Formation of Massive Stars: Theory

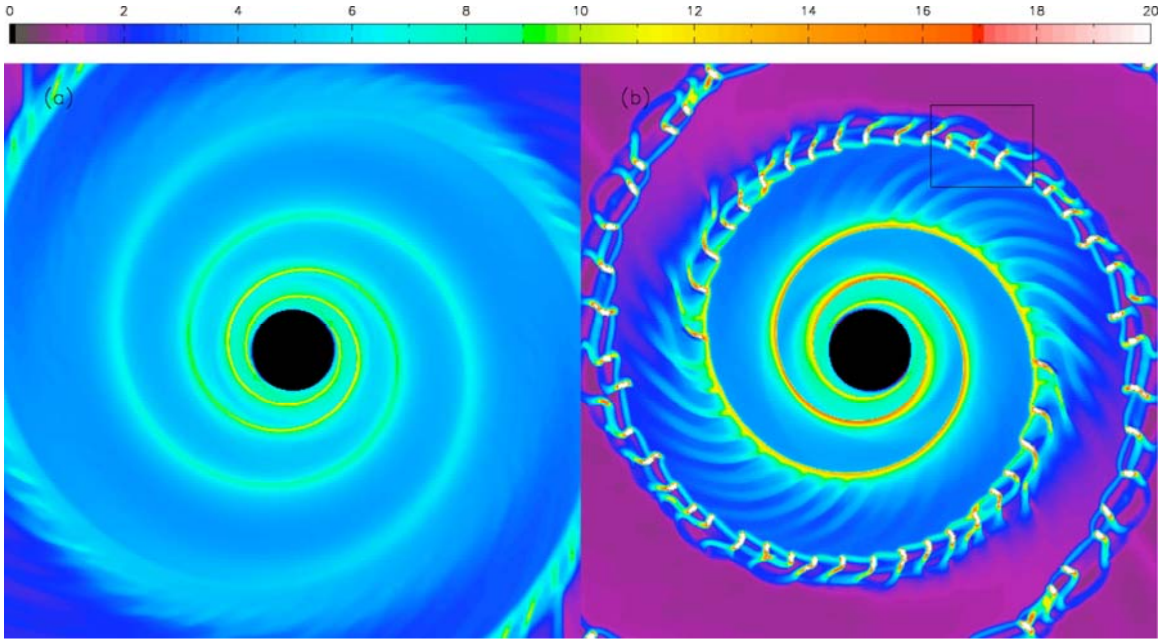
Frank H. Shu
University of California, San Diego

KITP Workshop
Santa Barbara,16 August 2007

Outline of Talk

- Massive star formation just a scaled-up version of low-mass star formation? Or something completely different, such as coagulation?
- Review of isolated low-mass star formation and why high-mass star-formation cannot be completely similar (mostly, higher $\dot{M}$).
  - Birthplace of OB stars in spiral galaxies & giant associations.
  - Solution for radiation-pressure problem.
  - Puzzle of Orion K-L region.

Spiral Substructure: Feathering & Ongoing Birth of New Stars



Include magnetic field and self-gravity of gas; turbulence treated as isothermal sound speed.

Local transient instability that gives rise to star-forming giant molecular clouds positioned at the head of “feathers”

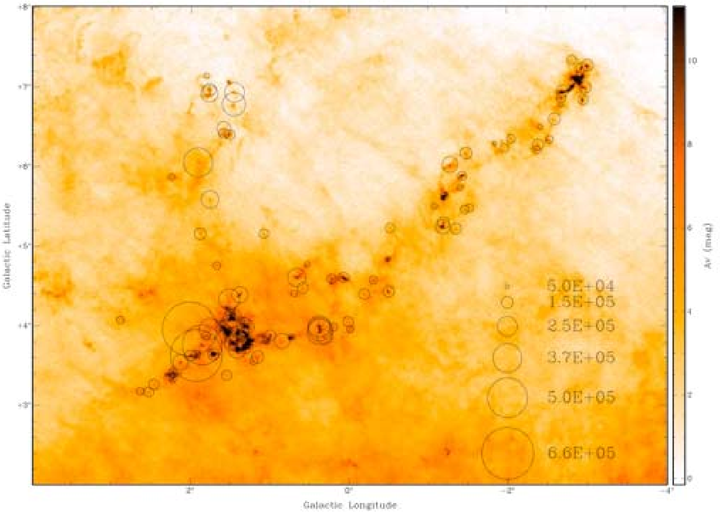
Shetty & Ostriker (2006)

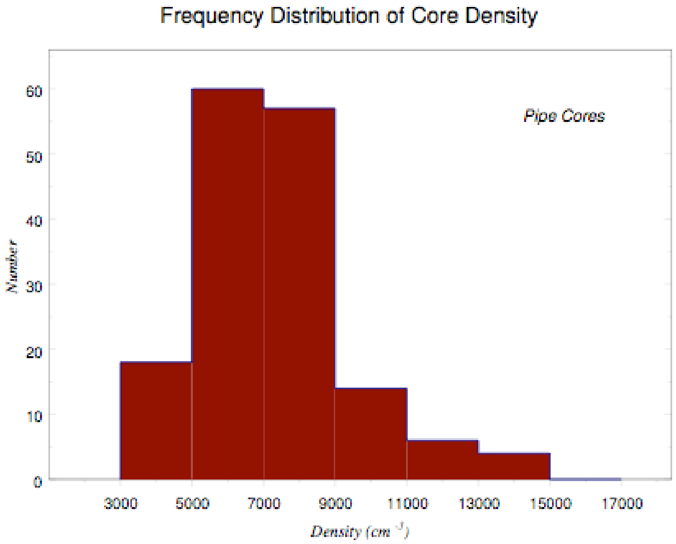
Relationship to K-S Law: Shu, Allen, Lizano, & Galli (2007)

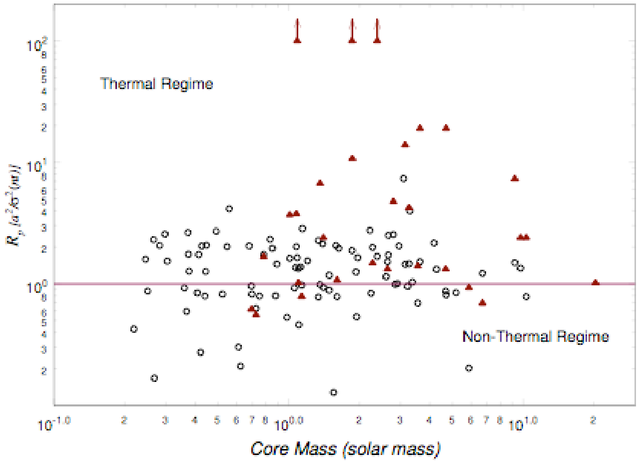
The Birth of Massive Stars

M42 (and M43) © Anglo-Australian Observatory Photo by David Malin

Pipe Nebula





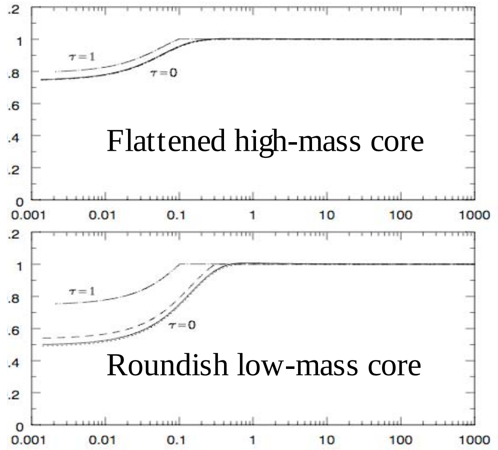


$\lambda^{-1} \equiv$

$B_z / 2\pi G^{1/2}\Sigma$

$\lambda^{-1} \equiv$

$B_z / 2\pi G^{1/2}\Sigma$

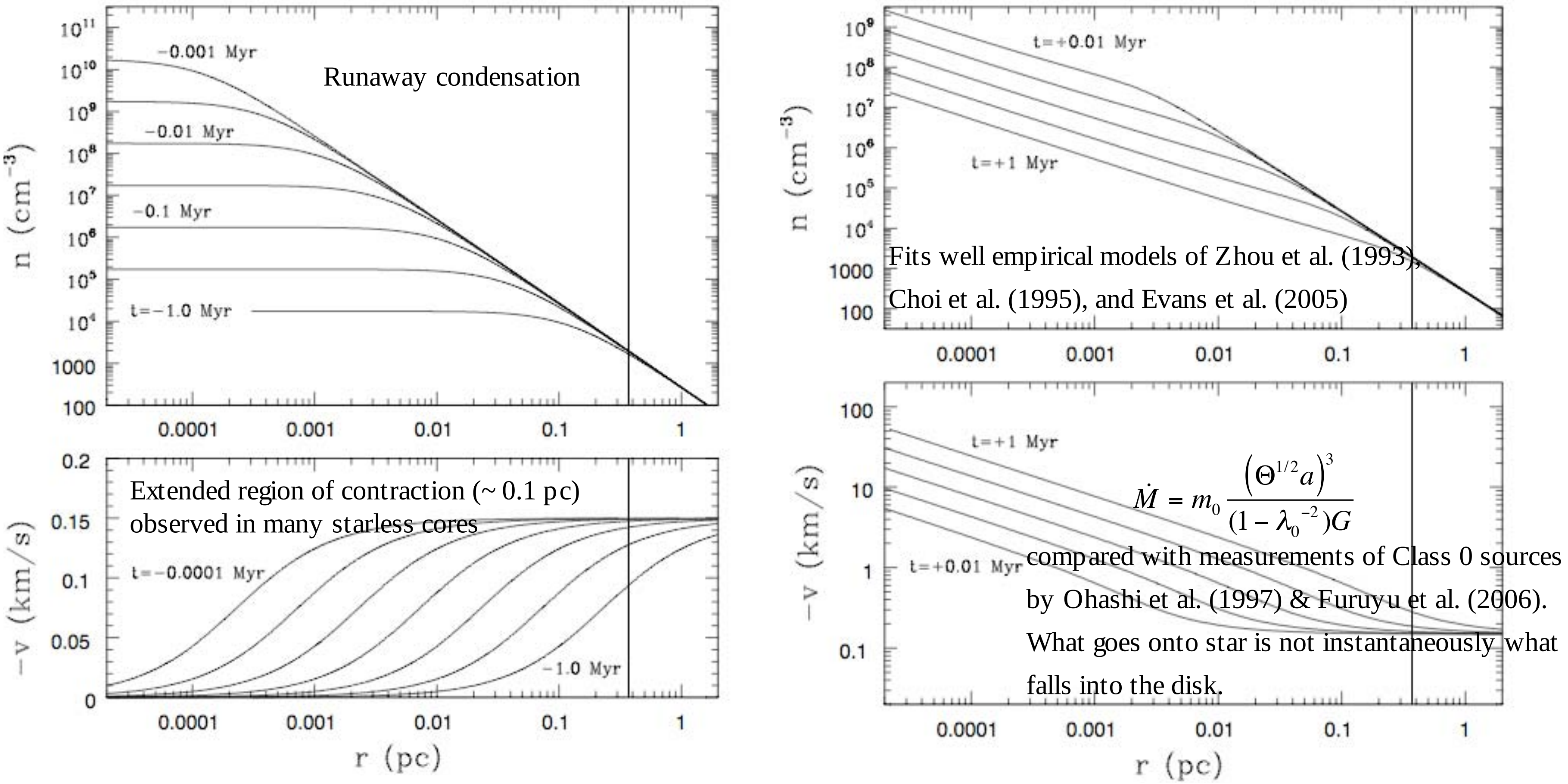


$$\lambda_0^{\,2}(\lambda_0 - 1) \approx 25\varepsilon$$

$$\text{where } \varepsilon \equiv \frac{\sqrt{8\pi G}}{\gamma \bar{C}}.$$

Lada, Muench, Rathborne, Alves, & Lombardi (2007); Adams & Shu (2007)

Evolution to Gravomagneto Catastrophe and Collapse



Runaway condensation

Extended region of contraction (~ 0.1 pc) observed in many starless cores

Fits well empirical models of Zhou et al. (1993), Choi et al. (1995), and Evans et al. (2005)

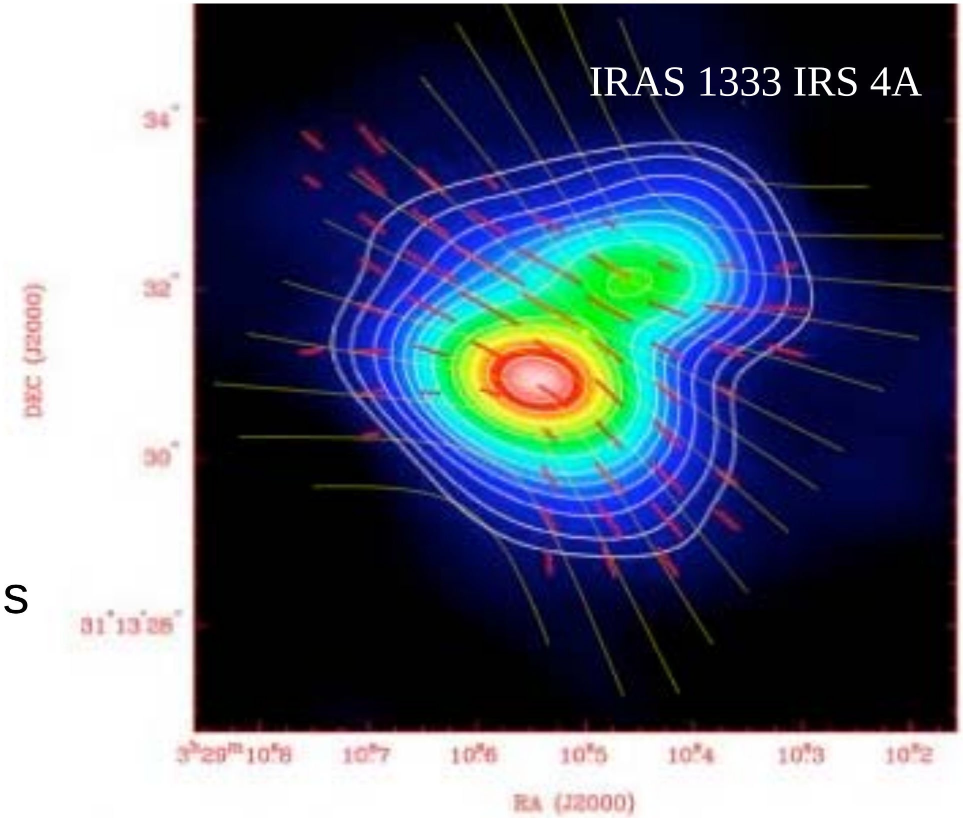
$$\dot{M} = m_0 \frac{\left(\Theta^{1/2} a\right)^3}{(1-\lambda_0^{-2})G}$$

compared with measurements of Class 0 sources by Ohashi et al. (1997) & Furuyu et al. (2006). What goes onto star is not instantaneously what falls into the disk.

Adams & Shu (2007); see also Shu (1977), Nakano (1979), Shu (1983), Lizano & Shu (1989), Basu & Mouschovias (1994) and Desch & Mouschovias (2001)

Rotating, Resistive Collapse Produces Magnetized Star + Disk

- Red dashed lines = measured directions of magnetic fields.
- White lines = best theoretical fit.
- Conclusion: magnetic fields brought into disks are about 1/2 as strong as if fields were frozen to the matter during the collapse.
- Fields are still strong enough to make disks magnetically “viscous” (MRI), leading to inward transport of mass and outward transport of angular momentum (sporadic?).



Girart et al. (2006); Gonzalez et al. (2007) Crutcher & Lai (2002): B dominates turb in W51, NGC2024, DR21OH (HMSF). See also Novak (2007) & Stone, Ostriker, & Gammie (1998) .

Complications of High-Mass SF

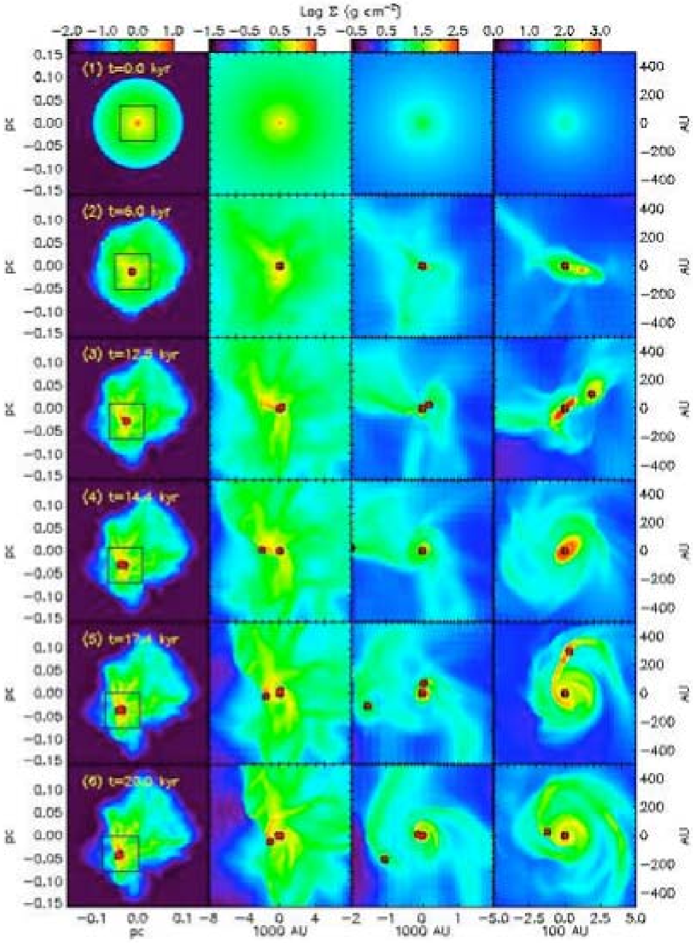
- Need large infall rate:

$$\dot{M} = m_0 \frac{\left(\Theta^{1/2} a\right)^3}{(1 - \lambda_0^{-2})G}$$

- More turbulence, larger isothermal sound speed, higher magnetization ($\lambda_0 \approx 1$)?
- Dust opacity κ makes

$$\frac{L_* / 4\pi c\kappa}{GM_*} > 1$$

when $M_* > 7\ M_\odot$.



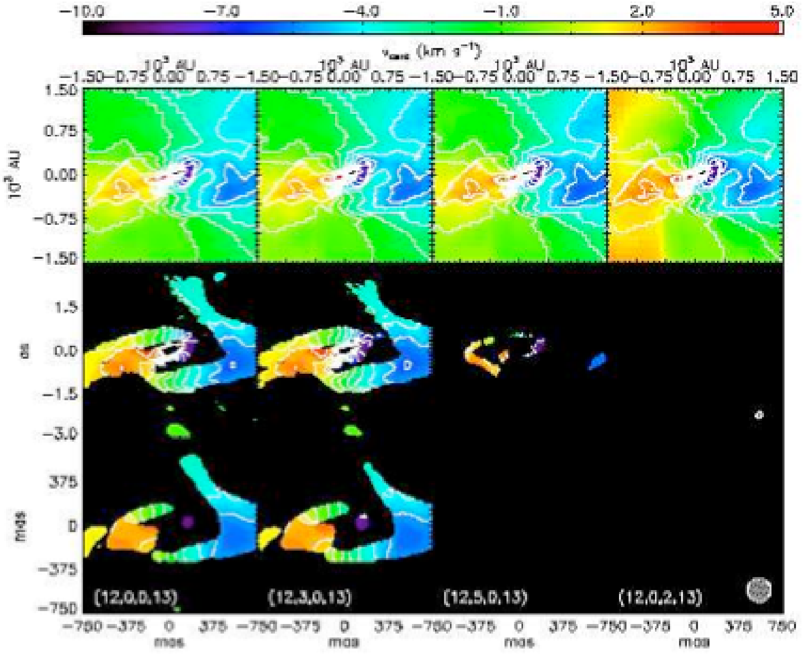
Krumholz, Klein, & McKee (2006) solution:

Matter goes in in one direction; radiation comes out in another.

See also Jijina & Adams (1996).

Challenge: Resolved Observations

- Regions of HMSF are generally far away, and they are crowded. Nevertheless, cloud cores in Rho Oph are internally quiet and do not move at highly supersonic speeds relative to one another (Andre et al. 2007).
- High-mass YSOs seem to (a) have collimated outflows, and (b) be surrounded by disks (e.g., Rodriguez, Zapata, & Ho 2007), just like low-mass

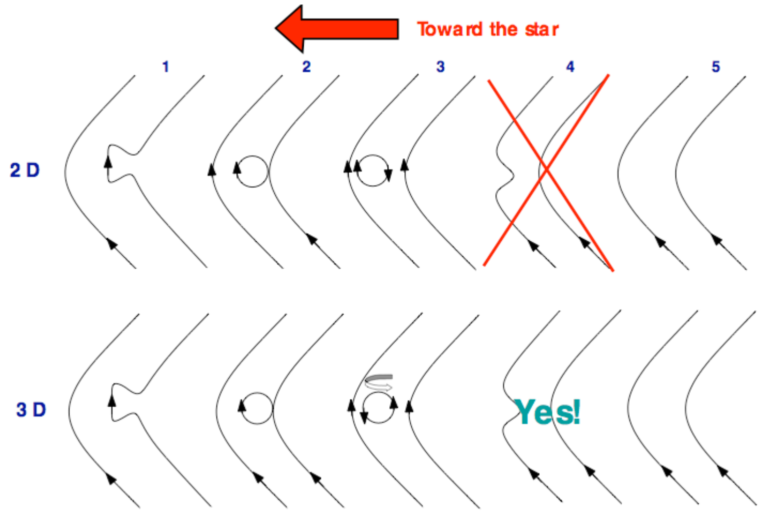


Krumholz, Klein, & McKee (2007)

Some coagulation of minor clumps (not stars!) if starting condition is highly turbulent.

MRI Turbulence in Magnetized Accretion Disks

All previous MRI simulations inapplicable to present problem which has a nonzero net magnetic flux. Reason why MRI simulations systematically give too small a viscosity compared to astrophysical systems (cf. **King, Livio, & Pringle 2007**).



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

- Turbulent viscosity:

$$\delta u \delta B_\varphi \sim \delta B_\varpi \varpi \frac{\partial \Omega}{\partial \varpi} \delta \varpi \text{ with } \delta u \sim \Omega \delta \varpi$$

$$\therefore\ \delta B_\varphi \sim \frac{\varpi}{\Omega} \frac{\partial \Omega}{\partial \varpi} \delta B_\varpi \text{ with } \delta B_\varpi \sim B_\varpi{}^+.$$

$$\text{Maxwell stress: } \frac{\delta B_\varpi \delta B_\varphi}{4\pi} \sim \frac{(B_\varpi{}^+)^2}{4\pi} \frac{\varpi}{\Omega} \frac{\partial \Omega}{\partial \varpi}.$$

$$\text{Cf. modeled viscous stress: } \rho \nu \varpi \frac{\partial \Omega}{\partial \varpi} \to \frac{\Sigma}{2z_0} \nu \varpi \frac{\partial \Omega}{\partial \varpi}.$$

$$\therefore\ \text{identify } \nu = F \frac{(B_\varpi{}^+)^2 z_0}{2\pi \Sigma \Omega} \text{ where } F \text{ is "form factor."}$$

$$\text{In steady state, } B_\varpi{}^+ = I_\ell B_z \Rightarrow \boxed{\nu = D \frac{B_z{}^2 z_0}{2\pi \Sigma \Omega}}$$

$$\text{where } D = I_\ell{}^2 F \text{ is an order unity parameter.}$$

Shakura-Sunyaev viscosity with magnetic pressure replacing gas pressure.

- Turbulent resistivity:

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

in quasi-steady state.

Four Astronomical Models

- Steady-state solution:

$$\Omega = f\left(\frac{GM_*}{\varpi^3}\right)^{1/2},$$

$$B_z = \left(\frac{2f}{3DA}\right)^{1/2}\left(\frac{GM_*\dot{M}_*^2}{\varpi^3}\right)^{1/4},$$

$$\Sigma = \frac{f}{1-f^2}\left(\frac{I_\ell}{3\pi DA}\right)\frac{\dot{M}_*}{(GM_*\varpi)^{1/2}}.$$

- Models:

$$A(\varpi) = 0.1(\varpi / 100\ \mathrm{AU})^{1/4}$$

$$M_D(R_\Phi) = \dot{M}_* t_{\mathrm{age}} \quad \text{where}$$

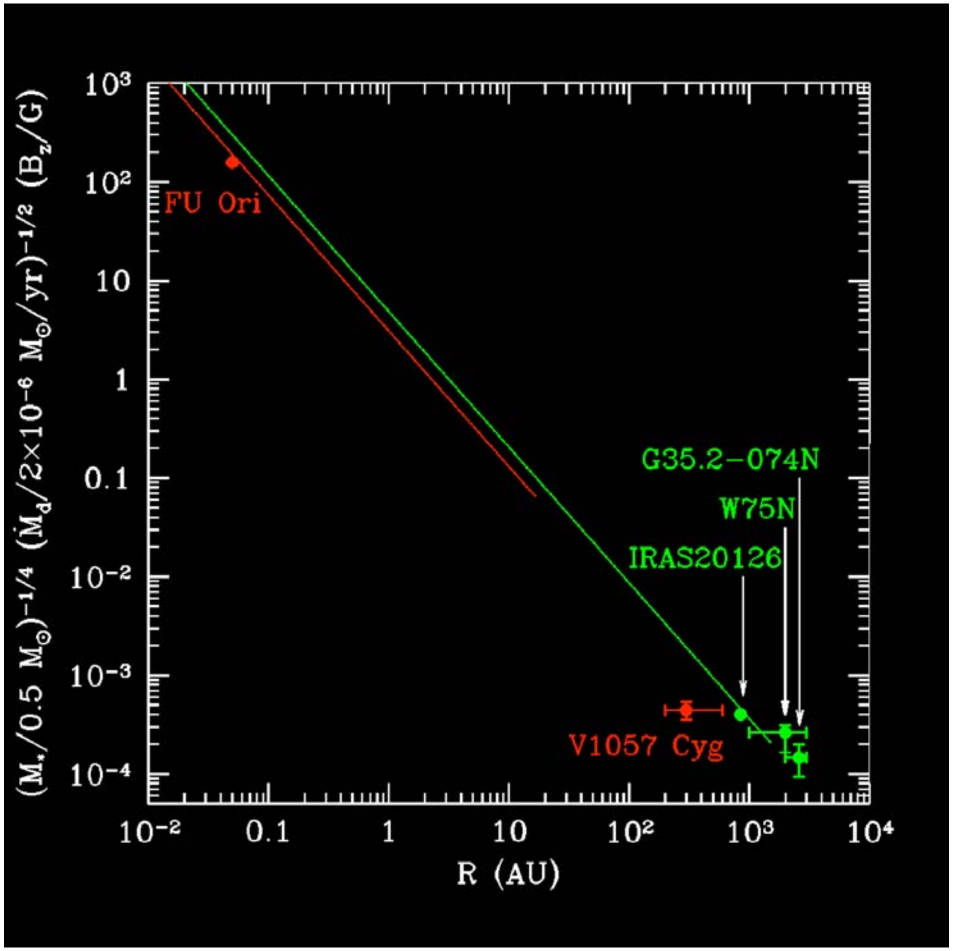
$$\int_0^{R_\Phi} B_z 2\pi\varpi d\varpi = 2\pi G^{1/2} M_* / \lambda_0 .$$

$\lambda_0 = 4$

Object	T Tau	LMP	FU Ori	HMP
$M_* / M_\odot$	0.5	0.5	0.5	25
$\dot{M}_*$ ($M_\odot$/yr)	$1\text{x}10^{-8}$	$2\text{x}10^{-6}$	$2\text{x}10^{-4}$	$1\text{x}10^{-4}$
t_{age}/yr	$3\text{x}10^{6}$	$1\text{x}10^{5}$	100	$1\text{x}10^{5}$
D	$10^{-2.5}$	1	1	1
$M_D / M_\odot$	0.03	0.20	0.02	10
f	0.658	0.957	0.386	0.957
R_Φ/AU	298	318	16.5	1,520
J_D ($M_\odot$ AU km/s)	5.12	51.4 binary?	0.473	39,700 binary?

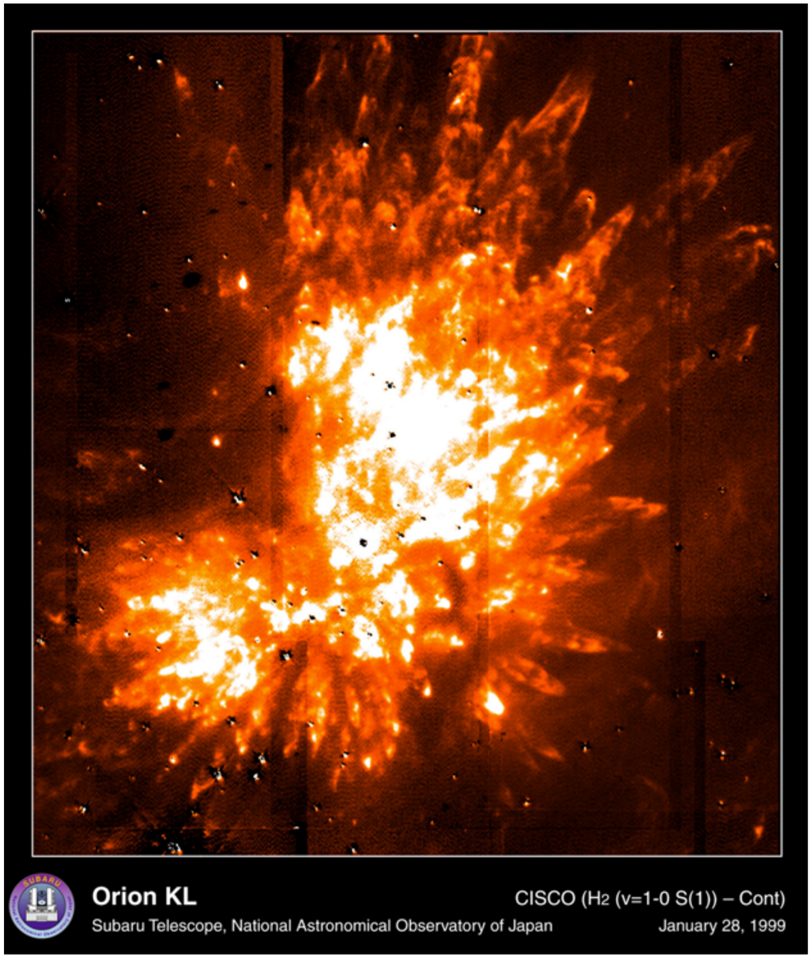
Magnetic Field Measurements in YSO Disks Compared to Theoretical Expectations

- In vast observational desert between 0.05 AU and 300 AU, there is only the meteoritical measurement of ~1 G at 3 AU in chondrules (see Levy & Sonnett 1978, Cisowski & Hood 1991). Is this measurement applicable?
- Observers have a lot of work to do in the ALMA era!



What’s Going on in Orion K-L Region?

- Mysterious explosion? Energy of explosion from merging protostars and tangled magnetic fields (Bally 2007)?
- Except for this mystery, no evidence (a) that HMSF is vastly different from LMSF, nor (b) that turbulence dominates over the roles of magnetic fields and self-gravitation in molecular cloud-core and star formation.



Orion KL

CISCO (H_2 (v=1-0 S(1)) – Cont)

Subaru Telescope, National Astronomical Observatory of Japan

January 28, 1999