Hydromagnetic Driving of Astrophysical Jets: II.

Arieh Königl
University of Chicago

Outline:

- Vertical angular momentum transport by large-scale magnetic fields: semianalytic models of jet-launching protostellar disks
- Hydromagnetic jet models: exact special-relativistic MHD solutions of GRB and AGN outflows
- Magnetic energy dissipation in jets: force-free equilibria of extragalactic radio sources

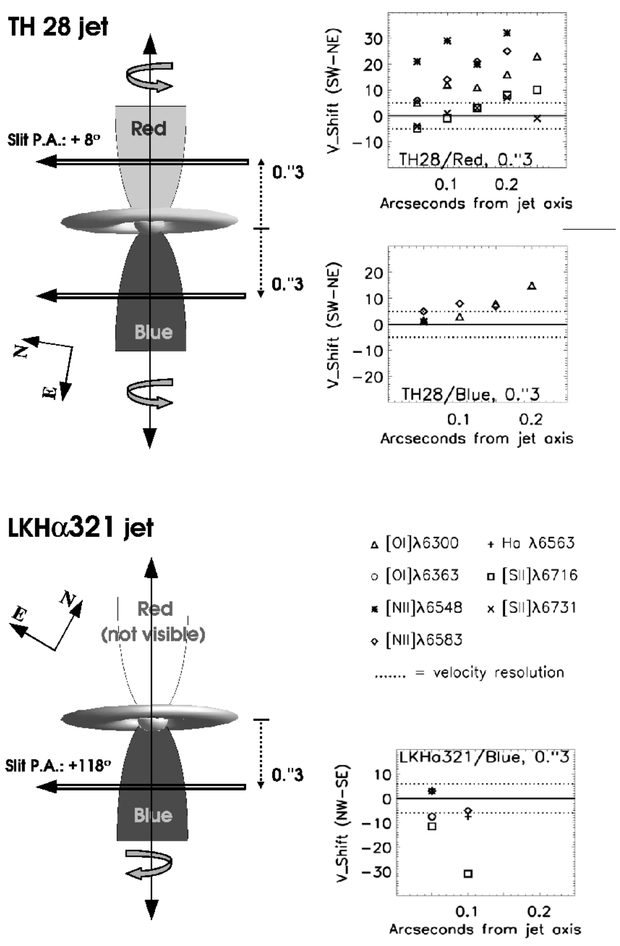
Steady-State Magnetic Disk–Wind Models

- Rotationally supported disk threaded by open magnetic field lines.
- At least part of the angular momentum removed from the accreted matter is transported vertically by the large-scale field (rather than radially by viscous stresses) and deposited in the outflow.
- In a steady state, radial advection and azimuthal shearing of the disk magetic field are balanced by magnetic diffusivity.

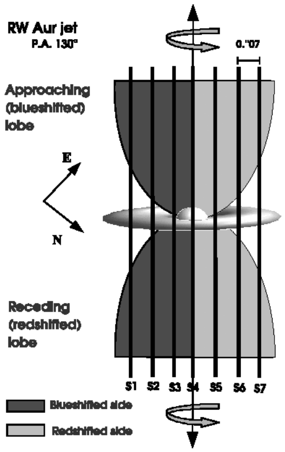
Example: protostellar accretion disks

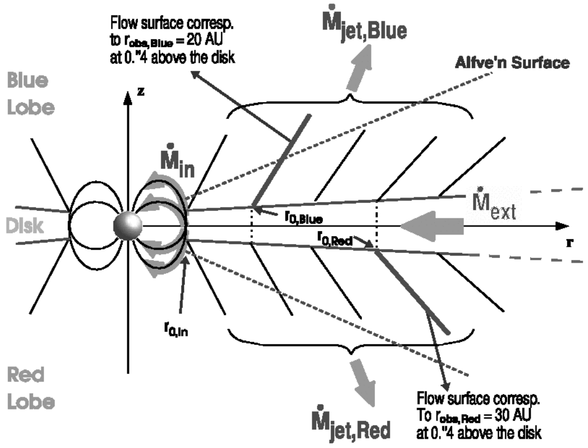
Woitas et al. (2005): Using STIS on board the HST...[and]...MHD models for the launch of jets, we find that the mass ejected in...the [RW Aur] outflow is accelerated from...the disk within about 0.5 AU from the star for the blue lobe, and within 1.6 AU for the red lobe. Using also previous results we estimate [that]...the angular momentum transport rate of the jet...can be a large fraction (2/3 or more) of the estimated rate transported through the relevant portion of the disk...Finally, using the general disk wind theory we derive the ratio B_ϕ/B_p...at about 80-100 AU above the disk...The toroidal component appears to be dominant..."

See also: Bacciotti et al. '02, Testi et al. '02, Anderson et al. '03 for DG Tau; Coffey et al. '04 for LkHα 321 & TH 28; Hartmann & Kenyon '96 (ARAA) for FU Ori objects.



Coffey et al. (2004)



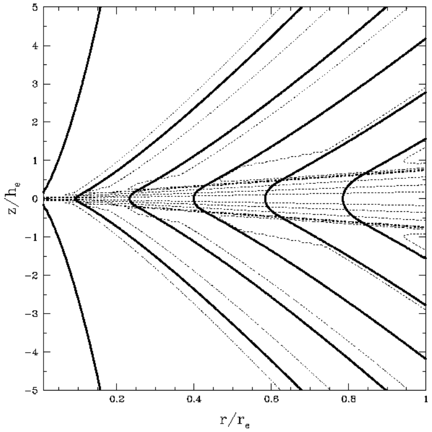


Woitas et al. (2005)

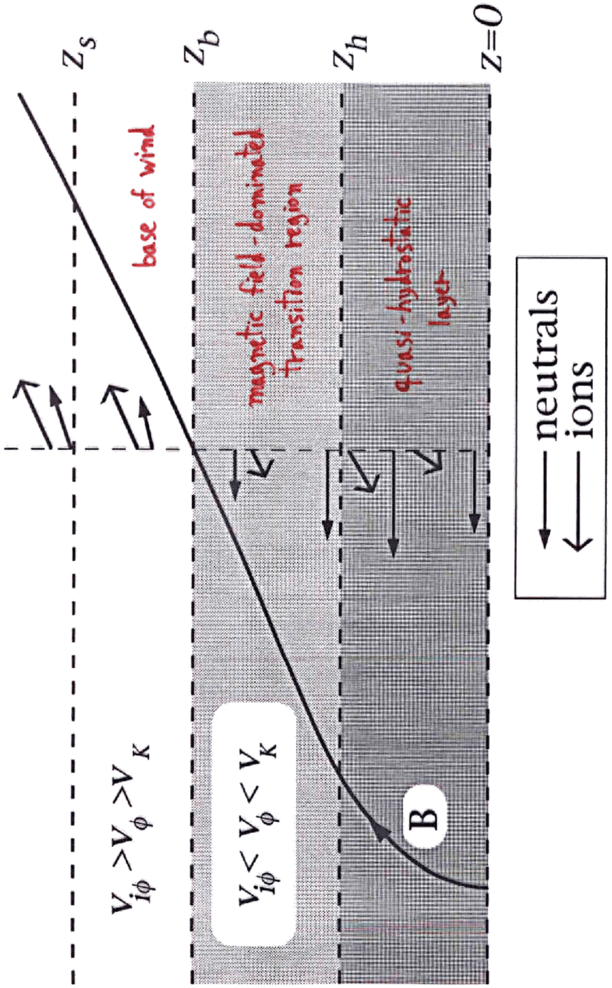
Equilibrium model of "pure" wind-driving disk in the ambipolar-diffusion/Hall regime (Wardle & Königl 1993):

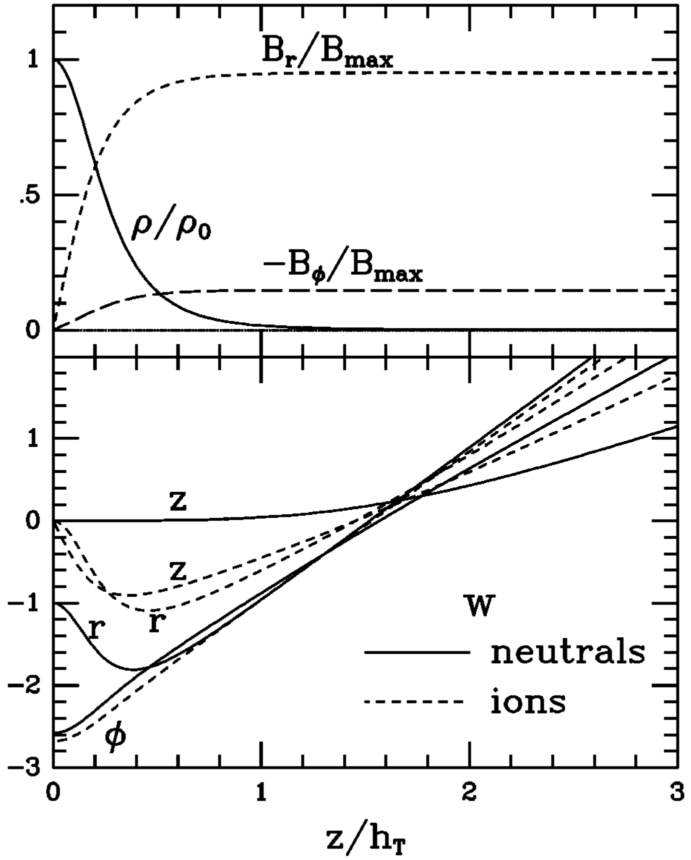
- Isothermal, geometrically thin, Keplerian rotation law, even field symmetry;
- Radially localized disk solution matched onto radially self-similar, ideal-MHD wind solution (Blandford & Payne 1982).

Results confirmed by global self-similar disk/wind solution (Li 1996).



Ferreira (1997)





$$\mathbf{W} = \frac{\mathbf{V} - V_K \hat{\phi}}{C_s}\,, \qquad h_T = \frac{C_s}{V_K}\, r$$

[N.B., $|V_r| \sim C_s$; relevant to onset of self-gravity (cf. Goodman 2003)]

wind/disk parameter space

wind parameters:

λ — normalized specific angular momentum

κ — normalized mass-to-magnetic flux ratio

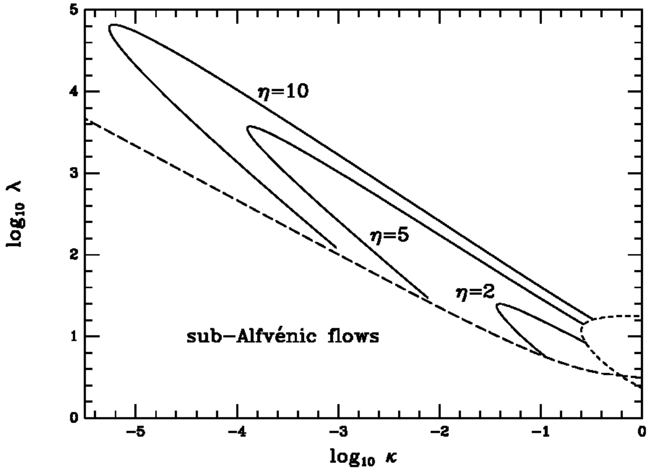
disk parameters:

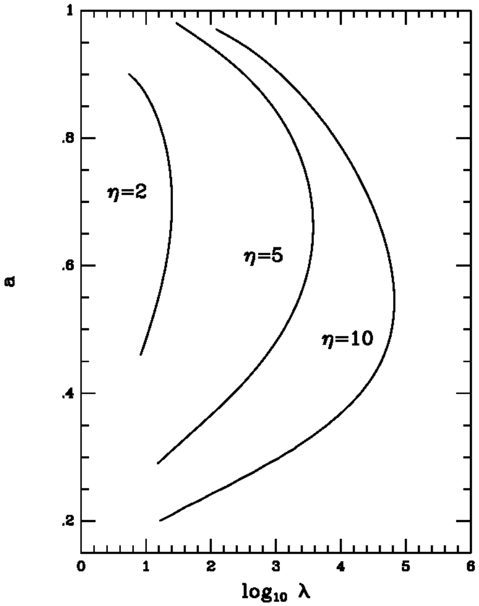
η — neutral-ion coupling parameter

a — field-strength parameter

$\eta > 1$ and $a \lesssim 1$ required to drive a wind

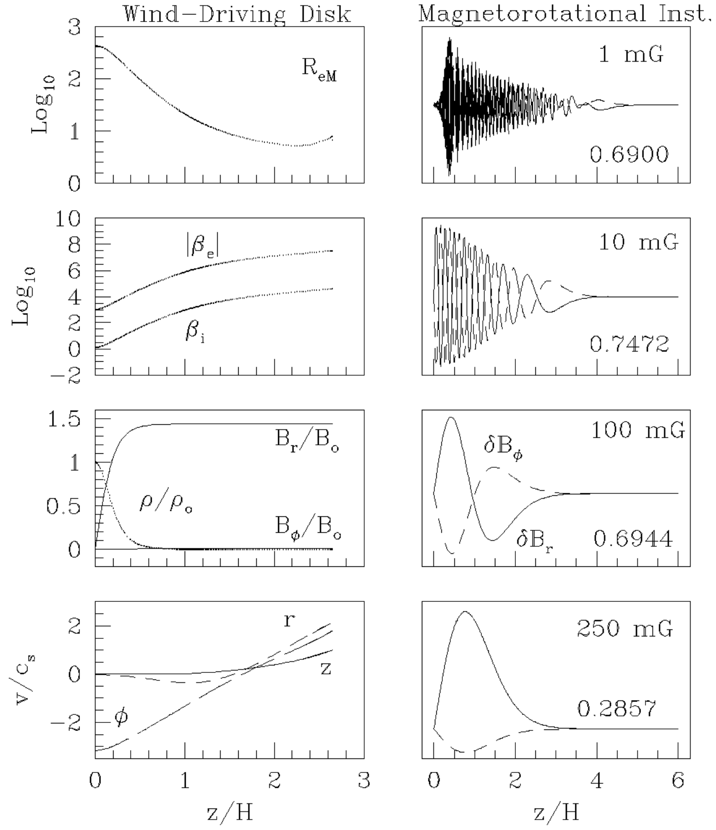
($\eta > 1$ everywhere in strongly coupled disks)





stability properties change at turning point of equilibrium curve — real systems likely correspond to stable branch (Königl 2004; cf. Lubow et al. 1994; Cao & Spruit 2002)

Equilibrium disks lie in stability “window”: $\mathbf{B}$ is strong enough to stabilize MRI but not so strong as to trigger radial interchange.

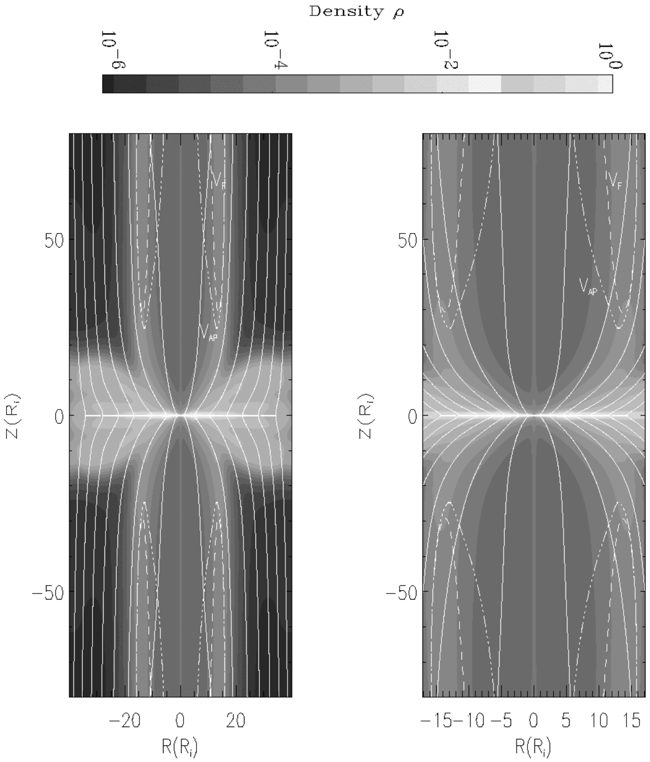


$R = 10$ AU , $\Sigma = 10$ g cm^{-2}

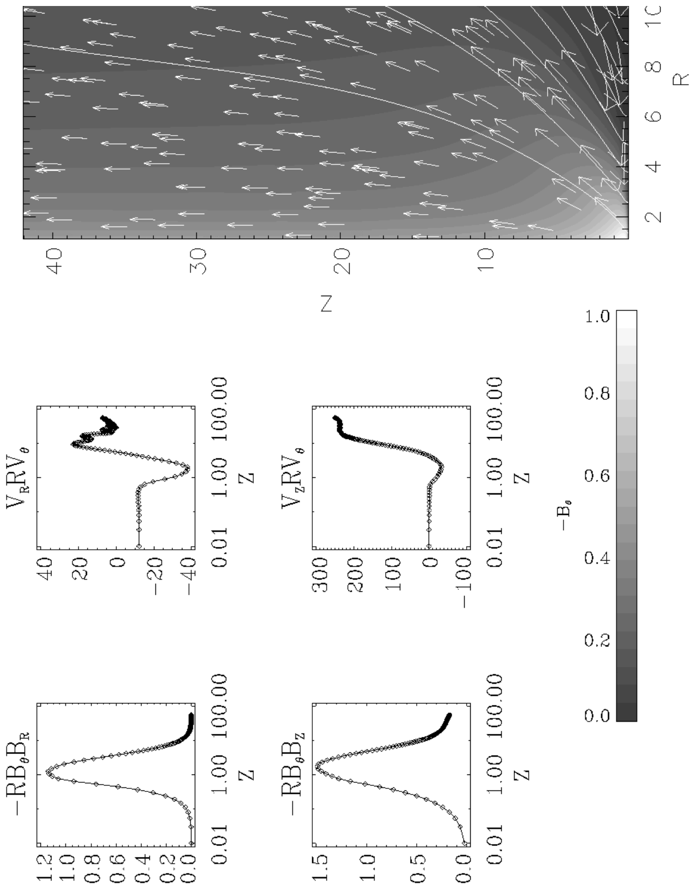
Jets: $\dot{M} = 10^{-7}\ M_\odot\ yr^{-1}$, $B = 300$ mG

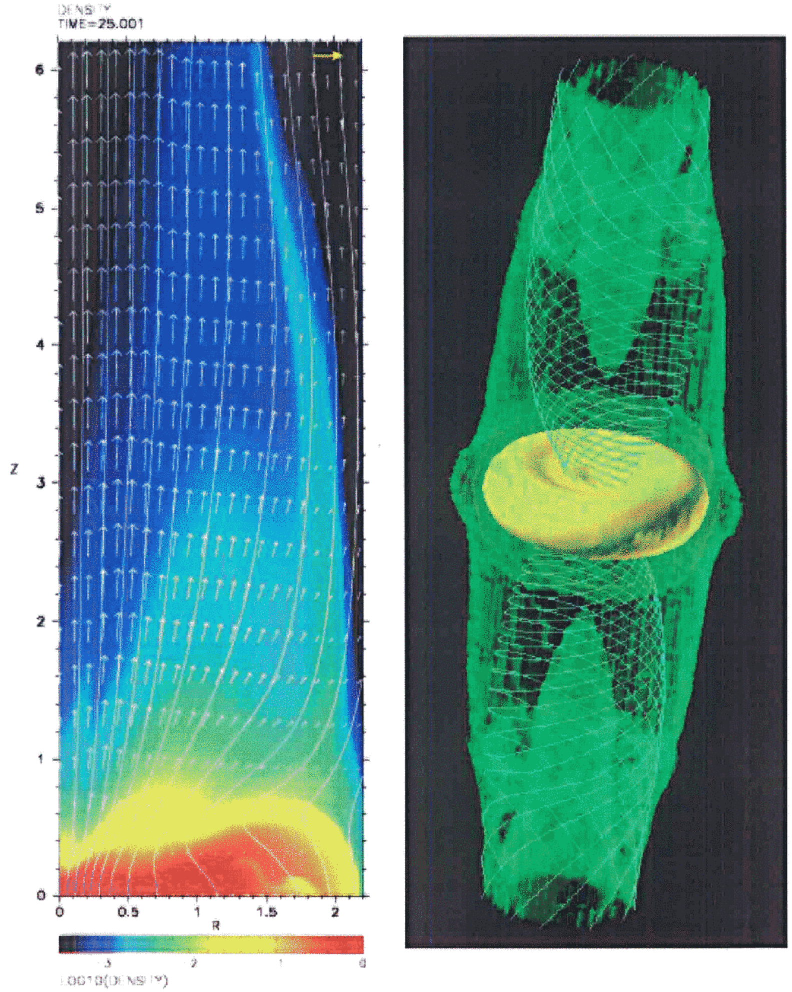
MRI: Salmeron & Wardle, 2005, MNRAS in press

simulations of jet-driving resistive disks



Casse & Keppens (2002)



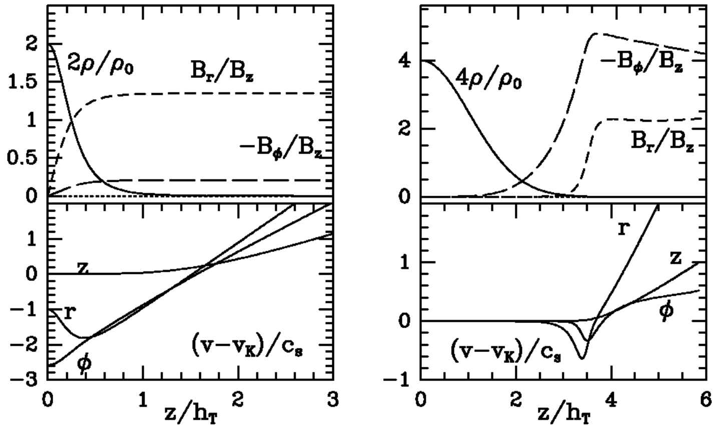


Kuwabara et al. (2005)

weakly coupled disks ($\eta > 1$ only near surface)

(Li 1996; Wardle 1997)

strong coupling (left) vs. weak coupling (right)

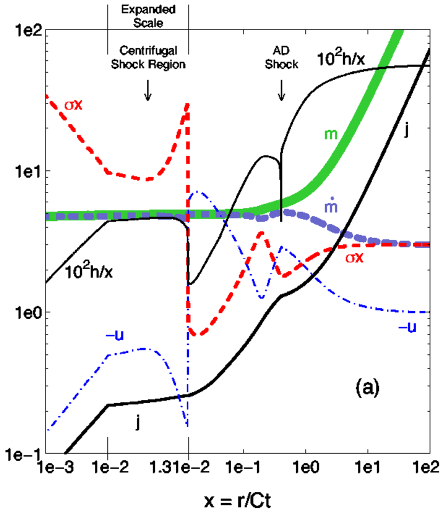


Wardle (1997)

Note that angular momentum is removed also from weakly coupled regions where $B_r \approx 0$ since torque $\propto B_z(dB_\phi/dz)$.

Origin of Disk Magnetic Field

- Rotationally supported circumstellar disks in protostellar systems evidently originate in the collapse of self-gravitating, rotating, molecular cloud cores.
- The cores are threaded by open interstellar magnetic field lines that are dragged inward once dynamical collapse is initiated.
- Krasnopolsky & Königl (2002) obtained a semianalytic self-similar (in r and t) solution describing the collapse of such a core. Their model incorporates ambipolar diffusion (AD) as well as magnetic braking (the vertical transport of angular momentum through torsional Alfvén waves).



- Outer region ($x > x_a$): Ideal-MHD infall.
- AD shock—resolved as a continuous transition.
- AD-dominated infall ($x_c < x < x_a$): near free-fall controlled by central gravity.
- Centrifugal shock — its location depends sensitively on the diffusivity parameter.
- Keplerian disk ($x < x_c$) — at any given time, it satisfies $\dot{M} = const$, $B \propto r^{-5/4}$, $B_{r,\mathrm{surface}}/B_z = 4/3$ ($r \to 0$ solution).

- The asymptotic disk solution implies a surface field-line inclination to the rotation axis of $\sim 53°$, indicating the likelihood of centrifugally driven winds.

- The steady-state, radially self-similar disk-wind solution of Blandford & Payne (1982) can be naturally incorporated into this solution since $B \propto r^{-5/4}$ in both cases.

- When interpreted in this fashion, the asymptotic solution is found to correspond to a weakly coupled disk/wind configuration.

Hydromagnetic Jet Models

Jets are accelerated to highly supersonic and super-Alfvénic speeds:

- Thermal and centrifugal acceleration may initially dominate.
- Further out, the magnetic $(B_\phi^2/8\pi)$ pressure-gradient force takes over.
- The magnetic acceleration continues beyond the classical fast-magnetosonic surface to the modified fast-magnetosonic surface (the "event horizon" for the propagation of fast-magnetosonic waves when the Bernoulli and Grad-Shafranov equations are solved simultaneously).

spatially extended acceleration is a distinguishing characteristic of MHD (vs. purely hydrodynamic) jets: it should be most readily discernible in relativistic jets.

Relativistic Jets in GRB sources and AGNs

- GRBs and afterglows evidently involve ultrarelativistic $(\gamma_\infty \sim 10^2 - 10^3)$, highly collimated $(\theta_{\rm j} \sim 2^\circ - 20^\circ)$ outflows. They are most likely formed through the 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 or magnetic field dissipation, may also power the acceleration.

- Highly relativistic flows $(\gamma_\infty \sim 10 - 10^2)$ have been indicated also in AGNs by measurements of apparent superluminal motions $(V_{\rm app}$ as high as $\sim 40\,c)$ and rapid Stokes-parameter variability in blazar jets. Magnetic fields are considered the most likely driving mechanism in this case as well (Blandford & Znajek 1977; Blandford & Payne 1982). Mildly relativistic motions of X-ray absorbing gas inferred in several QSOs are plausibly explained by MHD disk winds (Everett & Ballantyne 2004; Königl & Kartje 1994).

GRB Jets

Energy injected over time Δt from a source of area $\mathcal{A}$:

$$\mathcal{E}_{\rm i} \approx c\, E_{\rm i}\, B_{\phi,\rm i}\, \mathcal{A}\, \Delta t \ ,$$

where the electric field is given by

$$E = B_{\rm p} V_\phi / c - B_\phi V_p / c$$

(with p denoting *poloidal*).

The initial field amplitude is inferred to be $B_{\rm i} \sim 10^{14} - 10^{15}$ G. It is most plausibly generated by differential-rotation amplification of a much weaker poloidal field that originally threads the source.

$|B_{\rm p,i}/B_{\phi,\rm i}| > 1$ $\Rightarrow$ trans-Alfvénic outflow.

$|B_{\rm p,i}/B_{\phi,\rm i}| < 1$ $\Rightarrow$ super-Alfvénic flow from the start: this situation may correspond to amplified toroidal flux loops that have been disconnected by magnetic reconnection and escape from the source in a nonsteady fashion.

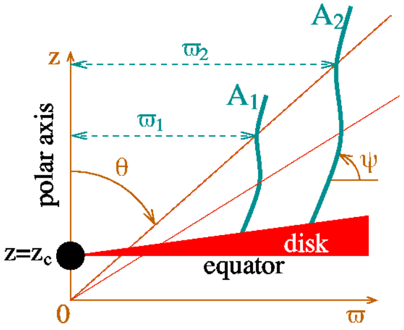
Exact Relativistic-MHD Solutions

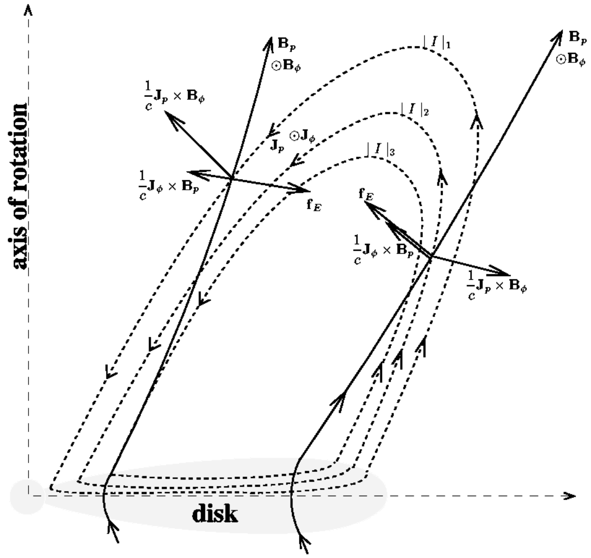
References: Vlahakis & Königl 2001 (ApJ 563, L129), 2003a,b (ApJ 596, 1080; 1104).

- Exact semianalytic solutions of GRB 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 burst time scale
  - Steady-state equations apply to the evolution of a given ejected 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

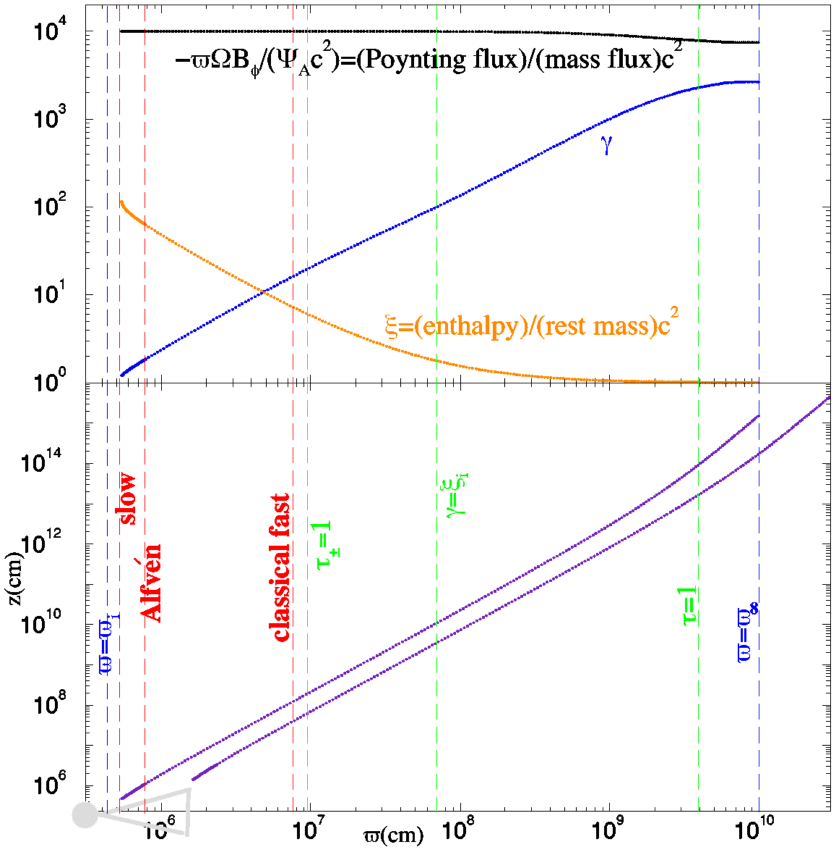
- The general problem requires the specification of 7 constraints: 4 associated with boundary conditions at the source and 3 determined by regularity requirement at the critical points of the joint solution of the Bernoulli and transfield (Grad-Shafranov) equations.

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: $r = \mathcal{F}_1(A)\mathcal{F}_2(\theta)$.





The derived solutions have been used to demonstrate that Poynting flux-dominated jets (either trans- or super-Alfvénic) 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.



Asymptotically cylindrical geometry attained for solutions in the current-carrying regime ($I_p = c\varpi B_\phi/2 \propto A^{(F-1)/F}$, $F > 1$; $I_p \to 0$ as $\varpi \to 0$ — applicable to near-axial flows).

Solutions in the return-current regime ($F < 1$; applicable at larger ϖ) reach conical asymptotics.

Example: "hybrid" ($F > 1 \to F < 1$) super-Alfvénic solution for an initially neutron-rich outflow.

Reference: Vlahakis, Peng, & Königl 2003 (ApJ 594, L23 [VPK03]).

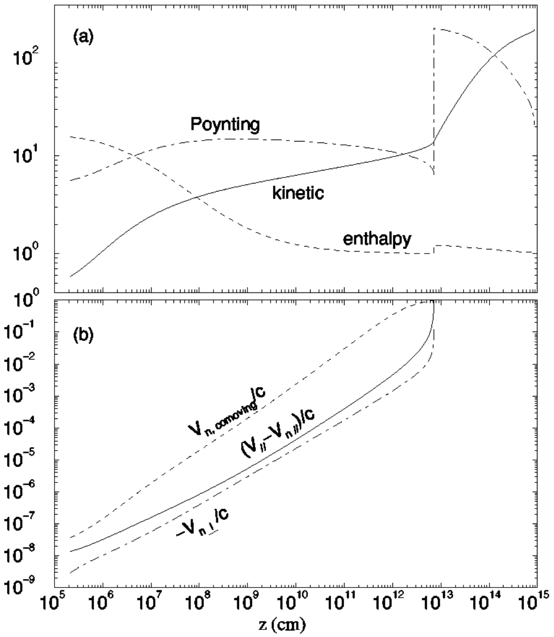
Disk-driven GRB outflows are expected to be neutron-rich, with n/p as high as $\sim 20-30$ (Pruet et al. 2003; Beloborodov 2003b, VPK03).

Since only the charged outflow component couples to the E&M field, the neutrons could potentially decouple from the protons before the latter attain their terminal Lorentz factor ($\gamma_\mathrm{d} < \gamma_\infty$; Fuller et al. 2000).

♠ An outflow with $\gamma_\mathrm{d} \ll \gamma_\infty$, which could evade the baryon loading problem, is only possible in a hydromagnetic (but not in a purely hydrodynamic) jet model.

- For super-Alfvénic flows, part of the enthalpy flux in the initial thermal acceleration region is converted into Poynting flux.
- This reduces the acceleration rate, so at the point of decoupling (when $V_\mathrm{proton} - V_\mathrm{neutron} \sim c$) the Lorentz factor is still comparatively low.
- The energy deposited into the Poynting flux is returned to the matter beyond the decoupling point as K.E., thereby enhancing the acceleration efficiency of the proton component.

(Alternative interpretation: baryon-poor outflow from BH magnetosphere; Levinson & Eichler 2003; McKinney 2005.)



- $\gamma_{\mathrm{d}} \approx 15$, $\gamma_\infty = 200$, $E_{\mathrm{K,proton}} \approx 10^{51}$ ergs $\approx 0.5\, E_{\mathrm{K,neutron}}$.

- The proton jet carries $\sim 1/3$ of the injected energy but only $\sim 3\%$ of the injected mass.

- Because of the magnetic collimation, the neutrons also acquire a transverse drift relative to the protons; this could give rise to a 2-component signature in the afterglow emission (Peng, Königl, & Granot 2005).

AGN Jets

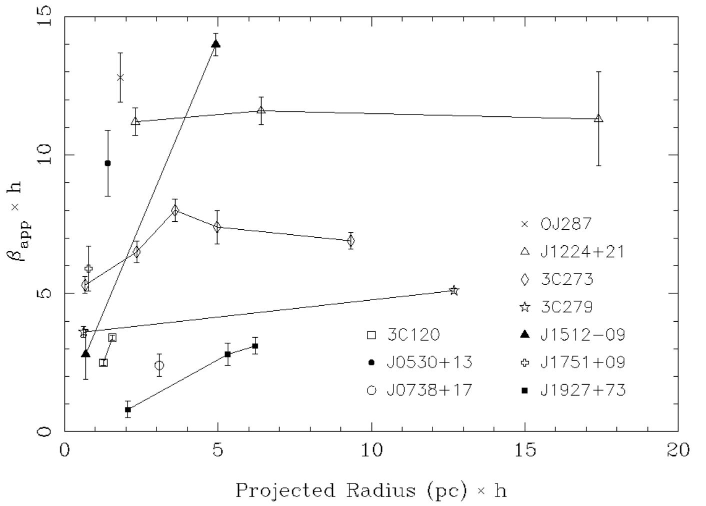
Reference: Vlahakis & Königl 2004 (ApJ 605, 656)

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.

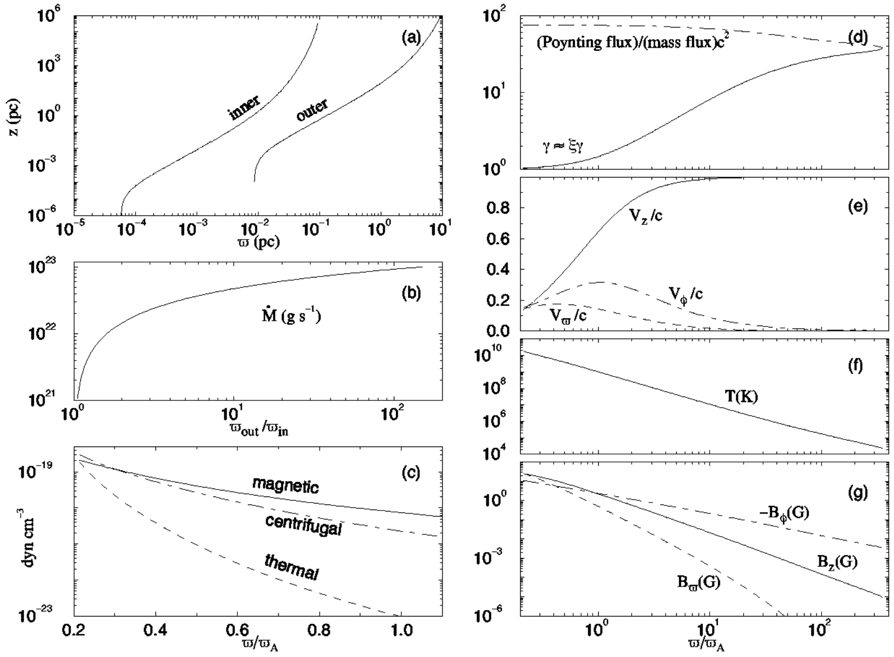
- Extended acceleration in the 3C 345 jet has been independently indicated by the increase in apparent component speed with separation from the nucleus (Zensus et al. 1995) and by the observed luminosity variations of the moving components (Lobanov & Zensus 1999). Similar effects in other blazars suggest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

Magnetic Energy Dissipation

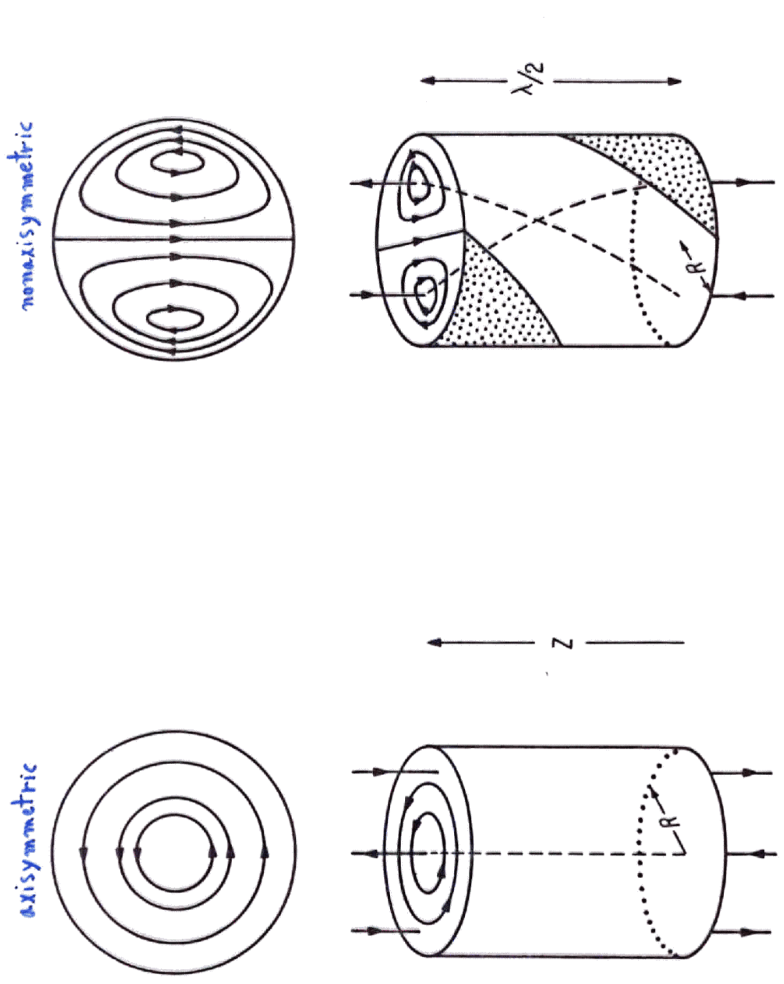
Even if most of the injected magnetic energy ends up as kinetic energy of bulk motion, the internal jet energy on large scales is still dominated by the magnetic component ($B_\perp \propto \varpi^{-1}$, $B_\parallel \propto \varpi^{-2}$, $P \propto \varpi^{-2\Gamma}$ for ideal-MHD, adiabatic evolution).

$\Rightarrow$ 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 ($\mu =$ 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., NGC 6251)

- 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 $d\Psi(\varpi_0) = 2\pi B_z(\varpi_0)\varpi_0 d\varpi_0$.



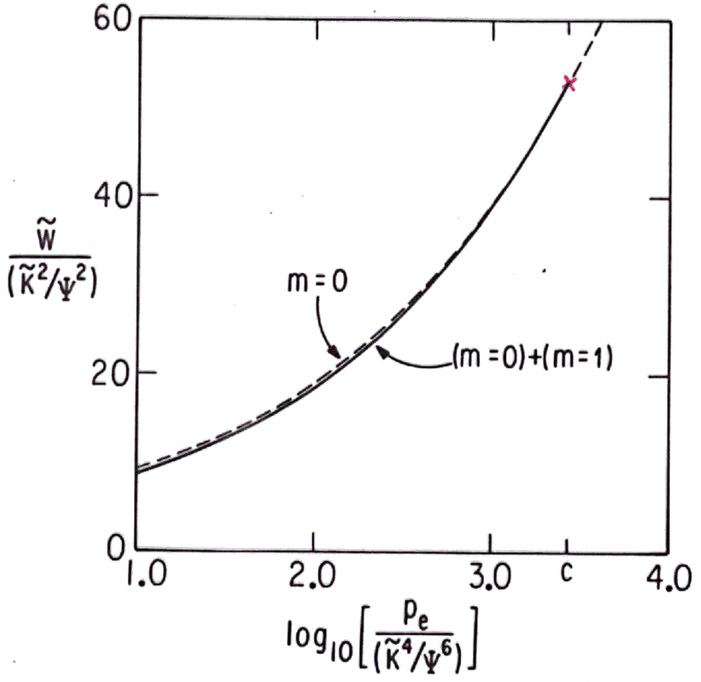
m=1
wavelength along the jet λ≈5R

m=0
accounts for net axial flux and current

Fig. 1

Evolution of Minimum-Energy Field Configuration in Force-Free Jet

the m=1 mode becomes energetically favorable when P_e drops below P_c



P_e - external pressure
$\tilde{K}$ - magnetic helicity/unit length
Ψ - axial magnetic flux
$\tilde{W}$ - magnetic energy/unit length

Fig. 2

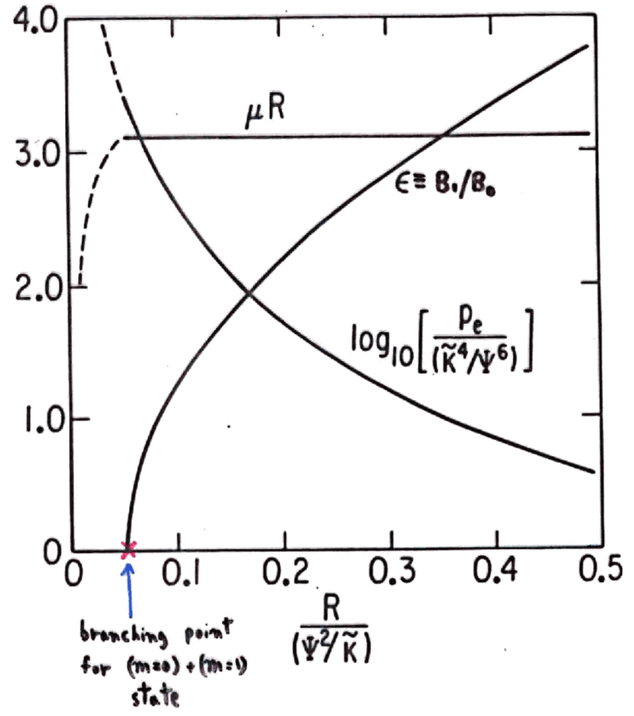


Fig. 3

Magnetic Energy Dissipation in Force-Free Jets

Q. is the field readjustment during the expansion of the jet accompanied by magnetic energy dissipation?

A. not in the "instantaneous readjustment" limit, when

$\mathcal{E} \equiv \frac{t_{reconnect}}{t_{expand}}$ is $\ll 1$

Proof: (Browning & Priest '85, Berger '85)

$$\frac{d\tilde K}{dt} = -\frac{2c}{8\pi}\int_{\tilde V_{ol}} \vec{\epsilon}\cdot\vec{B}\, d\tilde V_{ol} = 0$$

but $\vec{j} = \frac{\mu c}{4\pi}\vec{B}$, and $\mu \to$ const. when $\mathcal{E} \to 0$

$\Rightarrow$ dissipation rate $\propto \int_{\tilde V_{ol}} \vec{\epsilon}\cdot\vec{j}\, d\tilde V_{ol} \xrightarrow[\mathcal{E}\to 0]{} 0$

$\mathcal{E} \lesssim 1$ regime:

model in 2 steps-

i) ideal-MHD expansion with $\mu \neq$ const. over a time scale $\sim t_{expand}$

ii) relaxation to μ=const. minimum-energy state with dissipation of $\Delta\tilde W_t$ over a time scale $\sim t_{reconnect}$

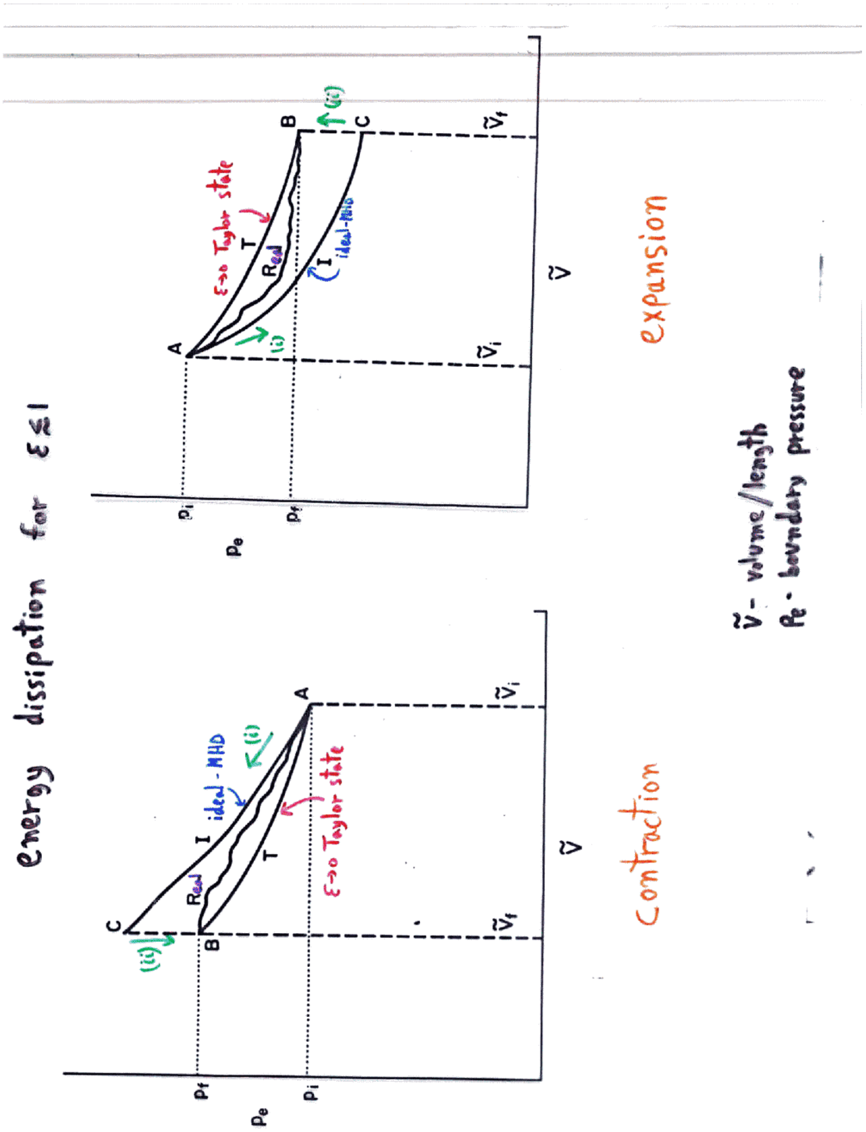
m=0 mode - $\Delta\tilde W_t = \Delta\tilde W_{ideal} - \Delta\tilde W_{min} \approx \mathcal{E}^2\left(\frac{\Psi}{4\pi R}\right)^2\frac{(\mu R)^6}{1152}$

(valid to $O((\mu R)^8)$ for $\mu R \lesssim 1.5$; Choudhuri & Königl '86)

$\rightarrow$ for $\mathcal{E}\sim 1$, $\mu R \gtrsim 1$, could account for synchrotron luminosity of jets

- analogous coronal heating models (Heyvaerts & Priest '84)

$$t_{reconnect} = \underset{\substack{\uparrow \\ \text{lab experiments}}}{?} \begin{cases} t_{tearing} & (\gg t_{expand} \text{ in jets \& solar corona}) \\ \sim 10\, t_{Alfvén} & (\text{in nonlinear regime?}) \end{cases}$$



Conclusions

- ♣ Vertical angular momentum transport involving outflows or Alfvén waves launched along open magnetic field lines that thread the disk is evidently important in protostellar systems and could be relevant also to other disk/jet sources.

- ♣ Semianalytic and numerical models have verified that diffusive accretion disks can reach steady, and likely stable, equilibrium states in which as much as 100% of the angular momentum is transported vertically through a magnetically driven outflow; in general, radial (MRI-induced) and vertical transport may occur simultaneously.

- ♣ Magnetic field configurations conducive to wind launching and vertical angular momentum transport originate naturally in the core-collapse scenario of protostellar disk formation; however, magnetic field advection may not be the only way of establishing such configurations in astrophysical disks.

- ♣ Exact semianalytic solutions of special-relativistic ideal MHD have established that relativistic jets in GRB sources and AGNs (and possibly also in Galactic microquasars) could be accelerated and collimated hydromagnetically.

- An extended acceleration region is a distinguishing characteristic of MHD driving. (The acceleration zone in AGN jets may well be resolved by radio interferometry.)
- Magnetic energy dissipation involving $B_\phi \rightarrow B_{\rm p}$ conversion and likely constrained by the conservation of magnetic helicity may govern the internal structure of MHD jets and possibly contribute to their emissivities.