Jet Launching – General Review

Arieh Königl
University of Chicago

Outline:

- Universality of the relativistic-jet phenomenon: to $\mathbf{B}$ or not to be
- Magnetic acceleration and collimation of relativistic jets: debunking a few myths and cherished beliefs
- Ideal-MHD models of relativistic outflows: application to superluminal AGN jets
- And you thought we understood it all: new puzzles from *Swift* observations of GRBs
- Magnetic energy dissipation: life is not always ideal
- Two-component jet models: life is not always simple
- Conclusions: facing up to the challenges

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

GRB sources

GRBs evidently involve ultrarelativistic ($\gamma_\infty \sim 10^2 - 10^3$), highly collimated ($\theta_{\rm j} \sim 2^\circ - 5^\circ$) 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.

Magnetic fields provide the most plausible means of extracting the energy on the burst timescale. They can also guide, collimate, and accelerate the flow.

Thermal energy, derived from neutrino emission, may contribute to the initial jet acceleration in these sources.

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 $\lesssim 1$ 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.

While the composition remains uncertain, there are indications that protons dominate the mass flux even as e^+e^- pairs dominate the particle flux in relativistic QSO jets.

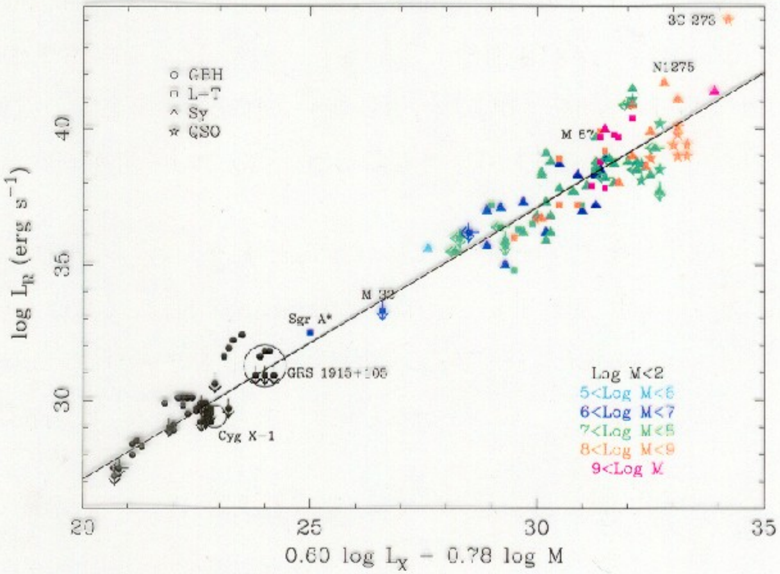
Magnetic fields are considered the most likely driving mechanism in this case as well (Blandford & Znajek 1977; Blandford & Payne 1982).

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 $\gtrsim 9\,c$ has already been measured in Cir X-1 (a NS binary), and it has been argued (Miller-Jones et al. 2006) that the jet Lorentz factors might be comparable to those of AGNs.

The same scaling relation between the radio ($L_{\rm R}$) and X-ray ($L_{\rm X}$) luminosities, normalized by the BH mass M, was inferred in AGNs and in Galactic BH sources (Merloni et al. 2003; Falcke et al. 2004):

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



Merloni et al. (2003)

- 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 (e.g., Fender et al. 2004). 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 (e.g., Jester 2005).

- 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 (Meier 2001; Livio et al. 2003) or with magnetic flux advection (Tagger et al. 2004; Spruit & Uzdensky 2005).

Magnetic Acceleration and Collimation: Popular Myths and Cherished Beliefs

There is a persistent and pervasive belief that ideal-MHD models cannot account for the observed acceleration and collimation of relativistic jets.

The myth:

1. "After passing through the classical critical points (slow-magnetosonic, Alfvén, and fast-magnetosonic), most of the energy of a (steady) relativistic outflow remains in the form of Poynting flux. Further acceleration of the flow is not straightforward within ideal MHD, although a limited degree of acceleration is possible if the flow has a decollimating shape (i.e., the magnetic field diverges faster than radial)."

   (A slightly reworked quote from a 2006 paper by a famous scientist.)

2. "An important property of relativistic outflows is that they are hard to collimate."

   (A quote from a 2006 paper by young, soon-to-be-famous scientist summarizing previous work on relativistic jets.)

The truth (further elaborated by N. Vlahakis):

Ideal-MHD acceleration can be quite efficient, typically leading to a rough equipartition between the Poynting and kinetic energy fluxes (although an almost complete conversion of magnetic to kinetic energy is possible).

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, however, does *not* mean that the field lines cannot collimate. Most early treatments assumed, for convenience, that the field lines have a radial (or nearly radial) shape, in which case acceleration is indeed poor, but this is the exception, not the rule.

Good collimation can be attained even for relativistic outflows by purely hydromagnetic means, although it is true that the collimation is most efficient in the region where the flow is not yet highly relativistic.

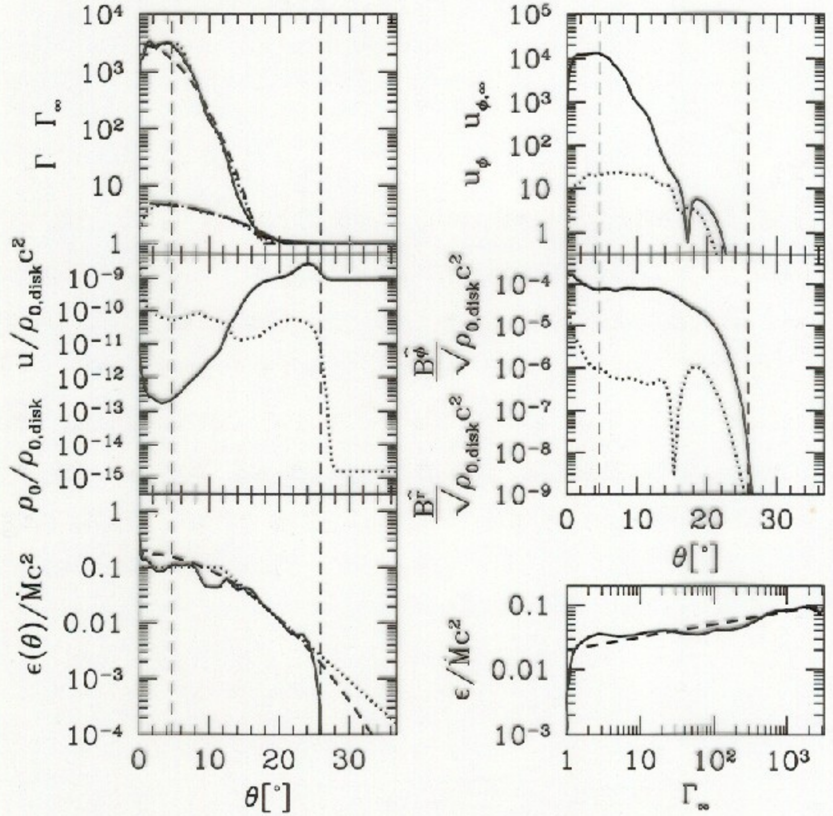
The bulk of the acceleration is due to a magnetic (B_ϕ) pressure gradient: it takes place well beyond the classical fast-magnetosonic point (the critical point of the Bernoulli equation) and persists out to the *modified* fast-magnetosonic surface (the "event horizon" for the propagation of fast-magnetosonic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

This overturns another cherished belief (inspired by purely hydrodynamic models), which has it that an outflow undergoes the bulk of its acceleration on the scale of the size of the mass distribution that initially confines it by its gravity.

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

♣ This presents a challenge to numerical simulations.

Recent advances have led to simulations of general-relativistic MHD outflows powered by the extraction of the rotational energy of a central black hole and/or a surrounding accretion disk (e.g., McKinney & Gammie 2004; De Villiers et al. 2005; Komissarov 2005). In all cases studied so far, the acceleration to the terminal Lorentz factor takes place on scales that are much larger than those actually simulated.



θ profile of outflow at $r = 5 \times 10^3\, r_{\rm G}$ (McKinney 2006)

One additional cherished belief:

3. “The inferred ratio of kinetic to internal energy in GRB outflow sources is unprecedented in gas dynamics. It is extremely hard to create a hypersonic, high Mach number flow in the laboratory using a carefully machined nozzle. There are always transient waves associated with the walls that cause large fluctuations in the velocity field and subsequent heating.”

   (A slightly reworked quote from a 2002 paper by a *truly* famous scientist who argues against the validity of applying ideal MHD to the modeling of highly relativistic outflows.)

But there is a surprise:

Magnetic energy dissipation naturally creates a magnetic pressure gradient (typically associated with a decrease of $|B_\phi|$ with distance from the source) 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). This dissipation may also be relevant to the observed radiation from the jet (more on this below).

Exact Relativistic-MHD Solutions

References: Vlahakis & Königl 2001 (ApJ 563, L129), 2003a,b (ApJ 596, 1080; 1104).

- Exact semianalytic solutions of relativistic outflows were constructed within the following framework:
    - Relativistic, ideal-MHD formulation
    - Axisymmetry
    - Poloidal magnetic flux distribution at the source (specified by the function A) is approximately constant on the relevant (e.g., burst) time scale
    - Steady-state equations apply even if the flow is not strictly continuous (consisting, instead, of distinct ejected shells) in the limit that the poloidal Lorentz factor is $\gg 1$ — analog of "frozen pulse" approximation in purely hydrodynamic models (e.g., Piran et al. 1993)
    - Initially relativistically hot $\{pe,\ e^+e^-,$ photon$\}$ gas evolves adiabatically with $\Gamma_{\rm ad} = 4/3$
    - Although gravity cannot be included, Keplerian rotation at the base can be mimicked

- The general problem requires the specification of 7 constraints: 4 associated with boundary conditions at the source and 3 determined by regularity requirement at the critical points of the joint solution of the Bernoulli and transfield (Grad-Shafranov) equations.

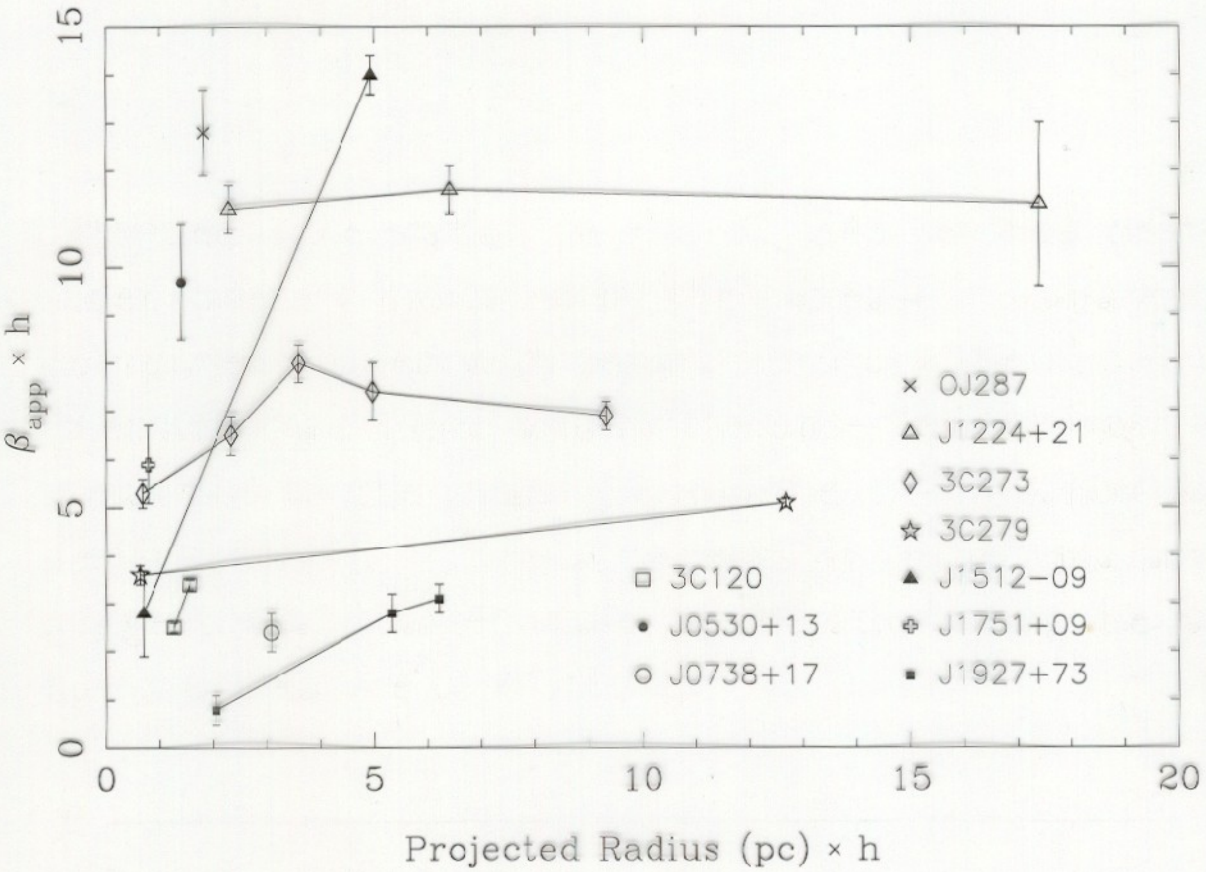
Application to AGN Jets

Reference: Vlahakis & Königl 2004 (ApJ 605, 656)

A growing body of data indicates that relativistic AGN jets undergo the bulk of their acceleration on parsec scales (>> 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).
- Unwin et al. (1997) combined a VLBI proper-motion measurement of component C7 in the quasar 3C 345 jet with an inference of the Doppler factor from an X-ray emission measurement (interpreted as SSC radiation) to deduce an acceleration from $\gamma \sim 5$ to $\gamma \gtrsim 10$ over $r \sim 3 - 20$ pc. 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 the quasar 3C 279 jet using a similar approach.

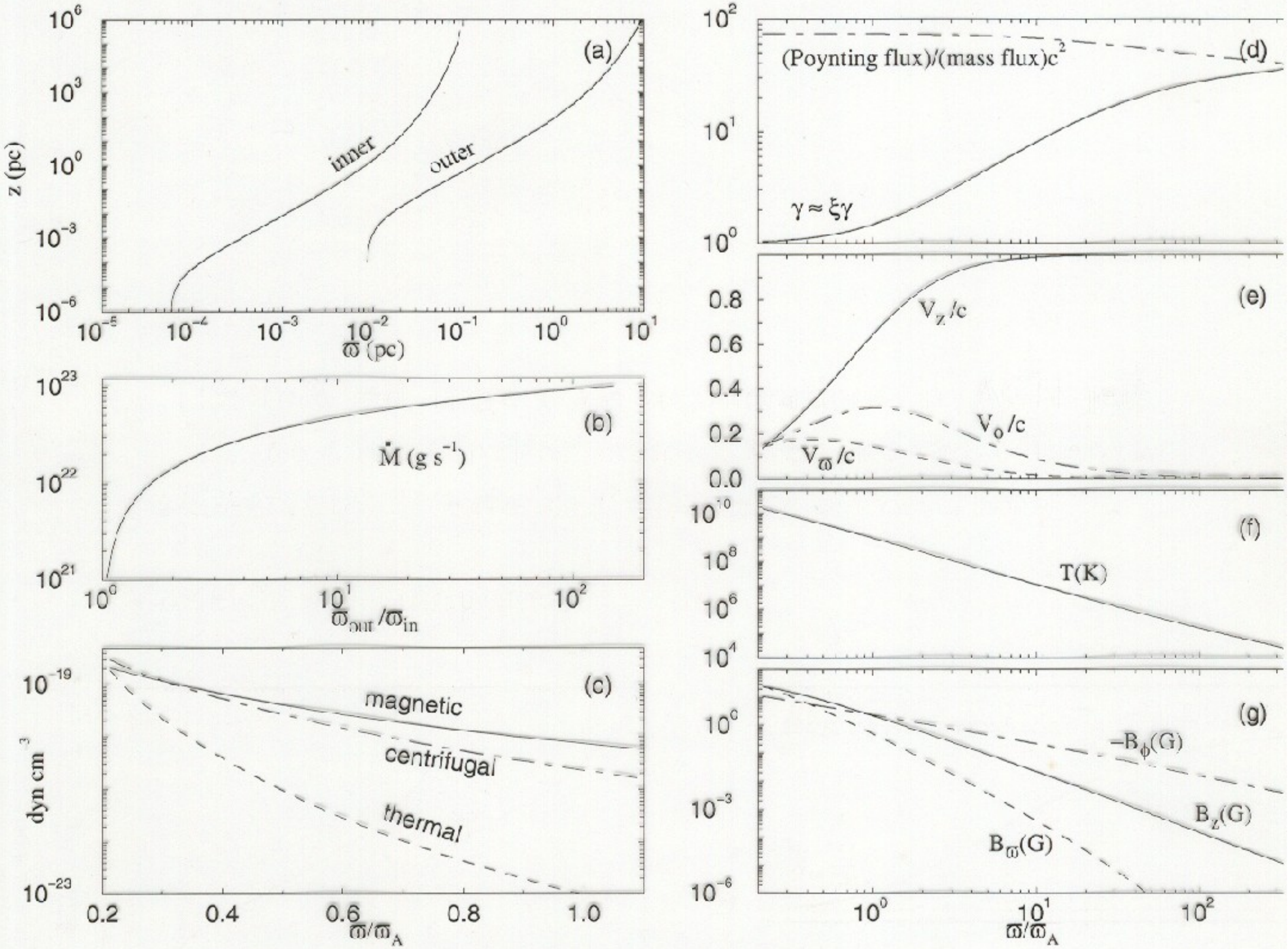
- Extended acceleration in the 3C 345 jet has been independently indicated by the increase in apparent component speed with separation from the nucleus (Zensus et al. 1995) and by the observed luminosity variations of the moving components (Lobanov & Zensus 1999). Similar effects in other blazars suggest that parsec-scale acceleration may be a common feature of AGN jets.



Homan et al. 2001

- The inferred large-scale accelerations in AGN jets cannot be purely hydrodynamic; they are most likely a manifestation of extended magnetic acceleration.

Model fit for component C7 in 3C 345



(ϖ_{A} is the Alfvén lever arm.)

$\gamma_\infty \approx 35$, consistent with values inferred in components C3 and C5.

Comprehensive Modeling of Superluminal Jets

Reference: Vlahakis, Marin, & Königl (2006, in prep.)

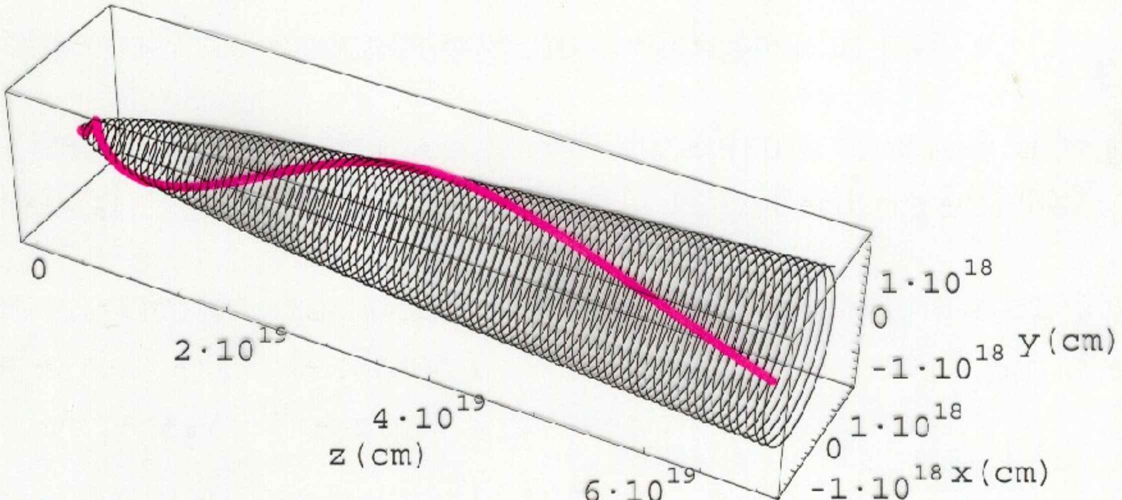
Kinematics

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).

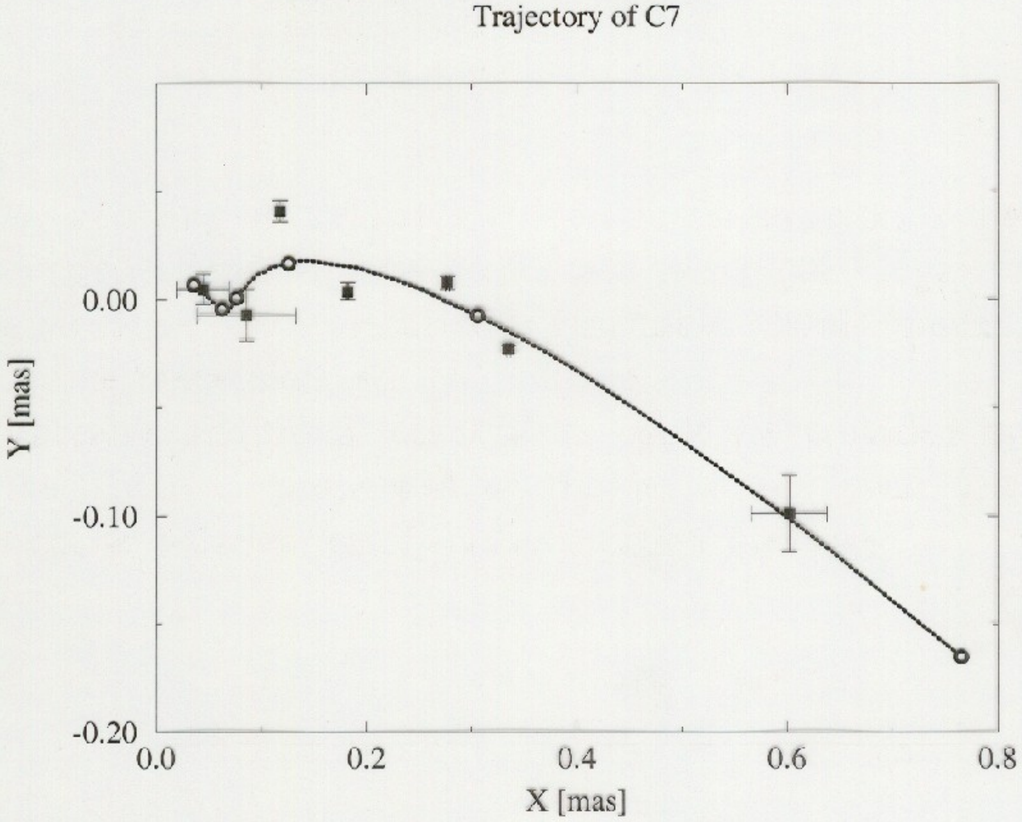
In particular, each component could correspond to an ejection episode along an isolated magnetic flux bundle that threads the nuclear accretion disk.

Model fit for 3C 345



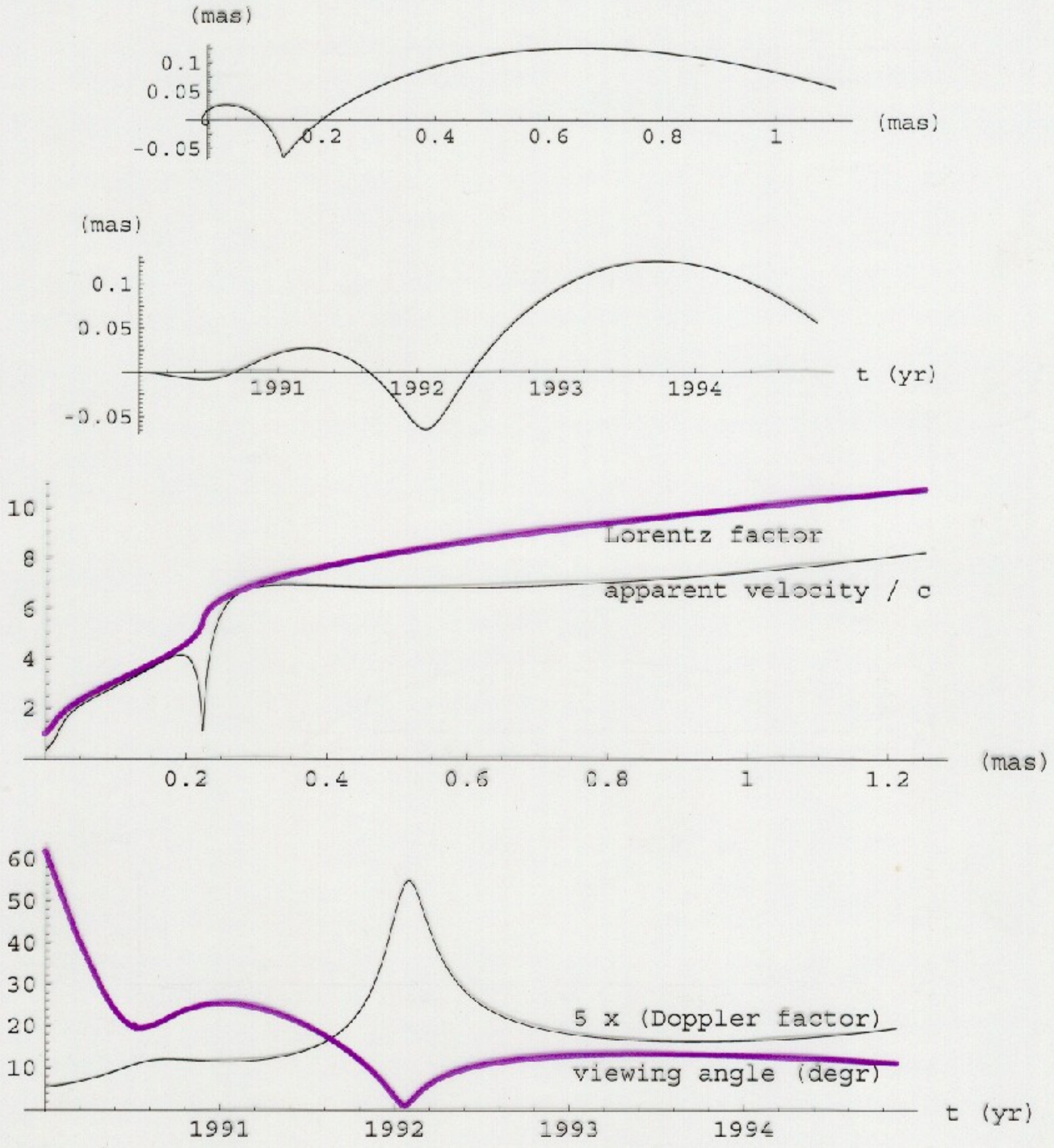
By applying all available kinematic constraints to the dynamical model, one could test this picture against alternative interpretations (unstable fluid modes, source precession, etc.).

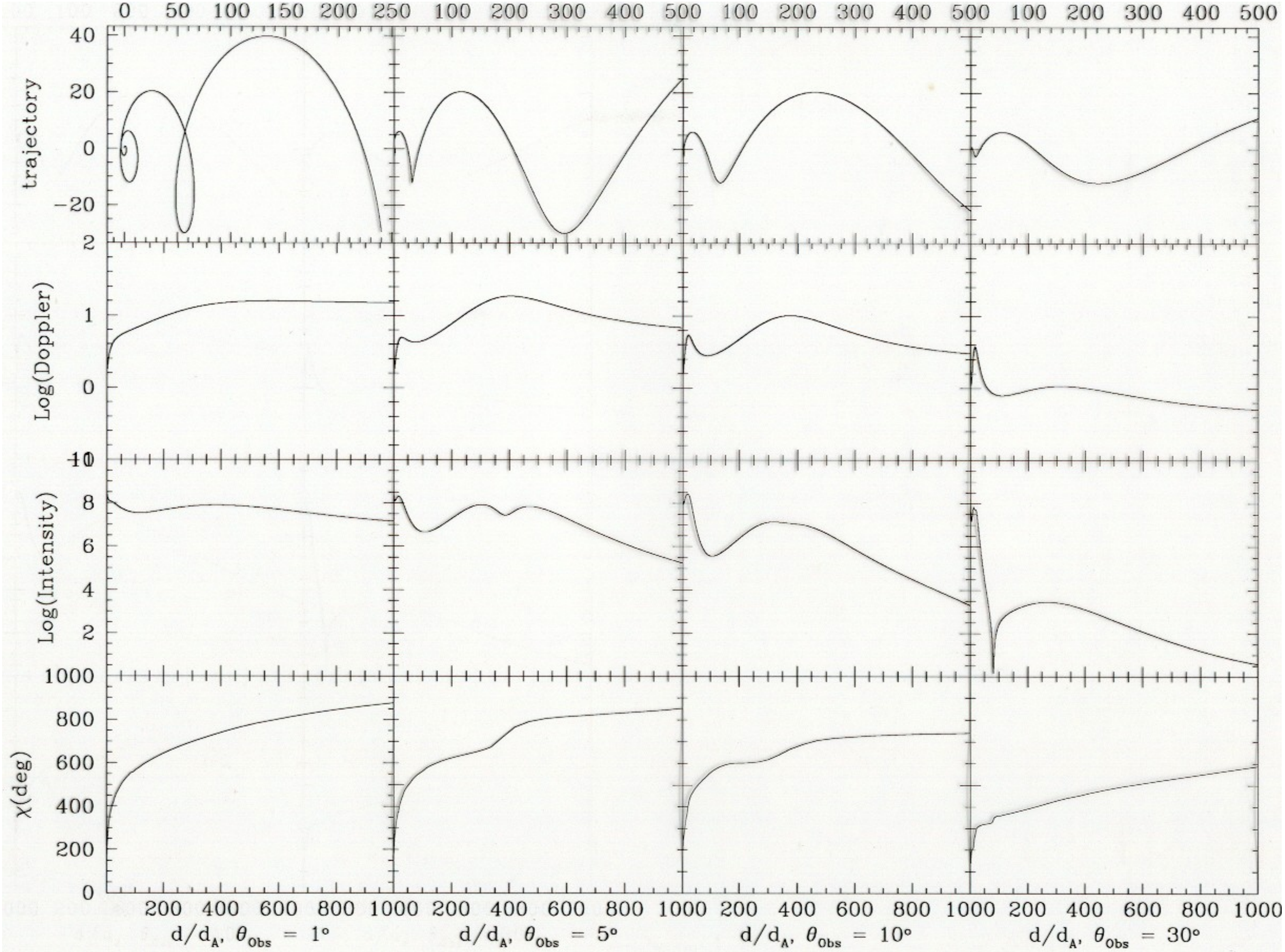
Valuable additional constraints could be provided by the radiative properties of the jet (flux, linear and circular polarization, Faraday rotation measure).



Lobanov 1996

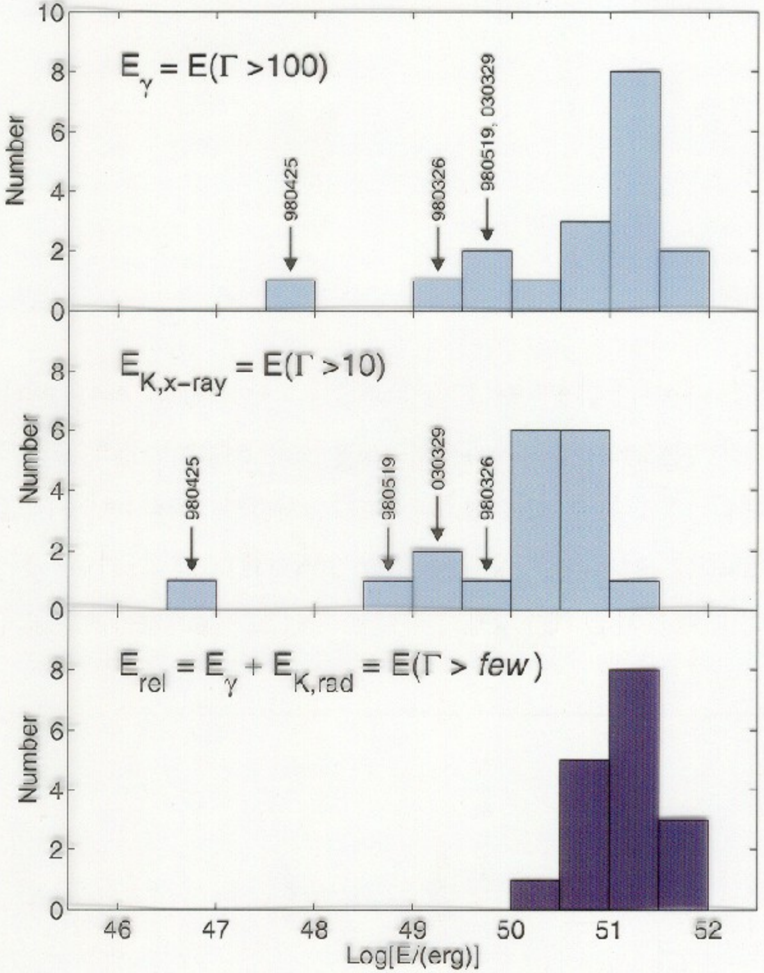
Fit to component C7




0 50 100 150 200 250
100 200 300 400 500
100 200 300 400 500
100 200 300 400 500
trajectory
40
20
0
−20
Log(Doppler)
2
1
0
−1
Log(Intensity)
10
8
6
4
2
χ(deg)
1000
800
600
400
200
0
200 400 600 800 1000
200 400 600 800 1000
200 400 600 800 1000
200 400 600 800 1000
d/d_A, θ_{Obs} = 1°
d/d_A, θ_{Obs} = 5°
d/d_A, θ_{Obs} = 10°
d/d_A, θ_{Obs} = 30°

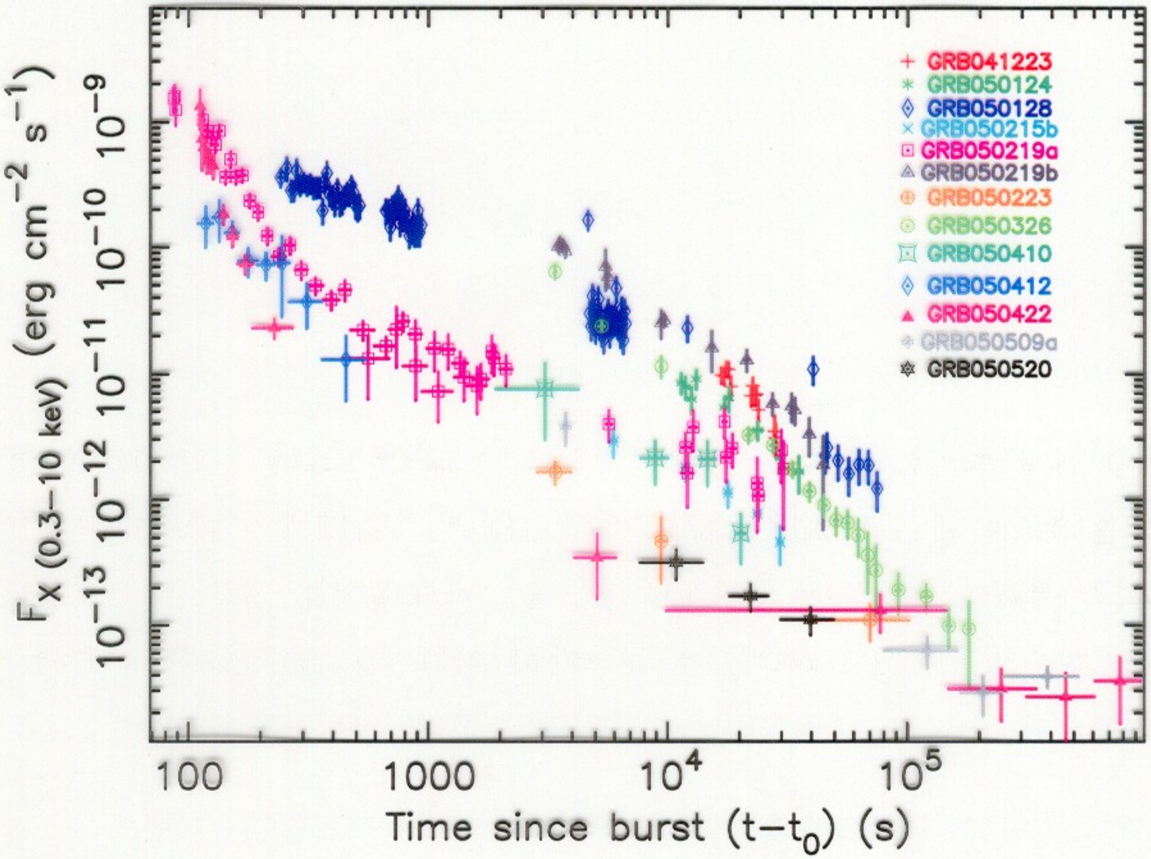
The Radiative Efficiency Problem in GRBs

Even before the launch of *Swift*, the relatively high ratio of (isotropic equivalent) gamma-ray energy to kinetic energy [as inferred from the late ($\gtrsim 10$ hr) afterglow] deduced in GRB outflows posed a strong challenge to the popular internal-shocks model of GRBs.

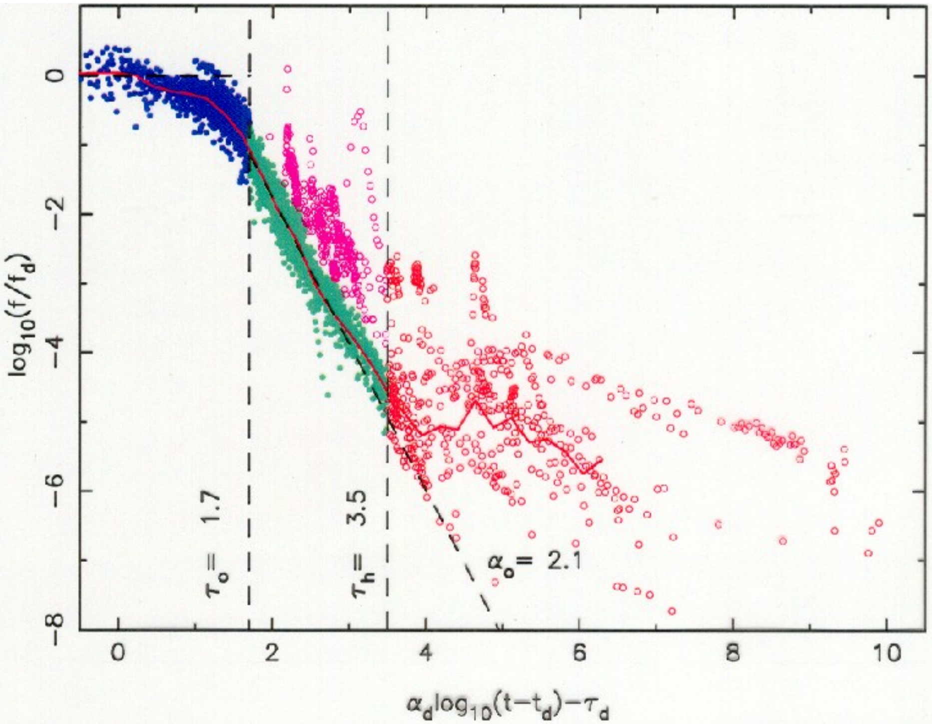


Berger et al. 2003

The problem was exacerbated by *Swift* observations, which indicated that in many cases the early afterglow emission is significantly (a factor of ~ 10) lower than the extrapolation of the late-afterglow light curve.



X-ray light curves of *Swift* GRBs (Nousek et al. 2006)



Composite X-ray decay curve of 40 *Swift* GRBs (O'Brien et al. 2006)

♣ When interpreted in the same manner as pre-*Swift* observations, these results imply a radiative efficiency $\gtrsim 90\%$ (and in some cases $\sim 99\%$) for the γ-ray emitting outflow component.

Magnetic Energy Dissipation

A promising interpretation of the large radiative efficiencies inferred in GRBs is that they arise from magnetic energy dissipation in Poynting flux-dominated jets.

Two distinct issues need to be addressed: the origin and extent of the magnetic energy dissipation and the nature and efficiency of the ensuing radiation process (in particular, its nonthermal component).

These processes have been considered in the framework of relativistic MHD as well as in the limit of force-free electromagnetism (e.g., Blandford 2002).

As already noted, magnetic energy dissipation could contribute also to jet acceleration. However, so far this effect has only been modeled in an approximate manner, using strong simplifications.

Dissipation Mechanisms

- In the context of the expansion of a force-free electromagnetic shell, Lyutikov (2006) proposed that dissipation is triggered by the development of a strong magnetic shear (which induces a tearing-mode instability; see also Komissarov, Barkov, & Lyutikov 2006) at the effective deceleration radius where most of the Poynting flux from the source has been reflected by the outer boundary (a contact discontinuity) of the shell.

- In an alternative realization of an electromagnetic outflow, Uzdensky & MacFadyen (2006) proposed that dissipation in GRB sources occurs when an expanding magnetic "tower," driven by the twisting (due to differential rotation) of magnetic field lines at the source, enters the collisionless regime, which facilitates fast reconnection of opposite-polarity field lines.

- In the context of an MHD jet model, Giannios & Spruit (2006) proposed that dissipation is associated with the development of the kink instability, which is induced by the progressive increase in $B_\phi/B_{\mathrm{poloidal}}$ as the jet expands (e.g., Eichler 1993).

The field dissipation process is, however, likely to occur under certain constraints (in particular, the conservation of magnetic helicity), which may limit the amount of dissipated energy and affect the magnetic field structure inside the jet.

The magnetic field will dominate the internal energy of an MHD jet beyond the classical fast-magnetosonic surface even if it were initially thermal-energy dominated ($B_\perp \propto \varpi^{-1}$, $B_\parallel \propto \varpi^{-2}$, $P \propto \varpi^{-2\Gamma}$ for ideal-MHD, adiabatic evolution).

$\Rightarrow$ in the jet frame the flow will be force-free ($\nabla \times B = \mu\mathbf{B}$)

If the jet possesses a magnetic-energy dissipation mechanism, it is plausible to assume [following Taylor (1974)] that it will settle into a minimum-energy linear force-free configuration ($\mu = \text{ constant locally}$).

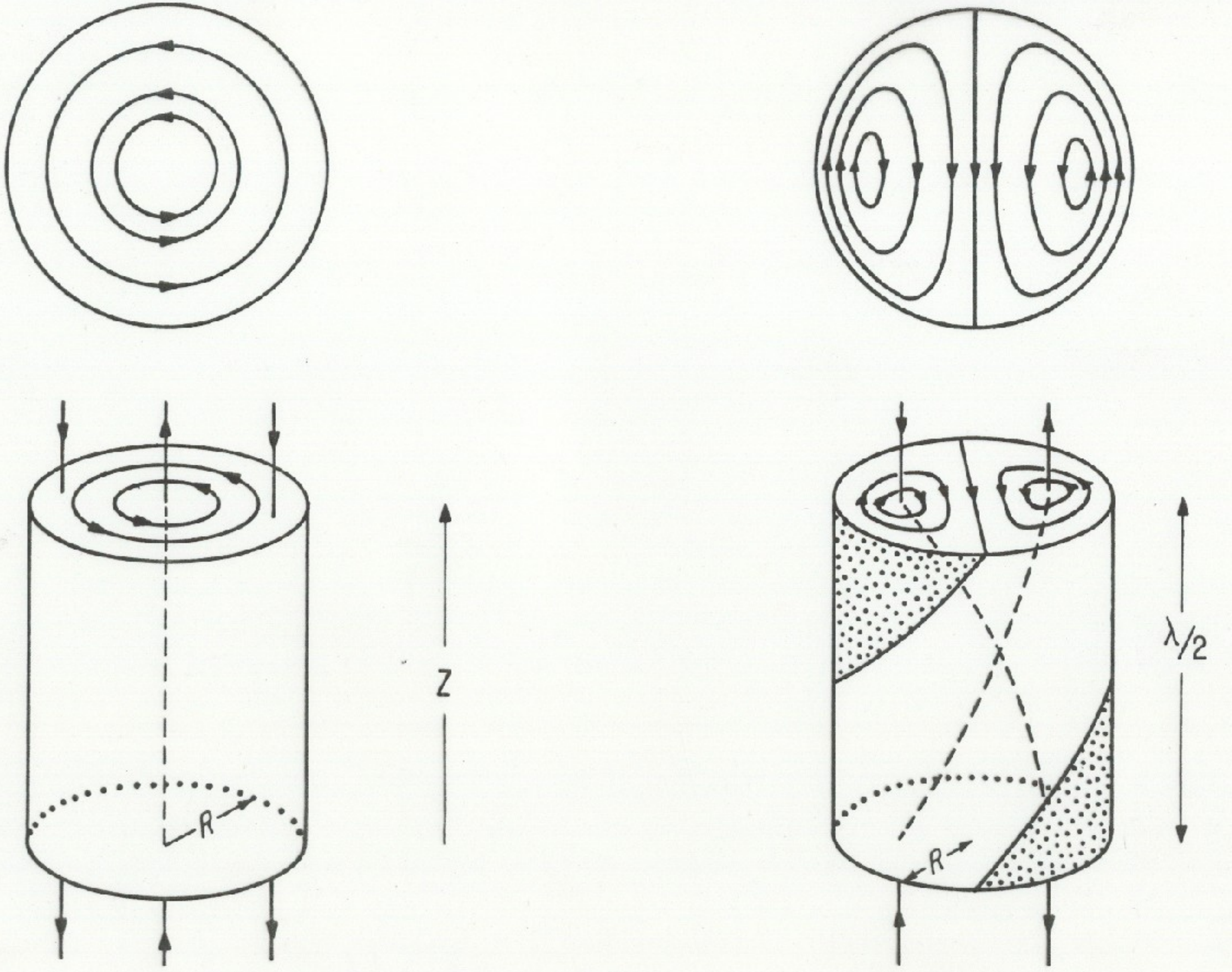
This picture can account for a variety of observed features in extragalactic radio jets (Königl & Choudhuri 1985a,b) and possibly also for the source of the radiated synchrotron power (Choudhuri & Königl 1986).
(N.B., kpc-sclae jets: NGC 6251; pc-scale jets: Lyutikov, Pariev, & Gabuzda 2005)

- A pressure-confined super-Alfvénic jet that is supersonic w.r.t. to the ambient gas can be locally approximated as a cylinder with a rigid boundary.

- In this case the minimum-energy state is a linear superposition of only 2 modes:
  $m = 0$ (axisymmetric; accounts for net axial magnetic flux Ψ in the jet)
  $m = 1$ (nonaxisymmetric)

- The $m = 1$ mode becomes energetically favorable when the external pressure $P_{\rm e}$ drops below $P_{\rm c} = 2.7 \times 10^{-3} \tilde{K}^4 \Psi^{-6}$ (where $\tilde{K}$ is the conserved magnetic helicity per unit length). [N.B., $m = 0$ configuration then becomes unstable to resistive tearing.]

- The helicity injection rate from a disk threaded by open magnetic field lines and rotating with angular velocity $\Omega(\varpi_0)$ is $|\dot{K}| = \int (\Omega / 8\pi^2) \Psi d\Psi \approx (\gamma V)_\infty \tilde{K}$, where $d\Psi(\varpi_0) = 2\pi B_z(\varpi_0) \varpi_0 d\varpi_0$.



axisymmetric

m = 0

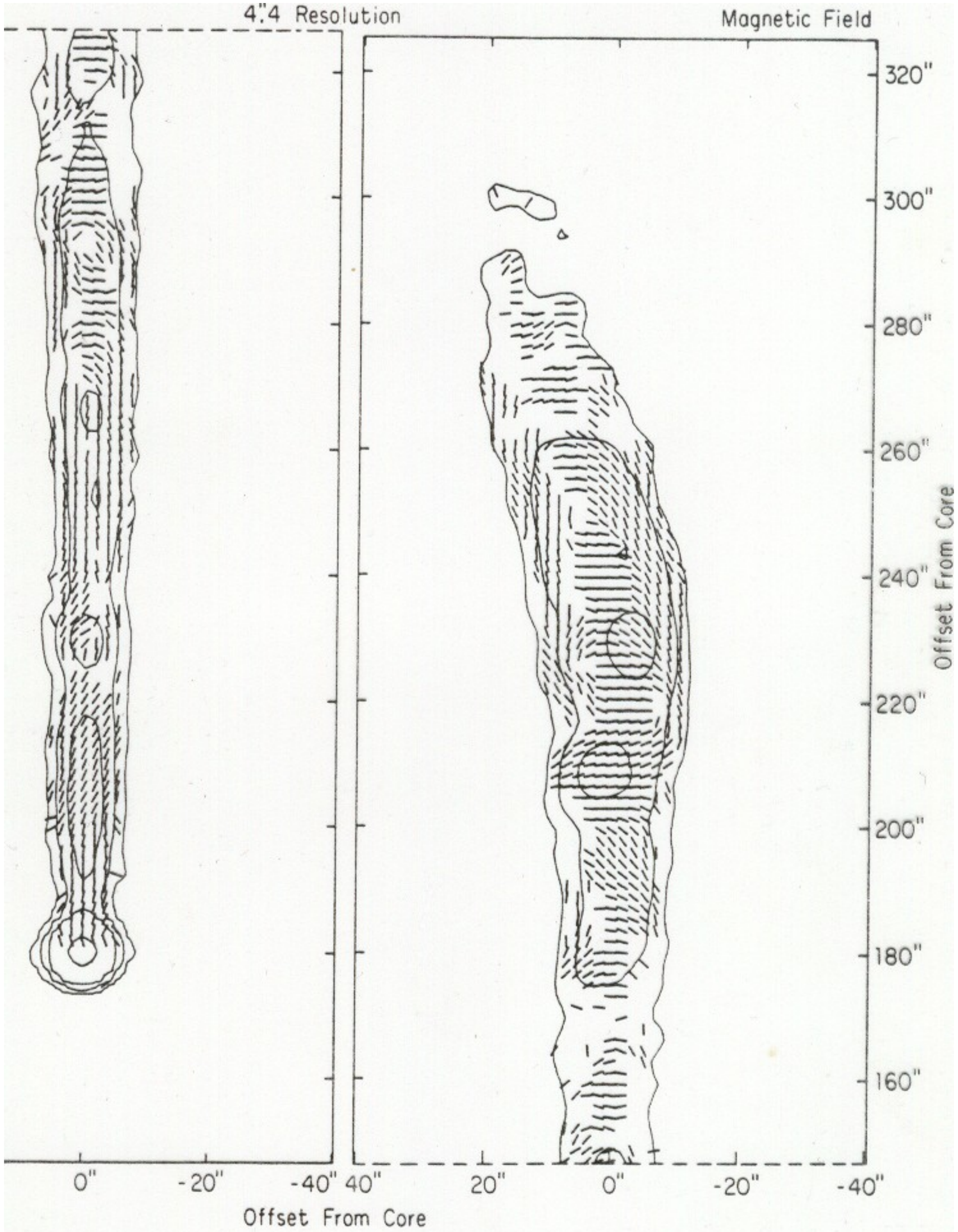
accounts for net axial flux and current

nonaxisymmetric

m = 1

wavelength along the jet $\lambda \approx 5R$

Fig. 1


4″.4 Resolution
Magnetic Field
320"
300"
280"
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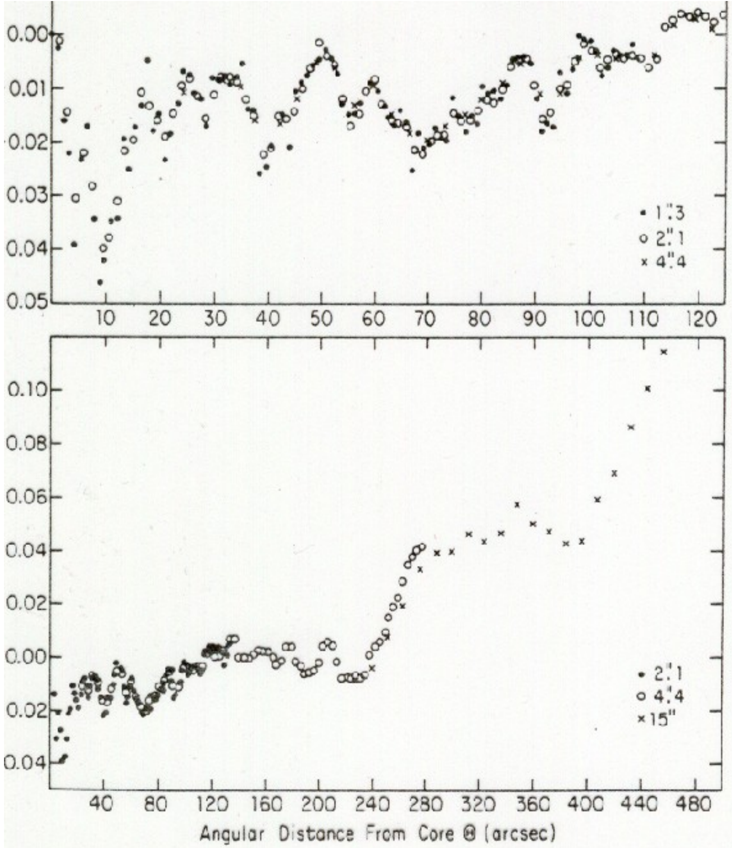
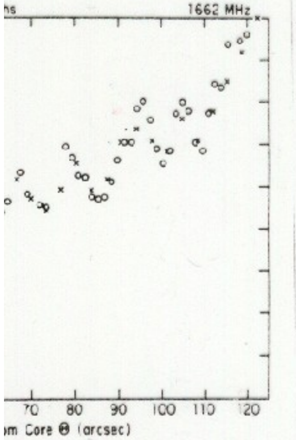
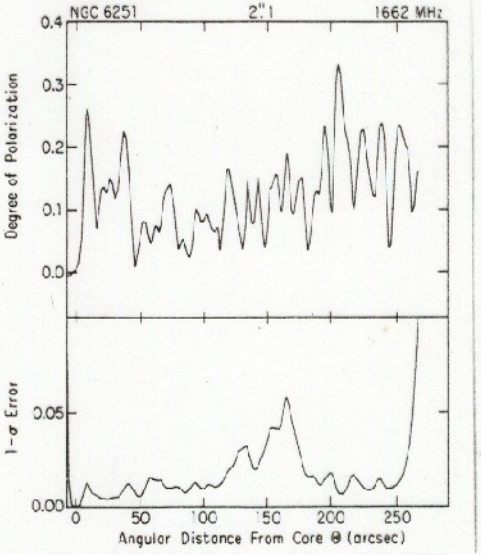
Offset From Core

& Willis '84





oscillations



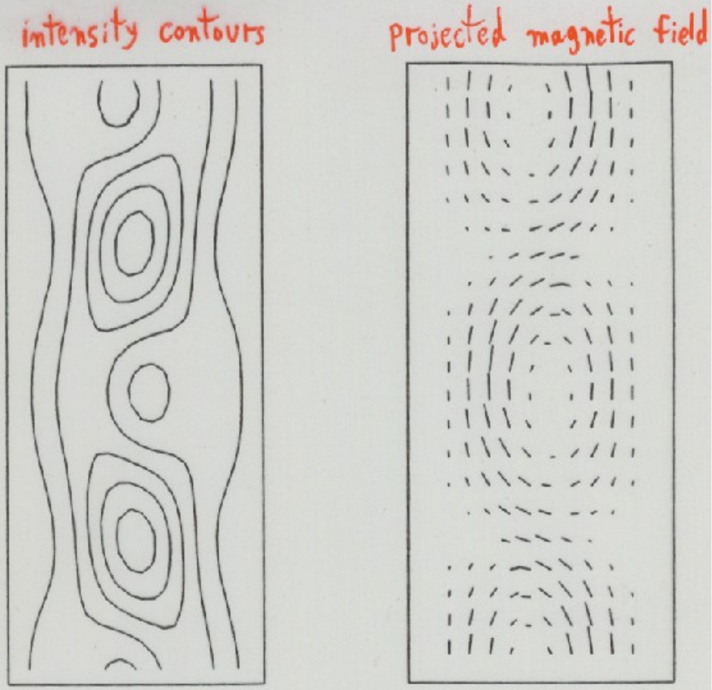
oscillations of the degree
of polarization along the
ridge line

$I \propto B_\perp^{1+\alpha}$

spectral index $\alpha \in \{0,1\}$

oscillations symmetric about the center line

$\lambda_{osc} = 5R$

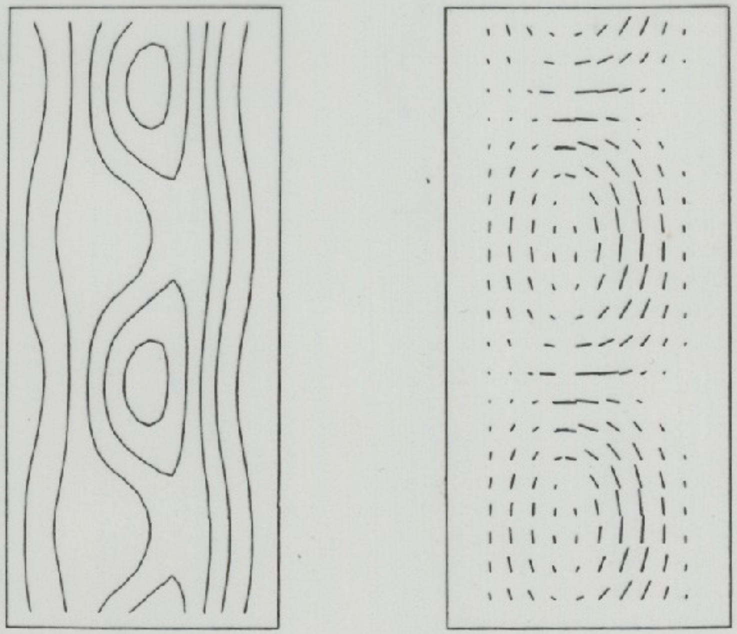


$\delta = 90°$ $m_0 : m_1 = 1:5$

$\delta =$ inclination angle of jet axis to line of sight

oscillations on one side of axis only

$\lambda_{osc} = 2.5 \cos\delta \, R$

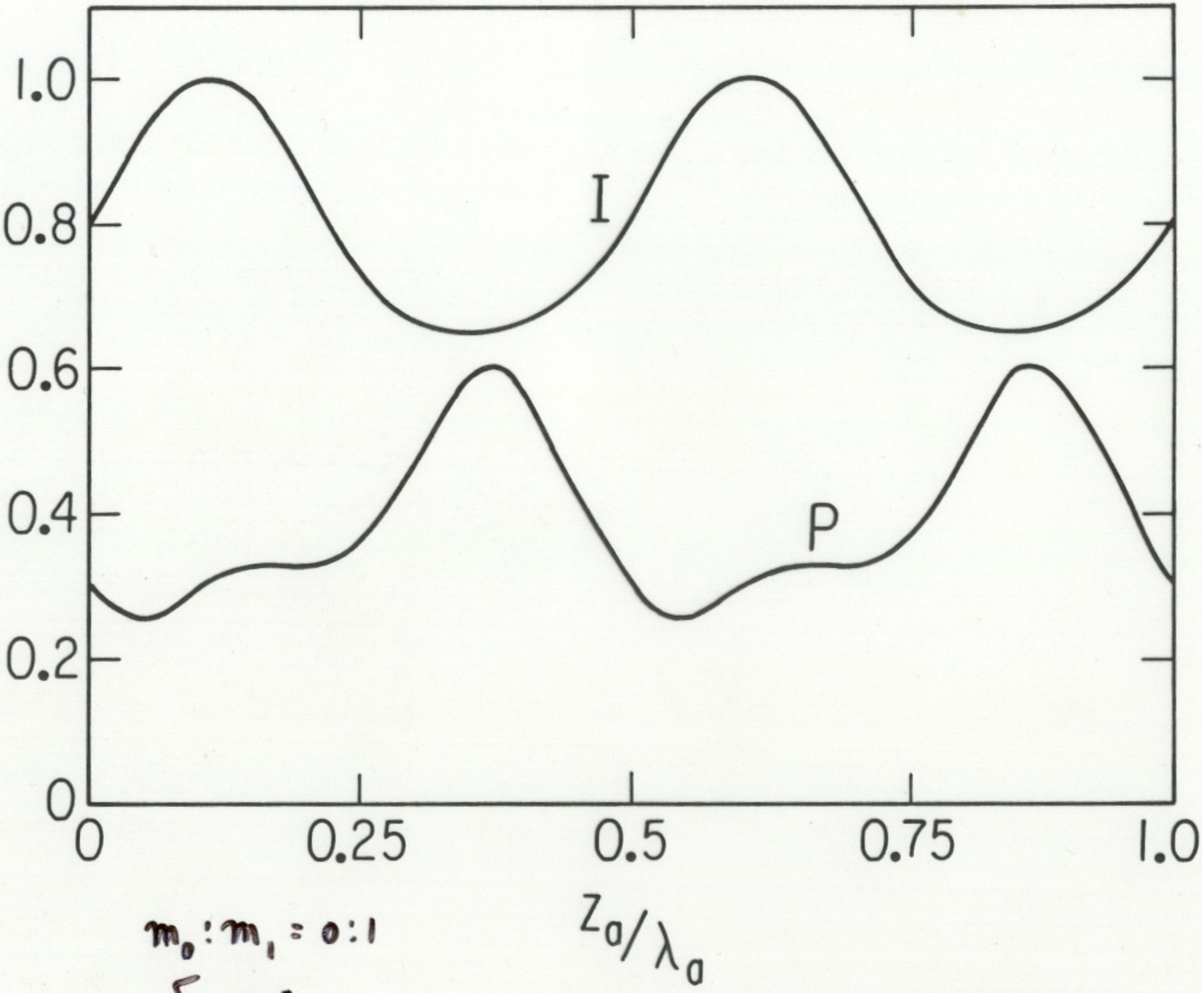


$\delta = 70°$ $m_0 : m_1 = 0:1$

I = total intensity

P = degree of polarization

} along the ridge line



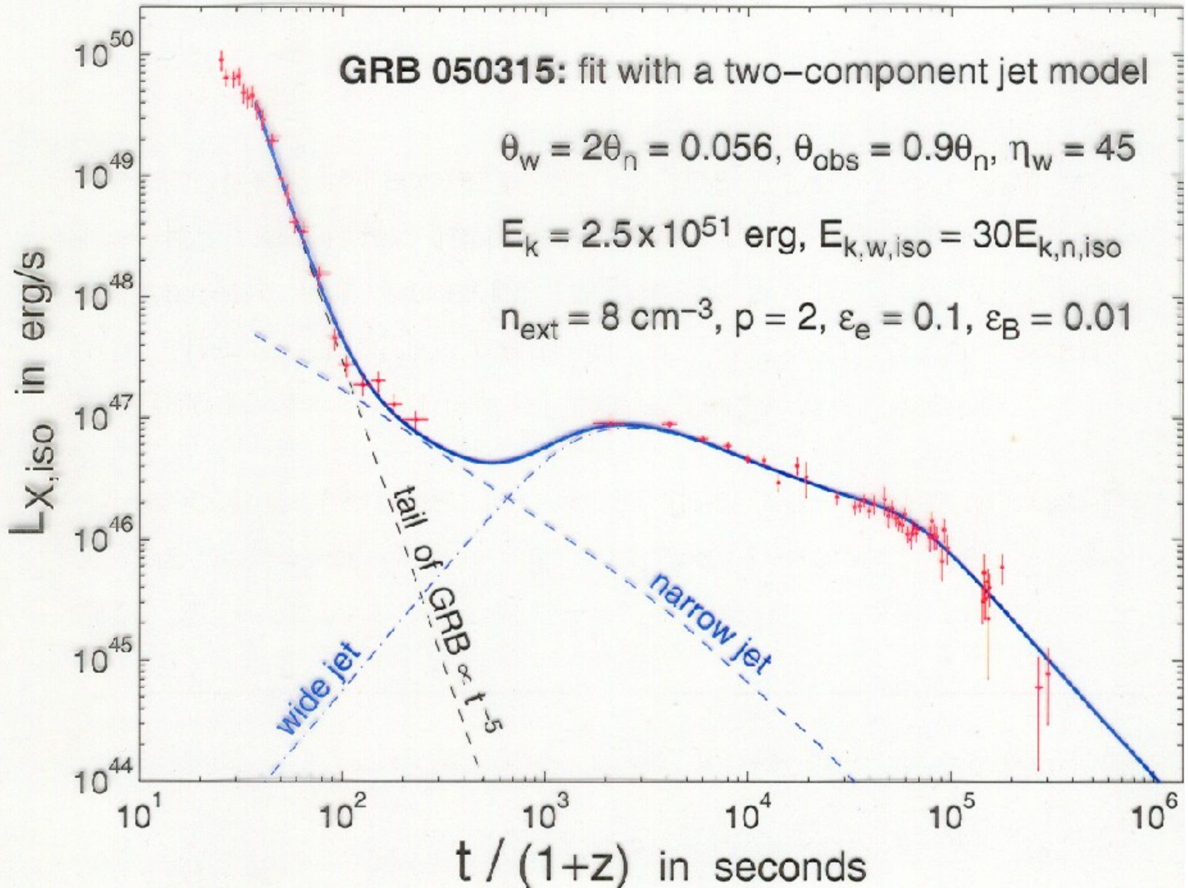
$m_0 : m_1 = 0:1$

$\delta = 70°$

Two-Component Outflows

The simplest interpretation of the *Swift* observations of GRB sources implies that the γ-ray emitting component (of Lorentz factor $\gamma \gtrsim 10^2$) is distinct from the moderately relativistic ($\gamma \gtrsim 10$) component that produces the bulk of the afterglow emission.

A two-component jet model of this type could account for the observed X-ray light curves (Granot, Königl, & Piran 2006).



The two jet components could correspond, respectively, to a nearly baryon-free outflow powered, for example, by a rotating black hole through the Blandford-Znajek mechanism (e.g., Levinson & Eichler 1993) and to a more baryon-rich outflow driven hydromagnetically from a surrounding accretion disk (e.g., Vlahakis, Peng, & Königl 2003). Recent estimates of the expected baryon loading from GRB disks (Levinson 2006) are consistent with this picture.

The disk wind could play a role in collimating the ultrarelativistic, baryon-poor outflow component (e.g., Levinson & Eichler 2000).

♣ An analogous two-component jet model has also been considered for AGNs (e.g., Sol, Pelletier, & Asséo 1989; Tsinganos & Bogovalov 2005).

The shear boundary layer between the two components is another potential site for energy dissipation and particle acceleration (e.g., Stawarz & Ostrowski 2002).

Conclusions

Magnetic fields are the most likely means of extracting the rotational energy of the source and of guiding, accelerating, and collimating relativistic outflows from compact astronomical objects (GRB sources, AGNs, and Galactic X-ray binaries).

An extended acceleration region is a distinguishing characteristic of the magnetic launching mechanism.

- The acceleration region is potentially resolvable in AGNs; it may thus be possible to test and constrain the magnetic acceleration model through VLBI studies of the kinematic and radiative properties of superluminal jets.

Numerical relativistic-MHD simulations hold great promise for clarifying the nature of the jet-launching process. These simulations can benefit from the exact special-relativistic self-similar solutions that have been obtained for these flows, which for the time being are the only means of studying the entire acceleration region of ultrarelativistic jets.

- The self-similar solutions could be useful for initiating and testing the simulations; the latter, in turn, could be used to test the generality and stability of the semi-analytic results.

- ♣ The recent *Swift* observations of GRB sources provide a motivation for studying the nature of energy dissipation and particle acceleration in Poynting flux-dominated jets.
  - The effects of magnetic energy dissipation on the flow acceleration need to be incorporated into the dynamical models, taking account of the likely conservation of magnetic helicity and of any other relevant constraints.

- ♣ The suggested existence of more than one outflow component in relativistic jet sources might be observationally testable in both GRBs and AGNs.

- ♣ The apparent relationship between the spectral states of XRBs and their outflow characteristics may hold valuable clues to the jet launching mechanism.
  - The physical basis of the $L_{\mathrm{R}} - L_{\mathrm{X}}$ correlation in XRBs and AGNs needs to be fully understood.