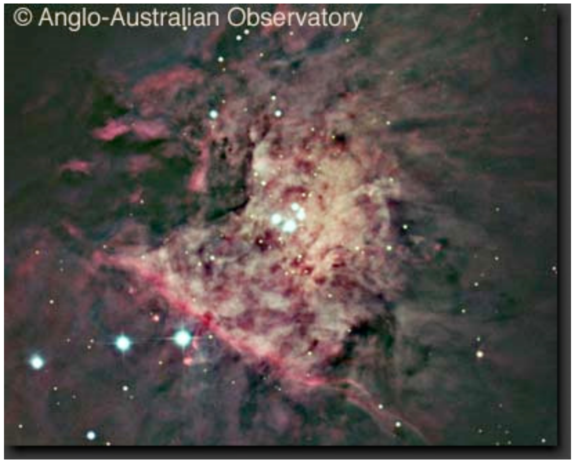
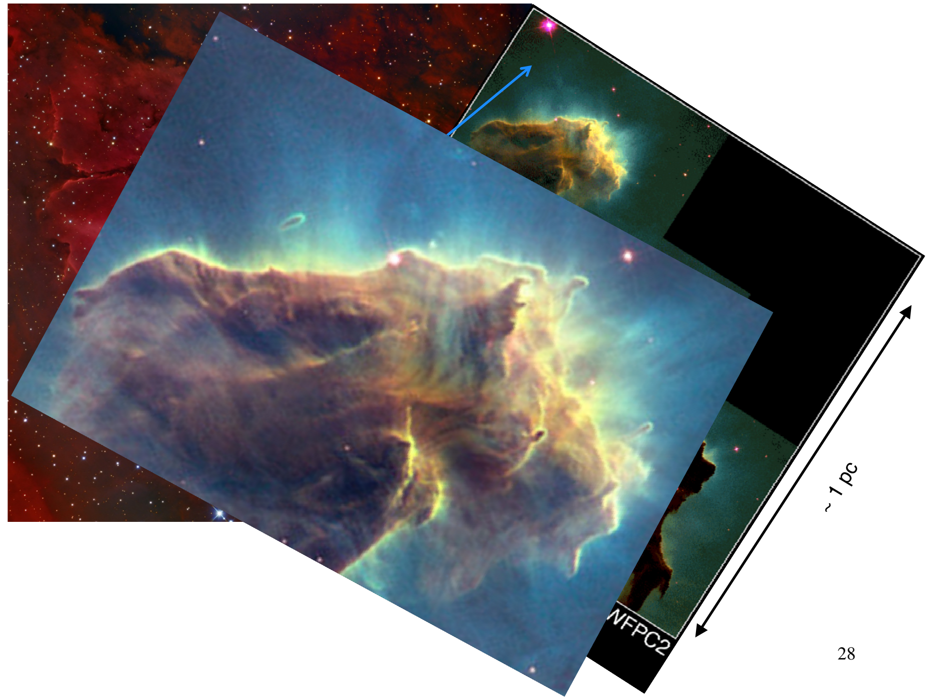
Star Formation



Motivating star formation: we see young star clusters (and HII regions) embedded in regions of dense molecular gas



Star formation

(sections 18.3-18.8)

- Gravitational collapse
  - Start with a collection of matter (e.g. a molecular cloud) somewhere in space and let gravity work on it. What happens?
  - It will collapse eventually unless something resists it (e.g. Sun isn't collapsing).
- What can resist gravitational collapse?
  - Gas pressure (particles in collapsing gas run into each other)
  - Radiation pressure (if matter becomes hot enough)
  - Magnetic pressure
  - Angular momentum (keeps stuff spinning instead of collapsing)
  - Turbulence
  - Dispersal due to, e.g., winds or supernovae from existing stars
- Collapse if gravity stronger than these effects.

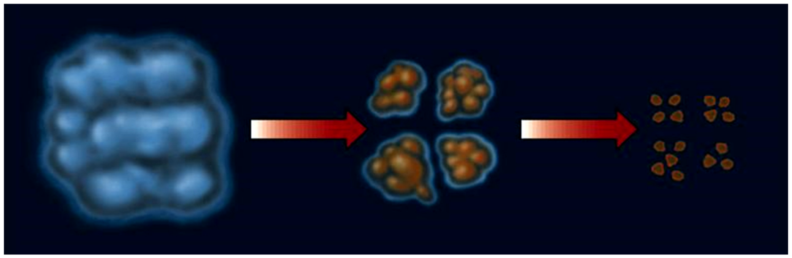
- Molecular clouds (or parts thereof) are coldest and densest clouds, where gravity seems to be winning. Although other parts of a cloud may be stable, or getting dispersed. Whole clouds live "only" ~ 30 Myr.

- So gravitational collapse and star formation happens in molecular clouds (yet how much denser is a star than a molecular cloud?)

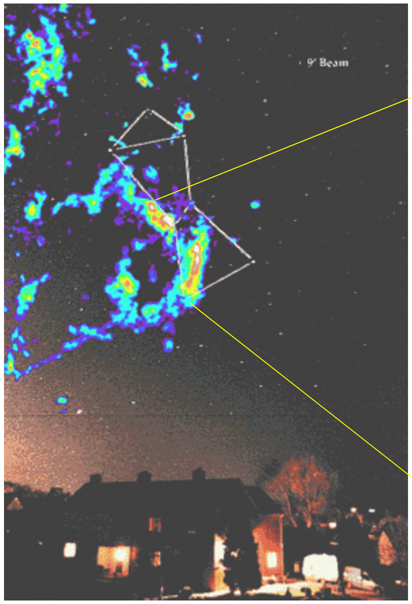
- Molecular clouds observed to be clumpy – structure on many scales

- Clusters of new stars are observed in some of them

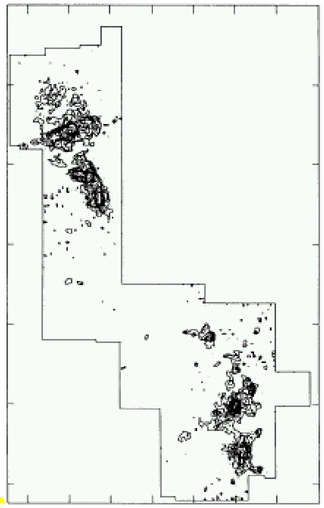
- If a clumpy cloud does collapse, clumps eventually start collapsing faster on their own, and cloud fragments (Jeans 1902). Fragments continue to collapse, they fragment, etc.



Map of CO emission in Orion molecular cloud



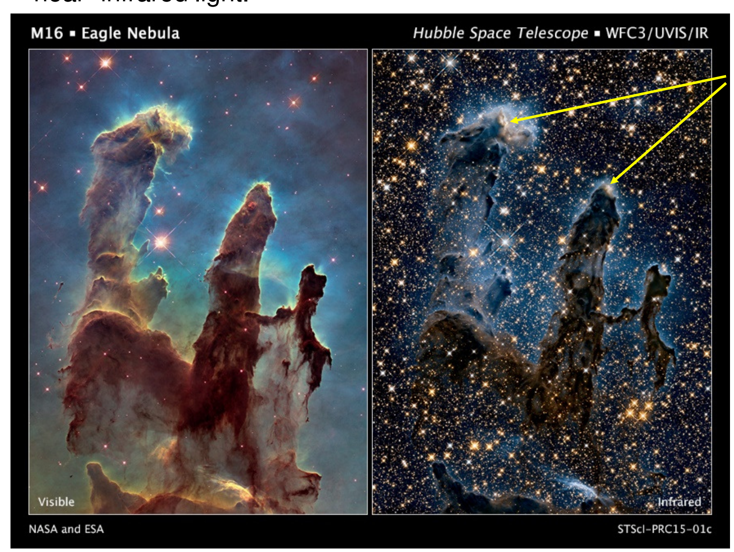
Map of CS emission in part of it, showing fragments about 10^2 - 10^3 x denser than average gas in cloud.



Optically, such dense clumps might appear as dark "Bok globules"

- Now follow one fragment. Destined to form star (or binary, etc.)
- First, gravity dominates and collapse is almost *free-fall*. Molecules are gaining energy of motion! Energy shared and turned into random motions by collisions. Energy initially escapes as radiation (in molecular rotational transitions), temperature rises little. This stage takes millions of years.
- Once density high enough, radiation has trouble escaping, T starts to rise, pressure ($P = nkT$) begins to slow collapse. Spectrum starts to become blackbody (hot dense objects). Can now call them "protostars".
- Protostars still cooler than stars, and generally embedded in much gas and dust – best seen in <u>infrared</u> for both reasons. But they become very luminous, driven by conversion of gravitational potential energy.

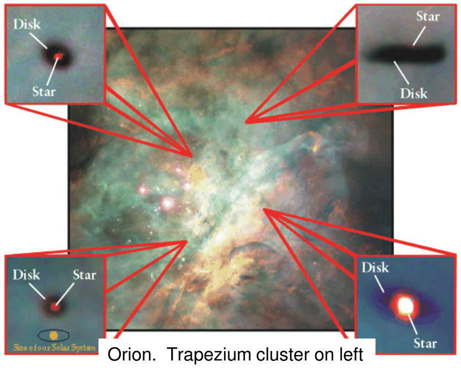
This gravitational collapse of clumps within a larger cloud to make protostars is happening in the Eagle Nebula, best revealed in "near" infrared light.



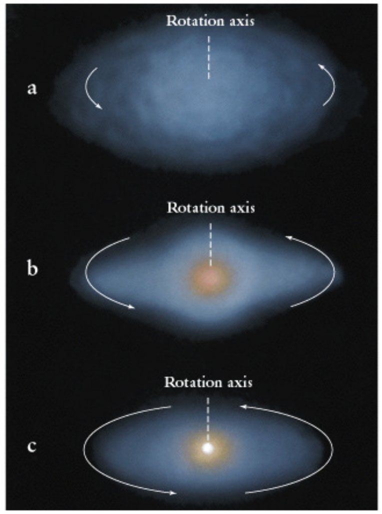
protostars not seen in visible light

- Initial rotation and conservation of angular momentum will cause the formation of a flattened disk around the forming star. Disk material feeds protostar ("accretion disk").

We observe these with HST!

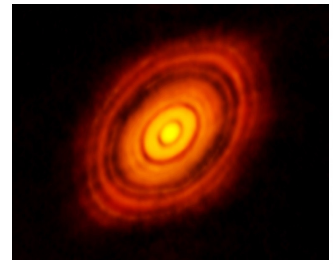


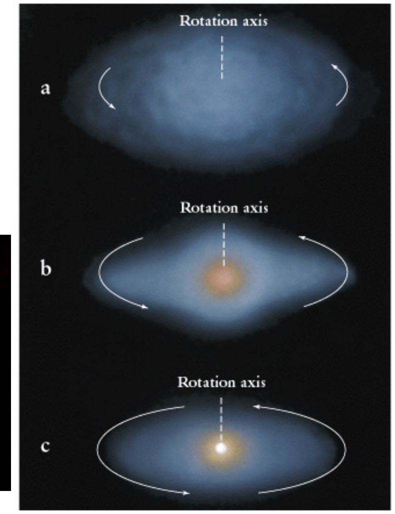
Orion. Trapezium cluster on left



- At some point the luminosity is large enough to blow away most of the surrounding gas. Strong winds observed in protostars ("T Tauri stars" and "Herbig-Haro objects"). Most gas never made it onto star. Planets may form in protostellar disk if it survives.

HL Tau proto-planetary disk, with ALMA. This is dust emission at 1.3mm Wavelength.



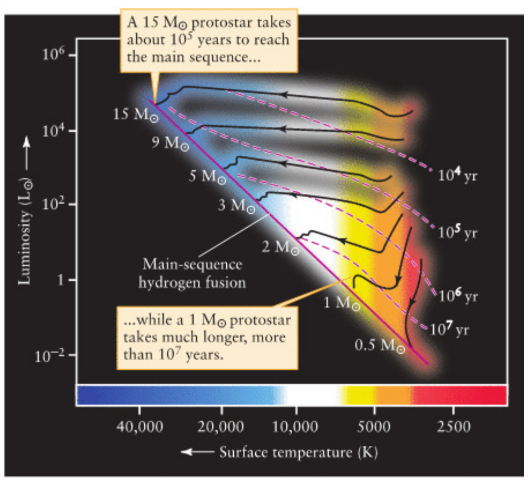


- Finally, protostar core hot enough to ignite nuclear H fusion. It becomes a star. Pressure from fusion stops collapse => stable.

- Once sufficiently hot and dense, can follow evolution on H-R diagram. Theory worked out by Hayashi = > Hayashi tracks.

- Basic evolution is to lower radii and higher surface temperatures. Luminosities of low-mass protostars large.

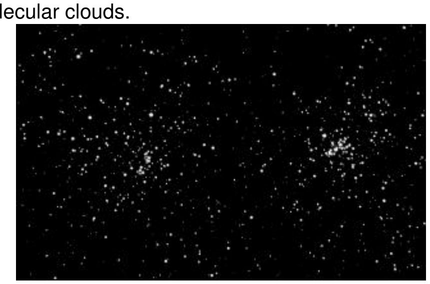
- Lower mass stars take longer to contract and reach Main Sequence.



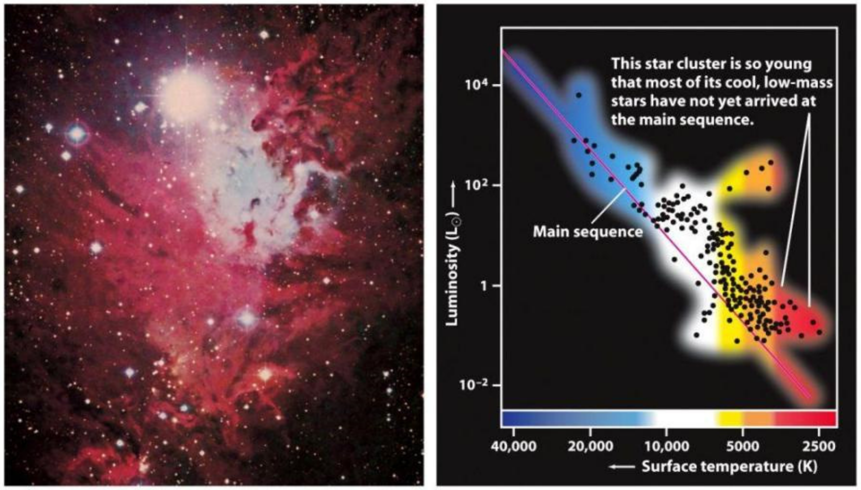
Open clusters provide evidence for the theory

- Stars tend to form in groups or in *clusters*, presumably due to fragmentation
- Clusters very useful because all stars form at about the same time and are at the same distance.
- There are two types of clusters – *open* and *globular*.
- Open clusters
  - Newly formed, 10^2 - 10^4 stars.
  - Confined to the disk of the Galaxy
  - Often associated with HII regions and molecular clouds.

The double cluster H and χ Persei.

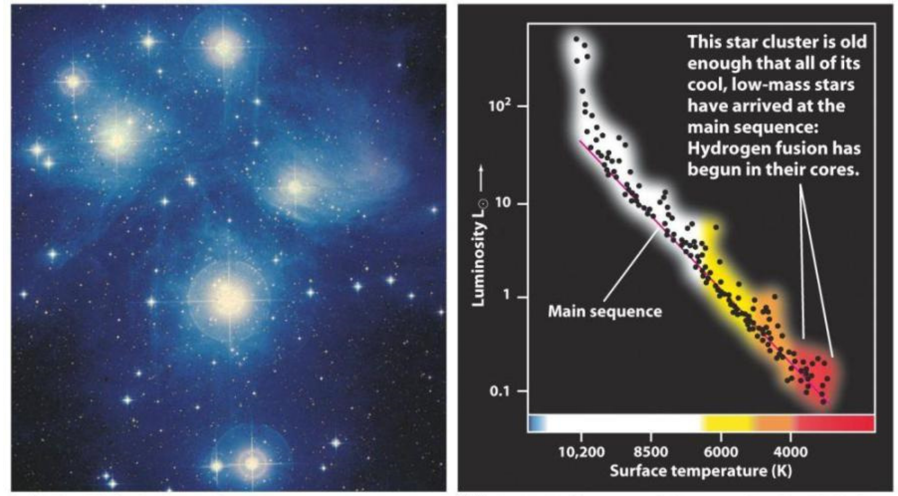


A young open star cluster – note that low mass stars haven't quite reached main sequence yet.



(a) The star cluster NGC 2264 **(b)** An H-R diagram of the stars in NGC 2264

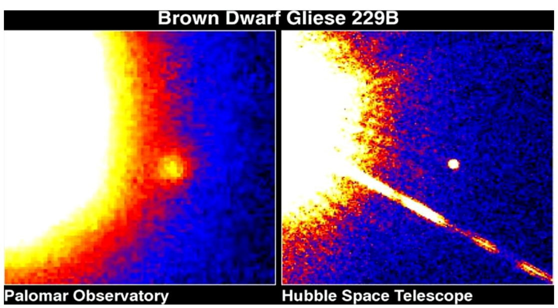
The Pleiades are older. All stars have reached the main sequence. Highest mass ones are already evolving off.



(a) The Pleiades star cluster **(b)** An H-R diagram of the stars in the Pleiades

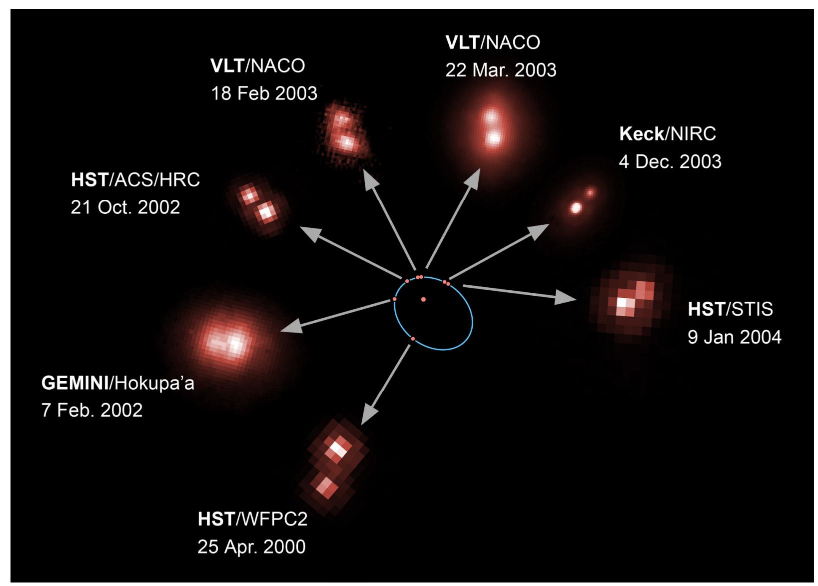
Brown Dwarfs

Some protostars not massive (< 0.08 M⊙) enough to begin fusion. These are Brown Dwarfs or failed stars. Very difficult to detect because so faint and cool. Best seen in infrared. First seen in 1994. Now ~2000 known.



Brown dwarfs slowly cool off by radiating internal heat.

Two new spectral classes, L (T<2500 K) and T (T<1300 K) were created. Recently, Y (roughly 300<T<500) proposed.



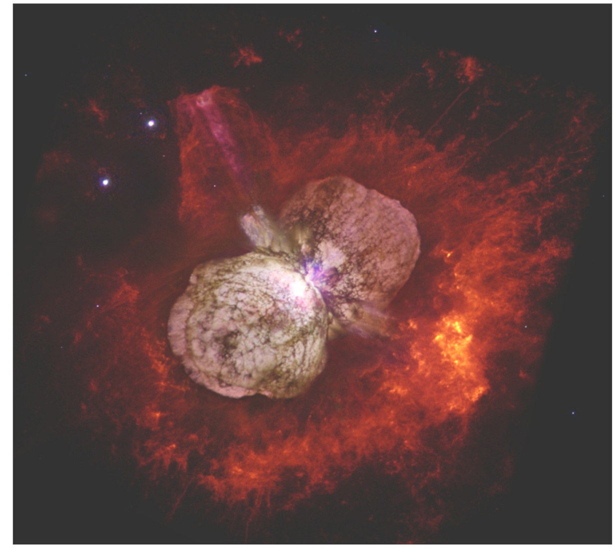
- Mass of star measured to be $0.085M_\odot$, mass of brown dwarf $0.066M_\odot$

Brown dwarfs in Orion

- IR image showing brown dwarfs in the Orion constellation.
- Easiest to spot in star forming regions, since they are still young and more luminous.

What is most massive star possible? If too massive, radiation pressure overwhelms gravity, drives matter out. Never forms stable star.

Eta Carinae with HST.
M ~ 100 – 150 $M_\odot$



Initial Mass Function (IMF)

Do more low mass or high mass stars form? Number of stars formed as function of mass follows a "power law":

$N(M) \; \alpha \; M^{-2.3}$ for $M > 0.5 \, M_\odot$

IMF "turns over" near 0.5 $M_\odot$