Star Formation

Stars form in dense, dusty gas

Giant molecular cloud	~50 pc	~10^5 $M_\odot$	~10^8 m^{-3}
Dense core of GMC	~1 pc	~100 $M_\odot$	~10^{14} m^{-3}
Bok globule	~1 pc	~10 $M_\odot$	~10^{12} m^{-3}

Sun: ~10^{-8} pc, ~10^{32} m^{-3}

Stars form by gravitational collapse

- A necessary condition for gravitational collapse
- The Jeans criterion (1877-1946)
- Stable, gravitationally bound system satisfies the virial theorem $E_{kin} + \frac{1}{2}E_{pot} = 0$
- The cloud will collapse only if $E_{kin} + \frac{1}{2}E_{pot} < 0$

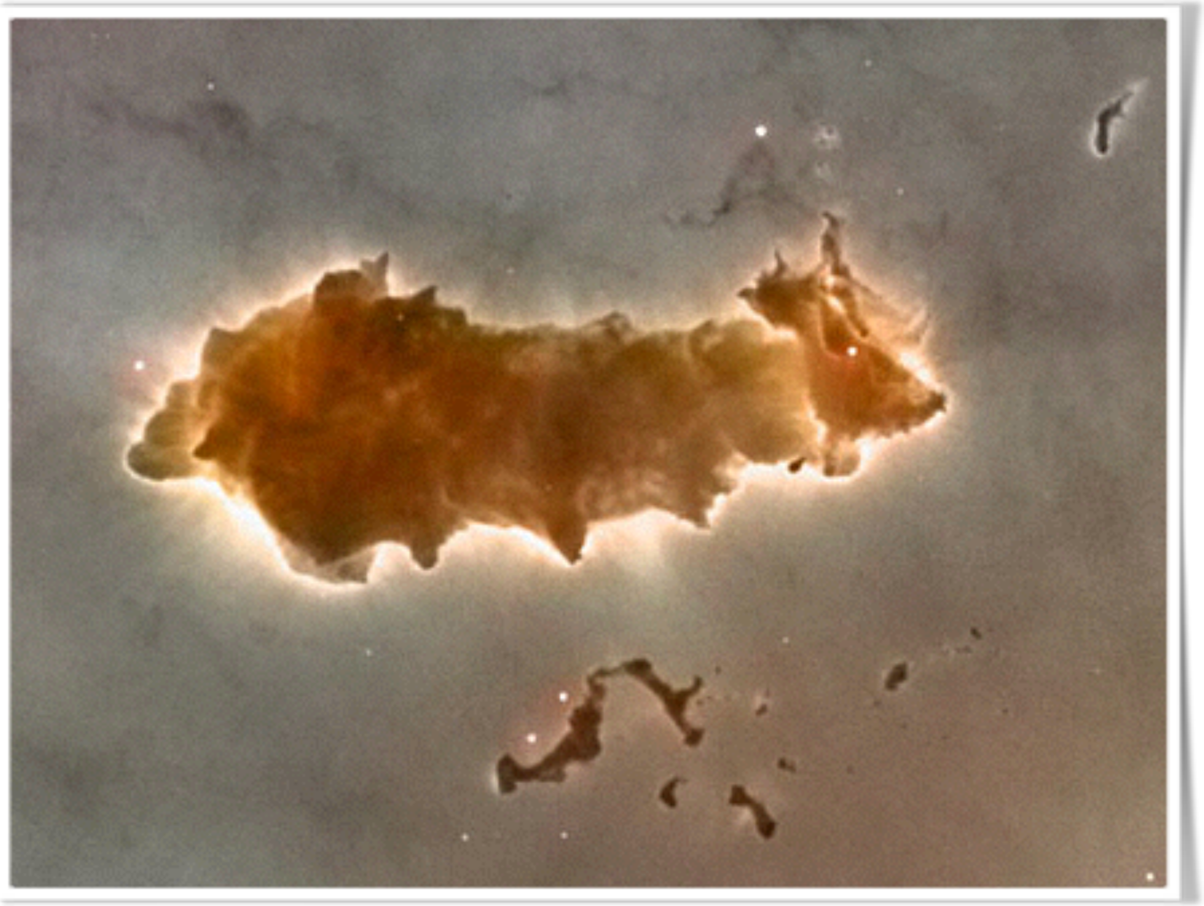
$$E_{\text{pot}} = -\frac{3}{5}\frac{GM^2}{R} \qquad E_{\text{kin}} = \frac{3}{2}NkT = \frac{3}{2}\frac{M}{\mu m_H}kT$$

$$E_{\text{kin}} < -\frac{E_{\text{pot}}}{2} \quad \longrightarrow \quad \boxed{M > M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}}$$

"Jeans mass"

Stars Form by Gravitational Collapse

Knowing the temperature and density of a cloud, we know the minimum mass it has to have in order to collapse under its own weight



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

Hotter → more pressure support → need more mass

Denser → need less mass

Diffuse hydrogen cloud, typically $< 10^2\ M_\odot$	$T \sim 50$ K	$n \sim 5 \times 10^8\ m^{-3}$	$M_J \sim 1500\ M_\odot$
GMC dense core, typically $10^2\ M_\odot$	$T \sim 150$ K	$n \sim 10^{14}\ m^{-3}$	$M_J \sim 17\ M_\odot$
Barnard 68 Dark cloud, $\sim 3\ M_\odot$	$T \sim 10$ K	$n \sim 10^{12}\ m^{-3}$	$M_J \sim 3\ M_\odot$

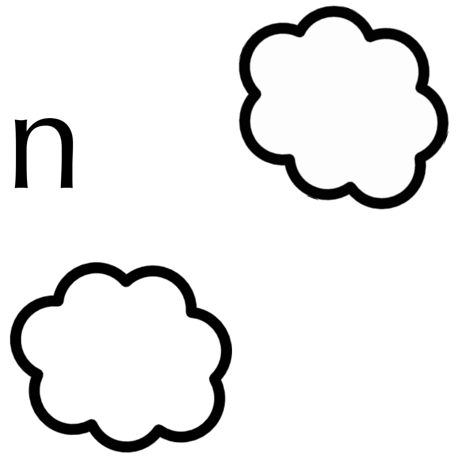
What happens during collapse?

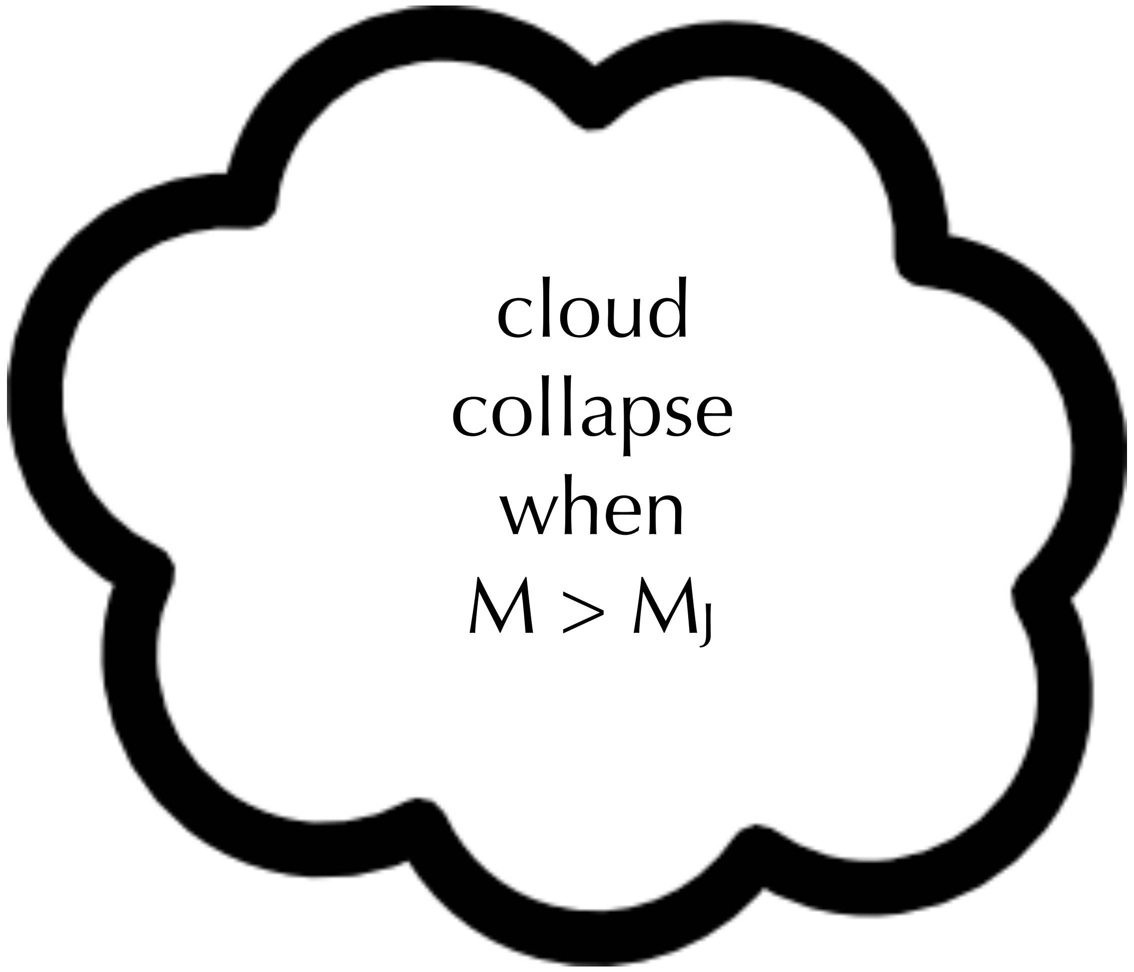
- First stage: free-fall (dynamical timescale)
  - gravity overcomes the pressure support
  - nearly free-fall collapse, $t \sim t_{dyn} \sim (G\rho)^{-1/2} \sim 10^3$ yr for dense core of GMC
    - center of the cloud higher density ➞ collapse faster ➞ central cusp
    - temperature of the cloud remains ~ constant (isothermal)
    - gravitational energy release is lost to the outside
      - this is possible as long as the cloud is still transparent to its own radiation
  - fragmentation occurs due to decreasing Jeans mass: $M_J \propto T^{3/2}\rho^{-1/2}$

The Cygnus Wall of Star Formation

Credit & Copyright: Michael Sherick

Cloud fragmentation





collapse is isothermal
(constant temperature)

↓

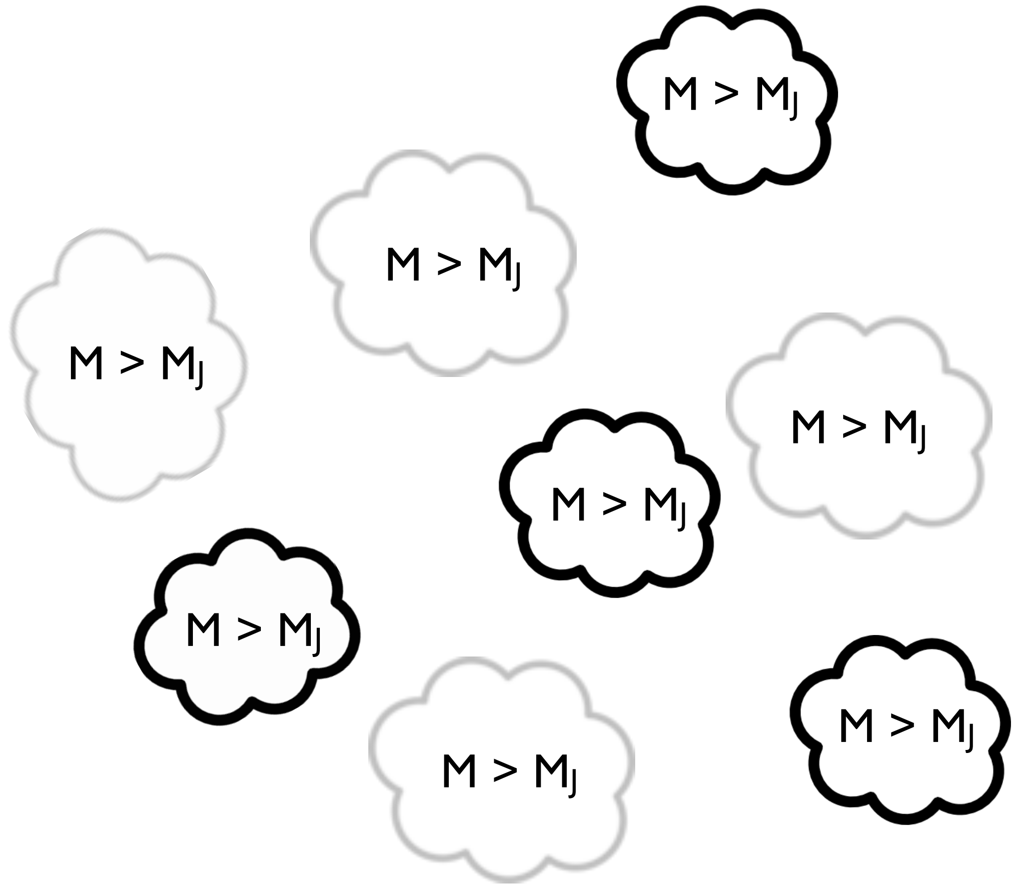
density increases

↓

Jeans mass decreases,
$$M_J \propto T^{3/2}\rho^{-1/2}$$

↓

smaller parts of cloud
become unstable,
can collapse



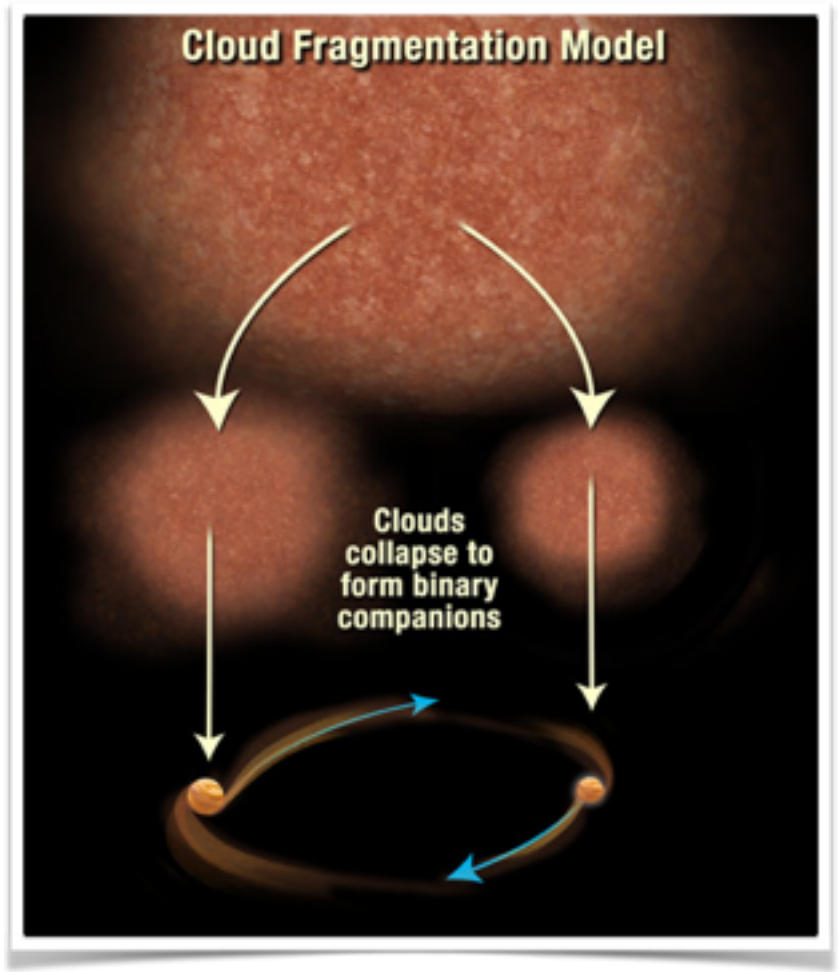
What happens during collapse?

- Second stage: pre-main-sequence (thermal timescale)
  - further contraction, cloud becomes optically thick (heat not lost instantly)
  - free-fall and fragmentation stop, contracts slowly as heat diffuses out
    - $t_{KH} \sim E/L \sim 10^7$ yr for 1 $M_\odot$
      - longer or shorter for higher/lower mass stars?
      - Kelvin-Helmholtz timescale: gravitational potential energy is the source of luminosity, released over time
      - tKH >> tff
      - timescale is longer for low mass stars, shorter for higher mass stars
    - strong stellar wind ($\sim 10^{-8}$ $M_\odot$/yr)
    - high angular momentum material forms disk
      - viscosity in the disk moves material inward
      - jets, stellar UV photons and winds disperse disk/cloud

- Third stage: main-sequence stars (nuclear timescale)
  - central temperature so hot that H burning starts, $t \sim t_{nuc} \sim Mc^2/L$

Distribution of stellar masses

- Star formation tends to form low mass stars
- Final stellar mass is not the initial M_J
- Fragmentation
  - Isothermal collapse phase, T constant, ρ increases ➞ M_J decreases
  - An initially collapsing cloud can fragment ➞ lighter stars
  - Fragmentation stops when isothermal phase stops
- Angular momentum
  - $d \sim 1$ pc ➞ $d \sim 10^{-8}$ pc
  - forming binary stars, triple stars....
- Observed:
  - 20 times as many stars $< 1\ M_\odot$ than $> 1\ M_\odot$ (to $0.1\ M_\odot$)
  - Average mass of a star $\sim 0.3\ M_\odot$
  - Distribution of stellar masses is called the initial mass function (IMF)



NASA, ESA, and A. Feild (STScI)

Star formation in galaxies

- The Milky Way is forming stars at a rate of ~1 $M_\odot$/yr
- Each star takes ~10^6 yr to mature to main sequence
- 10^{10} $M_\odot$ of gas, turned into stars at ~1 $M_\odot$/yr, can last 10^{10} yrs
  - Star formation can last longer - why?
- Some galaxies form stars at much higher rates, > 100 $M_\odot$/yr
  - "starburst galaxies"