The Formation and Early Evolution

of

Protostellar Accretion Disks

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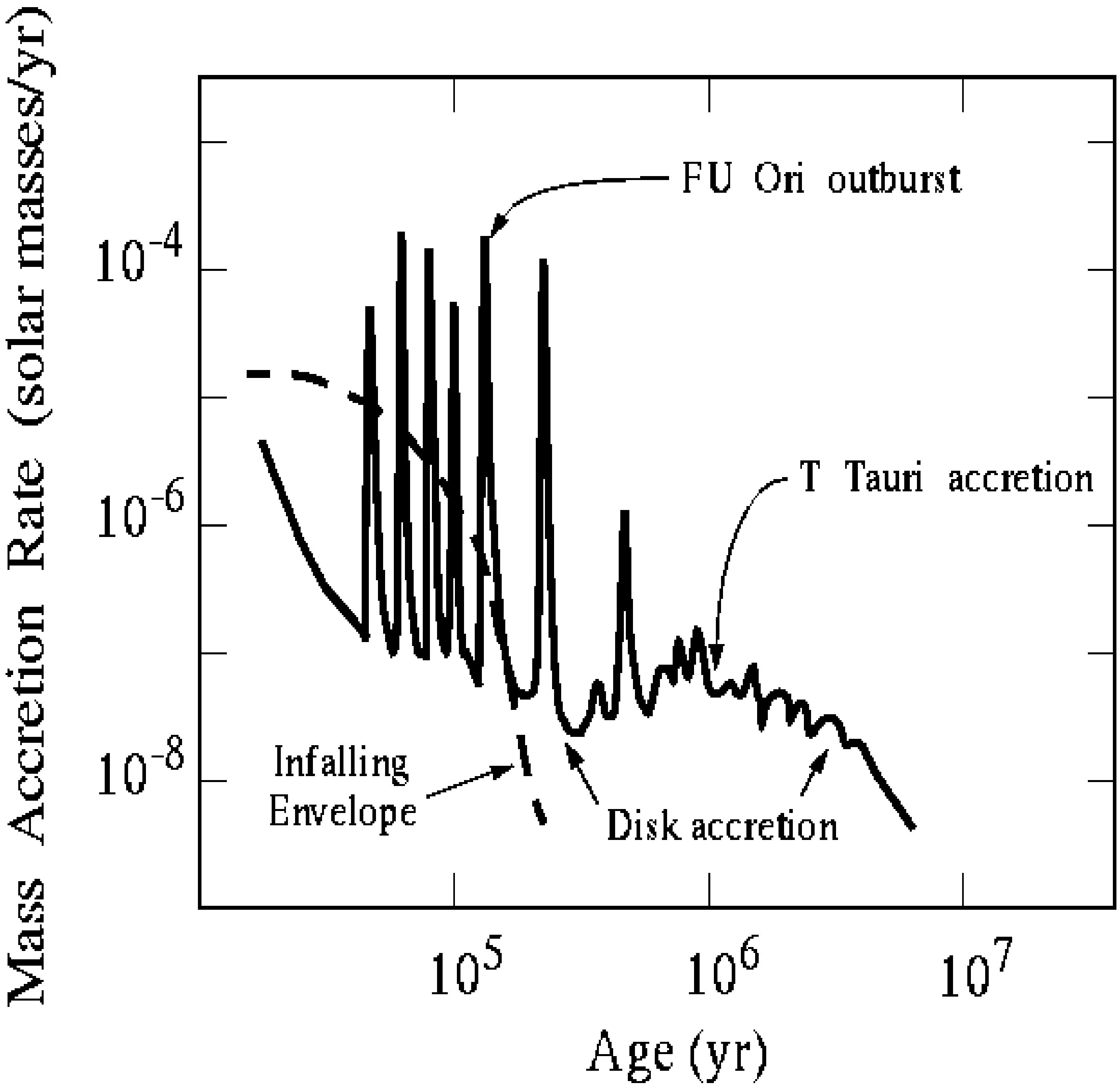
Observational Background

- Rotationally supported disks detected around most YSOs; generally consistent with being in Keplerian rotation

- A strong accretion–outflow connection is indicated ($\dot{M}_{\rm out}/\dot{M}_{\rm in} \sim 0.1$; e.g., Kurosawa et al. 2006; Podio et al. 2006).

- Most of the YSO mass is evidently assembled through the disk, likely in short-lived ($\sim 10^2 - 10^3$ yr) rapid accretion events ($\dot{M}_{\rm in} \sim 10^{-4}\, M_\odot/{\rm yr}$; Hartmann 1997)

- These FU-Orionis-type outbursts are also accompanied by outflows with $\dot{M}_{\rm out}/\dot{M}_{\rm in} \sim 0.1$ and appear to originate in a Keplerian disk (Hartmann & Calvet 1995)



Calvet et al. 2000

Outline

- Role of magnetic field in disk formation (beneficial? neutral? deleterious?)
- Role of magnetic field in driving outflows
- Do magnetically driven disk outflows play an important role in the accretion process?
- Open questions

Formation of a Rotationally Supported Disk from the Collapse of a Molecular Cloud Core

Initial Conditions

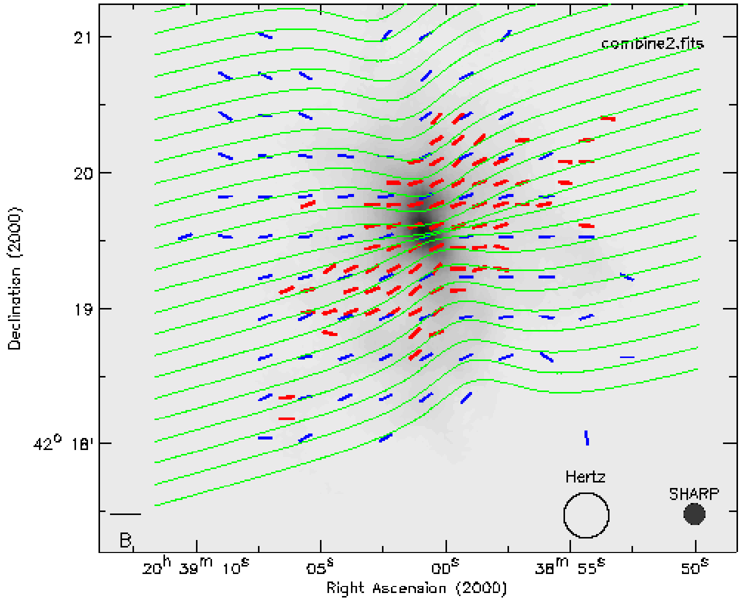
Rotation

Measured velocity gradients across cloud cores have been interpreted as evidence for specific angular momenta $l \sim 4 \times 10^{20} - 3 \times 10^{22}\,\mathrm{cm}^2$/s (overestimated? Dib et al. 2010).

For comparison, a $1\,M_\odot$ protostar of radius $2.5\,R_\odot$ rotating at breakup speed would have $l \approx 5 \times 10^{18}\,\mathrm{cm}^2$/s.

Role of Magnetic Field

Hourglass-shaped field morphology revealed in polarization measurements on sub-pc scales indicates that a large-scale, ordered interstellar field is dynamically important in supporting the core against collapse. DR21 Main (Kirby 2009)



- The predicted oblate morphology is consistent with observations of starless cores in Orion (Tassis 2007)

In this picture, the core is initially magnetically subcritical, and its gravitational collapse is triggered by ambipolar diffusion.

- ♣ This picture needs to be reconciled with evidence that many cores are prolate and may have formed from the fragmentation of filamentary clouds (e.g., Di Francesco et al. 2007)

- The filamentary structure is consistent with a supersonic turbulence scenario. In this picture, a collapsing core is supercritical from the start (e.g., Elmegreen 2007)

Dynamical Collapse

After dynamical collapse is triggered, material falls in at near free-fall speeds, advecting the magnetic field lines inward.

- However, once the central mass starts to grow, ambipolar diffusion is “revitalized” within its gravitational “sphere of influence” (Ciolek & Königl 1998). This leads to the formation of an ambipolar diffusion shock (cf. Li & McKee 1996)

Angular momentum transport is not effective during the collapse until the infall is stopped at a centrifugal shock and forms a rotationally supported disk.

- To accrete through the disk, angular momentum must be transported outward, either vertically or radially

Illustrative Model (Krasnopolsky & Königl 2002)

Main assumptions:

- Quasi-1D motion (corresponding to an initially subcritical core)

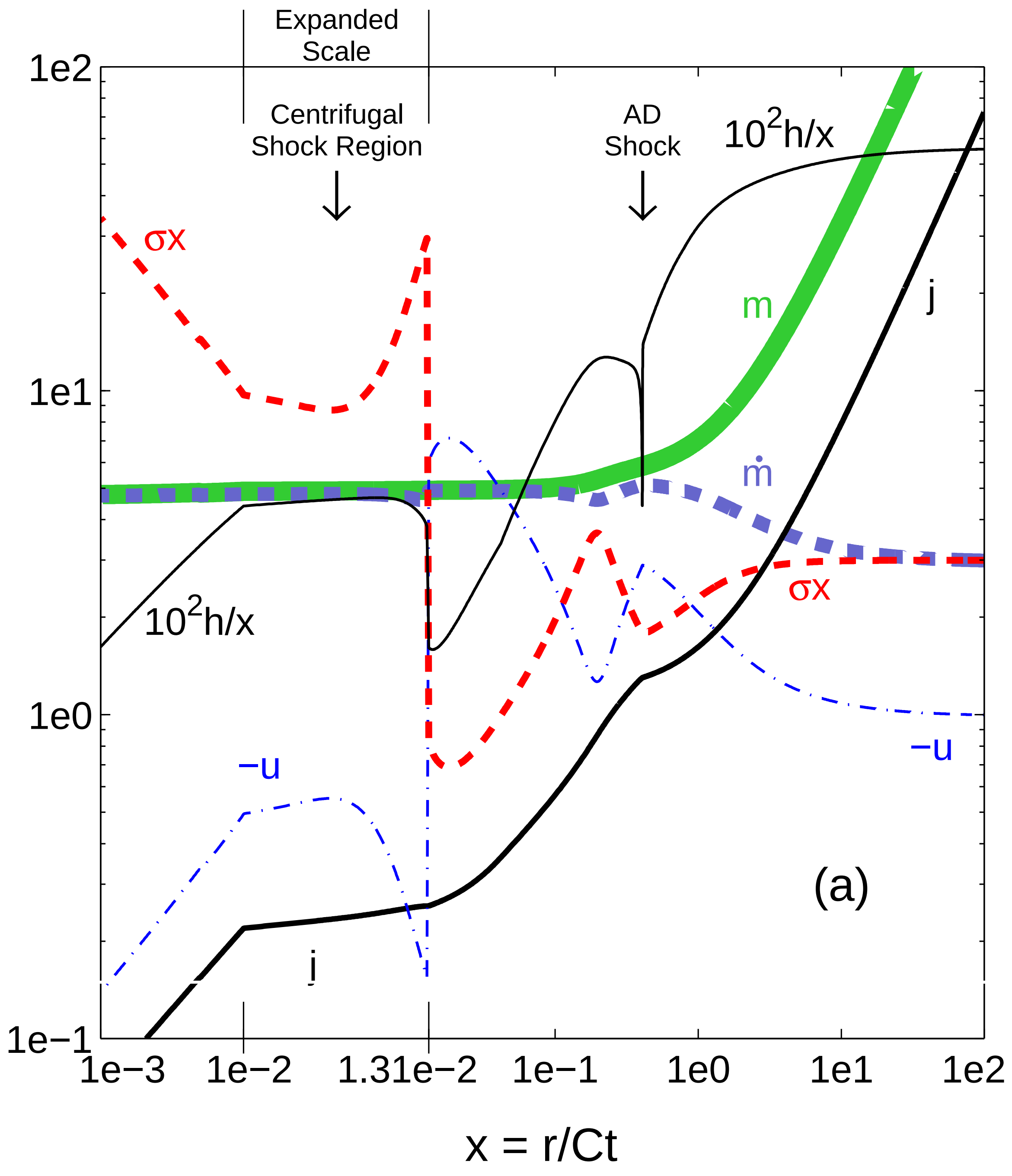
- Ambipolar diffusivity regime

[but Hall diffusivity (e.g., Tassis & Mouschovias 2005; Braiding's talk) and Ohm diffusivity (e.g., Shu et al. 2006; Tassis & Mouschovias 2007) could also play a role]

- Angular momentum transport by magnetic braking

(although a centrifugally driven wind solution can be naturally incorporated into the asymptotic disk solution)

Derive semi-analytic similarity solutions (in r and t).


Expanded
Scale
Centrifugal
Shock Region
AD
Shock
$10^2h/x$
σx
m
ṁ
j
σx
$10^2h/x$
−u
−u
(a)
j
1e2
1e1
1e0
1e−1
1e−3
1e−2
1.31e−2
1e−1
1e0
1e1
1e2
x = r/Ct

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

- The implied processing of the disk material in the AD and (in particular) centrifugal shocks may have implications to the composition of protoplanetary disks (e.g., the annealing of silicate dust; e.g., Harker & Desch 2002)

● The self-similarity solutions typically imply Keplerian disks – consistent with observations of Class II YSOs.

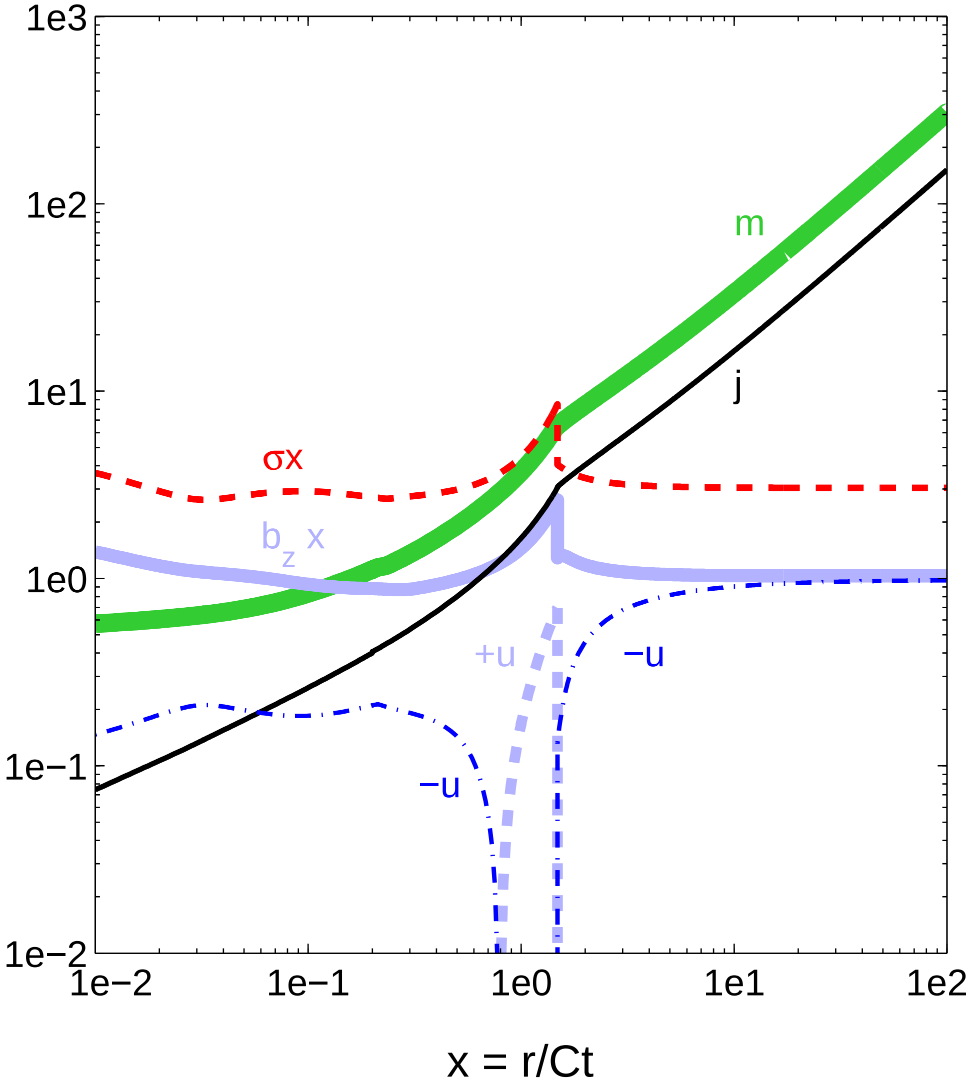
♣ Do they apply to earlier evolutionary phases?

More massive early-time disks can be obtained if the collapse is not quasi-1D (as in the case of a rotating Bonnor-Ebert sphere; e.g., Duffin & Pudritz 2009).

For sufficiently massive disks, $Q_{\rm Toomre} \equiv C\kappa/\pi G\Sigma < 1$ and angular momentum transport by mass fragments and nonaxisymmetric density perturbations can take place.

● Angular momentum transport by gravitational torques can lead to the prominent bursting behavior of young YSOs (e.g., Armitage et al. 2001; Vorobyov & Basu 2006; Zhu et al. 2009)

Fast Rotation

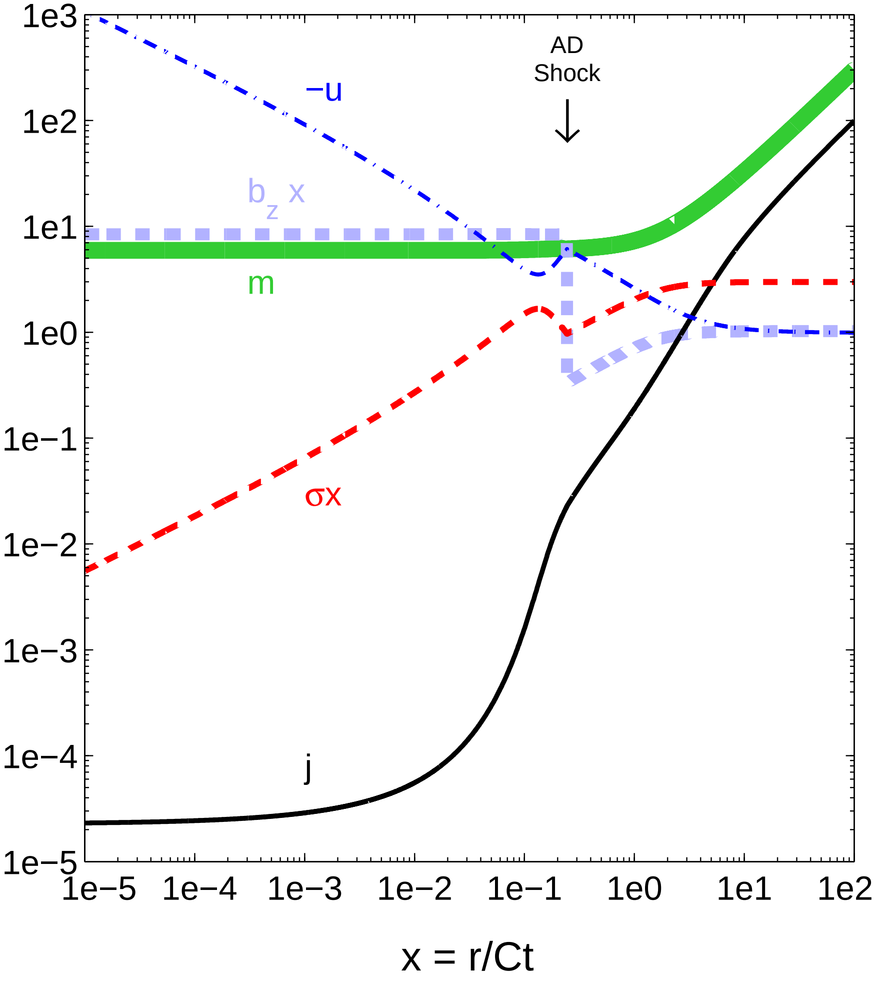


- Centrifugal shock is located within the self-gravity–dominated, ideal-MHD region

- Ideal-MHD $\Rightarrow$ AD transition occurs behind the shock and is gradual rather than sharp

- Non-Keplerian outer region; small central mass; backflowing layer behind the shock

Strong Braking



- No centrifugal shock (or circumstellar disk)

⋆ In general, the magnetic field enhancement behind the AD shock increases the efficiency of angular-momentum removal from the disk.

⋆ In the limiting case of strong braking, essentially all the angular momentum is removed well before the inflowing gas reaches the center. Such systems may correspond to slowly rotating YSOs that show no evidence of a circumstellar disk (e.g., Stassun et al. 1999; 2001; Rebull et al. 2006)

♣ It has, however, been claimed (based on 2D numerical simulations) that magnetic braking in the AD regime is always so efficient that no disk could form at all (Mellon & Li 2009)

Ways out(?)

- Use more realistic values of the ambipolar diffusivity in the relevant density regimes (Mouschovias' talk)
- Ohm diffusivity in the innermost region (Li's talk; Dapp's talk)
- Misaligned B and Ω (Hennebelle & Ciardi 2009; Hennebelle's talk)
- Disks form in full-3D simulations (Duffin & Pudritz 2009; Pudritz's talk)
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Disks and Outflows

- It is pretty clear by now that the observed energetic protostellar outflows are powered by accretion

- It is also widely accepted that sufficiently ordered and large-scale magnetic fields are the most plausible mediating agent between accretion and outflow

However, two key questions remain open:

♣ Does the magnetic field originate in the disk or the protostar?

⋆ Outflow driven from near the corotation radius (X-wind model; Shu et al. 1994)

⋆ Conical wind and axial jets driven from disk–magnetosphere boundary (Romanova et al. 2009; Romanova’s talk)

⋆ Some part of the outflow may be launched from the stellar surface (Matt & Pudritz 2008; Cranmer 2009)

A growing number of observations point to at least some outflow components originating in a disk, well away from the YSO’s surface, where they are likely driven by a magnetic field that has been advected in by the accretion flow or generated by a disk dynamo (e.g., Hartmann & Calvet 1995; Ray et al. 2007; Matthews et al. 2010).

- ♣ Do disk winds transport a significant fraction of the excess angular momentum in the wind-launching region?

No – radial transport by effective viscosity dominates

- ⋆ If the effective viscosity and magnetic diffusivity are everywhere of the same order (as expected in the interior of a turbulent disk) then a large-scale magnetic field will not be advected inward (e.g., Lubow et al. 1994)

- ⋆ However, the field is expected to be better coupled near the disk's surfaces and could therefore be dragged in after all (Rothstein & Lovelace 2008)

- ⋆ For a comparatively weak midplane field, $a_0^2 \ll 1$ ($a_0^2 \equiv V_{\mathrm{A}0}^2/C^2 = B_z^2/4\pi\rho_0 C^2$), outflows could form under these circumstances but would remove relatively little angular momentum (e.g., Murphy et al. 2010)

Yes – for a comparatively strong midplane field, $a_0^2 \lesssim 1$, a centrifugally driven wind (CDW) could transport the bulk of the disk's angular momentum.

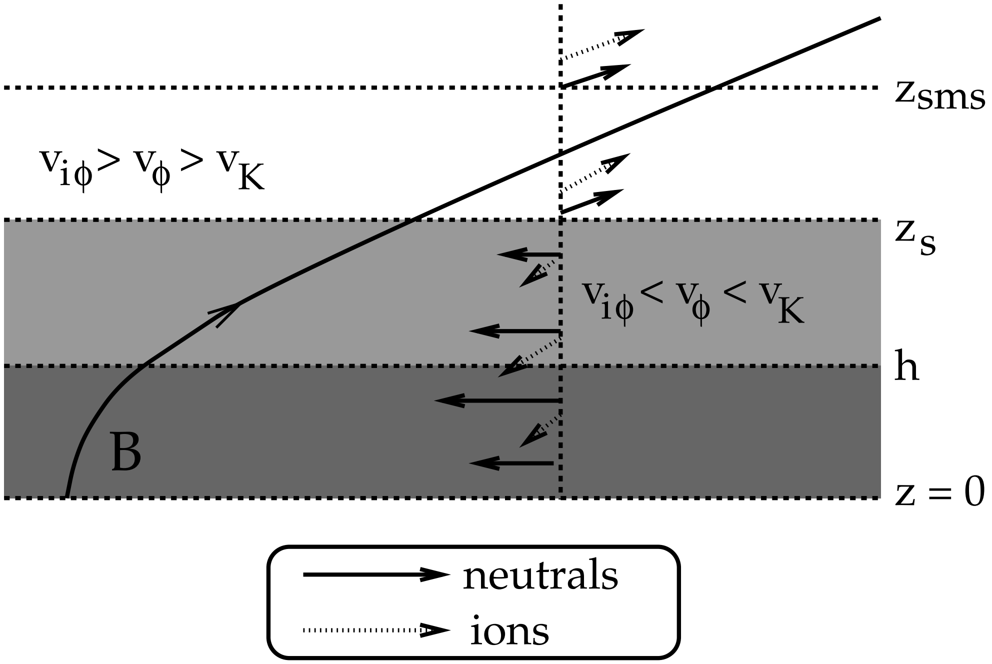
⋆ Inward flux advection is generally not an issue in this case

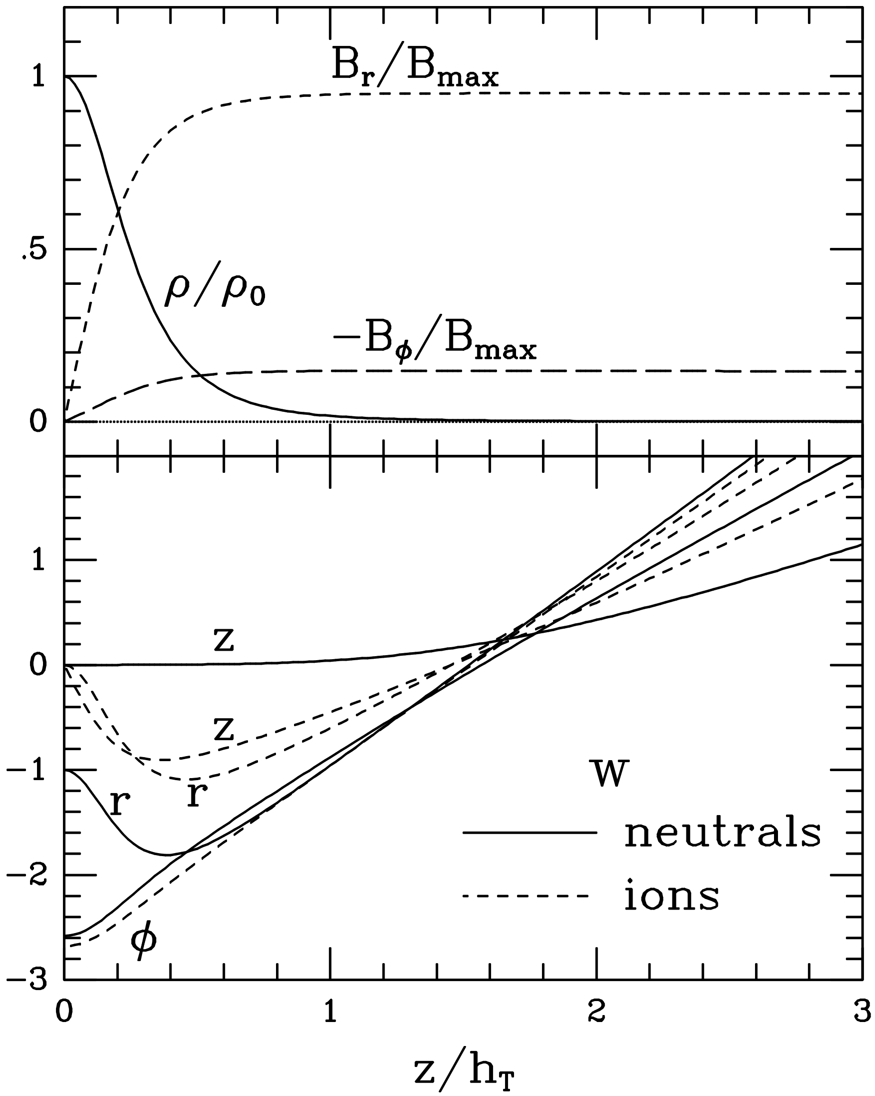
- Simple estimates indicate that this can be achieved if $\dot{M}_{\rm out}/\dot{M}_{\rm in} \sim 0.1$ (the observationally inferred value)

- High-resolution spectroscopy of several YSO jets (Ray et al. 2007) supports the conclusion that disk winds are a major contributor to the angular momentum transport at least in some localized regions

Pure vertical transport model in the ambipolar diffusivity regime (Wardle & Königl 1993):

- Isothermal, geometrically thin, Keplerian rotation, “open” $\mathbf{B}$
- Radially localized diffusive disk solution matched onto radially self-similar, ideal-MHD wind solution (Blandford & Payne 1982)
- Wind launching condition ($B_{r,s} > B_z/\sqrt{3}$) is satisfied





$$\mathbf{W} = \frac{\mathbf{V} - V_{\rm K}\hat{\phi}}{C}\,, \quad h_{\rm T} = \frac{C}{\Omega_{\rm K}}$$

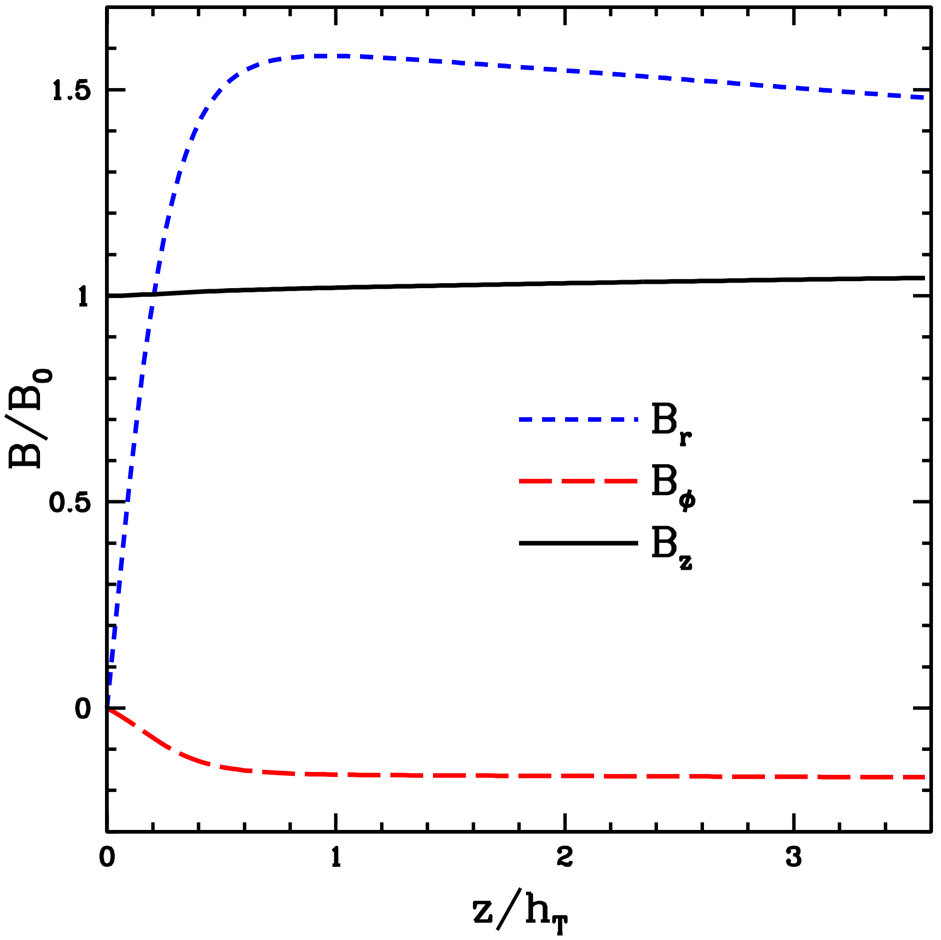
Recent Developments

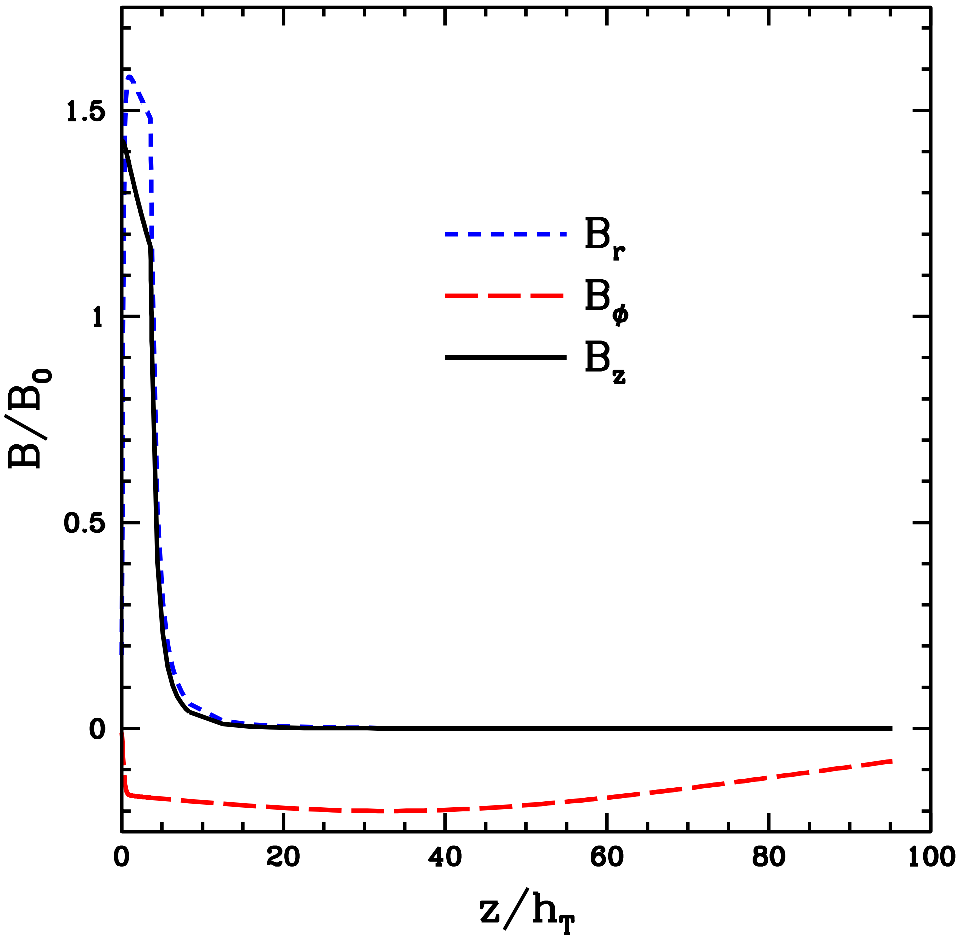
- Analytic and numerical results generalized to the Hall and Ohm diffusivity regimes (Königl et al. 2010; Salmeron et al. 2010; Salmeron’s talk)

- A global (radially self-similar) disk/wind model that self-consistently accounts for magnetic field advection has been constructed (Teitler 2010)

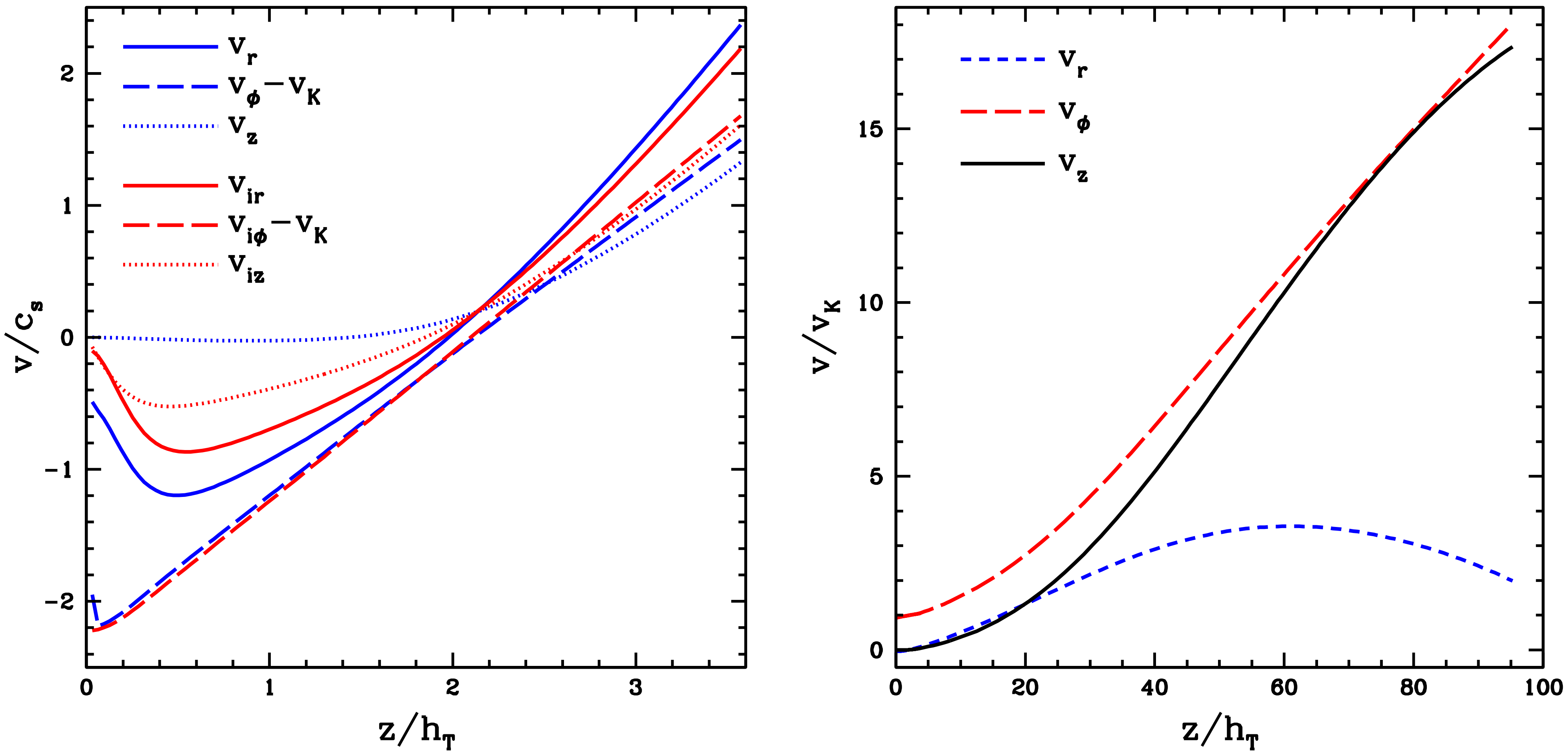
- Radially localized solutions with a realistic ionization and conductivity structure have been obtained (Königl & Salmeron 2010)

Global disk/wind solution in AD regime: magnetic field structure

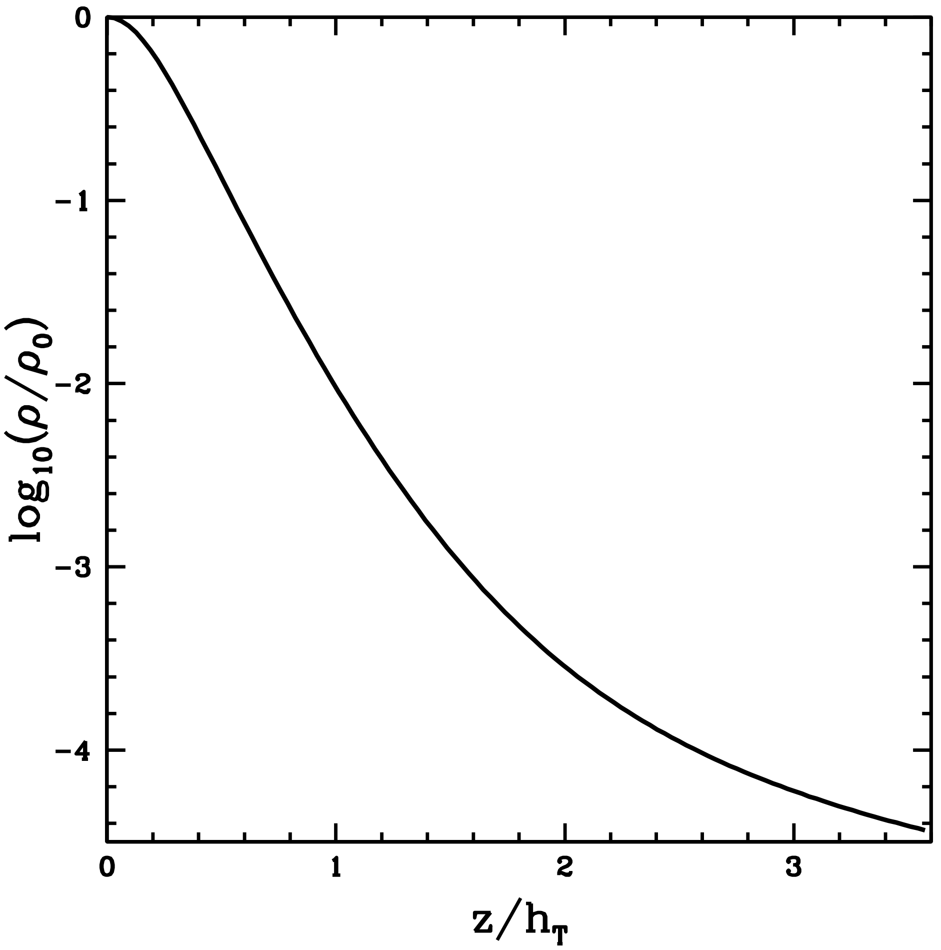


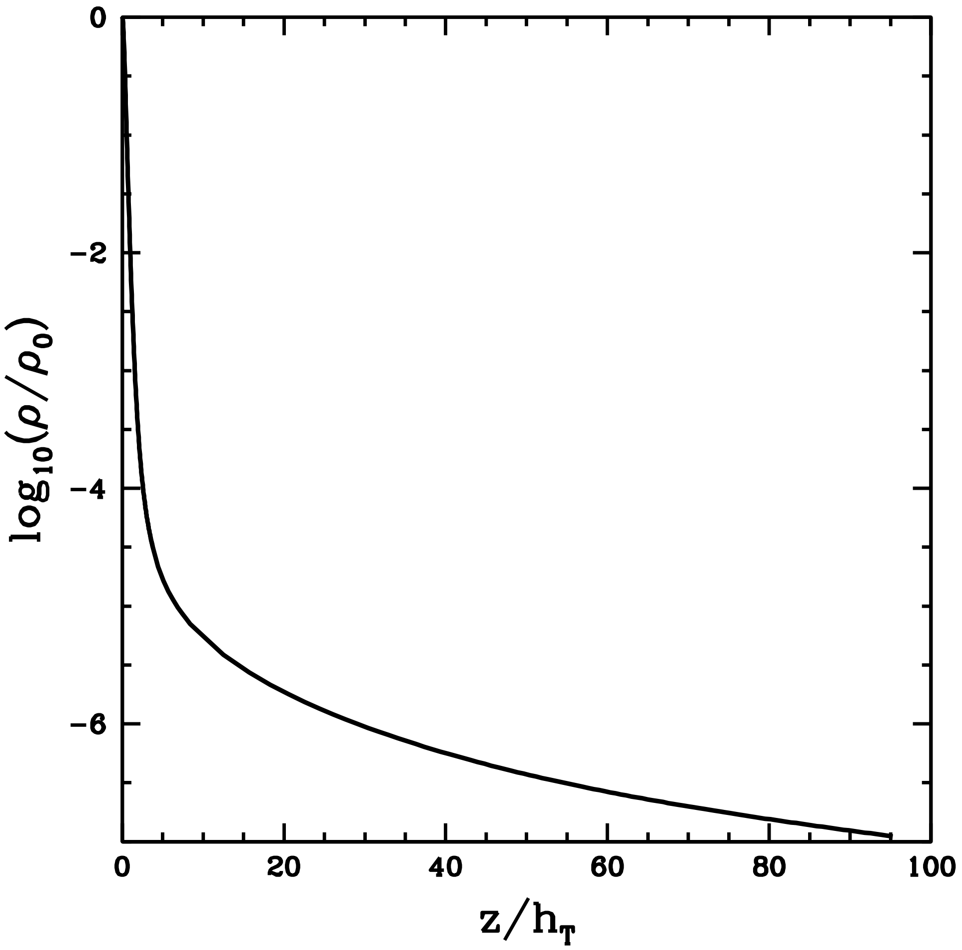


Global disk/wind solution in AD regime: velocity structure

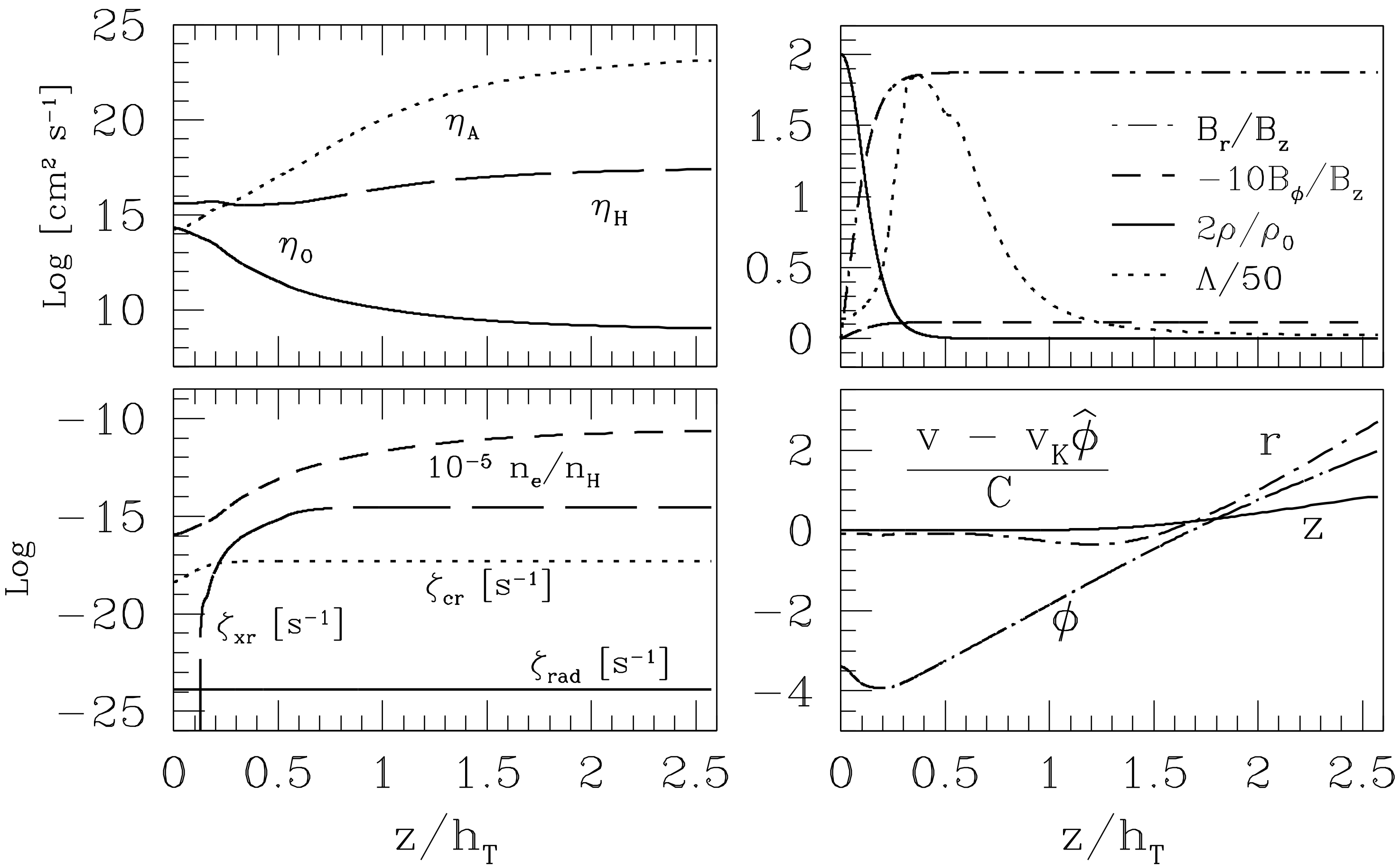


Global disk/wind solution in AD regime: density structure





Full-conductivity solution in the Hall/AD regime at 1 AU



$\Lambda \equiv V_A^2/\Omega_K\,\eta_\perp$ is the neutral–**B** coupling parameter

(where $\eta_\perp = c^2/4\pi\sigma_\perp$; expression valid in all conductivity regimes)

The good-coupling requirement (Λ should not be $\ll 1$) is essentially the same for vertical transport by a large-scale, ordered field (through a CDW) and for radial transport by a small-scale, tangled field (through MRI-induced turbulence).

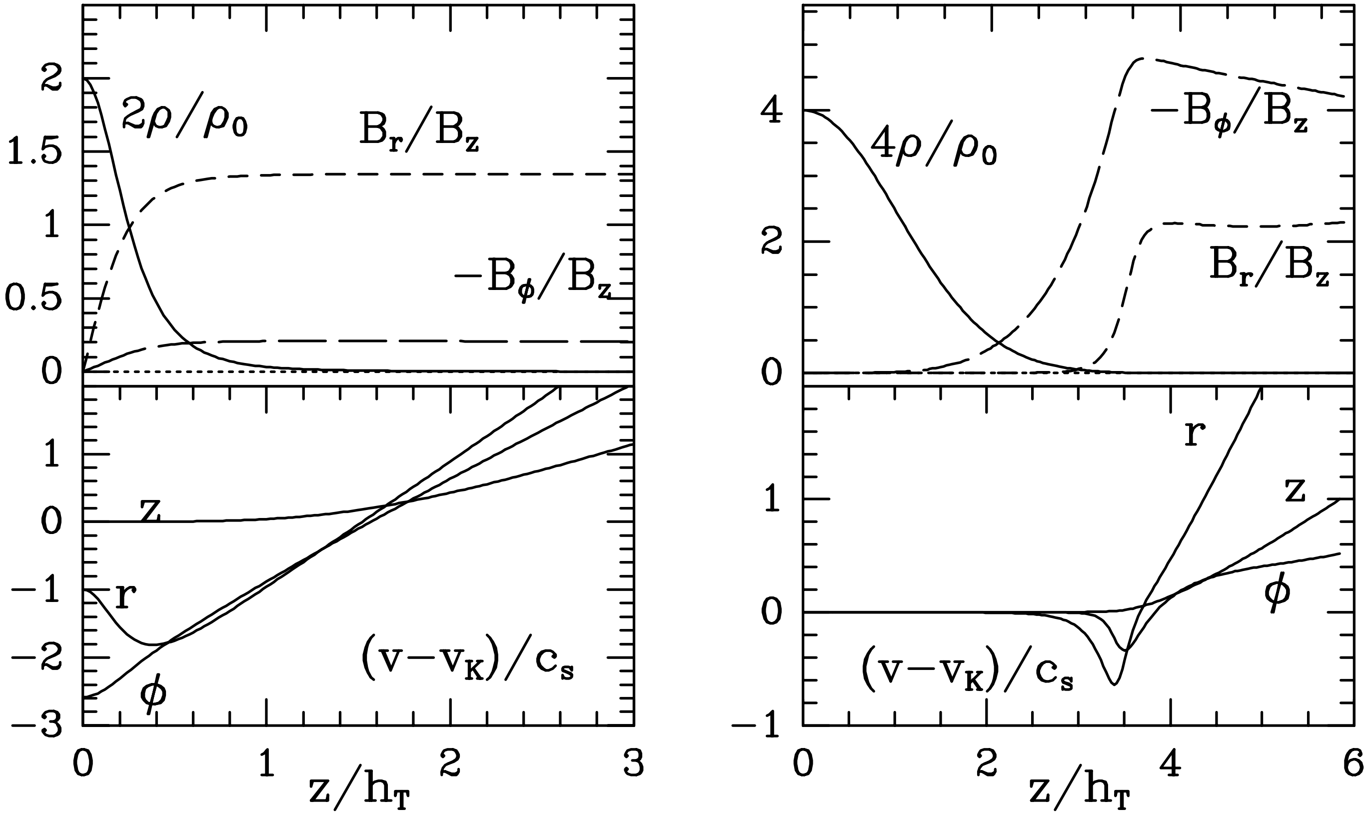
Wind launching from the AD-dominated regions near the disk surfaces occurs if $2\Upsilon a^2 \propto \rho_{\rm i}/\rho$ is $\gtrsim 1$ (where $\Upsilon \equiv \nu_{\rm ni}/\Omega_{\rm K}$ is the neutral–ion coupling strength); if this condition is violated then MRI turbulence can develop (Salmeron et al. 2007; Salmeron's talk).

- It is potentially possible for both radial and vertical angular momentum transport to occur at the same radial location

Weakly Coupled Disks

$\Lambda < 1$ near the midplane and increases to $\gtrsim 1$ near the surface (Li 1996; Wardle 1997)

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



In strongly coupled disks: $a_0 \lesssim 1$, $| < V_r > | \sim C$, $B_{r,\mathrm{s}} > |B_{\phi,\mathrm{s}}|$ (with B_r increasing already at $z = 0$).

In weakly coupled disks: $a_0 \ll 1$, $| < V_r > | \ll C$, $B_{r,\mathrm{s}} < |B_{\phi,\mathrm{s}}|$ (with B_r taking off only when $\Lambda \gtrsim 1$; $(dB_r/dB_\phi)_0 = -2\Lambda$).

● Angular momentum is transported vertically even in weakly coupled regions where B_r is very small but $|B_\phi| \gg B_r$, since the torque is $\propto B_z dB_\phi/dz$

⋆ This could have implications to the issue of "dead zones"

[N.B., (i) The $r - t$ similarity solution (magnetic braking + AD) implies the formation of weakly coupled disks; (ii) Wind-driving disks have comparatively small Σ, which promotes good coupling.]

Open Questions

- ♣ Do star-forming cores evolve from a subcritical configuration or do they directly form in a supercritical state?

- ♣ Are protostellar disks sufficiently massive during their earliest evolutionary phases to be gravitationally unstable ($Q_{\mathrm{Toomre}} < 1$) in their outer regions?

- ♣ Is magnetic braking so efficient that it suppresses disk formation (except on small radial scales or under special circumstances)?

- Are YSO outflows driven by a protostellar or a disk field?
    - If at least some outflow components indeed originate in a disk, what is the radial extent of such regions and does it depend on the evolutionary phase?
- Do disk outflows play a significant role in the local transport of angular momentum?
- Do YSO disks harbor “dead zones,” and, if so, how does their extent change with time?

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