Stages of star formation (the classical view)

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.

(Shu, Adams, & Lizano 1987)
Stages of star formation

(a) Pre-stellar dense cores -- fragmentation
(b) Gravitational collapse t=0
(c) Protostar with accretion disk and outflow (t < 10^4 yr)
(d) T Tauri, pre-main sequence with optically thin dust disk (t = 10^6-10^7 yr)
(d') Young stellar system with debris (protoplanetary) disk, t > 10^7 years
(c') Infrared protostar with optically thick circumstellar disk (t = 10^5 yr)
Stage (a): hierarchical fragmentation

Isothermal contraction of a cloud with \( M_0 > M_j \)
(sound speed \( a_0 \) constant)

\[
M_j \mu \rho_0^{-1/2}
\]

Parts of the original cloud become gravitationally unstable and start to contract: 
**fragmentation** of the original cloud.

The process is repeated as long as the gas is **isothermal**

When the fragment (with \( M_{\text{frag}} = M_j \)) becomes **optically thick**, its heats up and becomes a **hydrostatic core** near equilibrium, and the fragmentation ends
Stages (b, c): accretion and outflow

Infall onto the core is difficult to detect. Assymetry of line profiles, blue wing stronger than red wing.

High-mass star-forming region. Single dish observations (20''). Profiles characteristic of large-scale infall.

Contours of equal line-of-sight velocity for spherically symmetric infall.
Instead of observing gravitational contraction, what is easily seen are high-velocity outflowing motions.

Maximum velocity of gravitationally bound motion:

\[ \frac{1}{2} m v_{\text{max}}^2 - \frac{G M m}{R} = 0 \]

\[ v_{\text{max}} = \left( \frac{2 G M}{R} \right)^{1/2} \]

Discovery of **bipolar molecular outflows** in 1980

L1551: Snell, Loren, Plambeck

Cepheus A: Rodríguez, Ho, Moran
Stage (d): star with circumstellar disk

In the late stages, circumstellar disks are called **protoplanetary disks**. Disks lose their gas and the dust grain size increase, becoming **debris disks**.

- Start with a stable disk around central star.
- Jupiter-sized planet forms & clears gap in gas disk.
- Planet accretes along spiral arms, arms become unstable.
- Disk fragments into more planetary mass objects.
Instead of observing gravitational contraction, what is easily seen are high-velocity outflowing motions.

Maximum velocity of gravitationally bound motion:

\[ \frac{1}{2} m v_{\text{max}}^2 - \frac{G M m}{R} = 0 \]

\[ v_{\text{max}} = \left( \frac{2 G M}{R} \right)^{1/2} \]

Discovery of bipolar molecular outflows in 1980

**L1551**: Snell, Loren, Plambeck

**Cepheus A**: Rodríguez, Ho, Moran
Instead of observing gravitational contraction, what is easily seen are high-velocity outflowing motions.

Bipolar molecular outflow in L1551
Bipolar molecular outflows

Tabla 5.6: Propiedades medias de los flujos moleculares de alta velocidad

<table>
<thead>
<tr>
<th>Size</th>
<th>$R$</th>
<th>0.5 pc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masa</td>
<td>$M$</td>
<td>$3 M_\odot$</td>
</tr>
<tr>
<td>Temperatura cinética</td>
<td>$T_k$</td>
<td>20 K</td>
</tr>
<tr>
<td>Velocidad</td>
<td>$V$</td>
<td>25 km s$^{-1}$</td>
</tr>
<tr>
<td>Energía cinética</td>
<td>$E_{kin} = \frac{1}{2} M V^2$</td>
<td>$10^{45}$ erg</td>
</tr>
<tr>
<td>Edad característica</td>
<td>$t = \frac{R}{V}$</td>
<td>$2 \times 10^4$ años</td>
</tr>
<tr>
<td>Luminosidad mecánica</td>
<td>$L_{mech} = \frac{1}{2} M V^2 / t$</td>
<td>0.1 $L_\odot$</td>
</tr>
<tr>
<td>Tasa de momento</td>
<td>$\dot{P} = MV / t = MV^2 / R$</td>
<td>$10^{-3} M_\odot$ año$^{-1}$ km s$^{-1}$</td>
</tr>
</tbody>
</table>

Figure 7 Mechanical luminosity of high-velocity molecular outflows plotted against the total radiant luminosity of embedded central objects. The two quantities appear correlated, although the scatter is large. All sources fall below the relation $L_{HMF} = L_*$. The estimated uncertainties in the determinations of $L_{HMF}$ and $L_*$ for a typical source are indicated.

Figure 8 Force needed to accelerate the molecular outflows plotted against the total radiant luminosity of the embedded central objects. The two quantities appear weakly correlated. All sources fall above the relation $\dot{M}V = L_*/c$, which suggests that radiation pressure from the central objects is not sufficient to drive the flows. Estimated uncertainties in the derived parameters are indicated.
HH 211

- Class 0, very young stellar object
- Very collimated molecular outflow
- Visible in CO and SiO

- Cavity traced by the H2 emission at 2.12 \( \mu \text{m} \)

- Dense core traced by NH3, perpendicular to the outflow axis

- Dust envelope around the protoestar, traced by the continuum emission at 1 mm, perpendicular to the outflow axis
The quadrupolar molecular outflow in L723

A pair of major lobes E-W (blue-red)
A pair of minor lobes N-S (blue-red)

Distance = 300 ± 150 pc

3.6 cm

VLA 2: 0.42 mJy
Associated with dust and dense gas

VLA 1: 0.32 mJy
Not related with the outflow?

Separation ~15"
VLA 2: morphology characteristic of a thermal radiojet
- size $\mu \nu^{-0.7}$
- flux dens $\mu \nu^{0.6}$

The quadrupolar molecular outflow in L723
L723: dense gas traced by NH$_3$ (VLA)

Mass $\approx 6 \, M_{\odot}$, $T_{\text{rot}} \approx 12-14$ K

VLA 1 outside the dense core
Hot spots in VLA 2 and 10$''$ west (WHS)
L723: dust envelope (SCUBA of JCMT)

- 3.3 Jy at 850 μm
- 21 Jy at 450 μm
- $r_{\text{env}} = 1800$ AU
- $M_{\text{env}} = 3.9 M_{\text{sol}}$
L723 VLA 2: multiplicity (SMA)

1.3 mm Flux dens. Size
SMA 1 (D): 59 mJy 2''x<0.6''
SMA 2 (A+C): 45 mJy 2''x1''
Separation = 3''
L723 VLA 2: multiplicity (VLA 7 mm)

1.3 mm Flux dens. Size
SMA 1 (D): 59 mJy 2''x<0.6''
SMA 2 (A+C): 45 mJy 2''x1''
Separation = 3''
L723 VLA 2: multiplicity (VLA 3.6 cm)

Flux density (mJy)
3.6 cm 7mm
A: 0.11 0.7
B: 0.08 <0.37
C: 0.05 0.7
D: <0.02 0.6
HH 223: tracer of the $\text{H}_2$ outflow at large scales

Compound image:
- $\text{H} \alpha$ blue (ALFOSC, NOT)
- $\text{H}_2$ green (LIRIS, WHT)
- 4.5 $\mu$m red (IRAC, Spitzer)

Zoom showing the $\text{H}_2$ emission (color) and the SiO outflow (contours)
Identification of VLA 1 in the NIR. Possibly a Class III object (T Tauri)

HH 223: tracer of the H$_2$ outflow at large scales

Compound image:
H$\alpha$ blue (ALFOSC, NOT)
H$_2$ green (LIRIS, WHT)
4.5 $\mu$m red (IRAC, Spitzer)
Tracing outflows

L1157 outflow in CO (2-1) and dust at 8 μm

Zinnecker et al. (1998)
Herbig-Haro objects

Discovered in 1946 by George Herbig (USA) and Guillermo Haro (Mexico)

Astrophysical Journal 113, 697
HH 1-2: emission characteristic of shock excitation

Fig. 1.—*Above:* The region of NGC 1999, with objects Nos. 1, 2, and 3 marked. The negative was obtained with the Crossley reflector on January 20, 1947. The dimensions of the field are 0′2 by 10′5. South is at the top and east to the right.

*Below:* The spectrum of object No. 1, photographed with an exposure of 2.5 hours on November 12, 1950. Hα, Hγ, and λ 3727 are in emission all along the slit, due to faint nebulosity over the entire field. A few night-sky lines also are present.
Herbig-Haro objects

Discovered in 1946 by George Herbig (USA) and Guillermo Haro (Mexico)

HH 1-2 (HST)

Embebded exciting protostar
jet
bow shock
Herbig-Haro objects, jets, disks

Terminal bow shock, brightest HH knot, giving name to the system

Jet formed by a chain of HH knots. Each knot is the working surface of an internal shock of the jet material

Exciting protostar, embedded in a dust disk (seen edge on)
Protoplanetary disks in Orion

Protoplanetary disks seen against the bright background

Disk seen edge on. Some diffuse light from the central protostar can be seen

Disk seen face on. The protostar light escaping the system along the polar direction can be seen
Accretion disk and jet

HH 30 jet, disk, and counterjet

jet (proper motions)

diffuse light from the embedded protostar

disk silhouette in absorption

faint counterjet
Unified model of molecular outflows, jets, HH objects
Unified model of molecular outflows, jets, HH objects

HH34 jet exciting star HH 34N
HH 34 counterjet in the IR

Visible

Infrared

HH 34N

exciting star

Jet

HH 34

counterjet

exciting star

Jet
High-velocity outflows from YSOs: $\text{H}_2\text{O}$ masers

Maser emission comes from very compact (10-100 AU), very dense ($10^7$-$10^8$ cm$^{-3}$) condensations, where population inversion is driven by shocks from a YSO wind. Maser spots can have high velocities, $\sim$100 km s$^{-1}$.

Water masers in W51 (high-mass SFR) observed with VLBI (mas resolution)

Maser spots, showing radial velocity of emission

Maser emission spectrum integrated for all the region
Maser (Microwave Amplification by Stimulated Emission of Radiation)

Maser emission from a transition is produced when there is population inversion \( \frac{n_2/g_2}{n_1/g_1} > 1 \). In such a case, \( T_{ex} < 0 \) is equivalent to say that \( \frac{n_2/g_2}{n_1/g_1} > 1 \).

\[
1 < \frac{n_2/g_2}{n_1/g_1} = e^{-h\nu_{21}/kT_{ex}} \implies T_{ex} < 0.
\]

As a consequence, the optical depth is negative (indicating that the emission is amplified)

\[
T_{ex} < 0 \implies \tau_0 = \frac{c^3}{8\pi\nu_{21}^3\Delta\nu} A_{21} N_2 \left( e^{h\nu_{21}/kT_{ex}} - 1 \right) < 0,
\]

A rough analysis of the transfer equation shows that intensity is amplified exponentially.

\[
T_0 = (T_{ex} - T_{bg}) (1 - e^{-\tau_0}) \approx |T_{ex}| e^{\tau_0}.
\]

The brightness temperature of a maser transition can be extremely high. For example, for \( T_{ex} = -20 \text{ K} \), \( |\tau_0| = 20 \), we have \( T_0 = 10^{10} \text{ K} \).

Maser radiations is produced in very compact regions (maser spots), and the flux density is not extremely high.

Maser emission is highly variable, consequence of the amplification. For example, a variation of 10% in \( \tau_0 \) produces a factor 2 variation in intensity:

\[
\Delta T_0 \approx T_0 \Delta \tau_0.
\]
Maser emission from two levels, 2-1, is only possible when there is a **pumping mechanism**: transitions to and from other levels, which can be able to overpopulate the upper level 2.

Pumping can be represented by a third level, with a rate $P_{12}$, of excitation transitions from level 1 to 2, through level 3, and a rate $P_{21}$, of desexcitation transitions from level 1 to 2, through level 3.

Pumping can be originated by IR radiation from a luminous star (SiO, ...), or by collisions and shocks near young stellar objects (H$_2$O).
For simplicity, we assume that the two levels have equal weights \( g \), equal collisional coefficients \( C \), equal induced emission coefficients \( B \). \( \Omega_m \) is the maser emission (small) solid angle.

Assuming that collisions and induced emission dominate over spontaneous emission, and \( P_{12}, P_{21} \) are the pumping rates, the population ratio is given by:

\[
\frac{n_2}{n_1} = \frac{P_{12} + M + C}{P_{21} + M + C}.
\]

\( n \) is the total population, \( \Delta n \) the level 2 overpopulation, \( P \) the total pumping rate, \( \Delta P \) the net upward pumping rate,

The level 2 overpopulation in the limiting case of only pumping transitions is:

\[ \Delta n_0 = (n_2 - n_1)_{M=C=0} = n \frac{\Delta P}{P}. \]

In general when \( M \) and \( C \) are not zero, the level 2 overpopulation can be given as:

\[ \Delta n = \frac{\Delta n_0}{1 + 2(M + C)/P}. \]
With the assumptions made, the radiation transfer equation becomes:

The transfer equation can be written as:

where $\alpha$ is the amplification coefficient:

and the saturation intensity $I_{\text{sat}}$ is:

\[
\frac{dI_{\nu}}{dl} = -\kappa_{\nu} I_{\nu} + j_{\nu} \simeq -\kappa_{\nu} I_{\nu} = \frac{\hbar \nu_{21}}{4\pi} \Delta n B I_{\nu} \phi(\nu).
\]

\[
\frac{dI_{\nu}}{dl} = \frac{\alpha I_{\nu}}{1 + I_{\nu}/I_{\text{sat}}},
\]

\[
\alpha = \frac{\hbar \nu_{21}}{4\pi} B \frac{\Delta n_0}{1 + 2C/P} \phi(\nu),
\]

\[
I_{\text{sat}} = \frac{2\pi P}{B\Omega_m} \left(1 + \frac{2C}{P}\right).
\]
When the radiation intensity is low, \( I_\nu \ll I_{\text{sat}} \), pumping is sufficient to maintain the population inversion.

This is the **unsaturated case**
Radiation intensity grows **exponentially** with distance

The other limiting case, \( I_\nu \gg I_{\text{sat}} \), pumping cannot maintain the population inversion. Amplification is limited by the number of molecules in the upper level.

This is the **saturated case**
Radiation intensity grows **linearly** with distance

\[
\frac{dI_\nu}{I_\nu} = \alpha dl,
\]

\[
I_\nu = I_0 e^{\alpha l}.
\]

\[
\frac{dI_\nu}{dl} = \alpha I_{\text{sat}},
\]

\[
I_\nu = I_0 + \alpha I_{\text{sat}} l.
\]
Maser emission comes from very compact (10-100 AU), very dense (10^7-10^8 cm⁻³) condensations, where population inversion is driven by shocks from a YSO wind. Maser spots can have high velocities, ~100 km s⁻¹.

Water masers in W51 (high-mass SFR) observed with VLBI (mas resolution)

Maser spots, showing radial velocity of emission

Maser emission spectrum integrated for all the region
Larson (1969, 1972): numerical model of a collapsing core, down to a pre-main sequence object

**Initial conditions**

**Homogeneous isothermal sphere of 1 \( M_J \), 1 \( R_J \):** For instance, for \( M_J = 1 M_{\odot} \), \( T = 10 K \), \( M = 1 M_{\odot} \), \( R = 0.05 \) pc, \( n = 10^4 \) cm\(^{-3} \) (\( \rho = 10^{-19} \) g cm\(^{-3} \))
Gravitational collapse (Larson model)

Larson (1969, 1972): numerical model of a collapsing core, down to a pre-main sequence object

Initial conditions

**Homogeneous isothermal sphere of** \(1 M_J, 1 R_J\): For instance, for \(M_J = 1 M_{\text{sol}}\), \(T=10 \text{ K}, M=1 M_{\text{sol}}, R=0.05 \text{ pc}, n=10^4 \text{ cm}^{-3} (\rho=10^{-19} \text{ g cm}^{-3})\)

Isothermal collapse

Infalling material is optically thin, thus gravitational energy released is radiated away. Density grows faster at the center.
Gravitational collapse (Larson model)

Larson (1969, 1972): numerical model of a collapsing core, down to a pre-main sequence object

**Initial conditions**

*Homogeneous isothermal sphere of $1 \, M_J, 1 \, R_J$. For instance, for $M_J=1 \, M_{\odot}$, $T=10 \, K$, $M=1 \, M_{\odot}$, $R=0.05 \, pc$, $n=10^4 \, cm^{-3}$ ($\rho=10^{-19} \, g \, cm^{-3}$)*

**Isothermal collapse**

Infalling material is optically thin, thus gravitational energy released is radiated away. Density grows faster at the center.

(a) Formation of the first hydrostatic core

When central density attains $10^{-13} \, g \, cm^{-3}$, material becomes optically thick, temp. and pression grow, halting the collapse at center. A core of $0.01 \, M_{\odot}$ is formed.
Gravitational collapse (Larson model)

Larson (1969, 1972): numerical model of a collapsing core, down to a pre-main sequence object

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\[ T = 10 \, \text{K}, \quad M = 1 M_{\text{sol}}, \quad R = 0.05 \, \text{pc}, \quad n = 10^4 \, \text{cm}^{-3} \quad (\rho = 10^{-19} \, \text{g cm}^{-3}) \]

**Isothermal collapse**

Infalling material is optically thin, thus gravitational energy released is radiated away. Density grows faster at the center

(a) **Formation of the first hydrostatic core**

When central density attains \( 10^{-13} \, \text{g cm}^{-3} \), material becomes optically thick, temp. and pressure grow, halting the collapse at center. A core of 0.01 \( M_{\text{sol}} \) is formed

(b) **First core collapse**

When core temperature reaches 2000 K, \( \text{H}_2 \) dissociates, absorbing energy, and core collapses. A second hydrostatic core forms, with \( \rho_{\text{in}} = 10^{-3} \, \text{g cm}^{-3} \), \( T_{\text{in}} = 10^4 \, \text{K} \). First core is accreted rapidly onto the second core
Larson (1969, 1972): numerical model of a collapsing core, down to a pre-main sequence object

**Initial conditions**

**Homogeneous isothermal sphere of $1 \, M_\odot$, $1 \, R_\odot$.** For instance, for $M_j = 1 M_\odot$, $R = 0.05 \, pc$, $n = 10^4 \, cm^{-3}$ ($\rho = 10^{-19} \, g \, cm^{-3}$) 

**Isothermal collapse**

Infalling material is optically thin, thus gravitational energy released is radiated away. Density grows faster at the center

(a) Formation of the first hydrostatic core

When central density attains $10^{-13} \, g \, cm^{-3}$, material becomes optically thick, temp. and pressure grow, halting the collapse at center. A core of $0.01 \, M_\odot$ is formed

(b) First core collapse

When core temperature reaches 2000 K, $H_2$ dissociates, absorbing energy, and core collapses. A second hydrostatic core forms, with $\rho_{in} = 10^{-3} \, g \, cm^{-3}$, $T_{in} = 10^4 \, K$. First core is accreted rapidly onto the second core

(c) Main accretion phase

Envelope falls onto the second core, almost in free-fall. Infall velocity, density, and temperature grow toward the center:

$$v \propto r^{-1/2}, \rho \propto r^{-3/2}, T \propto r^{-1/2}.$$ 

Protostar luminosity comes from the infall, and is radiated in the IR.
Gravitational collapse (Larson model)

Larson (1969, 1972): numerical model of a collapsing core, down to a pre-main sequence object

**Initial conditions**

**Homogeneous isothermal sphere of 1 \(M_J\), 1 \(R_J\):** For instance, for \(M_J=1 \ M_{\text{sol}}\), \(T=10 \ K\), \(M=1 \ M_{\text{sol}}\), \(R=0.05 \ pc\), \(n=10^4 \ cm^{-3}\) (\(\rho=10^{-19} \ g \ cm^{-3}\))

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When central density attains \(10^{-13} \ g \ cm^{-3}\), material becomes optically thick, temp. and pression grow, halting the collapse at center. A core of 0.01 \(M_{\text{sol}}\) is formed

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First core is accreted rapidly onto the second core

(c) **Main accretion phase**

Envelope falls onto the second core, almost in free-fall.

Infall velocity, density, and temperature grow toward the center:

\[
\nu \propto r^{-1/2}, \quad \rho \propto r^{-3/2}, \quad T \propto r^{-1/2}.
\]

Protostar luminosity comes from the infall, and is radiated in the IR.

**Pre-main sequence evolution**

When the envelope is almost accreted, it becomes optically thin and the protostar becomes visible, as a pre-main sequence object.

For instance, \(M_{\text{star}}=1 \ M_{\text{sol}}\), \(R_{\text{star}}=2 \ R_{\text{sol}}\), \(L_{\text{star}}=1.3 \ L_{\text{sol}}\), \(T_{\text{eff}}=4000 \ K\)
Gravitational collapse (Shu model)

Shu (1977): autoconsistent initial conditions

**Isothermal autogravitating sphere in equilibrium**

The density is no longer uniform, but goes as $r^{-2}$:

$$\rho(r) = \left(\frac{a_0^2}{2\pi G}\right) r^{-2}$$

The sphere has infinite density at the center:

**Singular Isothermal Sphere (SIS)**

The gravitational collapse begins at the densest point, in the center, and it propagates outwards at the sound speed: “inside-out collapse” model.

The inner part of the envelope that is collapsing has a density characteristic of free-fall, $\rho(r) \propto r^{-1.5}$.

The accretion rate is constant, and depends on the sound speed $a_0$.

The protostar mass grows linearly with time,

$$M_*(t) = \dot{M} t.$$  

and the accretion luminosity is $L_* = GM_*(t)M / R_*$. 
Gravitational collapse example: VLA 1623

For $T = 20$ K, the isothermal sound speed is $a_0 = \left(\frac{kT}{\mu m_H}\right)^{1/2} = 0.34$ km s$^{-1}$. The mass accretion rate is:

$$\dot{M} = \frac{0.975 a_0^3}{G} = 9.1 \times 10^{-6} \, M_\odot \, \text{año}^{-1}$$

Assuming a protostar radius of $5 \, R_\odot$, the luminosity of $1 \, L_\odot$ gives a protostar mass:

$$M_*(t) = \frac{L_*(t) R_*}{GM} = 1.7 \times 10^{-3} \, M_\odot,$$

$$t = \frac{M_*(t)}{\dot{M}} = 1.9 \times 10^3 \, \text{años},$$

**Time necessary to accrete** this mass: The protostar is extremely young.

The observed flux density at submm from the dust, allows the estimation of the envelope mass:

$$\left[ \frac{M}{M_\odot} \right] = 1.6 \times 10^{-6} \left[ \frac{\nu}{1000 \, \text{GHz}} \right]^{-2(2+\beta)} \left[ \frac{S_\nu}{\text{Jy}} \right] \left[ \frac{T_d}{\text{K}} \right]^{-1} \left[ \frac{D}{\text{pc}} \right]^{-2},$$

where $\nu = 682$ GHz, $S_\nu = 40$ Jy, $T_d = 20$ K y $D = 160$ pc,

$$M = 0.31 \, M_\odot.$$

Thus, the mass accreted onto the protostar is much lower than the envelope mass.

From the observed diameter, we can calculate the hydrogen column density:

$$\theta = 12''$$

$$R = \frac{1}{2} D \tan \theta = 1.4 \times 10^{16} \, \text{cm},$$

$$N(H_2) = \frac{M}{\pi R^2} = 2.8 \times 10^{23} \, \text{cm}^{-2}.$$ 

Extinction in the visible (proportional to column density) is very high (the object is deeply embedded):

$$\left[ \frac{A_v}{\text{mag}} \right] = 1.1 \times 10^{-21} \left[ \frac{N(H_2)}{\text{cm}^{-2}} \right] = 310 \, \text{mag},$$

Fit for $T_d = 20$ K, $\beta = 1.5$, $L = 1 \, L_\odot$.
The observation of high-mass star formation is much more difficult than for low-mass stars:

- High-mass star-forming regions are farther than low-mass. The closest is the Orion molecular cloud, at 500 pc (compared with Taurus at 140 pc)
- High-mass protostars evolve much faster than low-mass. So it is more difficult to find a young high-mass stellar object than a low-mass
- High-mass stars never form in isolation. They always form in clusters
- Once a high-mass star begins to burn hydrogen, an HII region is formed that can disrupt the molecular cloud. This can produce induced star formation
Shu's standard model CANNOT form stars of more than \( \sim 10 \, M_{\text{sol}} \)

Accretion characteristic time (free-fall time)

\[
t_{\text{ff}} = \left( \frac{3\pi}{32G\rho} \right)^{1/2}
\]

only depends on density. For a dense core, \( n=10^4 \, \text{cm}^{-3}, \, t_{\text{ff}}=4\times10^5 \, \text{yr} \)

Characteristic time for the protostellar core contraction (Kelvin-Helmholtz time)

\[
t_{\text{KH}} = \frac{R_*}{(dR_*/dt)}
\]

\[
L_* = d\Omega_G/dt = d(-GM_*/R_*)/dt = (-GM_*^2/R_*^2) \, dR_*/dt
\]

\[
t_{\text{KH}} = \frac{G \, M_*^2}{R_* \, L_*}
\]

For a low-mass star \( t_{\text{KH}} \gg t_{\text{ff}} \) (for a 1 \( M_{\text{sol}} \) star, \( t_{\text{KH}} = 3\times10^7 \, \text{yr} \))

The protostar becomes a pre-main sequence star (T Tauri star).

However, for a high-mass star \( t_{\text{KH}} \ll t_{\text{ff}} \) (for a 50 \( M_{\text{sol}} \) star, \( t_{\text{KH}} = 3\times10^4 \, \text{yr} \))

The star has not enough time to accrete more than \( \sim 10 \, M_{\text{sol}} \) before starting to burn hydrogen, ionizing the material around the star, and disrupting the dense core.
For a high-mass protostar radiation pressure acting on dust grains can become large enough to reverse the infall of matter:

\[ F_{\text{grav}} = \frac{G M_* m}{r^2} \]

\[ F_{\text{rad}} = \frac{L \sigma}{4 \pi r^2 c} \]
How can high-mass stars be formed?

Eta Carinae, one of the most massive stars known, with a mass between 100 and 150 $M_{\text{sol}}$ and a luminosity of $4 \times 10^6 L_{\text{sol}}$. 

---

**Eta Carinae**

PRC96-23a • ST ScI OPO • June 10, 1996

J. Morse (U. CO), K. Davidson, (U. MN), NASA
How can high-mass stars be formed?

Non-spherical accretion
- Very high mass-accretion rates
- Reduce the effective luminosity by making the radiation field anisotropic

Coalescence of lower-mass stars in a stellar cluster
- Problem with cross section for coalescence.
- Observational consequences of such collisions?
High-mass star formation

Competitive accretion and coalescence in a stellar cluster

Formation of a cluster of protostellar cores
Competitive accretion in a cluster
Coalescence at the cluster center
H ignition, HII region induced SF

Model d’acreció competitiva i coalescència: $M \geq 50 M_\odot$, Duració = 0,1 Ma

<table>
<thead>
<tr>
<th>Fase preestel·lar</th>
<th>Fase d’acreció competitiva</th>
<th>Fase de coalescència</th>
<th>Fusió de l’hidrogen i nova formació estel·lar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esfondrament de diversos nuclis densos i formació de nuclis protoestel·lars a les parts més denses d’un núvol molecular.</td>
<td>Les protoestrelles competeixen per acseat gas del seu embol·call i del núvol molecular comú. Les estrelles que són al centre del núvol s’emporten més material.</td>
<td>Al centre del núvol la densitat estel·lar és suficient perquè s’uneixin dos o més nuclis protoestel·lars i provoquin l’ejecció de matèria en forma explosiva i la fragmentació del disc.</td>
<td>El nucli protoestel·lar sorgit per coalescència ha guanyat molta massa i arriba de seguida a la temperatura de fusió de l’hidrogen, emetent radiació ultraviolada i ionitzant el gas circumdant. L’expansió del gas ionitzat pot induir la formació de noves estrelles.</td>
</tr>
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5 anys llum
High-mass star formation

Non-spherical accretion through the equatorial region

Dense core fast collapse    High rate accretion and outflow    H ignition, HCHII    HII region, induced SF

Model d’esfondrament monolític amb rotació per $8 M_\odot < M \leq 30 M_\odot$. Duració = 0,5 Ma

Fase preestel·lar
Esfondrament d’un nucli dens en rotació en un medi turbulent i formació d’un nucli protoestel·lar.

Fase protoestel·lar
L’embolcall del nucli dens cau cap al nucli protoestel·lar, envoltat pel disc d’acreció. La ràpida acreció fa que l’embolcall s’escafi molt. El ritme d’ejecció de material és elevat.

Fusió de l’hidrogen al nucli protoestel·lar
La fusió de l’hidrogen (que emet radiació ultraviolada) fa que s’ionitzi el material de l’embolcall, que cau sobre el disc. A mesura que cau l’embolcall es fa menys dens, el gas ionitzat s’expandeix i frena la caiguda de material.

Desenvolupament d’una regió d’hidrogen ionitzat
El gas ionitzat empren cap a l’exterior les restes del material de l’embolcall i queda l’estrella massiva envoltada de gas ionitzat.
Bipolar outflow, disk in rotation, gravitational infall

G24.78+0.08, a clear example

The inner material is infalling toward the central protostar

NH$_3$

Main line: optically thick line. Traces the outer material, facing the observer.

Satellite line: optically thinner line. Traces the inner material.