Star Formation

Stars are formed in dense molecular cloud cores, whereas planets are formed, contemporaneously, in young circumstellar disks.

➔ Compression of gas from a cloud size $\sim 10^{18}$ cm down to a stellar size $\sim 10^{11}$ cm, i.e., density increases by a factor of $\sim 10^{21}$.

Draine Chap 41, 42

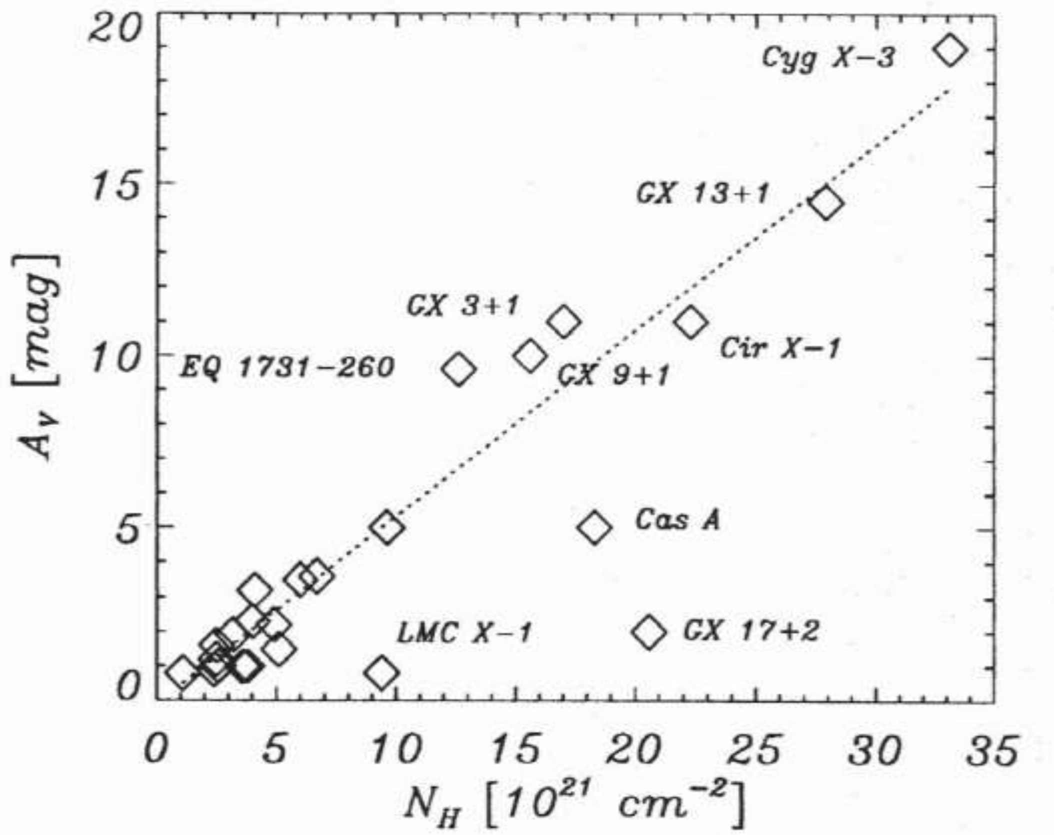


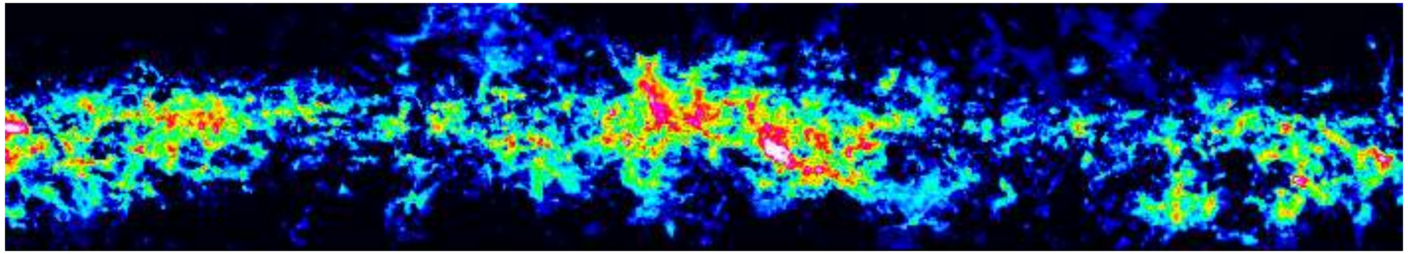
Fig. 3. Visual extinction vs. equivalent hydrogen column density. The fit (dotted line) does not contain GX 17+2 and LMC X-1. It yields $N_H = 1.79 \pm 0.03\ A_V[mag] \times 10^{21}[cm^{-2}]$

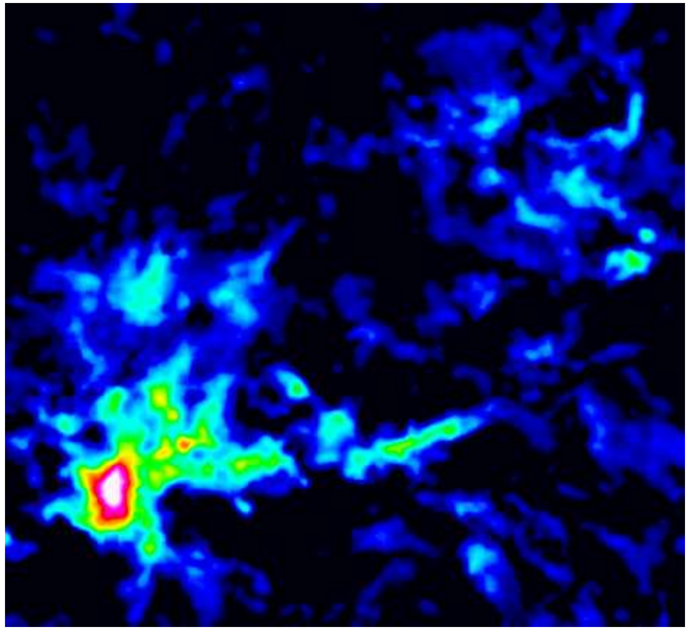
A gas-to-dust ratio ~100 (by mass) seems universal.

$$\frac{N_H}{A_V} \approx 1.8 \times 10^{21} \text{atoms cm}^{-2}\ \text{mag}^{-1}$$

Predehl & Schmitt (1995)

Filamentary Molecular Clouds





Molecular clumps/ clouds/condensations

$n \sim 10^3\ \mathrm{cm}^{-3}$, $D \sim 5$ pc,
$M \sim 10^3\, \mathcal{M}_{\odot}$

Dense molecular cores

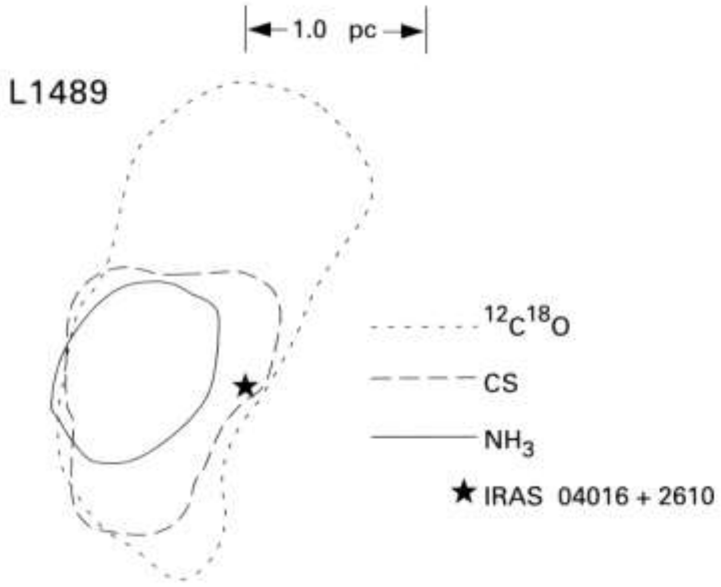
$n \geq 10^4\ \mathrm{cm}^{-3}$, D ~ 0.1 pc,
$M \sim$ 1-2 $\mathcal{M}_{\odot}$

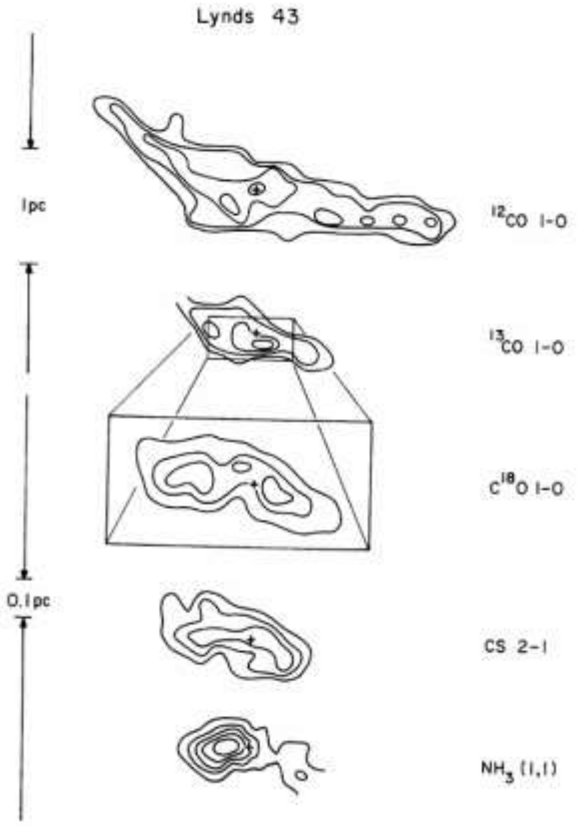
Giant Molecular Clouds

D=20~100 pc
$\mathcal{M} = 10^5 \sim 10^6\, \mathcal{M}_{\odot}$
$\rho \approx 10 \sim 300\ \mathrm{cm}^{-3}$
$T \approx 10 \sim 30$ K
$\Delta v \approx 5 \sim 15\ \mathrm{km}^{-1}$

http://www.bu.edu/galacticring/outgoing/PressRelease/

Stars are formed <u>in groups</u> → seen as star clusters if gravitationally bound. Groups of young stars are found at the densest parts of the molecular clouds.





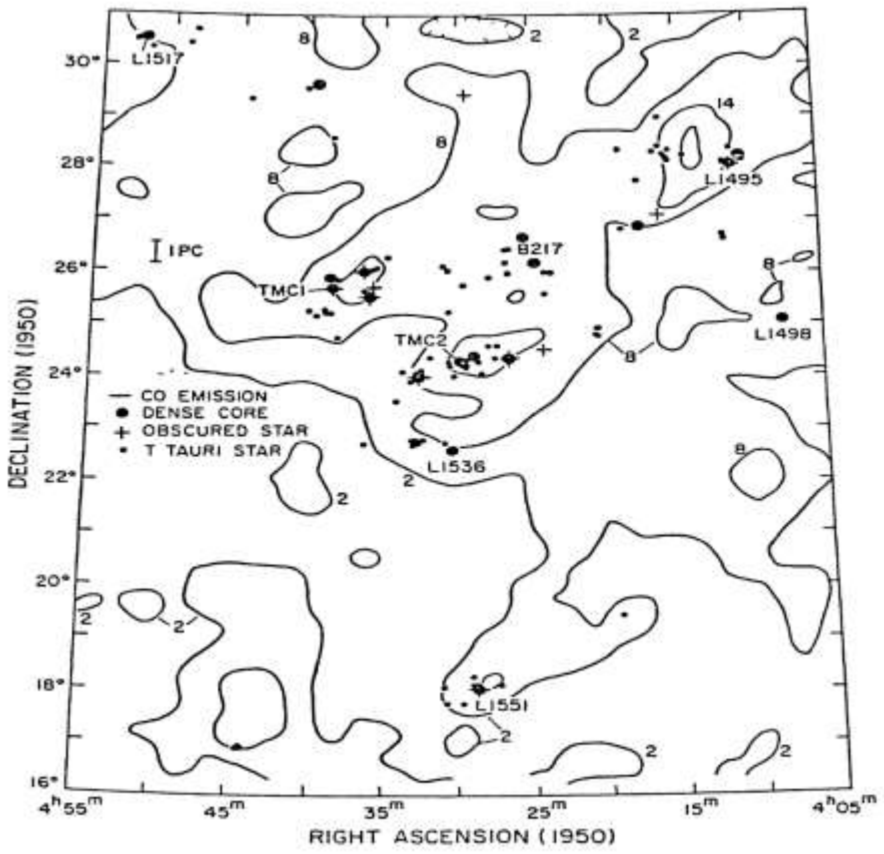


Figure 2 CO contour map of the Taurus molecular cloud with positions of dense NH_3 cores, embedded infrared sources, and visible T Tauri stars (from Myers 1986).

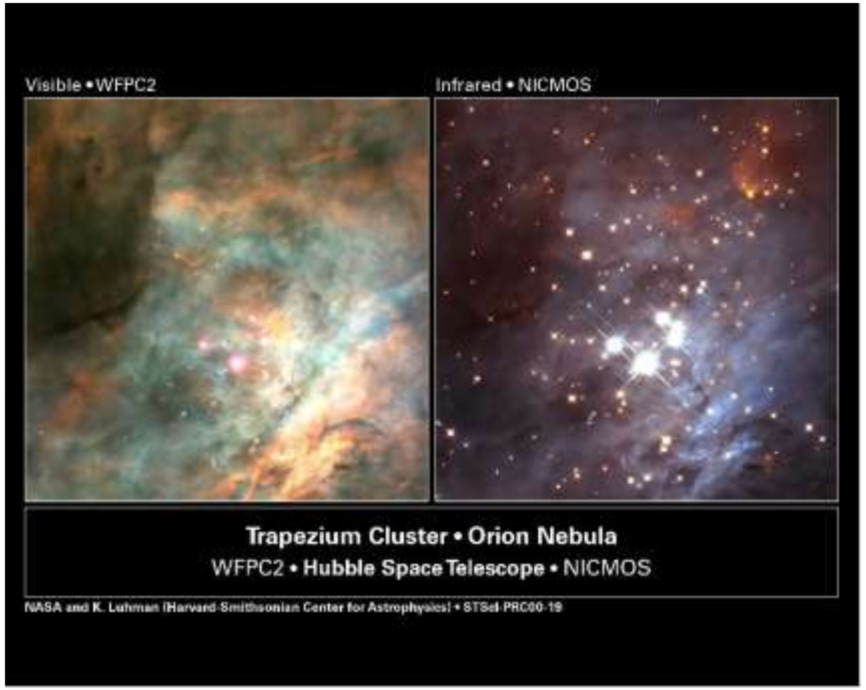
Molecular clouds observed by different tracers …

Taurus molecular cloud

Nearby Examples

Massive Star-Forming Regions

- *Per OB2* (350 pc)
- *Orion OB Association* (350--400 pc) … rich



Low-Mass Star-Forming Regions

- *Taurus Molecular Cloud (TMC-1)* (140 pc)
- *Rho Ophiuchi cloud* (130 pc)
- *Lupus* (140 pc)
- *Chamaeleon* (160 pc)
- *Corona Australis* (130 pc)

4/5 in the southern sky … why?

Stability: The Virial Theorem

In a spherically symmetric cloud of temperature T, for each particle, the equation of motion is $\boldsymbol{F}_i = m_i\,\ddot{\boldsymbol{r}}_i = \dot{\boldsymbol{p}}_i$, the momentum change with time.

Sum up all particles and take time derivative

$$\frac{d}{dt}\sum_i \boldsymbol{p}_i \cdot \boldsymbol{r}_i = \sum_i \dot{\boldsymbol{p}}_i \cdot \boldsymbol{r}_i + \sum_i \boldsymbol{p}_i \cdot \dot{\boldsymbol{r}}_\mathrm{i}$$

$$= \sum_i \boldsymbol{F}_i \cdot \boldsymbol{r}_i + \sum_i m_i \dot{\boldsymbol{r}}_i \cdot \dot{\boldsymbol{r}}_\mathrm{i}$$

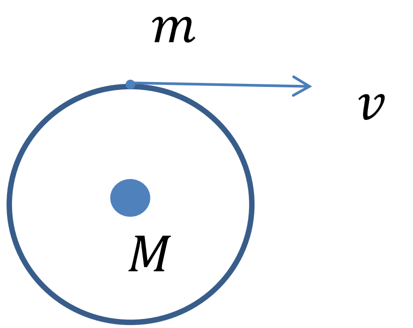
$$= E_p + 2E_k$$

$$\frac{d}{dt}\sum_i m_i \dot{r}_i \cdot r_i$$

$\sum_\mathrm{i} \boldsymbol{F}_i \cdot \boldsymbol{r}_i$ = virial of Clausius

For moment of inertia, $I = \sum_i m_i r_i^2$,

$$\frac{d^2 I}{dt^2} = \frac{d}{dt}\left[\sum_i m_i 2\, r_i\, \dot{r}_i\right]$$



Hence

$$\frac{1}{2}\frac{d^2 I}{dt^2} = 2E_k + E_p$$

$$\frac{GmM}{r^2} = m\frac{v^2}{r}$$

To be stable, LHS = 0

$$\boxed{2E_k + E_p = 0}$$

$$2\left({}^1\!/_2\right) mv^2 = GmM/r$$

LHS = 0 → stable

LHS < 0 → collapsing

LHS > 0 → expanding

E_K a variety of kinetic energies

- ✓ Kinetic energy of molecules
- ✓ Bulk motion of clouds
- ✓ Rotation
- ✓ …

E_P a variety of potential energies

- ✓ Gravitation
- ✓ Magnetic field
- ✓ Electrical field
- ✓ …

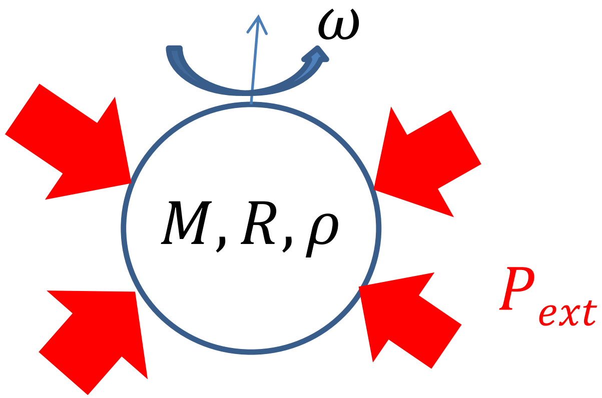
Note:

Virial theorem governs the motion status, whereas the total energy

$$\boldsymbol{E_{total} = E_K + E_P}$$
$$\boldsymbol{= E_K + \Omega \text{ (mostly)}}$$

governs whether the system is dynamically bound.

A coins flying either upward or downward is bound.



Cloud of mass M, radius R, rotating at ω

$$E_{rot} = \frac{1}{2} I \omega^2 \qquad I = \frac{2}{5} M R^2 \qquad \Omega = -\frac{3}{5}\frac{GM^2}{R}$$

Generalized virial theorem

$$\frac{1}{2}\frac{d^2 I}{dt^2} = 2 < E_K > + \int \vec{r} \cdot \vec{F} dm + 3 \int P dV - \oint P \vec{r} \cdot d\vec{s}$$

If $\omega = 0$, and $P_{ext} = 0$

$$2 \cdot \frac{3}{2} \frac{M}{\mu m_H} kT - \frac{3}{5}\frac{GM^2}{R} = 0$$

$$R_J = \frac{1}{5}\frac{GM \mu m_H}{kT}$$

This is the **Jeans length**.

$\mu \approx 2.37$ for solar abundance with H_2

Jeans length = critical spatial wavelength (length scale)

If the perturbation length scale is longer
→ Medium is decoupled from self-gravity ➔ stable

$$M_J = \frac{4}{3}\pi R_J^3 \rho \qquad R_J = \left(\frac{15}{4\pi}\frac{kT}{\mu m_H G\rho}\right)^{1/2} \sim \sqrt{\frac{T}{\rho}}$$

$$M_J = \left(\frac{\pi kT}{4\mu m_H G}\right)^{3/2} \sqrt{\frac{1}{\rho}} \sim \frac{T^{3/2}}{\rho^{1/2}}$$

This is the **Jeans mass** … the **critical** mass for onset of gravitational collapse

If cloud mass $M > M_{\text{Jeans}}$ ➔ cloud collapse

Note the above does not consider external pressure, or other internal supporting mechanisms.

A non-magnetic, isothermal cloud in equilibrium with external pressure → a **Bonnor-Ebert sphere** (Bonnor 1956, Ebert 1955)

$$2E_K + E_P - 3P_{\text{ext}}V = 0$$

The potential term may include, other than the gravity, also rotation, magnetic field, etc.

At first, the cloud is optically **thin**.

Contraction → density ↑ → collisions more frequent
→ molecules excited and radiated → radiation escapes
→ cooling → less resistance to the contraction
→ cloud collapse (free fall)

$R_J \approx c_s\,\tau_{\text{ff}}$ = [isothermal sound speed] * [free fall time]

To maintain $2E_K + E_P = 0$, <u>the total energy</u> $E_t = E_K + E_P$ <u>must change</u>. The gravitational energy

$$\Omega \sim -\frac{GM^2}{r} \longrightarrow d\Omega \sim \frac{dr}{r^2}$$

For contraction, $dr < 0$, so $d\Omega < 0$, then

$$dE_t = dE_k + d\Omega = {}^1/_2\ d\Omega = Ldt$$

This means to maintain quasistatic contraction, **<u>half</u>** of the gravitation energy from the contraction is radiated away.

Eventually the cloud becomes dense enough (i.e., optically **<u>thick</u>**) and contraction leads to temperature increase.

The cloud's temperature increases while energy is taken away
→ negative heat capacity

Numerically,

$$M_J = 1.0 \left(\frac{T}{10\ \mathrm{K}}\right)^{3/2} \left(\frac{n_{\mathrm{H}_2}}{10^4\ \mathrm{cm}^{-3}}\right)^{-1/2}\ [\mathcal{M}_\odot]$$

- H I clouds

  $T \approx 100$ K, $n_H \approx 100$, $R_\mathrm{J} \approx 25$ pc; $M_\mathrm{J} \approx 300\ \mathcal{M}_\odot > M_\mathrm{obs}$

  So H I clouds are not collapsing.

- Dark molecular clouds

  $T \approx 15$ K, $n_H \approx 10^5$, $M_\mathrm{J} \approx 20\ \mathcal{M}_\odot < M_\mathrm{obs} \approx 100-1000\ \mathcal{M}_\odot$

  So H_2 clouds (dense cores and Bok globules) should be collapsing. But observations show that most are not.

  → There is additional support other than the thermal pressure, e.g., rotation, magnetic field, turbulence, etc.

If $\mathcal{M}_{\text{cloud}} > \mathcal{M}_{\text{crit}}$ → <u>supercritical</u> → Cloud collapses dynamically
➔ Massive star formation

If $\mathcal{M}_{\text{cloud}} < \mathcal{M}_{\text{crit}}$ → <u>subcritical</u> → Cloud collapses quasistatically
➔ Low-mass star formation

Clouds tend to condense with $\mathcal{M} \sim 10^4 M_\odot$, but the observed stellar mass ranges $0.05 \le \mathcal{M}/M_\odot \le 100$

Why is there a lower mass limit and an upper mass limit for stars?

Cloud collapse → (local) density increase → (local) M_J decrease → easier to satisfy $M > M_J$, i.e., cloud becomes more unstable

➔ <u>fragmentation</u>

Formation of a cluster of stars ~~

Recall $M_J \approx 1.2 \times 10^5 \left(\frac{T}{100\ K}\right)^{3/2} \left(\frac{\rho_0}{10^{-24}\ \mathrm{g\ cm^{-3}}}\right)^{-1/2} \frac{1}{\mu^{3/2}}\ [M_\odot]$

$$\propto T^{3/2} / \rho^{1/2}$$

A small/decreasing M_J favors cloud collapse.

If during collapse, local $M_J \downarrow$ → subregions become unstable and continue to collapse to ever smaller (**fragmentation**).

Since during collapse ρ always ↑, the behavior of M_J depends on T.

If gravitational energy is radiated away, i.e., $\tau_{\mathrm{cooling}} \ll \tau_{\mathrm{ff}}$ and collapse is **isothermal**, $T =$ const, so $M_J \propto \rho^{-1/2}$ ➔ collapse continues

Equation of motion for a spherical surface at r is

$$\frac{d^2r}{dt^2} = -\frac{GM}{r^2}$$

Dimensional analysis yields

$$\frac{R}{t^2} \sim \frac{GM}{R^2} \Longrightarrow t_{ff} \sim \frac{1}{\sqrt{G\rho}}$$

More accurately, $t_{\rm ff} = \left(\frac{3\pi}{32\,G\rho_0}\right)^{\frac{1}{2}} = \frac{3.4\times10^7}{\sqrt{n_0}}$ [yr] $= 35/\sqrt{\rho}_{\rm cgs}$ [min]

It takes the Sun ~30 minutes to collapse (the **free-fall time scale**).

Ex: How long does a typical dense molecular core take to collapse?

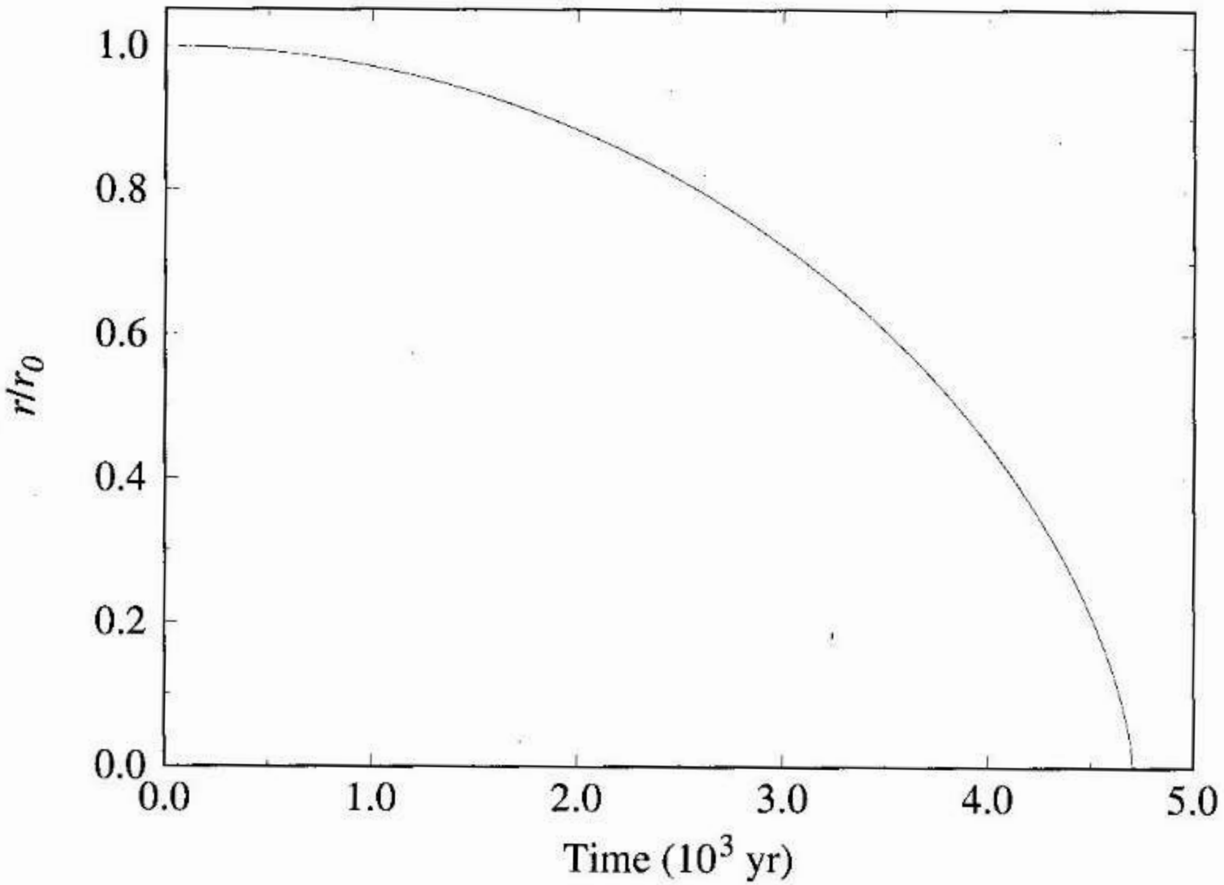


Figure 12.5 The ratio of the radius relative to its initial value as a function of time for the homologous collapse of a molecular cloud. The collapse is assumed to be isothermal, beginning with a density of $\rho_0 = 2 \times 10^{-16}$ g cm^{-3}.

Carroll & Ostlie

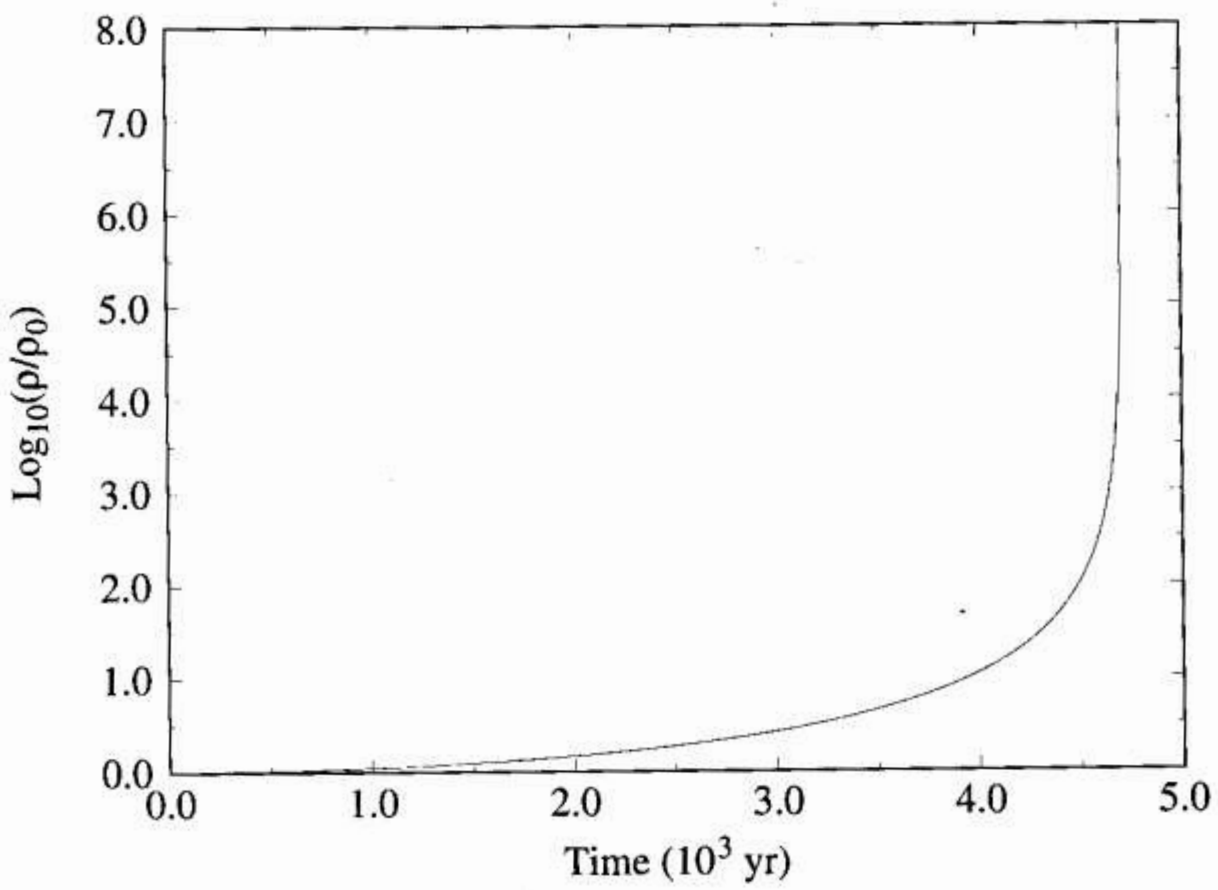


Figure 12.6 The ratio of the cloud's density relative to its initial value as a function of time for the isothermal, homologous collapse of a molecular cloud with an initial density of $\rho_0 = 2 \times 10^{-16}$ g cm^{-3}.

Carroll & Ostlie

Note that $t_{\rm ff} \propto \frac{1}{\sqrt{G\rho_0}}$ has no dependence on r_0.

If ρ_0 is uniform, all m collapse to the center at the same time

→ **homologous collapse**

In reality, ρ_0 is somewhat centrally condensed, as observed,

e.g., $\rho_0 \propto r^{-1}$ to r^{-2}, inner region (small r), $t_{\rm ff}$ ↓↓

→ **inside-out collapse**

A protostellar core is formed, followed by material "raining down" → **accretion**

Gravitational energy → kinetic energy → heat

$L_{\rm acc} \sim GM_* \dot{M} / R_*$

Ann. Rev. Astron. Astrophys. 1987. 25: 23–81

STAR FORMATION IN MOLECULAR CLOUDS: OBSERVATION AND THEORY

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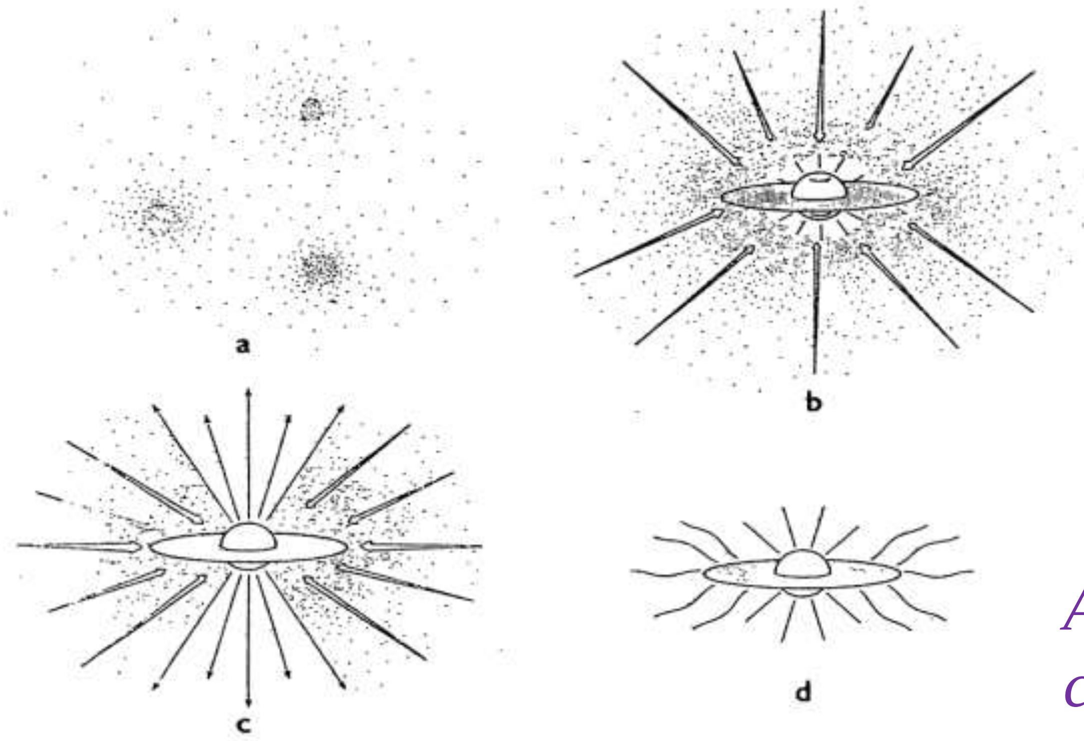
Cores form within molecular clouds.

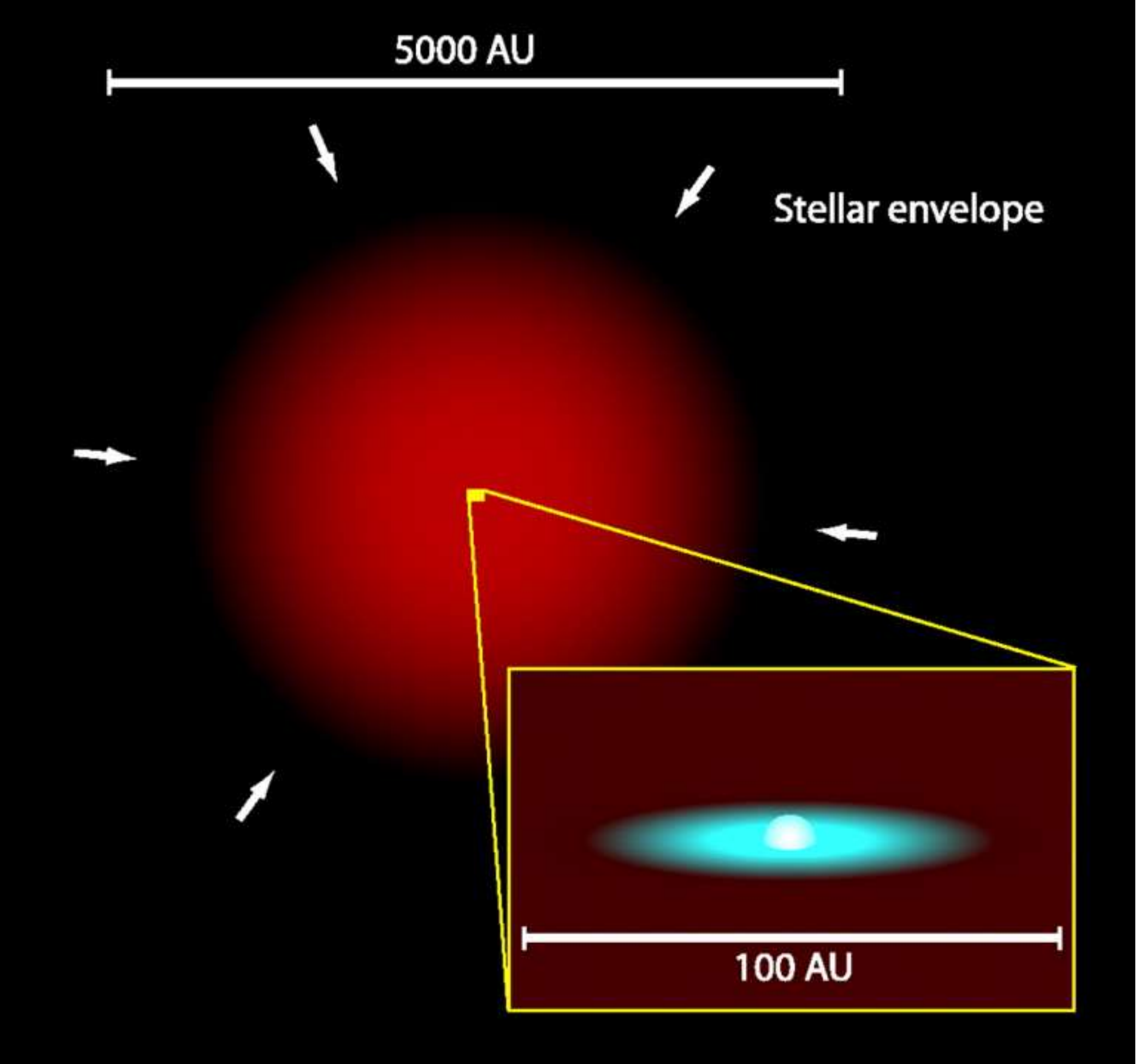
A core collapse inside-out and form a protostar with a toroid.



A stellar wind with a bipolar flow forms.

A star is form with a circumstellar disk.

Figure 7 The four stages of star formation. (*a*) Cores form within molecular clouds as magnetic and turbulent support is lost through ambipolar diffusion. (*b*) A protostar with a surrounding nebular disk forms at the center of a cloud core collapsing from inside-out. (*c*) A stellar wind breaks out along the rotational axis of the system, creating a bipolar flow. (*d*) The infall terminates, revealing a newly formed star with a circumstellar disk.



Central condensed protostar,
$r \sim$ a few $R_\odot$

Circumstellar disk,
$r \sim 100$ au

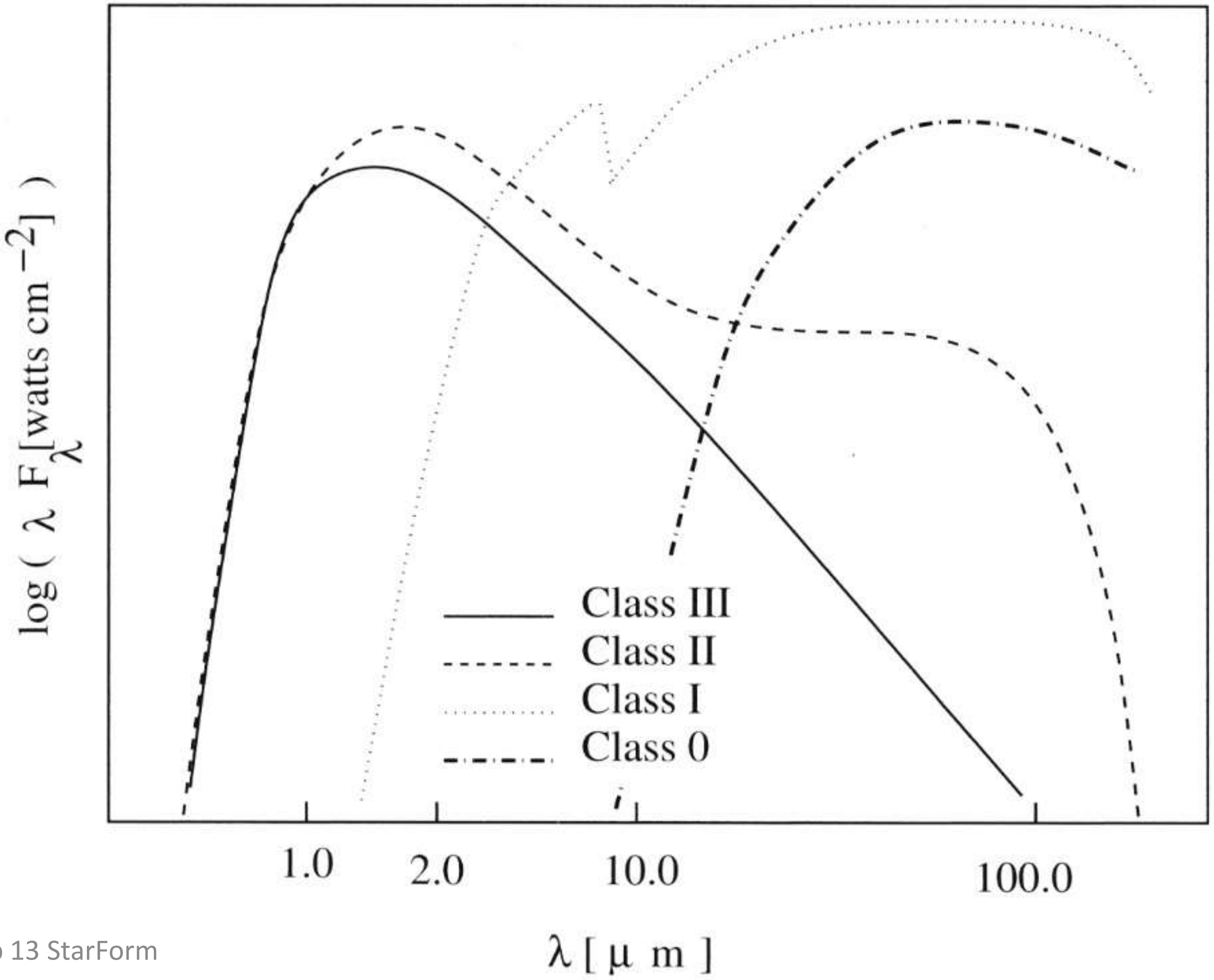
Surrounding envelope,
$r \sim 5000$ au

Matter accretes from the envelope via the disk onto the protostar

Ward-Thomson (2002)

Spectral energy distribution

F_λ vs λ
or $\log \lambda F_\lambda$ vs $\log \lambda$



Spectral index useful to classify a young stellar object (YSO)

$$\alpha = \frac{d \log (\lambda F_\lambda)}{d \log (\lambda)}$$

Where λ=wavelength, between 2.2 and 20 μm; F_λ=flux density

Class 0 sources --- undetectable at $\lambda < 20$ μm

Class I sources --- $\alpha > 0.3$

Flat spectrum sources --- $0.3 > \alpha > -0.3$

Class II sources --- $0.3 > \alpha > -1.6$

Class III sources --- $\alpha < -1.6$

➔ Evolutionary sequence in decreasing amounts of circumstellar material (disk clearing)

Annu. Rev. Astron. Astrophys. 1996. 34:111–54

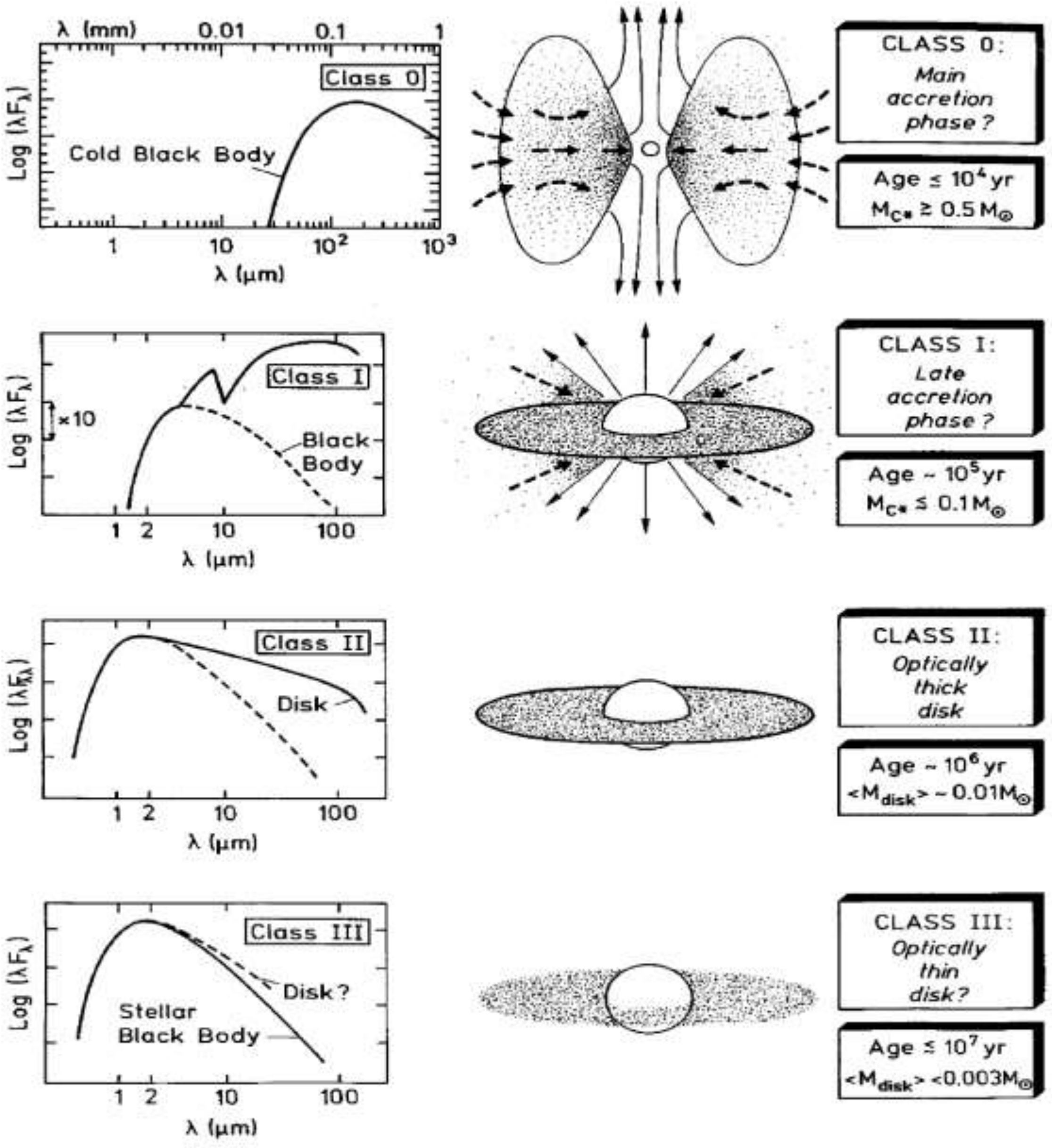


Figure 11 Evolutionary sequence of the spectral energy distributions for low-mass YSOs as proposed by André (1994). The four classes 0, I, II, and III correspond to successive stages of evolution.

Class 0
Submilimeter cores

Class I
Protostars

Class II
Classical T Tauri stars

Class III
Weak-lined T Tauri stars

Rafael Bachiller

Basic Questions in Star Formation

- The rate and efficiency of SF as a function of time and position in the Galaxy, and in external galaxies? How are these quantities measured?
- Cloud fragmentation to form clusters?
- Triggered SF?
- Different processes for high-mass and low-mass?
- Mass spectrum? Typical $0.1 - 1\ M_{\odot}$, why?
- Formation of multiple systems?
- What is a protostar observationally?
- Evolution of disks?
- Origin of bipolar outflows?
- Environments for planet formation?
- Role of rotation and magnetic field?

Bodenheimer