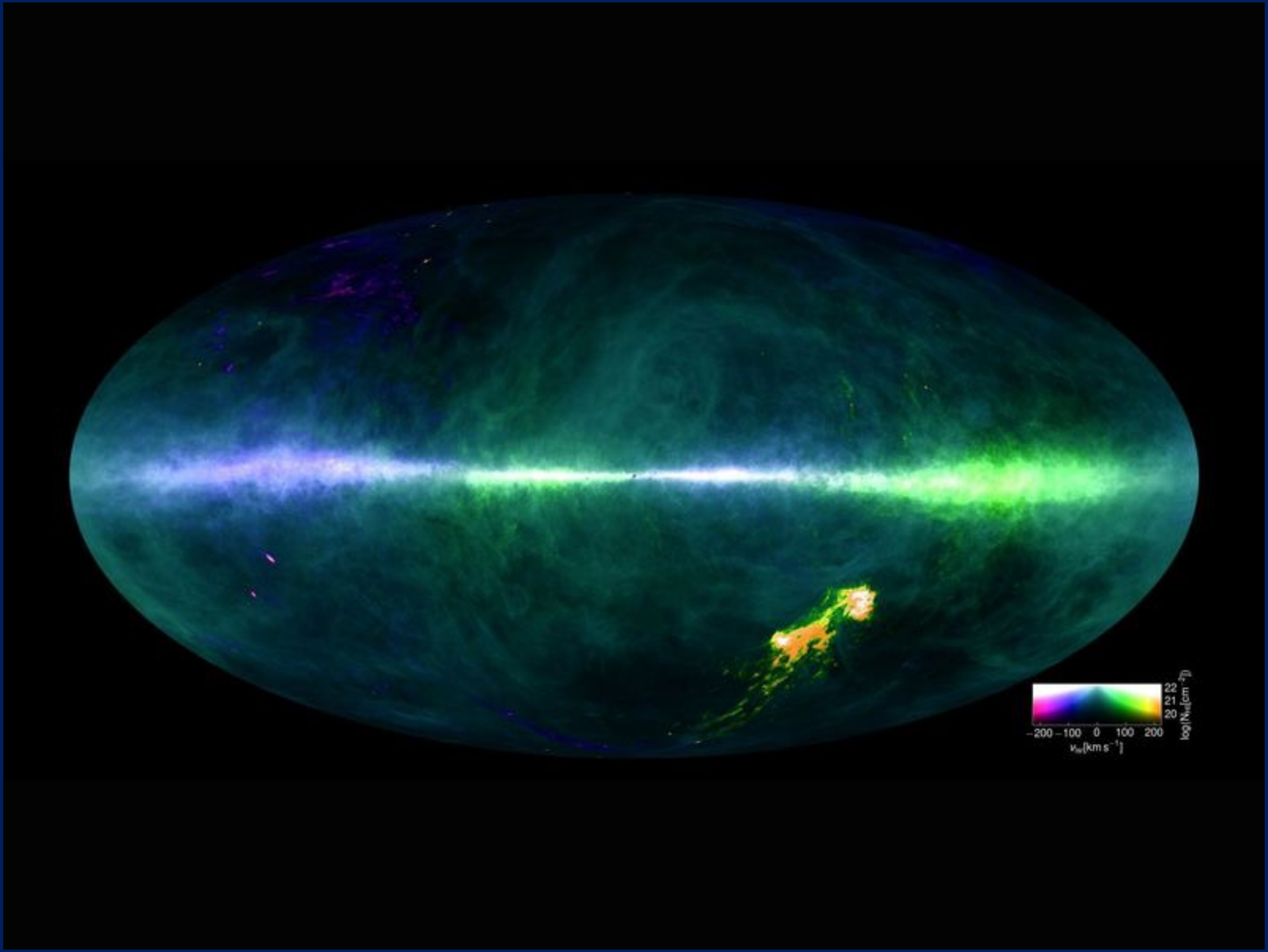
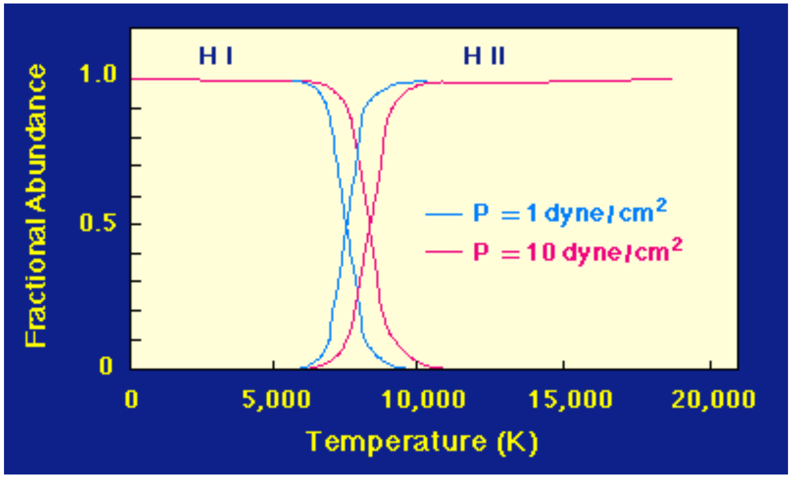
21-cm (1420 MHz) map of neutral hydrogen in the Milky Way



Component	**Phase**	**T(K)**	**n(cm^{-3})**
Neutral	Cold (molecular)	10-50	10^3-10^7
	Cool (atomic)	100	1
	Warm	8×10^3	10^{-1}
Ionized	Warm	10^4	10^0-10^4
	Hot	5×10^5	10^{-3}



Emission nebulae - HII regions

- *nebula* = cloud (plural nebulae)
- ~5000/cm^3 (diffuse)
- T≅10^4 K (H essentially completely ionized)
- Sizes 1-20pc

Rosette Nebula

Hot, tenuous gas => emission lines (Kirchoff's laws)

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In the Orion Nebula, the Trapezium Cluster stars provide energy for the whole nebula.

- UV energies are required to ionize the atoms
- Provided by hot and massive O, B stars
- e^- quickly recombine with the p
- Dominant emission $H\alpha$, at λ = 656 nm. Color?


© Anglo-Australian Obs./Royal Obs. Edinburgh

Lagoon Nebula


© Anglo-Australian Observatory

Tarantula Nebula

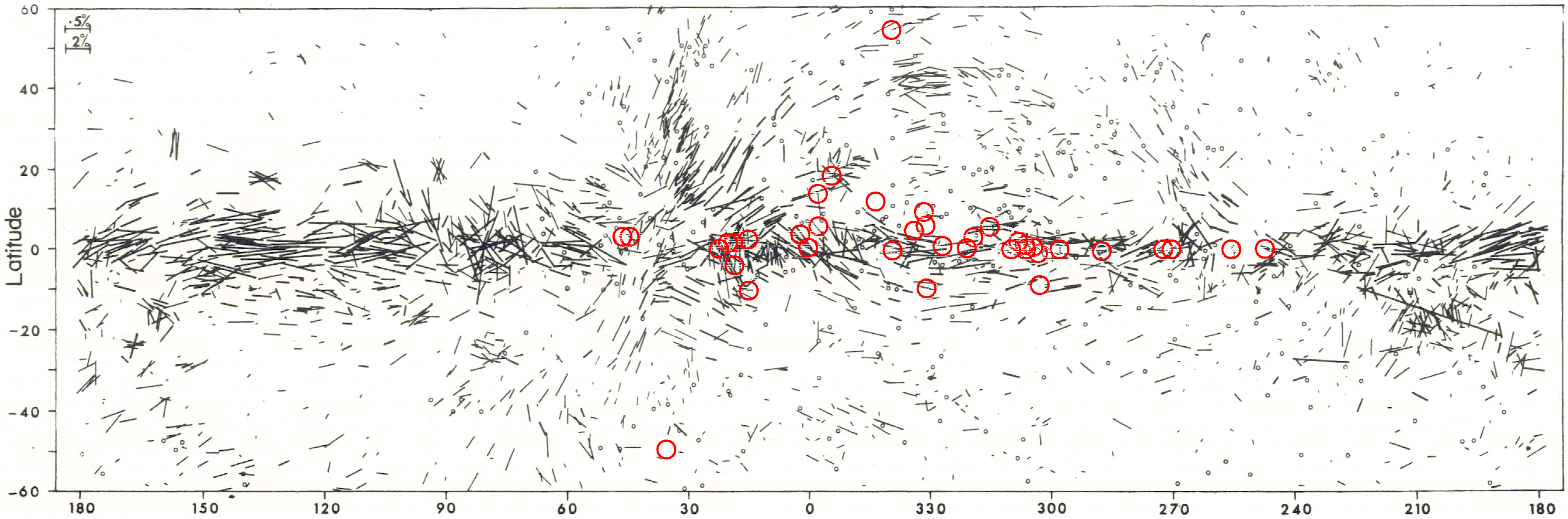
Reflection nebulae

- Blue color resulting from dust reflecting (scattering) light from nearby, bright hot stars
- Shorter wavelengths are most effectively scattered (why the sky is blue)

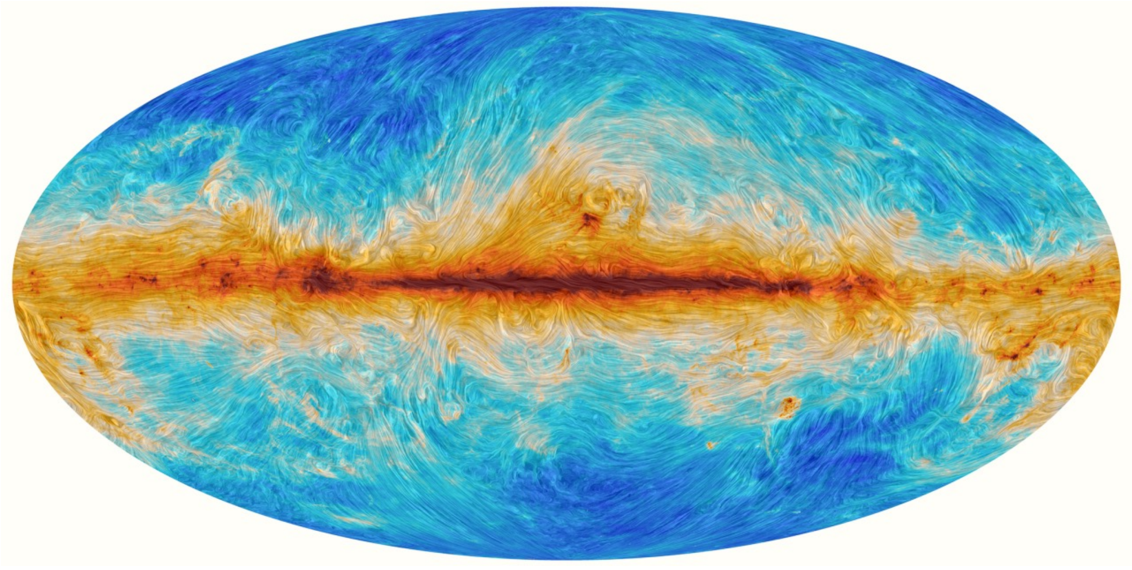
What kind of spectrum would you expect?

Other ISM components

- Hot gas X-ray emission; $T \cong 10^6$ K; very low density
- Cosmic Rays high energy particles, interact with B-fields ⇒radio emission
- Magnetic fields 10^{-3}-10^{-6} of Earth’s, widespread
- Supernova remnants radio, optical, x-ray
- Planetary Nebulae isolated objects – more later



- Polarization of starlight (direction and degree) – Mathewson 1970
- Indicates the presence of a large scale magnetic field



Planck all-sky map
showing polarization
of the dust emission

Which of these are involved with star formation?

-- HII regions, molecular clouds, dust clouds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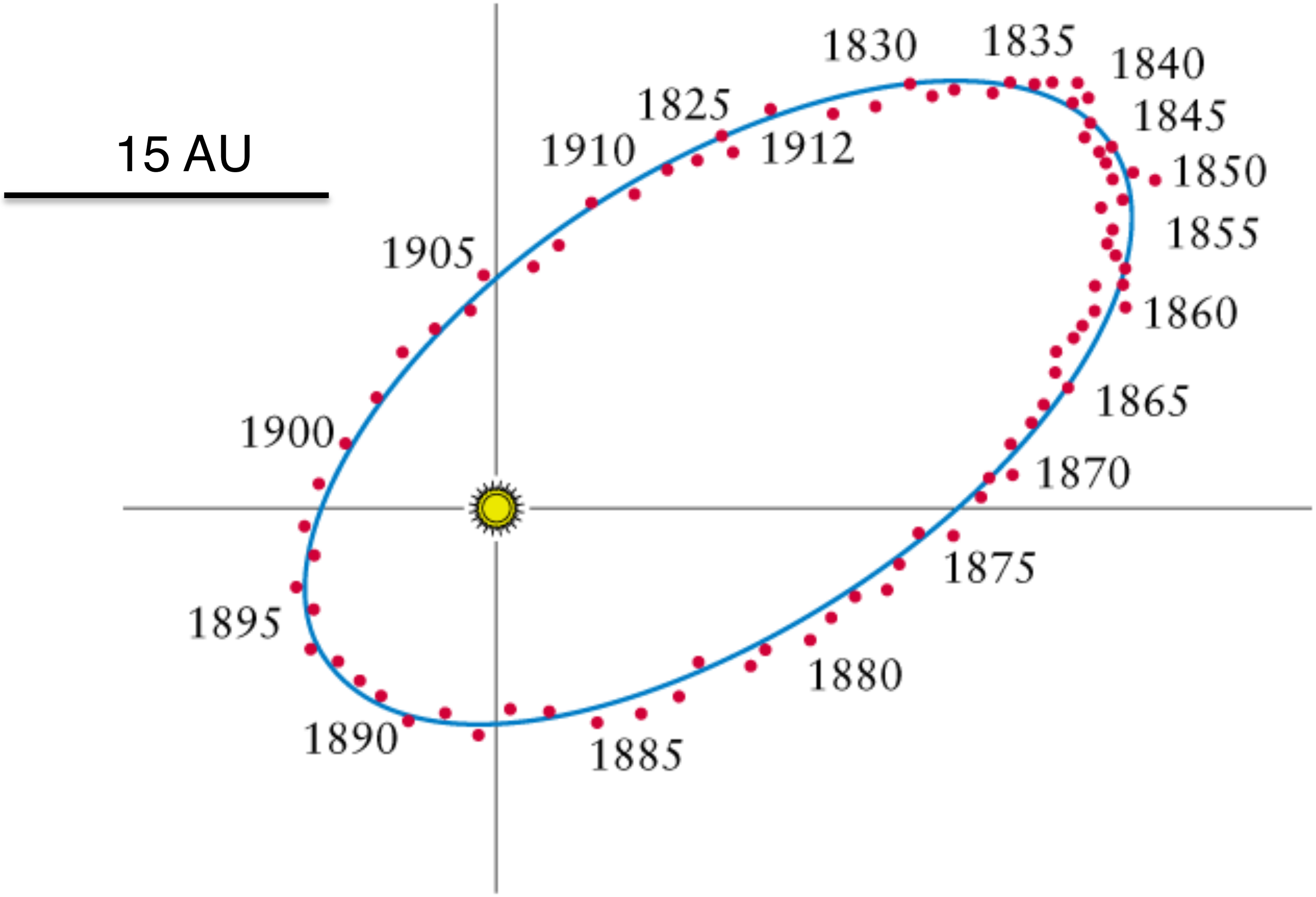
Binary star orbits ….

Worksheet: Calculate the total mass of the visual binary star system 70 Ophiuchi with orbit below.



Star formation

Chapter 18

Star formation

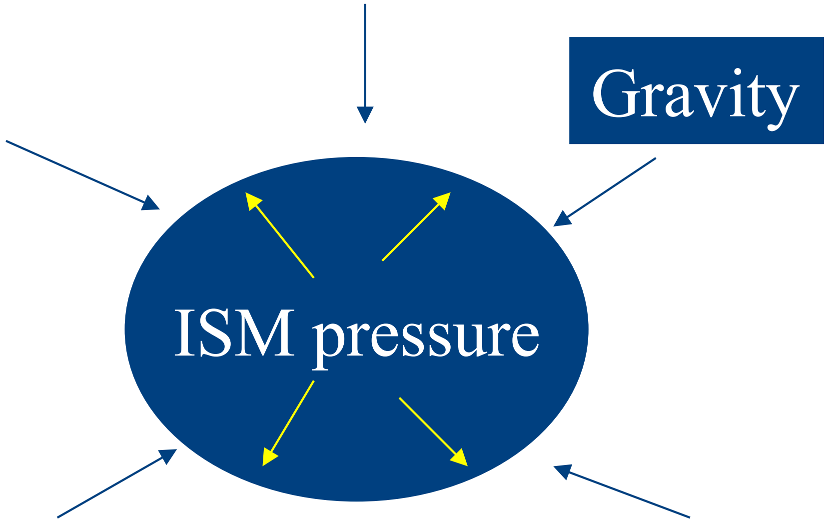
- Gravitational collapse
  - Start with a collection of matter (e.g. a molecular cloud) somewhere in space and let gravity work on it. What happens?
  - Unless matter distribution perfectly uniform and infinite it will collapse eventually unless something stops it.
- What can stop gravitational collapse?

Star formation

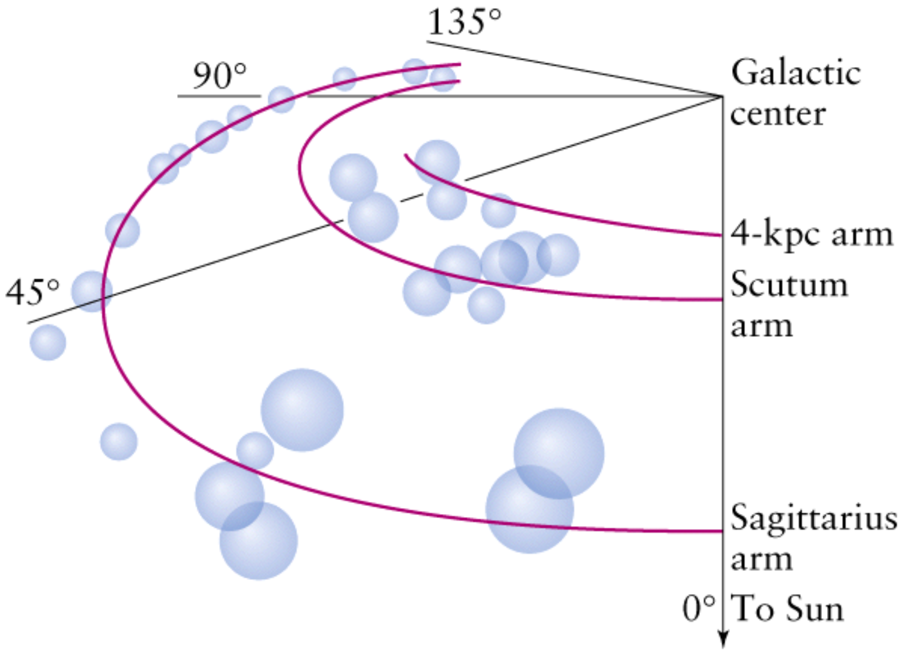
- Gravitational collapse
  - Start with a collection of matter (e.g. a molecular cloud) somewhere in space and let gravity work on it. What happens?
  - Unless matter distribution perfectly uniform and infinite it will collapse eventually unless something stops it.
- What can stop gravitational collapse?
  - Gas pressure (hitting the matter it is falling onto)
  - Radiation pressure (if matter becomes hot enough)
  - Magnetic pressure
  - Angular momentum (keeps stuff spinning instead of collapsing)
  - Electron degeneracy pressure

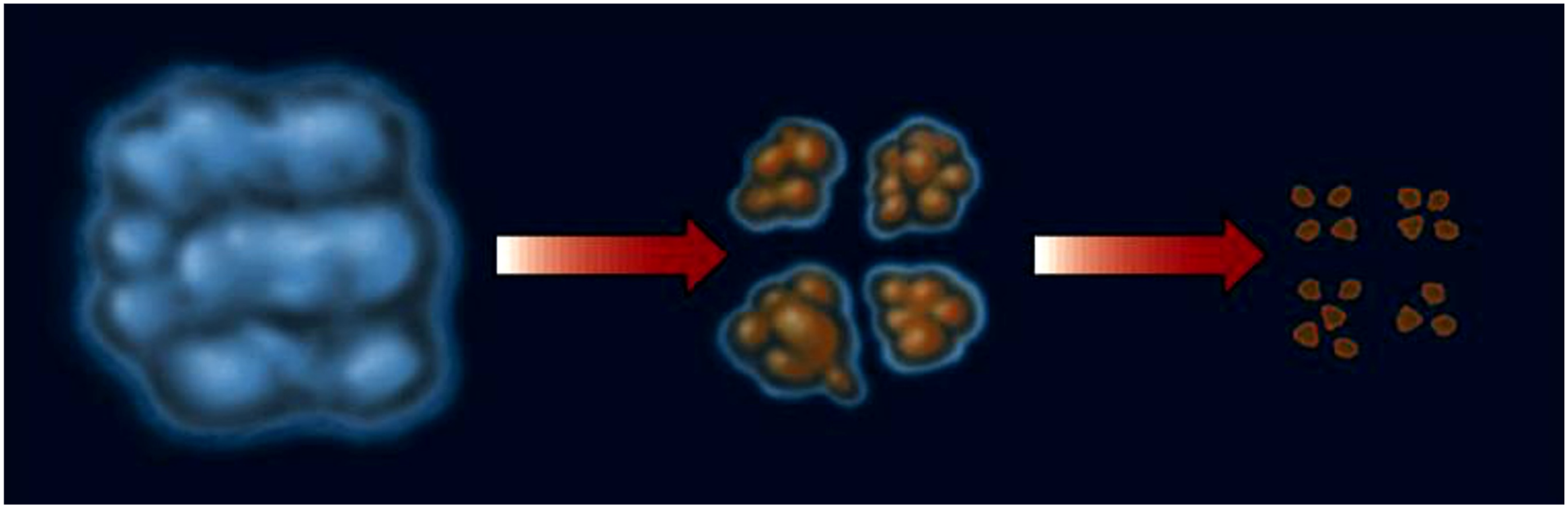
Stage 1: Cloud collapse

- Desired result: a star, with n~10^{24} cm^{-3}
- Resources: the interstellar medium (ISM), with n~10^5 - 10^7 cm^{-3} (dense molecular clouds)
- Recall: a cloud withstands gravitation by its internal pressure



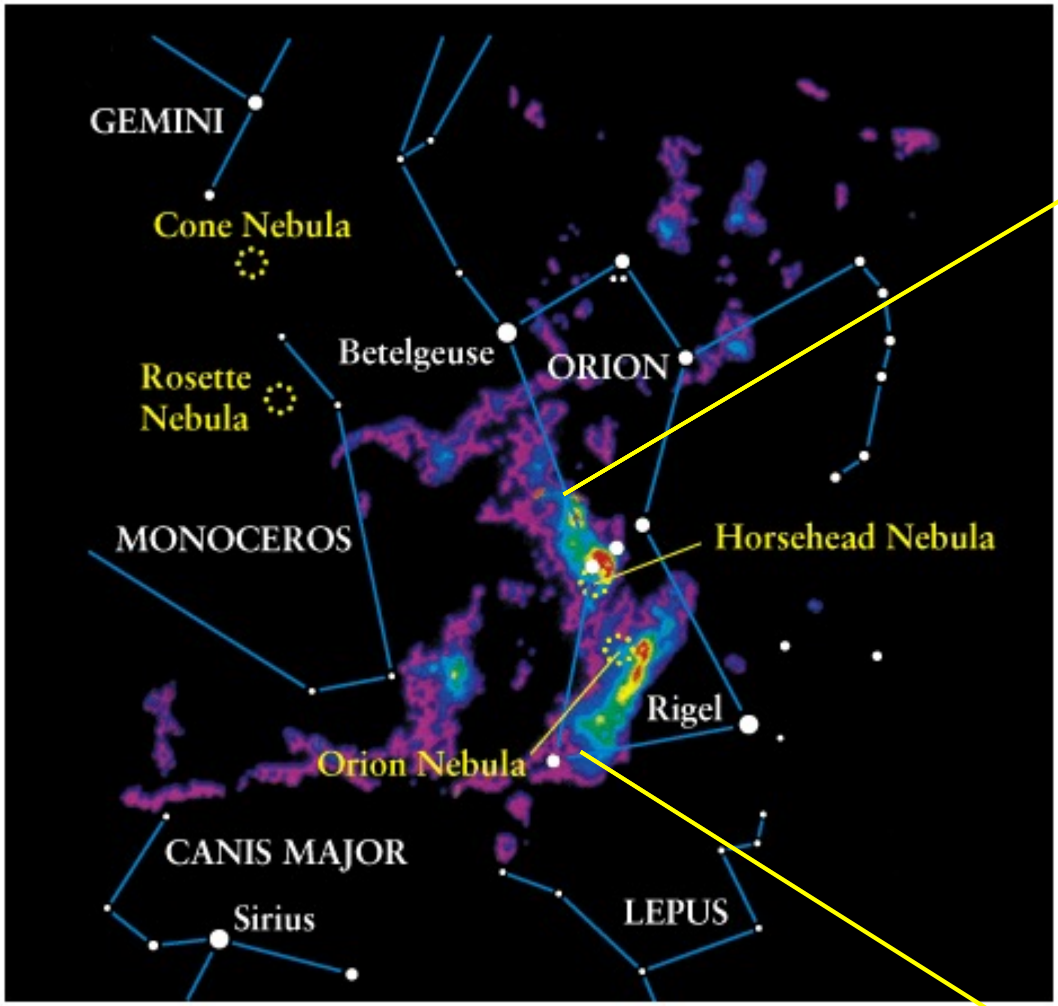
- Internal pressure sources: gas pressure from internal heat, radiation pressure, plus pressure from embedded magnetic fields
- A collapse (gravity>internal pressure) can be triggered by
  - Collisions with other clouds (cloud-cloud collisions)
  - Shocks from supernovas
  - Passage through a spiral arm in the Galaxy (density enhancement)

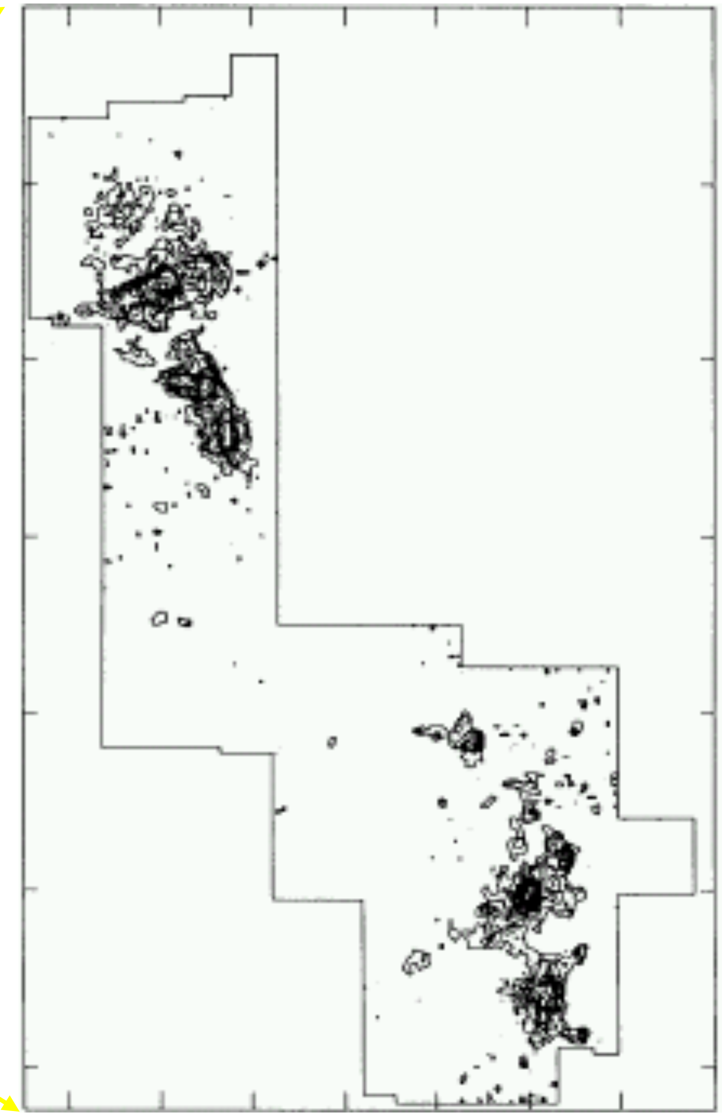




- Clouds are inhomogeneous - clumpy.
- Clumps start to collapse, densest clumps collapses first and fastest => fragmentation.
- 100s to 1000s of fragments may exist in one collapsing molecular cloud.

Fragments in Orion MC, about 1000 times denser than average gas in cloud.





- Bok globules are good examples of very small fragments of dense gas.

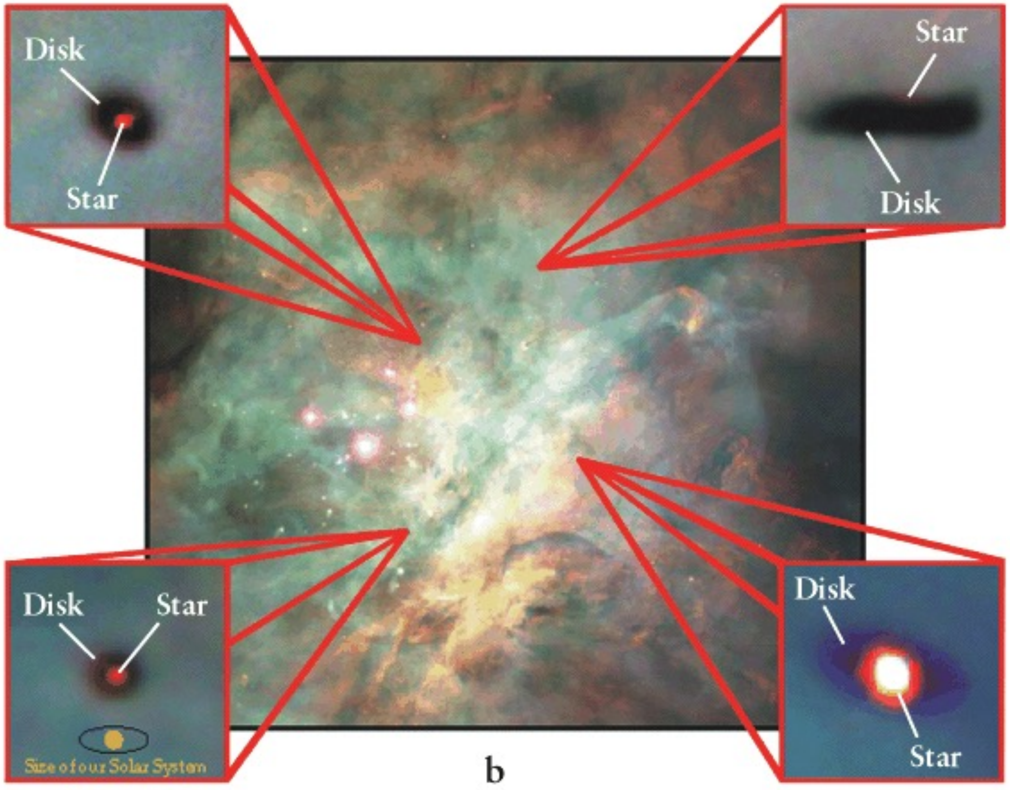
The Eagle nebula

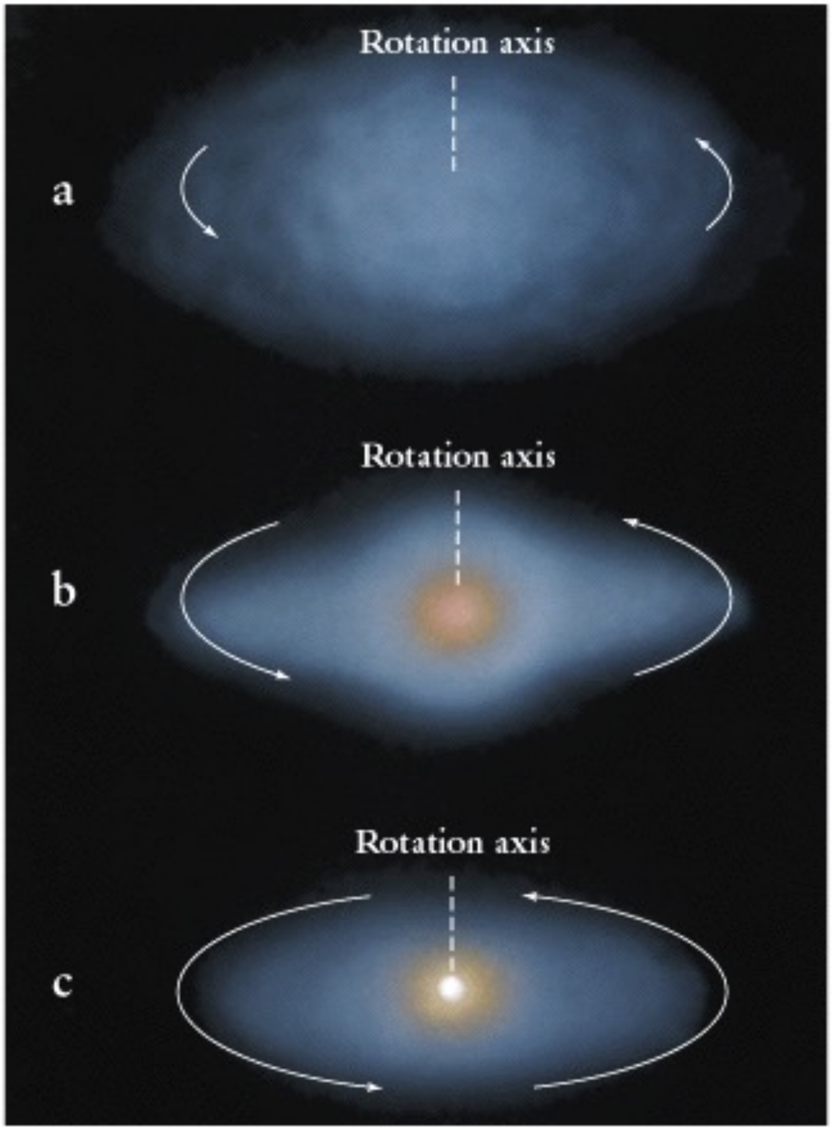
JWST mid-infrared

JWST near-infrared

Stage 2: Clump to protostar

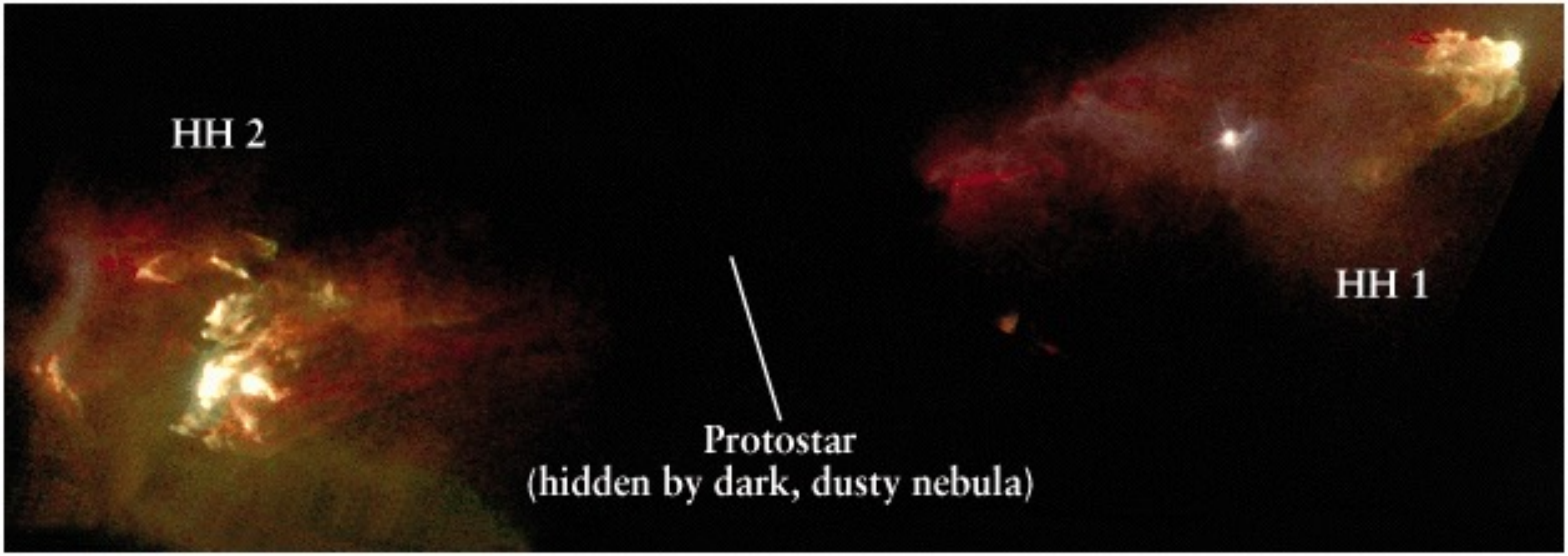
- Initial rotation and conservation of angular momentum will cause the formation of a protostar and a flattened disk





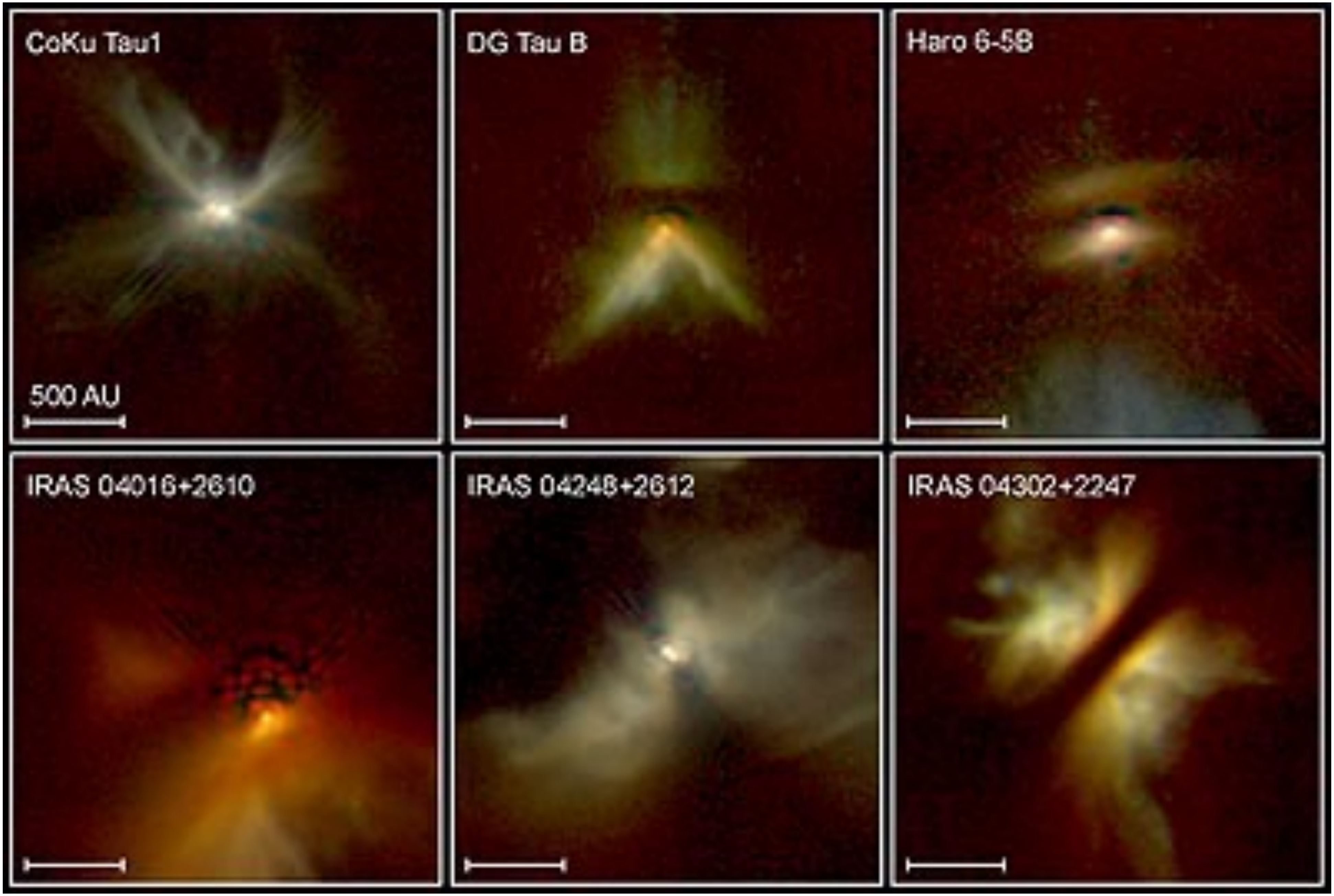
DEMO

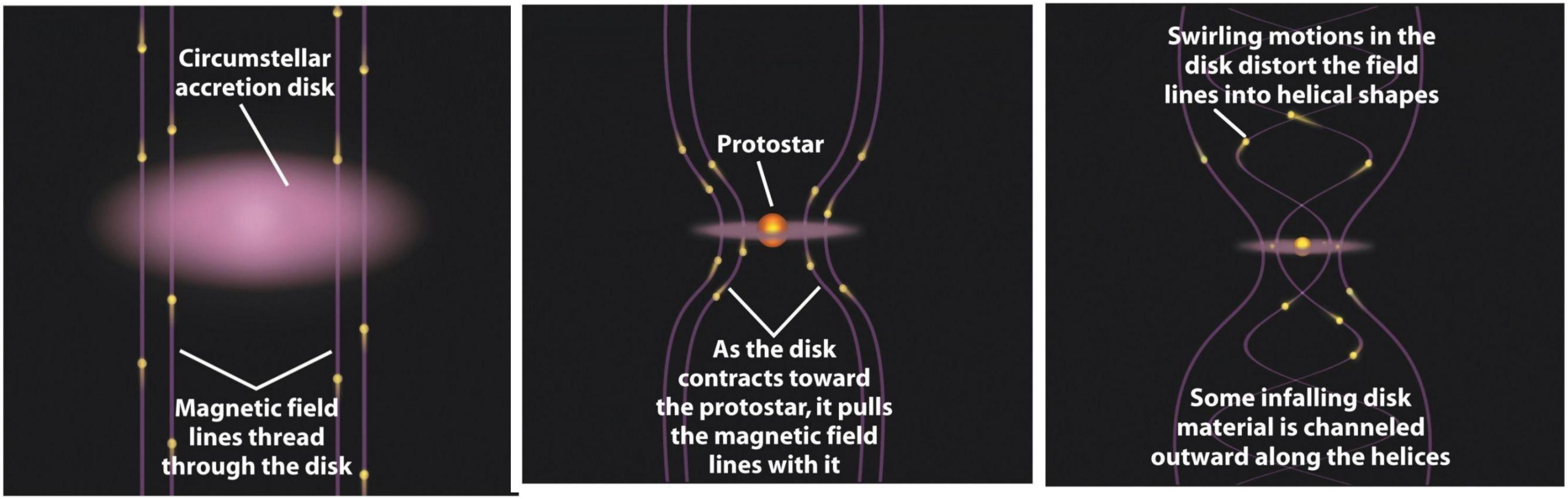
Some protostars (T Tauri types) eject gas, and create Herbig-Haro objects as ejected gas hits nearby ISM.

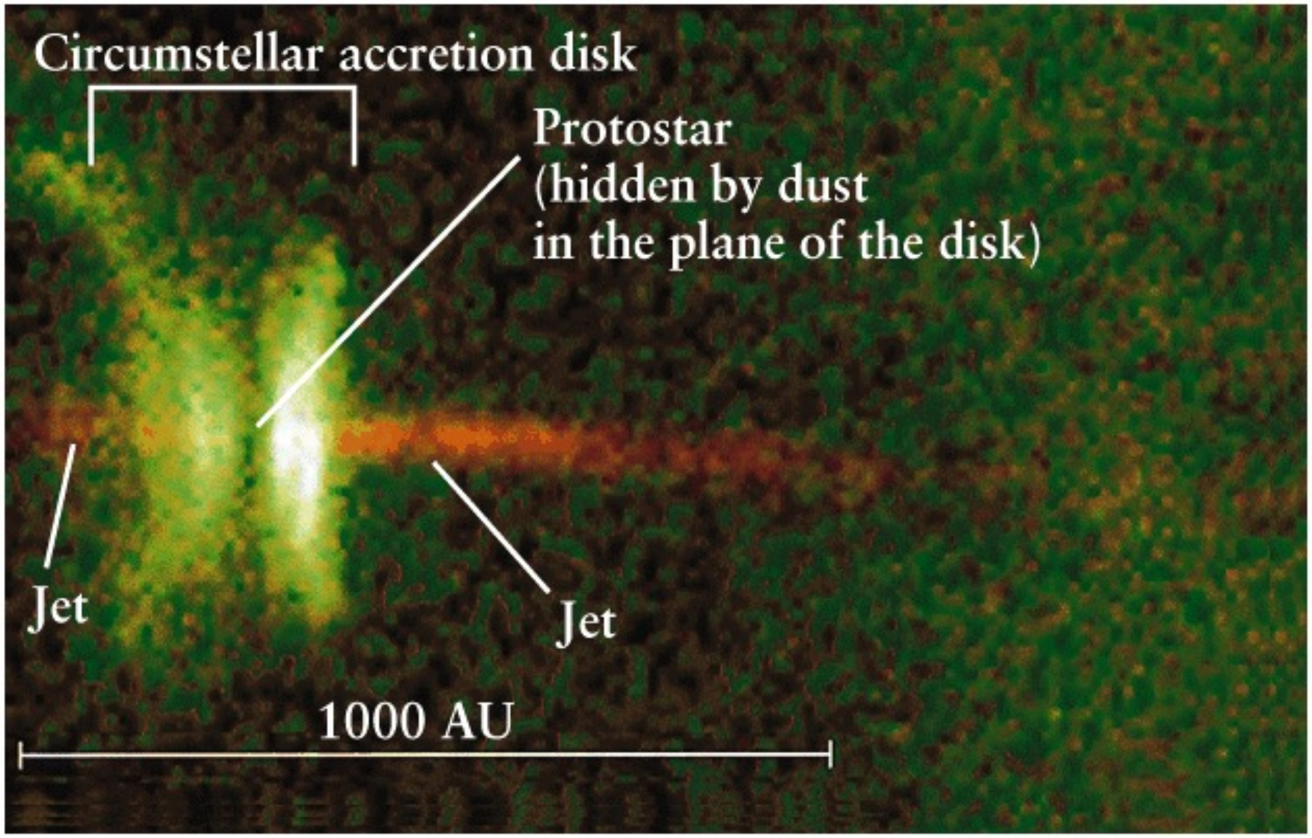


The protostar lies between ejected gas blobs, still embedded deep in the parent cloud.

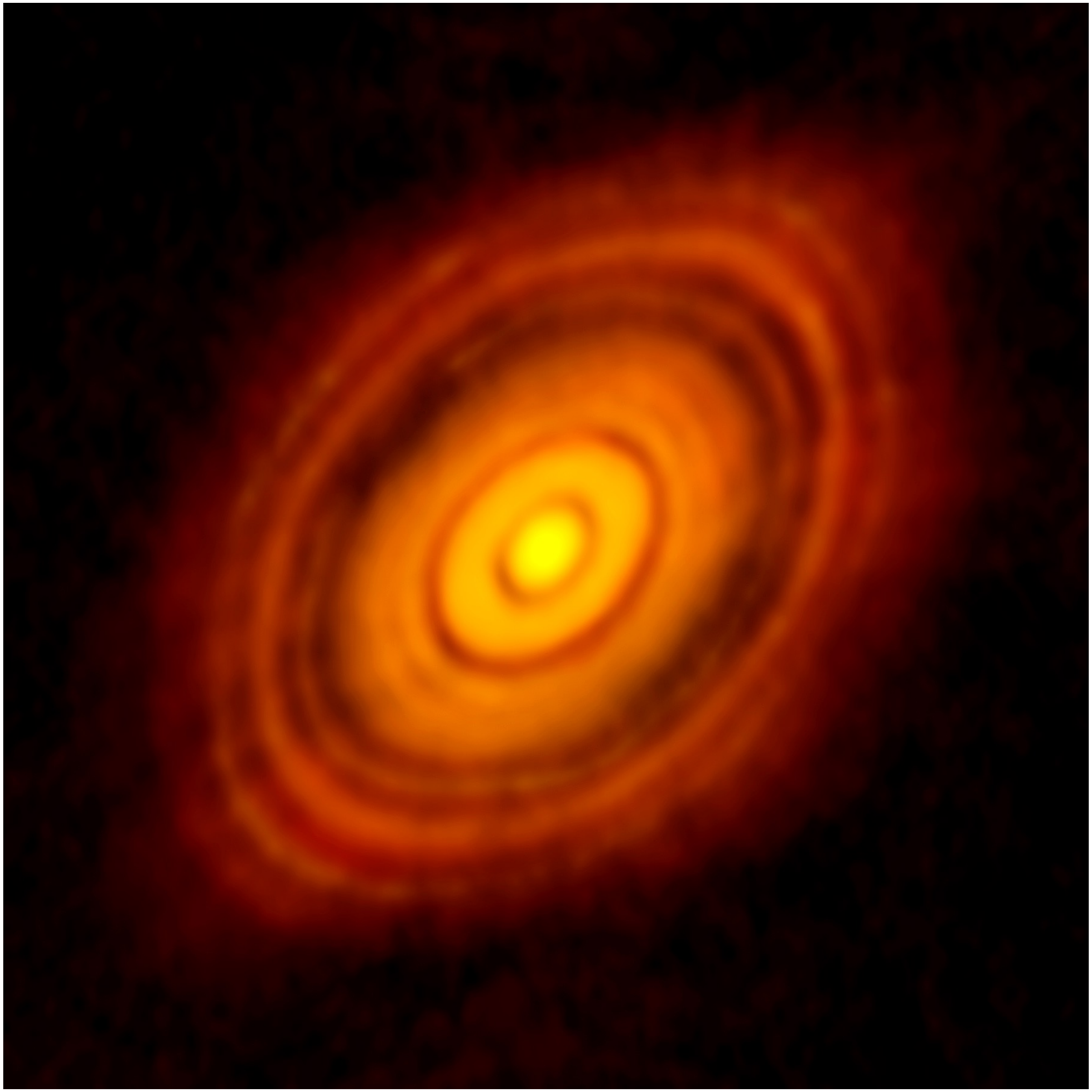
More Herbig-Haro objects. Note the equatorial dust.




Circumstellar accretion disk
Magnetic field lines thread through the disk
Protostar
As the disk contracts toward the protostar, it pulls the magnetic field lines with it
Swirling motions in the disk distort the field lines into helical shapes
Some infalling disk material is channeled outward along the helices


Circumstellar accretion disk
Protostar (hidden by dust in the plane of the disk)
Jet
Jet
1000 AU

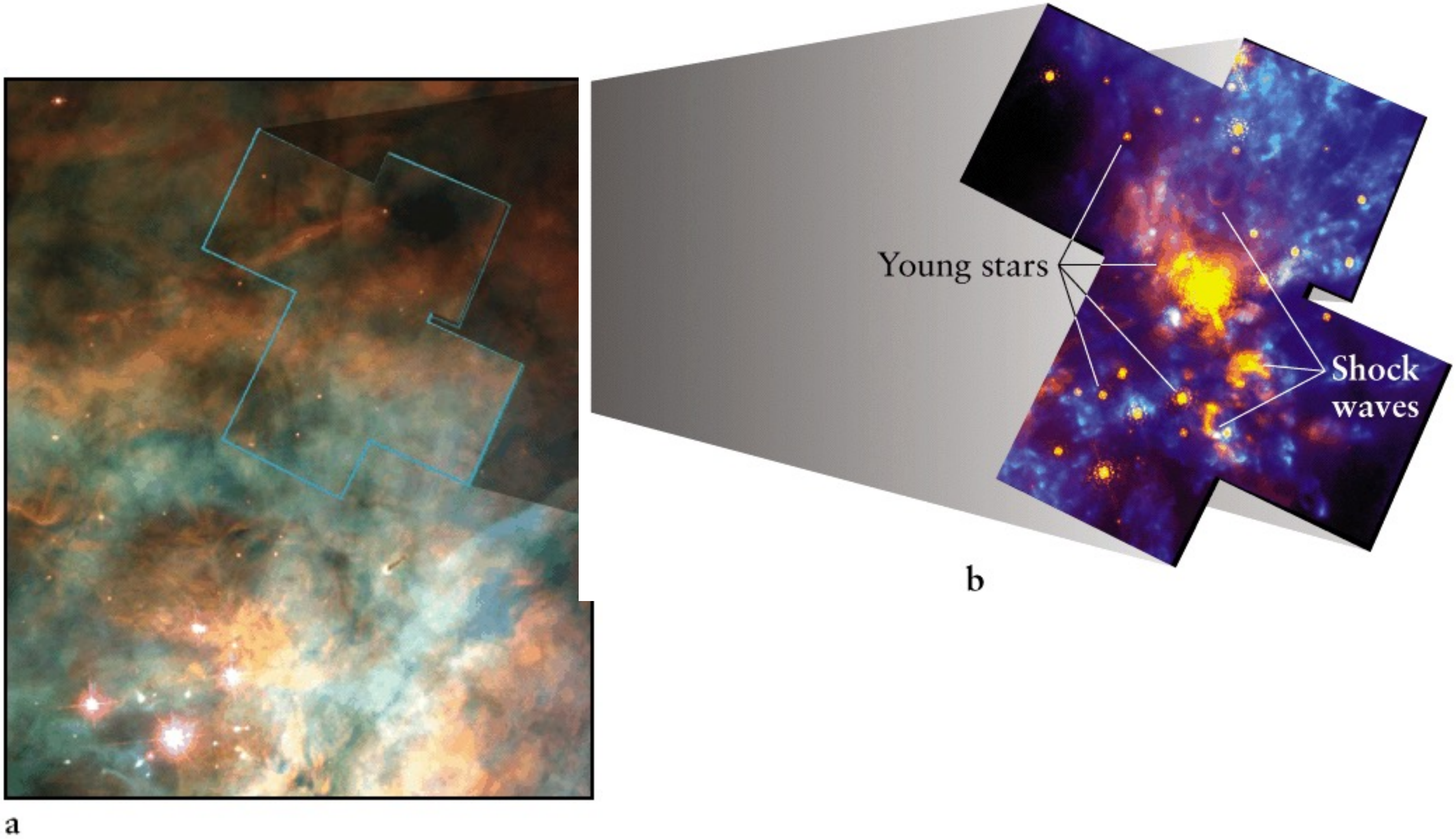
Proto Planetary Disks seen in the millimeter



HL Tau
< 2 Myr old

Gaps swept out by
planets formation

- During the protostar stage: at first low density, and no heating of the gas.
- As the protostar contracts, it will become less transparent => photons become trapped, and will heat the gas.
- This is the start of the protostar trying to reach hydrostatic equilibrium
- Hydrostatic equilibrium *almost* reached
- Energy source gravitational contraction (Kelvin-Helmholtz contraction)
- Embedded in the parent gas cloud, and a short-lived phase (10^4-10^5 years) => hard to observe.



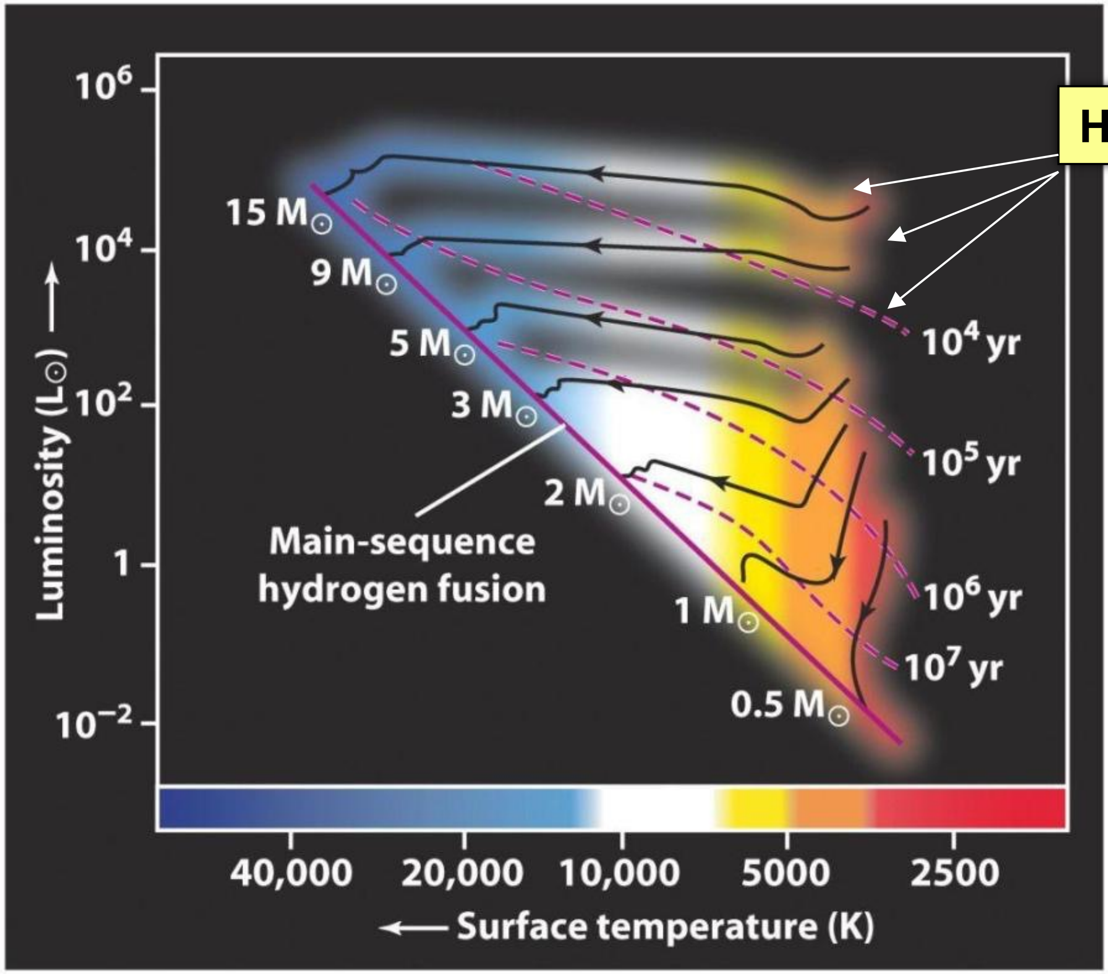
Orion: Visible (left) and IR (right)

Stage 3: Core ignition

- Eventually, the contracting protostar will become hot and dense enough in core for nuclear reactions to start (~a few million K).
- Enormous energy released, stopping gravitational contraction.
- The star enters the main sequence burning hydrogen to helium.

Entering the main sequence

- In the H-R diagram the Zero Age Main Sequence (ZAMS) is the location of newly formed stars. The location of a star on the ZAMS is entirely a result of its mass.



Hayashi tracks

Highest mass protostars get to main sequence fastest, and at high luminosity and temperature. Why?

Time scales

- Kelvin-Helmholtz time scale (gravitational binding energy vs luminosity)

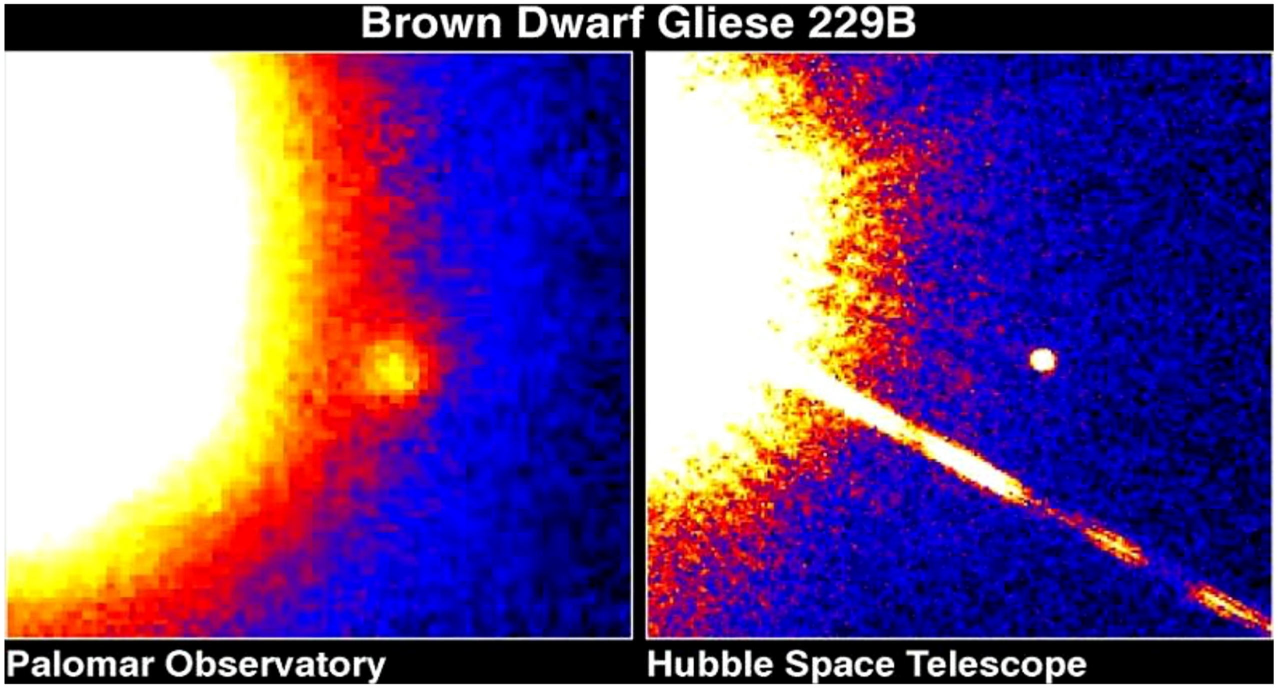
$$t \propto \frac{M^2}{RL}$$

- => 30 Myr for 1 $M_\odot$
- Short time scale for high-mass protostars, long for low-mass protostars

$$t \propto \frac{M^2}{RL} \propto \frac{M^2}{R^3T^4}$$

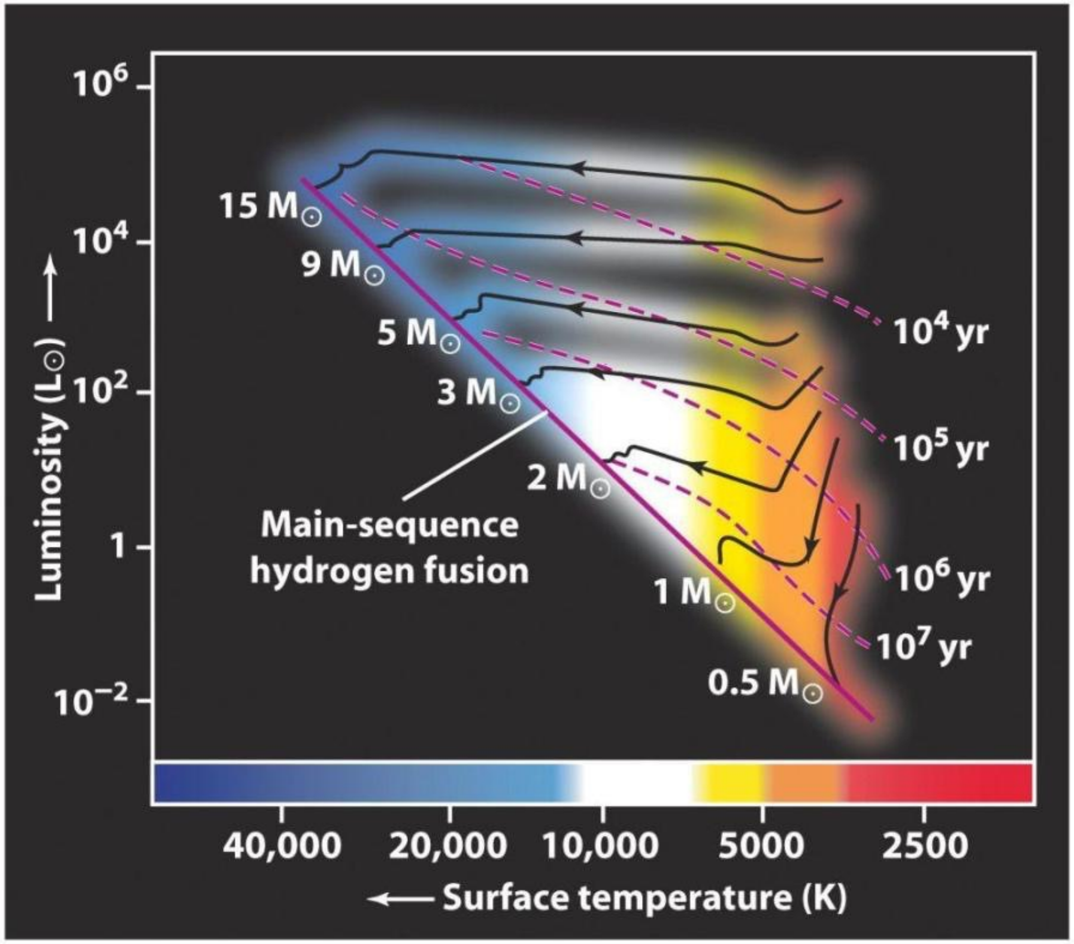
Mass limits

- Limits to possible sizes of MS stars
- Cannot be <0.08 $M_\odot$ (core pressure too low for nuclear reactions). Brown dwarf.
- Cannot be >200 $M_\odot$ (temperature and pressure so high it blows itself apart).



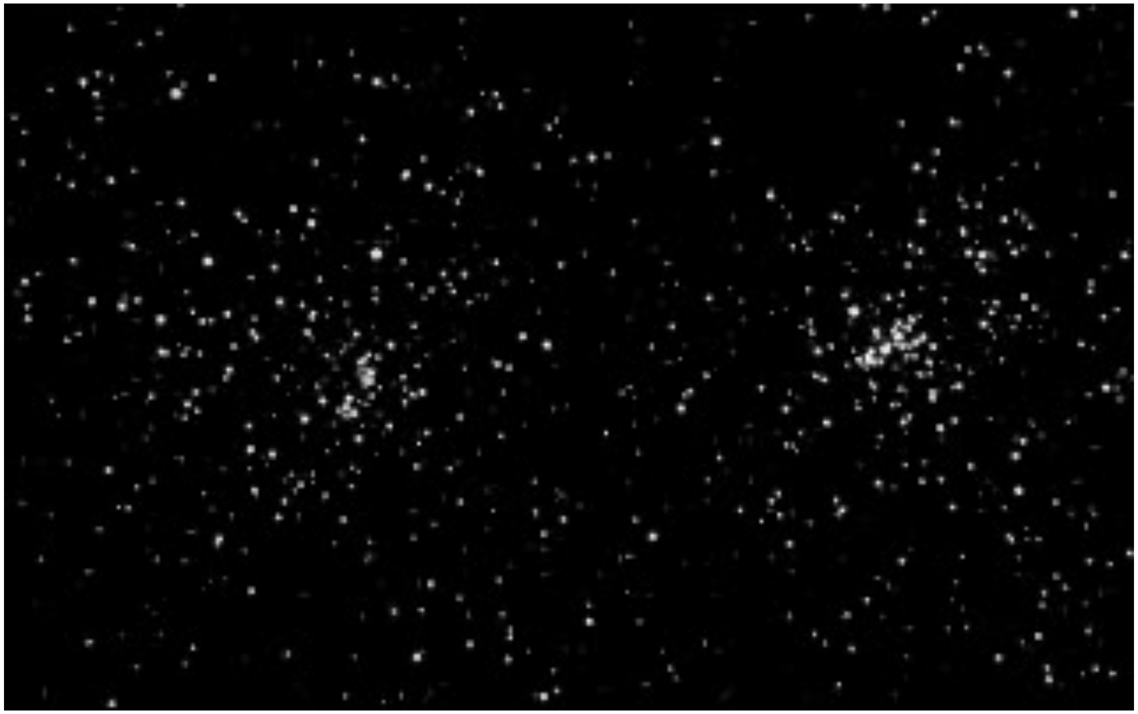
What do we see?

- Stars in all phases, but more stars that are in their long-lived phase



Open clusters confirm the theory

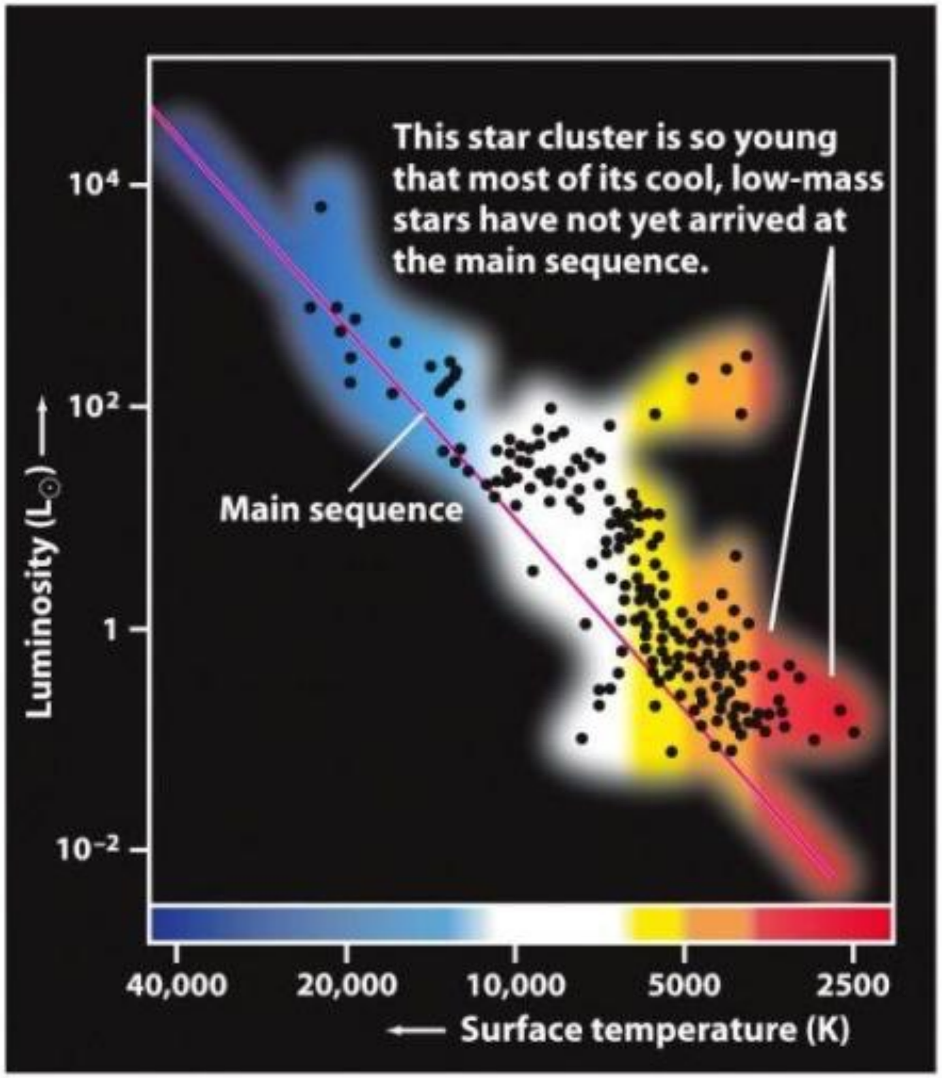
- Stars tend to form in groups or in *clusters*.
- There are two types of clusters – *open* and *globular*.
- Open clusters
  - Newly formed, 10^2 - 10^4 stars.
  - Confined to the plane of the Galaxy
  - Often seen near HII regions and molecular clouds.



The double cluster H and χ Persei (NB: not at the same distance).

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

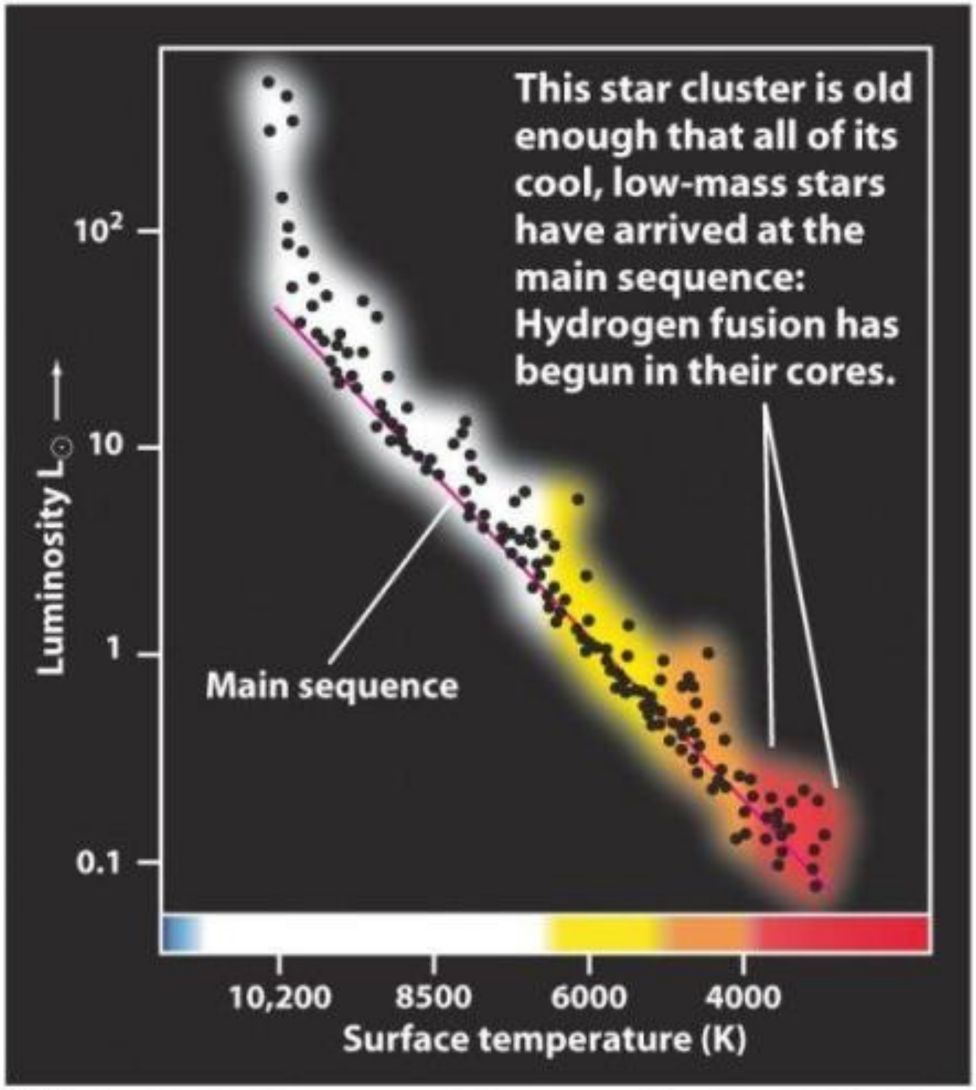

(a) The star cluster NGC 2264



(b) An H-R diagram of the stars in NGC 2264

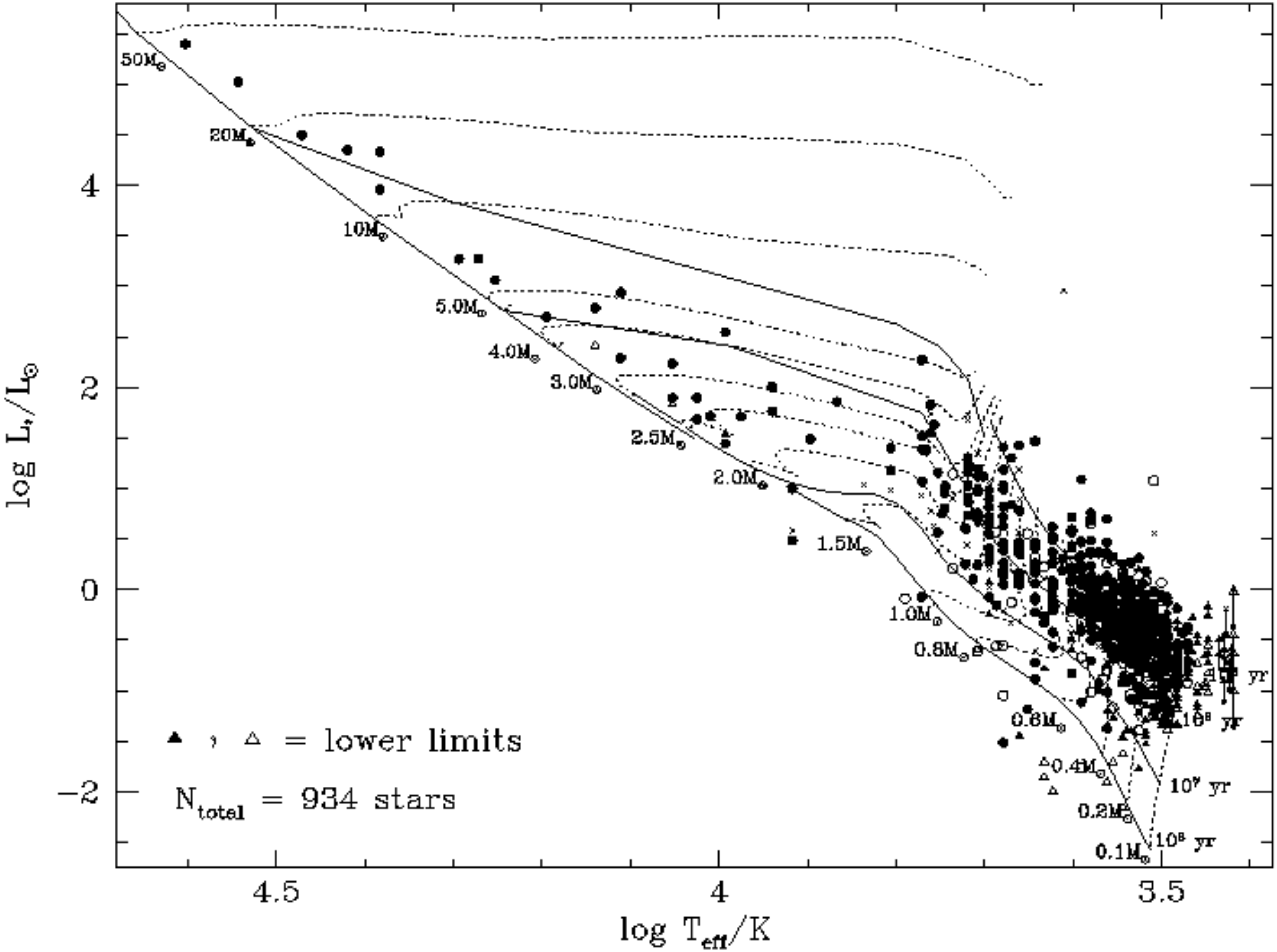
The Pleiades are older. All stars have reached the main sequence. Highest mass ones are already evolving off.

(a) The Pleiades star cluster



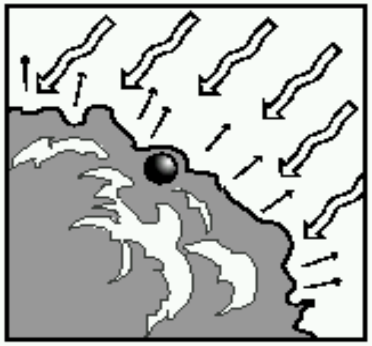
(b) An H-R diagram of the stars in the Pleiades

H-R Diagram of Orion Nebular Cluster

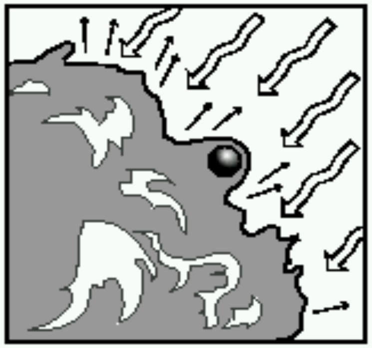


from Lynne Hillenbrand

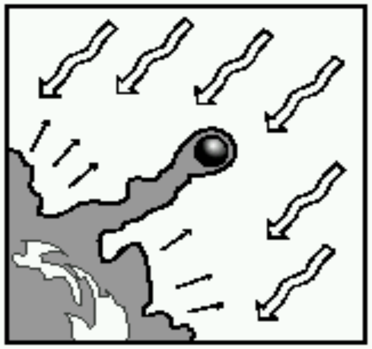
- HII regions eat their way across molecular clouds. Newly formed O and B stars blow away leftover dust and gas.



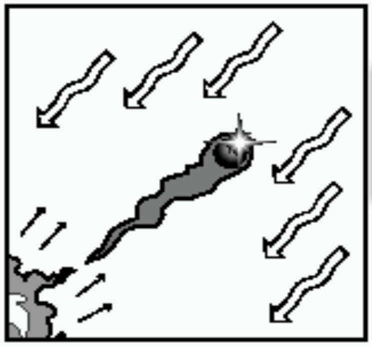
Molecular cloud surface illuminated by O, B stars



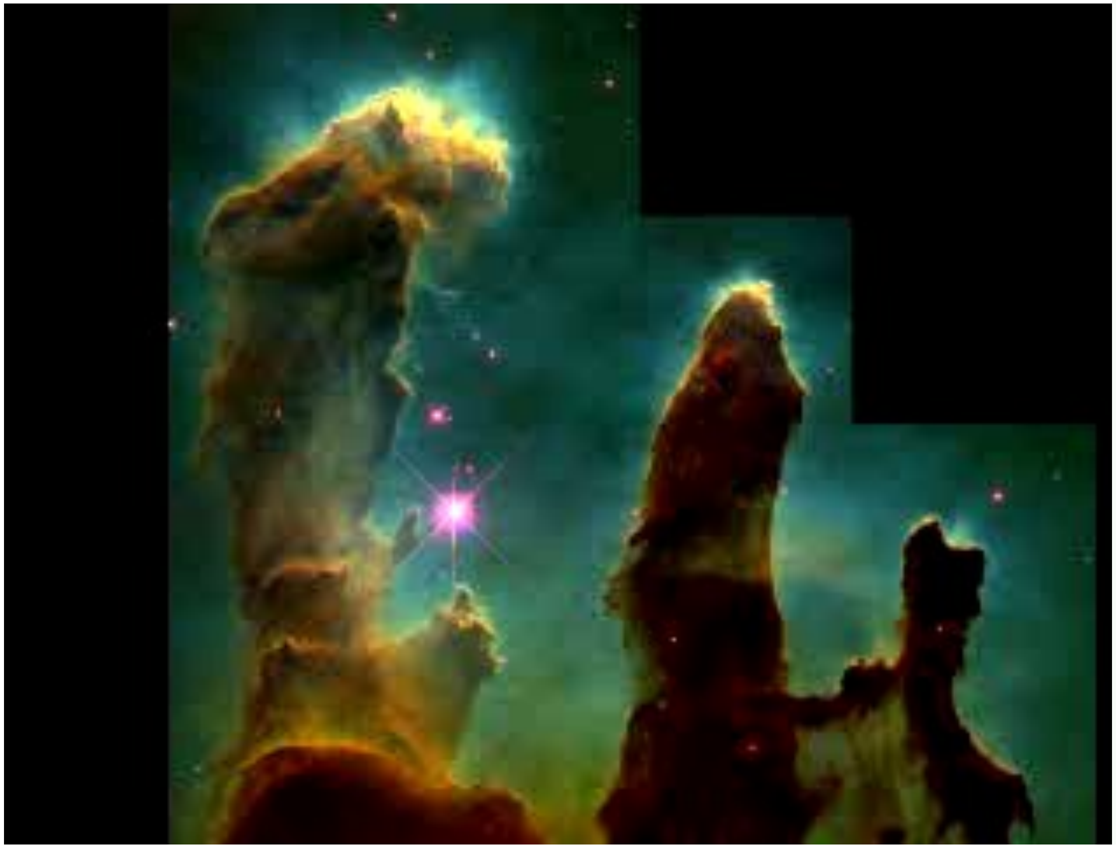
Radiation evaporates surface, revealing a protostar



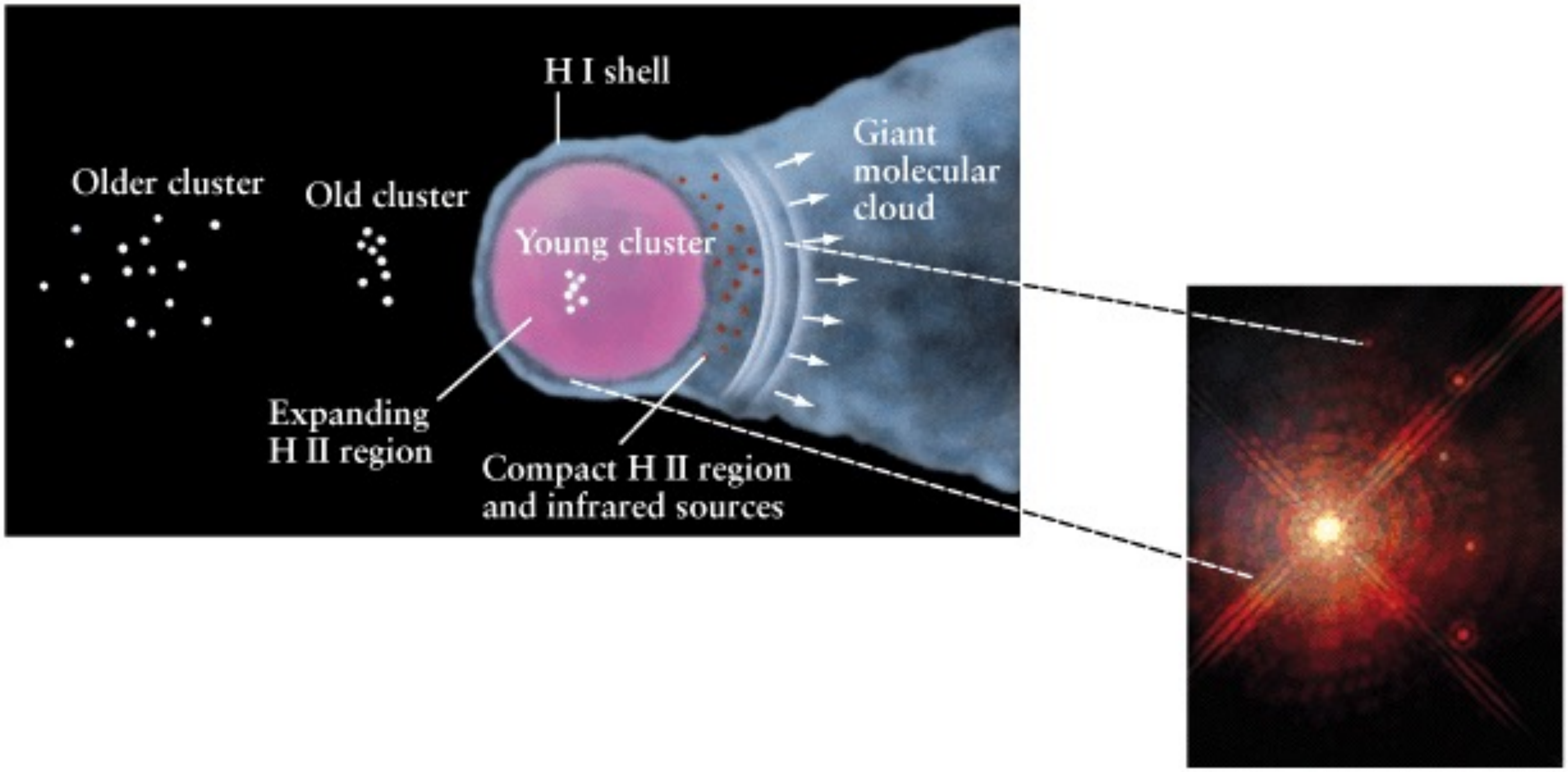
Shadow protects a column of gas behind it



Eventually structure separates from cloud



- Stellar winds and UV radiation compress the gas leading to the next group of forming stars.



- Supernovae can also compress the ISM and trigger star formation

Under pressure: the ideal gas law

- To determine gas pressure we use the ideal gas law, $P=nkT$
- If you hold T constant and compress a gas you will find that P is inversely proportional to the volume
- The core of the star formation problem is what happens to P, n and T when gravity acts.

- If two clouds co-exists with the same pressure P (*pressure equilibrium*), they are stable when pressures balanced.
- If pressures not balanced, the higher pressure region will compress the lower pressure region until pressure equilibrium is restored. Thus,

$$n_1T_1=n_2T_2$$

Are hot or cold clouds denser under the same pressure?

K-H heating: gravitational heating

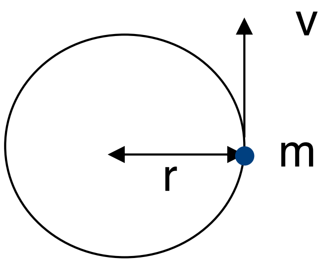
- Kelvin-Helmholtz contraction is contraction under gravity:
  - Gravitational potential energy converted into kinetic energy of the gas, which in turn converts into heat.
  - Recall: $E=mv^2/2 - GMm/r$
  - As cloud contracts, potential energy gets more highly negative to keep *E* the same, thus kinetic energy more highly positive.
  - Some heat radiated away at the surface of the cloud, the rest raises *T*
  - The more massive a cloud, the more potential energy available, the hotter it gets in the center.

Gravitational stability

- As a protostellar cloud collapses, it heats up, but it also gets more dense => increase in pressure $P=nkT$
- If the cloud is not dense enough for a given T, the pressure wins and cloud will not collapse - the cloud is *gravitationally stable.*
- To continue a collapse, the cloud must lose heat, it must *cool*.
- Thermodynamics says heat flows from hot to cold. Three ways to transport heat:
  - Radiation
  - Convection
  - Conduction (some materials carry heat directly, like solid metals)
- Cooling of a cloud takes long time, since they are not very dense and therefore do not radiate efficiently (and do not convect at all).
- Very massive, cold clouds collapse easily - gravity is too strong.

Angular momentum

- Angular momentum, *L,* is a property of motion related to rotation about some point. Also related to the spin concept.
- *L* of a body of mass *m* moving at velocity *v* perpendicular to the line from the center to the body at distance *r* is *L=mvr.*



- *L* conserved in systems where only gravity is operating (friction can destroy *L*).
- Example: planets move faster in their elliptical orbits when closer to center of mass.

Spin up problem

- Rotation frequency f given by $f=v/2\pi r \Rightarrow L=2\pi mfr^2$
- Thus, in a cloud collapse rotation gets amplified by the factor $f_2/f_1=(r_1/r_2)^2$
- Example: start with a cloud ~0.1pc in size and collapse it to the size of the Sun

  $\Rightarrow (r_1/r_2) = (3\times10^{15}m/7\times10^8m) = 4\times10^6$

  $\Rightarrow (r_1/r_2)^2=1.8\times10^{13}$

  Thus, the cloud will spin up in rotation frequency by this factor! Even an extremely slowly spinning cloud (random motions) will be amplified into extreme rotation speeds - this is NOT seen!

- What really happens? Gas friction causes it to form a spinning disk (*protostellar disks)*, which may be precursors for planetary systems formation.
- Binary stars can also form, as this is a way to store angular momentum

Magnetic fields

- Protostellar clouds have magnetic fields, and during the cloud collapse the magnetic field will be compressed and thus grow in strength.
  - Grows as inverse of volume: $B_2/B_1=(R_1/R_2)^3$
- B-field exerts a pressure, which is proportional to B^2: $P_2/P_1=(R_1/R_2)^6$.
- When cloud collapses by a factor 4×10^6, the magnetic pressure increases by a factor 4×10^{39}. Even initial tiny B-fields would grow to completely dominate any other pressure.
- However, stars are forming, and therefore there must be a removal of the B-field, along with the angular momentum, during a collapse.
- Done via magnetic diffusion, where the B-field (through action of small amounts of ionized gas) will diffuse out of the spinning cloud and drag along gas, removing angular momentum. This is also what slowed down the Sun's rotation.