momentum $L(A) = \xi\gamma\varpi V_\phi - \frac{\varpi B_\phi}{\Psi_A}$
  ($\hat{\phi}$ component of momentum equation)
  ④ the total energy-to-mass flux ratio $\mu(A)c^2 = \xi\gamma c^2 - \frac{\varpi\Omega B_\phi}{\Psi_A}$
  (momentum equation along $\mathbf{V}$)
  ⑤ the adiabat $Q(A) \equiv P/\rho_0^\Gamma$
  (entropy equation)
- only one equation remains, the transfield force-balance


(a)
inner
outer
z (pc)
ϖ (pc)
(b)
Ṁ (g s^{-1})
ϖ$_{out}$/ϖ$_{in}$
(c)
magnetic
centrifugal
pressure
dyn cm^{-3}
ϖ/ϖ$_A$
(d)
(Poynting flux)/(mass flux)c^2
γ≈ξγ
(e)
V$_z$/c
V$_\phi$/c
V$_\varpi$/c
(f)
T(^{0}K)
(g)
−B$_\phi$(G)
B$_z$(G)
B$_\varpi$(G)
ϖ/ϖ$_A$


0
2·10^19
4·10^19
6·10^19
z (cm)
1·10^18
0
-1·10^18
y (cm)
1·10^18
0
-1·10^18
x (cm)


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


(mas)
0.1
0.05
-0.05
0.2
0.4
0.6
0.8
1
(mas)


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

Conclusion

AGN jets can be modeled as magnetized outflows

- ⋆ the observed pc-scale acceleration can be attributed to B-fields (magnetic acceleration in a Poynting-dominated flow)
- ⋆ the collimation could be due to B-fields
- ⋆ the observed polarization maps are in principle compatible with helical B-fields