Theory of Wind-Driving Protostellar Disks

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Outline:

- Disk–wind connection in protostars
- Vertical angular momentum transport in accretion disks
- Formation of magnetically threaded protostellar disks
- Equilibrium structure and stability of disk/wind systems
- Application: dust uplifting and cycling

The Disk–Wind Connection

- Strong correlations found between outflow signatures (P-Cygni line profiles, forbidden line emission, thermal radio radiation, well developed molecular lobes) and accretion diagnostics (UV, IR, and mm emission excesses, inverse P-Cygni line profiles) in $\sim 1 - 10\ M_\odot$ YSOs; similar accretion and outflow phenomena seen in very-low-mass stars and brown dwarfs.

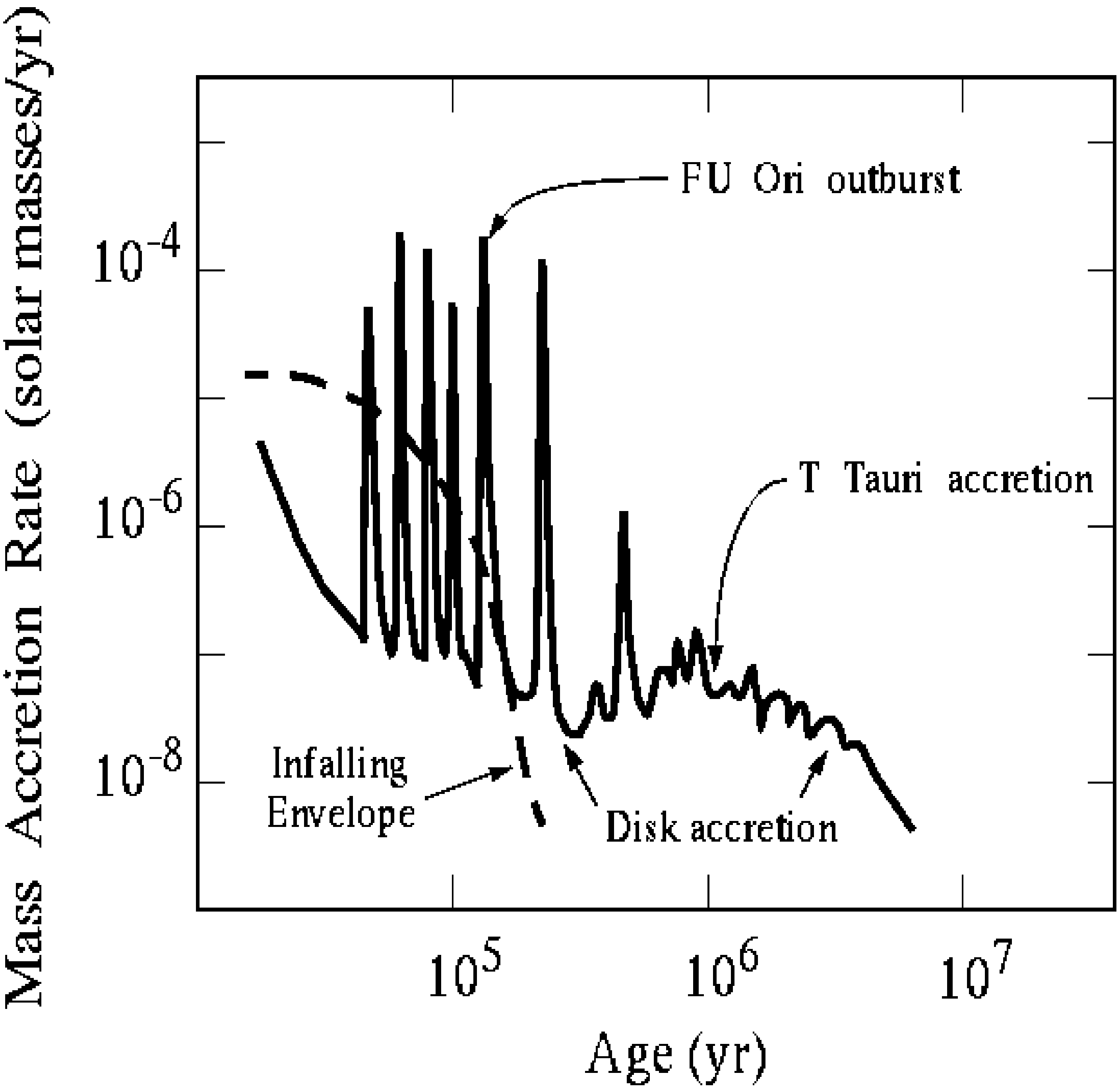
- $\dot{M} \propto L_{\rm bol}^q$ ($q \sim 0.6 - 0.7$) correlations found in low- and high-M_* YSOs for both $\dot{M}_{\rm in}$ and $\dot{M}_{\rm out}$; typically infer $\dot{M}_{\rm out}/\dot{M}_{\rm in} \sim 0.1$.

- Apparent decline in outflow activity with stellar age follows a similar trend exhibited by disk frequency and inferred $\dot{M}_{\rm in}$.

♣ These results strongly suggest that outflows are powered by accretion and that the same basic physical mechanism operates across the entire mass range of YSOs.

There is strong evidence for a disk origin of outflows in FU Orionis outbursts that occur in rapidly accreting YSOs.
It is inferred that the emission during an outburst ($\Delta t \sim 10^2$ yr) originates in a rotating disk and that the outflow represents a wind that accelerates from the disk surface (with $\dot{M}_{\rm w}/\dot{M}_{\rm in} \sim 0.1$; $\dot{M}_{\rm in} \sim 10^{-4}\ M_\odot\ {\rm yr}^{-1}$). It has been suggested (Hartmann 1997) that most of the mass accumulation and ejection of YSOs occurs during recurrent outbursts of this type.

- A $\sim 1\ {\rm kG}$ magnetic field on scales $\sim 0.05\ {\rm AU}$ has been inferred from Zeeman measurements in FU Ori (Donati et al. 2006).



Calvet et al. 2000

Angular Momentum Transport in Disks

Gravitational torque: radial transport in the disk plane through nonaxisymmetric density perturbations; Toomre Q parameter $Q \equiv C\kappa/\pi G\Sigma$ required to be $\lesssim 1$.

Magnetic torque in disks threaded by a large-scale $\mathbf{B}$ field:

For a comparatively weak field, $a^2 \ll 1$
($a^2 \equiv V_{\mathrm{A}z0}^2/C^2 = B_z^2/4\pi\rho_0 C^2$),
radial transport by MRI-induced turbulence.

For a comparatively strong field, $a^2 \lesssim 1$,
vertical transport by a centrifugally driven wind (CDW).

- Effective lever arm for back torque: the (cylindrical) radius $r_{\rm A}$ of the Alfvén critical surface.

- In both radial and vertical transport, a small fraction of the accreted mass carries the excess angular momentum to large (radial or vertical) distances. For a CDW that transports the bulk of the disk angular momentum, $\dot{M}_{\rm w}/\dot{M}_{\rm in} \sim (r_0/r_{\rm A})^2$.

- CDW solutions often yield $r_{\rm A}/r_0 \sim 3-10$

$\Rightarrow$ outflows with $\dot{M}_{\rm w}/\dot{M}_{\rm in} \sim 0.1$ are consistent with being (at least in some localized radial range) a dominant contributor to disk angular momentum transport.

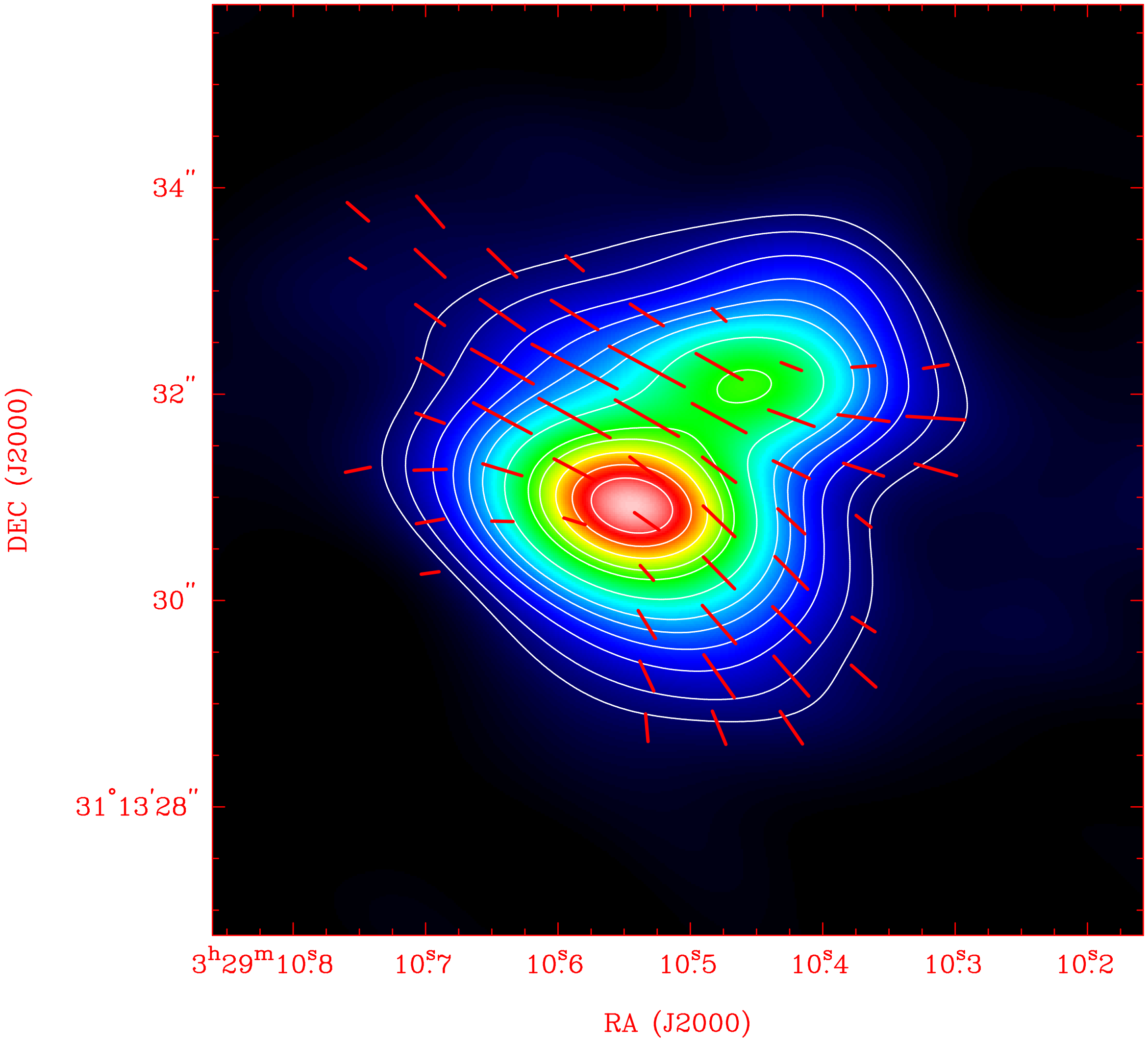
CDW launching condition: $b_{rs} \geq 1/\sqrt{3}$, where $b_{rs} \equiv B_{rs}/B_z$ ("bead on a wire").

If this condition is not satisfied, vertical magnetic angular momentum transport can take place through the propagation of torsional Alfvén waves (magnetic braking); back torque exerted by ambient medium that is set into rotation by the waves.

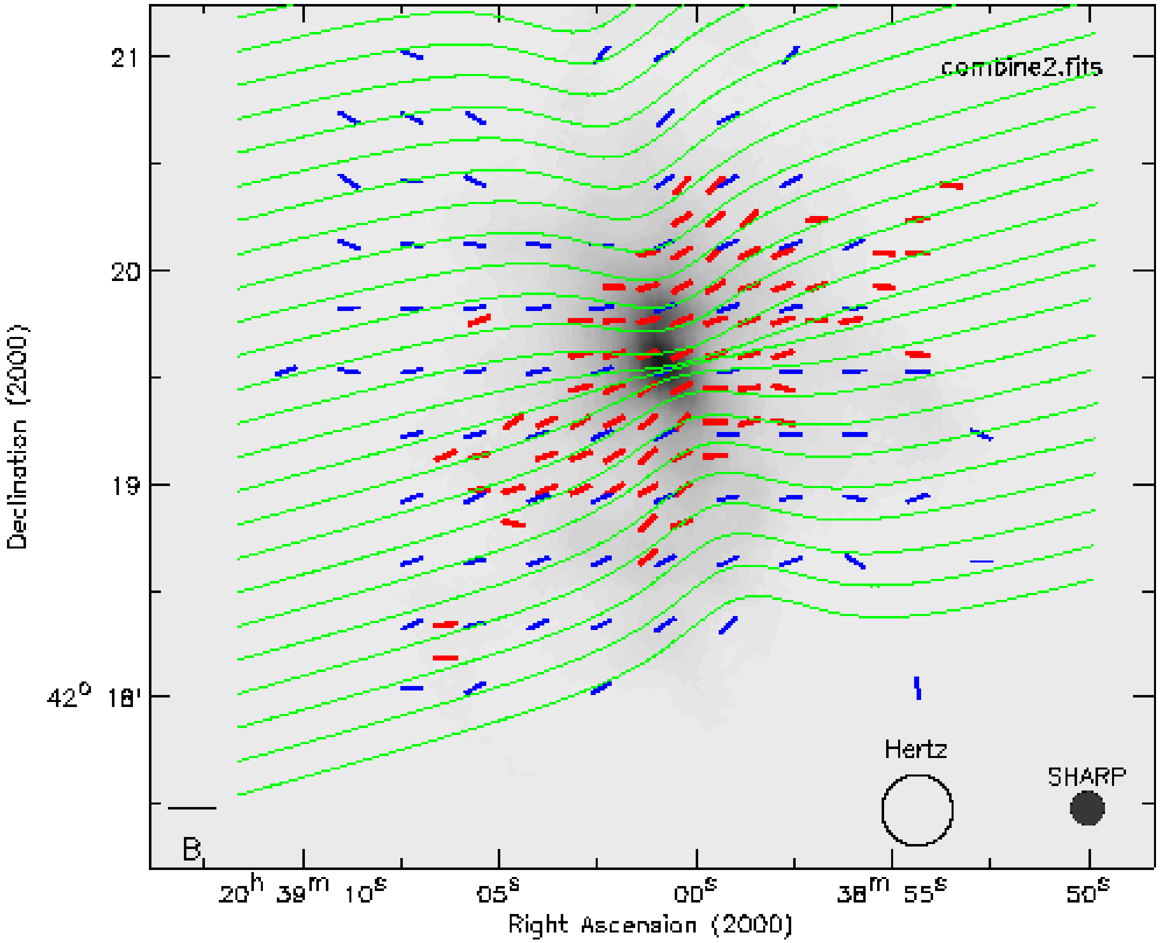
- This process was already invoked to account for the measured rotations of the parent molecular cloud cores; could align $\mathbf{\Omega}$ and $\mathbf{B}$ on a dynamical time and would thus operate even if clouds did not last much longer than that (as in turbulent ISM scenarios).

- Large-scale, ordered, and dynamically important $\mathbf{B}$ fields have been detected in several molecular cloud cores by polarization and Zeeman measurements.

NGC 1333 Iras 4A (Girart et al. 2006)



DR21 Main (Kirby 2008)



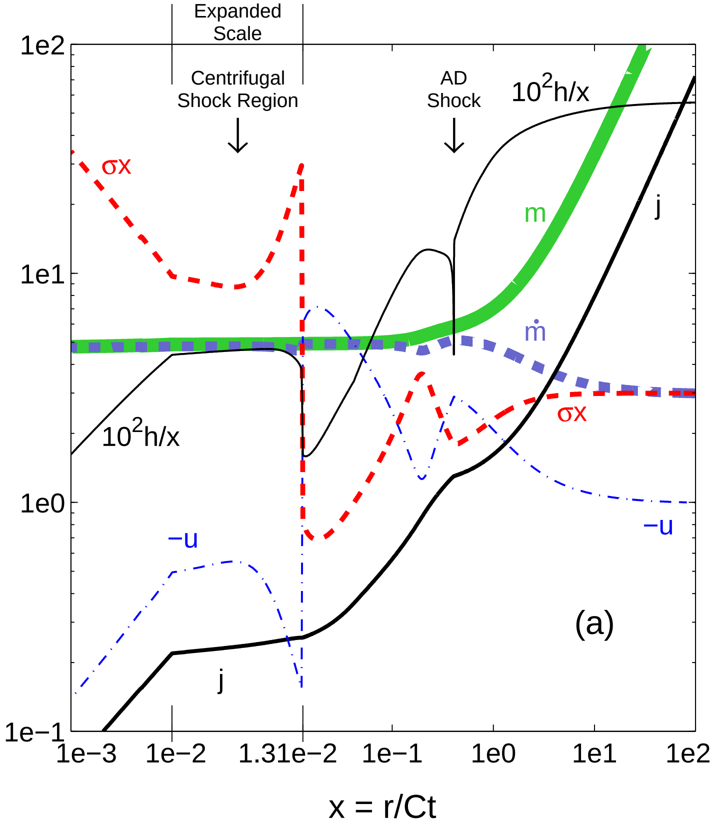
Formation of Magnetically Threaded Disks

The interstellar $\mathbf{B}$ field threading the natal cloud core is a natural origin of a large-scale “open” field in the inner disk; alternative possibilities are a disk dynamo or, right next to the YSO, stellar field lines that penetrate the disk (as in the X-wind scenario).

- If the effective disk viscosity and magnetic diffusivity have a similar origin (turbulence) and hence magnitude (but see Shu et al. 2007), an interstellar field will not be advected inward by the accretion flow (Lubow et al. 1994a; Rothstein & Lovelace 2008).

- This caveat is eliminated if the field diffusivity and the angular momentum transport derive from different physical processes.

This was demonstrated in a semi-analytic $r - t$ similarity solution incorporating ambipolar diffusion (the drift of ions/electrons/$\mathbf{B}$ relative to neutrals in a weakly ionized gas) and magnetic braking (Krasnopolsky & Königl 2002).



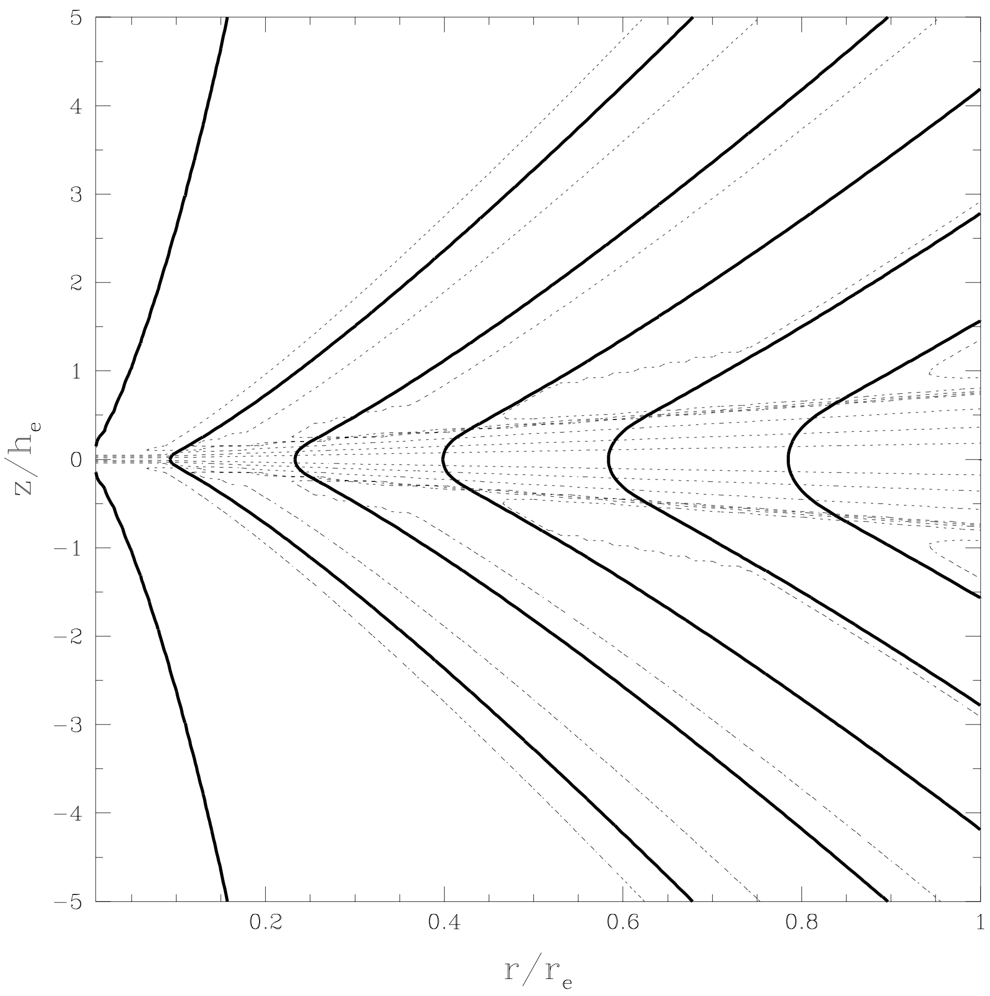
- Outer region ($x > x_{\rm a}$): Ideal-MHD infall.
- AD shock—resolved as a continuous transition.
- AD-dominated infall ($x_{\rm c} < x < x_{\rm a}$): ambipolar diffusion is "revitalized" within the YSO's gravitational "sphere of influence."
- Centrifugal shock — its location is sensitive to the diffusivity.
- Keplerian disk ($x < x_{\rm c}$) — at any given time, it satisfies $\dot{M}_{\rm in}(r) =$ const, $B \propto r^{-5/4}$, $b_{r,{\rm s}} \approx 4/3$ ($r \rightarrow 0$ solution).

⋆ The implied value of $b_{r,{\rm s}}$ $\Rightarrow$ a CDW could be launched.

⋆ Interestingly, the steady-state, radially self-similar wind solution of Blandford & Payne (1982) also has $B \propto r^{-5/4}$ and thus can be naturally incorporated into this solution.

- Non-ideal MHD simulations (e.g., Machida et al. 2007) support these results.

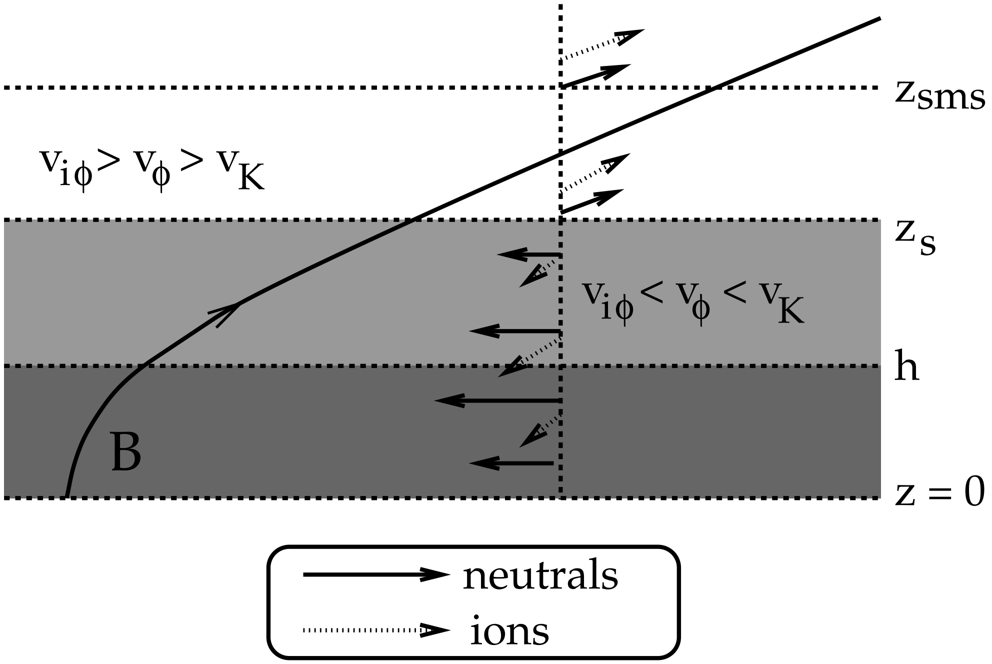
Equilibrium Structure of Wind-Driving Disks

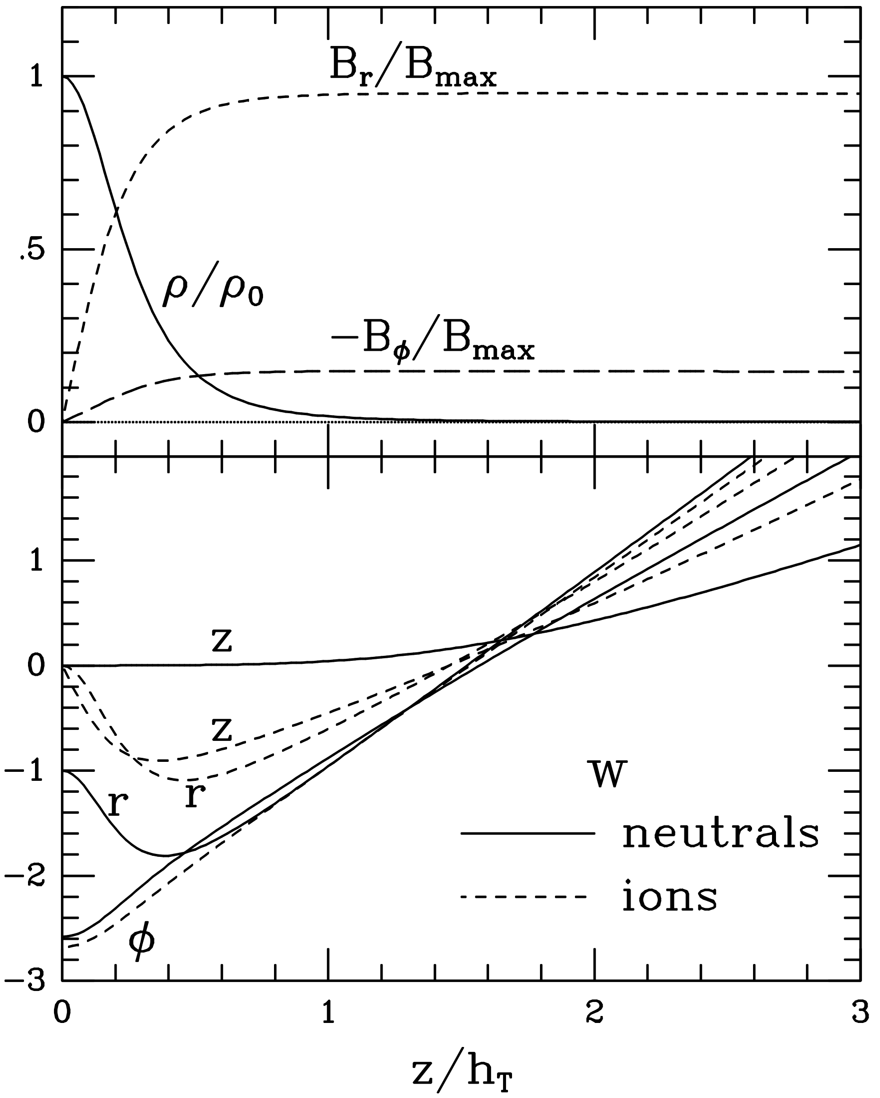


Ferreira (1997)

Pure vertical transport model in the ambipolar-diffusion/Hall 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)
- Results confirmed by global self-similar solution (Li 1996)





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

wind parameters:

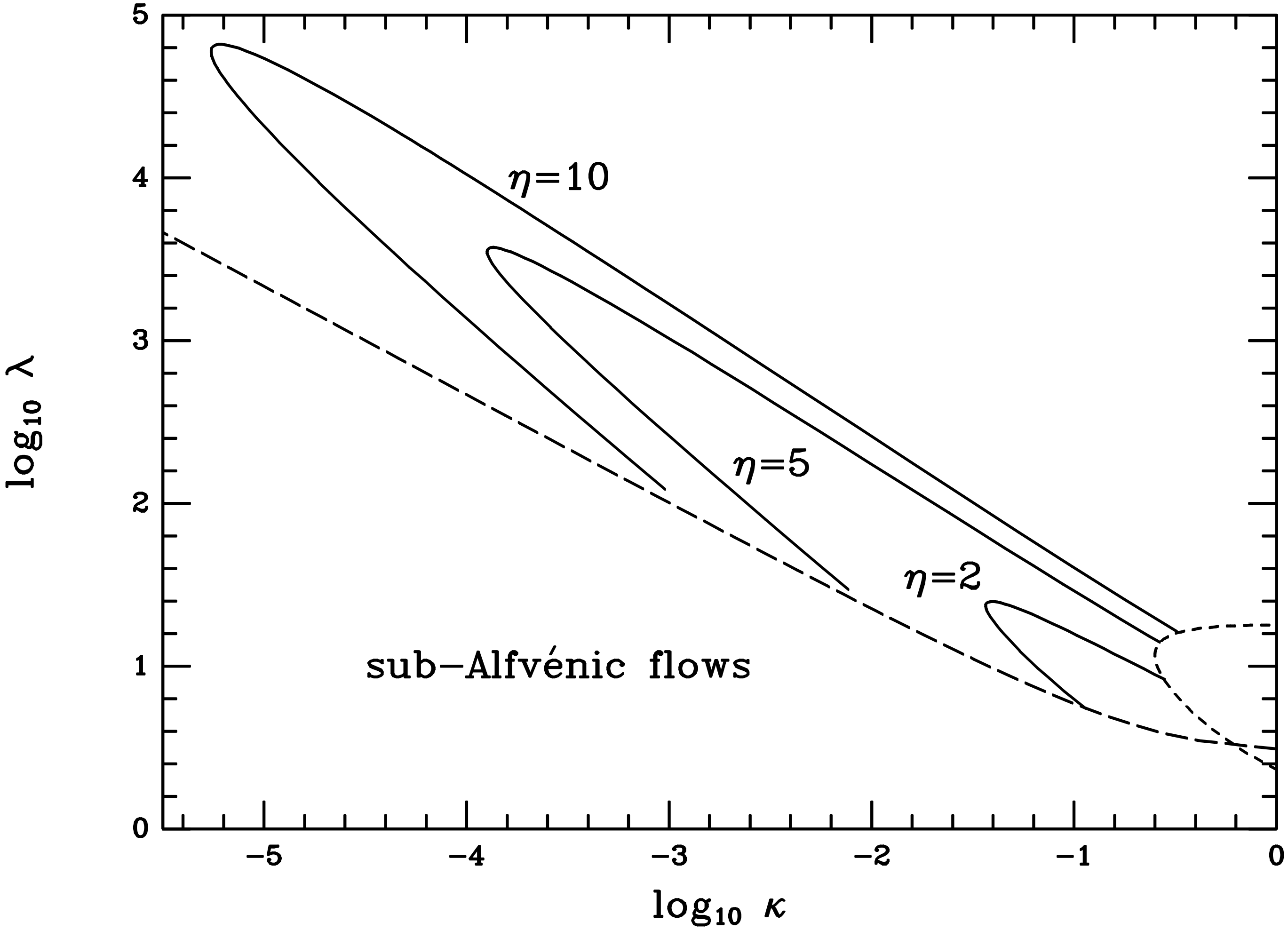
$\lambda \equiv l/(V_{\rm K} r_0)$: normalized specific angular momentum
$\kappa \equiv k(V_{\rm K}/B_0)$: normalized mass/magnetic flux ratio

disk parameters:

$\epsilon_B \equiv -V_{\rm i0}/C$: normalized drift speed of $\mathbf{B}$ lines
$\eta \equiv \nu_{\rm ni}/\Omega_{\rm K}$: neutral–ion coupling strength $[\nu_{\rm ni} = (\rho_{\rm i}/\rho_{\rm n})\nu_{\rm in}]$
$a \equiv V_{{\rm A}z0}/C$: magnetic field strength

Three parameters determined by conditions outside disk:

κ by sonic-point constraint
$|b_{\phi{\rm s}}| = \kappa(\lambda - 1)$ by Alfvén-point constraint
$b_{r{\rm s}}$ ($\Rightarrow a$) by global field distribution (cf. Ogilvie & Livio 2001)



$\eta > 1$ and $a \lesssim 1$ required to drive a wind
($\eta > 1$ everywhere in strongly coupled disks)

By employing the hydrostatic approximation ($V_z \to 0$), one obtains a set of algebraic relations that can be used to derive useful constraints on the disk solutions.

In the case of a strongly coupled, ambipolar diffusion-dominated disk with a constant η ($\propto \rho_{\rm i}$), one finds:

$$(2\eta)^{-1/2} \lesssim a \lesssim \sqrt{3} \lesssim \epsilon\eta \lesssim V_{\rm K}/2C$$

Inequality

1 ⇔ disk remains sub-Keplerian throughout
2 ⇔ wind launching condition ($b_{r{\rm s}} > 1/\sqrt{3}$)
3 ⇔ top of disk ($z_{\rm s}$) $>$ density scale height (h)
4 ⇔ Joule heating $<$ gravitational energy release

1st & 2nd inequalities ⇒ coupling parameter $\eta \gtrsim 1$

2nd & 3rd inequalities ⇒ magnetic squeezing dominates the vertical confinement of the disk ($h/h_{\rm T} \approx a/\epsilon\eta < 1$)

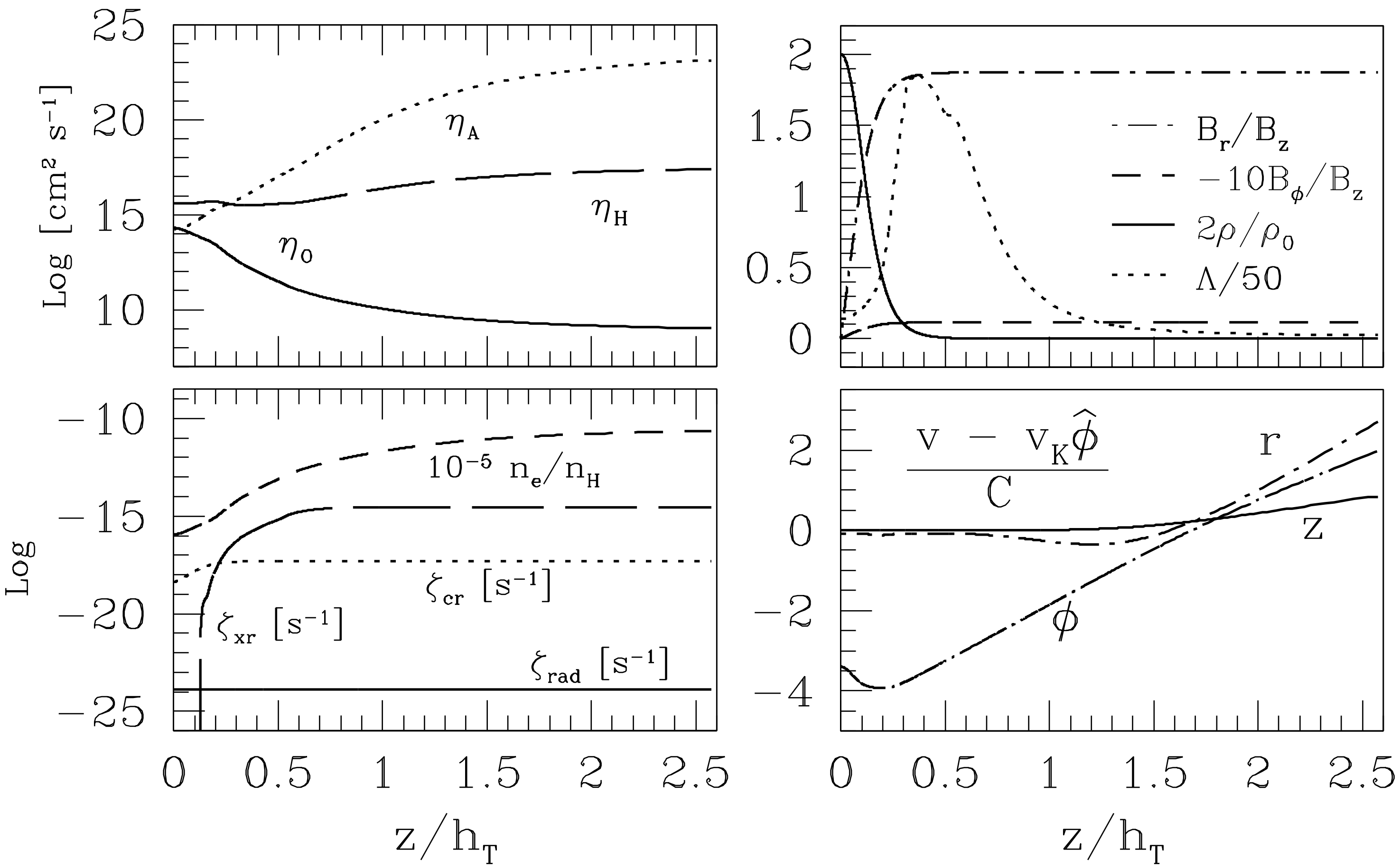
♣ These inequalities can also be used to:

● Demonstrate that the minimum wavelength of the most unstable linear MRI mode exceeds the disk scale height.

● Identify the region in the disk that is susceptible to MRI ⇒ one can construct “hybrid” disk models in which both radial and vertical angular momentum transport mechanisms operate (Salmeron et al. 2007; poster by R. Salmeron).

♣ This analysis can be extended also to the Hall and Ohm diffusivity regimes (Salmeron et al. 2008; poster by R. Salmeron).

Full-conductivity solution in the Hall/AD regime (Salmeron 2008)



$\Lambda \equiv V_{Az0}^2/\Omega_K\, \eta_{\perp 0}$ is the neutral–**B** coupling parameter

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

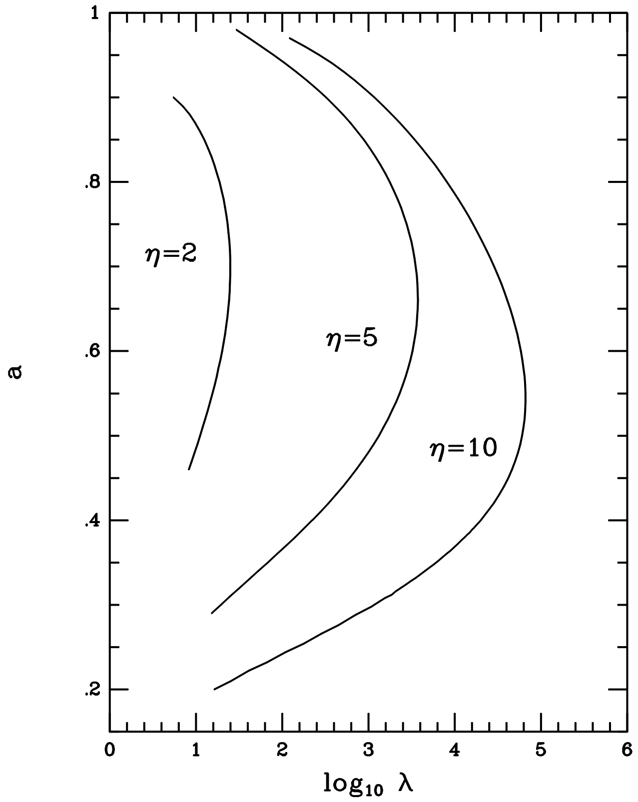
Stability of Disk/Wind Systems

- Strongly coupled wind-driving disks naturally lie in a stability "window," in which the magnetic field is strong enough to largely suppress the MRI but not so strong as to be subject to the radial interchange instability (Königl & Wardle 1996).

- It was, however, suggested that such disks might be inherently unstable because of the expected increase in $\dot{M}_{\mathrm{w}}/\dot{M}_{\mathrm{in}}$ with increasing $b_{r\mathrm{s}}$ (Lubow et al. 1994b; Cao & Spruit 2002).

- The turning point in the equilibrium curve of the diffusive disk models nevertheless indicates that there must also be a stable branch (Königl 2004).

$\star$ Along stable branch $b_{rs} \Uparrow$ ($\Leftrightarrow a \Downarrow$) $\Rightarrow \dot{M}_{\rm w}/\dot{M}_{\rm in} \Downarrow$ ($\Leftrightarrow \lambda \Uparrow$) (higher ang. momentum transport due instead to lever arm $\Uparrow$).

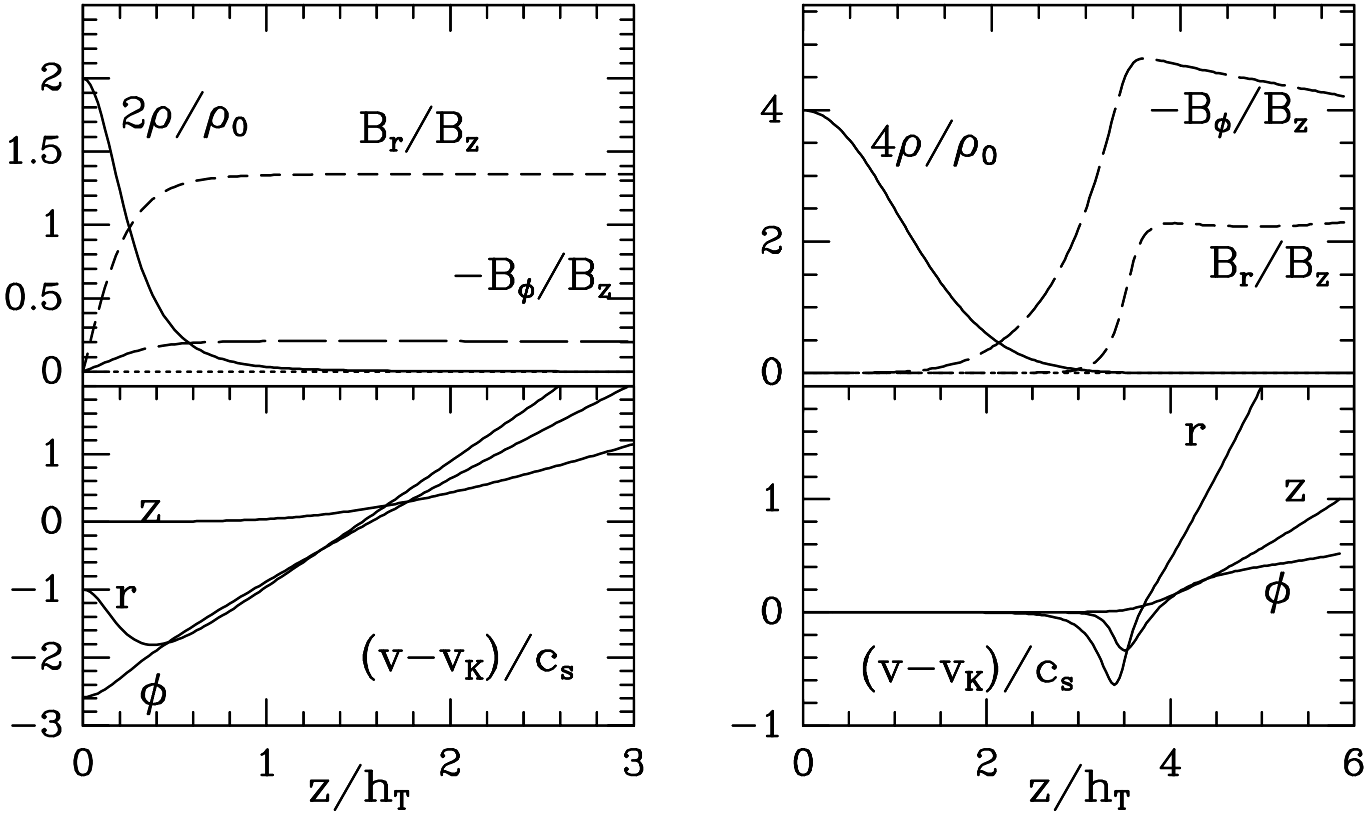


This result could be tested by non-ideal MHD simulations (cf. Casse & Keppens 2002; Meliani et al. 2006; Zanni et al. 2007).

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: $V_{\mathrm{A},0} \lesssim C$, $| < V_r > | \sim C$, $B_{r,\mathrm{s}} > |B_{\phi,\mathrm{s}}|$ (with B_r increasing already at $z = 0$).

In weakly coupled disks: $V_{\mathrm{A},0} \ll C$, $| < V_r > | \ll C$, $B_{r,\mathrm{s}} < |B_{\phi,\mathrm{s}}|$ [with B_r taking off only when Λ increases above 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 $\propto B_z dB_\phi/dz$.

$\star$ This could have implications to the issue of “dead zones” in YSO disks.

Dust Uplifting and Cycling in Wind-Driving Disks

♣ The mass fraction and size distribution of dust grains in the disk have a strong influence on the ionization structure and hence on the degree of coupling between the gas and $\mathbf{B}$.

Grains affect the degree of ionization in several ways:

- enhance recombination rate
- are the dominant charge carriers at high densities
- adsorb metal atoms

♣ The dust distribution is also relevant to the IR spectra and images of YSO disks and to their evolution into planetary systems (grains are the building blocks of planetesimals).

♣ Grain distribution determined by balance of several processes:

● grain-grain collisions due to Brownian motion, differential vertical-settling speeds, and turbulence lead to coagulation, cratering, or fragmentation

● collisional drag force exerted by the gas (due to “deficit” of thermal pressure and magnetic forces) causes vertical settling and radial migration

● sufficiently small grains are advected by the gas

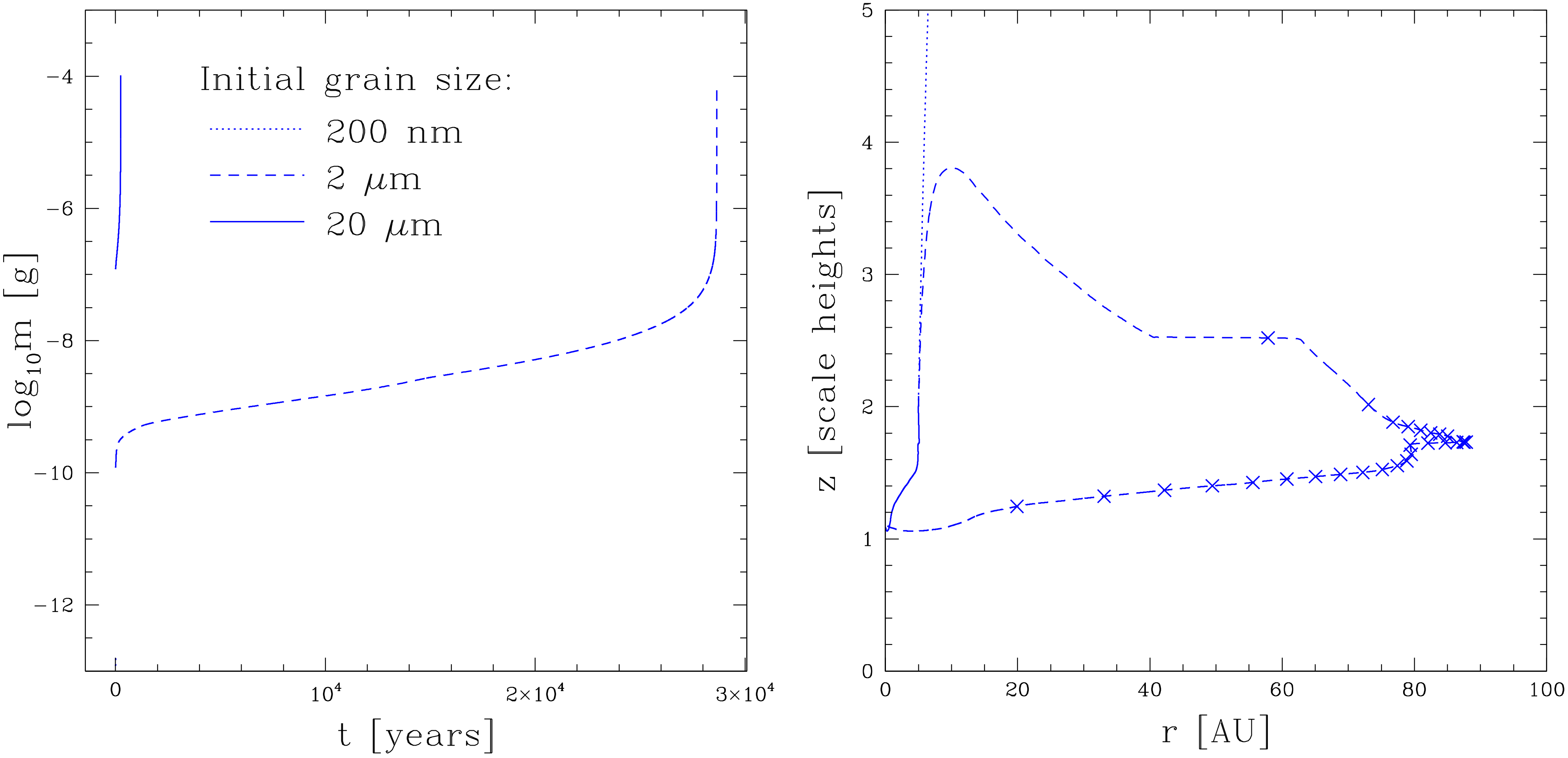
● grains at high elevations and small radii can be evaporated

♣ Some observational puzzles:

- μm-size grains detected near T Tauri disk surfaces, with inferred rapid growth in size from ~ 0.1 to ~ 1 μm; in standard viscous disk models expect coagulation to $\gtrsim 100$ μm in 10^4 yr.
- Particle samples collected from the Kuiper Belt comet Wild 2 by the *Strardust* mission were found to contain an abundance of crystalline silicates, which indicated that $\gtrsim 10\%$ of the comet's mass was transported in the form of particles larger than ~ 1 μm from the inner regions of the solar nebula.
- Outward transport of crystalline grains also indicated in several YSO disks by IR observations (occurred when age was $\lesssim 1$ Myr).

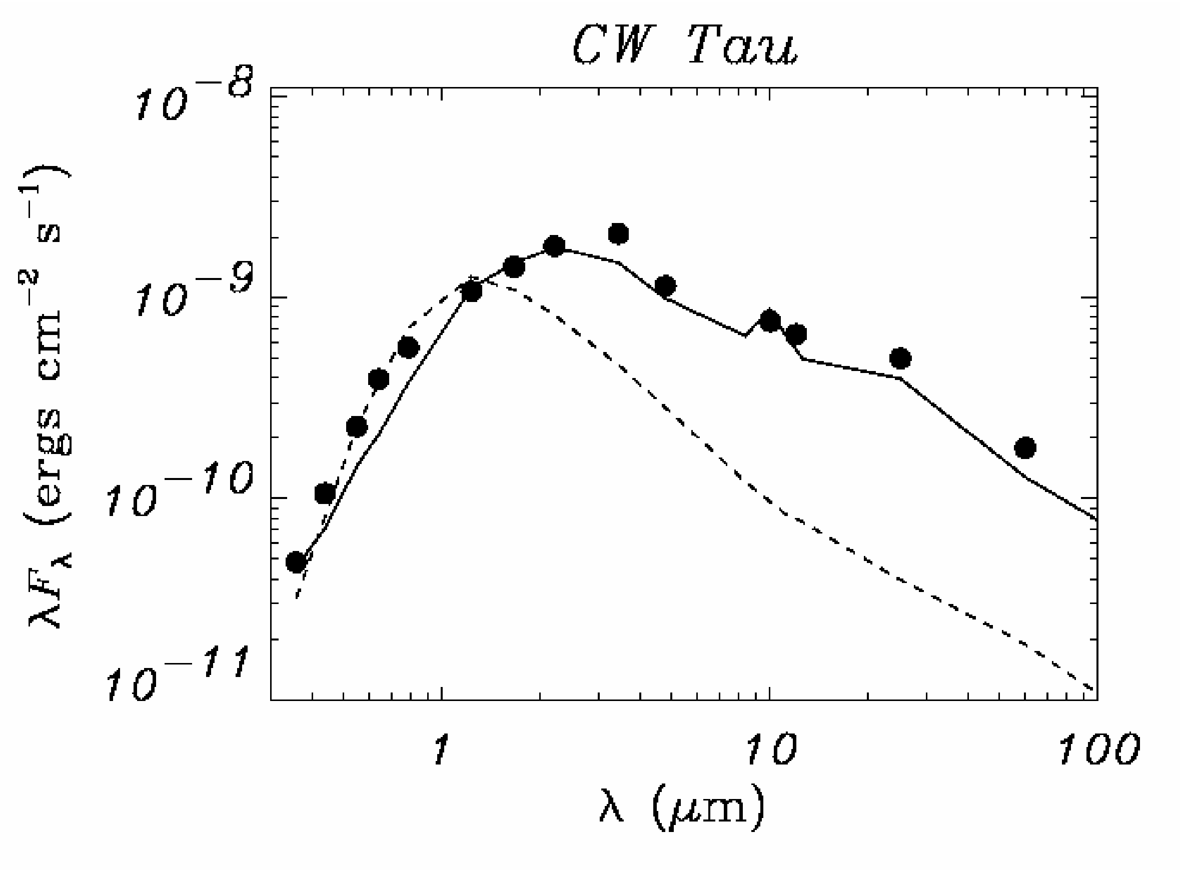
♣ Wind/disk models may provide new clues to these puzzles.

Toy-model calculation of 1-particle dust evolution in a “windy” disk



The X’s mark 10^3- yr intervals (Teitler 2008)

Spectral reprocessing by uplifted dust (Safier 1995)



- Possible alternative to “puffed up inner wall” interpretation of strong NIR bumps exhibited by YSOs.

Conclusions

- ♣ CDWs are an efficient means of angular momentum transport in disks, and can even dominate the transport in regions where $\dot{M}_{\rm w}/\dot{M}_{\rm in} \sim 0.1$ (or even less).
  - The launching region of an FU Orionis-type outflow could be a case in point.

- ♣ A natural origin for a large-scale, ordered $\mathbf{B}$ in a YSO disk is the interstellar field that threaded the parent cloud core.
  - Vertical angular momentum transport along the field (by torsional Alfvén waves or a CDW) could ensure that the field is advected inward by the accretion flow.

- ♣ The structure of wind-driving disks can be modeled under realistic ionization and conductivity conditions using semi-analytic techniques. Further progress is being made by numerical simulations that employ non-ideal MHD codes.
  - Algebraic expressions obtained in the hydrostatic approximation have proven useful in delineating the relevant parameter ranges in the different conductivity regimes.
  - One can distinguish between strongly coupled disks, with $| < V_r > | \sim C$, and weakly coupled disks, with $| < V_r > | \ll C$.
  - One can also construct models that incorporate vertical angular momentum transport by a large-scale mean field and (in regions where the field is comparatively weak) radial transport by a disordered, small-scale $\mathbf{B}$.

- Wind-driving YSO disks have a stable equilibrium branch and on the whole are immune to MRI and to magnetic interchange.
  - The results of time-dependent simulations are consistent with basic stability, but further studies with MHD codes that have non-ideal, 3D, and heating/cooling capabilities are needed.
- Wind-driving disks have distinct properties with potentially important observational consequences; dust uplifting and cycling is one example.