Magnetic Acceleration Models of AGN Outflows

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Outline:

- Hydromagnetic driving in context:
  large-scale winds and small-scale jets;
  other driving mechanisms

- Hydromagnetic outflow models:
  exact MHD solutions of winds and jets

- Related issues: multiphase outflows;
  origin of fields; stability

- Future prospects:
  relationship to other outflow sources;
  detailed modeling of "superluminal" jets

AGN Outflows

large-scale ($\sim 10^4 - 10^6\ r_{\rm G}$) "thermal" winds

- Evidence from UV and X-ray spectroscopy in Seyfert 1 galaxies for gas outflowing at $\sim 10^2 - 10^3$ km s^{-1} that likely originates on the scale of the broad emission-line region ($R_{\rm BELR} \approx 0.02\, L_{\rm opt,45}^{0.7}$ pc).

- The outflowing gas in Sy 1's is often seen in absorption (inferred global covering factor $\gtrsim 0.5$) and separates into distinct kinematic components that exhibit a range of physical properties (ionization parameter, density) and FWHM widths.

- The strongest absorption components in Sy 1's lie completely outside the BELR, but at least some of the absorbing gas is likely located at $r \lesssim 1\ \mathrm{pc}$. This partially ionized "warm absorber" is manifested in UV and X-ray spectra, with the UV and X-ray components evidently overlapping. A UV/X-ray "warm absorber" is detected also in QSOs.

- Broad Absorption-Line QSOs exhibit a distinct outflow component: speeds are typically $\sim 10^3 - 10^4\ \mathrm{km\ s^{-1}}$, but range up to $\sim 0.1\,c$. The absorbing gas lies (at least in part) outside the BELR and has a covering factor $\gtrsim 0.3$ at the source. Whereas Sy 1's are viewed at a comparatively small angle to the symmetry axis, BALQSOs are likely observed at a relatively large angle.

- Associated QSO Systems (blueshifted relative to QSO by up to $\sim 0.1\,c$) may potentially also originate in the QSO itself.

- The presence of dust within the outflow has been inferred in some warm absorbers and BALQSOs. There is a direct indication from spectropolarimetry in the Sy 1.8/1 galaxy NGC 2622 for a $\sim 10^3\ \mathrm{km\,s^{-1}}$ outflowing dust (Goodrich 1989).

- Evidence for an association of at least some of the BELR outflow components with a disk comes from the spectral and variability properties of the broad emission lines (interpreted in terms of a rapidly accelerating flow from a rotationally supported disk) as well as from various indications of a disk geometry in radio-loud QSOs and in BALQSOs.

small-scale ($\sim 1 - 10^2 \, r_{\rm G}$) "nonthermal" 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.

♣ Inner-scale jets (rather than outer-scale winds) evidently dominate the inferred AGN mechanical heating of galaxy clusters (offset cooling in cluster core; provide entropy "floor" on larger scales) and the mechanical feedback on galactic bulges that was proposed to regulate the $M - \sigma$ relation.

Wind Driving Mechanisms

radiation pressure

- Continuum (bound-free) and line (bound-bound) radiation-pressure driving evidently play a role in accelerating AGN outflows (e.g., Arav 1996; Chelouche & Netzer 2003; Everett 2005).

- Both the central continuum and the local disk continuum may drive the flow, but shielding of the central continuum that reduces the ionization level of the gas is generally required for efficient acceleration.

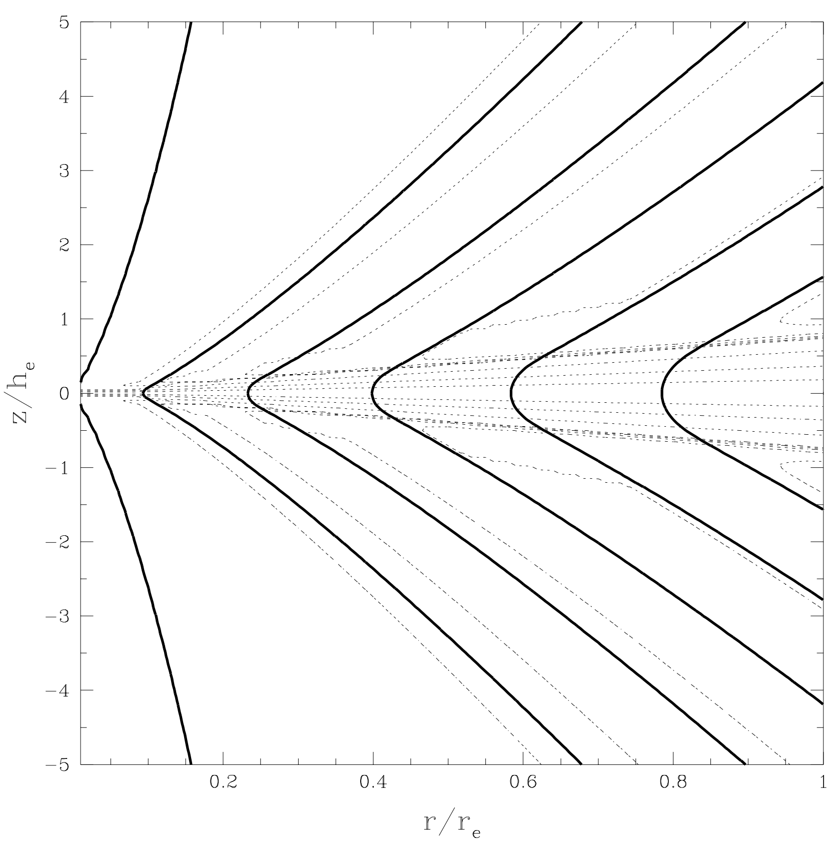
- It was proposed (Murray et al. 2005) that radiatively driven disk outflows can be self-shielded by their innermost "failed wind" zones. This possibility was supported by subsequent numerical simulations (Proga et al. 2000; Proga & Kallman 2004); however, in view of the various approximations employed by these simulations, this issue requires further scrutiny.

thermal pressure

- X-ray ionized and heated outflows can be driven by thermal pressure gradients to speeds as high as $\sim 1000\ \mathrm{km\,s^{-1}}$ when the Compton temperature and L/L_{Edd} are sufficiently high (Balsara & Krolik 1993; Woods et al. 1996). This mechanism was proposed for the warm-absorber outflow in the Sy 1 galaxy NGC 3783 (Chelouche & Netzer 2005). More detailed modeling is, however, needed to validate this interpretation.

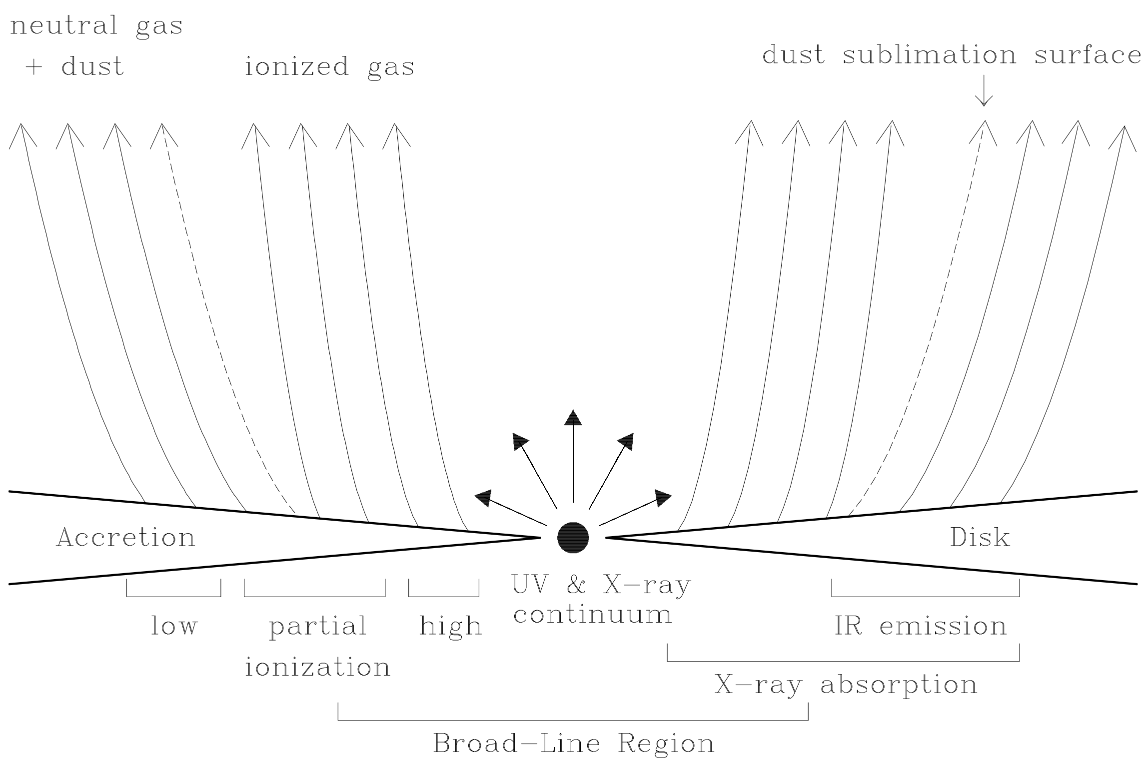
magnetic stresses

- Disks threaded by open magnetic field lines can produce high-speed, high-momentum-discharge, centrifugally driven outflows (Blandford & Payne 1982). Such outflows may arise naturally in accretion disks since they are also efficient at transporting angular momentum.

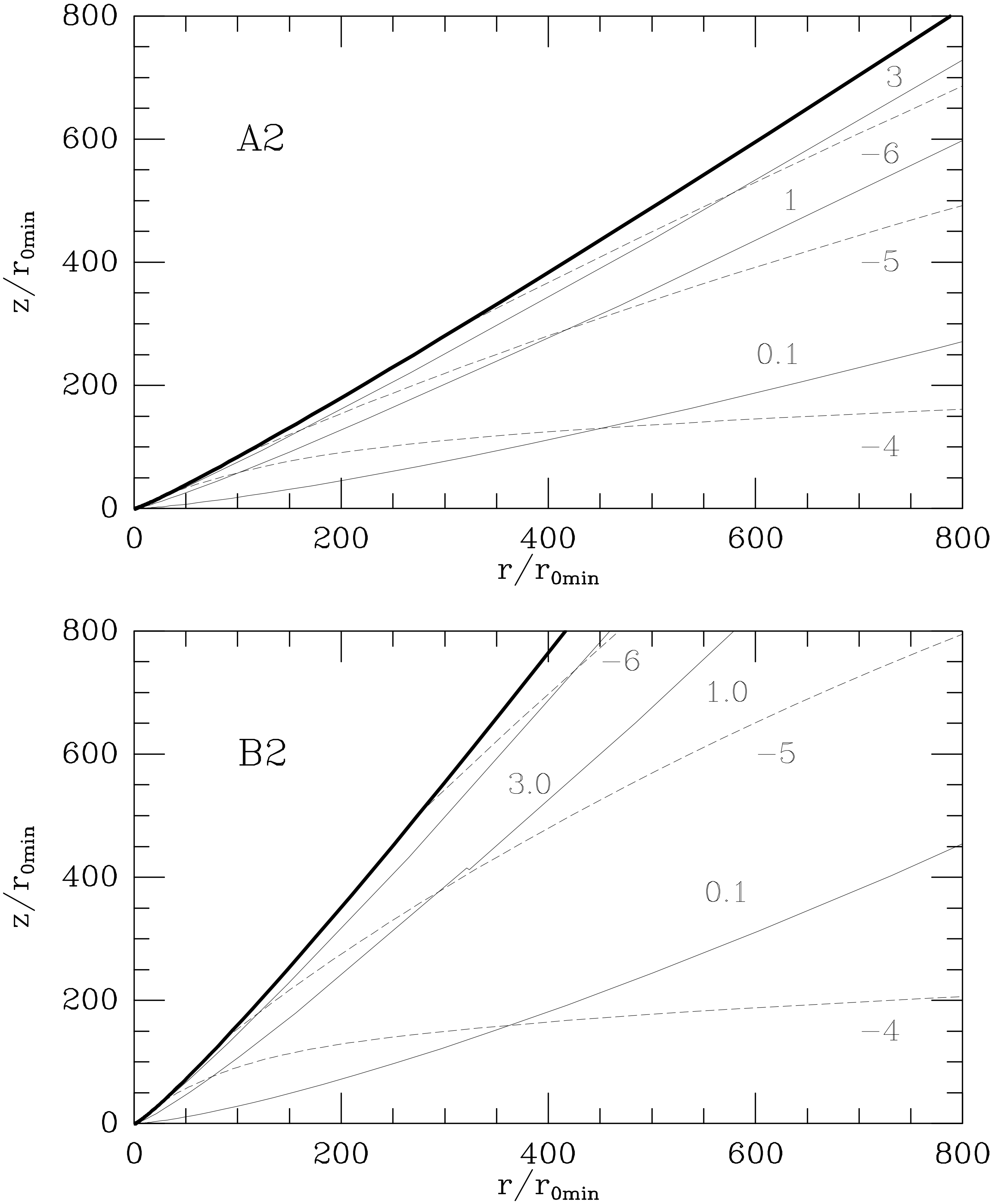


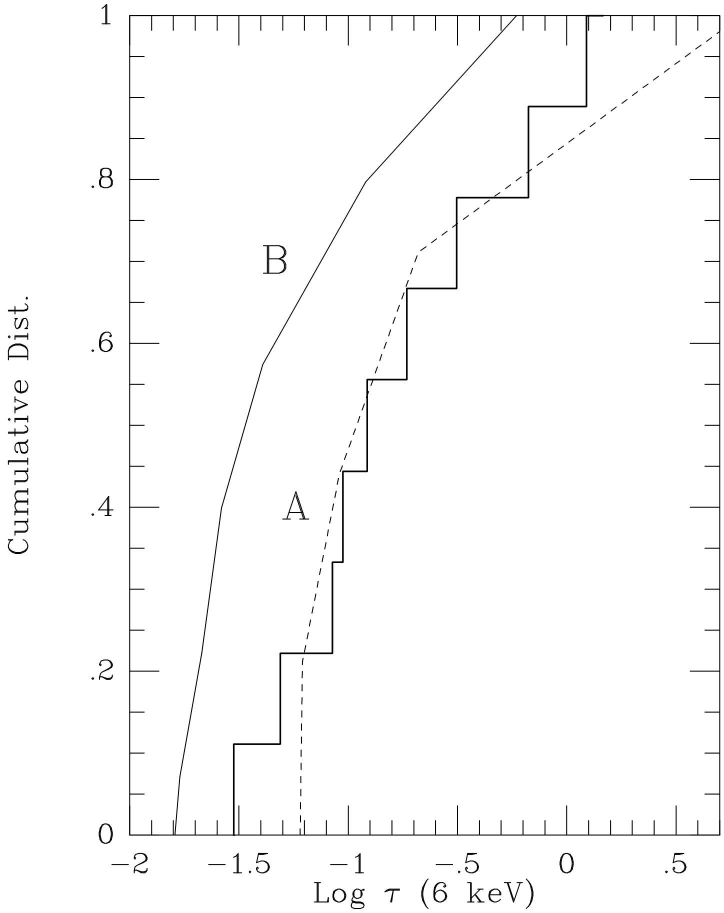
Ferreira (1997)

- AGN disk winds of this type would have a strongly stratified vertical density profile and would be photoionized in their inner regions and dusty in their outer zones. These configurations could naturally account for the “fuzzy” molecular tori that underlie the Type 1 / Type 2 AGN unification scheme (Königl & Kartje 1994; Kartje 1995).



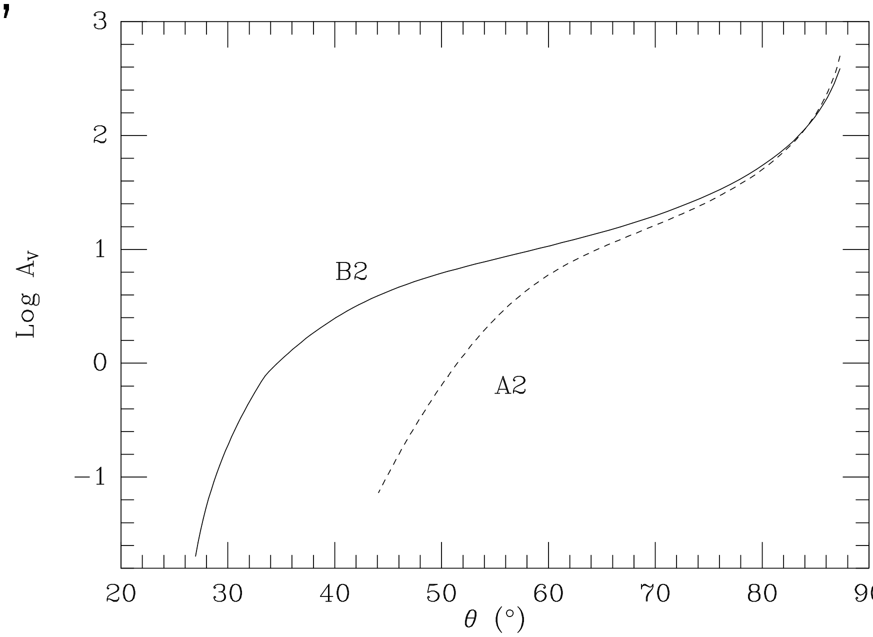
Königl & Kartje (1994)


A2
B2
z/r0min
r/r0min
3
−6
1
−5
0.1
−4
1.0
3.0
0
200
400
600
800

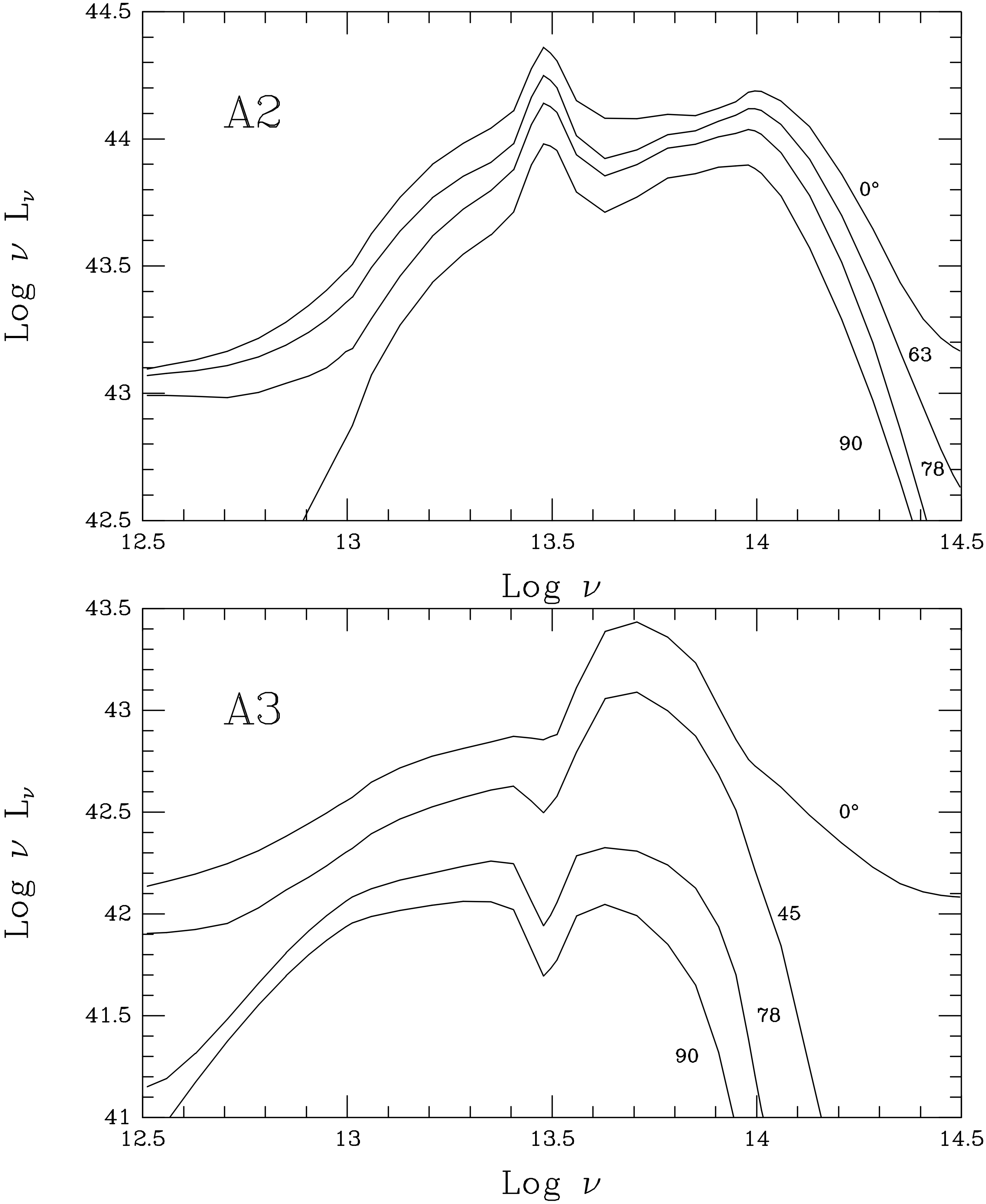


Cumulative Dist.
Log τ (6 keV)
B
A

,

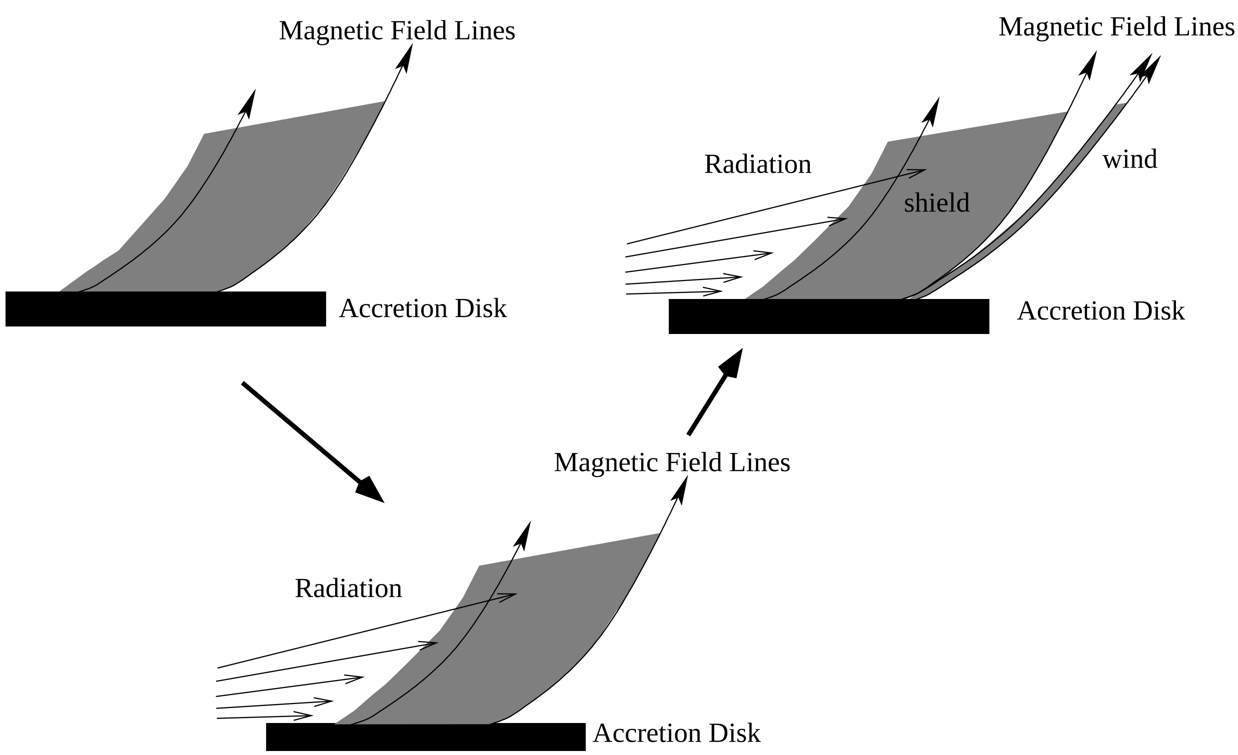


Log A_V
θ (°)
B2
A2


A2
0°
63
78
90
Log ν L_ν
Log ν
44.5
44
43.5
43
42.5
12.5
13
13.5
14
14.5
A3
0°
45
78
90
Log ν L_ν
Log ν
43.5
43
42.5
42
41.5
41
12.5
13
13.5
14
14.5

magnetic + radiative driving

- Magnetic stresses uplift gas from the disk (possibly assisted by the local disk radiation field); the inner regions of this wind naturally shield the outer zones, which can then be accelerated radiatively by the central continuum.



Everett (2005)

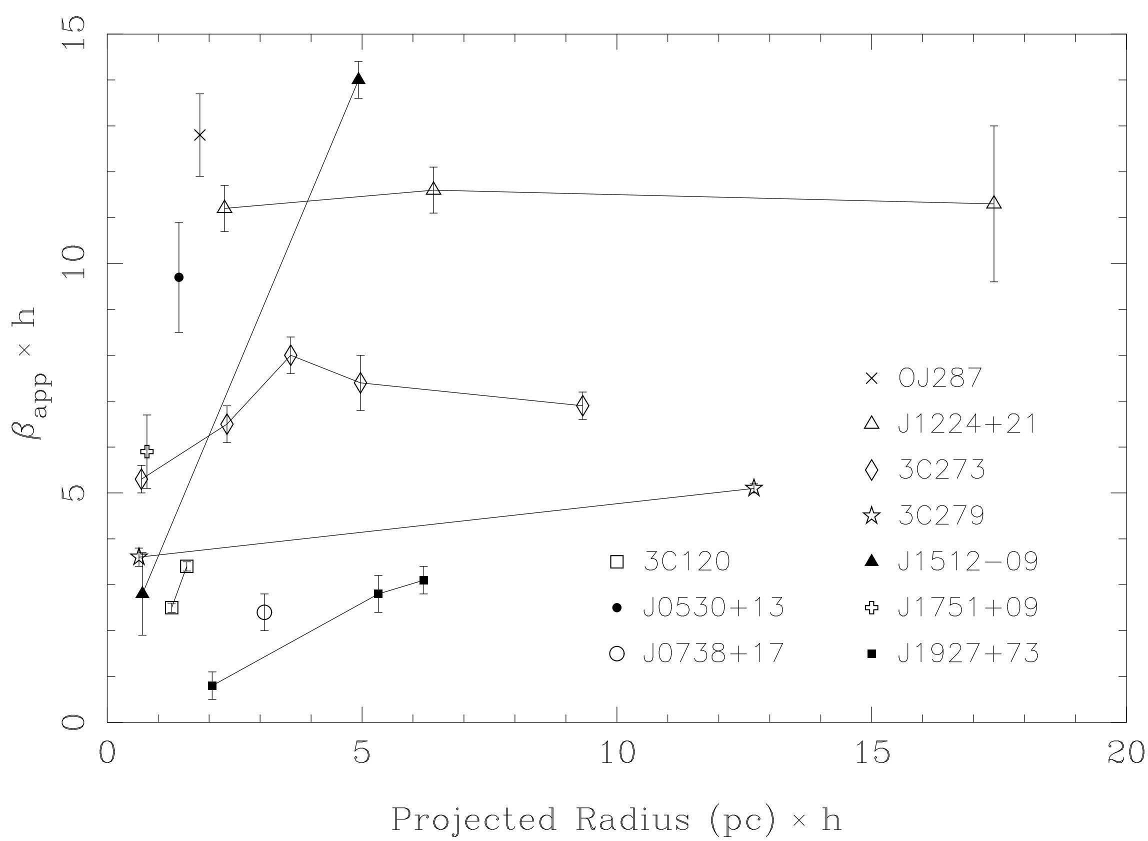
Jet Driving Mechanisms

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).

- Proper-motion and X-ray emission measurements were used to infer a pc-scale acceleration from $\gamma \sim 5$ to $\gamma \gtrsim 10$ for knot C7 in the 3C 345 jet (Unwin et al. 1997) and from $\gamma = 8$ to $\gamma = 13$ in the 3C 279 jet (Piner et al. 2003).

- Extended acceleration in the 3C 345 jet has been independently indicated by the increase in apparent component speed with projected distance 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 pc-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 pressure-gradient acceleration (Vlahakis & Königl 2004).

- This conclusion was reached on the basis of exact semianalytic solutions of the equations of special-relativistic, Ideal MHD, derived by separating variables under the most general ansatz for radial self-similarity.

- The derived solutions also demonstrate that magnetic stresses can produce efficient collimation. A slower wind from the outer regions of the disk may aid in the collimation process (e.g., Bogovalov & Tsinganos 2005).

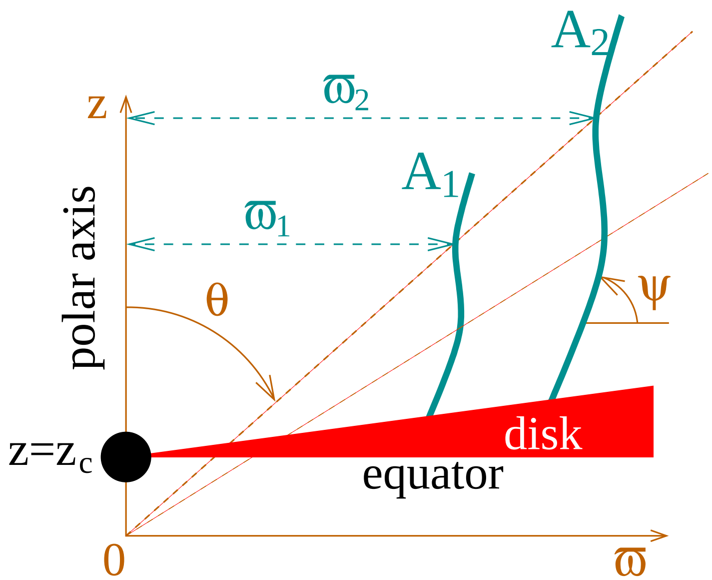
Exact Relativistic-MHD Solutions

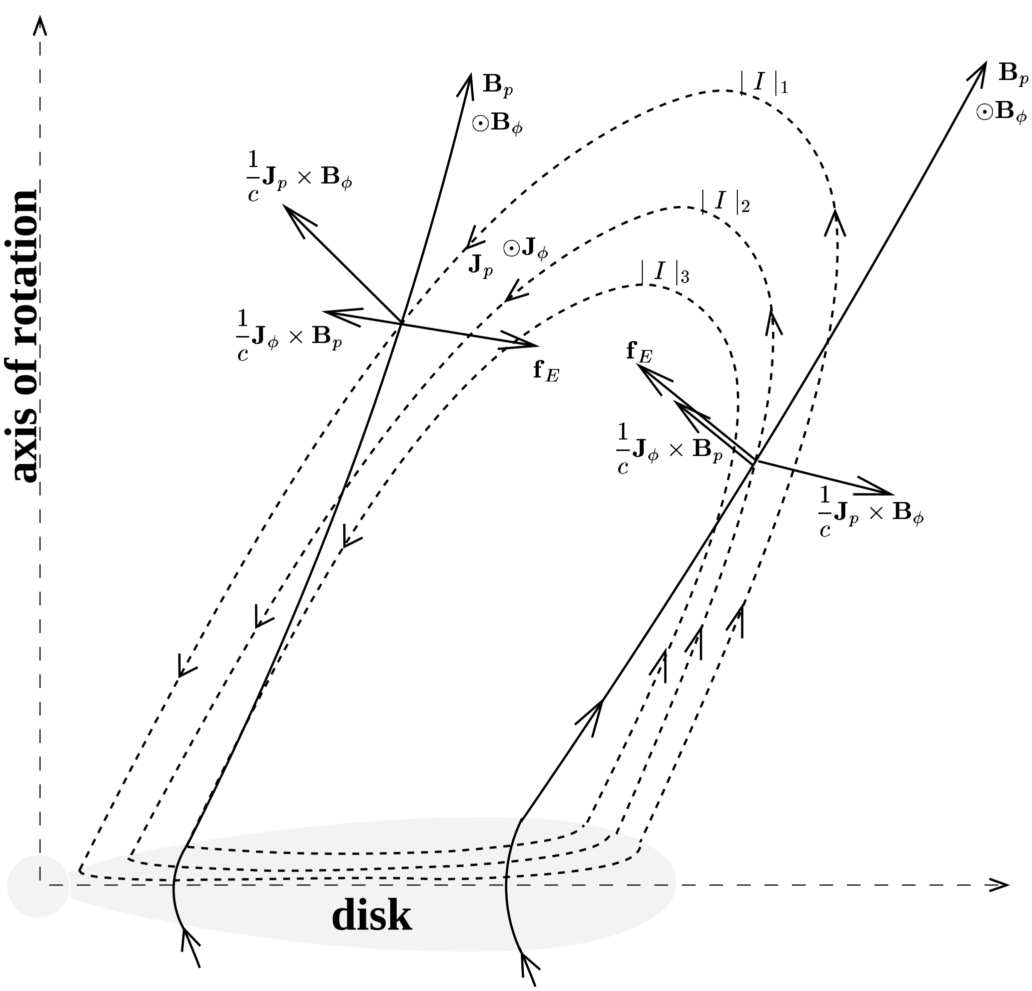
References: Vlahakis & Königl 2001 (ApJ 563, L129), 2003a,b (ApJ 596, 1080; 1104).

- Exact semianalytic solutions of relativistic outflows were constructed within the following framework:
  - Special-relativistic, ideal-MHD formulation
  - Axisymmetry
  - Poloidal magnetic flux distribution at the source (specified by the function A) is approximately constant on the time scale of interest
  - Steady-state equations apply to the evolution of a given ejected mass shell in the limit $\gamma_p \gg 1$ — 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

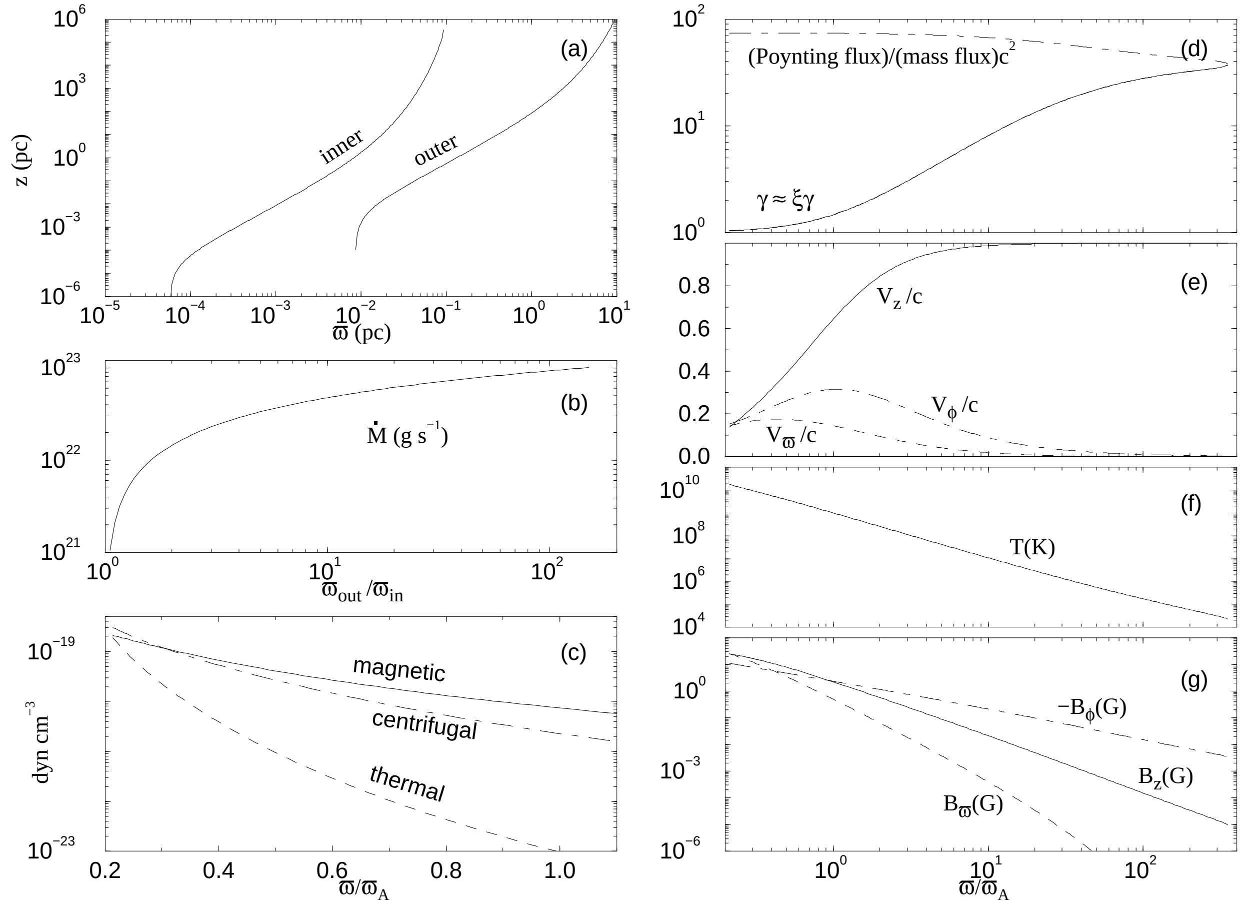
- The general problem requires the specification of 7 constraints: 4 associated with boundary conditions at the source and 3 determined by regularity requirement at the critical points of the joint solution of the Bernoulli and transfield (Grad-Shafranov) equations.

Solutions derived by separating variables under the most general ansatz for radial self-similarity [in spherical coordinates $(r\,,\theta\,,\phi)$], in which the shape $r(\theta, A)$ of the poloidal field lines is given as a product of a function of A times a function of θ: $r = \mathcal{F}_1(A)\mathcal{F}_2(\theta)$.





Model fit for component C7 in 3C 345



($\varpi_{\rm A}$ is the Alfvén lever arm.)

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

♣ The source of energy for the jet is the rotational energy of the central black hole and/or the surrounding accretion disk (e.g., McKinney & Gammie 2004; De Villiers et al. 2005; Komissarov 2005). In either case, the acceleration to the terminal Lorentz factor $\gamma_\infty \gtrsim 10$ takes place on scales $\gg r_{\rm G}$ (although the detailed structure of the flow is influenced by the specific boundary conditions at the source; e.g., Vlahakis & Königl 2003).

There is growing evidence that AGN winds represent multiphase outflows (e.g., Arav et al. 1999; Everett et al. 2002).

The different phases may correspond either to discrete clumps (e.g., Krongold et al. 2005) or to a more continuously variable density distribution (e.g., Steenbrugge et al. 2005; Chelouche & Netzer 2005).

In either case, magnetized outflows provide the most natural explanation:

- Discrete clumps may be condensations confined by the magnetic field of a continuous disk outflow (e.g., Emmering et al. 1992) and possibly also accelerated by the ram pressure of the underlying wind (Kartje et al. 1999).

- A more continuous density spectrum may correspond to transient features in a turbulent magnetized outflow (MHD turbulence; Bottorff & Ferland 2000).

Origin of Driving Magnetic Field

- The field could in principle be interstellar in origin, advected by the accretion flow and amplified by compression, as inferred in YSO systems. Alternatively, the field could be shear-amplified locally in the disk by an MRI/dynamo process.

- The advection scenario could naturally give rise to a large-scale, open field configuration that is conducive to driving a wind. Such a field could in principle be produced also through a large-scale dynamo process in which magnetic buoyancy or a disk outflow play a role (Brandenburg 1998; Bardou et al. 2001). The generation and conservation of magnetic helicity are key concepts in these "inverse dynamo" models (Blackman & Brandenburg 2003).

- Small-scale dynamo processes produce disordered, small-scale magnetic fields. However, temporal and spatial statistical averages of such configurations could also in principle provide both acceleration (Heinz & Begelman 2000) and collimation (Li 2002).

Jet Stability

- Magnetized jets are expected to become (linearly) kink unstable beyond the Alfvén surface, where B_ϕ becomes the dominant magnetic field component (e.g., Hardee & Rosen 1999).

- Numerical simulations of the nonlinear development of the instability have, however, revealed that the jets could stabilize through a self-limiting process that maintains the average Alfvén Mach number within the jet at a value $\mathcal{O}(1)$ (e.g., Ouyed et al. 2003).

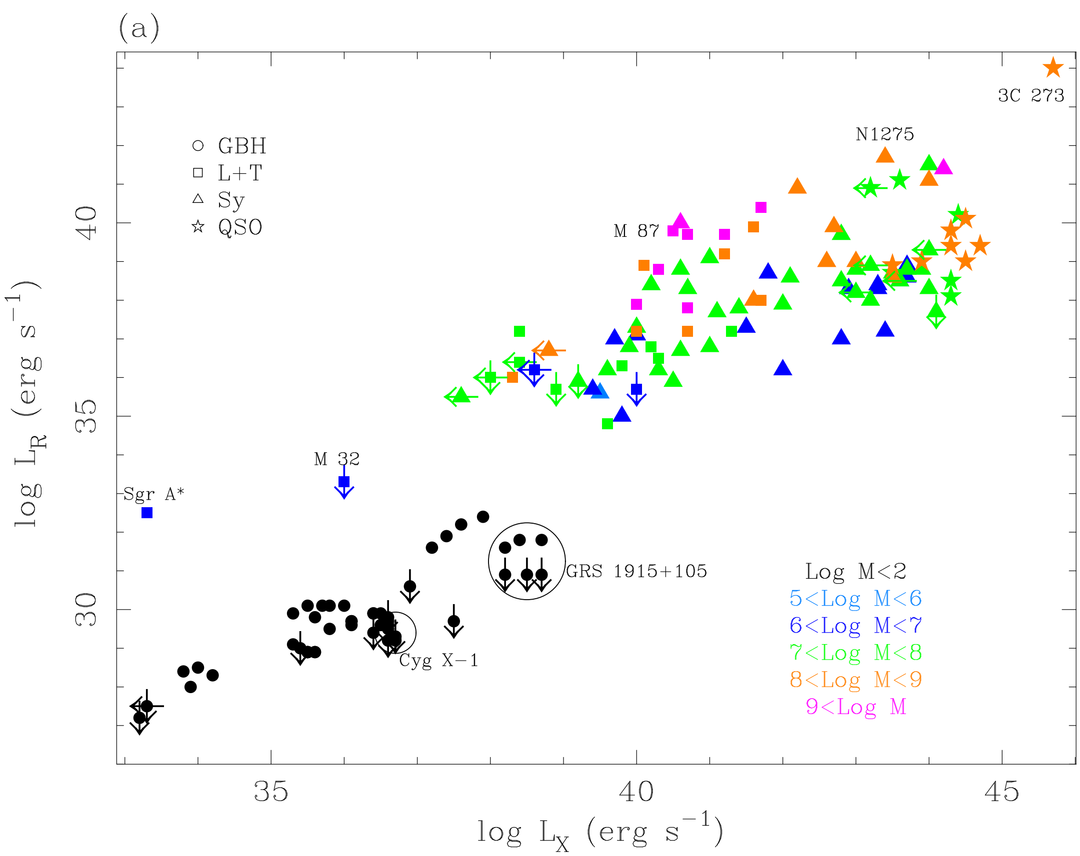
- Alternatively, the jet could maintain a stable magnetic field configuration (with $|B_\phi| \sim |B_p|$) if internal magnetic energy dissipation (constrained by the conservation of magnetic helicity) keeps it at a minimum-energy, force-free state (Königl & Choudhuri 1985).

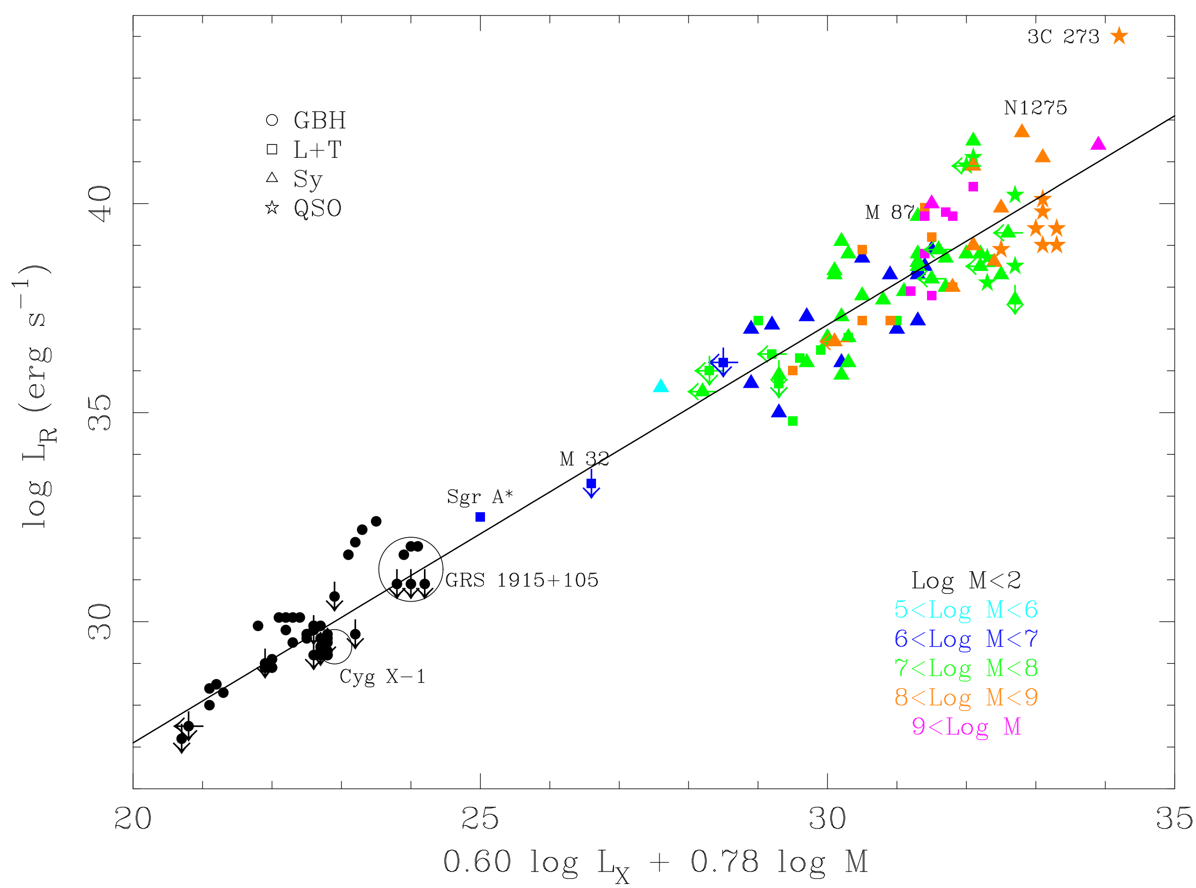
Relationship to Other Jet Sources

Galactic black-hole binaries (microquasars)

The same scaling relation between the radio (L_R) and X-ray (L_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):

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





Merloni et al. (2003)

♣ The extension of the microquasar $L_{\rm R} - L_{\rm X}$ scaling to AGNs was critiqued by Bregman (2005) on the grounds that it was based on a flux-limited (rather than volume-limited) sample.

- 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).

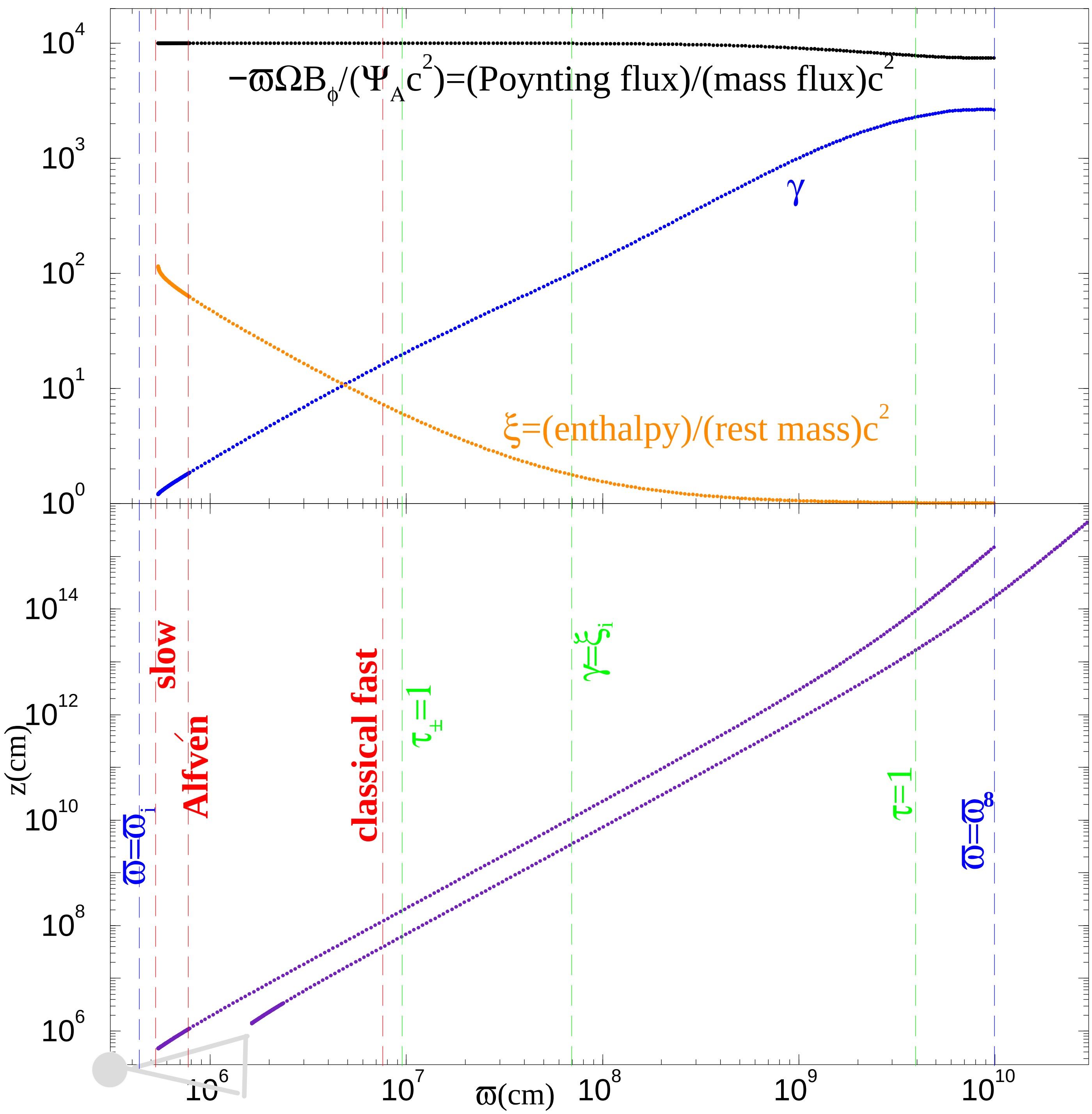
GRB sources

GRBs evidently involve ultrarelativistic ($\gamma_\infty \sim 10^2 - 10^3$), highly collimated ($\theta_{\rm j} \sim 2^\circ - 20^\circ$) 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.

♣ Exact semianalytic solutions of the special-relativistic, ideal-MHD equations, constructed within the same modeling framework that was employed in the fitting of superluminal AGN jets, can be used to demonstrate that Poynting flux-dominated jets can transform $\gtrsim 50\%$ of their magnetic energy into kinetic energy ($E_{\rm K} \sim 10^{51}$ ergs) of $\gamma_\infty \sim 10^2 - 10^3$ baryons (Vlahakis & Königl 2001, 2003a,b).



$-\varpi\Omega B_\phi/(\Psi_A c^2)$=(Poynting flux)/(mass flux)c^2
γ
ξ=(enthalpy)/(rest mass)c^2
10^0
10^1
10^2
10^3
10^4
z(cm)
10^6
10^8
10^{10}
10^{12}
10^{14}
$\varpi=\varpi_i$
slow
Alfvén
classical fast
$\tau_\pm=1$
$\gamma=\xi_i$
$\tau=1$
$\varpi=\varpi_\infty$
ϖ(cm)
10^7
10^9

- An extended acceleration region is again a distinguishing characteristic of these solutions, as in the AGN case. However, only in AGN jets is the acceleration zone potentially resolvable (by radio interferometry), which could make it possible to use observations of blazar jets to test and constrain the magnetic outflow model.

- There are indications that magnetic energy dissipation may contribute to the jet emissivity (and possibly also to the flow acceleration) in GRB sources. Similar effects may occur also in AGN jets (e.g., Choudhuri & Königl 1986).

Comprehensive Modeling of AGN Jets

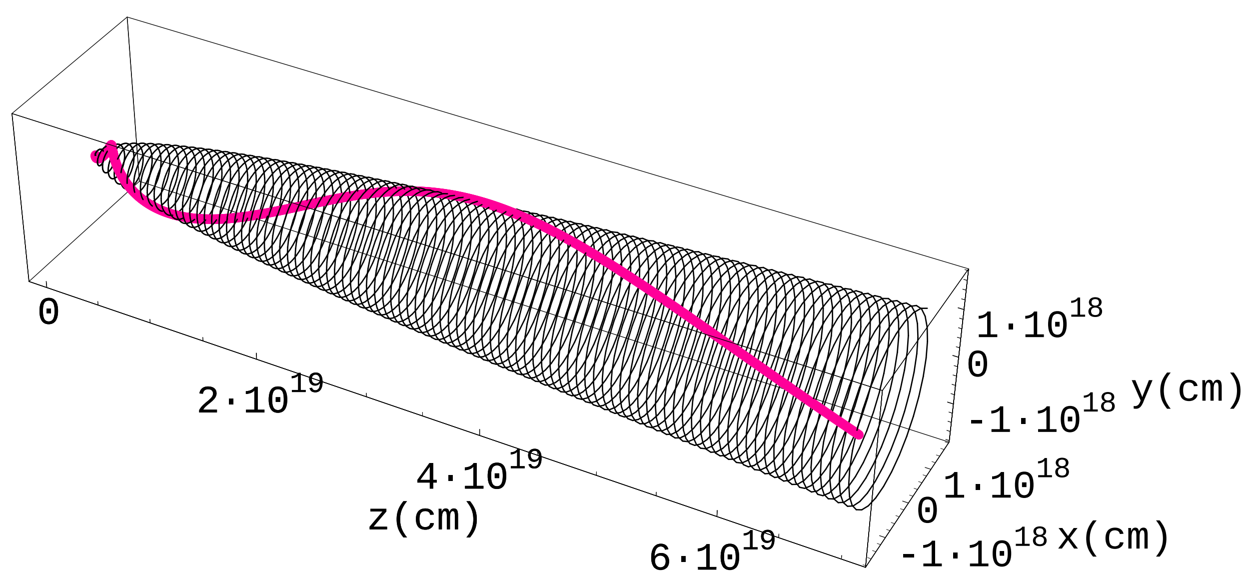
Kinematics

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

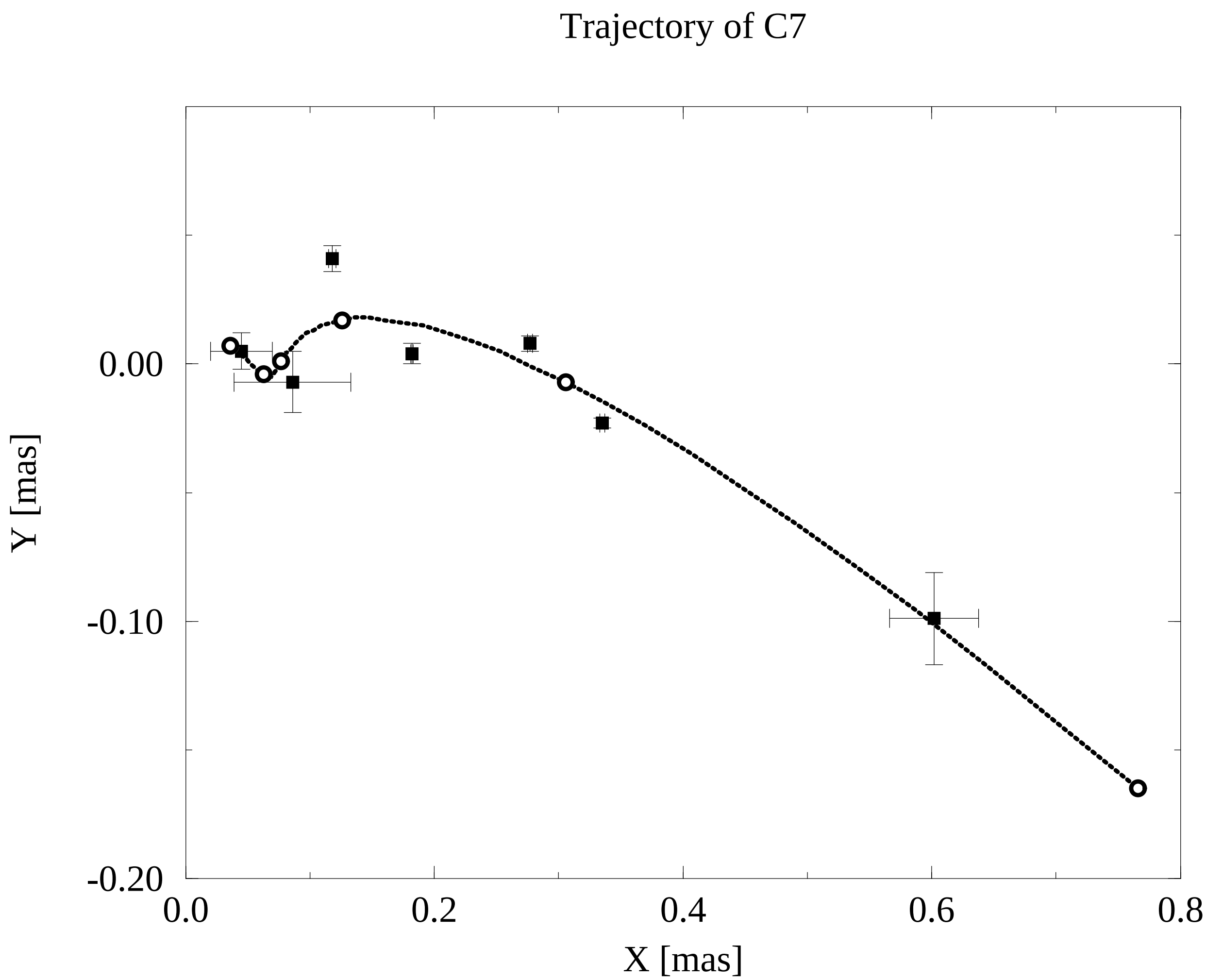
The trajectory shapes could arise from motion along helical field lines (Camenzind & Krockenberger 1992).

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

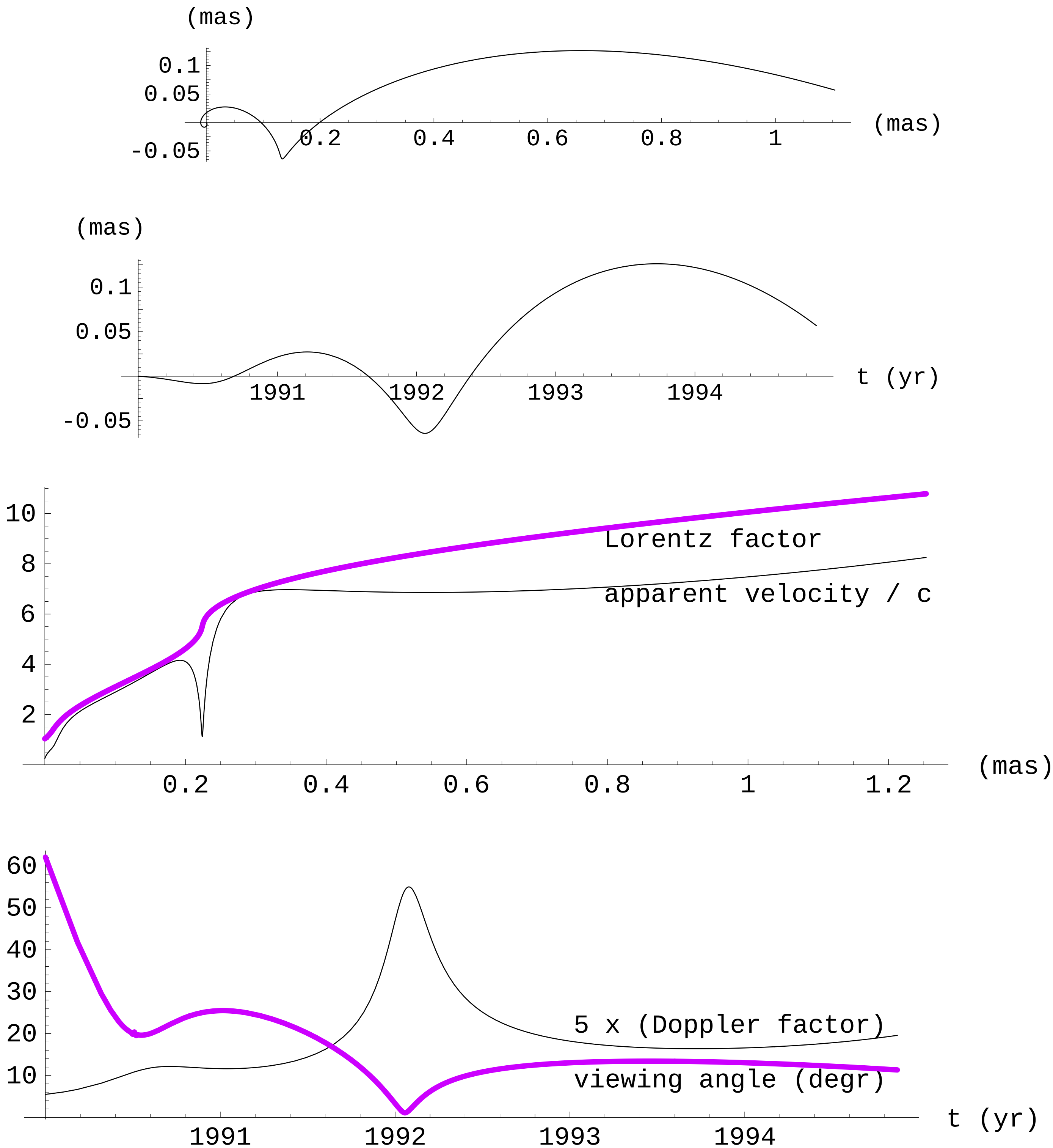


By applying all available kinematic constraints to the dynamical model, one could test this picture against alternative interpretations (unstable fluid modes, source precession, etc.).
Valuable additional constraints could be provided by the radiative properties of the jet (flux, linear and circular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



Lobanov 1996

Preliminary fit to component C7



Conclusions

- ♣ Large-scale ($\lesssim 1$ pc) AGN disk winds are evidently driven, at least in part, by continuum and line radiation pressure exerted by the central ionizing continuum. For the acceleration to be effective, the high-energy portion of the incident continuum must be attenuated by an intervening shield.
  - A "failed" inner-disk outflow driven by the disk's radiation field is a conceivable (but not yet conclusively demonstrated) means of shielding the large-scale wind.

- ♣ Centrifugal magnetic driving is an alternative mechanism of driving the large-scale wind. Such an outflow is typically highly stratified and can possess an outer dusty region; it is thus a natural candidate for the generic "inner warm absorber" and "outer molecular torus."
  - Both radiative and magnetic forces could conceivably operate in a given source. In this case the magnetically driven inner wind could shield the outer outflow and thereby enable it to be radiatively accelerated by the central continuum; in turn, the radiation pressure force on the gas and dust might "open up" the flowlines and flatten the obscuring "torus."

- ♣ Jets emanating from the inner disk regions of a radio-loud AGN typically contain a relativistic outflow component and carry most of the linear momentum and energy that such an AGN deposits into its surroundings. Magnetic stresses provide the most probable mechanism of accelerating and collimating relativistic jets, with a slower, outer disk wind possibly contributing to the collimation.
  - Magnetic acceleration of relativistic flows (by a B_ϕ pressure gradient) is, in general, spatially extended; superluminal AGN jets may provide a unique testbed for this interpretation.
- ♣ AGN jets may be closely related to their counterparts in GRB sources and Galactic BH binary systems.
  - If confirmed, the apparent similarity between the low/hard state of BH binaries and certain AGNs may indicate a common physical origin.