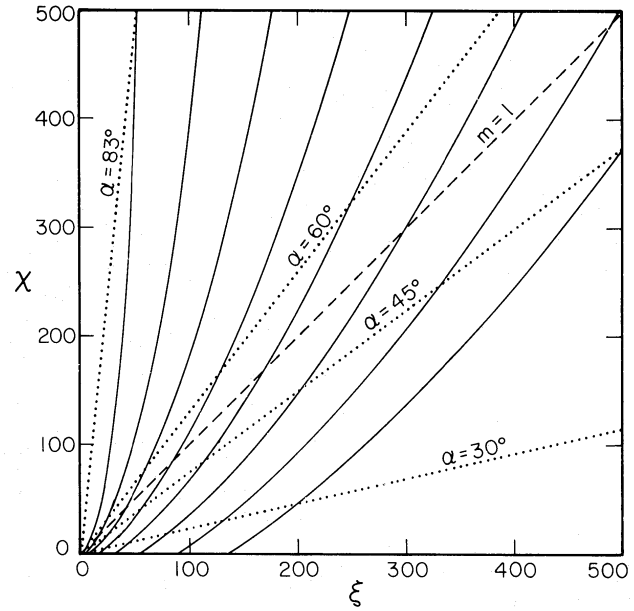
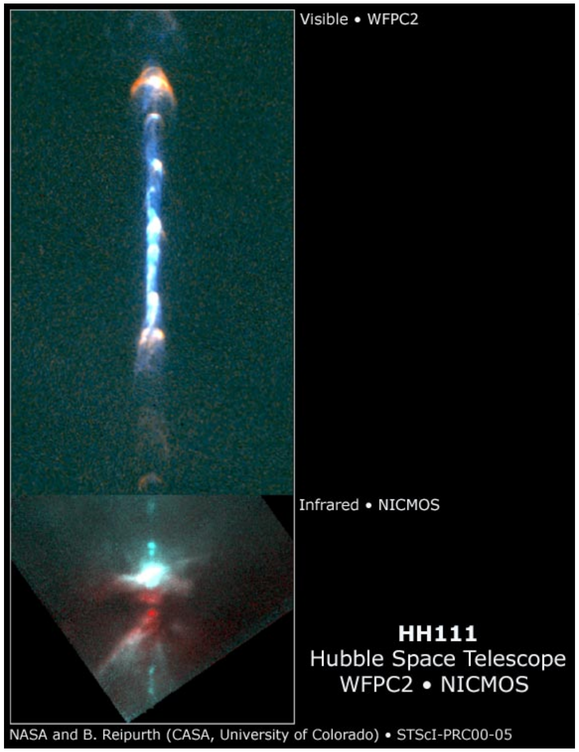


Disk-wind? (BP82)



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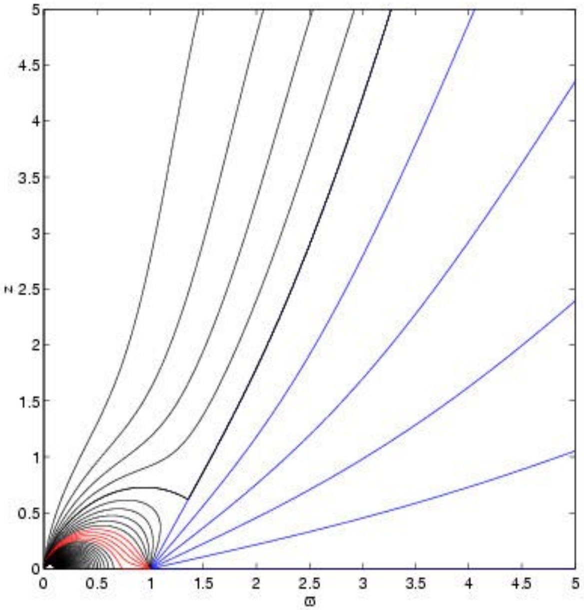


X-wind? (SNORLW94)

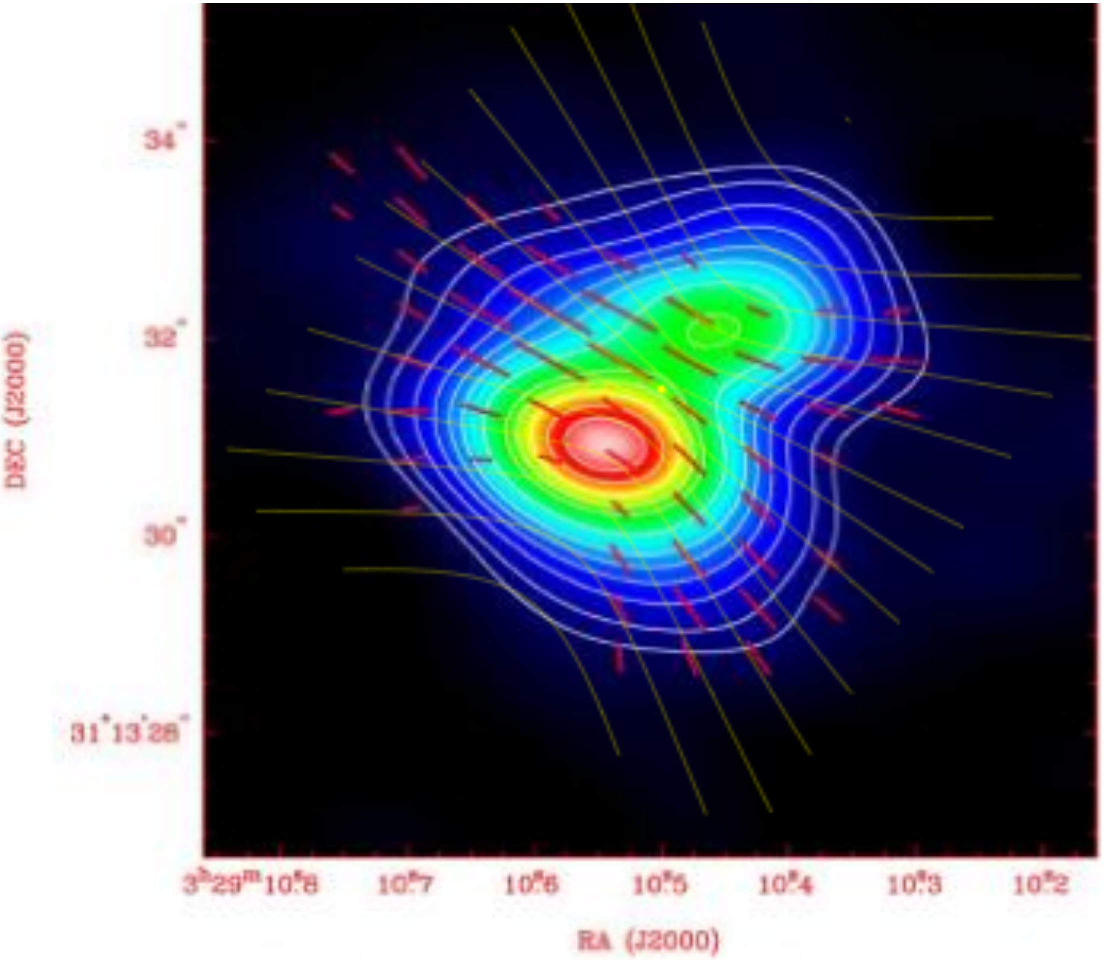
Outflows from Young Stars

Frank H. Shu
Academia Sinica & University of California
ALMA/NAASC 2012 Workshop
3 March 2012
Charlottesville, VA

Outline and Logic of Talk

- Contemporary formation of high- and low-mass stars is dominated by how $\lambda \equiv 2\pi G^{1/2} M / \Phi$ becomes ≥ 1.
- Nonideal MHD collapse leads to some loss of flux at tens of AU scale, with $\lambda = 4$ to 10 being a typical outcome.
- Most of the mass ends up in the star; almost all of the flux in the disk. MRI gives turbulent ν and η.
- The latter yield $\Sigma(\varpi),\ B_z(\varpi),\ \Omega(\varpi) = \bar{f}\left(GM_* / \varpi^3\right)^{1/2}$ with $\bar{f} < 1$ (sub-Keplerian rotation) of inner disk.
- Viscous/resistive heating is too weak to launch a magnetocentrifugal disk-wind, but photoevaporation can assist a wind in the outer disk.
- Fast jet (X-wind) originates in the innermost part of the disk before truncation by a funnel flow onto a strong stellar magnetic field.
- In transients, magnetic pressure (“magnetic tower”) can help drive the outflow, but effect is sensitive to details of ν and η. Asymptotically in time, such a magnetic tower becomes an X-wind.

LMSF: NGC 1333 IRS 4A
Girart, Rao, Marrone (2006)



Binary formation: Kratter, Matzner, Krumholz, Klein (2010)

Best Fit:Goncalves, Galli, Girart (2008) based on ideal (Allen, Li, Shu 2003) & non-ideal collapse theory (Galli, Lizano, Shu, Allen 2006).

$\lambda_{\text{split monopole}} \approx 1.6$

$R_{\text{Ohm}} \approx 5 - 50\ \text{AU}$

$\eta \approx 1 - 4 \times 10^{20}\ \text{cm}^2/\text{s}$

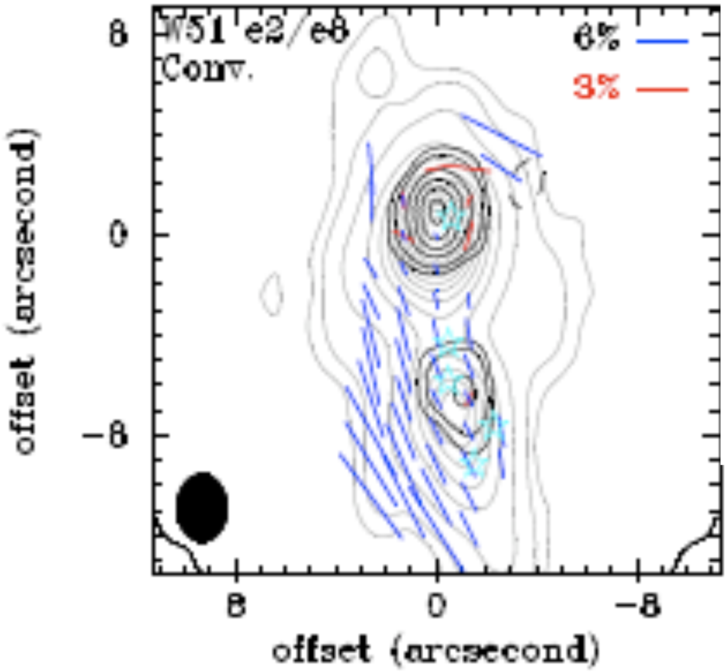
for d = 300 pc.

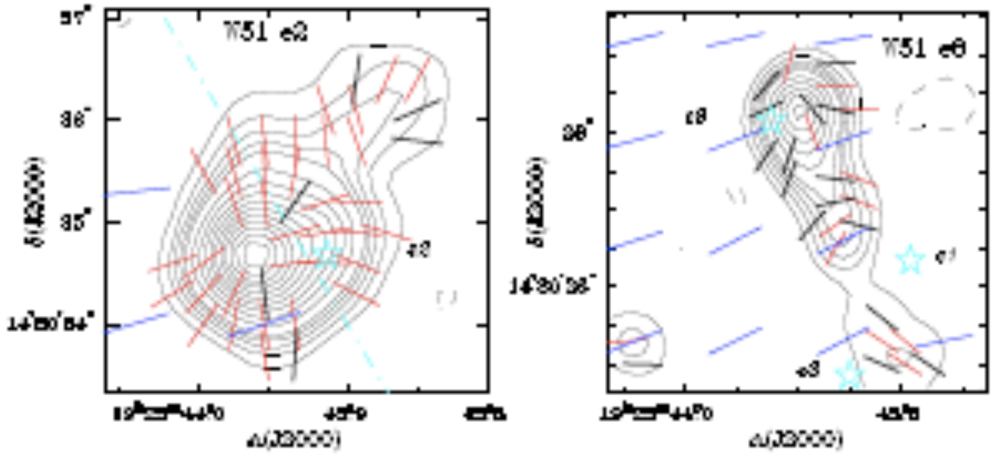
Likely value in star plus disk: $\lambda_0 \approx 4$.

HMSF: W51

- 1.3 mm Polarization Map (Lai et al. 2001)

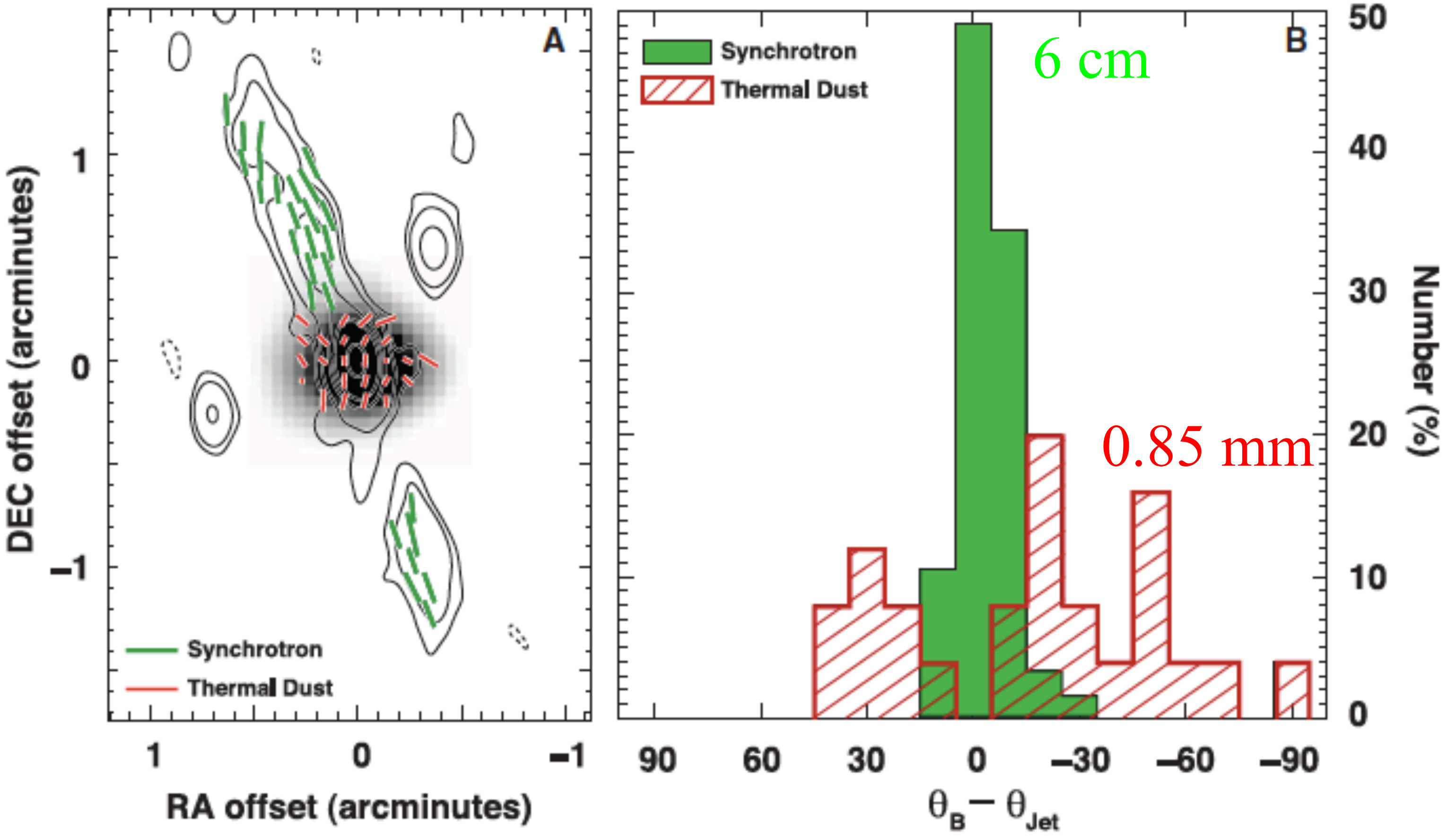
0.87 mm Polarization Map (Tang et al. 2009)





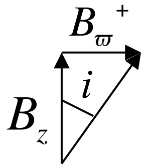
IMSF: Polarized Radio Emission
Carrasco-Gonzalez et al. (2010)

IRAS 1862-2041

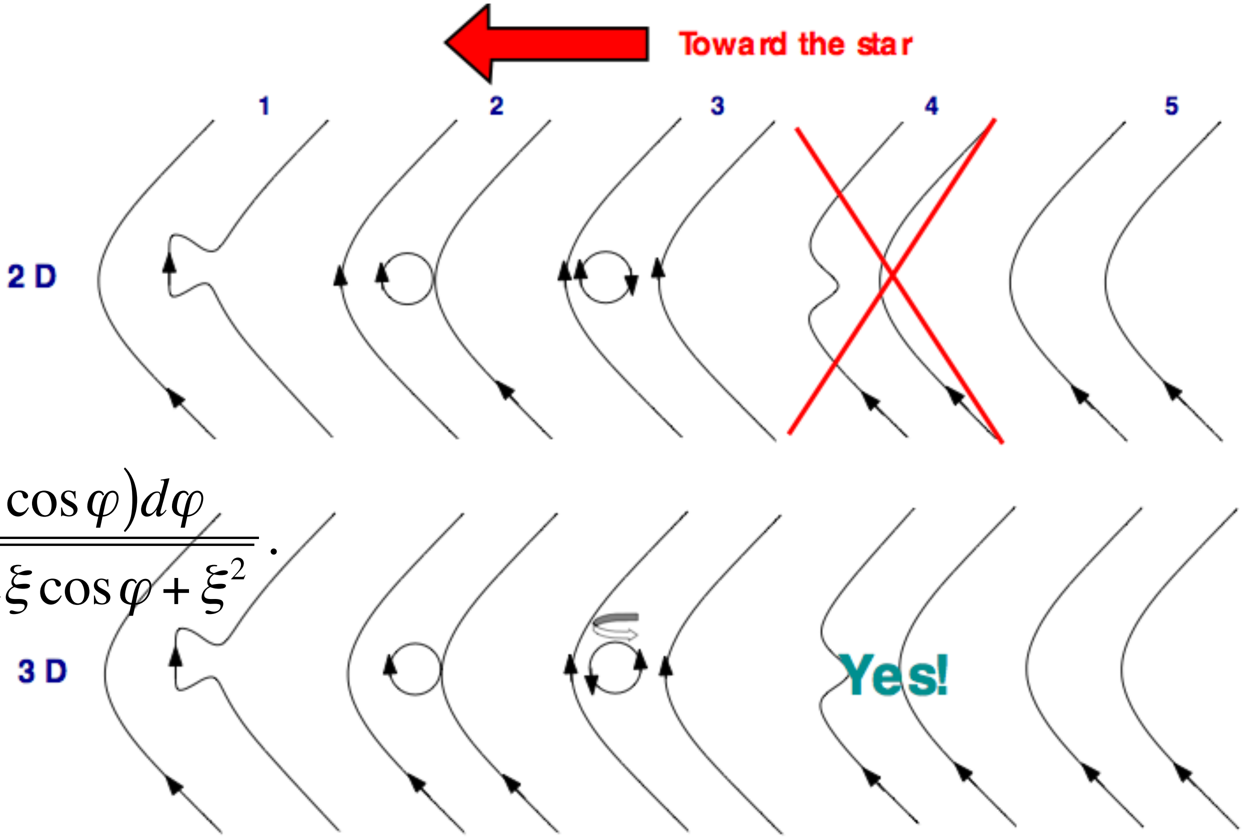


Mixing-Length Theory of MRI Loop Soup

(Shu, Galli, Lizano, Glassgold, Diamond (2007)



$$\frac{B_\varpi^+}{B_z} = \tan i \equiv I_\ell$$



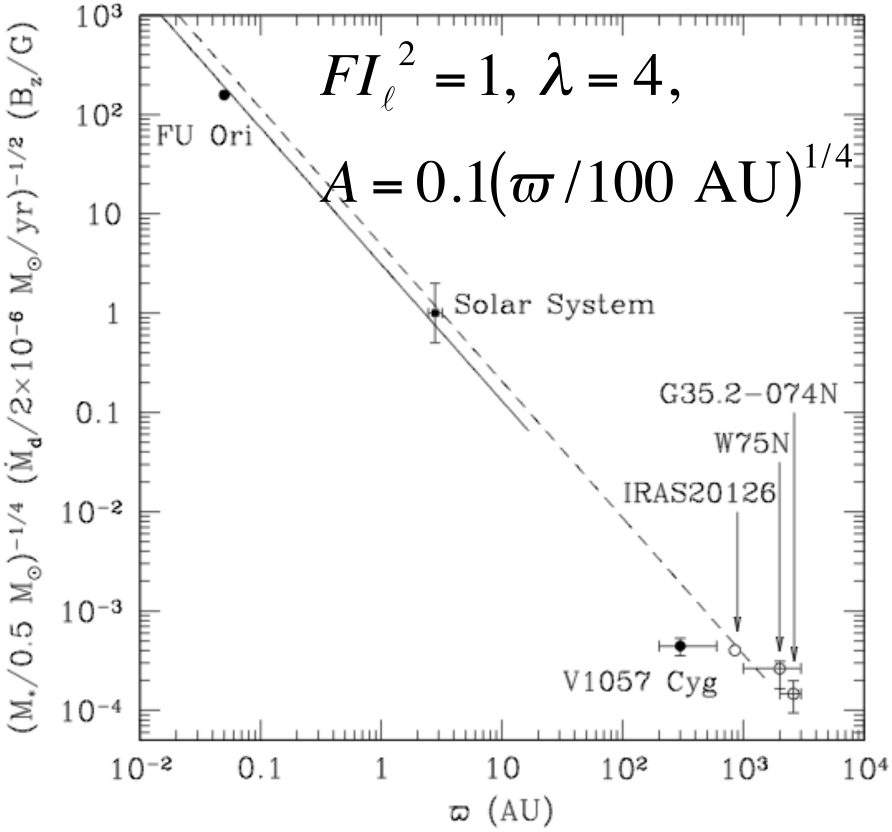
$$I_\ell = \frac{1}{2\pi}\int_0^\infty \xi^{-\ell} d\xi \oint \frac{(1-\cos\varphi)\,d\varphi}{\sqrt{1-2\xi\cos\varphi+\xi^2}}.$$

$$A = \frac{z_0}{\varpi} \propto \varpi^{(4\ell-1)/2},$$

$$\nu = F\frac{\left(B_\varpi^+\right)^2 z_0}{2\pi\Sigma\Omega}, \quad \eta = F\left(-\frac{z_0}{\Omega}\frac{\partial\Omega}{\partial\varpi}\right)\left(\frac{B_z B_\varpi^+ z_0}{2\pi\Sigma\Omega}\right), \quad \frac{\eta}{\nu} = \frac{3}{2I_\ell}\left(\frac{z_0}{\varpi}\right) << 1.$$

Cf. Lubow, Papaloizou, Pringle (1994); Bai & Stone (2010), local sim.

Strongly Magnetized Disks Are Sub-Keplerian
Shu, Lizano, Galli, Mohanty, Cai (2008)



Sub-Keperianity $\bar{f} \le 1$ and disk compression $A/A_0 \le 1$, where $A_0^{\,2} \equiv 2a^2\varpi/GM_* \ll 1$, are related to magnetization $\mu \equiv B_z^{\,2}/4\pi P_0$:

$$1-\bar{f}^{\,2} = \frac{A_0}{I_\ell}\left(\frac{A_0}{A}-\frac{A}{A_0}\right),$$

$$\frac{A}{A_0} = \left(1-\frac{I_\ell^{\,2}}{2}\mu\right)^{1/2}.$$

For model of Blandford & Payne (1982), $B_z \propto \varpi^{-5/4}$, $\ell = 1/4$, $I_\ell = 1.43 = \tan i$, $i = 55^\circ > 30^\circ$, good news for disk-winds.

Problem: $1-\bar{f}^{\,2} = O(A_0)$ if $A/A_0 \sim 0.5$.

Thermal launch: $1-\bar{f}^{\,2} = O(A_0^{\,2})$. ⊗

Disk winds cannot both thermally launch and fling unless magnetic diffusivity is large (e.g., Konigl, Salmeron, Wardle 2009).

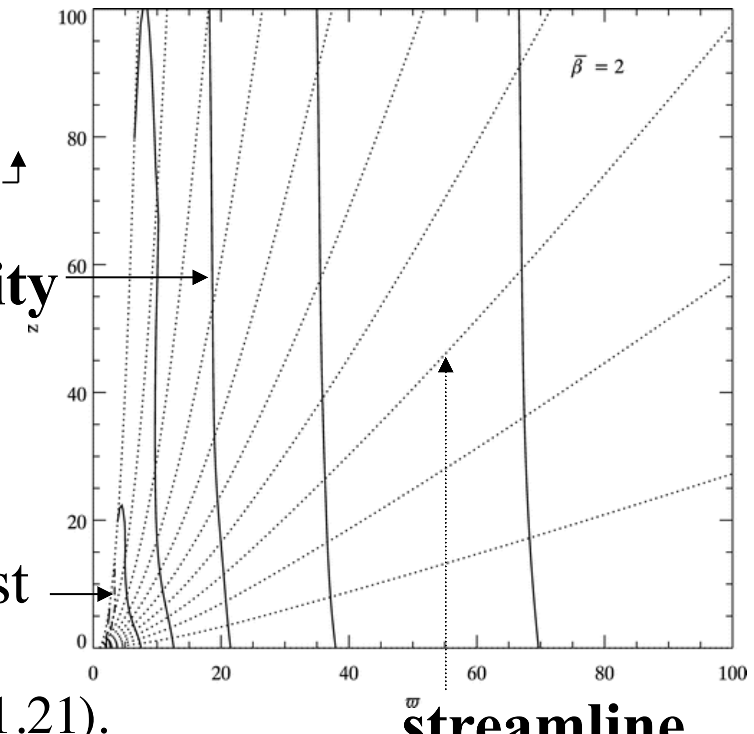
X-winds in Action
Cai, Shang, Lin, Shu (2008)

- Heinemann & Olbert (1978), Hartmann & MacGregor (1982), Shu, Lizano, Ruden, Najita (1988), Shu et al. (1994)
- Cold limit of ideal, axisymmetric, steady MHD:

$$\nabla\cdot\left(A\,\nabla\psi\right)+\frac{1}{A}\left(\frac{J}{\varpi^{2}}-1\right)\frac{J'}{\varpi^{2}}+\frac{2\beta\beta' V_{\mathrm{eff}}}{(\beta^{2}-\varpi^{2}A)^{2}}=0,$$

$$\frac{\varpi^{2}}{2}A^{2}\left|\nabla\psi\right|^{2}+\frac{\varpi^{2}}{2}\left(\frac{J}{\varpi^{2}}-1\right)^{2}+\frac{\varpi^{4}V_{\mathrm{eff}}A^{2}}{(\beta^{2}-\varpi^{2}A)^{2}}=H(\psi)=0,$$

$$A=\frac{\beta^{2}\rho-1}{\varpi^{2}\rho}.$$ Elliptic from X to F, hyperbolic afterward.



Isodensity contour

fast

streamline

- Action:

$$S=\iint\left[\frac{A}{2}\left|\nabla\psi\right|^{2}-\frac{1}{2A}\left(\frac{J}{\varpi^{2}}-1\right)^{2}+\frac{V_{\mathrm{eff}}}{\beta^{2}-\varpi^{2}A}\right]\varpi\, d\varpi\, dz.$$

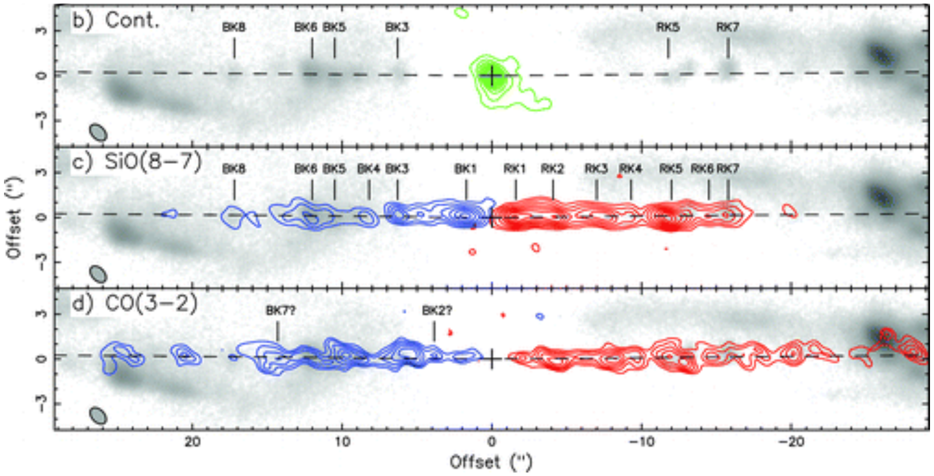
Example: inverse loading $\beta=\frac{3}{2}\bar{\beta}(1-\psi)^{-1/3}$,

$\bar{\beta}=1,\ 2,\ 3$ ($\bar{J}_w=2.64,\ 4.36,\ 6.20$; $f_w=\frac{1}{3}$ for $\bar{\beta}$=1.21).

Difficulties of Jet-Rotation Predictions for Fast, Lightly Loaded, Disk Winds

Rotation of jets best tested in edge-on systems. Compare with HH211 (Lee et al. 2007).

Similar situation in HH212 (Lee et al. 2008).



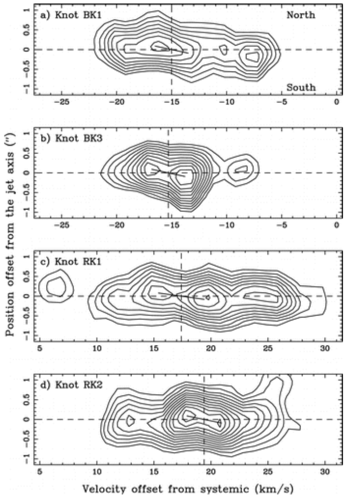
$$v_t \geq 200 \text{ km/s},$$

$$j_t \leq 30 \text{ AU} \cdot 1.5 \text{ km/s} = 45 \text{ AU km/s}.$$

$$v_t = \sqrt{2J_w - 3}\ \varpi_b \Omega_b, \ \ j_t = J_w \varpi_b{}^2 \Omega_b.$$

$$\therefore \varpi_b = \frac{\sqrt{2J_w - 3}}{J_w} \frac{j_t}{v_t} \leq 0.225 \frac{\sqrt{2J_w - 3}}{J_w} \text{ AU}.$$

Also Anderson, Li, Krasnolpolski, Blandford (2003)

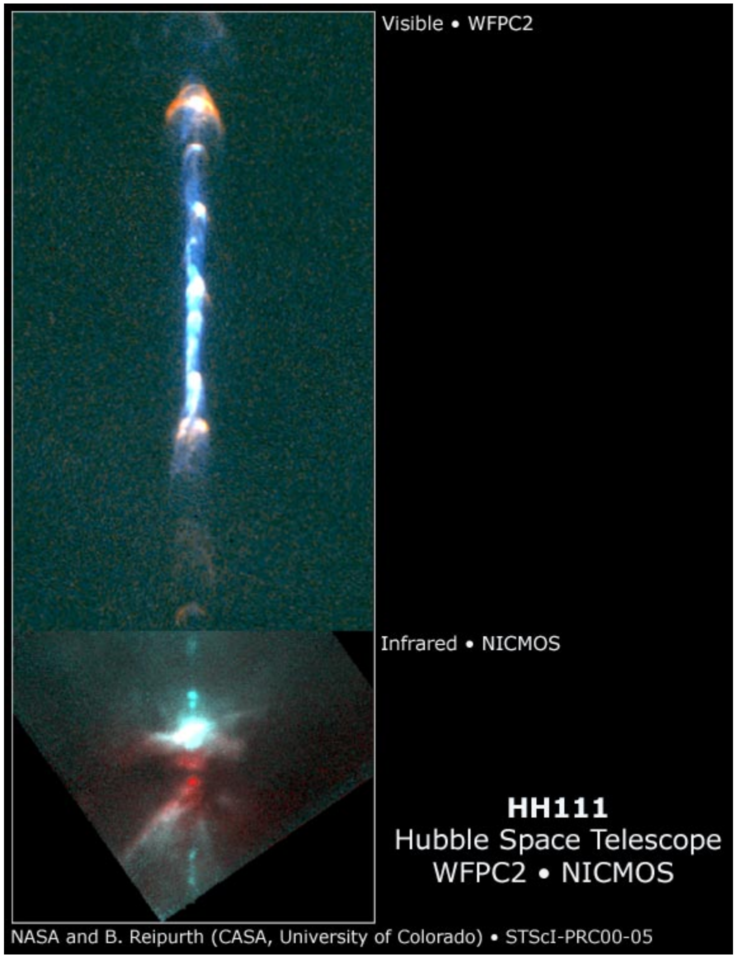


J_w	4	20	400
$\frac{\varpi_b}{\text{AU}} \leq$	0.13	0.07	0.02

Any disk wind for jet has to look ~ X-wind:

$$R_X \sim 0.05 \text{ AU}.$$

Synthetic Image of Pure X-wind (Shang, Glassgold, Shu, Lizano 2002)



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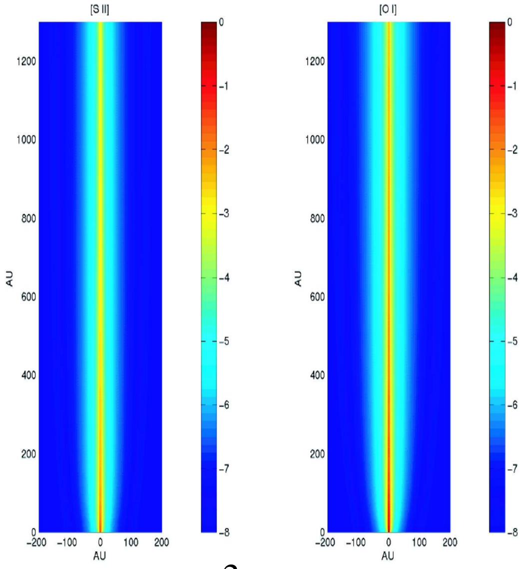
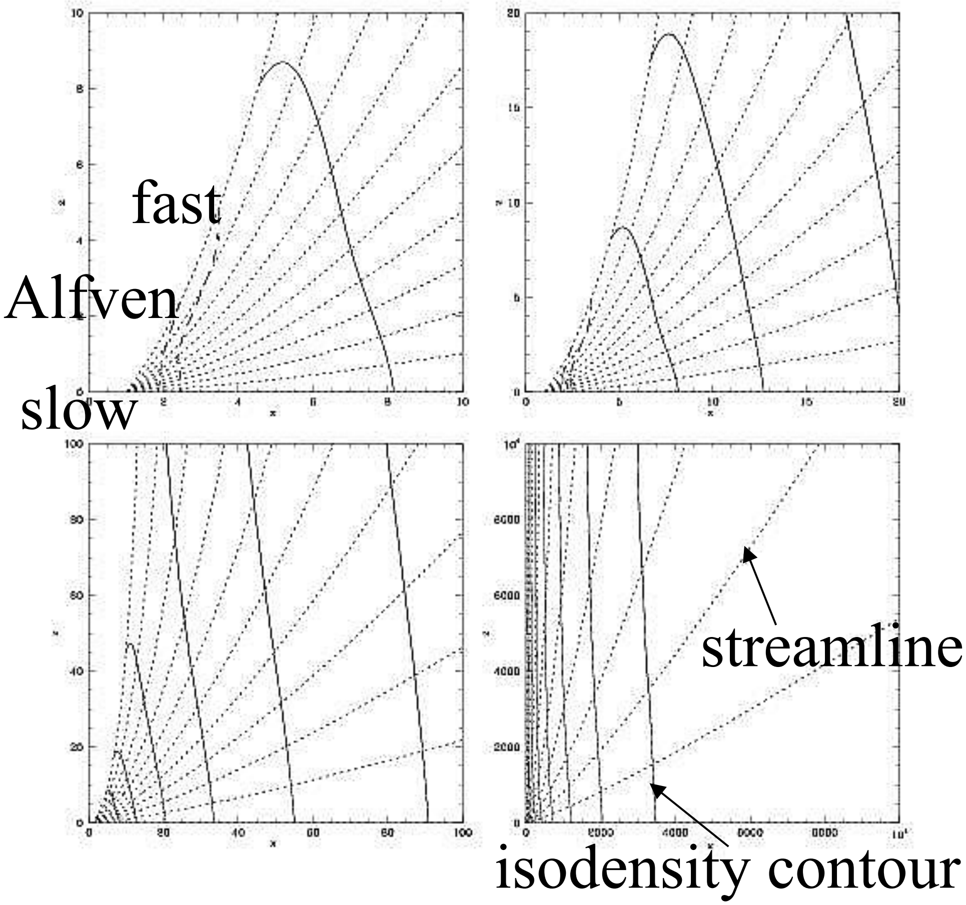


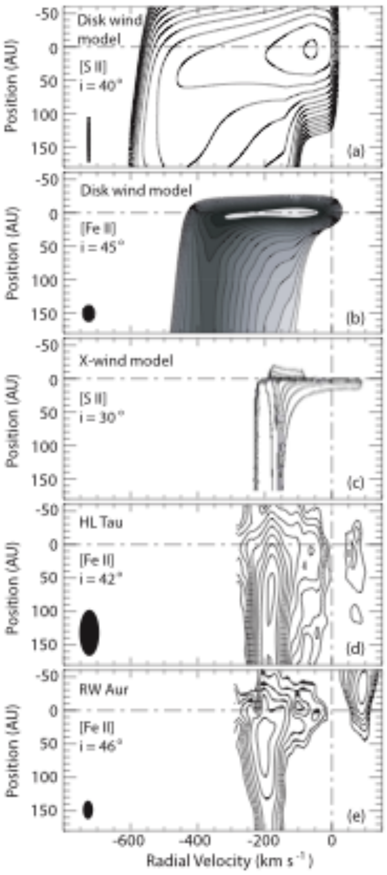
$$\Gamma = \alpha \frac{\rho v^3}{s} \text{ with } \alpha \ll 1,$$

fast shocks not possible in self-similar disk winds (Hartigan, pers. comm.).

Predictions for Position-Velocity Diagram



Shu, Najita, Ostriker, Shang (1995)



Pyo et al. (2006)

Cabrit, Ferreira, Raga (2003)

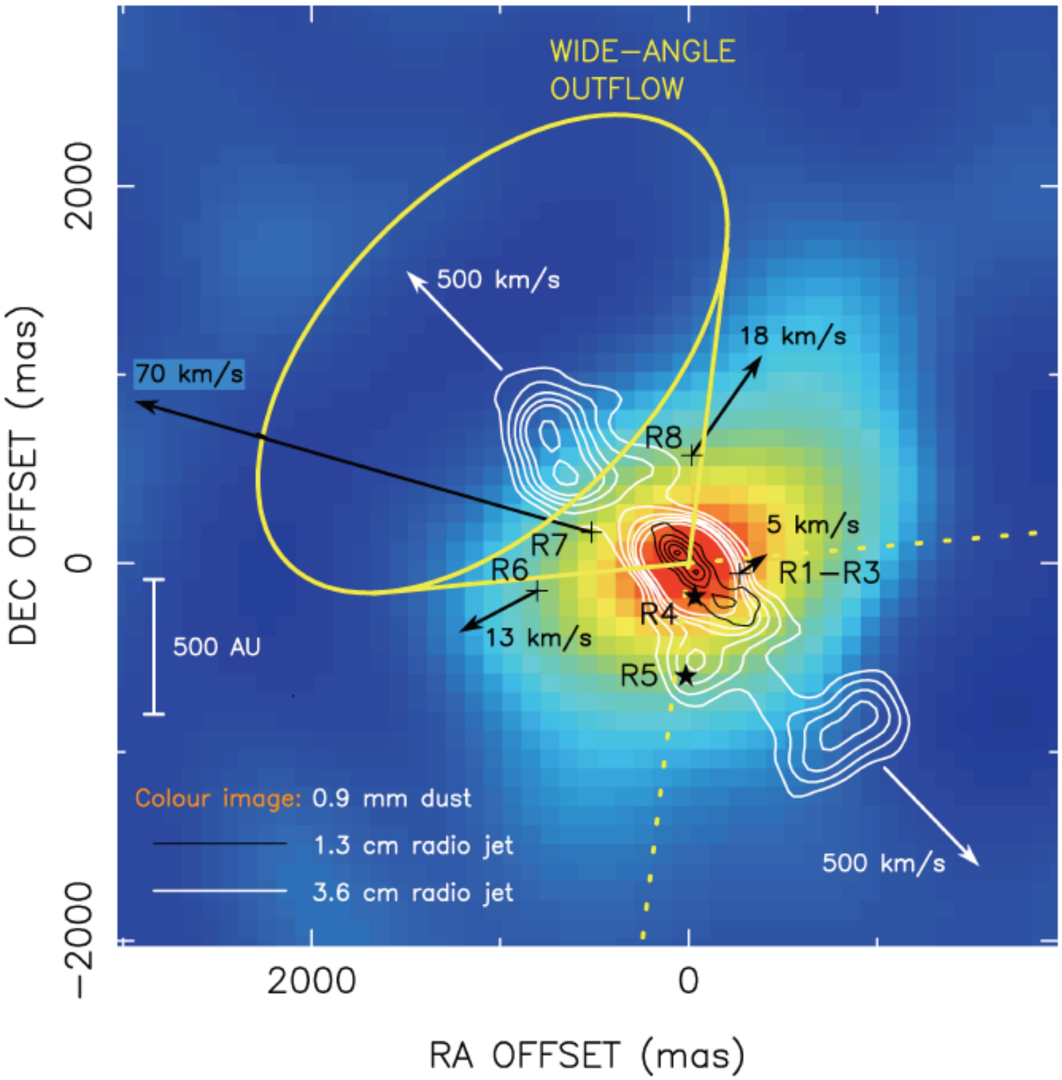
Shang, Glassgold, Shu (1998)

RW Tau

Liu &Shang (2012)

Jets arise from narrow range of ϖ, like X-wind.

Coexistence Fast Jet & Slow Wide-Angle Wind in Cepheus A HW2: Torrelles et al. (2011)



Slow rotating wide-angle wind = photoevaporative MHD disk flow?

Disk Truncation & Funnel Flows

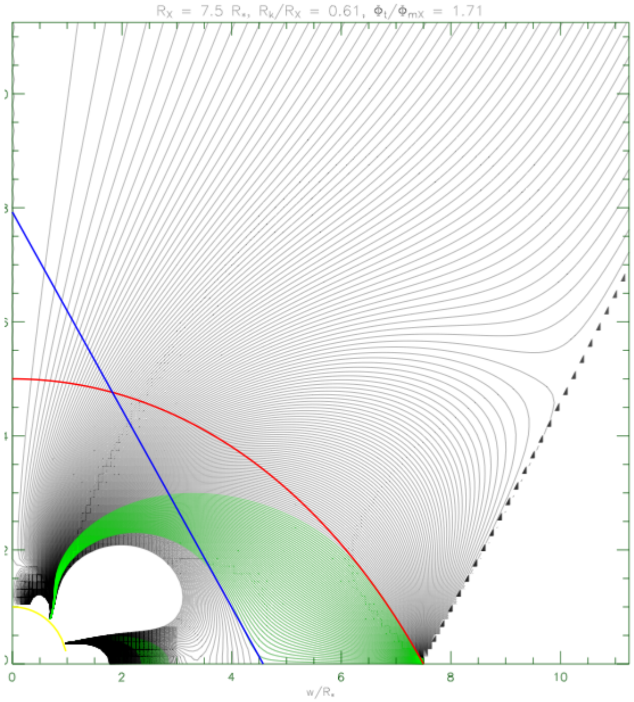
- Ram pressure balance:

  Ghosh & Lamb (1978)
- Angular momentum balance:
  - Funnel vs. disk viscosity
    Cameron & Campbell (1993)
  - Funnel vs. X-wind

    Ostriker & Shu (1995);
    Johns-Krull & Gafford (2002);
    Mohanty & Shu (2008)
- Concept of trapped flux for any multipole superposition:

$$F_h \bar{B}_h = \bar{\beta} f^{1/2} \left(\frac{G M_* \dot{M}_\mathrm{d}^{\,2}}{R_*^{\,5}} \right)^{1/4} \left(\frac{R_X}{R_*} \right)^{3/4}$$

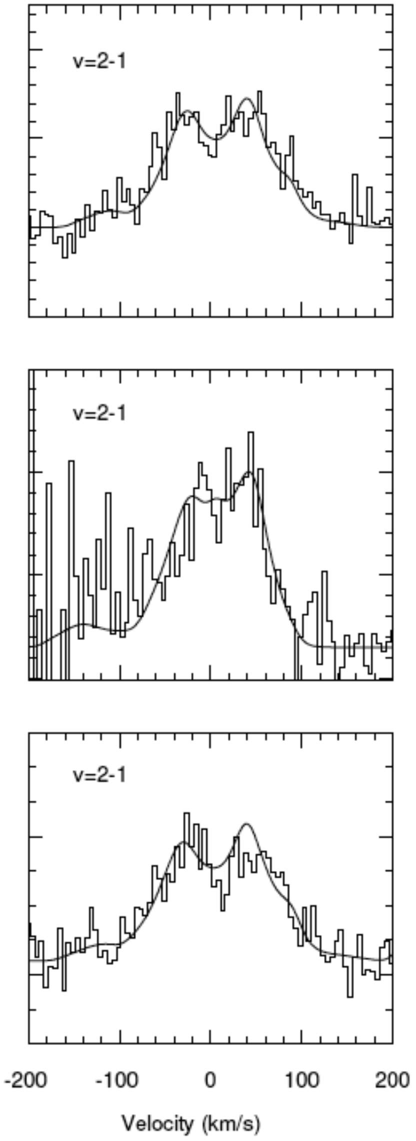
with $\bar{\beta} = 1.21$ for $f = 1/3$ (Cai et al. 2008).

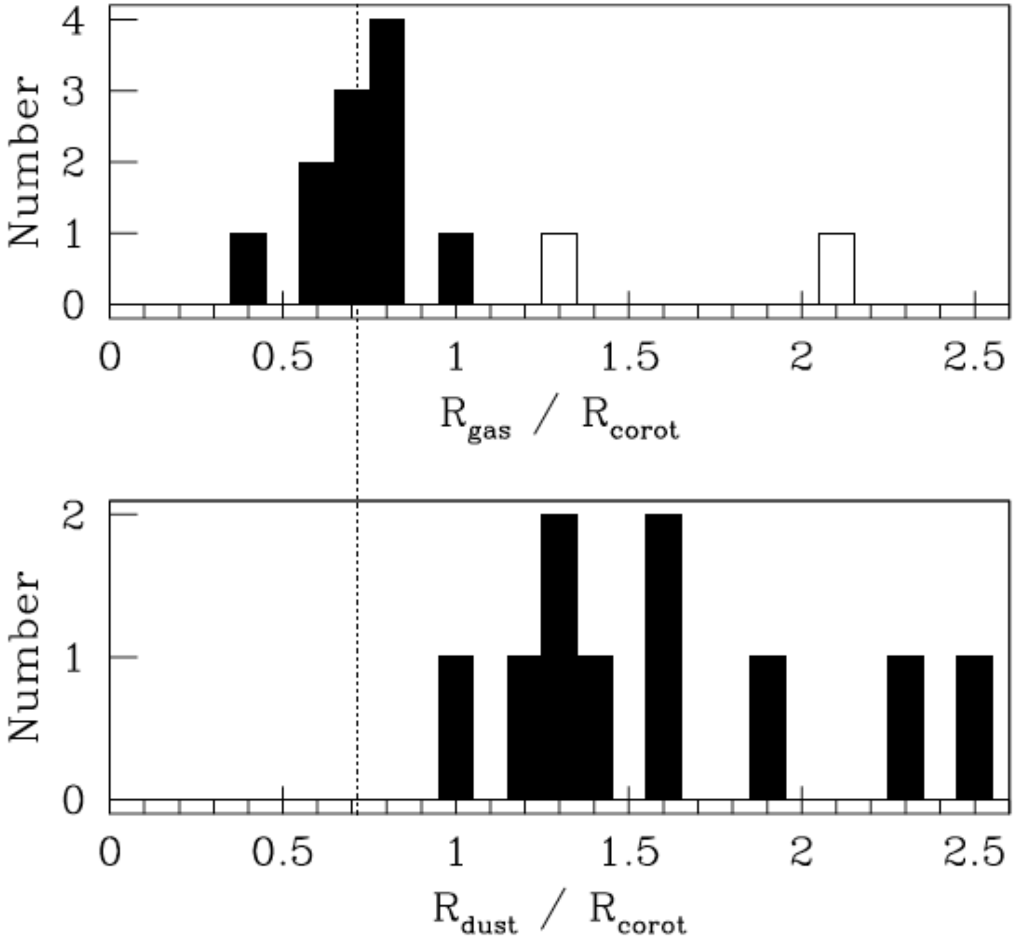


	$F_h \bar{B}_h$ (obs)	$F_h \bar{B}_h$ (theory)
V2129 Oph	100 G	79 G
BP Tau	180 G	160 G

Donati et al. (2006, 2008)

CO Rovib Emission from T Tauri Disk
Carr (2007)



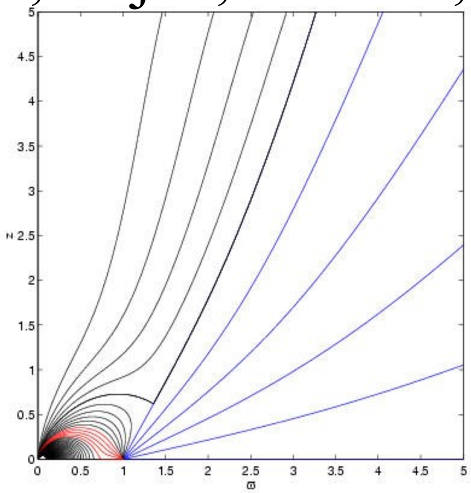


Simple prediction of inner hole: $R_{\mathrm{gas}}/R_{\mathrm{corot}} = 1$,

But funnel flows inside corot. $R_{\mathrm{dust}} > R_{\mathrm{gas}}$?

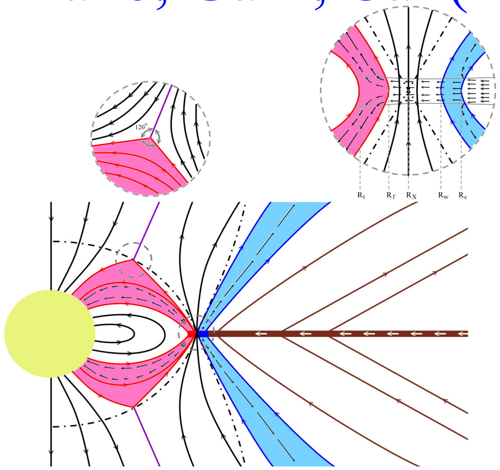
Funnel Flows and X-winds Appear Simultaneously in Theory and in Simulations where $\eta \ll \nu$

Shu, Najita, Ostriker, Shang (1995)

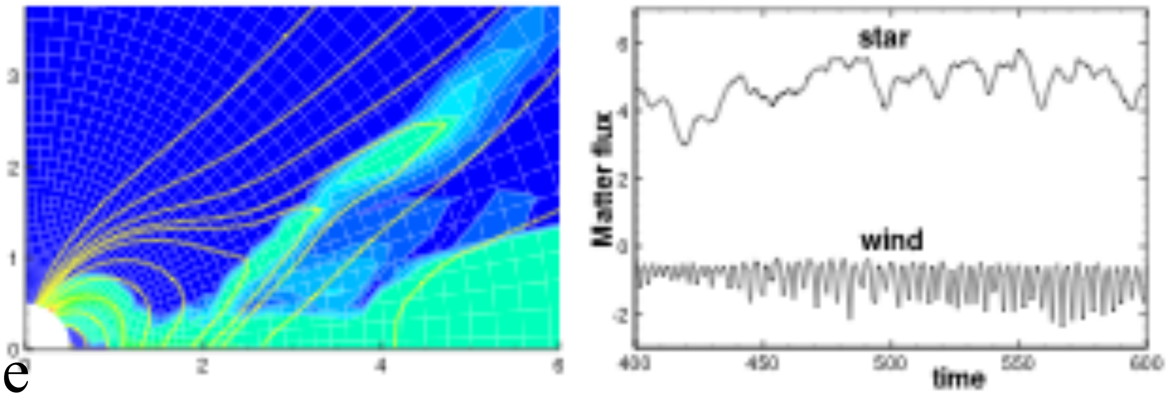


Shu, Lizano, Galli, Cai (2007)

Needed extension: account of interstellar field trapped in disk.



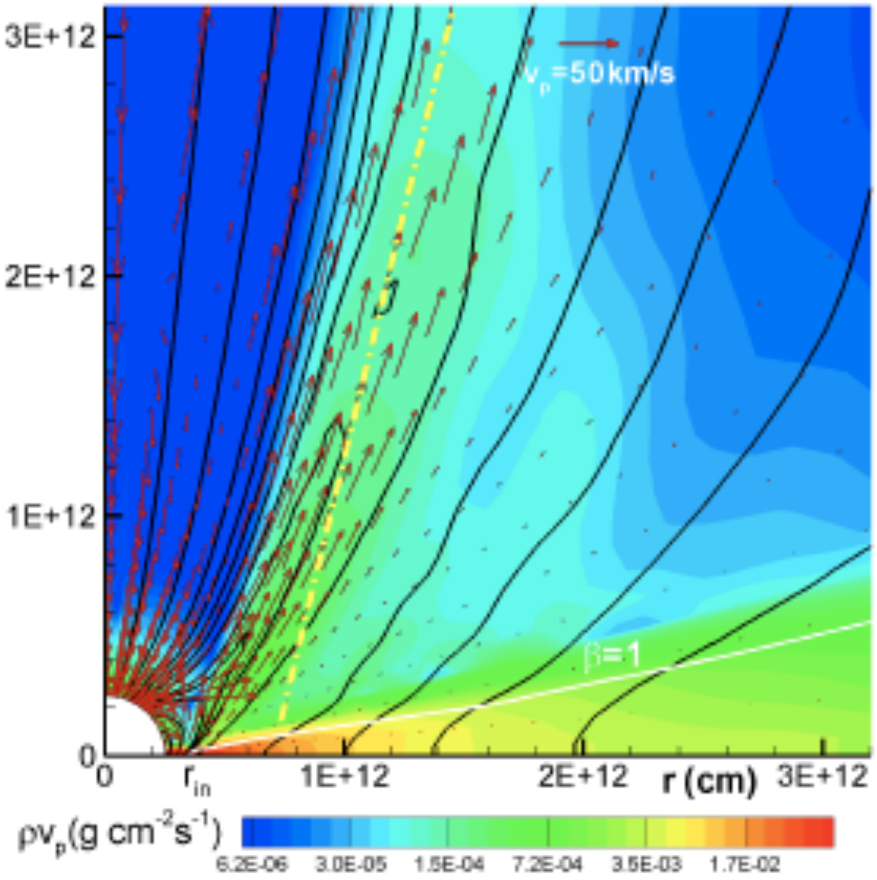
Note “puffed rim”, that gives larger “$R_{\text{dust.}}$” CAIs launched from inner ring (Shu, Shang, Lee 1996). This main explain O-isotope anomalies of SS (Clayton 1973; McKeegan 2011).



Romanova, Long, Kulkarni, Kurosawa, Ustyugova, Koldoba, Lovelace (2007)

et al. 2007.

Transient FU Orionis Outbursts
Konigl, Romanova, Lovelace (2011)



Similarities to “steady” models (Shu et al. 1988, 2008): diffusivities and spatial/temporal extent of outburst.

Difference: Star not equilibrium rotator but drives “magnetic bubble or tower” (Draine 1983, Lynden-Bell 1996).

Asymptotically in time (toward end of outburst), star is spun up and magnetic tower becomes X-wind.

Conclusions

- Trapping of interstellar flux in SF plus MRI viscous/resistive diffusion automatically produces **B** configuration conducive to disk wind.
- However, fields strong enough to fling gas to high velocity imply disks sufficiently sub-Keplerian as to make thermal loading difficult.
- Observations favor YSO jets originating from a small range of disk radii, as in X-winds, but the slow (rotating) component in some observed outflows may come from a magneto-centrifugally assisted photo-evaporative wind in outer disk.
- Transient outbursts (high states in disk accretion) can compress the stellar field and yield “magnetic towers.” Spin-up of the central star then asymptotically yields X-winds.
- Thus, in different situations, realistic YSO outflows may be X-winds, magnetic towers, magneto-centrifugally assisted photo-evaporative winds, or swept up shells (not discussed).
- ALMA will provide much more stringent, exquisite tests.