Hydromagnetic Driving of Astrophysical Jets

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Outline:

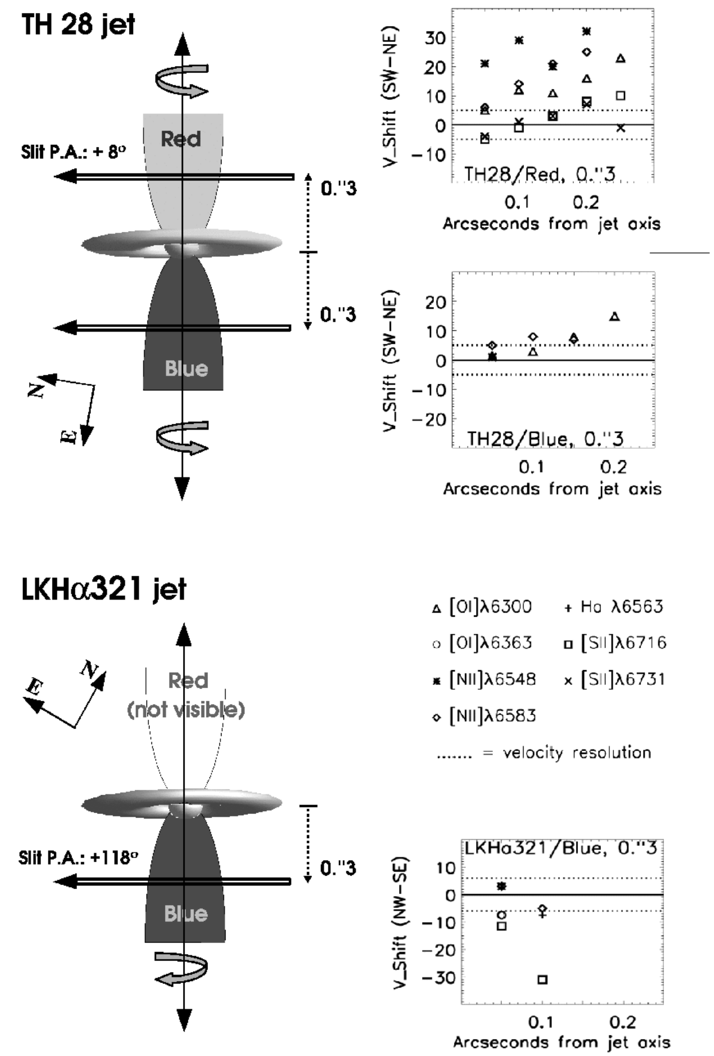
- Angular momentum transport by jets — history and recent observations
- Protostellar disk/jet systems — equilibrium models and stability considerations
- Origin of disk magnetic field
- Conclusions

Vertical Angular Momentum Transport in Accretion Disks

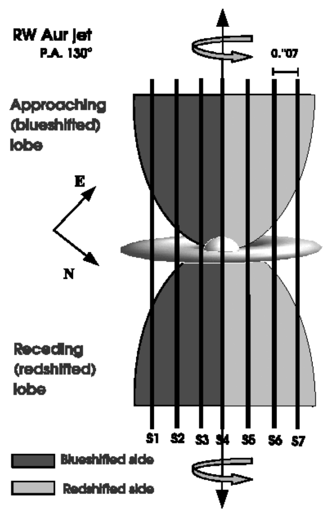
- Blandford & Payne (1982): "The possibility is examined that angular momentum is removed magnetically from an accretion disk by field lines that leave the disk surface, and is eventually carried off in a jet moving perpendicular to the disk. The mechanism is illustrated by a self-similar MHD solution..."
- Königl (1989): "It is suggested that the strong correlation that appears to exist between the presence of circumstellar disks and the occurrence of energetic winds...could be interpreted...as a reflection of the fact that the outflows regulate the angular momentum transport in the disk and hence are a necessary ingredient in the accretion process."

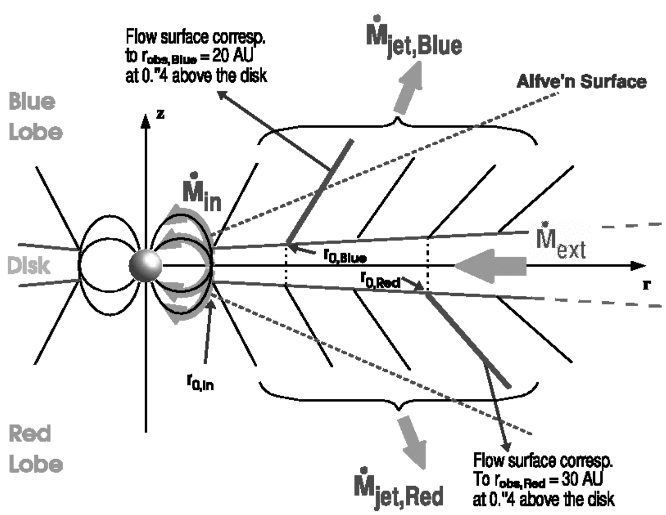
- Woitas et al. (2005): Using STIS on board the HST...[and]...MHD models for the launch of jets, we find that the mass ejected in...the [RW Aur] outflow is accelerated from...the disk within about 0.5 AU from the star for the blue lobe, and within 1.6 AU for the red lobe. Using also previous results 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 $B_\phi/B_{\rm p}$...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)

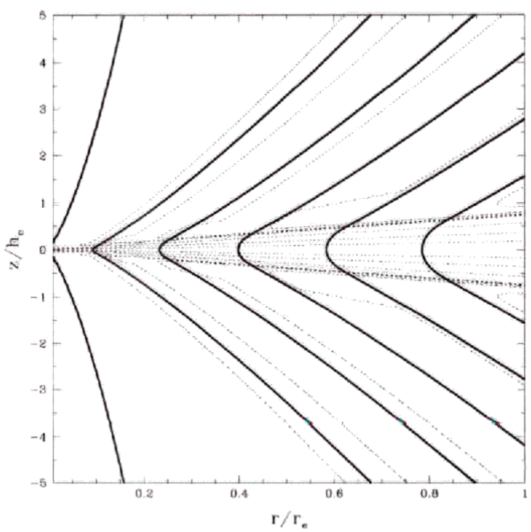
Equilibrium Disk/Wind Models

- Rotationally supported disk threaded by open magnetic field lines.
- Entire angular momentum removed from the accreted matter is transported vertically by the large-scale field and deposited in the outflow.
- In a steady state, radial advection and azimuthal shearing of the disk magnetic field are balanced by magnetic diffusivity.

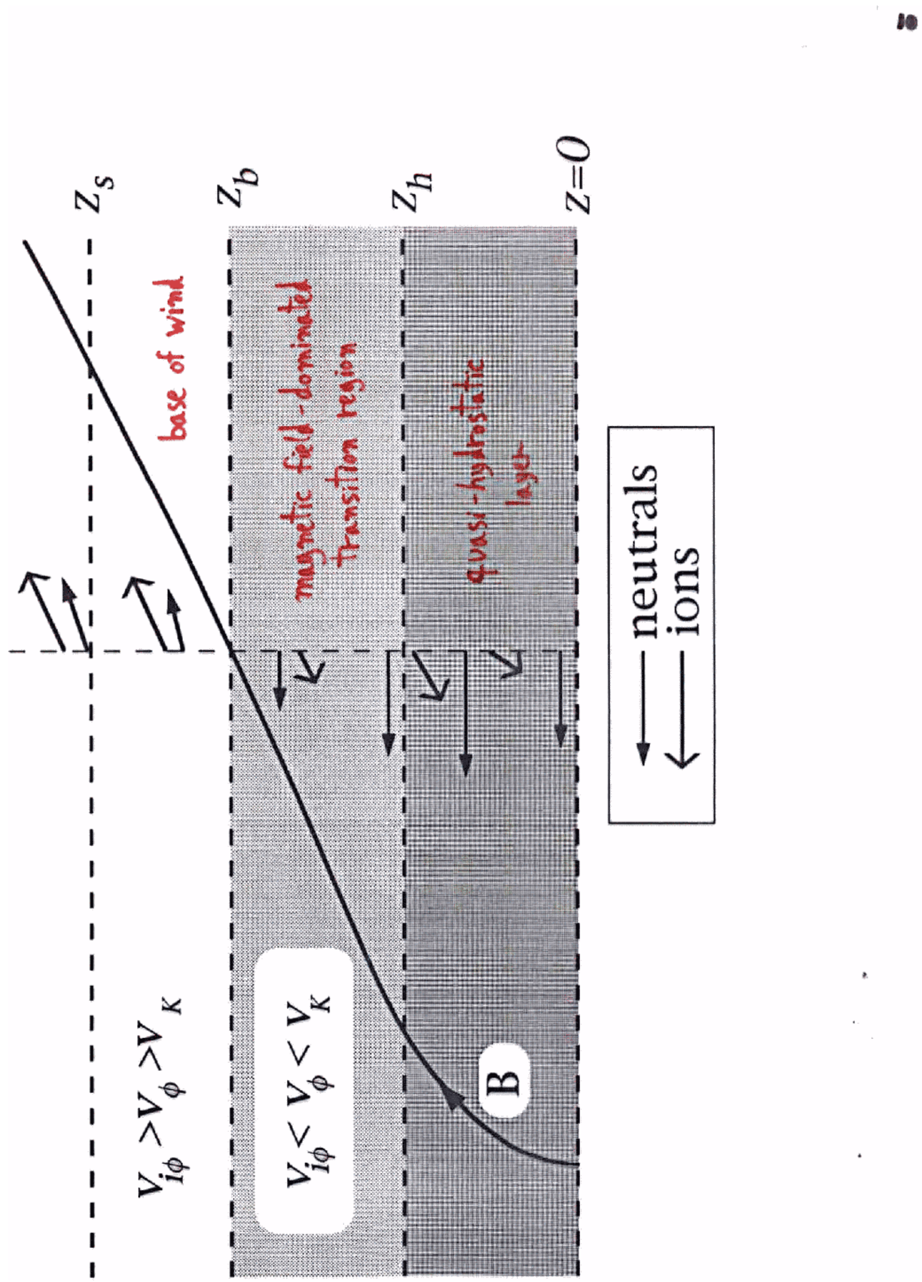
Example: Wardle & Königl (1993)
weakly ionized disk (ambipolar-diffusion/Hall)

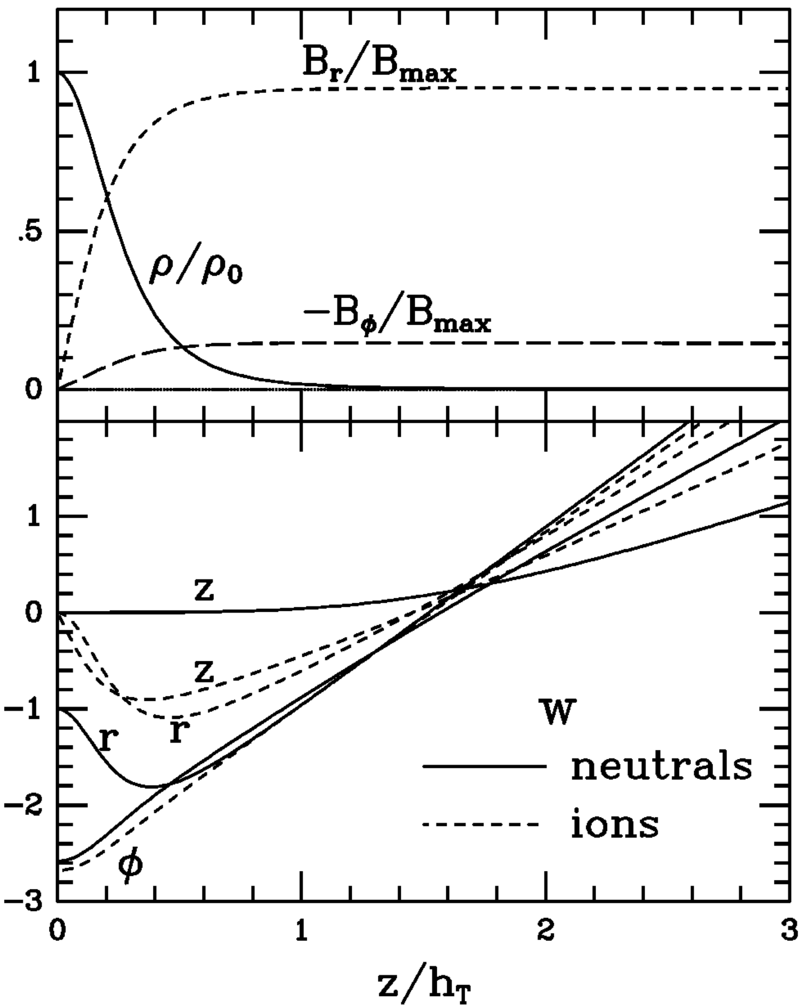
- Isothermal, geometrically thin, Keplerian rotation law, even field symmetry.
- Radially localized disk solution matched onto radially self-similar, ideal-MHD wind solution (Blandford & Payne 1982).

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



Ferreira '97





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

wind/disk parameter space

wind parameters:

λ — normalized specific angular momentum

κ — normalized mass-to-magnetic flux ratio

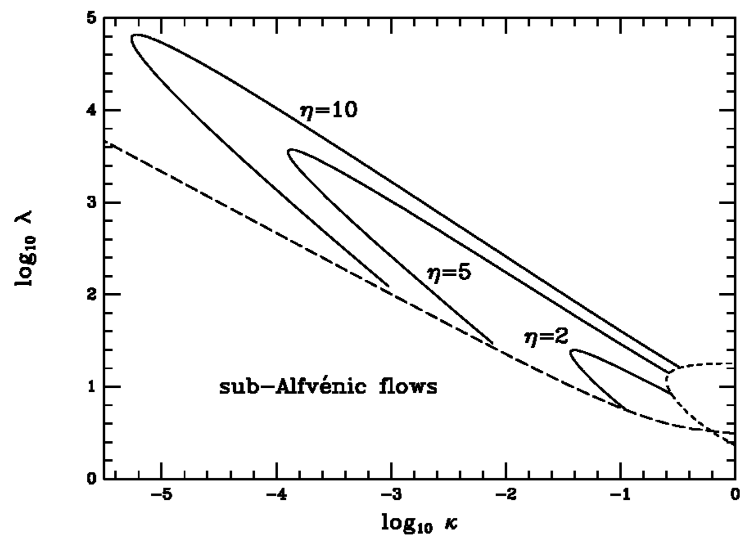
disk parameters:

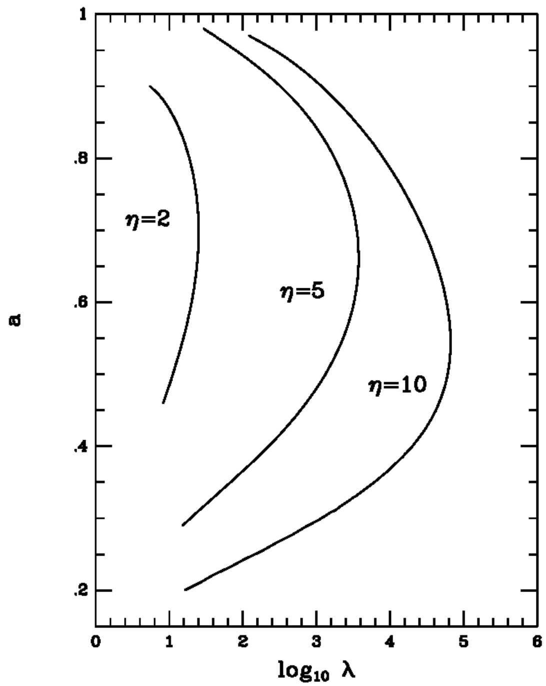
η — neutral-ion coupling parameter

a — field-strength parameter

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

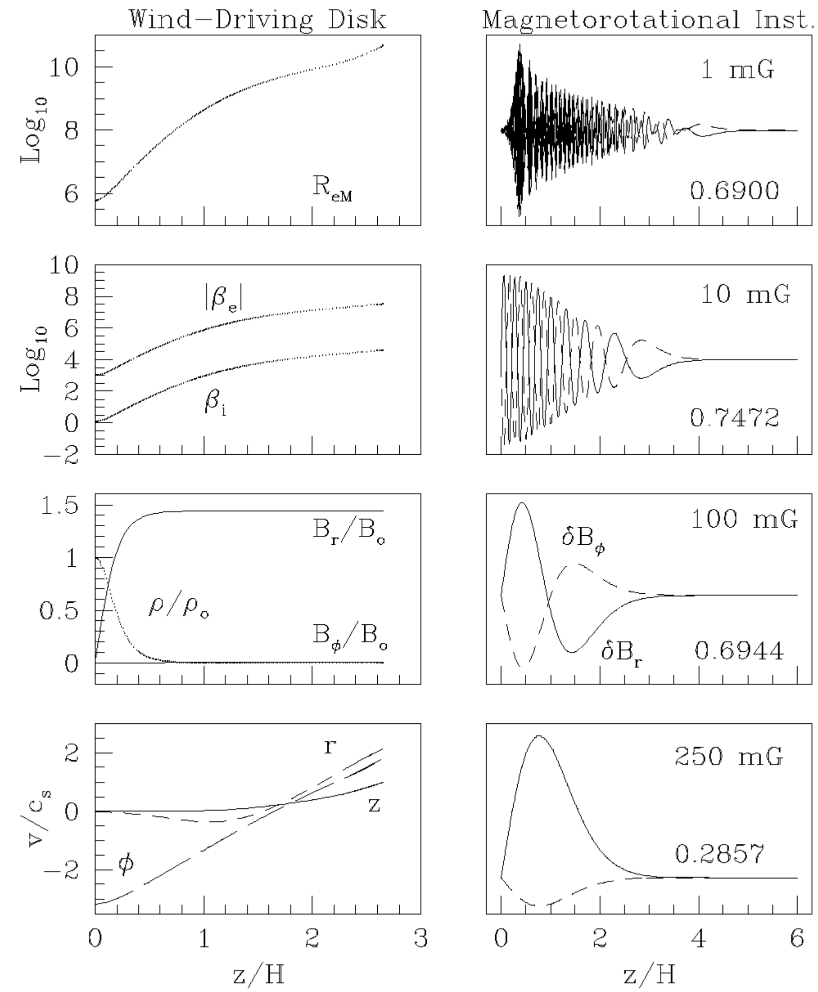
($\eta > 1$ everywhere in strongly coupled disks)





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.

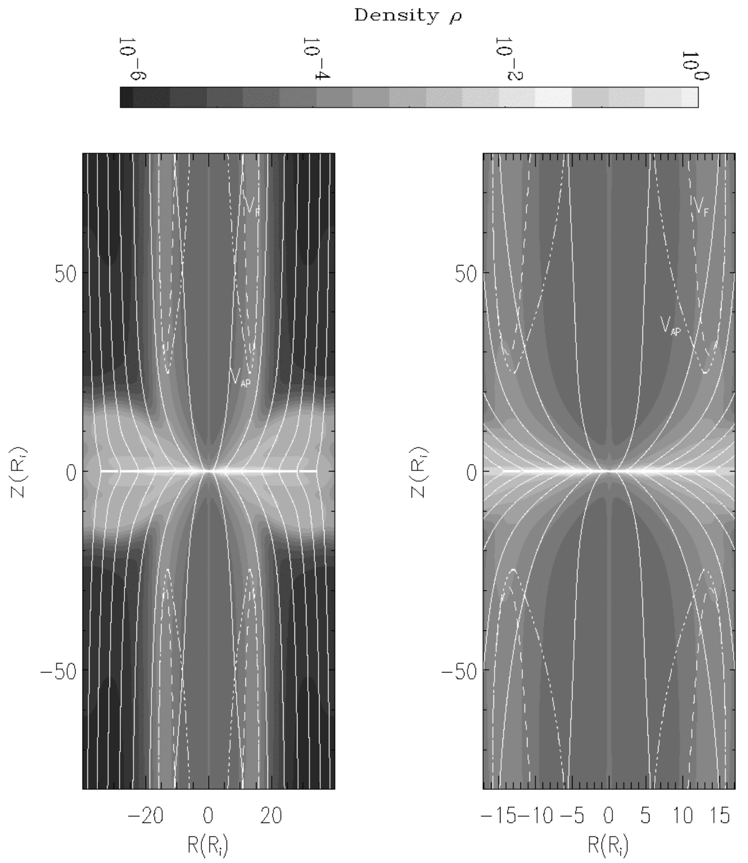


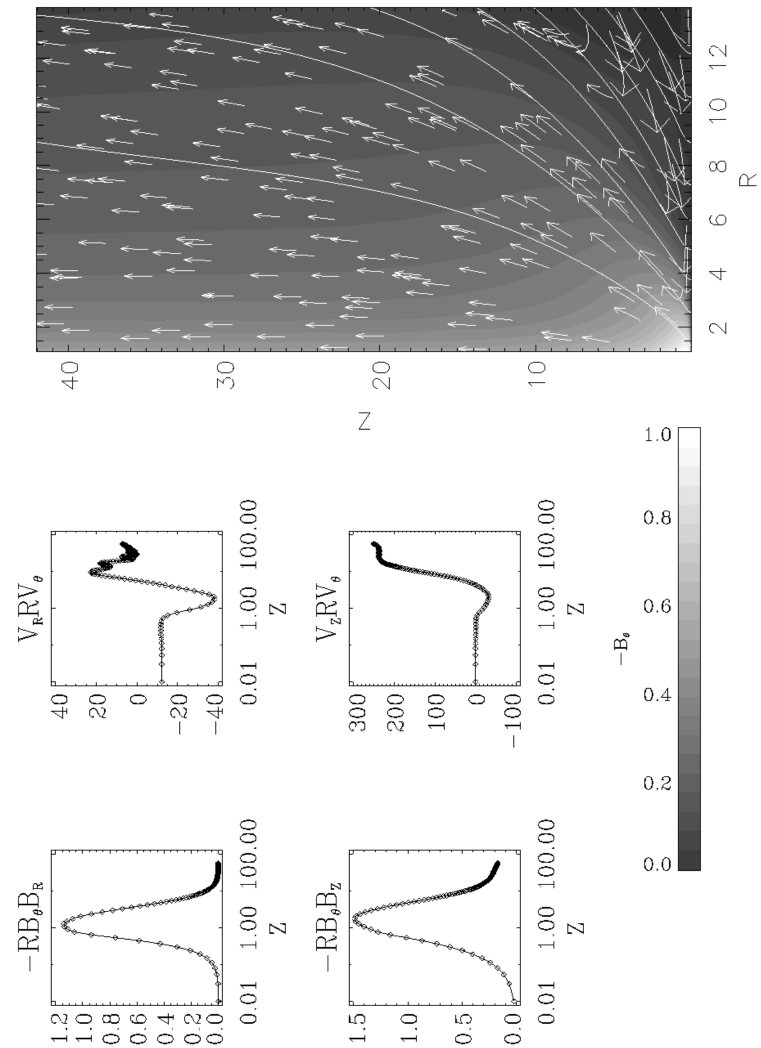
R = 10 AU , Σ= 10 g cm^{-2}

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



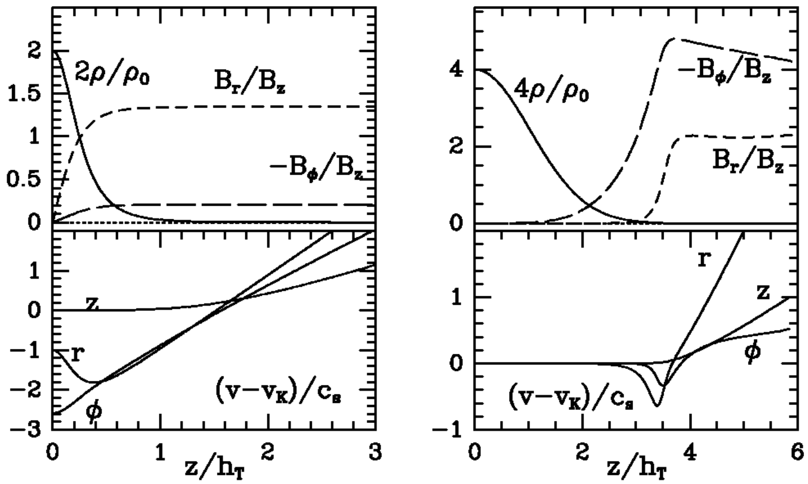


Casse & Keppens (2002)

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

(Li 1996; Wardle 1997)

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

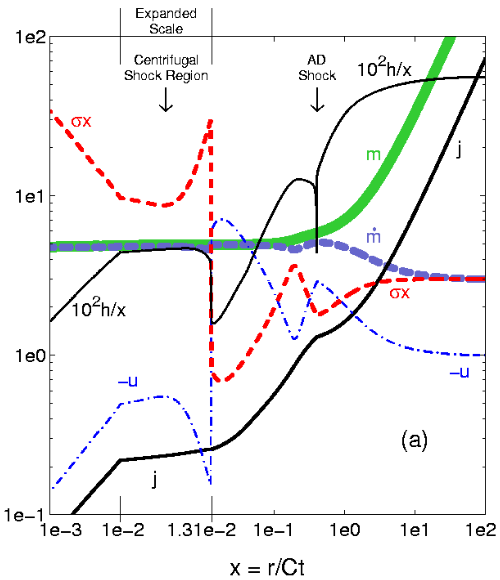


Wardle (1997)

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.

Conclusions

- High-resolution observations of protostellar jets have provided strong evidence that they originate in circumstellar accretion disks and dominate the angular momentum transport in the launching region.

- 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.

- Magnetic field configurations conducive to wind launching and vertical angular momentum transport originate naturally in the core-collapse scenario of protostellar disk formation.

- Vertical magnetic angular momentum transport plausibly occurs also in other astrophysical jet sources, although it is conceivable that the open magnetic field may have a different origin in non-protostellar systems.