# Relativistic Jets:

## Open Problems and Challenges

Arieh Königl

University of Chicago

# Outline

- Describe a basic dynamical model for the acceleration and collimation of relativistic jets
- Identify the main issues that arise in applications to different astrophysical settings
- Interpreting jet observations:
  emission mechanisms and model testing
- The accretion–outflow connection

# Relativistic Outflows in GRB, AGN, and X-ray Binary Sources

## GRB sources

GRBs evidently involve ultrarelativistic ($\Gamma \sim 10^2 - 10^3$; e.g. GRB 080916C), highly collimated ($\theta_\mathrm{j} \sim 2^\circ - 5^\circ$) outflows. They are likely powered by extraction of rotational energy from a newly formed stellar-mass BH or rapidly rotating NS, or from a surrounding debris disk.

# AGN Jets

Apparent superluminal motions ($V_{\rm apparent}$ as high as $\sim 40\,c$) and rapid Stokes-parameter variability point to a relativistic outflow component on scales $\lesssim 1\ {\rm pc}$ in AGN radio jets.

Although the jets may also contain nonrelativistic components, there is evidence that the relativistic component persists to large (kpc to Mpc) scales: detection of apparent superluminal motions (e.g. 3C 120); indications of deceleration from relativistic speeds in the termination radio lobes; X-ray emission in quasar jets (model-dependent).

# X-Ray–Binary Jets

Although the measured apparent superluminal motions in XRB sources ($V_{\rm apparent} \sim 2 - 5\,c$) appear to be lower than in AGNs, a value $\geq 12\,c$ has already been measured in Cir X-1 (a NS binary).

In all cases, magnetic fields provide the most plausible means of extracting (rotational) energy from the source. They can also guide, collimate, and accelerate the flow.

In the case of GRBs, thermal energy may contribute to the initial jet acceleration (through neutrino emission from the disk) and to the re-acceleration of shocked jet material when it emerges from the progenitor star.

# Magnetic Acceleration and Collimation: General Characteristics

Based on exact (axisymmetric) solutions to the equations of special-relativistic, ideal MHD obtained in semi-analytic form (employing radial self-similarity) and through multi-scale numerical simulations that attain a quasi-steady state (but applicable also to episodic ejections in “frozen pulse” approximation).

[e.g.: Li et al. 1992; Contopoulos 1994; Vlahakis & Königl 2003a,b, 2004; Beskin & Nokhrina 2006; Komissarov et al. 2007, 2009; Lyubarsky 2009a,b.]

Complications of relativistic treatment:

- displacement current and charge density cannot be neglected
- different flow directions coupled through the Lorentz factor
- appearance of a characteristic speed ($c$) prevents the incorporation of central gravity into the self-similarity formulation
- modeling gravitational effects may require using GRE

The steady-state problem involves deriving the joint solution of the Bernoulli and transfield (Grad-Shafranov) equations.

# Summary of Main Results

Ideal-MHD acceleration can be quite efficient, typically leading to a rough equipartition between the Poynting and K.E. fluxes.

The bulk of the acceleration is due to a magnetic ($B_\phi$) pressure gradient: it takes place well beyond the classical fast-magnetosonic (*fms*) point (the critical point of the Bernoulli equation) and persists out to the modified *fms* surface (the "event horizon" for the propagation of *fms* waves when the Bernoulli and G-S equations are solved simultaneously; e.g., Bogovalov 1997).

MHD acceleration is thus in general spatially extended ("gradual unwinding of a twisted rubber band"); this distinguishes it from a purely hydrodynamical (thermal) acceleration.

The acceleration process is intimately tied to the shape of the (poloidal) field lines, which needs to be derived (using the Grad-Shafranov equation) simultaneously with the kinematic properties of the flow (obtained from the Bernoulli equation).

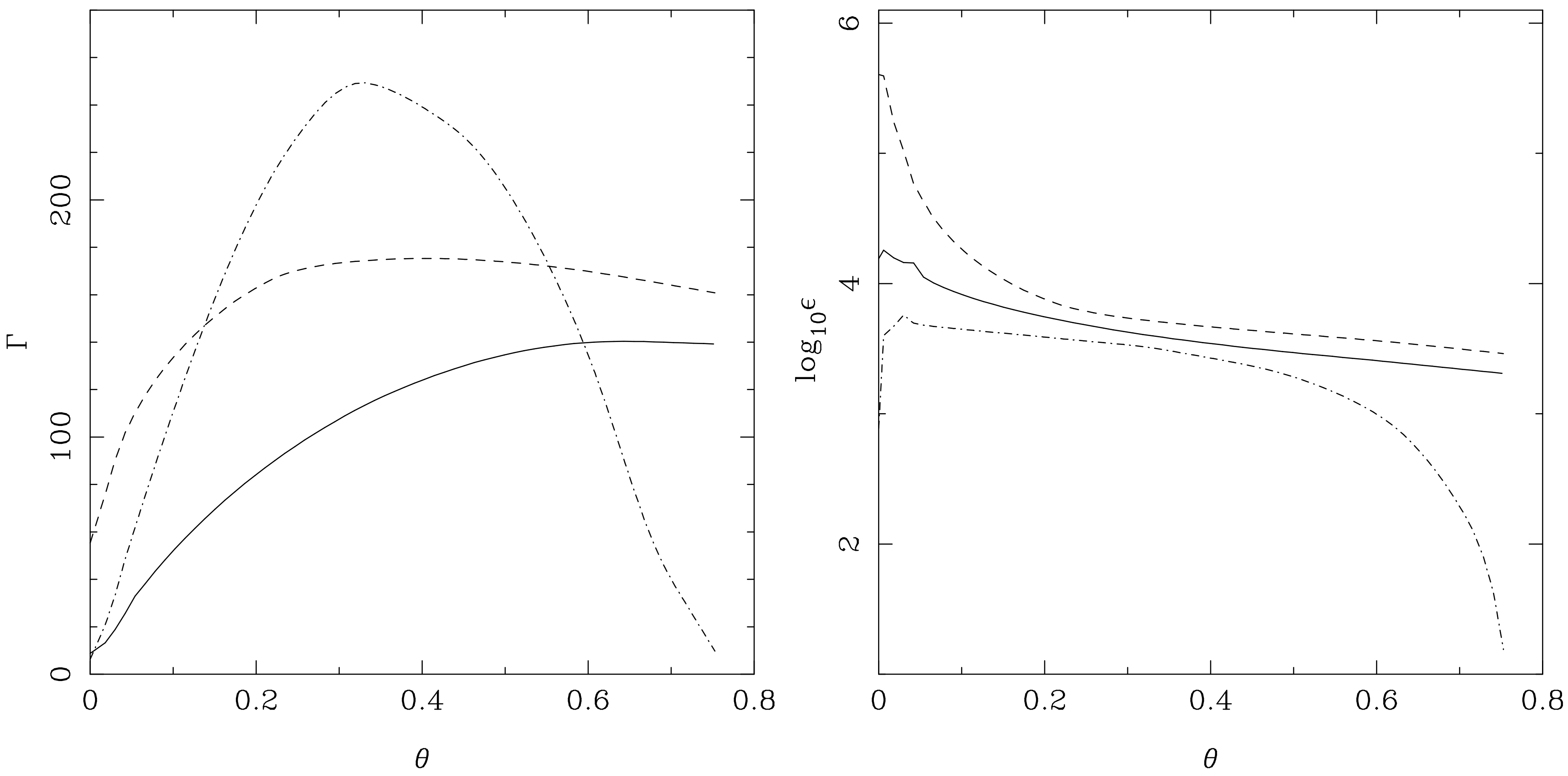
In order for the flow to accelerate, the transverse distance between neighboring field lines must increase faster than their cylindrical radius.

This can occur naturally in current-carrying jets, which develop a cylindrical core (due to compression by the $B_\phi$ hoop stress) even as the outer parts of the flow collimate more slowly.

A general asymptotic result for MHD-accelerated jets: $\Gamma \tan\theta_{\rm v} \approx \Gamma\theta_{\rm v} \approx 1$, where $\theta_{\rm v} \equiv \arctan(dr/dz)$ is the local opening half-angle of the flow. (It can be $\gg 1$ only if the confining pressure drops with $z$ slightly faster than $z^{-2}$.)

The Lorentz factor $\Gamma(\theta)$ typically peaks away from the axis (since the acceleration is due mainly to the gradient along the flow of the magnetic pressure associated with $B_\phi$, and $B_\phi$ vanishes on the axis by symmetry).

However, the kinetic power per unit solid angle $\epsilon(\theta)$ usually does peak at $\theta \approx 0$ (reflecting the higher density attained in the collimated core).




Komissarov et al. (2009)

- These generic distributions are very different from those commonly adopted in phenomenological jet models (e.g. the "universal" model of GRB outflows, $\epsilon \propto \theta^{-2}$, or the "hollow cone" model, which assumes that both $\Gamma(\theta)$ and $\epsilon(\theta)$ peak away from the axis).

- The inferred basic properties should characterize any magnetically accelerated outflow, including highly relativistic pulsar winds and the mildly relativistic outflows that carve out pulsar wind nebulae (e.g. Kirk et al. 2007).

# Confinement and Collimation

The collimation by the magnetic hoop stress of the innermost streamlines of a current-carrying jet relative to the outer streamlines represents the self-collimation property of magnetized outflows.

However, a magnetized jet cannot be ‘self-confined’: an ambient (thermal, magnetic, or ram) pressure needs to confine the flow.

The spatial distribution of the confining external pressure (e.g. $p_{\rm ext}(z) \propto z^{-\alpha}$) determines the shape of the flow boundary (e.g. $z \propto r^{\beta}$) and hence the acceleration efficiency.

$\alpha \Leftrightarrow \beta$ correspondence:

$\alpha < 2 \ \Leftrightarrow \ \beta = 4/\alpha > 2\,,$

$\alpha = 2 \ \Leftrightarrow \ 1 < \beta \leq 2$ (magnitude of $p_{\rm ext}$ fixes value of $\beta$),

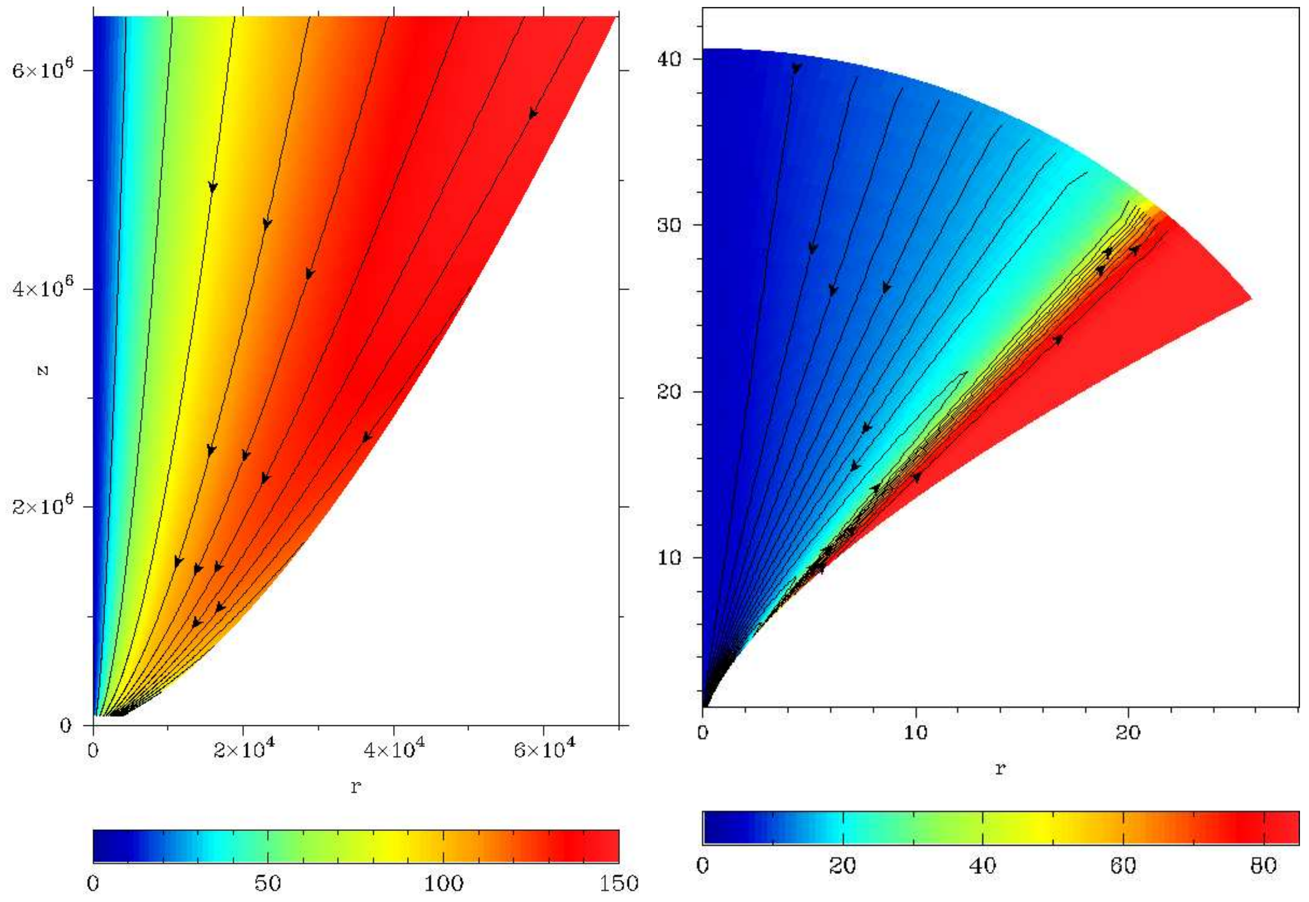
$\alpha > 2 \ \Leftrightarrow \ \beta = 1$ (asymptotically).

In order for the bulk of the flow to be efficiently accelerated, there has to be causal connectivity across the flow: the inner and outer streamlines must be able to communicate (through the propagation of *fms* waves) on the radial expansion time.

Causal connectivity cannot be maintained if $\alpha > 2$. In that case the boundary asymptotically approaches a conical shape (‘free’ ballistic expansion) and significant acceleration occurs only near the axis.

(N.B. a super-*fms* jet that emerges into a lower-pressure environment may experience a rarefaction wave-induced boost when it becomes unconfined, leading to $\Gamma\theta_{\rm v} \gg 1$ on the outer streamlines; Tchekhovskoy et al. 2009.)

# Confined vs. Unconfined Jets



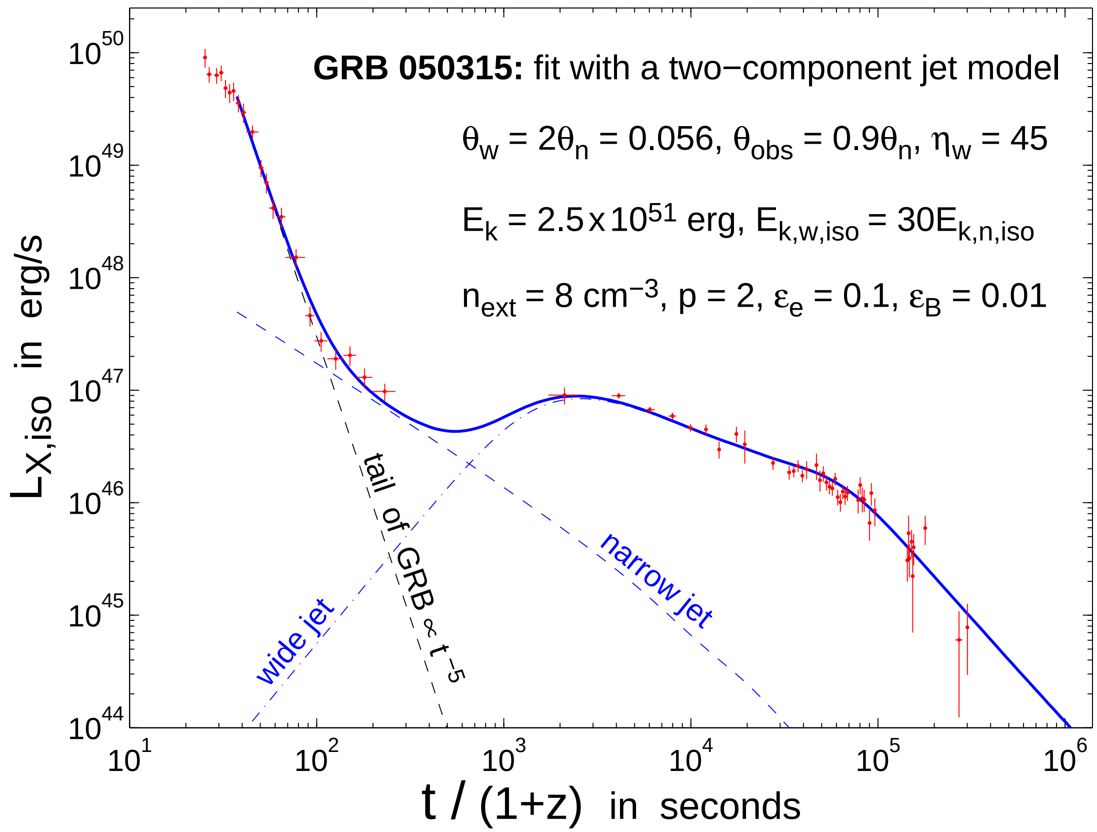

Komissarov (2009)

External confinement is particularly important for relativistic flows since, as $\Gamma$ becomes $\gg 1$, the increased inertia and the growth of the electric force (which nearly cancels the transverse magnetic force) reduce the collimation efficiency.

A natural confining agent is a disk wind, which could itself be driven hydromagnetically.

This leads naturally to a two-component jet model, with a fast, narrow “spine” surrounded by a wider, slower, outflow. The fast component could be associated with the central object (e.g. a Blandford-Znajek jet from the black hole ergosphere) or else correspond to the innermost disk outflow.

• In the case of GRBs, the disk outflow could itself be relativistic ($\Gamma \gtrsim 10$) and might account for the bulk of the afterglow emission.




Granot et al. (2006)

- In the case of AGNs, this type of model has long been advocated given that distinct relativistic and nonrelativistic outflow components are directly observed. The relative contribution of two such components – attributed to the BH and disk, respectively – is one possible explanation of the FR I/FR II dichotomy.

! Test observationally through measurements of broad iron lines (in FR IIs).

- The possible presence of localized ultrarelativistic components within a moderately relativistic outflow was proposed also for AGNs to account for the fast TeV variability in blazars (e.g. Ghisellini et al. 2009a; Giannios et al. 2009).

# Confrontation of Model with Observations

## GRB Sources

+

- Long-duration GRB jets could potentially be confined by the envelope of the massive stellar progenitor. MHD model estimates of the acceleration distance to $\Gamma \sim 100$ are $\sim 10^{10} - 10^{12}$ cm.

- Short-duration GRB jets could potentially be confined by a disk wind from a merging binary BH if they have lower Lorentz factors ($\Gamma \gtrsim 30$).

- The relation $\Gamma\theta_{\rm v} \approx 1$ implies $\theta_{\rm v} \lesssim 1^\circ$ for $\Gamma \gtrsim 100$. This is consistent with the inferences from early afterglow observations of certain sources (e.g. GRB 070401).

- The inference $\Gamma\theta_{\rm v} \gg 1$, made from the interpretation of an apparent panchromatic break in the afterglow lightcurve of some GRBs at much later times ($\gtrsim 1$ d) might be related to the emergence of the jet from the stellar progenitor (Tchekhovskoy et al. 2009)

# ?

- It would be difficult to interpret late-time panchromatic breaks in the lightcurves of short-duration GRBs in this picture.

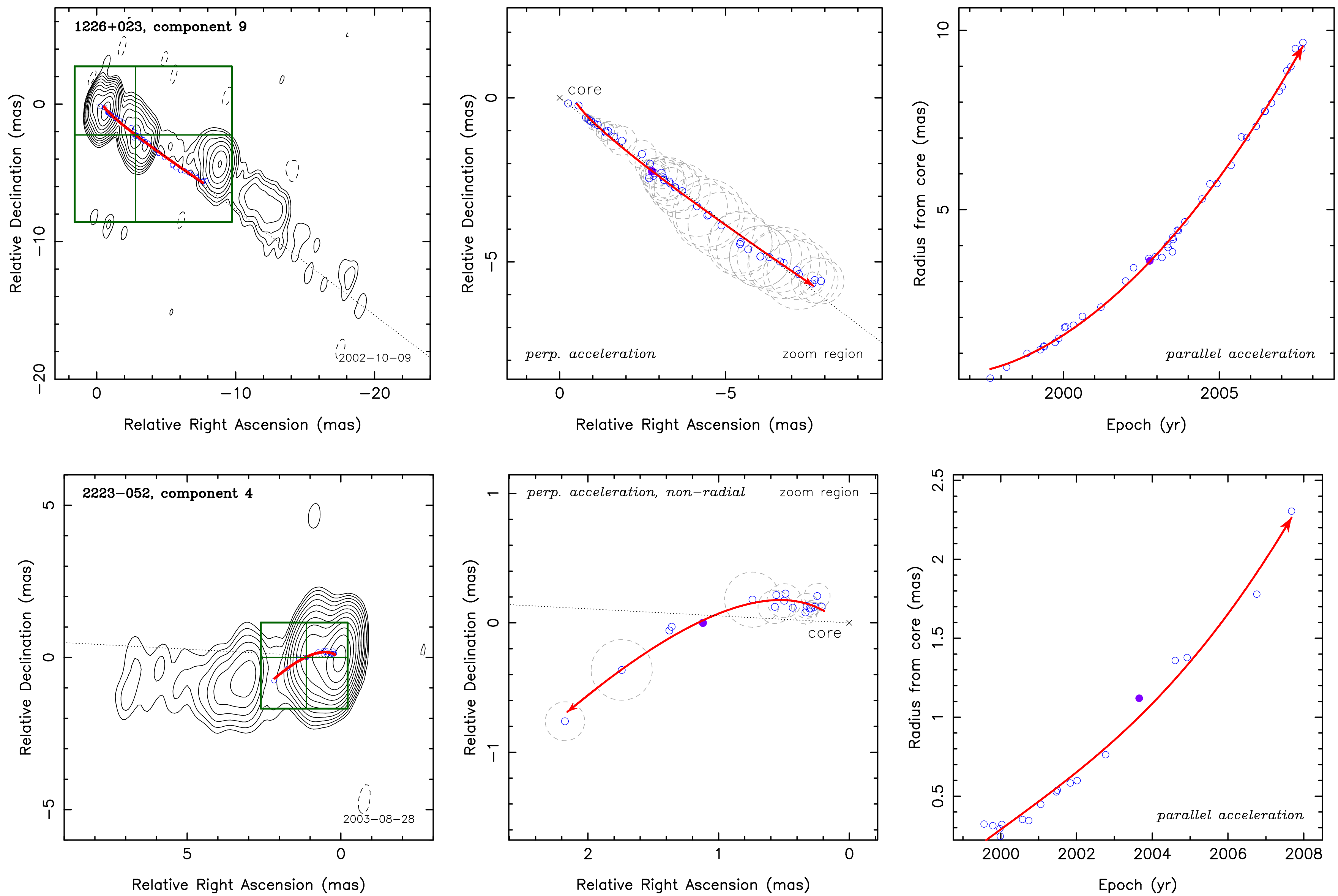
- Certain models of long-duration GRBs invoke the contribution of a hot cocoon of gas created by the jet material that was shocked while the jet propagated inside the progenitor star. Such cocoons are unlikely to form for Poynting flux-dominated outflows (e.g. Komissarov & Barkov 2007).

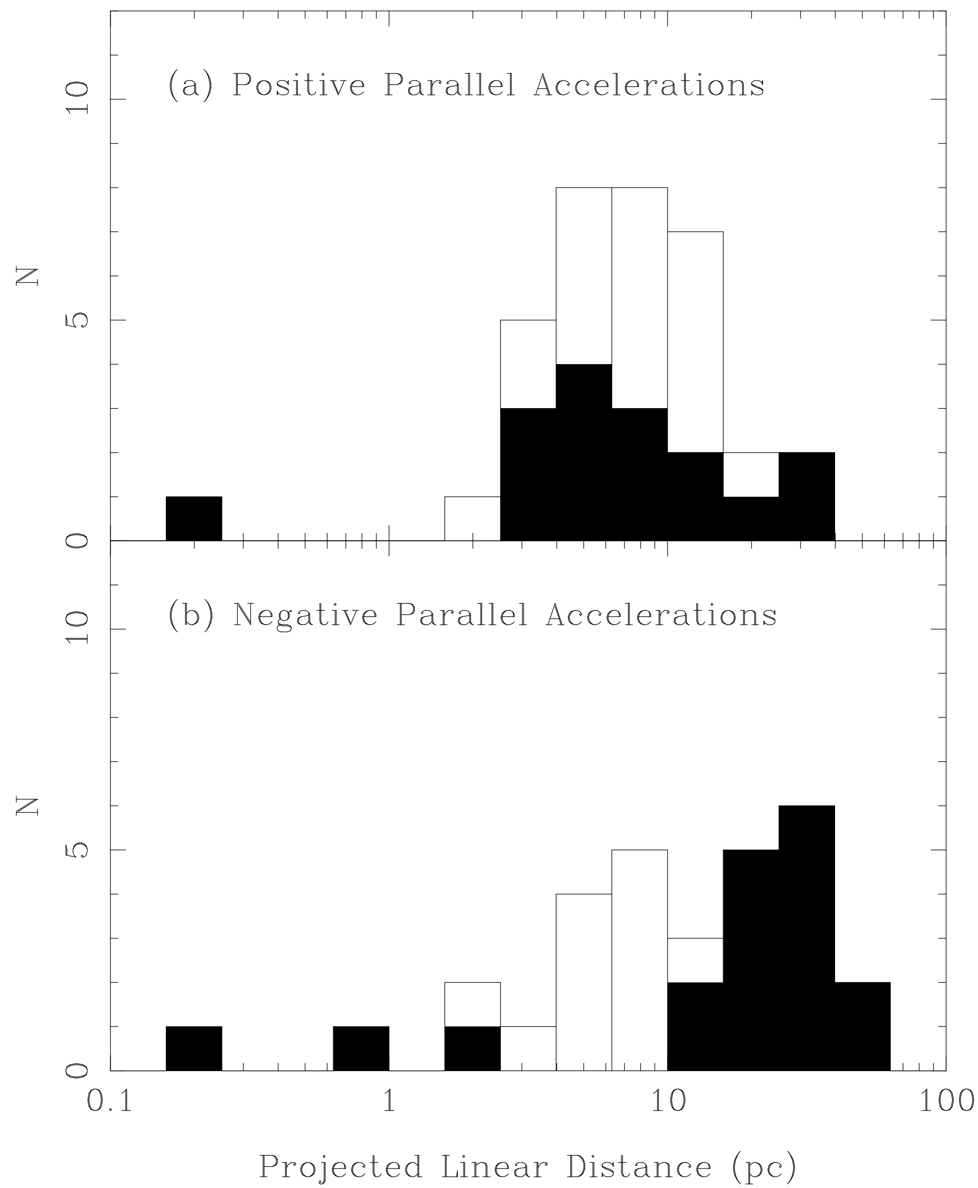
# AGN Jets

A growing body of data indicates that relativistic AGN jets undergo the bulk of their acceleration (and much of their collimation – e.g. M87) on $\gtrsim 0.1$ pc scales ($\gg$ size of central black hole).

- The absence of bulk-Comptonization spectral signatures in blazars implies that Lorentz factors $\gtrsim 10$ must be attained on scales $\gtrsim 10^{17}$ cm (Sikora et al. 2005).

- VLBI monitoring of a growing sample of blazar jet components (e.g., in the MOJAVE project; Homan et al. 2009)


1226+023, component 9
2002−10−09
Relative Declination (mas)
Relative Right Ascension (mas)
core
perp. acceleration
zoom region
Radius from core (mas)
Epoch (yr)
parallel acceleration
2223−052, component 4
2003−08−28
perp. acceleration, non−radial



(a) Positive Parallel Accelerations
(b) Negative Parallel Accelerations
N
0
5
10
0.1
1
10
100
Projected Linear Distance (pc)

!

# Comprehensive Modeling of Superluminal Jets

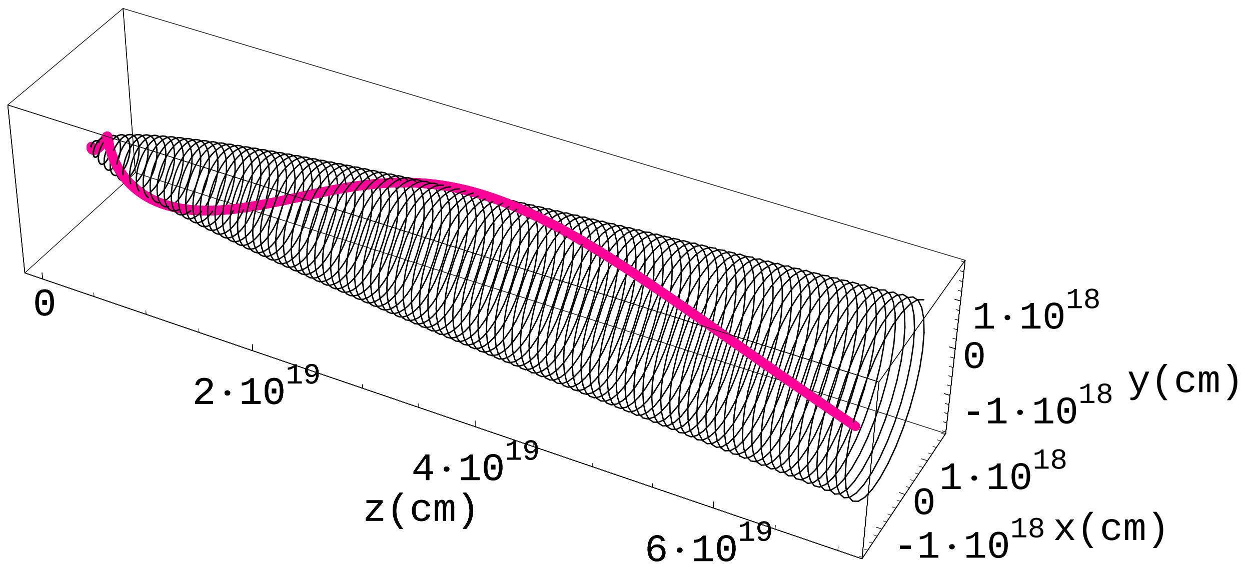
## Kinematics

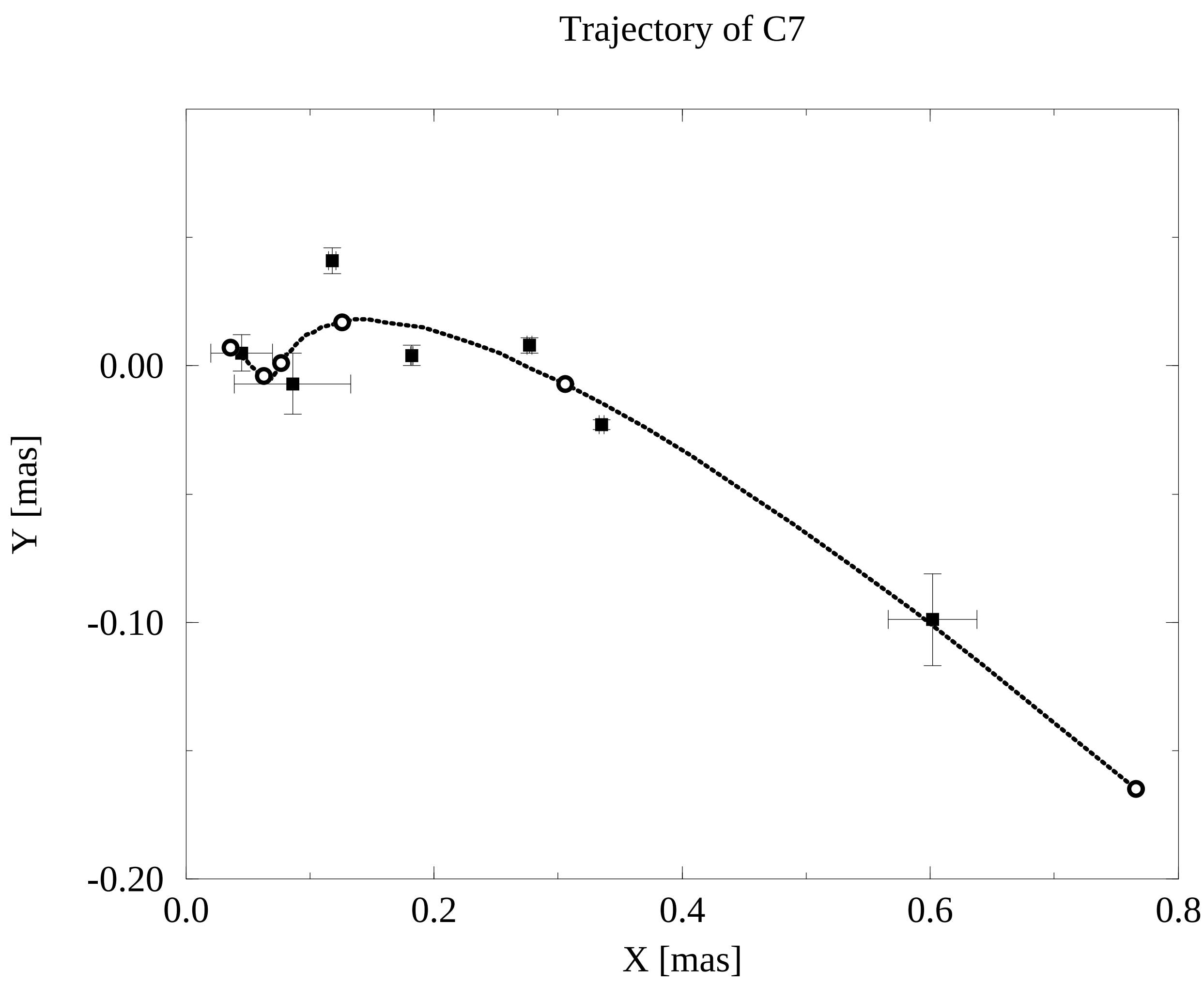
Detailed recent VLBI observations have revealed that superluminal components move on helical paths.

The trajectory shapes could arise from motion along helical field lines (Camenzind & Krockenberger 1992).

In particular, each component could correspond to an ejection episode along an isolated magnetic flux bundle that threads the nuclear accretion disk.

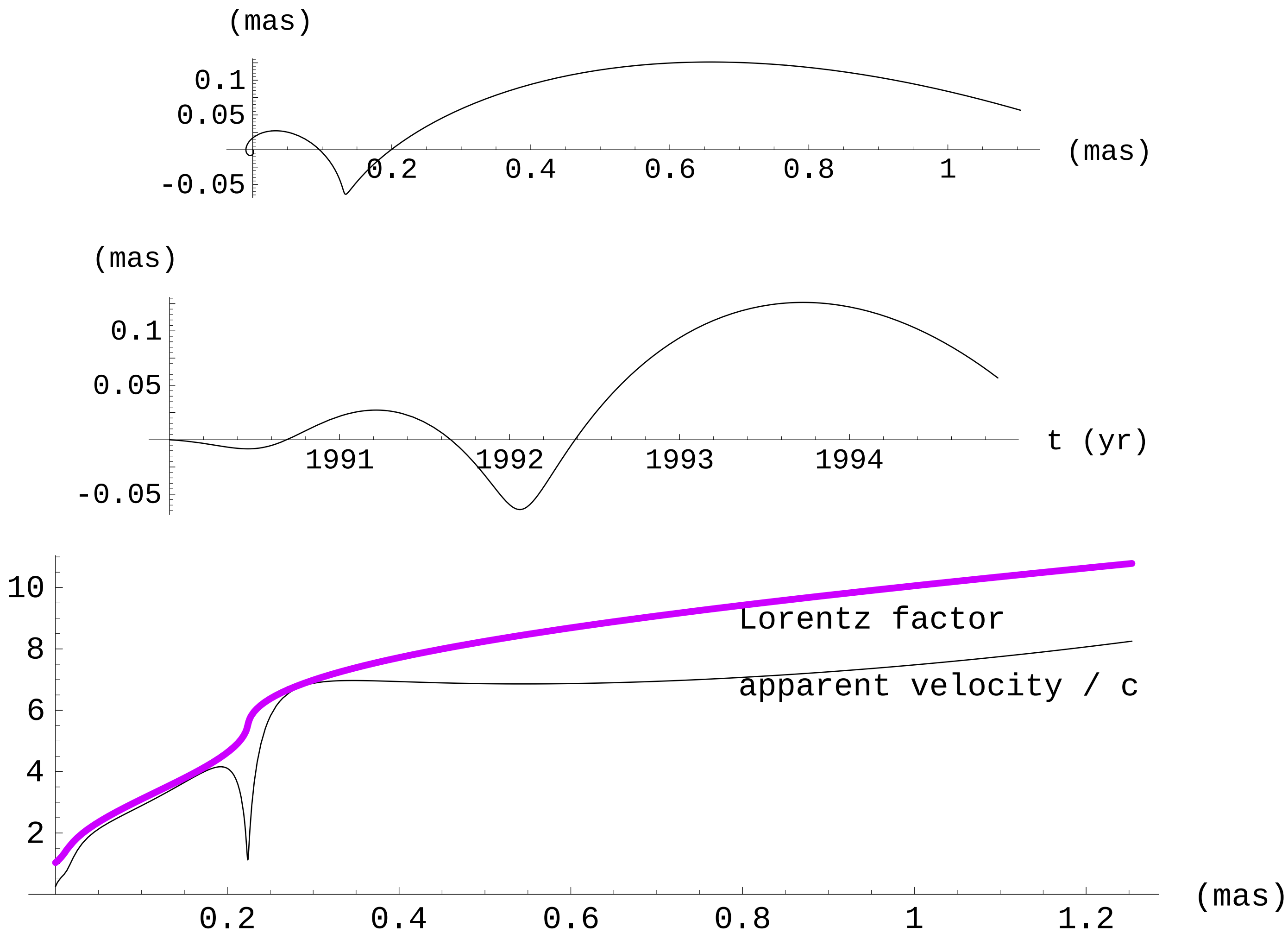
# Model fit for 3C 345

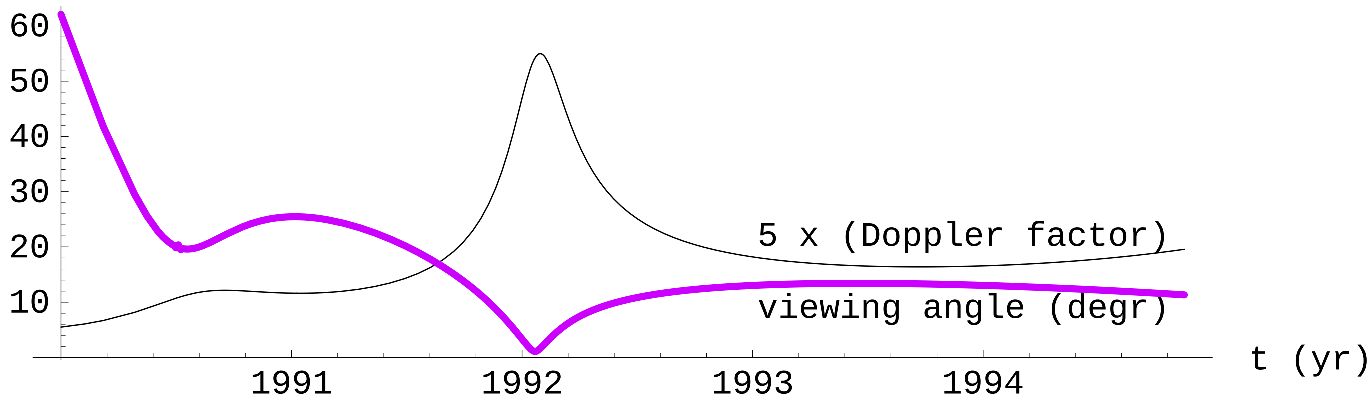




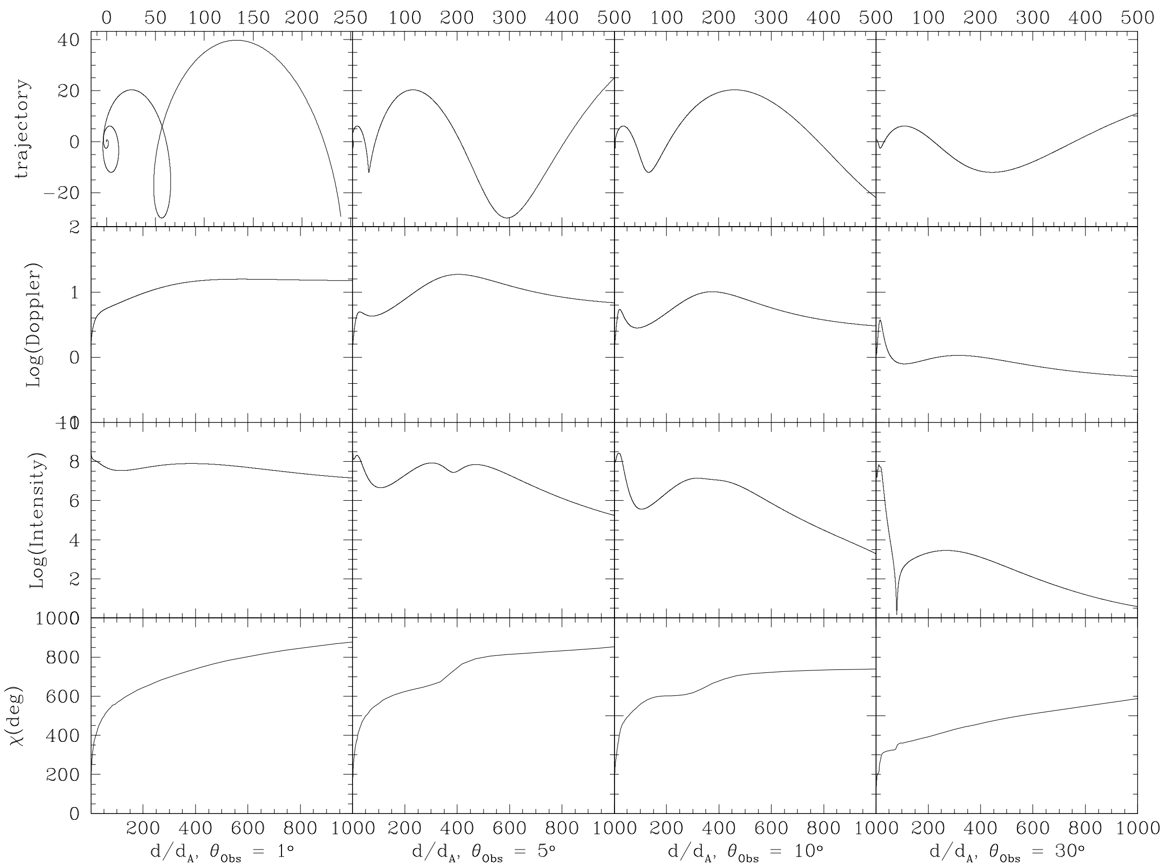

Lobanov 1996

# Fit to component C7






By applying all available kinematic constraints to the dynamical model, one could test this picture against alternative interpretations (unstable fluid modes, source precession, etc.). Valuable additional constraints could be provided by the radiative properties of the jet (flux, linear and circular polarization, Faraday rotation measure).



trajectory
Log(Doppler)
Log(Intensity)
χ(deg)
d/d_A, θ_Obs = 1°
d/d_A, θ_Obs = 5°
d/d_A, θ_Obs = 10°
d/d_A, θ_Obs = 30°

# Radiative Effects

♣ Intimately related to dynamical model

- At the source (neutrino emission generating a “hot” GRB jet)
- On the way out (inverse-Compton constraint and photon breeding mechanism in AGNs)
- In the jet (origin of prompt and afterglow emission in GRBs; origin of highest observed $\gamma$-rays in GRBs and AGNs; origin of X-ray emission from quasar jets)

## Thermal Acceleration Effects

- If the enthalpy per baryon mass is $\gg 1$ at the source then the initial acceleration will be thermal, but the poloidal magnetic field will guide the flow even if the Poynting/enthalpy flux ratio is initially $< 1$ provided that the flow is sub-Alfvénic at the origin.

- Depending on the confining pressure distribution and the adiabatic index of the gas, the enthalpy flux in the thermal acceleration region could either go only into kinetic energy or else be partially converted into Poynting flux (thereby contributing to the jet acceleration further out).

- Initially hot flows tend to shift the angular distribution of the jet kinetic power toward the axis.

## Interaction with the Ambient Radiation field

- The ambient radiation could arise from direct disk irradiation, scattered or reprocessed disk radiation, broad-line region emission, and the microwave background.

- Besides the spectral effects embodied in the “external” inverse-Compton component (e.g. the *Fermi* blazars’ divide), this interaction can place strong limits on the distance of the acceleration region from the source.

- By considering also the possible conversion of upscattered photons into $e^+e^-$ pairs through $\nu - \nu$ collisions, Stern & Poutanen (2006, 2008) came up with the photon breeding mechanism.

In this picture, a significant fraction of the jet kinetic energy could potentially be converted into high-energy emission.

! Two key assumptions of this model still need to be verified (by numerical simulations):

1. Dynamical response of ambient medium. (Significant acceleration? Development of a turbulent boundary layer?)

2. Nature of postulated magnetization of ambient medium. (An MHD disk wind? What would be the effect of a direct dynamical interaction between the wind and the jet?)

## Uncertainties about the Jet Emission Mechanisms

Example: GRB sources

- What is the origin of the prompt emission?

(And is it synchrotron or jitter or SSC?)

The popular internal-shocks model has been challenged, among other things, by indications from *Swift* and *Fermi* measurements that the emission region is fairly distant ($\gtrsim 10^{15} - 10^{16}$ cm; e.g. Lyutikov 2006; Zhang & Pe'er 2009).

One possible alternative is relativistic turbulence due to magnetic energy dissipation in an electromagnetically driven outflow (e.g. Lyutikov & Blandford 2003). It has been argued that GRB 080319B can be interpreted in this way (Kumar & Narayan 2009).

! This possible overturning of the prevailing paradigm has important dynamical implications.

- Should the MHD description be replaced by a magnetodynamical one (force-free electrodynamics; $\rho_{\rm e}\mathbf{E} + \mathbf{j}\times\mathbf{B} = 0$)?

While the MHD model has the advantage of being able to explicitly calculate the jet velocity and magnetic-to-kinetic energy conversion efficiency, the basic parameter scalings obtained in this model can also be derived in the force-free approximation (Tchekhovskoy et al. 2008; Komissarov et al. 2009).

- Even if the MHD picture is applicable, ideal MHD may not be (Blandford 2002).

Magnetic energy dissipation naturally creates a magnetic pressure gradient that, even on its own (i.e., without incorporating the acceleration that occurs in the absence of dissipation), may lead to a highly efficient acceleration to relativistic speeds (Drenkhahn & Spruit 2002).

! So far this effect has only been modeled in an approximate manner, using strong simplifications: it needs to be studied with the help of resistive relativistic-MHD codes.

♣ The field dissipation process might occur under certain constraints (in particular, the conservation of magnetic helicity) that may limit the amount of dissipated energy and affect the magnetic field structure inside the jet.

The magnetic dissipation may be tied to current-driven instabilities (in particular $m = 1$ kink) in the jet (e.g. Giannios & Spruit 2006; Moll et al. 2008).

! It is however still debatable whether the jet might become only marginally unstable (e.g. McKinney 2006) or even remain entirely stable (e.g. Mizuno et al. 2008; McKinney & Blandford 2009).

♣ The issue of magnetic energy dissipation in a Poynting flux-dominated outflow is directly related to the low-$\sigma$ problem in pulsar-wind theory.

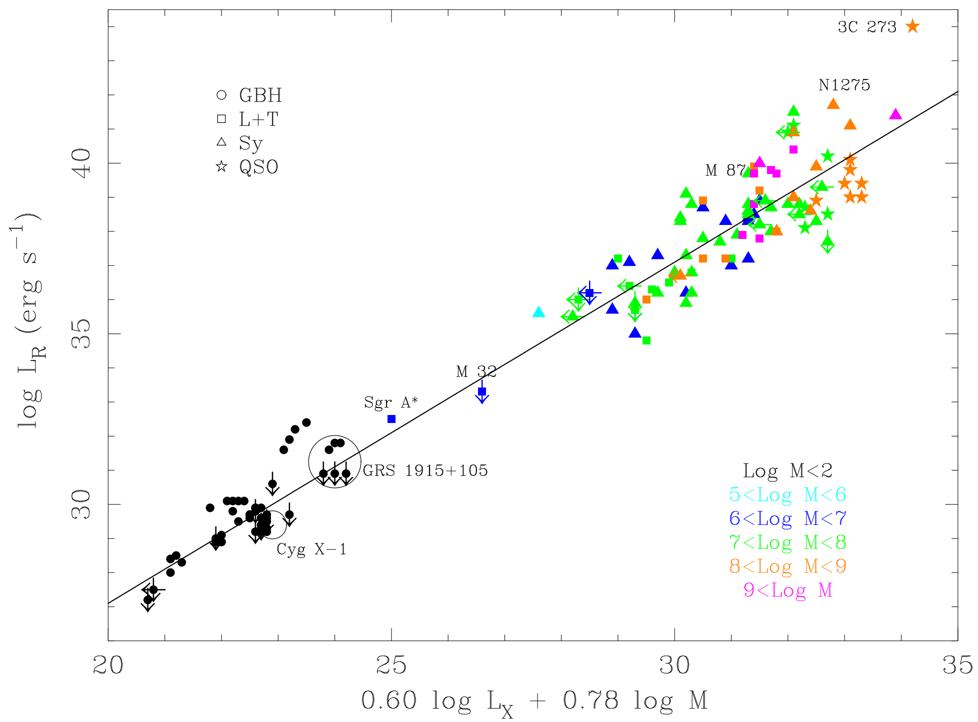
• Particle acceleration in relativistic outflows may conceivably occur also by tapping directly into a cross-flow velocity shear (e.g. Stawarz & Ostrowski 2002; Lyutikov & Ouyed 2007).

- What is the origin of the afterglow emission?
- How many distinct outflow components contribute at any given phase?
- What are the relative contributions of the synchrotron and inverse-Compton processes to the observed emission?
- What is the origin of the magnetic field inferred from synchrotron radiation models – post-shock instability (Weibel); pre-shock amplification tied to particle acceleration (as inferred from X-ray synchrotron emission in SNRs); field carried in the jet from the source?

- What is the role of the reverse shock in the emission – dominant (e.g. Genet et al. 2007; Uhm & Beloborodov 2007) or negligible (on account of a high magnetization of the ejecta; e.g. Mimica et al. 2009)?

- To what extent do afterglow lightcurves exhibit panchromatic lightcurve breaks that provide information about the flow collimation?

# The Accretion–Outflow (Disk–Jet) Connection




AGNs and XRBs (Merloni et al. 2003)

The same scaling relation between the radio ($L_{\rm R}$) and X-ray ($L_{\rm X}$) luminosities, normalized by the BH mass $M$, is inferred in AGNs and in Galactic BH sources:

$$\log L_{\rm R} \approx 0.60 \log L_{\rm X} + 0.78 \log M + 7.33$$

$L_{\rm X}$ and $L_{\rm R}$ can be regarded as proxies for the accretion and outflow luminosities, respectively.

• A positive correlation between the jet power and the luminosity of the accretion disk is found also in broad-line blazars when the observed $\gamma$-ray luminosity is used as a proxy for the jet power (Ghisellini et al. 2009b).

- Galactic BHs exhibit this relation in the low/hard state; the radio emission is quenched when the X-ray luminosity grows to $\lesssim 10\% \, L_{\rm Edd}$ and the source enters the high/soft state.

- A similar quenching of the radio emission is inferred in AGNs; AGNs such as Narrow-Line Seyfert 1 galaxies may correspond to the high/soft state.

- The low/hard state in Galactic BH binaries has been interpreted as an accretion phase during which steady-state jets carry away most of the liberated power. Transient jet outflows may occur at higher accretion rates during the very-high (or steep-power-law) state, of which powerful radio-jet sources may be the AGN analogs.

- It was proposed that jet dominance during the low/hard state might be related to the formation of a large-scale poloidal field configuration, possibly associated with the thickening of the disk during a radiatively inefficient accretion phase or with magnetic flux advection.

- Other possibilities include: (i) field amplification when the disk becomes convectively unstable during the radiatively inefficient phase, (ii) a correlation between the confining gas pressure and the strength of the magnetic field threading the ergosphere, and (iii) better collimation of an inner relativistic outflow by a stronger disk wind.

! A strong accretion–outflow connection is indicated in all cosmic jet sources (including young stellar objects), but its specific nature (e.g.: origin in central source or disk?) remains a puzzle.

- One might gain new insights from relativistic jet sources (e.g. by comparing NS and BH XRBs to clarify role of BH spin).