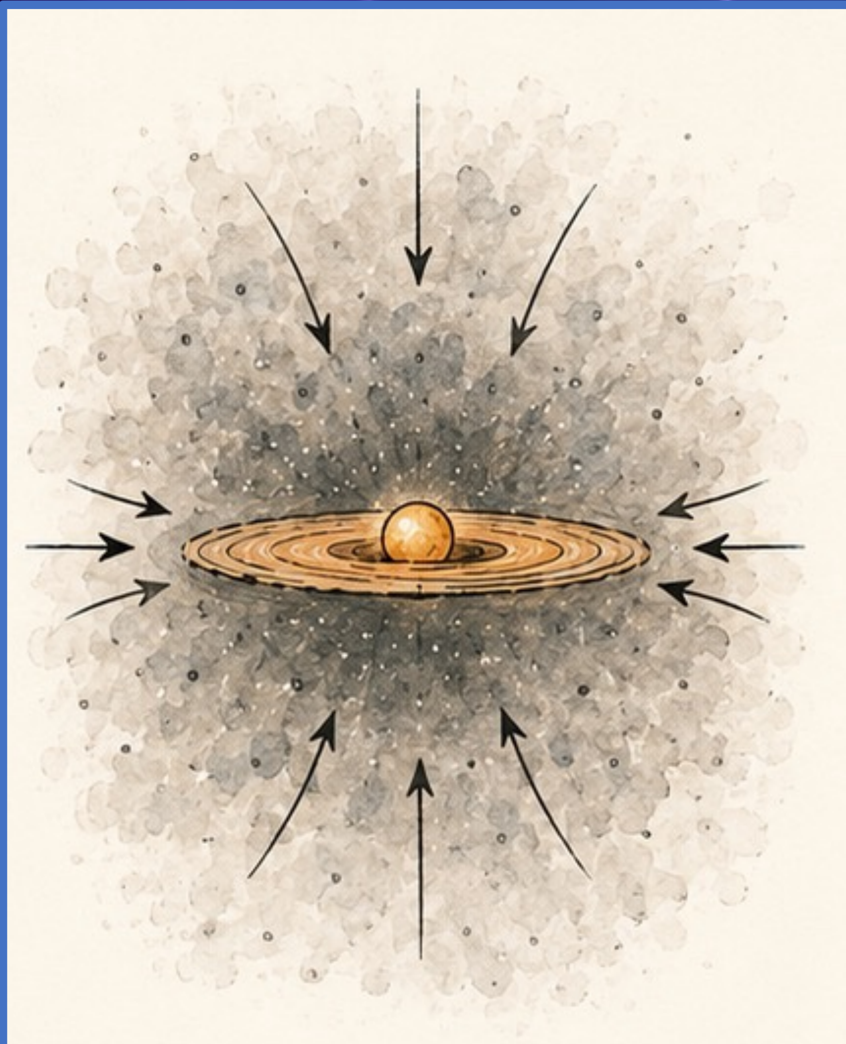
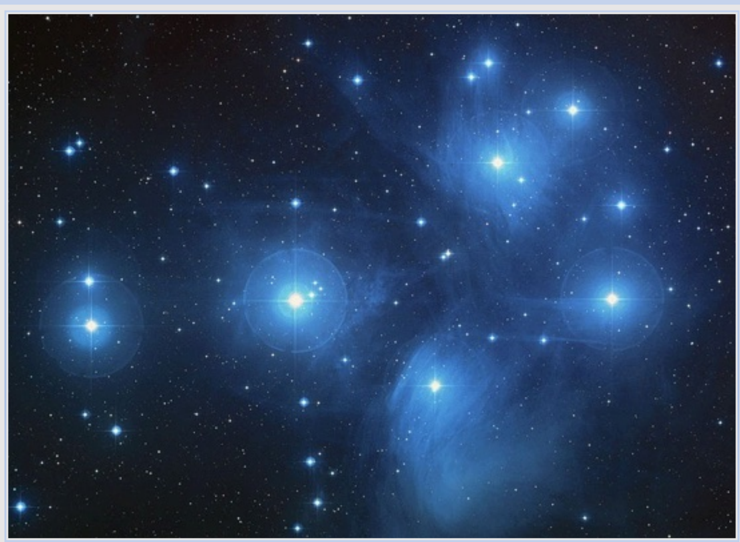


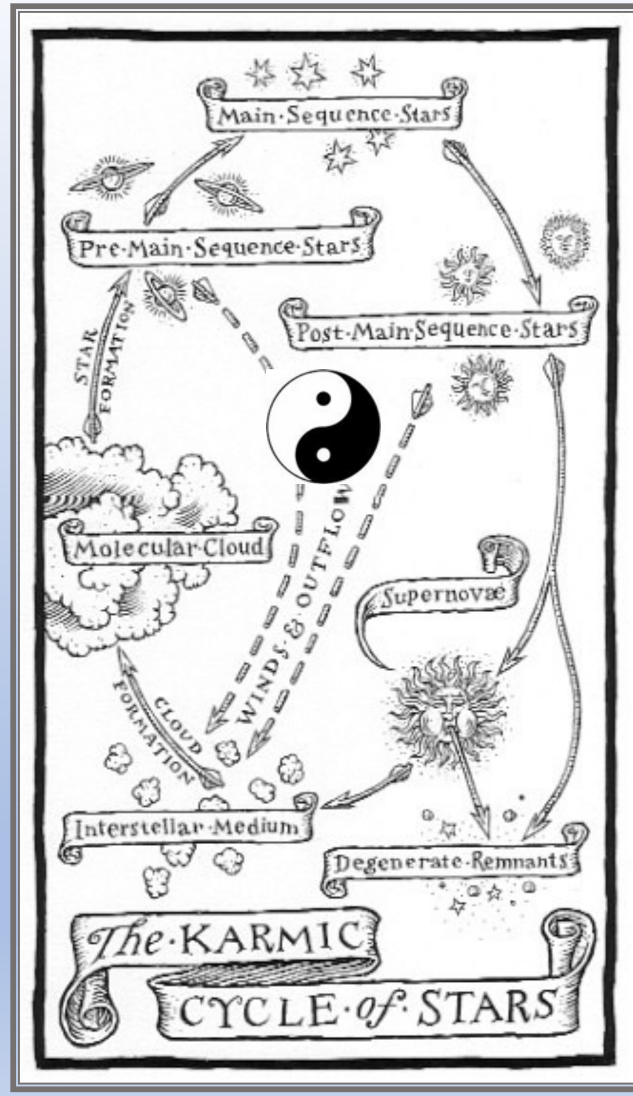
ASIAA Summer Program 2026

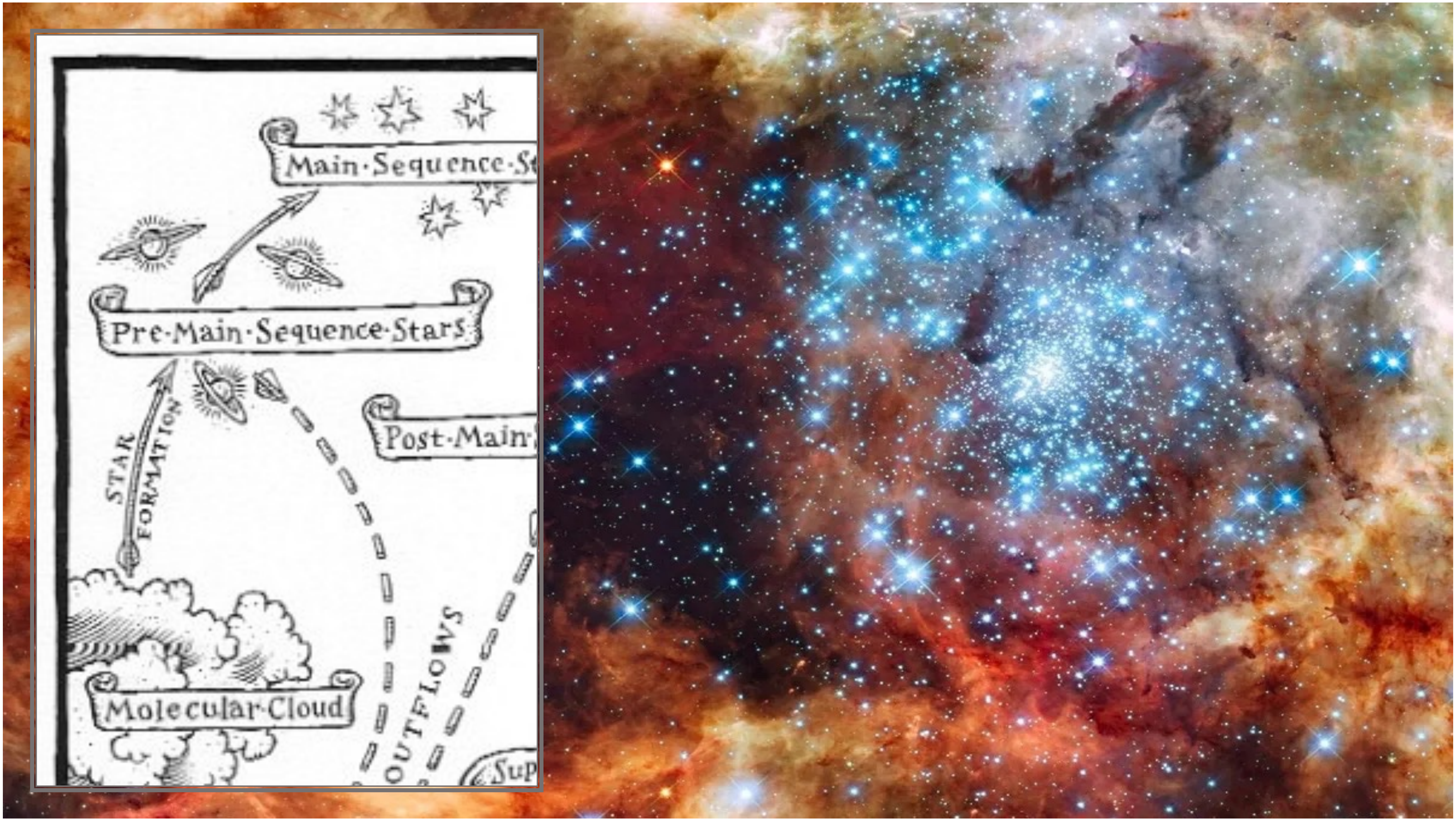
Lecture One: Star Formation

Fred C Adams
University of Michigan

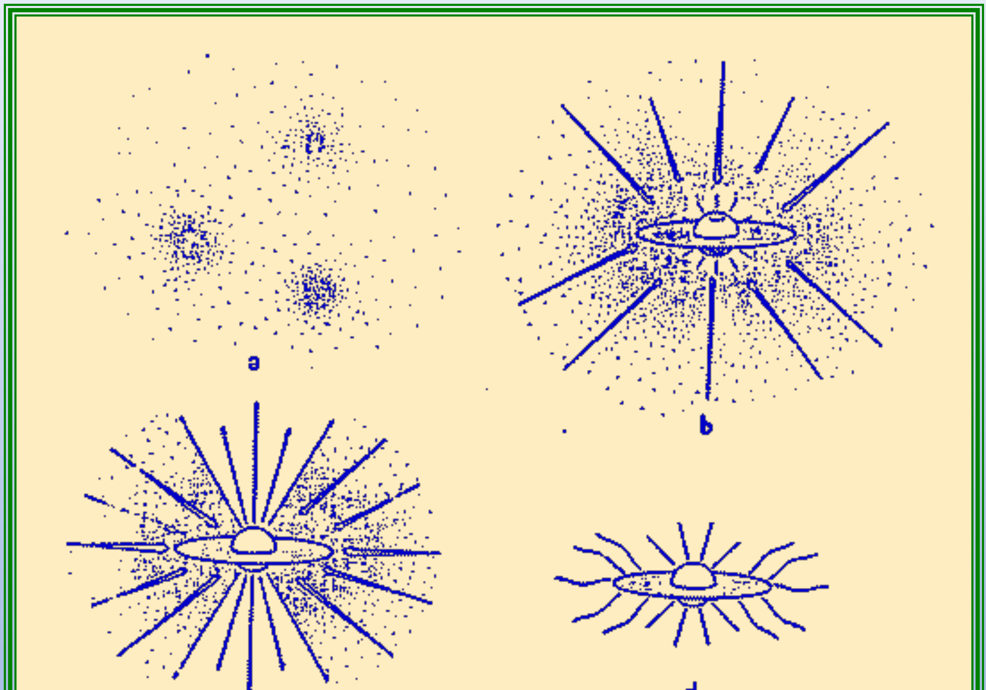
Star Formation is a vitally important physical process in the grand scheme of Galactic Ecology, which represents an overarching cycle of Birth and Death



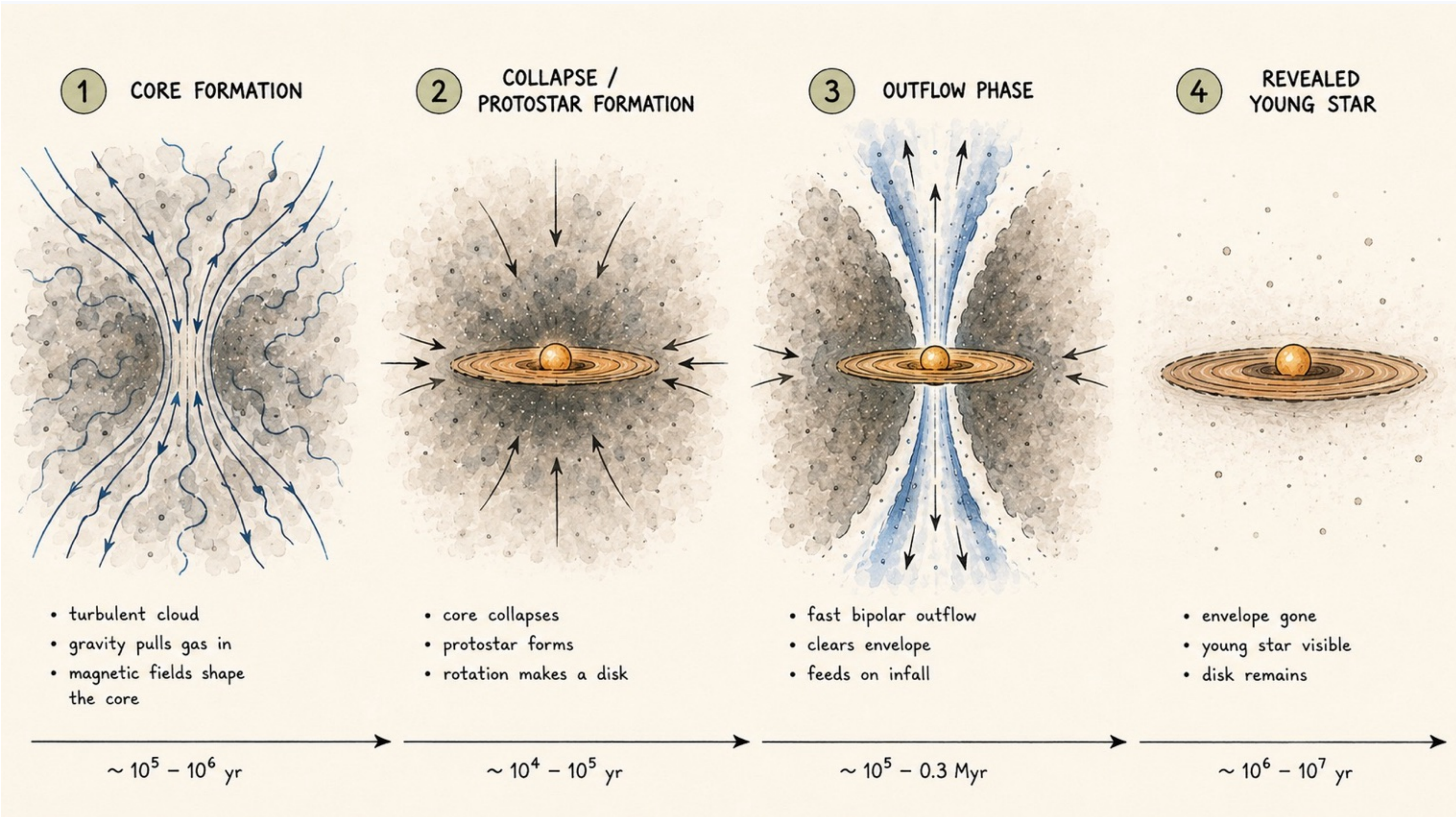



Main·Sequence·S
Pre·Main·Sequence·Stars
Post·Main·
STAR FORMATION
OUTFLOWS
Molecular·Cloud
Sup

The 4 Stages of Star Formation



(Shu, Adams, Lizano 1987)


1 CORE FORMATION
2 COLLAPSE / PROTOSTAR FORMATION
3 OUTFLOW PHASE
4 REVEALED YOUNG STAR
• turbulent cloud
• gravity pulls gas in
• magnetic fields shape the core
• core collapses
• protostar forms
• rotation makes a disk
• fast bipolar outflow
• clears envelope
• feeds on infall
• envelope gone
• young star visible
• disk remains
~ $10^5 - 10^6$ yr
~ $10^4 - 10^5$ yr
~ 10^5 – 0.3 Myr
~ $10^6 - 10^7$ yr

CLASSIC PROBLEM I: Angular Momentum Problem

$$\mathit{specific\ angular\ momentum} = j = \langle v\ r \rangle = \langle \Omega\ r^2 \rangle$$

Molecular cloud: $J = 10^{24}$ cm^2/s
Mol. Cloud core: $J = 10^{21}$ cm^2/s
Star at breakup: $J = 10^{18}$ cm^2/s

Angular Momentum must be lost/transferred

CLASSIC PROBLEM II: Magnetic Flux Problem

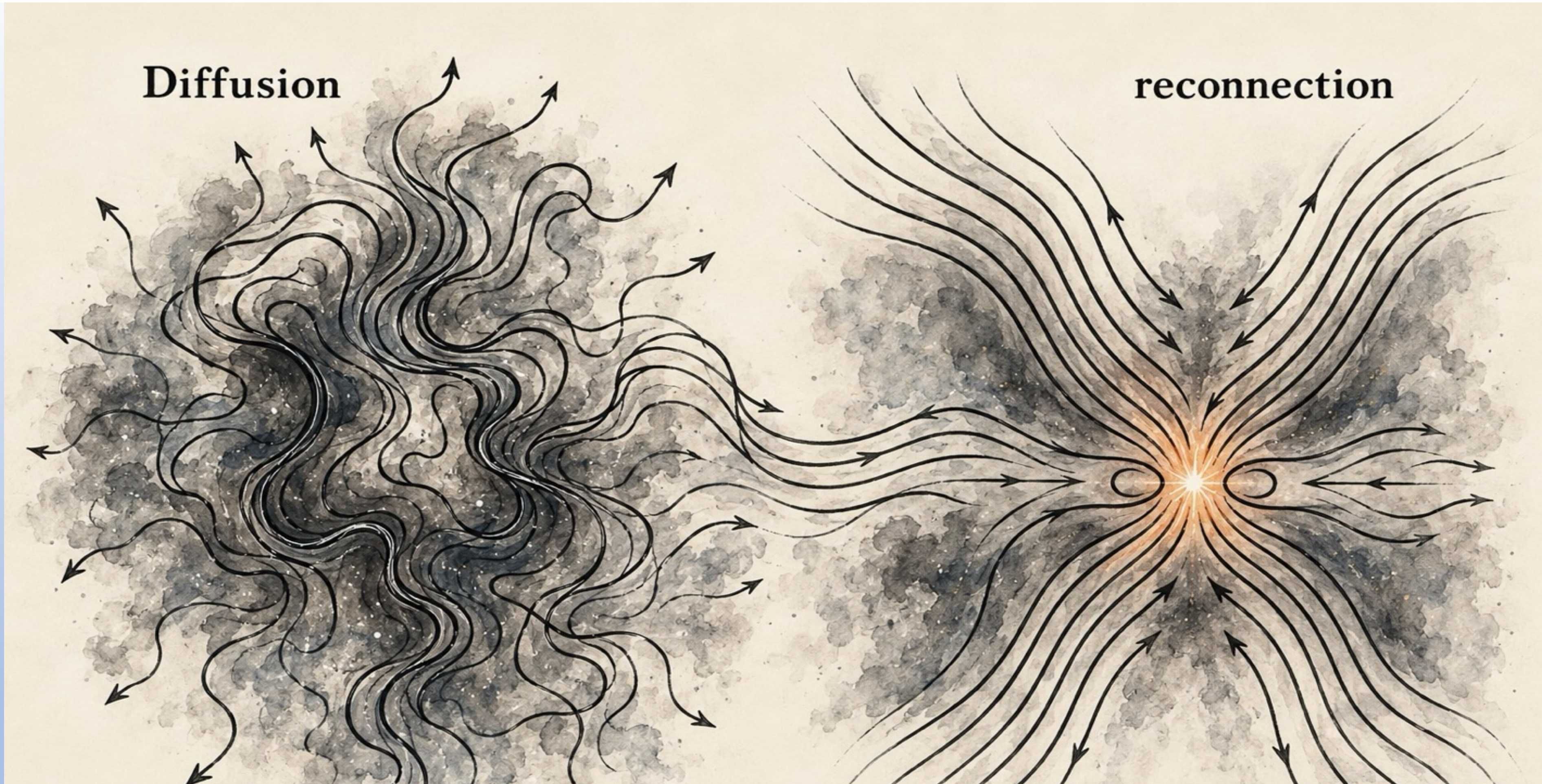
$$M_{CR} \approx 0.13 \frac{\Phi}{G} \approx 1000\, M_{sun} \left(\frac{B}{30 \mu G} \right) \left(\frac{R}{2\, pc} \right)^2$$

Magnetic flux can support a cloud as long as its mass does not exceed the critical value given above. For typical magnetic field strengths, this mass scale is much larger than the typical stellar mass.

Magnetic flux must be `lost' for stars to form

CLASSIC ISSUE:

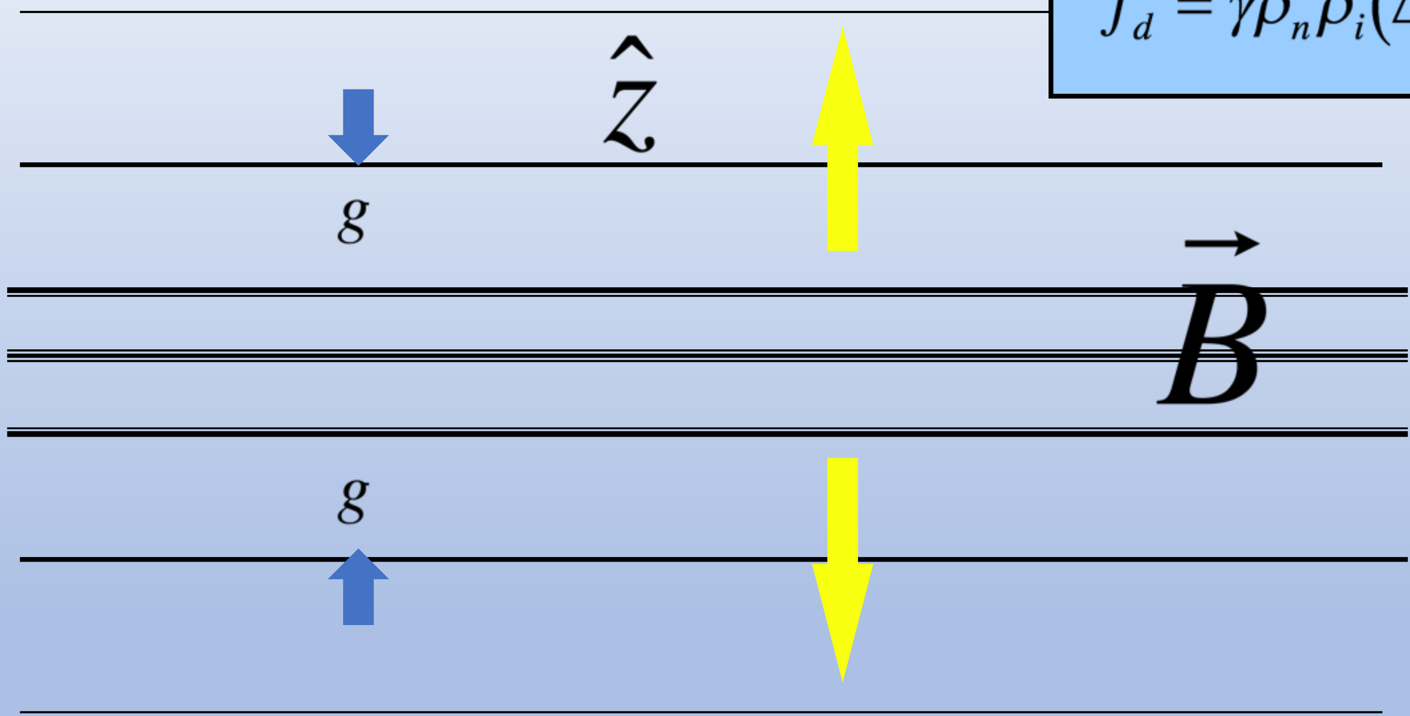
Star formation is a highly inefficient process. During the collapse time of a molecular cloud, only a few percent of the cloud mass is converted into stars.



Two Ways to get rid of Magnetic Fields

AMBIPOLAR DIFFUSION in GAS SLAB

$$\vec{f}_d = \gamma \rho_n \rho_i (\Delta \vec{v})$$



(Shu 1983, 1992)

DIFFUSION CONSTANT

$$\varepsilon \equiv \frac{\sqrt{8\pi G}}{\gamma C} \approx 0.18 << 1$$

A small (<1) dimensionless quantity: Can solve force and continuity equations separately for a given flux-to-mass ratio, and then solve diffusion equation to determine time evolution of flux ratio.

Ambipolar Diffusion Process leads to Nonlinear Diffusion Equation

$$\frac{\partial}{\partial t}\left[\frac{B}{\rho}\right] = \frac{\partial}{\partial \sigma}\left\{D\frac{\partial B}{\partial \sigma}\right\}$$

with diffusion constant $D = \frac{B^2}{4\pi\gamma C\rho^{1/2}}$

$$\frac{\partial z}{\partial \sigma} = \frac{1}{\rho}$$

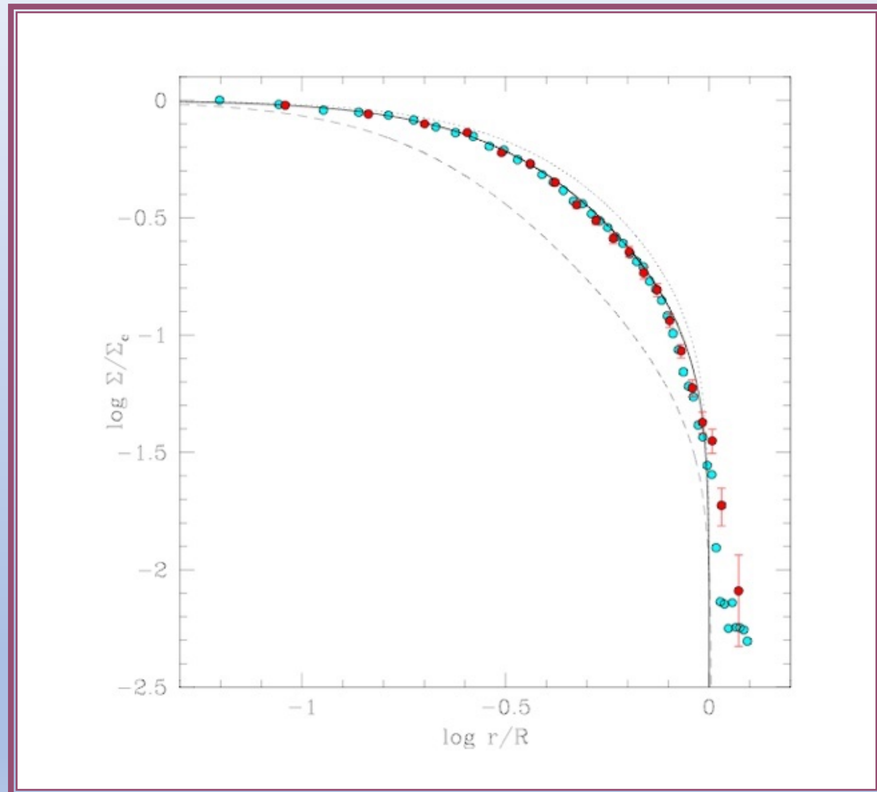
Lagrangian spatial variable

ISSUES IN CORE FORMATION:

- Observations (ratio of starless cores) indicate that core formation takes place more rapidly than simplest AD theory
- Nonzero inflow velocities are observed in starless cores (e.g., Lee et al. 2001)
- Observed cores resemble BE spheres w. constant density center (e.g., Lada)
- Cores move through cloud - SUBVIRIAL

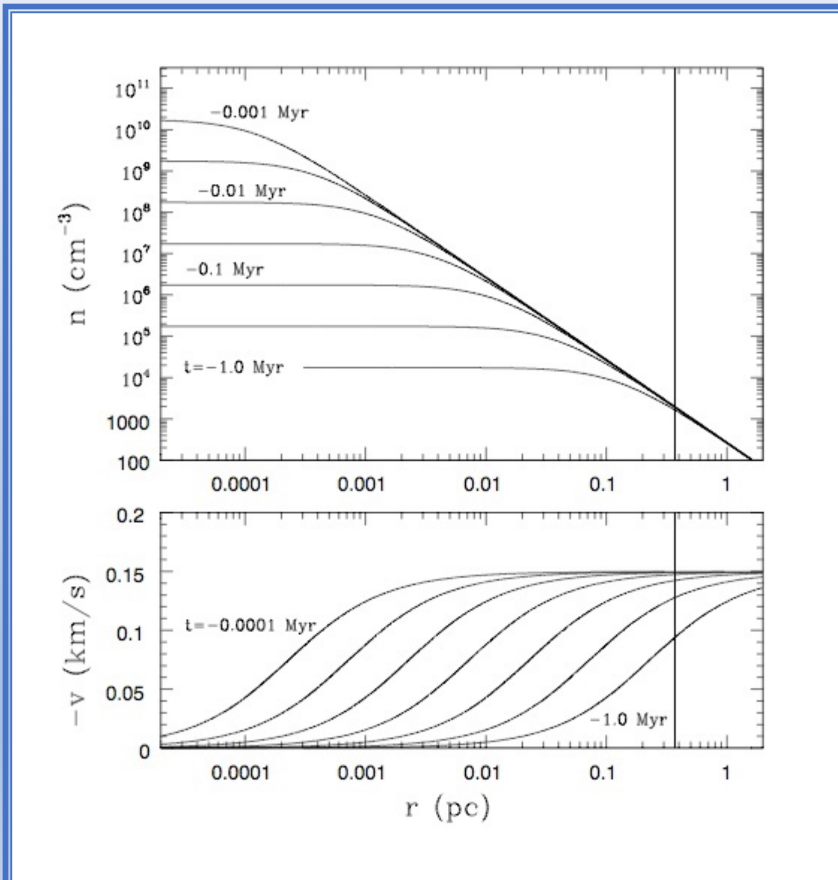
Star formation more ``dynamic” than original 4 stages paradigm….

Bonnor Ebert Sphere: Barnard 68

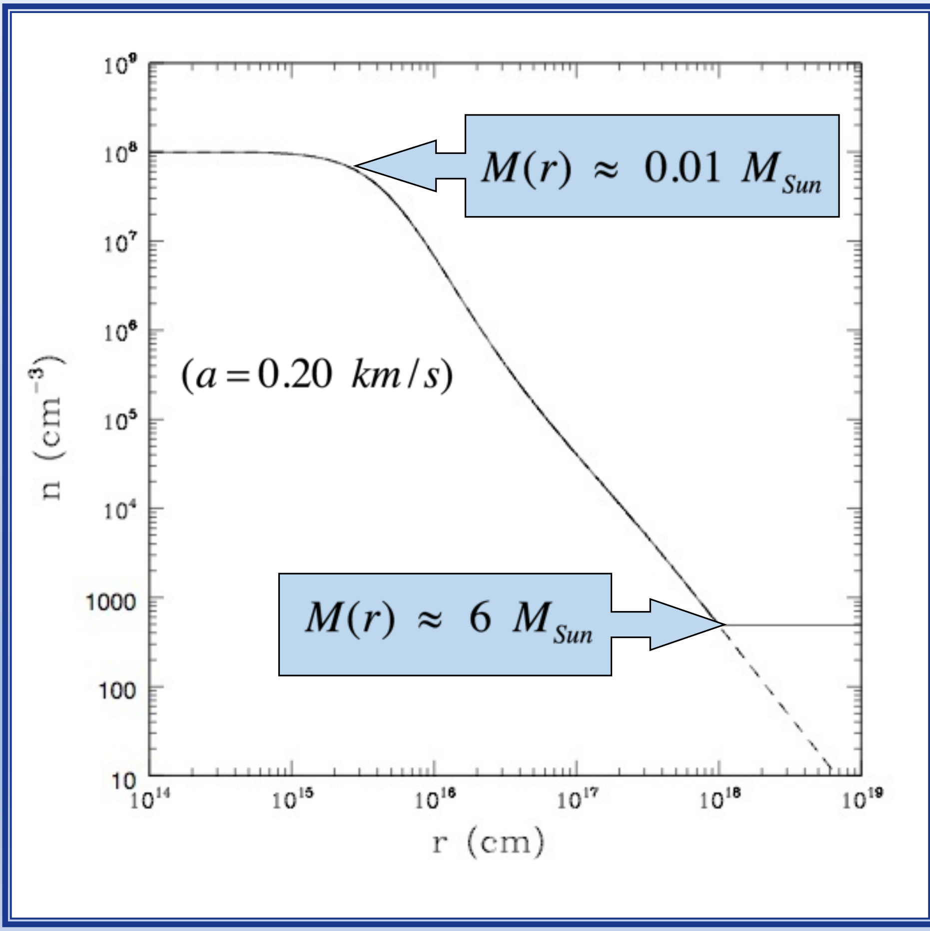


(from Burkert & Alves)

Physical Diffusion Solutions



Mass Scales Defined by Core



NOTE: The collapse of a uniform density gaseous sphere leads to the formation of a transient `first core', which is not the same. The uniform density central region can arise from three different reasons:

[1] Transient first core from collapse of uniform density sphere

[2] Hydrostatic equilibrium with finite central density

[3] Shrinking central region as magnetic fields diffuse outward

SELF-SIMILAR COLLAPSE MODEL

$$\rho = \frac{a^2}{2\pi G r^2} \qquad M(r) = \frac{2a^2 r}{G} \qquad u = 0$$

Initial state

$$\frac{dM}{dt} = m_0 a^3 / G$$

$$\rho \to C\ r^{-3/2}$$

$$u \to -\sqrt{GM/r}$$

Inner collapse solution

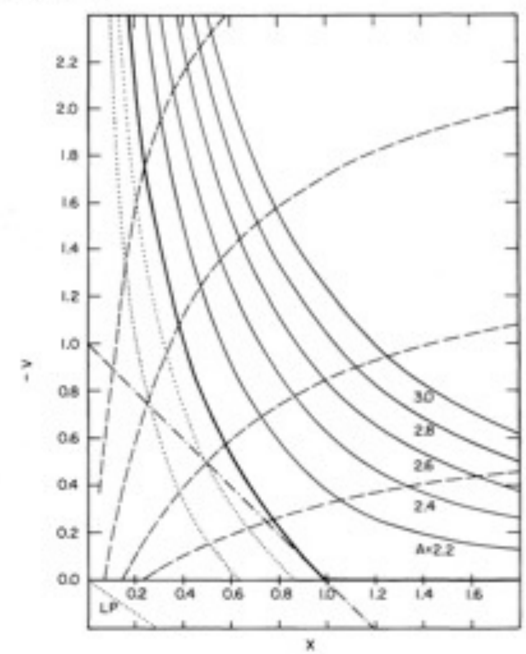


FIG. 2.—Similarity solutions for the reduced velocity in isothermal flow. The line inclined at $-45°$ with respect to the x-axis gives the locus of the critical points: $-v = 1 - x$. Only the solid curves give acceptable solutions for the collapse problem; in particular, the heavy solid curve gives the collapse solution for a singular sphere which is initially hydrostatic ("expansion-wave collapse solution").

(Shu 1977, ApJ, 214, 488)

Some Key Issues

- The collapse process leads to a well-defined mass infall <u>rate</u>, but not a well-defined mass <u>scale</u>
- Star formation is an inefficient process → the total amount of mass available is always much larger than the amount of mass that ends up in stars
- Something must stop the final process (some combination of angular momentum requirements and outflows from the stars)

AMIPOLAR DIFFUSION in the presence of Turbulent Fluctuations

Nonlinear Diffusion Equation

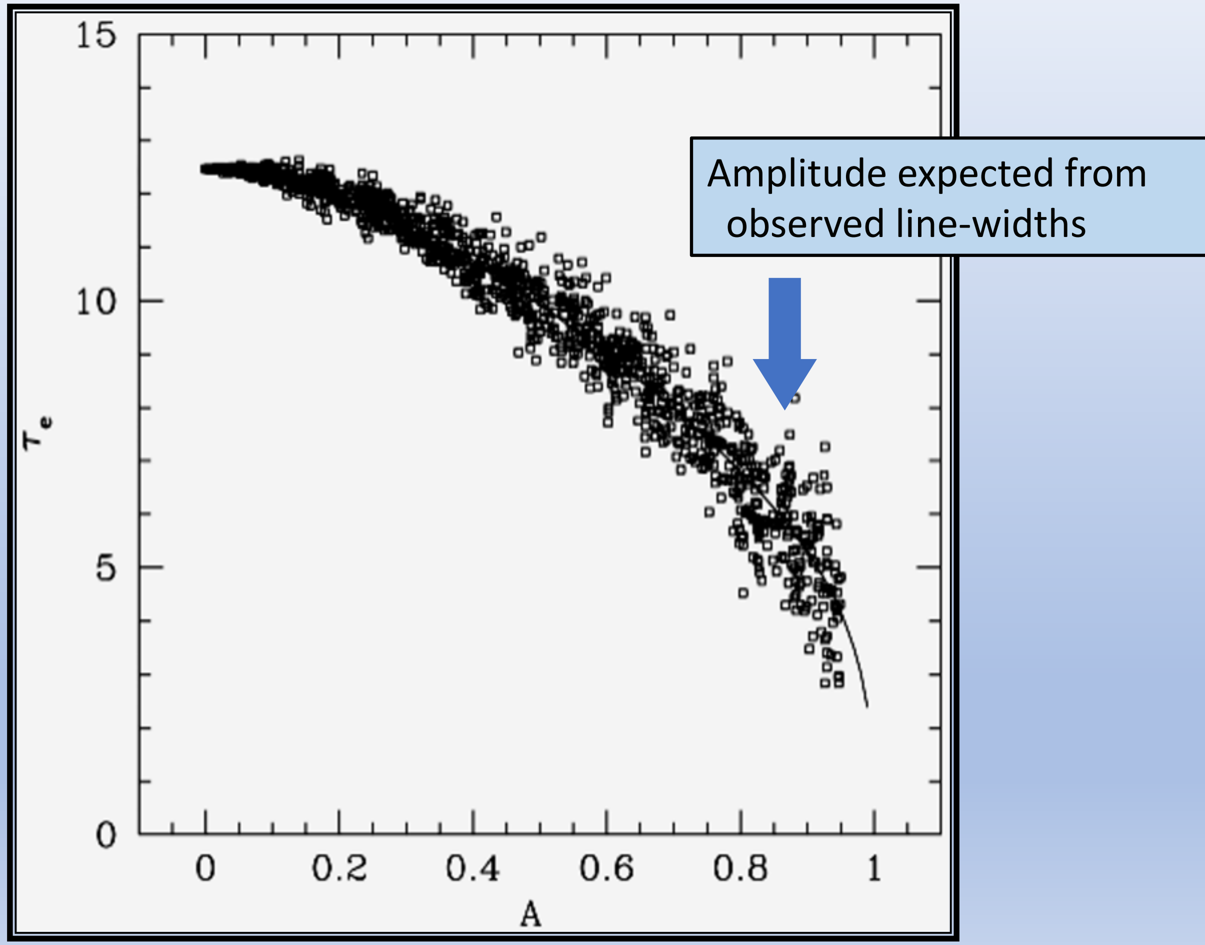
let $B \rightarrow B(1+\xi),\ \rho \rightarrow \rho(1+\eta)$

$$\frac{\partial}{\partial t}\left[\frac{B(1+\xi)}{\rho(1+\eta)}\right] = \frac{1}{1+\eta}\frac{\partial}{\partial \sigma}\left\{D\frac{\partial}{\partial \sigma}[B(1+\xi)]\right\}$$

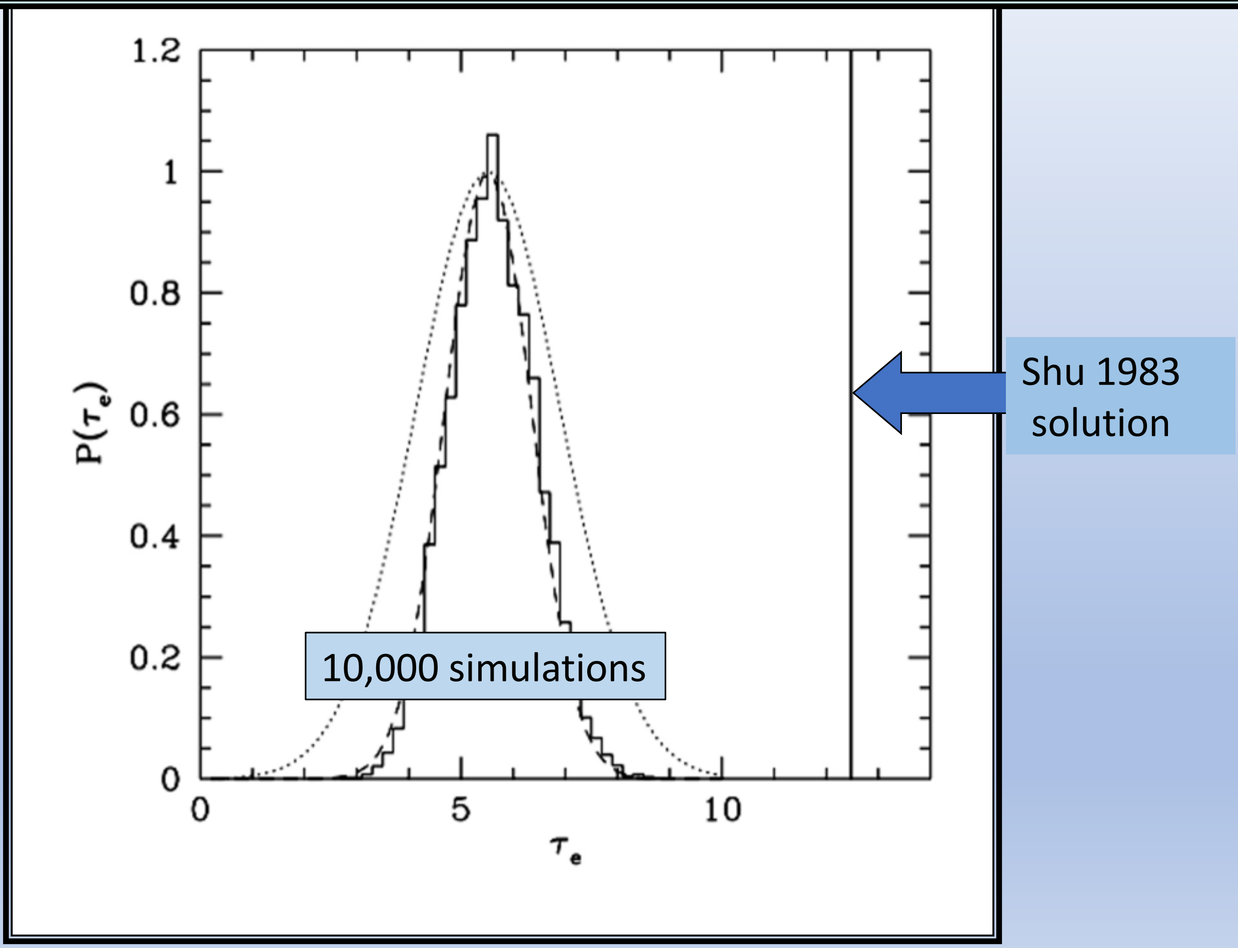
where $$D = \frac{B^2(1+\xi)^2}{4\pi\gamma C\rho^{1/2}(1+\eta)^{3/2}}$$

Fatuzzo & Adams, 2002, ApJ, 570, 210

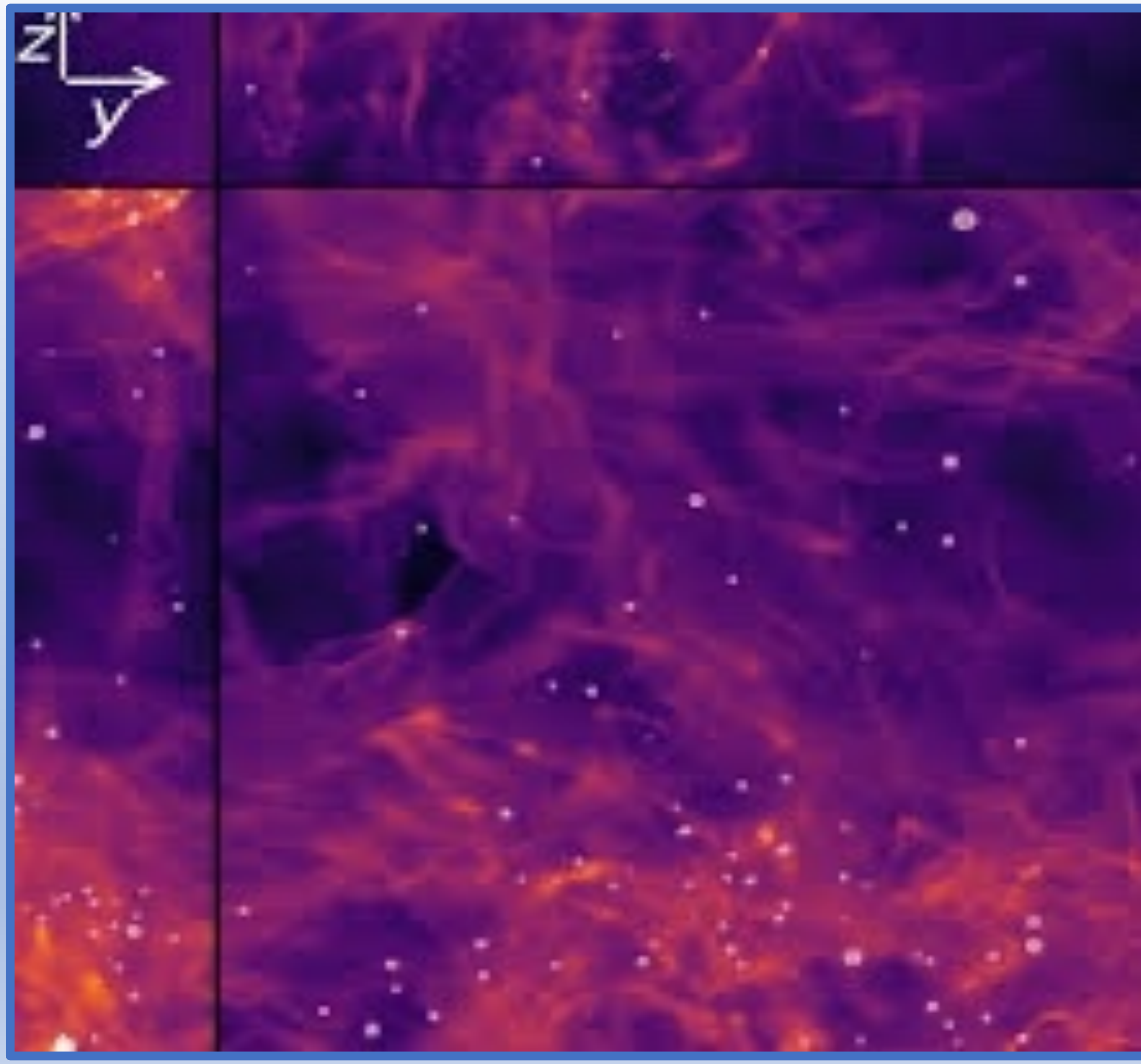
Diffusion Time vs Fluctuation Amplitude



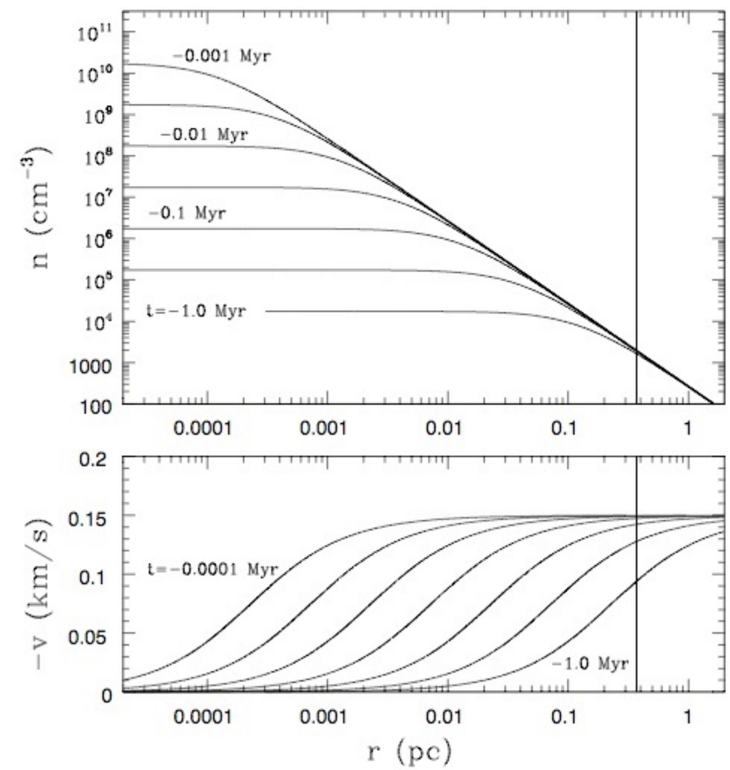
Distribution of Ambipolar Diffusion Times



Put it all together: Start with star formation region. Turbulence leads to formation of overdense regions



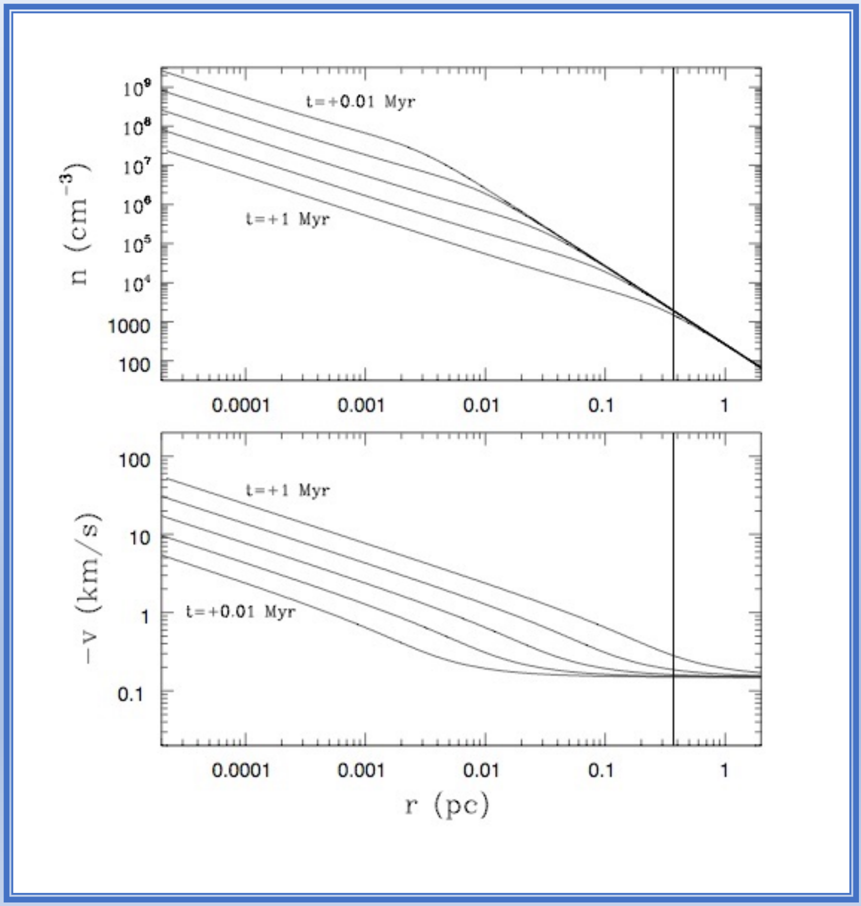
Physical Diffusion Solutions



GRAVOMAGNETO CATASTROPHE!

@t=0

Physical Collapse Solutions



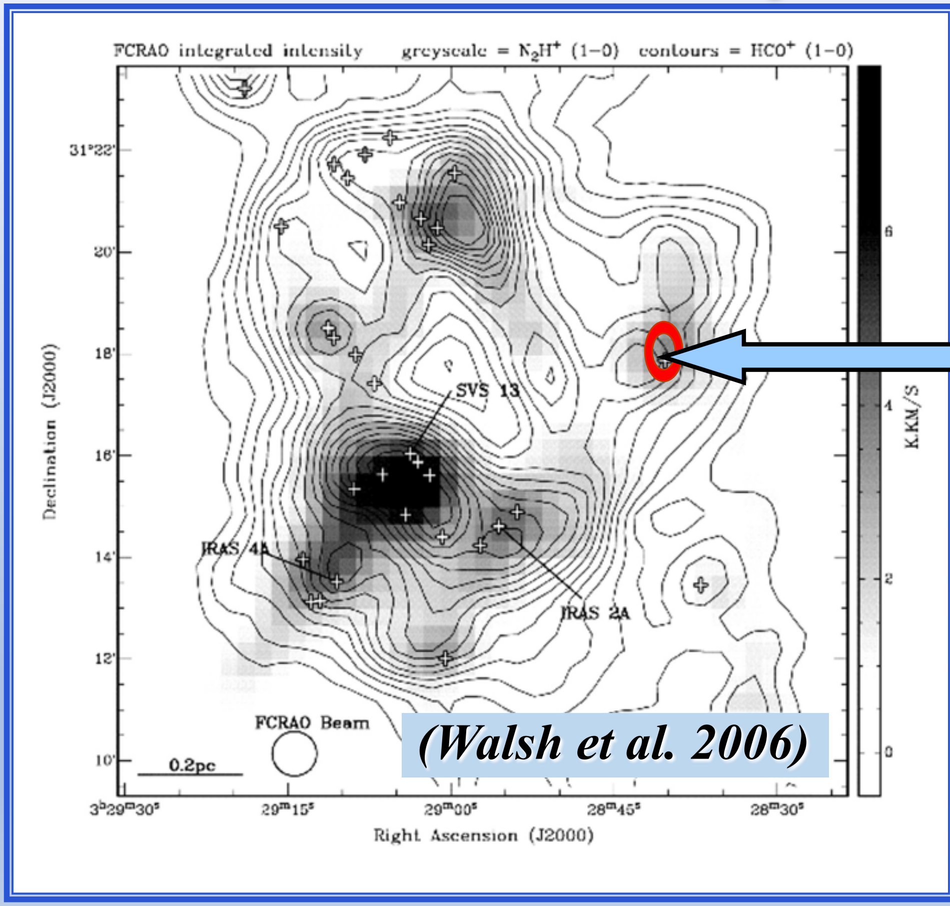
Transition from
t < 0 phase to
t > 0 phase
will occur in a
transient epoch
not described
by solution…

Magnetic Flux Problem: Partial Solution

Magnetic flux is lost in stages: Cloud cores have lower magnetic flux ratios than molecular clouds, much flux is lost as cores condense through the process of ambipolar diffusion, some flux is dragged into the forming star and plays a role in formation of winds, jets, and outflows (Reipurth, Shang, Tafalla). Some magnetic flux is lost via reconnection.

$$M_{CR} \approx 0.13 \frac{\Phi}{G} \approx 1000 M_{sun} \left(\frac{B}{30 \mu G} \right) \left(\frac{R}{2 pc} \right)^2$$

Observed Core Speed in Cluster



$(\Delta v)_Z \approx 0.1\ km/s$

$(\Delta v)_T(\Delta t)_{SF} \approx 0.02\,pc$

NGC 1333
(cold start)

Core Speed in Cluster: Theory

$$\vec{F}_f = \gamma \rho_n \rho_i (\Delta \vec{v})(Vol) \quad (from \quad friction)$$

$$\vec{F}_C = \frac{2\pi G \rho_0 r_0}{(1+\xi)^2} M_{core} \qquad \rho_C = \frac{\rho_0}{\xi(1+\xi)^3}, \quad \xi = \frac{r}{r_o}$$

$$core \quad reaches \quad equilibrium \quad speed:$$

$$(\Delta v) = \frac{2\pi G \rho_0 r_0}{\gamma C \rho_n^{1/2} (1+\xi)^2} \approx \varepsilon \frac{r_0}{t_{ff}} \left(\frac{\rho_0}{\rho_n} \right)^{1/2} \approx 0.1 \ km/s$$

Balance of Frictional Drag Force on core with the Gravitational Force of background cluster results in terminal speed close to that observed.

Angular Momentum Problem: Partial Solution

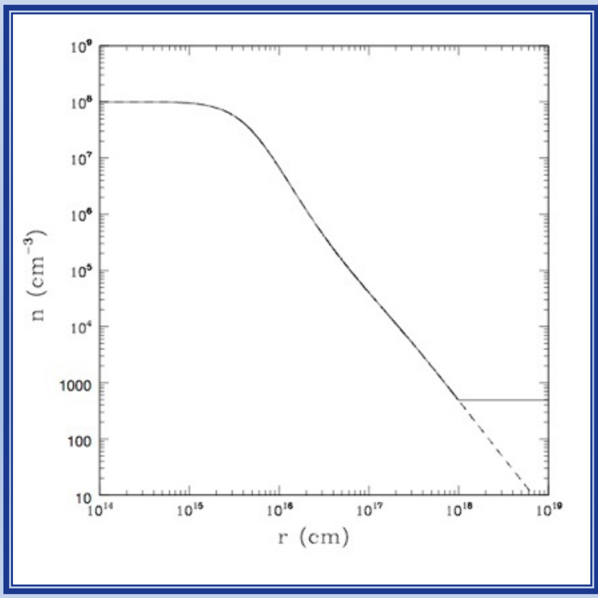
$$j = \langle v \; r \rangle = \langle \Omega \; r^2 \rangle$$

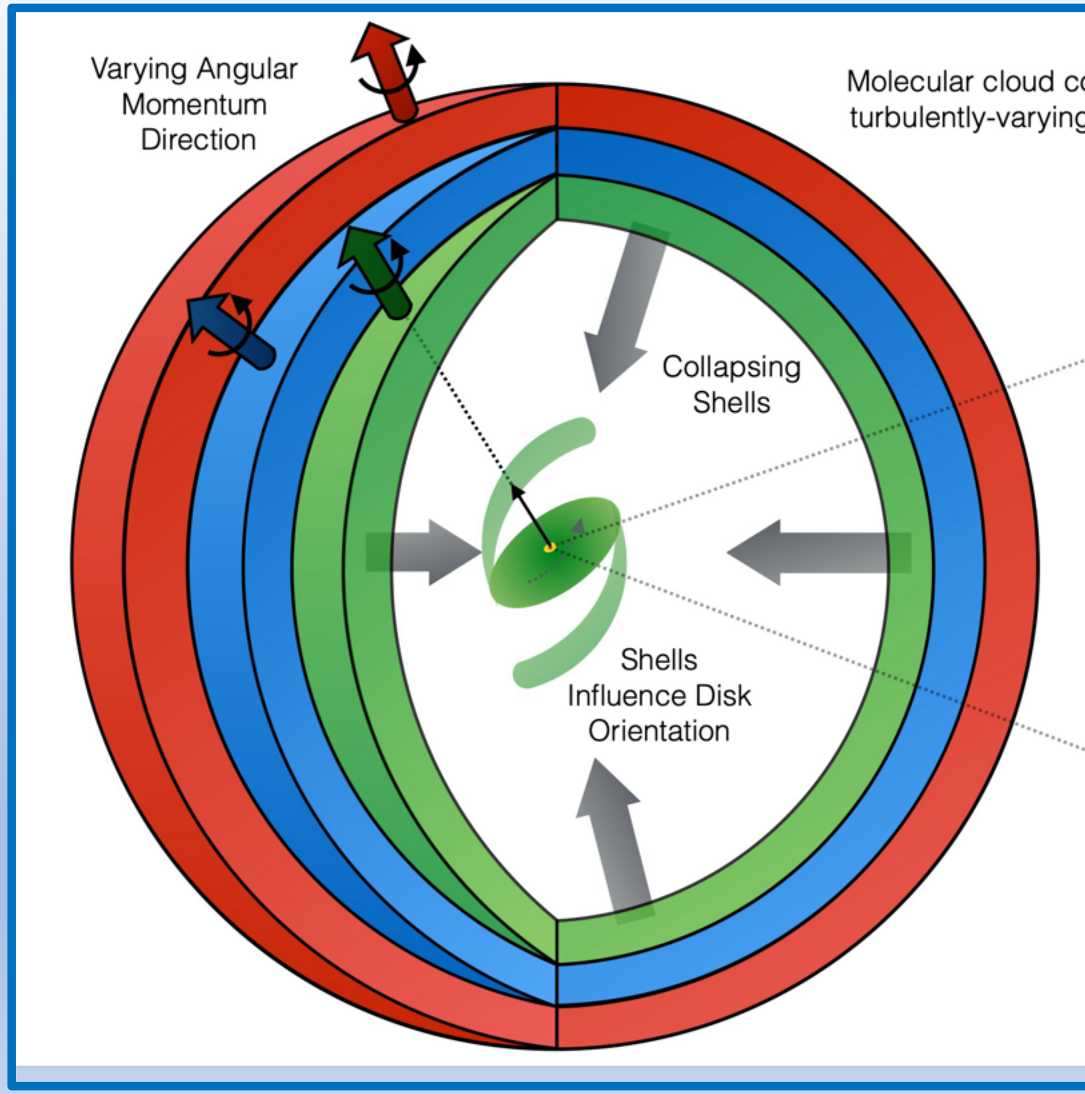
Angular momentum is lost in stages:
Cores have much lower `J' than clouds.
Observed core angular momentum allows collapse to Solar System size scales.
Disk accretion must transfer angular momentum to allow actual star to form.

Angular Momentum Profile: Initial State

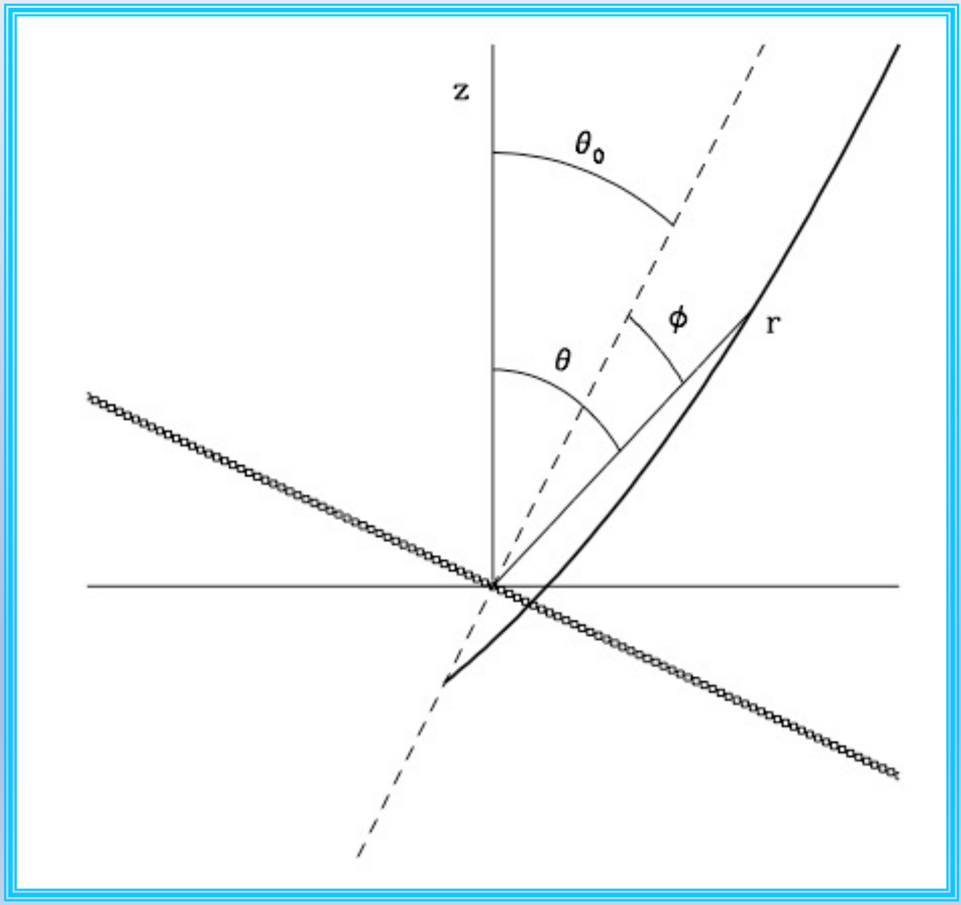
$$j = \langle v \ r \rangle = \langle \Omega \ r^2 \rangle$$

$$\Omega \sim 1 \ km/s/pc$$





GEOMETRY OF ROTATING INFALL



Rotating Infall Solutions

$$\text{Zero Energy Orbits:} \qquad E = \frac{1}{2}v_r^2 + \frac{1}{2}\frac{j^2}{r^2} - \frac{GM}{r} = 0$$

$$1 - \frac{\mu}{\mu_0} = (1-\mu_0^2)\,\frac{R_C}{r} \equiv \zeta(1-\mu_0^2) \qquad \text{where} \qquad R_C \equiv \frac{j_\infty^2}{GM} = \frac{\Omega^2 G^3 M^3}{16a^8}$$

$$v_r = -\left(\frac{GM}{r}\right)^{1/2}\left\{2 - \zeta(1-\mu_0^2)\right\}^{1/2}, \qquad v_\theta = \left(\frac{GM}{r}\right)^{1/2}\left\{\frac{1-\mu_0^2}{1-\mu^2}\,(\mu_0^2-\mu^2)\,\zeta\right\}^{1/2},$$

$$\text{and} \qquad v_\varphi = \left(\frac{GM}{r}\right)^{1/2}(1-\mu_0^2)\,(1-\mu^2)^{-1/2}\,\zeta^{1/2}$$

$$\rho(r,\theta)\,v_r\,r^2\sin\theta\,d\theta\,d\varphi = -\frac{\dot{M}}{4\pi}\sin\theta_0\,d\theta_0\,d\varphi_0 \qquad \Rightarrow \qquad \rho(r,\theta) = \frac{\dot{M}}{4\pi|v_r|r^2}\frac{d\mu_0}{d\mu}$$

$$R_C \sim \frac{\Omega^2 M^3}{a^8}$$

$$\Omega \approx 1\ km\ s^{-1}pc^{-1} \approx 3\times10^{-14}\,rad/s \quad \Rightarrow \quad R_C = 10 - 100AU$$

Rotational Mass Scale for Core

- Set rotational speed = virial speed to define an outer core boundary
- Mass contained with this boundary represents a rotational mass scale
- Mass scale is Upper Limit to star mass

$$M_{rot} = \frac{2\sqrt{2}\ a_S^3}{G\ \Omega} \approx 5.7\, M_{sun} \left(\frac{a_S}{0.2 km/s} \right)^3 \left(\frac{\Omega}{1 km/s/pc} \right)^{-1}$$

Most of the mass falls onto the disk instead of the star:

$$M_* \rightarrow 1.293[16 a_S^8 R_* / G^3 \Omega^2]^{1/3}$$

In the absence of disk accretion, only a few percent of the total mass falls directly onto the stellar surface.
Disk accretion is necessary to provide stellar mass and protostellar luminosity.

Equivalent Spherical Envelope

- Rotation (angular momentum) results in mass NOT falling as far inward
- This effect can be illustrated by taking spherical average of non-spherical infall
- Provides correct optical depth for protostars

$$\langle \rho \rangle = \int \rho(r,\theta) \sin\theta d\theta = C r^{-3/2} A(u)$$

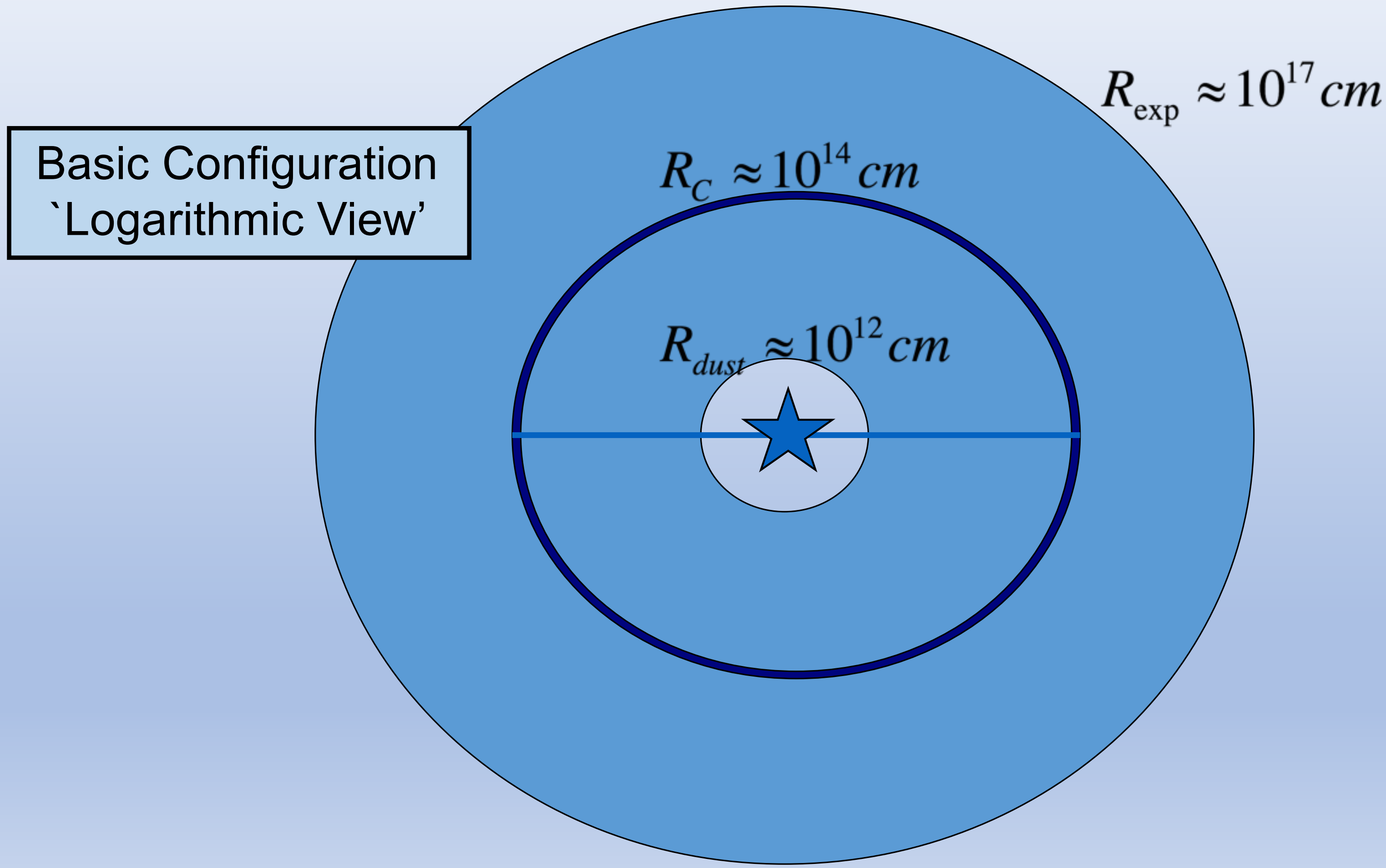
$$A(u) = (2u)^{1/2} \log\left[\frac{1 + (2u)^{1/2}}{(1-u)^{1/2} + u^{1/2}}\right] \quad for\ u \leq 1$$

$$A(u) = (2u)^{1/2} \log\left[\frac{1 + (2u)^{1/2}}{(2u-1)^{1/2}}\right] \quad for\ u \geq 1$$

These rotating collapse solutions do not include the magnetic field

If magnetized inside-out collapse is too
highly non-axi-symmetric, rapid magnetic flux
loss can lead to instability and fragmentation
(e.g., see Galli, Li, etc for further detail).
For highly rotating magnetic collapse without
Ambipolar Diffusion, and ideal MHD, can get
strong magnetic braking, fragments, etc.
(e.g., see numerical simulations for further detail).

Schematic of Protostellar Structure

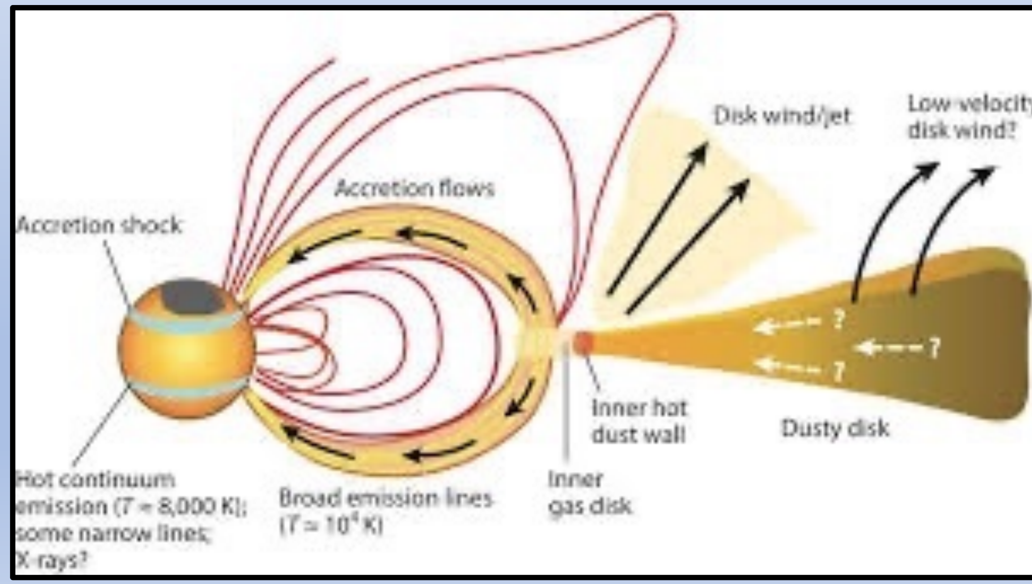


Luminosity Contributions

Basic Luminosity Scale:

$$L_o = \frac{GM}{R_*}\frac{dM}{dt}$$

- Direct accretion shock on stellar surface
- Direct accretion shock on disk surface
- Mixing luminosity on star
- Mixing luminosity on disk
- DISK ACCRECTION



Luminosity Contributions (from rotating infall solutions)

$$L_*^S = \int_{S_*} \left(\frac{1}{2}v_r^2\right) \rho |v_r| dA = \frac{1}{6u_*}\left[6u_* - 2 + (1-u_*)^{1/2}(2-5u_*)\right] L_0$$

$$L_\mathrm{d}^S = \int_{S_\mathrm{d}} \left(\frac{1}{2}v_\theta^2\right) \rho |v_\theta| dA = \frac{u_*}{4}\left\{\ln\left[\frac{1+(1-u_*)^{1/2}}{1-(1-u_*)^{1/2}}\right] - 2(1-u_*)^{1/2}\right\} L_0$$

$$L_\mathrm{d}^M = \int_{S_\mathrm{d}} \frac{1}{2}\left\{v_r^2 + \left[v_\phi - (GM/r)^{1/2}\right]^2\right\} \rho |v_\theta| dA$$

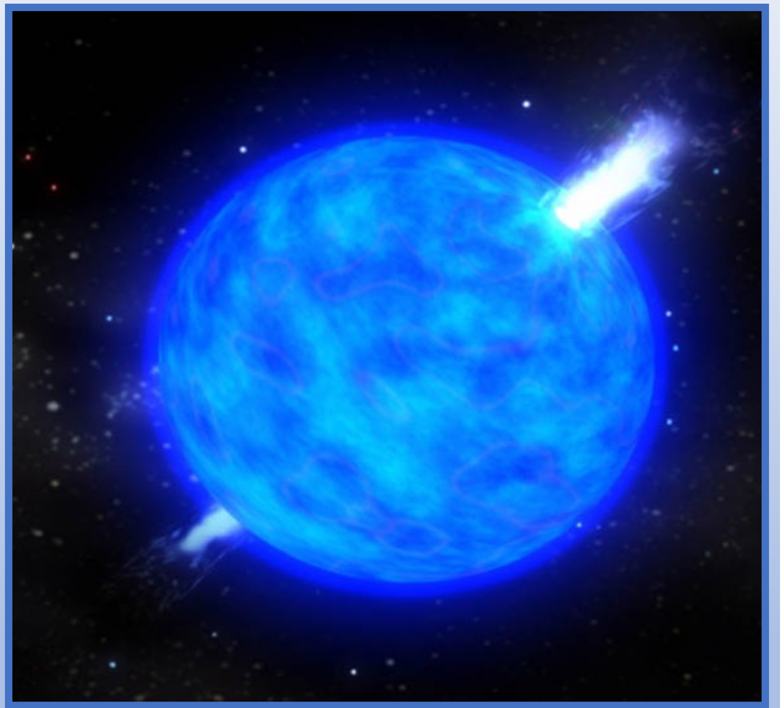
$$= \frac{u_*}{2}\left\{\ln\left[\frac{1+(1-u_*)^{1/2}}{1-(1-u_*)^{1/2}}\right] + (1-u_*)^{1/2} + \pi - 2\mathrm{atan}\left[u_*(1-u_*)^{-1/2}\right]\right\} L_0$$

$$L_\mathrm{d}^{ACC} = \eta_\mathrm{d}\left\{\frac{GM\dot{M}}{2R_*} - L_\mathrm{d}^S - L_\mathrm{d}^M\right\} \quad \text{and} \quad L_*^M = \eta_* GM_* \frac{\dot{M}_* + \eta_\mathrm{d}\dot{M}_\mathrm{d}}{2R_*}$$

(the most important uncertain parameter is from disk accretion)

Stellar Properties (low mass stars)

- Determined by stellar structure equations with accretion outer B.C.
- No Hydrogen burning during formation
- Deuterium burning in Class I phase; takes place well above D-threshold
- Internal luminosity sub-dominant



$$P_C = nkT_C \quad \Rightarrow \quad kT_C = f\,\frac{GM^2/R^4}{M/\mu R^3} = f\,G\mu\frac{M}{R}$$

$$H \;\; burning \;\; T_C \approx 10^7 K; \;\; D \;\; burning \;\; T_C \approx 10^6 K$$

Kelvin-Helmholtz Time Scale

- KH Time = time required for star to radiate gravitational potential energy
- Defines time scale on which star evolves
- KH Time much longer than formation time scale for low mass stars

$$\tau_{KH} = \frac{GM_*^{\,2}/R_*}{L_*} \approx 30\,Myr \left(\frac{M_*}{M_{Sun}}\right)^2 \left(\frac{R_{Sun}}{R_*}\right)\left(\frac{L_{Sun}}{L_*}\right)$$

ORDERING of SCALES

$$R_* << R_{disk} << R_{\exp} = a_S t < R_{core} < R_{clump} < R_{cloud}$$

- Clean separation of spatial scales
- Inner boundary condition for one scale provide outer boundary for next scale

$$M_{\rho=const} << M_* << M_{core} < M_{clump} < M_{cloud}$$

TIME SCALES

- Core formation time = 1 Myr
- Infall collapse time = 0.2 – 0.4 Myr
- Disk lifetime = 3 – 10 Myr
- Kelvin Helmholtz time scale = 10 – 20+ Myr

Star formation takes place much faster than the time required for stars to start burning nuclear fuel.

Radiation Pressure

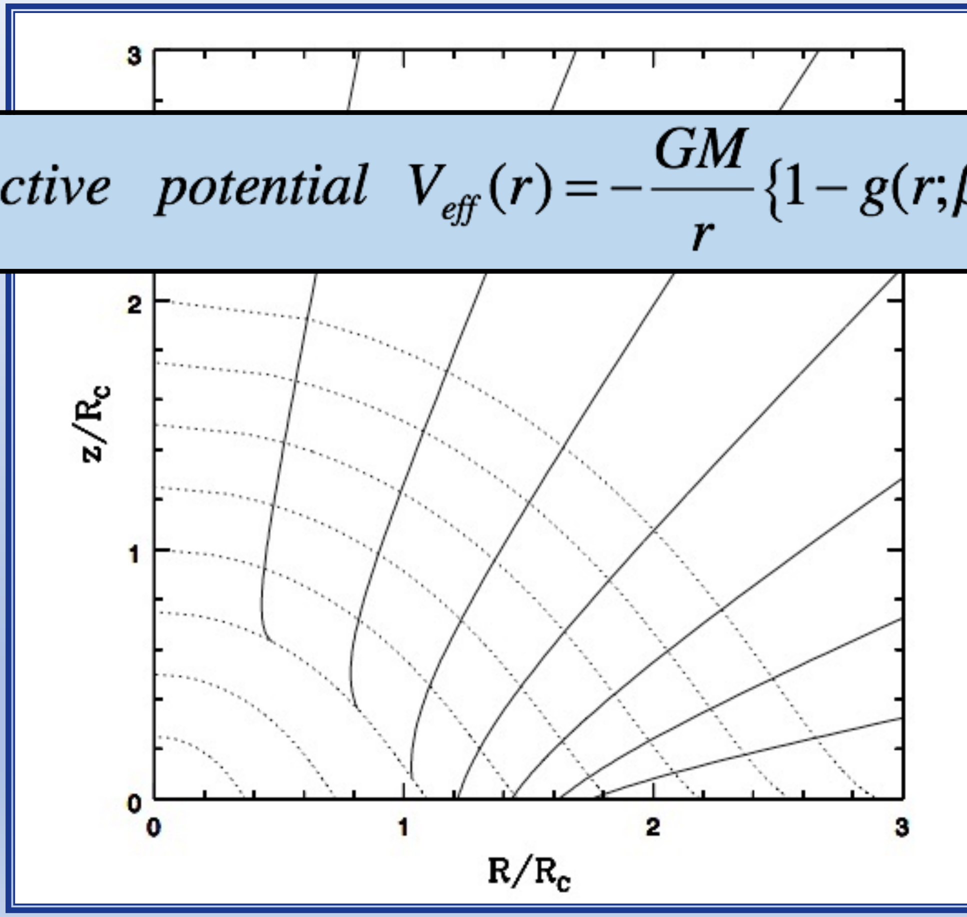
- Modifies infall at high masses (7 Msun)
- Must be overcome to form high mass stars

Define force per unit mass due to radiation and and dimensionless parameter to measure effect:

$$f = \int \frac{\kappa_\nu L_\nu}{4\pi r^2} d\nu = \frac{L}{4\pi c} \frac{\langle \kappa \rangle (T)}{r^2}$$

$$\beta \equiv \frac{L \langle \kappa \rangle (T_0)}{6\pi G M c} \left(\frac{r_0}{r_d} \right)^{1/2} \approx 0.0016 \frac{L / L_{Sun}}{M / M_{Sun}}$$

Infall with Radiation Pressure



$$effective\quad potential\quad V_{eff}(r) = -\frac{GM}{r}\{1 - g(r;\beta)\}$$

On High Mass Stars:

- Radiation pressure in spherical geometry prevents star formation at 7 Msun
- Rotation allows higher mass stars
- Angular momentum profile of initial state affects action of radiation pressure
- High infall rates make stars larger (in radius) and reduces luminosity and pressure
- 3-Dimensional effects help also
- Time scale for star formation becomes shorter than K-H time for stars larger than about 7 Msun
- Stars larger than about 8 Msun eventually supernova!

The JEANS MASS

- Constant density & temperature
- Infinite spatial extent
- Infinitesimal perturbations
- Geometry of plane waves (1D)

$$\omega^2 = k^2 a_s^2 - 4\pi G\rho$$

$$\lambda_J = {(2\pi a_s)} \big/ {\sqrt{4\pi G\rho}} \qquad M_J = \frac{4\pi}{3}\rho\lambda_J^3$$

JEANS MASS (continued)

$$M_J = \frac{4\pi}{3}\rho\lambda_J^3 \quad \propto \quad a_s^3 G^{-3/2}\rho^{-1/2}$$

- **Density has range of factor of 10^6**
- **Rotation, magnetic field, turbulence**
- **Distributions of variables in cloud do not produce stellar IMF**
- **Centrally condensed configuration has a Jeans mass at every radius**

Jean Mass is too simple (incomplete)

Mass Scales:

$$M_J = A\ a_S^3 G^{-3/2} \rho^{-1/2}$$

Jeans Mass

$$M_{*direct} = 1.293[16 a_S^8 R_* / G^3 \Omega^2]^{1/3}$$

Direct Stellar Mass

$$M_{CR} \approx 0.13 \Phi / G$$

Magnetic Critical Mass

$$M_{rot} = 2\sqrt{2}\ a_S^3 / G\Omega$$

Rotation Core Mass

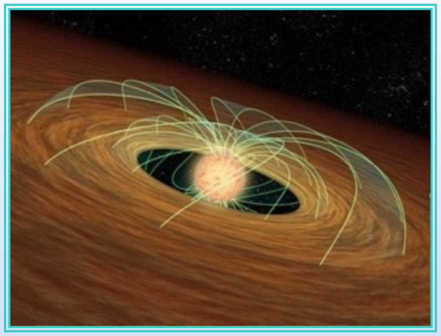
$$M_{core} = \frac{A\theta_0 a^2}{(1-f_0^2)G} r_{ce} = A \frac{1+2f_0^2}{1-f_0^4} \left[\frac{a^2 r_{ce}}{G} \right]$$

Eigenvalue Core Diffusion Mass

+mass of constant density inner region
+mass within outer core boundary
+maximum mass from outflows, radiation….

Disk Properties

- Surface density distribution
- Temperature distribution
- Scale height versus radius
- Central hole, boundary layer



$$T_d(r) = T_0\left(\frac{r_0}{r}\right)^q \qquad \Sigma_d(r) = \Sigma_0\left(\frac{r_0}{r}\right)^p \qquad H(r) = \frac{a_s}{\Omega} = H_0\left(\frac{r_0}{r}\right)^{(q-3)/2}$$

Initial surface density profiles determined by infall:
Standard collapse solutions imply p = 3/2, 5/3, 7/4…

Disk Radiative Transfer

$$I_\nu(r,\theta) = B_\nu[T_d(r)]\left\{1 - \exp[-\tau_\nu^d(r)/\cos\theta]\right\}$$

$$\tau_\nu^d = \kappa_\nu \Sigma(r)$$

$$4\pi r^2 F_\nu^d = 4 g_*(\theta) \cos\theta \exp[-\tau_\nu^{ISM}]$$

$$\times \int \pi B_\nu[T_d(r)]\left\{1 - \exp[-\tau_\nu^d(r)/\cos\theta]\right\} 2\pi r dr$$

(for geometrically flat disk, single temperature disk photosphere, with shadowing function)

Optically Thick Limit

$$\nu F_\nu^d \propto g_*(\theta)\int \pi\nu B_\nu[T_d(r)]2\pi r dr \propto \nu^n$$

$$where \quad n = 4 - 2/q$$

$$\int [] \propto \nu(\nu^3)r^2 \propto \nu^4(1/T^{1/q})^2 \propto \nu^{4-2/q}$$

$$classic \quad slope \quad q = 3/4 \Leftrightarrow n = 4/3$$

(limit of geometrically flat disk)

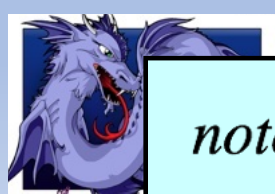
Optically Thin Limit

$$I_\nu(r,\vartheta) = B_\nu[T_d(r)]\left\{\tau_\nu^d(r)/\cos\theta\right\}$$

$$4\pi r^2 F_\nu^d = 4g_*(\theta)\exp[-\tau_\nu^{ISM}]\int \pi B_\nu[T_d(r)]\kappa_\nu \Sigma(r) 2\pi r dr$$

$$T = const \Rightarrow 4\pi r^2 F_\nu^d = 4g_*(\theta)\exp[-\tau_\nu^{ISM}]\pi B_\nu[T_{disk}]\kappa_\nu M_{disk}$$

$$RJ\ \ regime \quad \Rightarrow \quad 4\pi r^2 F_\nu^d \propto \nu^3 \kappa_\nu \quad \Rightarrow \quad \nu F_\nu^d \propto \nu^4 \kappa_\nu$$



note difference between F_ν *and* νF_ν

Stellar Contribution

$$4\pi r^2 F_\nu^* = g_d(\theta)\exp[-\tau_\nu^{ISM}]\ 4\pi R_*^2 B_\nu[T_*]$$

- Radius determined by stellar structure eqs.
- Temperature determined by luminosity
- Luminosity determined by infall, internal,…

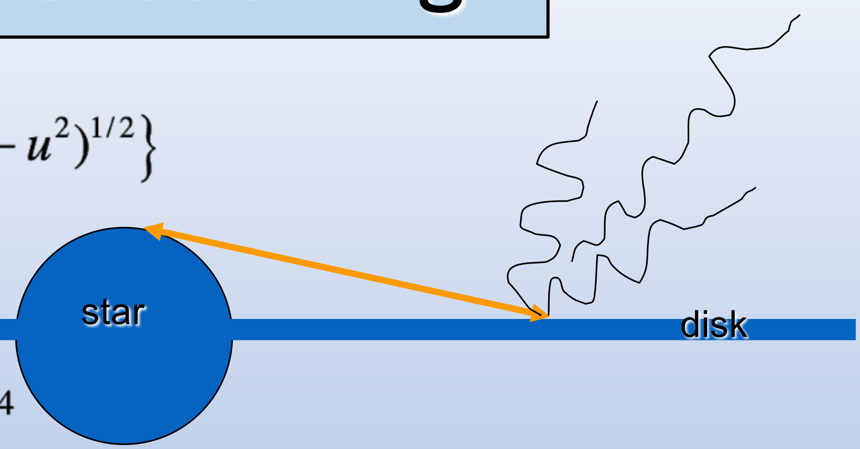
$$L_* = 4\pi R_*^2 \sigma T_*^4$$

(assume blackbody radiation to leading order)

Heating and Shadowing

$$\sigma T_{disk}^4 = \frac{\sigma T_*^4}{\pi}\left\{\arcsin u - u(1-u^2)^{1/2}\right\}$$

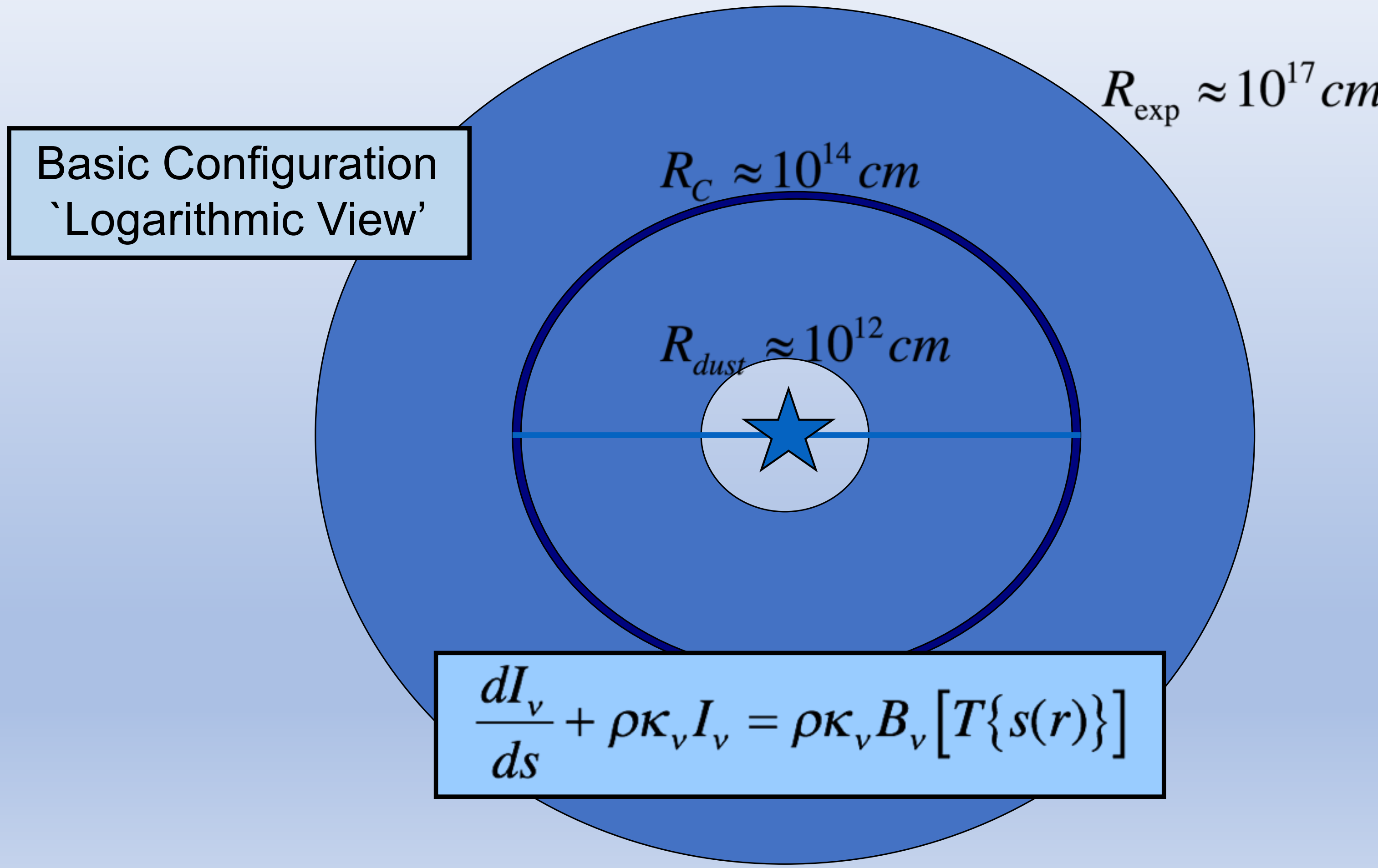
$$where \quad u = R_* / r$$



$$for \quad r >> R_*, \;\; T_{disk} \propto r^{-3/4}$$

Since the star and disk share the same 4π solid angle, they not only intercept radiation from each other, but that radiation causes both surfaces to be hotter than they would be otherwise. This heating effect does not violate conservation of energy because of shadowing, i.e., the full surfaces (both star and disk) are not visible.

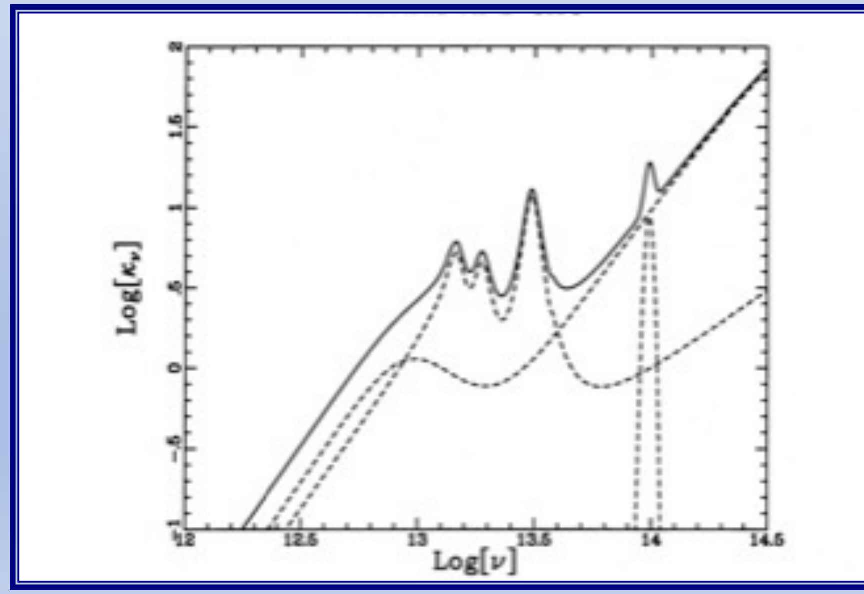
Radiative Transfer in Protostellar Envelopes



$$\frac{dI_\nu}{ds} + \rho\kappa_\nu I_\nu = \rho\kappa_\nu B_\nu\left[T\{s(r)\}\right]$$

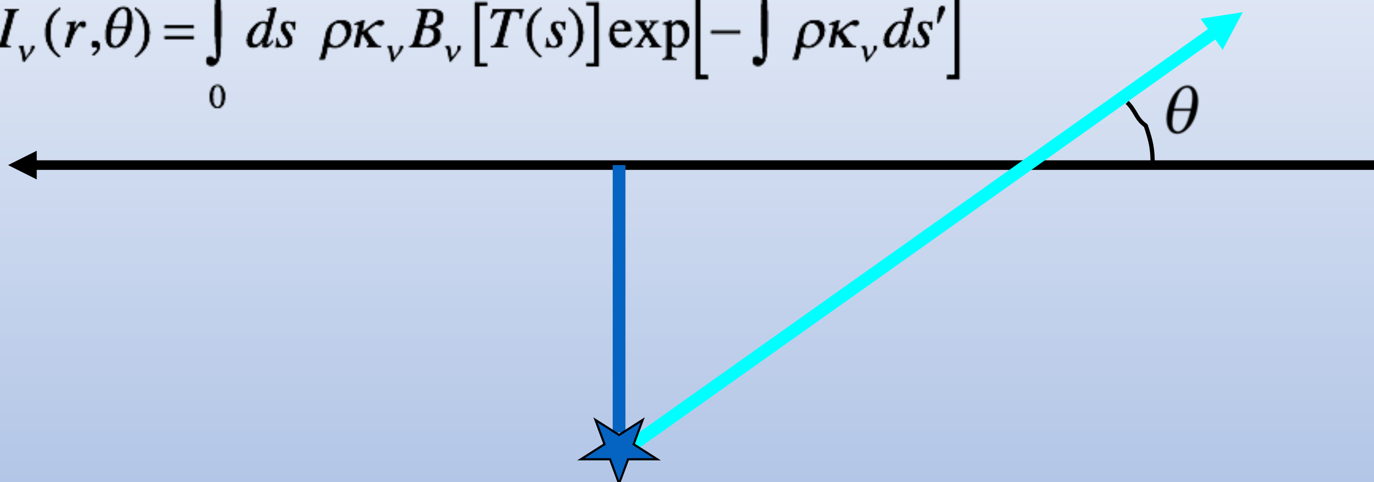
Radiative Transfer Notes

- Specific intensity = distribution function
- Local thermodynamic equilibrium (LTE)
- 1D spatial problem => 2D Rad. Transfer
- 2D spatial problem => 4D Rad. Transfer
- Ignore scattering for long wavelengths (and hence deeply embedded sources)
- Optical properties of dust important



Formal Solution (Spherical)

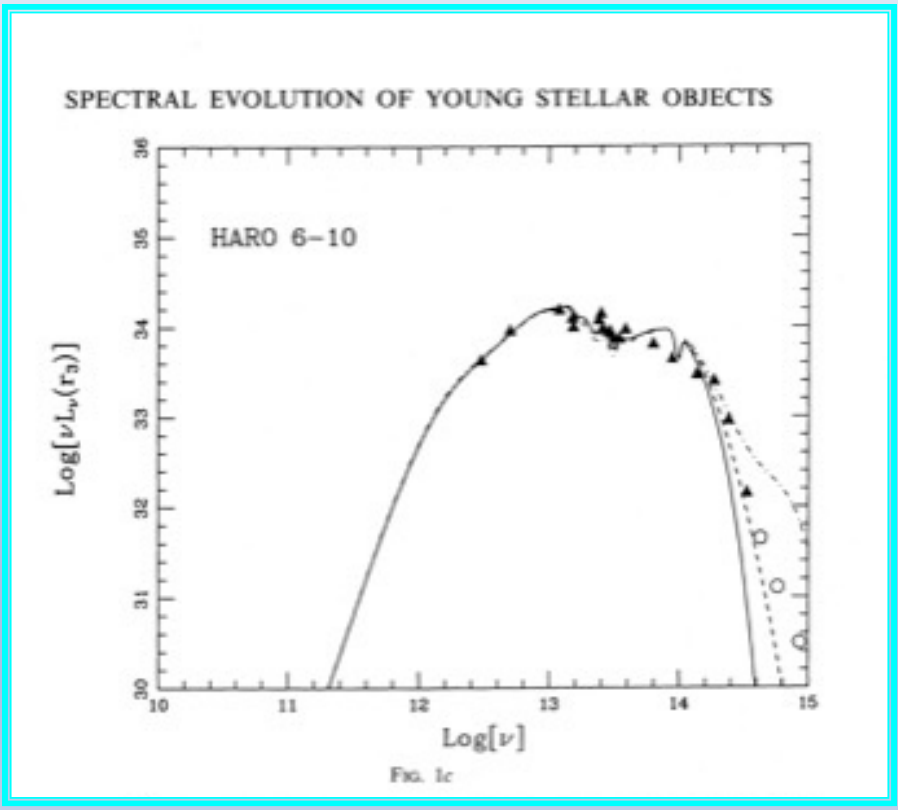
$$I_\nu(r,\theta) = \int_0^\infty ds \;\; \rho\kappa_\nu B_\nu [T(s)] \exp\left[-\int \rho\kappa_\nu ds'\right]$$



$$\frac{dL_\nu}{d\mu} = -(4\pi r^2) 2\pi I_\nu(r,\mu) \qquad L(r) = \int_0^\infty L_\nu d\nu = L_{bol} = const$$

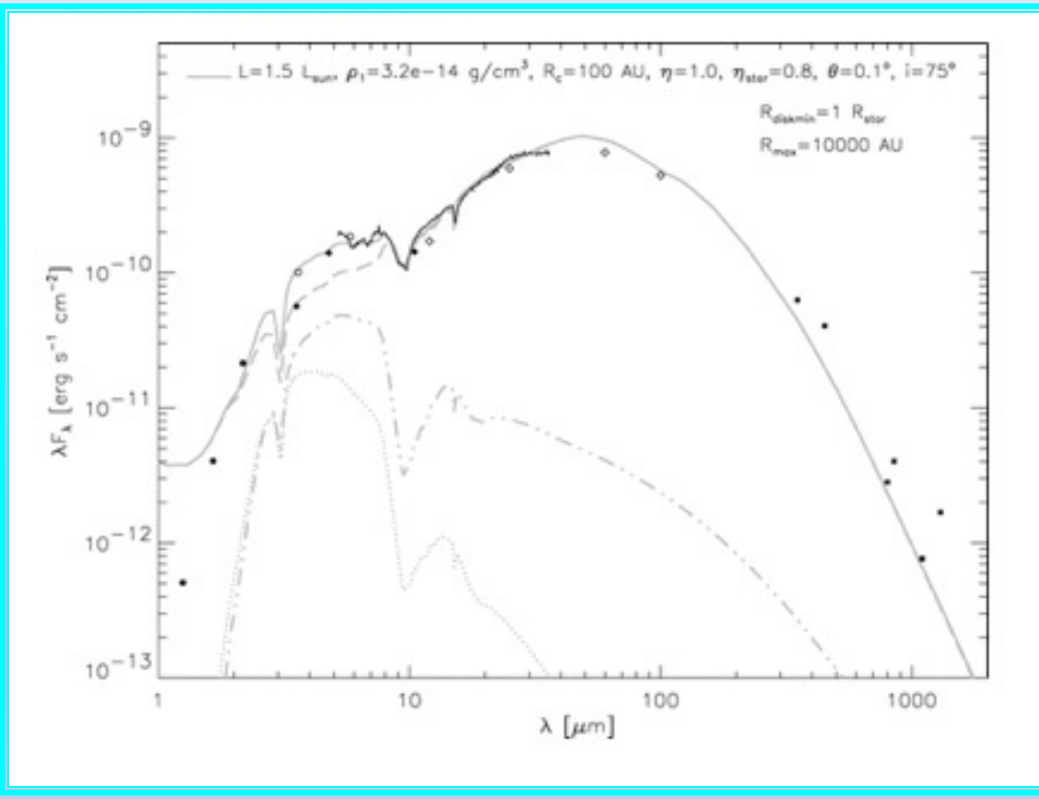
Must solve self-consistently for temperature profile using constraint of conservation of energy….

Class I Spectral Energy Distribution (original calculation)



The SED spans more than four decades in frequency/wavelength and four decades in flux density. The SED is much wider than a single temperature blackbody => the protostar does NOT have a well-defined photosphere…

Class I Spectral Energy Distribution (modern calculation, 04169+2702)

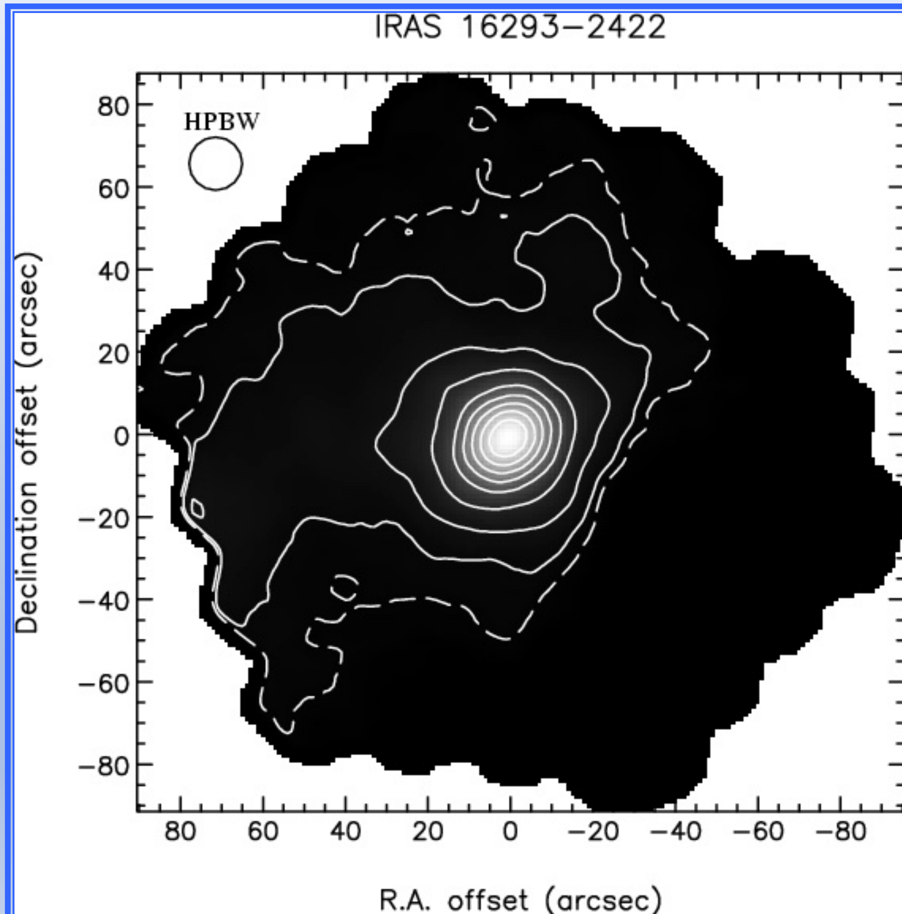


Furlan et al. 2008, ApJS, 176, 184

Protostellar Emission Maps

Protostellar objects display extended emission profiles and can be mapped at millimeter and submm wavelengths. Observed maps can be compared with theoretical models as an additional constraint…

(Correia et al. 2004)

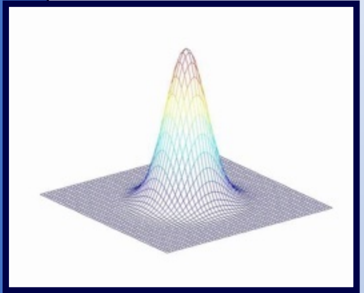


Radiative Transfer in Protostellar Maps

$\rho \propto r^{-p}$ *and* $T \propto r^{-q}$

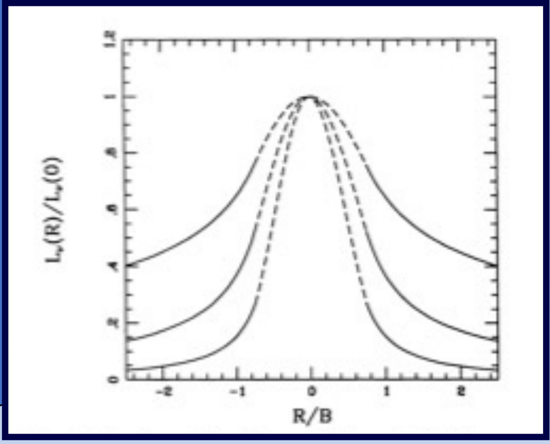
then $flux = F(p,q)$

Telescope Beam Profile



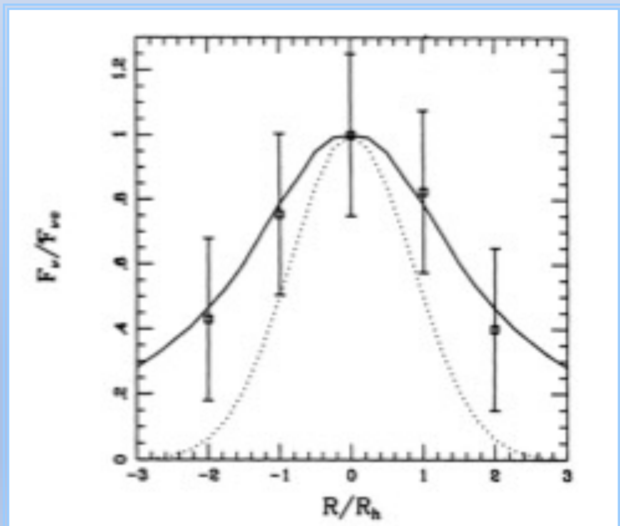
Impact Parameter ϖ

Integrate along line of sight to get specific intensity field; convolve with the response function of telescope to get flux versus impact parameter

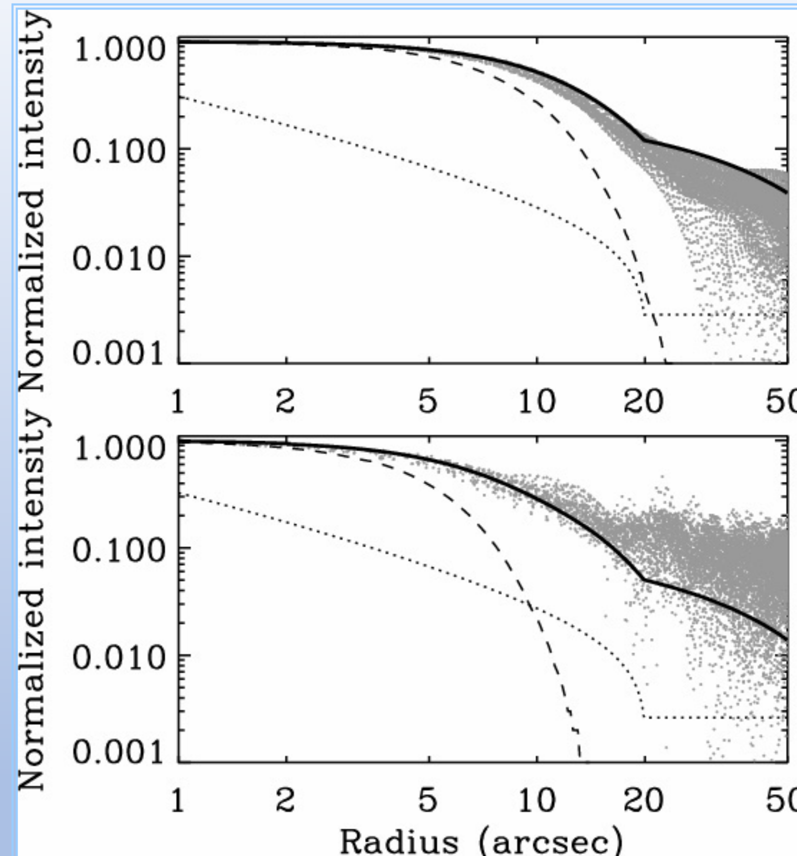


EXTENDED EMISSION

- **Protostellar envelopes are resolved**
- **Observed emission profiles consistent with infall-collapse picture**

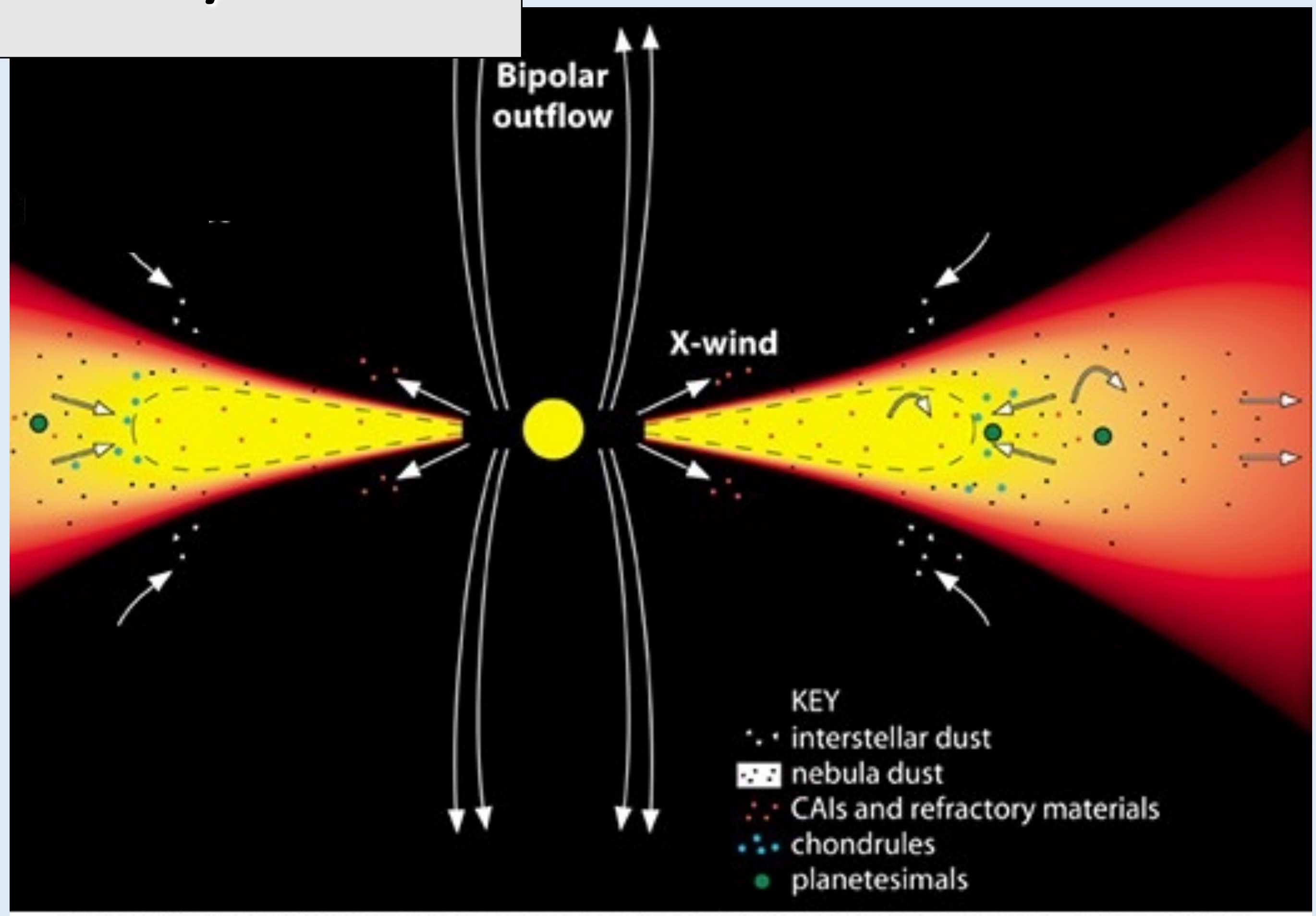


L1551 (Walker et al. 1990)



IRAS 16293-2422
(Correia et al. 2004)

Class II: Star/Disk Systems

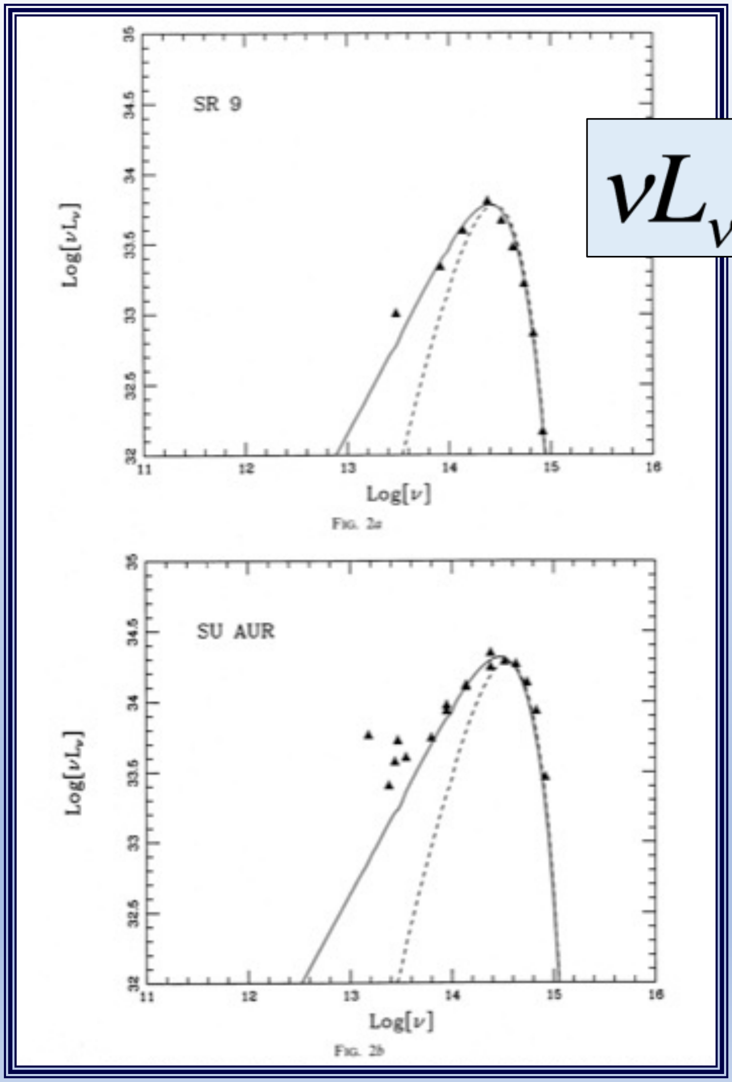


(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)

Class II Spectral Energy Distributions (original calculation)

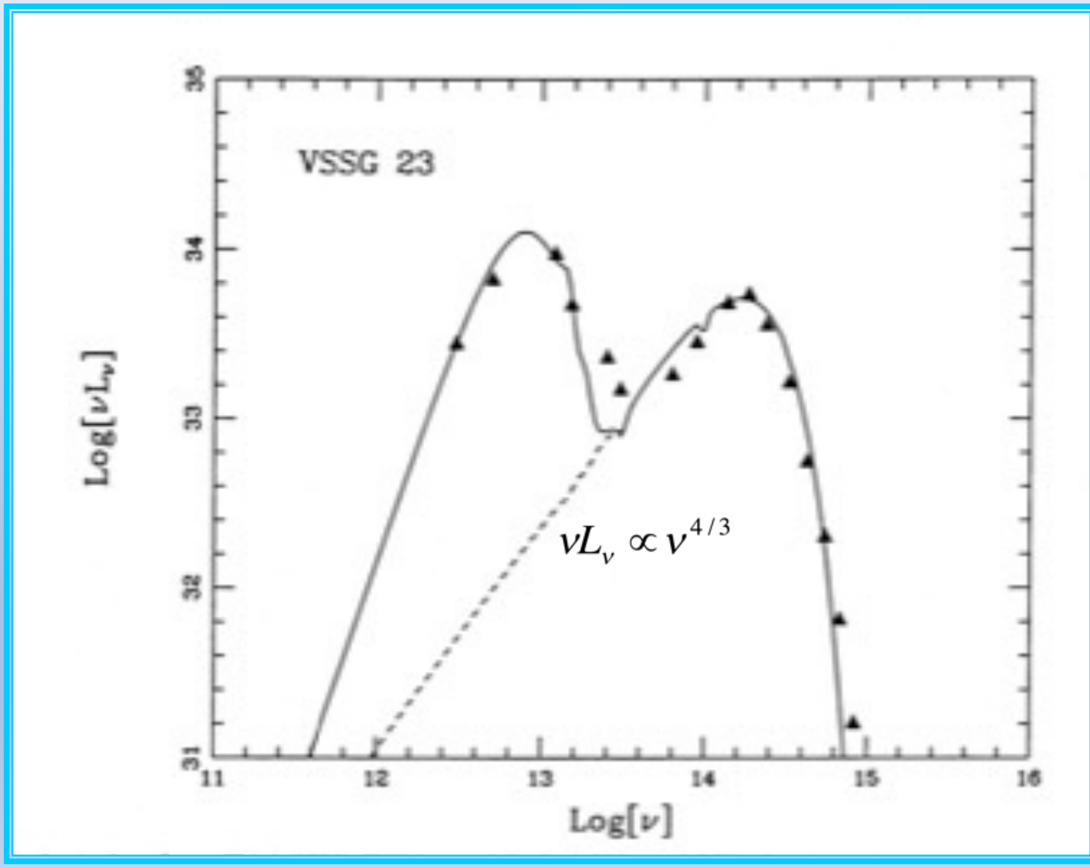
The disk creates an INFRARED EXCESS that makes the SED wider than blackbody with shallower slope. This IR excess led to these sources being classified as Class II (Wilking & Lada 1984).

(Adams, Lada, Shu 1987)



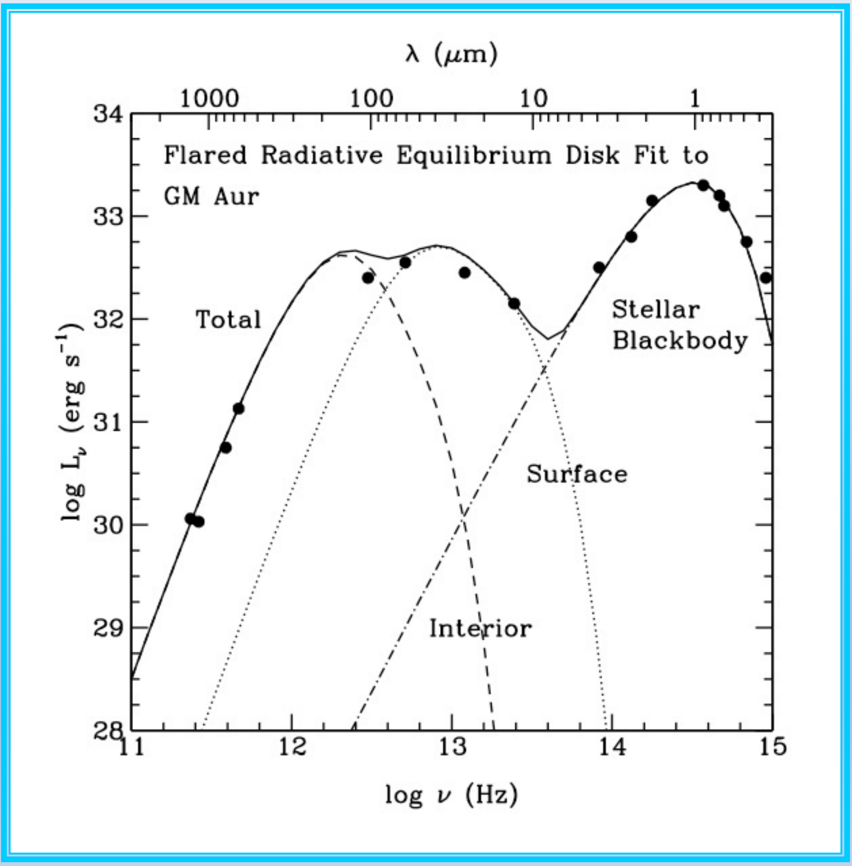
$$\nu L_\nu \propto \nu^{4/3}$$

Class II Spectral Energy Distribution (with optically thin envelope)



ALS 1987

Class II Spectral Energy Distribution (modern calculation, GM Aur)



Model includes self-consistent treatment of disk heating and disk scale height (i.e. disk flaring).

Chiang & Goldreich 1997
Kenyon & Hartmann 1987

Optically Thin Envelopes: An Uncertainty Warning

For radiative transfer models that need or use optically thin components, the problem of lack of uniqueness is SEVERE. In systems with such optically thin components, one can ``see'' all of the material and hence the radiation can be added. This property allows multiple models to be fit to the same observational data.

CONCLUSION/SUMMARY

- **Simple analytic model for ambipolar diffusion, matching onto collapse phase**
- **Allows correct formation time scale and observed values of head start velocity**
- **Enhancement of diffusion rates due to turbulent fluctuations (+ distribution)**
- **Reconnection also enhanced by turbulence**
- **Collapse solutions w. head start velocity**

CONCLUSION (continued)

- Rotating inner collapse solutions:
- Match onto outer self-similar flow
- Naturally produce disks, R = 10-100 AU
- Include radiation pressure
- Most of the mass falls onto the disk
- Need disk accretion - essential!
- No nuclear reactions during star formation
- Collapse defines mass infall rate, but not a well-defined mass scale
- Jeans Mass too simple