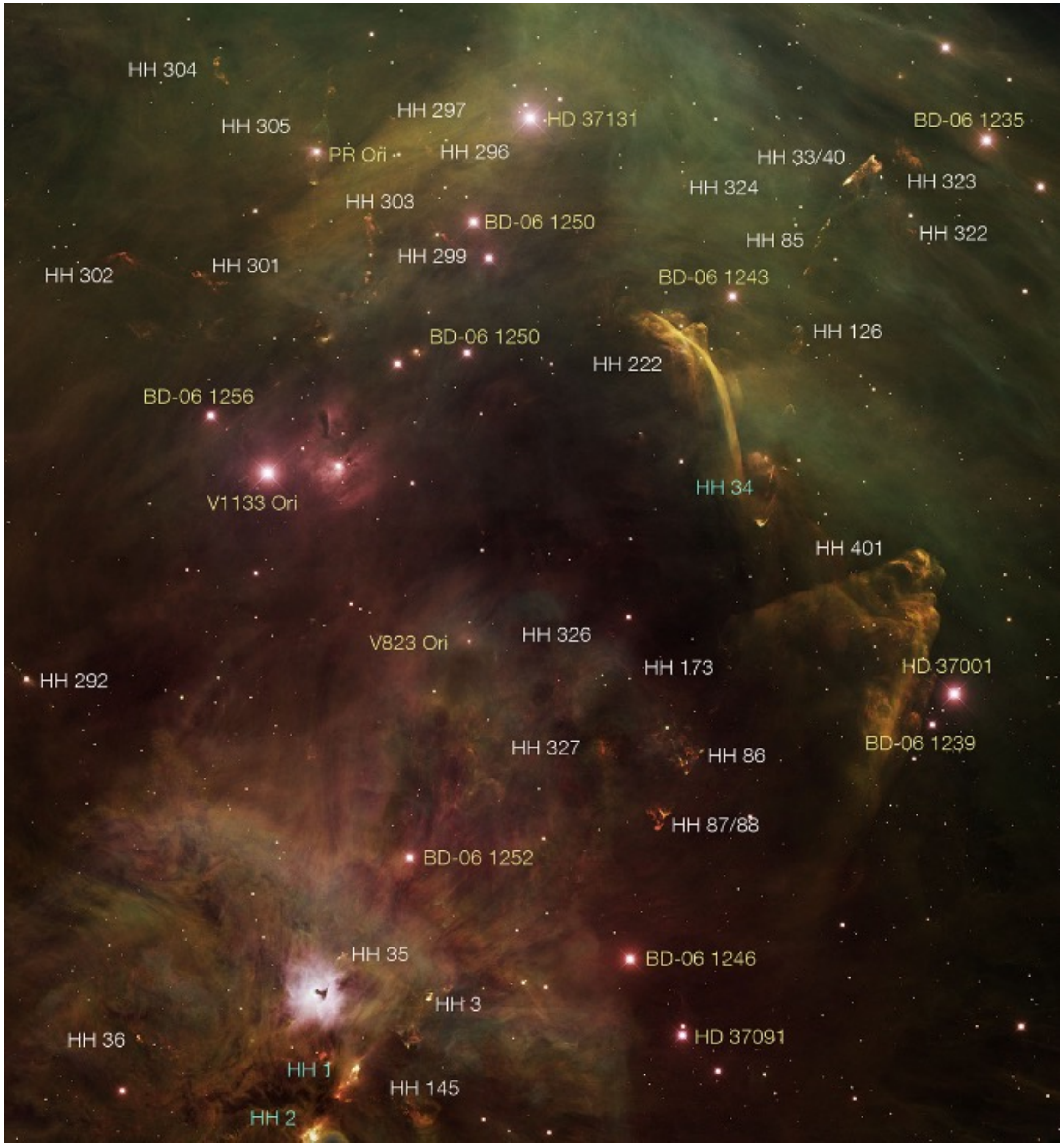
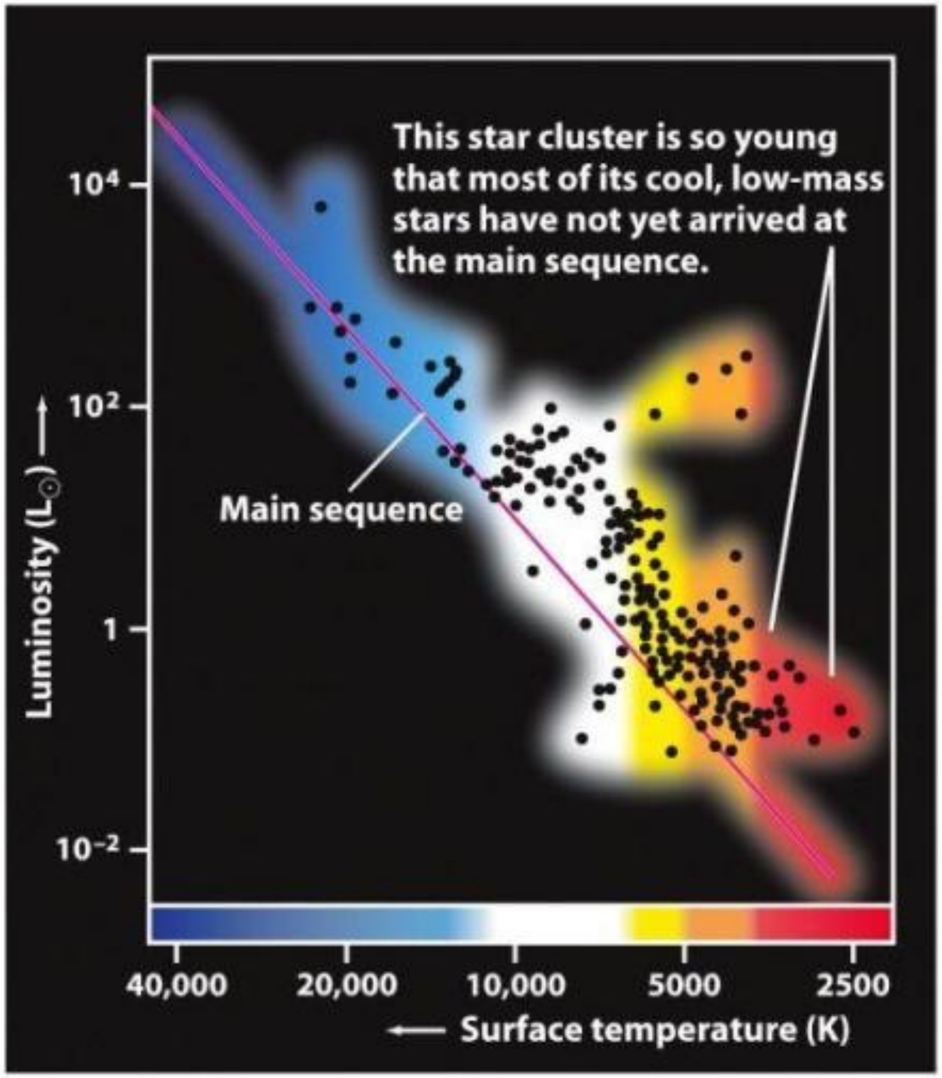
# Herbig Haro Stars

- Ages ~ 10,000 years to 1 Myr
- Numbers ~ 100,000+ in the Milky Way galaxy
- Host stars can have wide range of masses



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

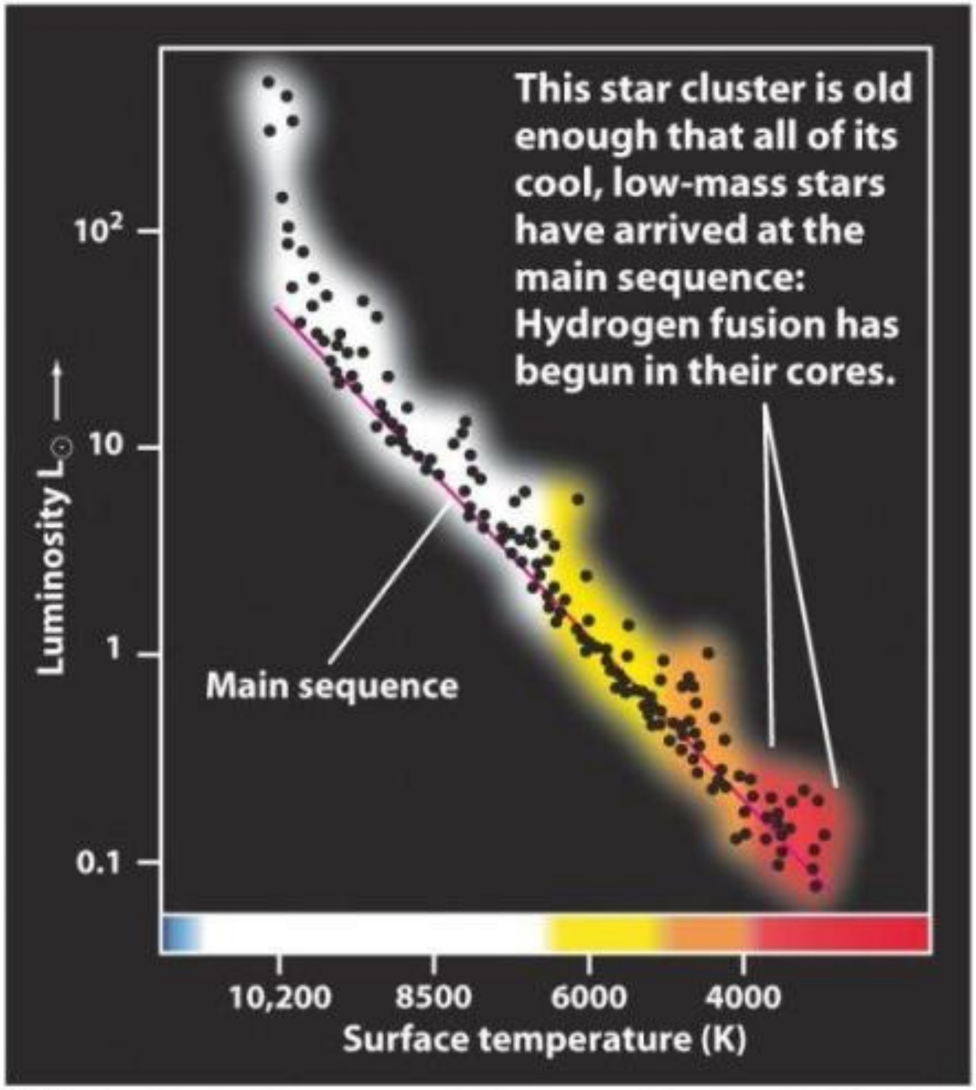
**(a) The star cluster NGC 2264**



**(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.

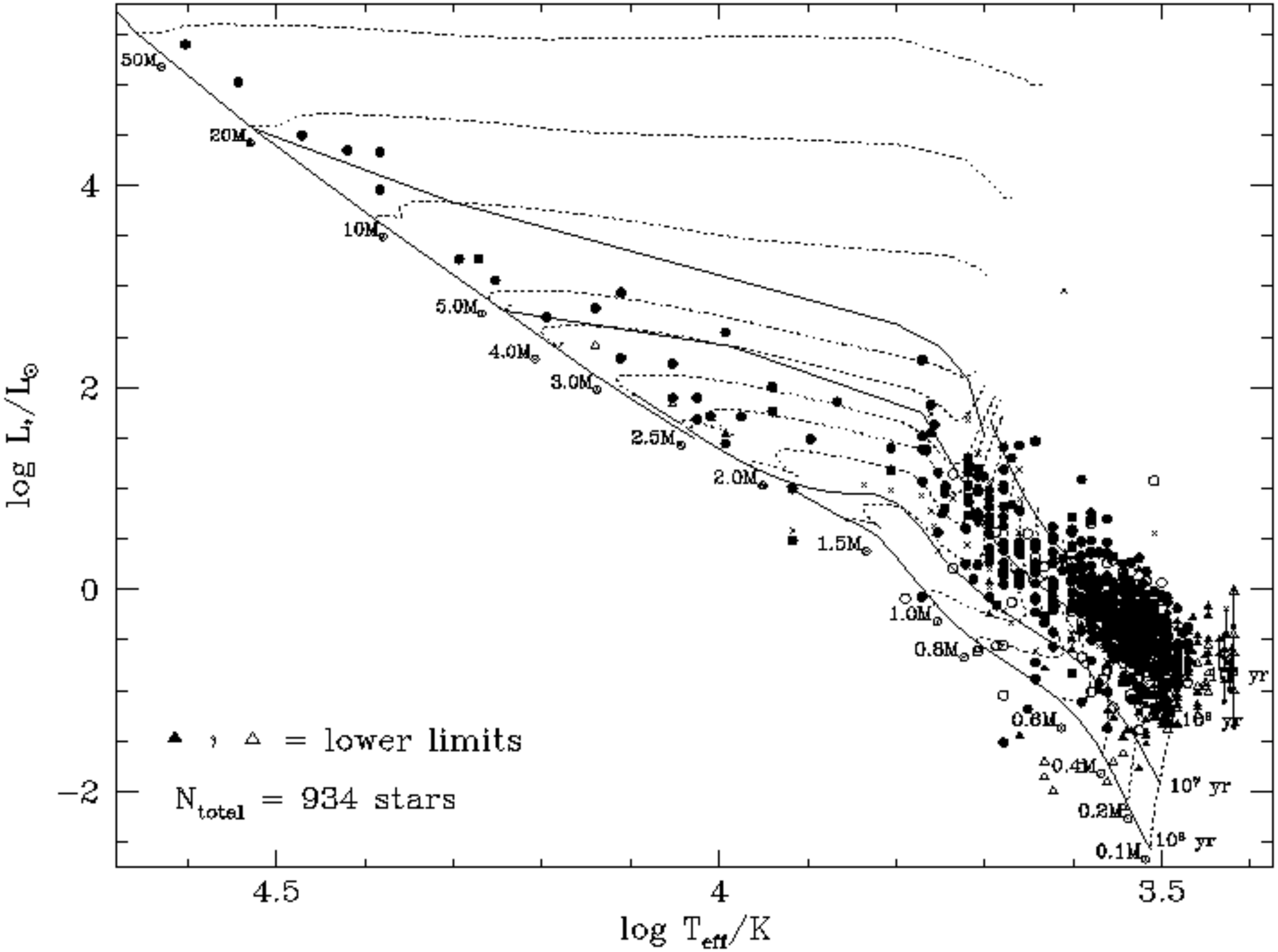
(a) The Pleiades star cluster



This star cluster is old enough that all of its cool, low-mass stars have arrived at the main sequence: Hydrogen fusion has begun in their cores.

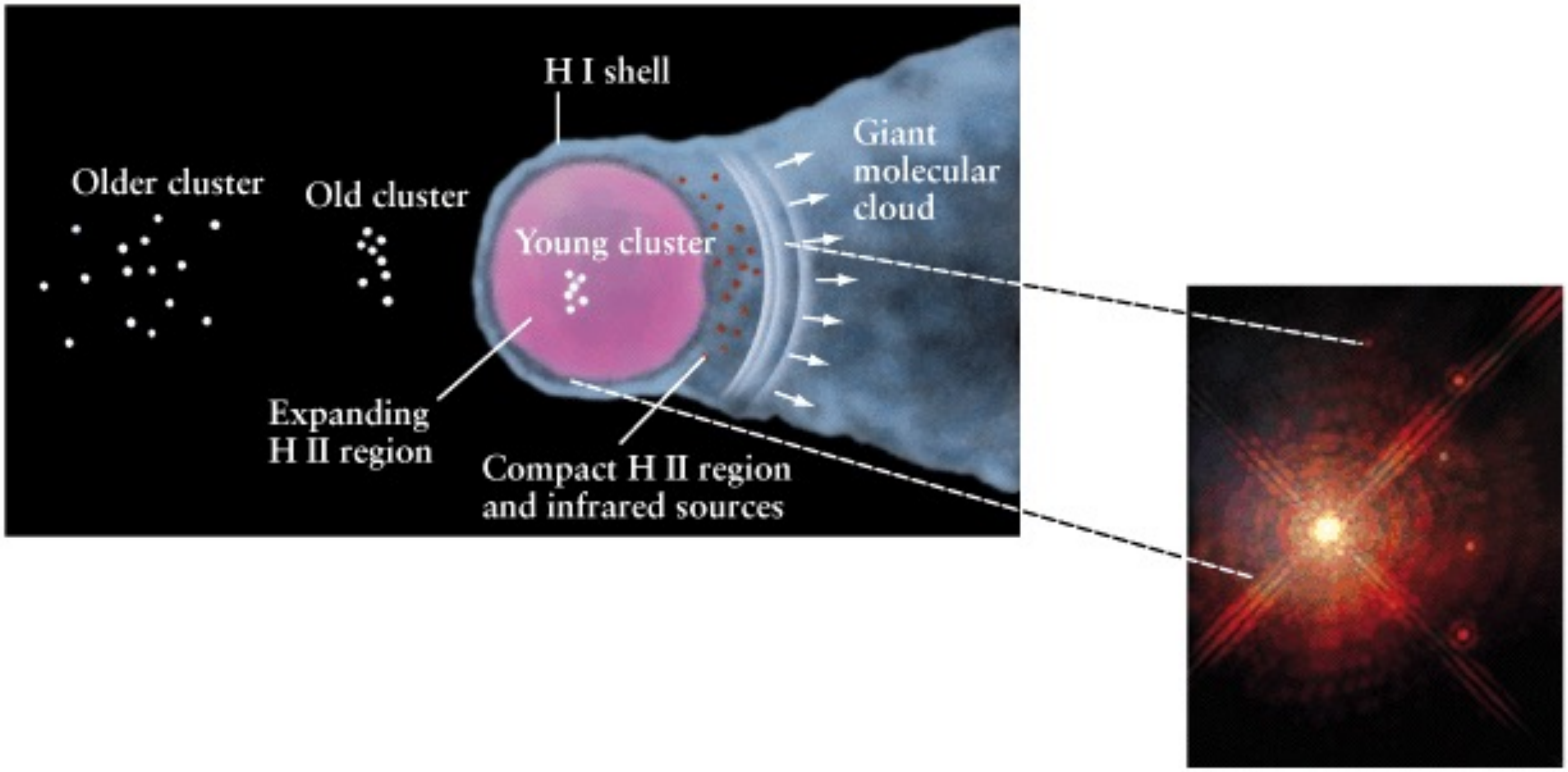
(b) An H-R diagram of the stars in the Pleiades

# H-R Diagram of Orion Nebular Cluster



from Lynne Hillenbrand

- 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

# More about brown dwarfs

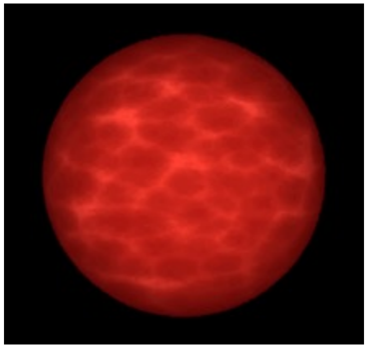
- Sub $0.08M_\odot$ protostars never become hot enough to start hydrogen fusion, and instead form a degenerate core (more on that later), with a high pressure preventing further K-H contraction.

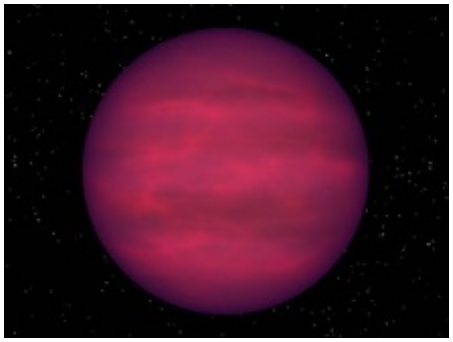
- This failed star will slowly cool off by radiating its internal heat. It radiates most strongly in the IR.
- Two new spectral classes, L (T<3500 K) and T (T<1500 K) were created.

- In the T class, methane is formed altering the appearance.

- Can also be distinguished from low-mass stars via, for example, lithium lines. Lithium is rapidly destroyed during fusion processes, but will be seen in brown dwarfs.

- Distinguished from planets via density and energy output. At ~15 M_Jupiter or 0.015 M_Sun, deuterium fusion begins in the core.


L type

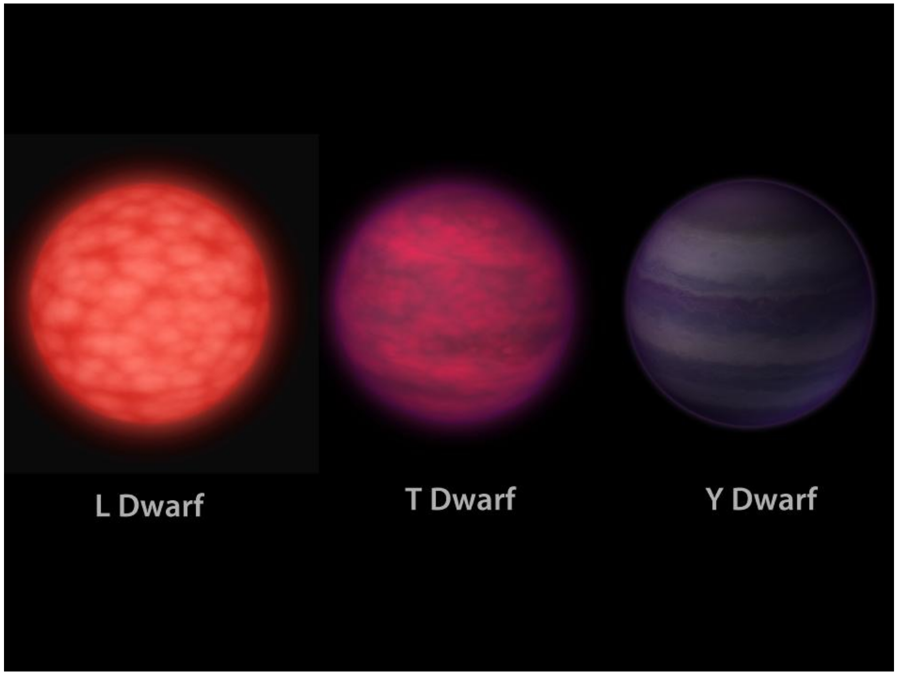

T type

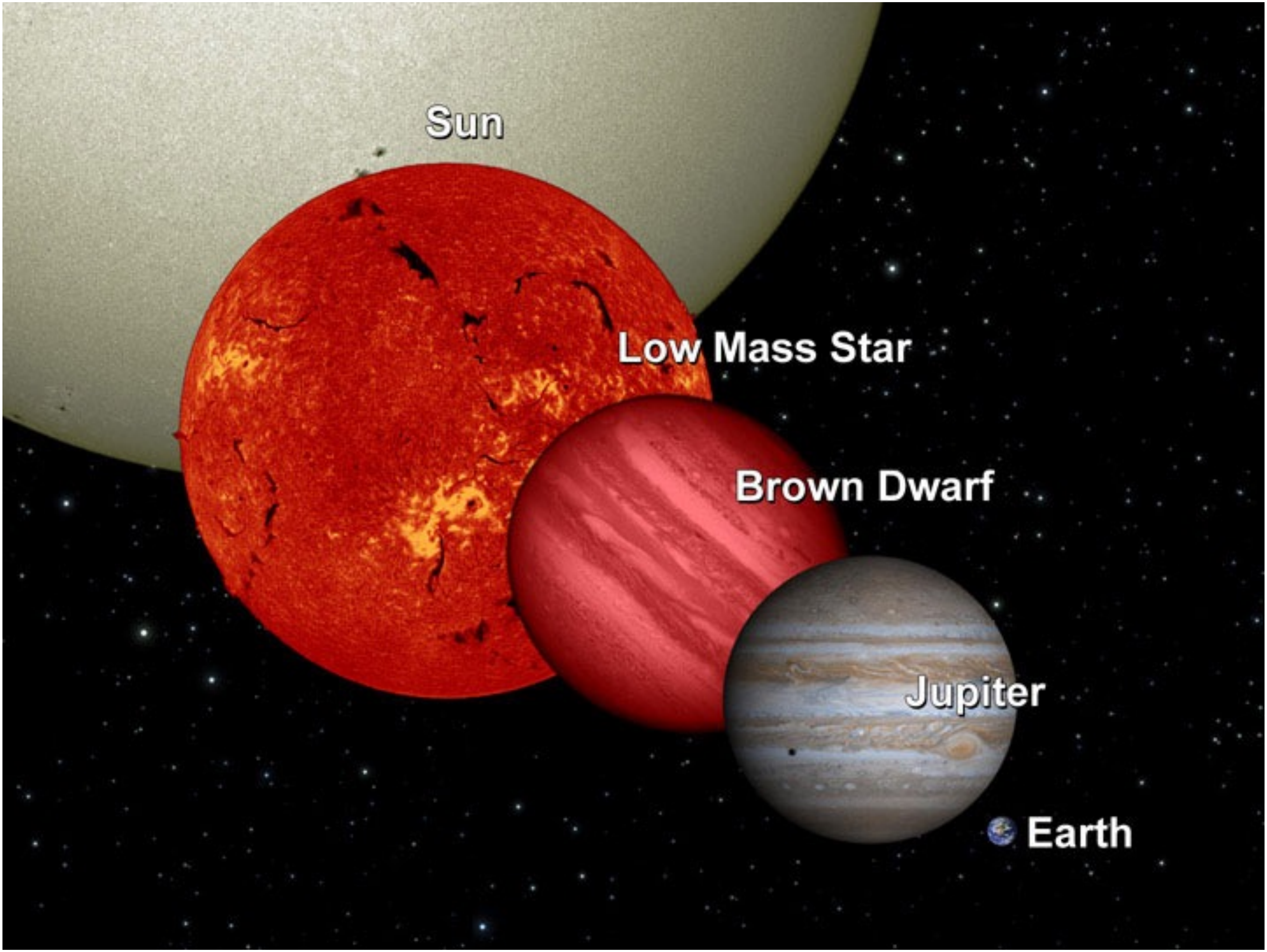
# ClassY - The Coolest Brown Dwarfs

CFBDS J005910.90-011401.3 – T9/Y0 - first class Y, 30 light-years distance, Temp 620K, Mass 15-30 M_Jup

WISE 0855–0714 – Y2 - coolest at Temp ~ 250K, 7.3 light-years distance, Mass ~10 M_Jup

Why are all brown dwarf stars about the same size, even if the mass ranges from 15-100 M_Jup?




Sun
Low Mass Star
Brown Dwarf
Jupiter
Earth

# Most Massive Planets?

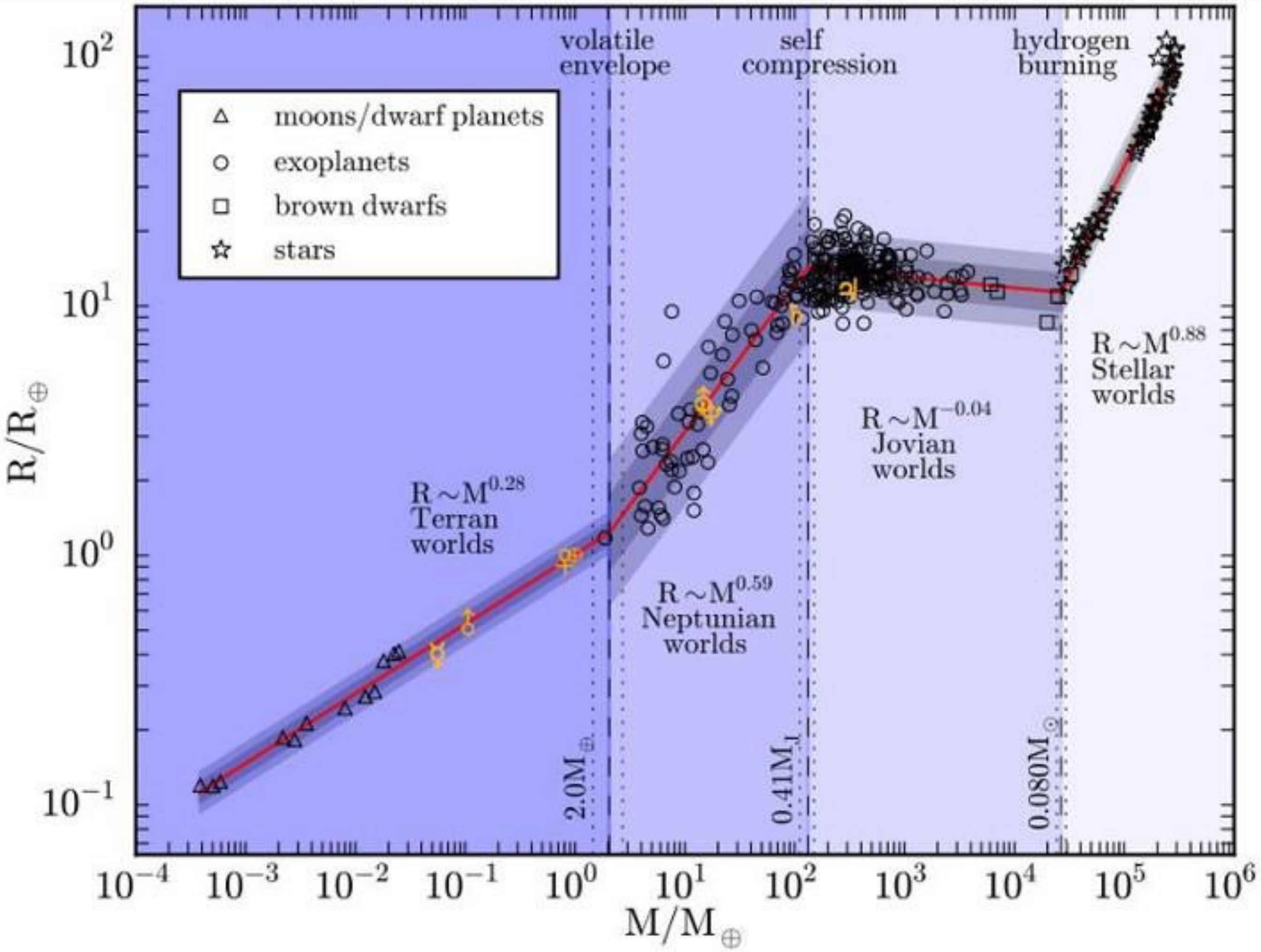
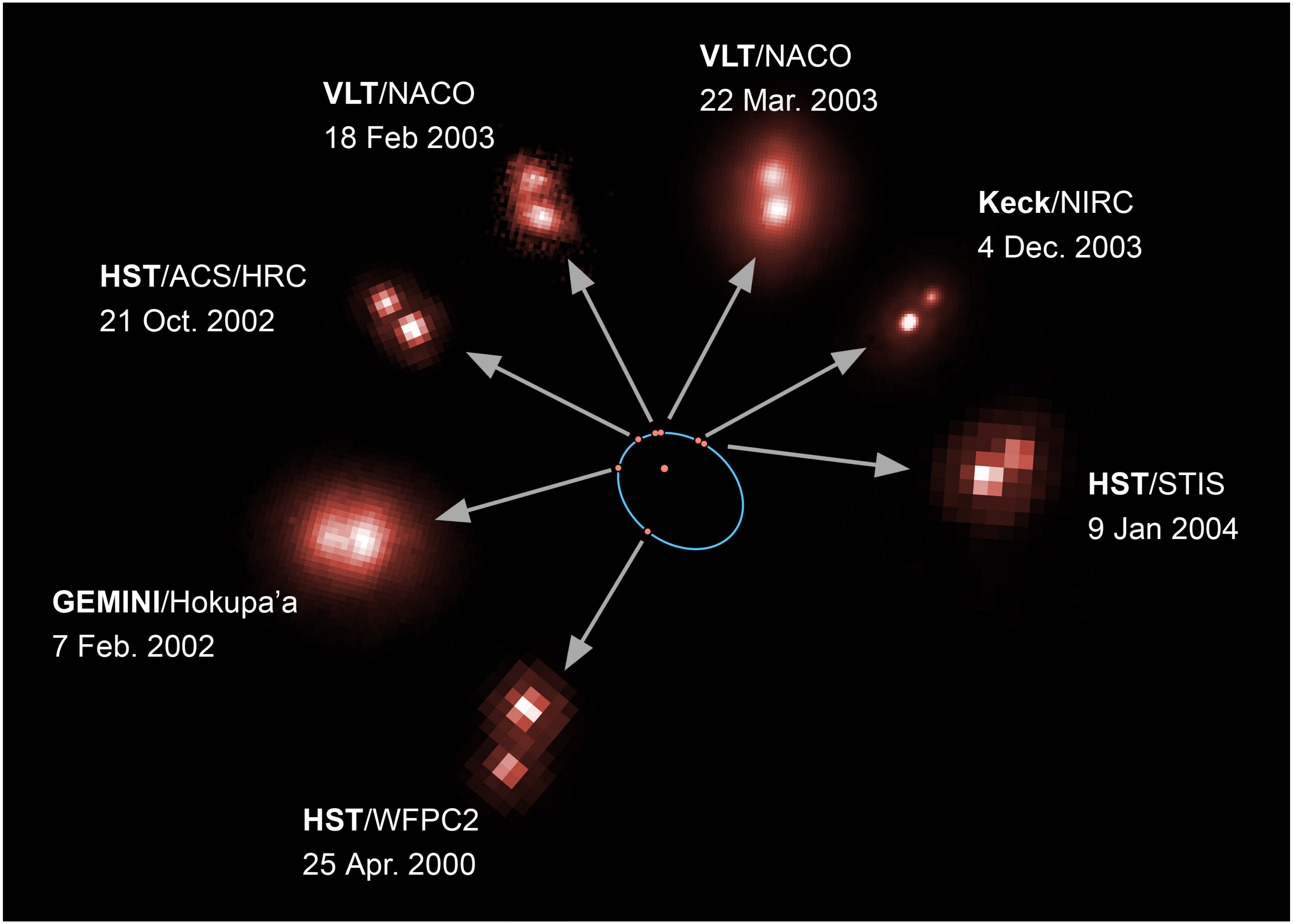


**Figure 3.** The mass-radius relation from dwarf planets to late-type stars. Points represent the 316 data against which our model is conditioned, with the data key in the top-left. Although we do not plot the error bars, both radius and mass uncertainties are accounted for. The red line shows the mean of our probabilistic model and the surrounding light and dark gray regions represent the associated 68% and 95% confidence intervals, respectively. The plotted model corresponds to the spatial median of our hyper parameter posterior samples.



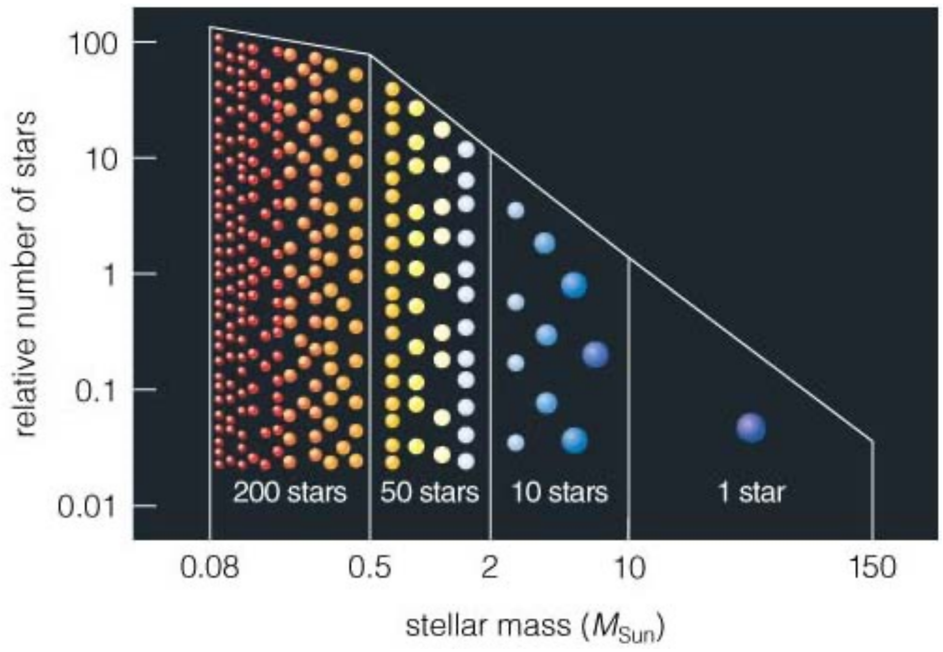
- Mass of star measured to $0.085M_{\odot}$, mass of brown dwarf $0.066M_{\odot}$

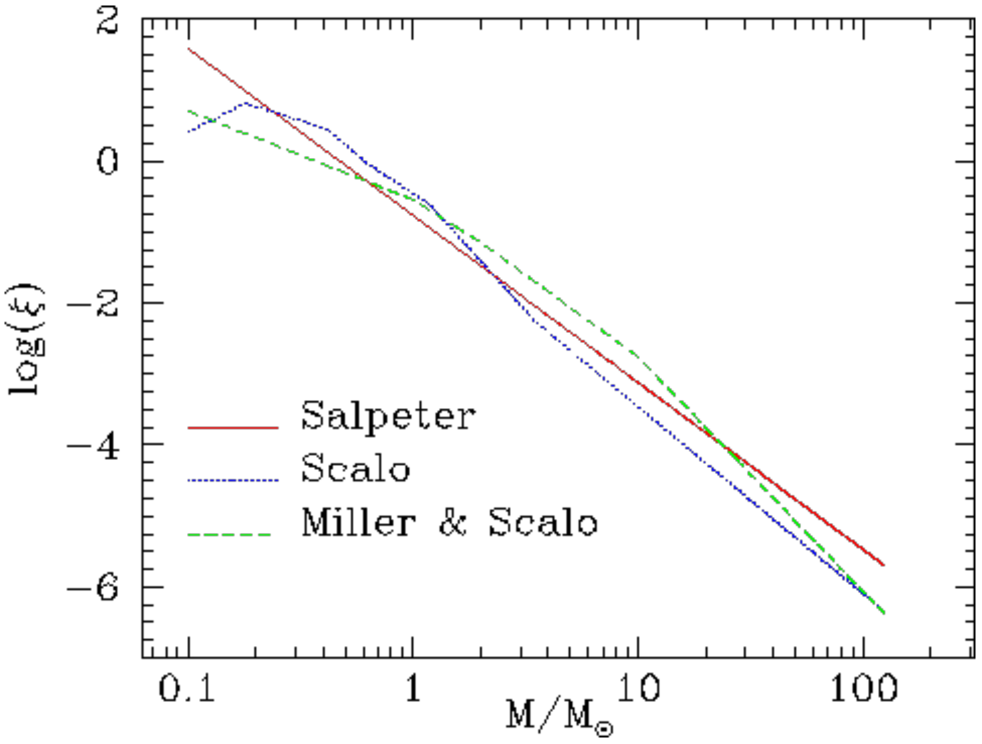
# Brown dwarfs in Orion

- IR image showing brown dwarfs in the Orion constellation.
- Easiest to spot in star forming regions, since they are still young and hence have a lot of their thermal energy left, emitting strongly in the IR (age ~1Myr).
- ~1000 brown dwarfs detected to date.
- Probably 25 billion in our Milky Way Galaxy

# How many brown dwarfs are there?

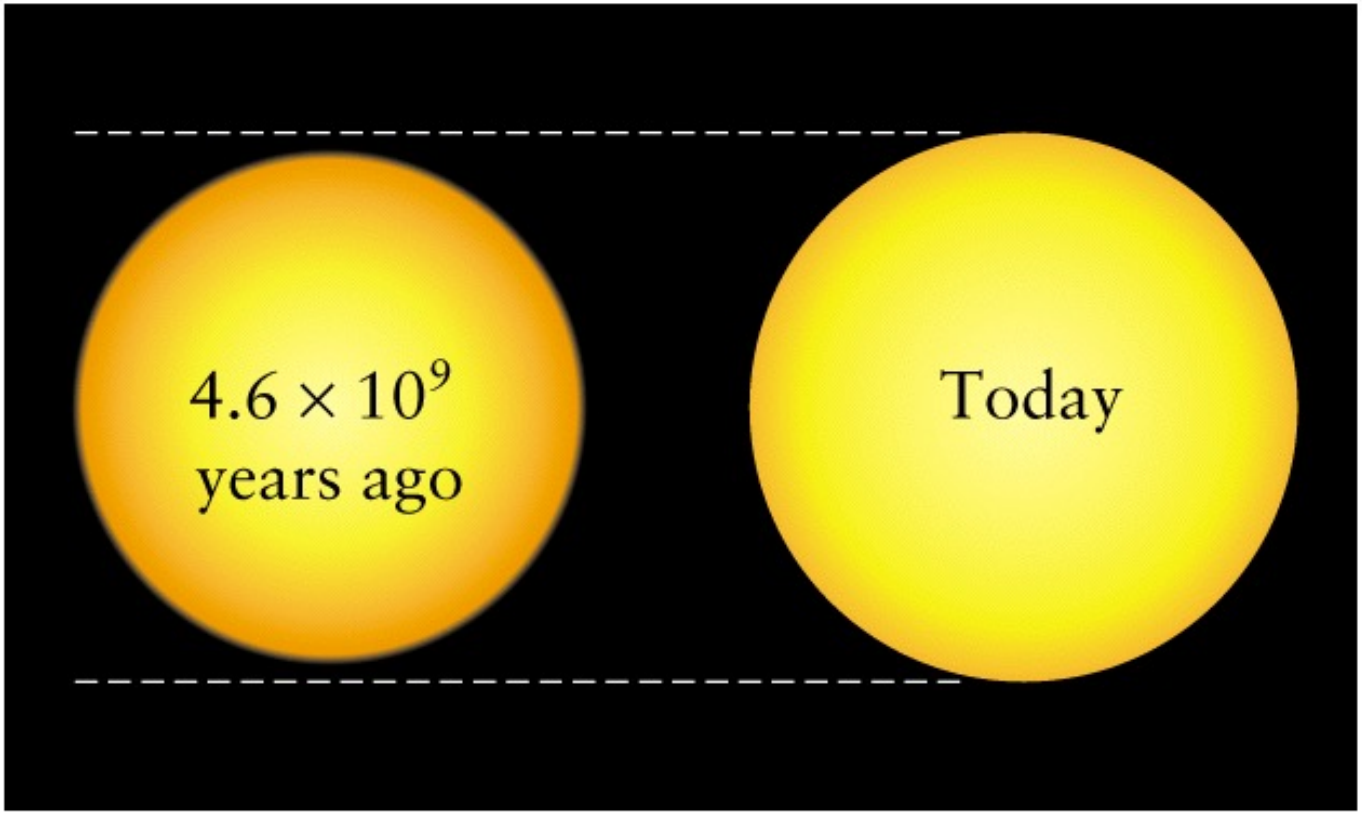
- Should be at least as many as the number of stars, according to our best IMFs (Initial Mass Functions)





# Post main sequence evolution

Chapter 19



# Key concepts

- The evolutionary path (on the H-R diagram) of a star
  - Life as a low mass star
  - Life as a high mass star

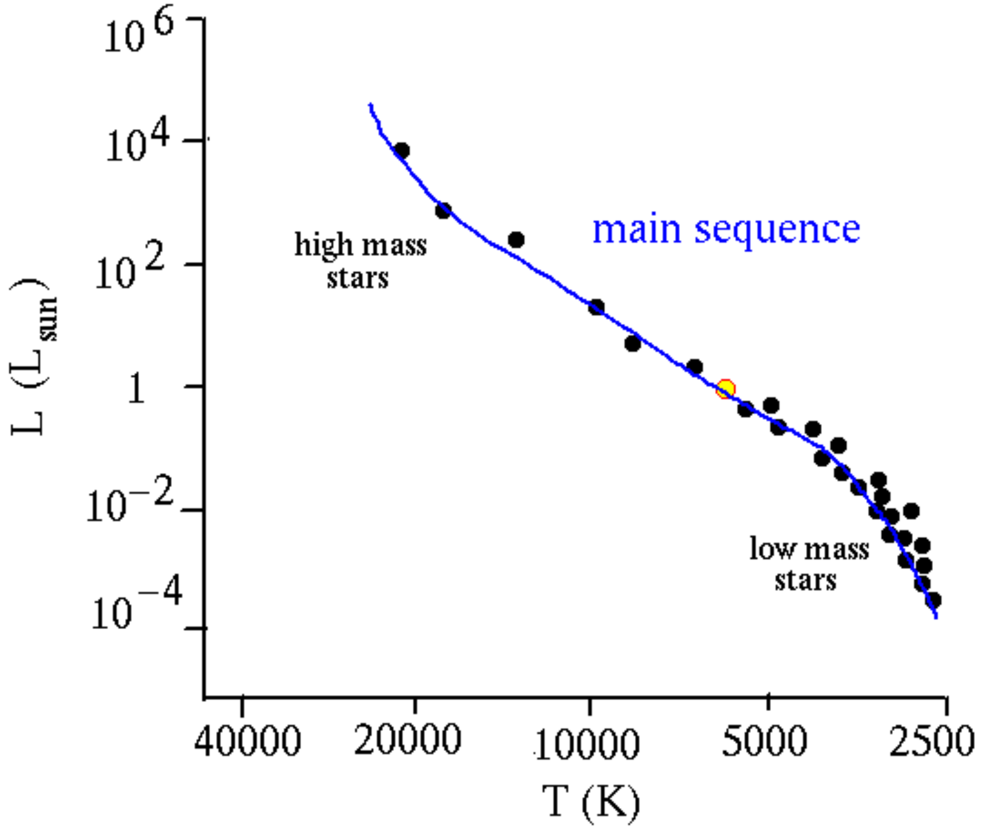
- Core hydrogen exhaustion

- Degeneracy

# "Stellar midlife" - main sequence

Main sequence stars must:

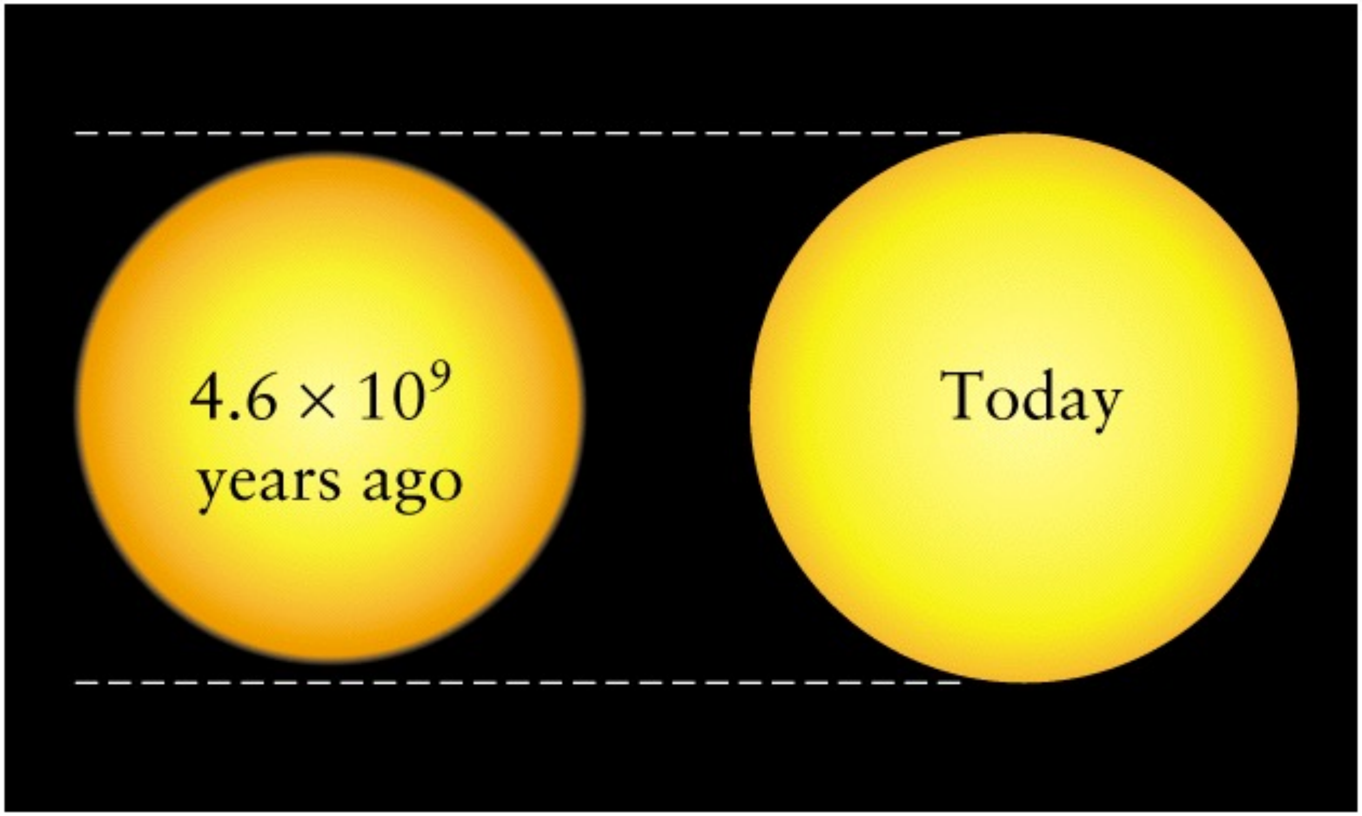
- "Fuse" H to He
- Maintain hydrostatic equilibrium
- Maintain thermal equilibrium



# MS stars get brighter with age

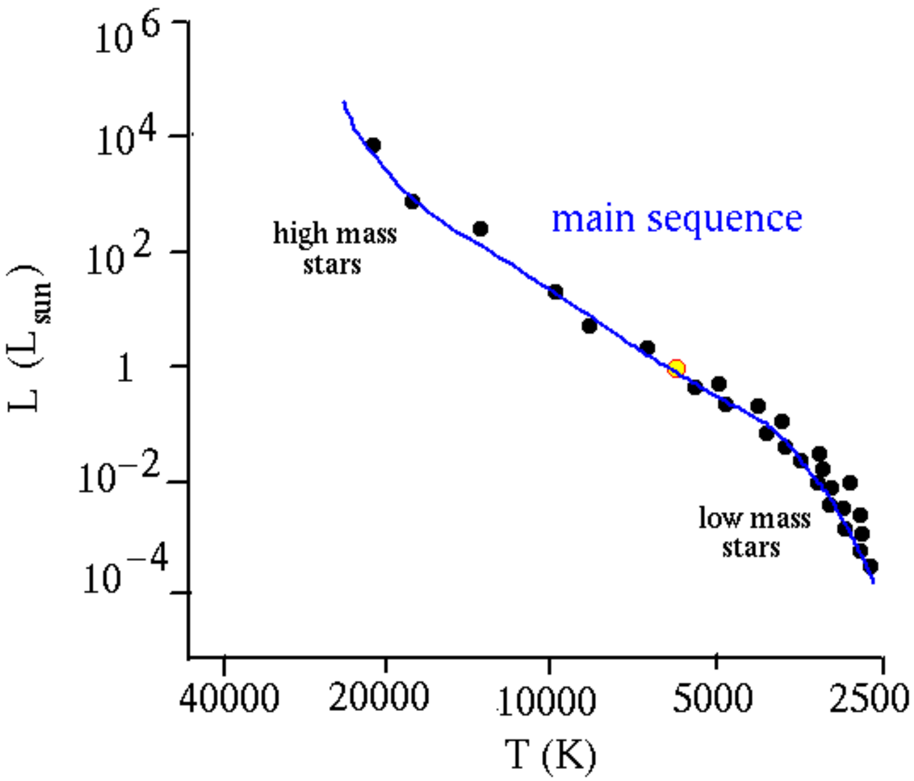
- Assume ideal gas ($pV=NkT$) => $p \propto nT$
  - T: speed of particles, N: number of molecules, V: volume, n: #particles/$cm^3$
- Fusion: 4 H => 1 He. Then, each particle must move faster to maintain the same pressure.
- As a result the core will slowly heat up, and fusion will be faster.
- The star will slowly increase in luminosity.

Thus, stars change a little during their MS lifetime.



Luminosity change: ~0.7% every 100 Myr.

The Sun is 30-40% more luminous, has a 6% larger radius and is ~300 K hotter than it was as a ZAMS star.



Low-mass stars are cooler and fainter

High-mass stars are hotter and brighter

- Nuclear reactions are highly sensitive to core T
  - p-p chain: $\propto T^4$
  - CNO cycle: $\propto T^{18}$
- Differences in internal structure of stars within MS (dividing line around $1.1 M_{\odot}$).

# Post main sequence evolution: evolved stars

**Core hydrogen exhaustion**

1. During the MS, He forms at core and replaces H.

   ⇒ core runs out of fuel at some point.

   Can it immediately "burn" He? No, the coulomb (electrical charge) barrier is too high.

   => core produces much less energy.

   => internal pressure drops.

2. Core contracts

   => gas heats up.

   => smaller, hotter core.

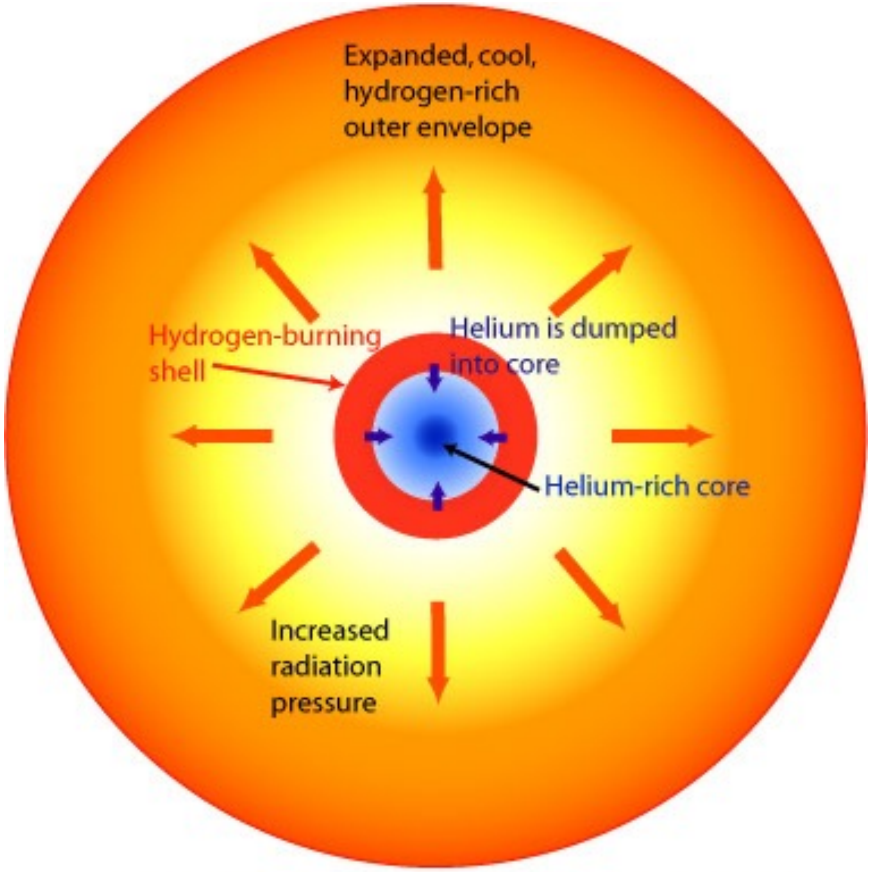
   => H burning moves outward in a shell, liberating new energy flowing out to the stellar envelope

3. Collapsing, inert He core heats the H shell

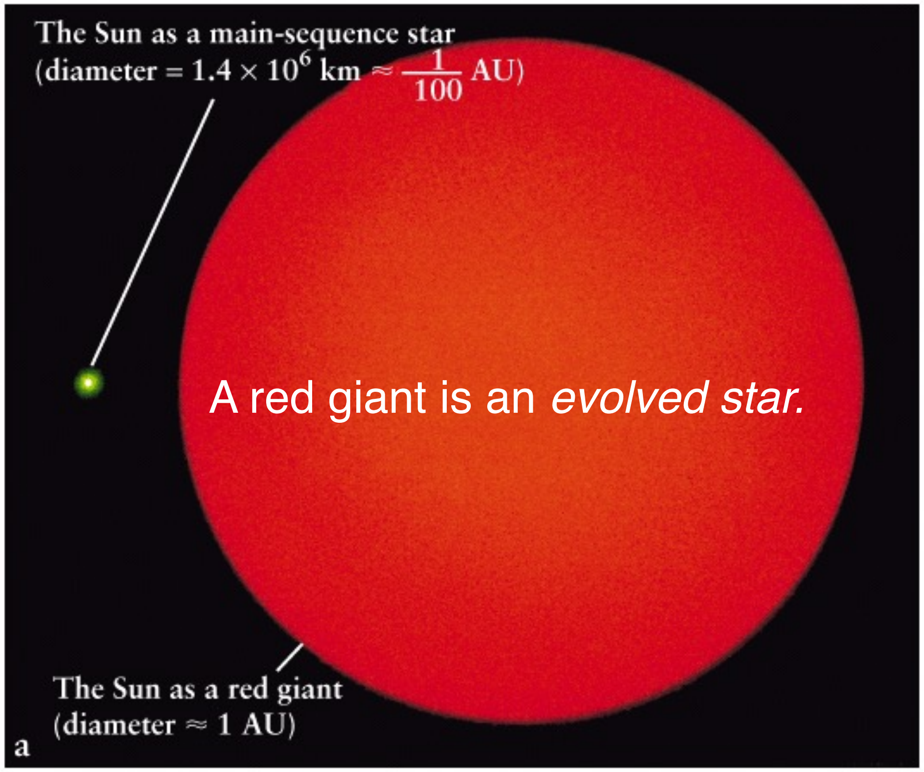
   => faster fusion

4. Faster fusion = more heat

   => internal pressure>gravity



Hydrogen Shell Burning on the Red Giant Branch



A red giant is an *evolved star.*

5. Outer layers will be pushed outwards

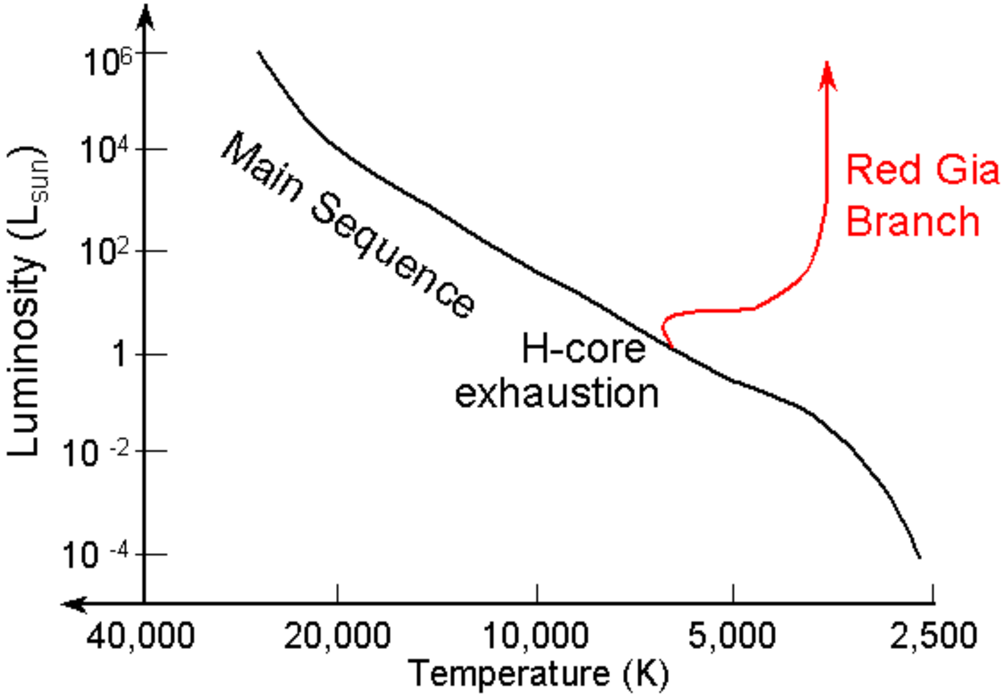
   => those layers will cool due to expansion.

6. A tiny, hot core + cool, expanded outer layers is the result of the core hydrogen exhaustion: We have a red giant.

Red giant stars in Auriga

# Evolving along the red giant branch

- The envelope structure was setup to be in equilibrium with hydrogen burning core. Now it has extra energy from the core and is too dense to let all the new heat and radiation out fast enough. To compensate, it will expand in radius, drop in density and thus surface temperature.
- Radius can increase as much as 25 times => star moves to cooler regions in the H-R diagram (to the right).
- Eventually, the envelope has dropped sufficiently in density to allow new luminosity to come out of the surface, moving upward in the H-R diagram.
- Takes about 250Myr for ≤ 2-3 $M_\odot$ stars (c.f. $t_{ms}$~10 Gyr for the Sun).



# Helium burning

- At T=$10^8$ K helium will start to fuse .

$$^{4}He + {}^{4}He \Rightarrow {}^{8}Be + \gamma$$
$$^{8}Be + {}^{4}He \Rightarrow {}^{12}C + \gamma$$

**Be nucleus is extremely unstable: Be does not build up in core.**

Fusing $^{4}$He to C is called *triple alpha process.*

- Add another helium nucleus:

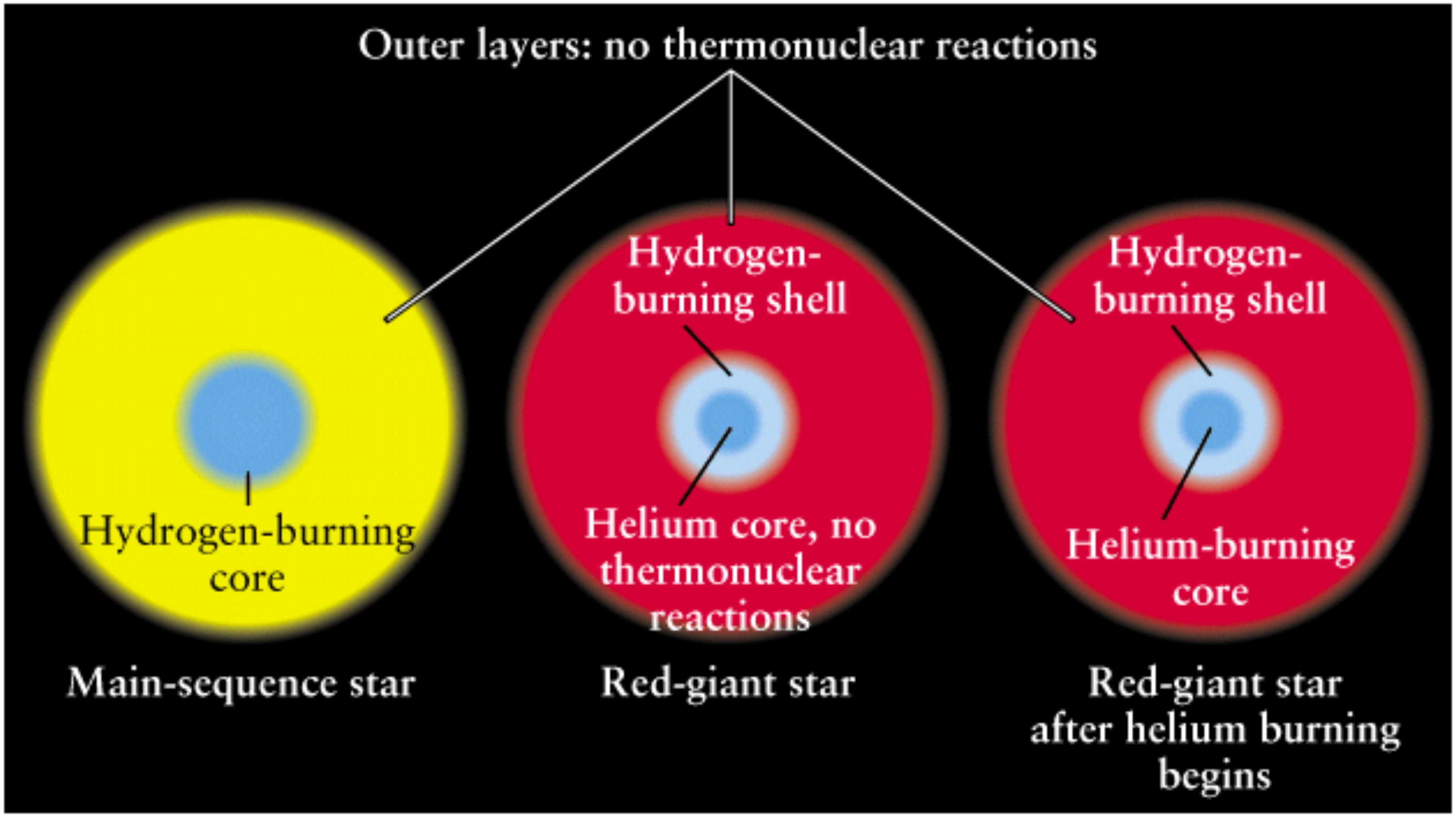
$$^{12}C + {}^{4}He \Rightarrow {}^{16}O + \gamma$$

- Or we can add a $^{1}$H fusion step and get

$$^{12}C + {}^{1}H \Rightarrow {}^{13}N + \gamma$$

**Everything needed for organic chemistry!**

The core of the red giant becomes complex. H burning goes on in a shell around the core while the core itself starts to burn He.



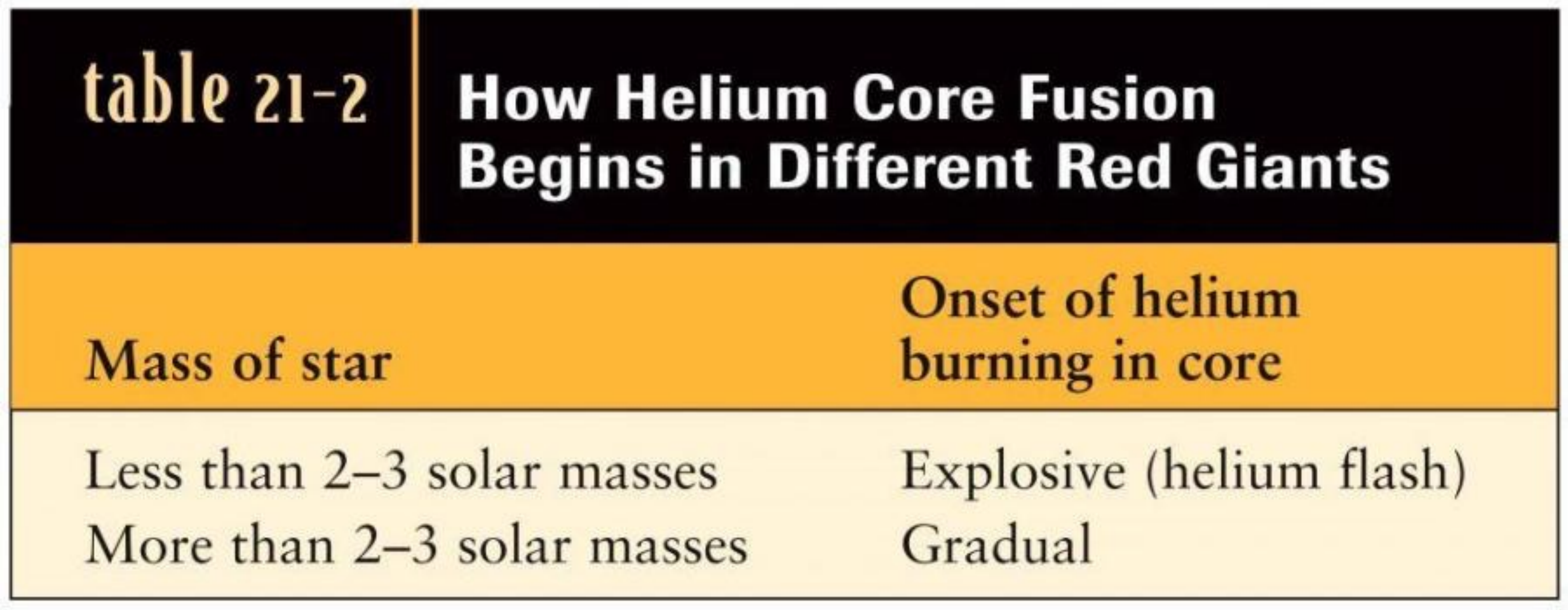


**table 21-2** **How Helium Core Fusion Begins in Different Red Giants**

| Mass of star | Onset of helium burning in core |
|---|---|
| Less than 2–3 solar masses | Explosive (helium flash) |
| More than 2–3 solar masses | Gradual |

Why is the onset of helium burning slower in higher mass stars?

To understand that, we need the concept of degeneracy, and degenerate matter.

# Electron degeneracy

- In cores of low-mass red giants conditions are extreme (not an ideal gas): very high *T*, *p*, so matter is completely ionized

- During collapse, He cores (and those of heavier elements) collapses to about 0.01 of their initial radius, which means the density is increasing by a factor of $10^6$.

- Electrons and nuclei of the ionized gas are squeezed tighter and tighter.

- However, electrons obey the Pauli Exclusion principle:

*No two electrons can occupy the same quantum state.*

This delimits how compressed the core can become.

- As you compress the gas, you 'fill up the parking-lot'. To add more electrons they have to go to higher energy orbitals. A completely full system is said to be *degenerate.*

- If you try to push the electrons closer than this, they will resist very strongly, exerting a stiff pressure against further compression.

- Causes a new internal pressure, *electron degeneracy pressure,* which does not depend on temperature.

- Thus, adding heat to the degenerate matter will not increase pressure. All heat goes into motion of nuclei.

So, with this background, what causes the sudden onset of He burning in low-mass stars, while it is slower in high-mass stars?

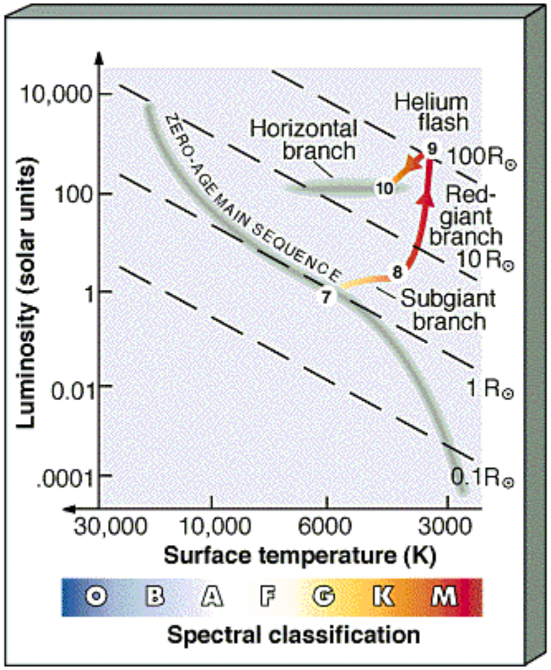
# Low-mass stars: the helium flash

- Core He burning begins explosively in low mass red giants because of the degenerate core.

- He core heats up but pressure doesn't change so the star cannot cool via expansion

=> At $T=10^8$ K helium will start to fuse, adding more energy and heat
=> The triple alpha process gets faster (really fast!)
=> Resulting in a flash-like onset of the He burning.

- When T is high enough, gas pressure will take over again (lifting degeneracy) and the star expands again.



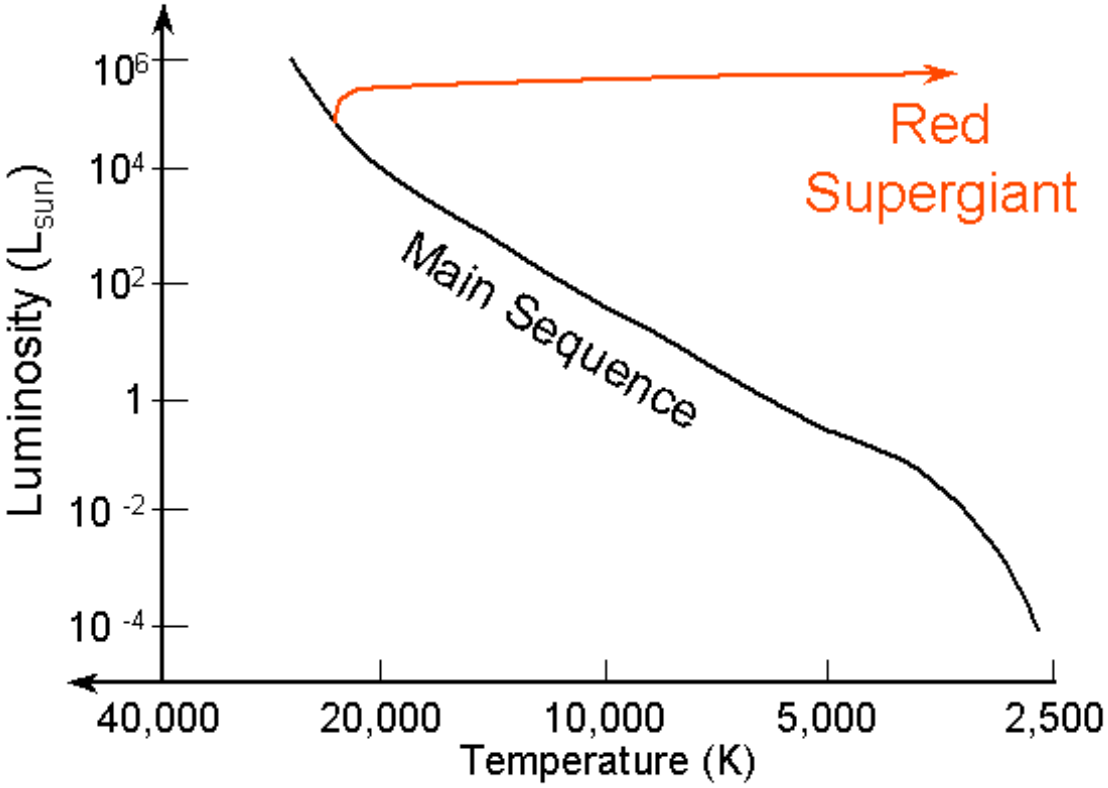
# High-mass star: helium burning onset

- Initially higher core temp: gas pressure has a companion in the radiation pressure

- Radiation pressure is high enough that core will not become degenerate

=> Slower onset of He burning

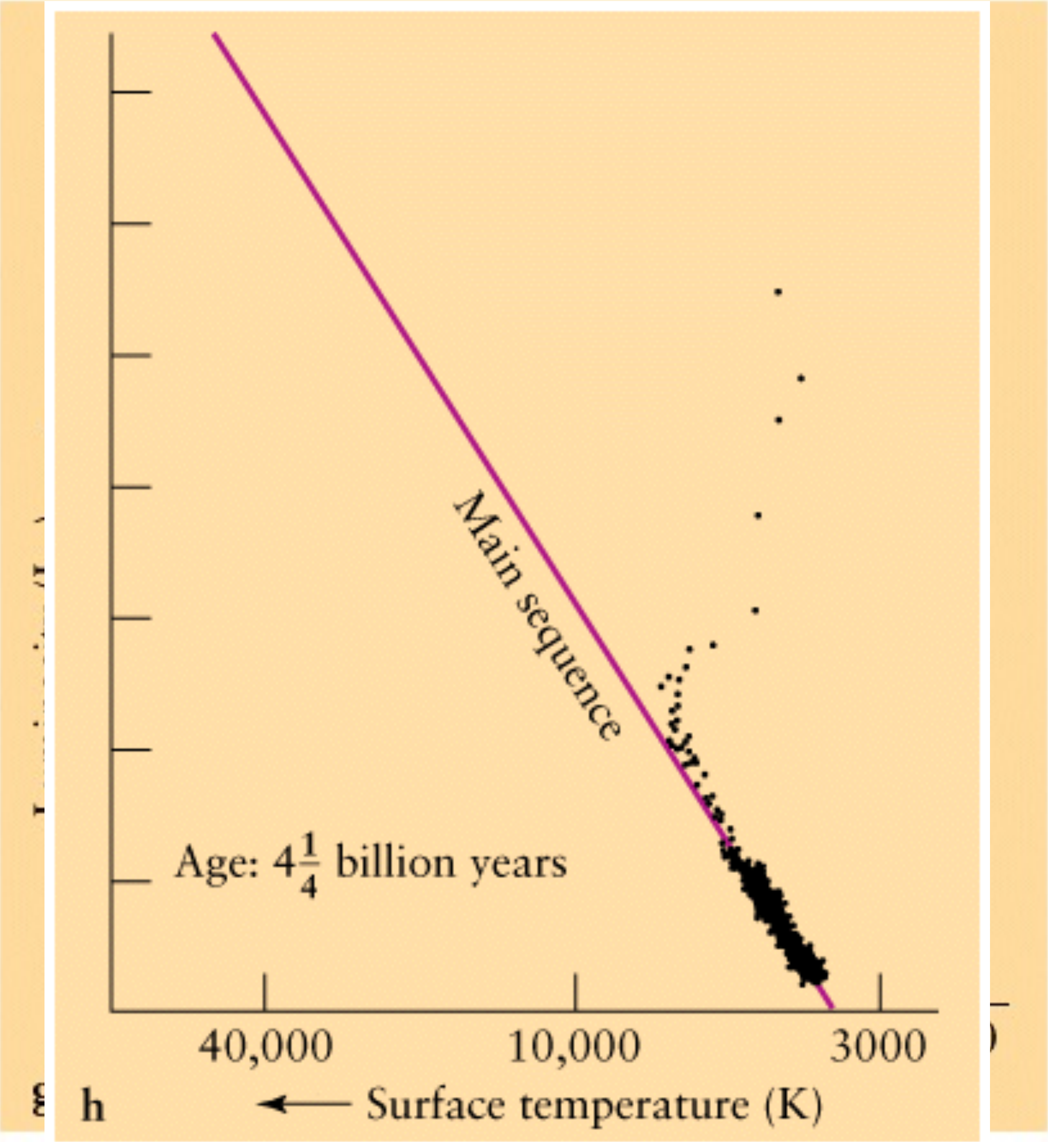
- Moves horizontally across the H-R diagram.



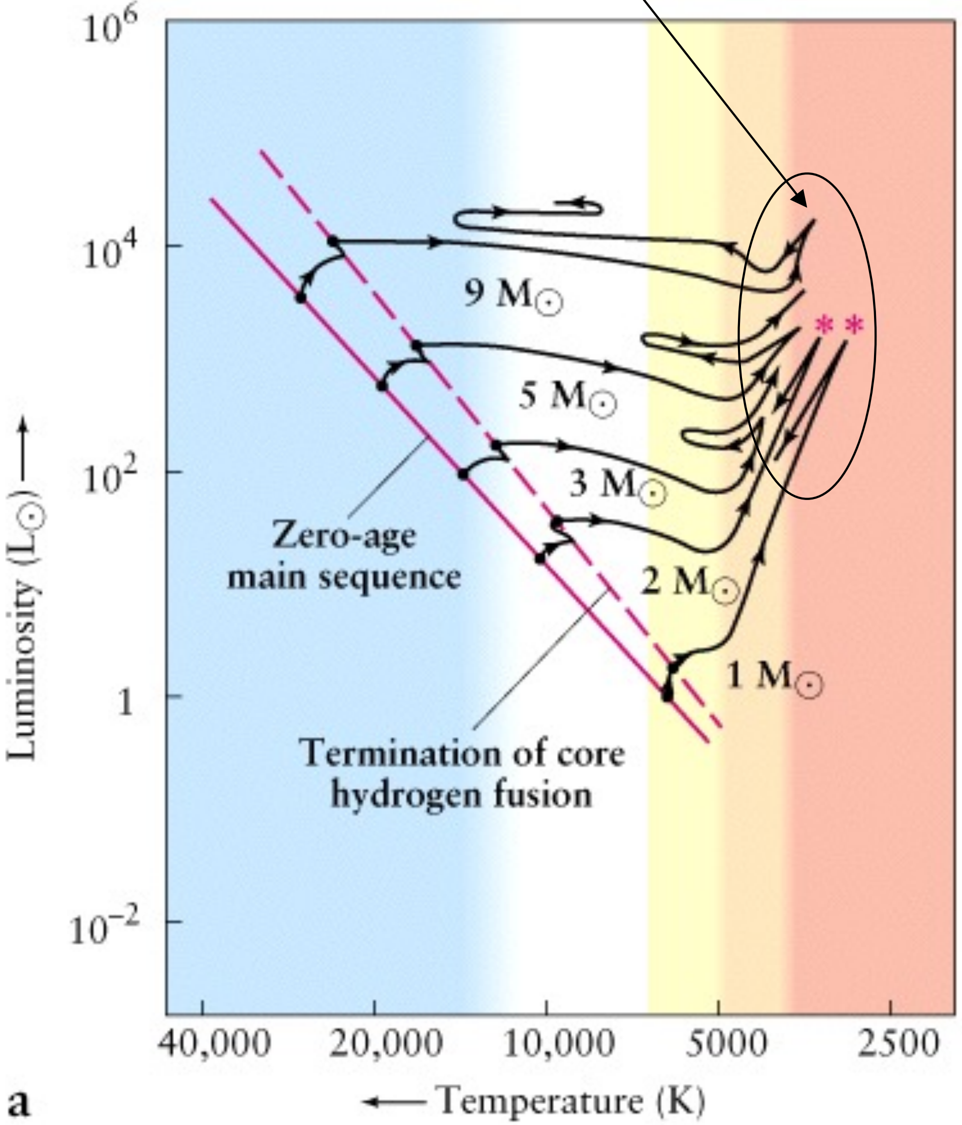
These are theories, and we cannot see deep down into stars. How can we test whether these models are viable?

Answer: compare theoretical “evolutionary tracks” on the H-R diagram with real stars.

# Theoretical tracks:

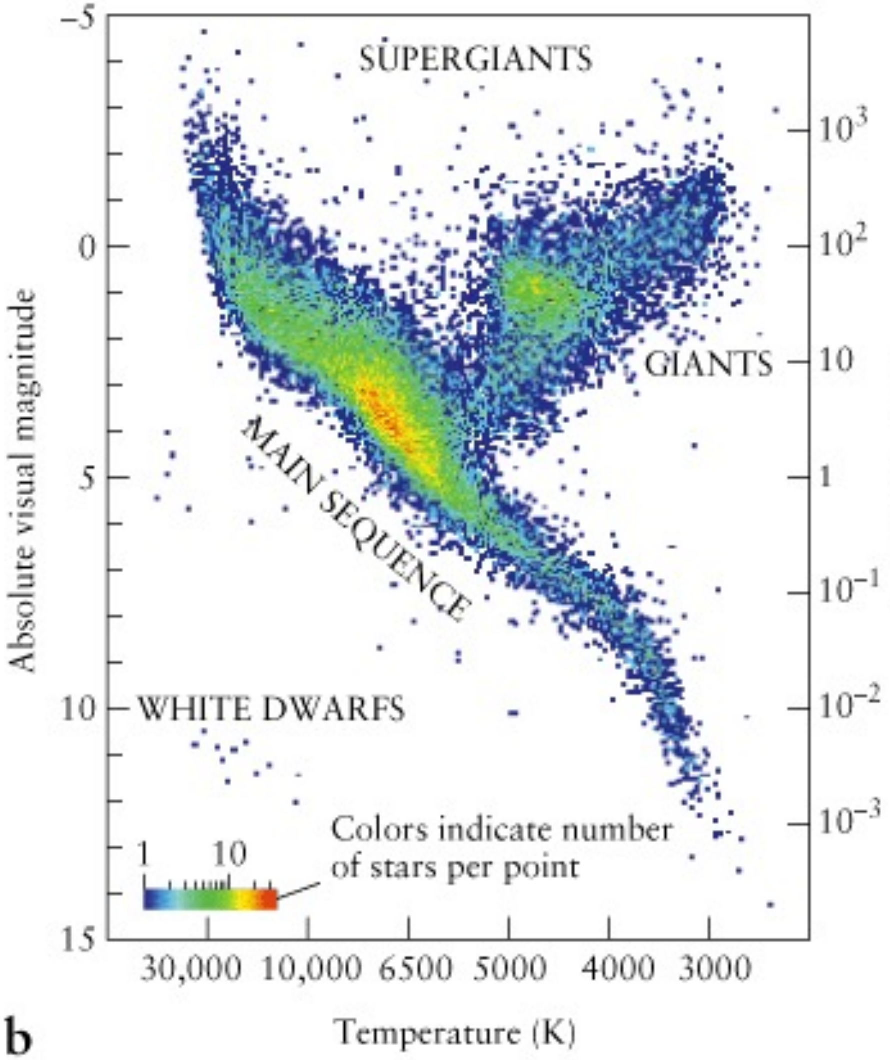


Helium ignition
occurs here



a

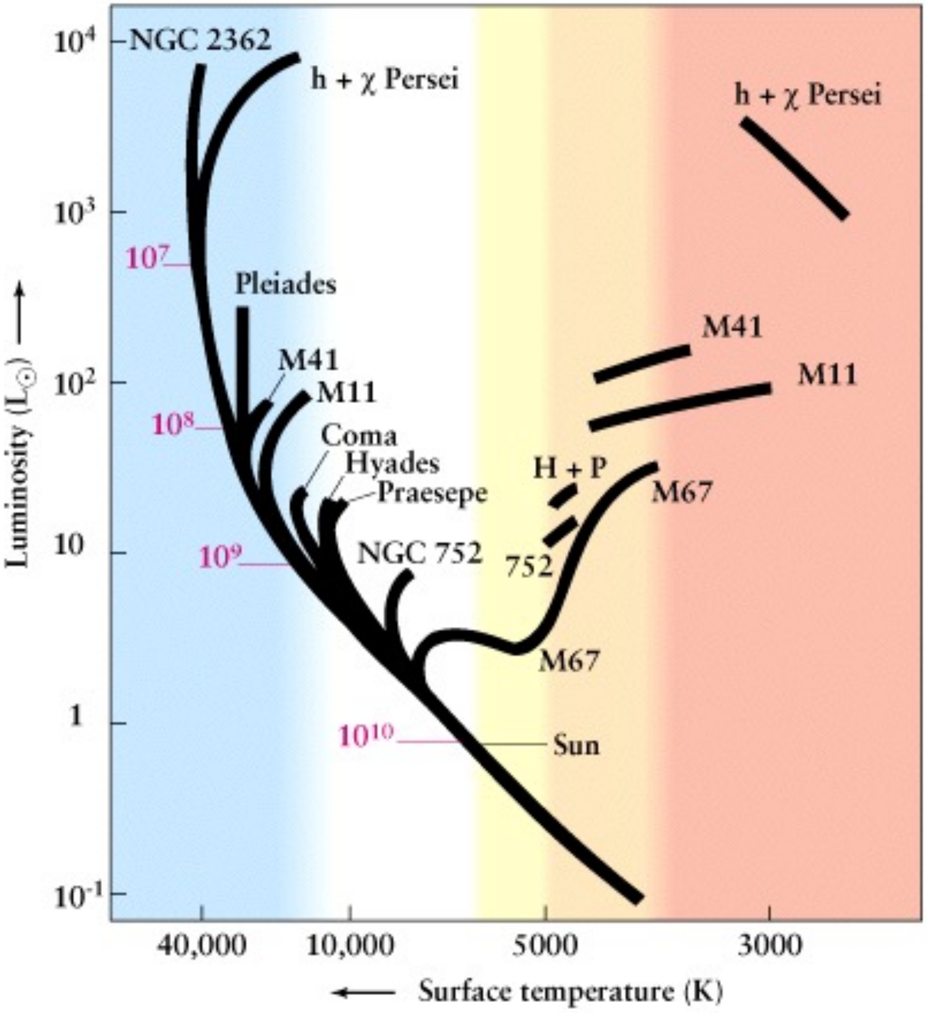
H-R diagram for 21,000 stars from Hipparcos. Note that ages are not homogeneous as in H-R diagrams of clusters.



b

# Comparison theory and observations

- The H-R diagrams of open clusters show that the turnoff point is the key to determining age.



# HR Diagram - Worksheet #6

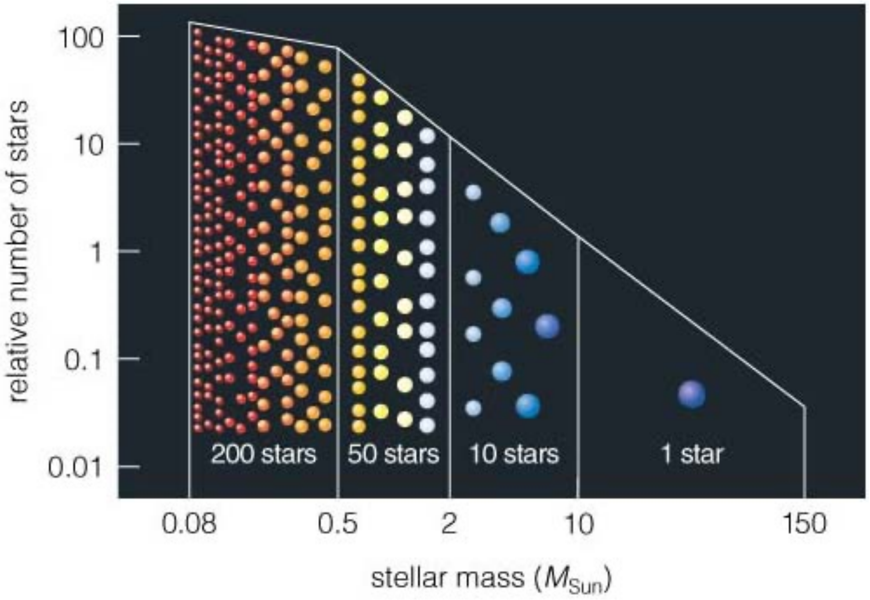
- Sketch the HR Diagram for an Open Cluster with age 10 Gyr

# Star clusters

- Groups of stars moving together through space

- All stars in a cluster
  - Are at the same distance (easy to compare e.g. luminosities)
  - Have the same age
  - Have the same chemical composition
  - Have a wide range of stellar masses

- A cluster provides a snapshot of what stars of different masses look like, at the same age and with the same composition



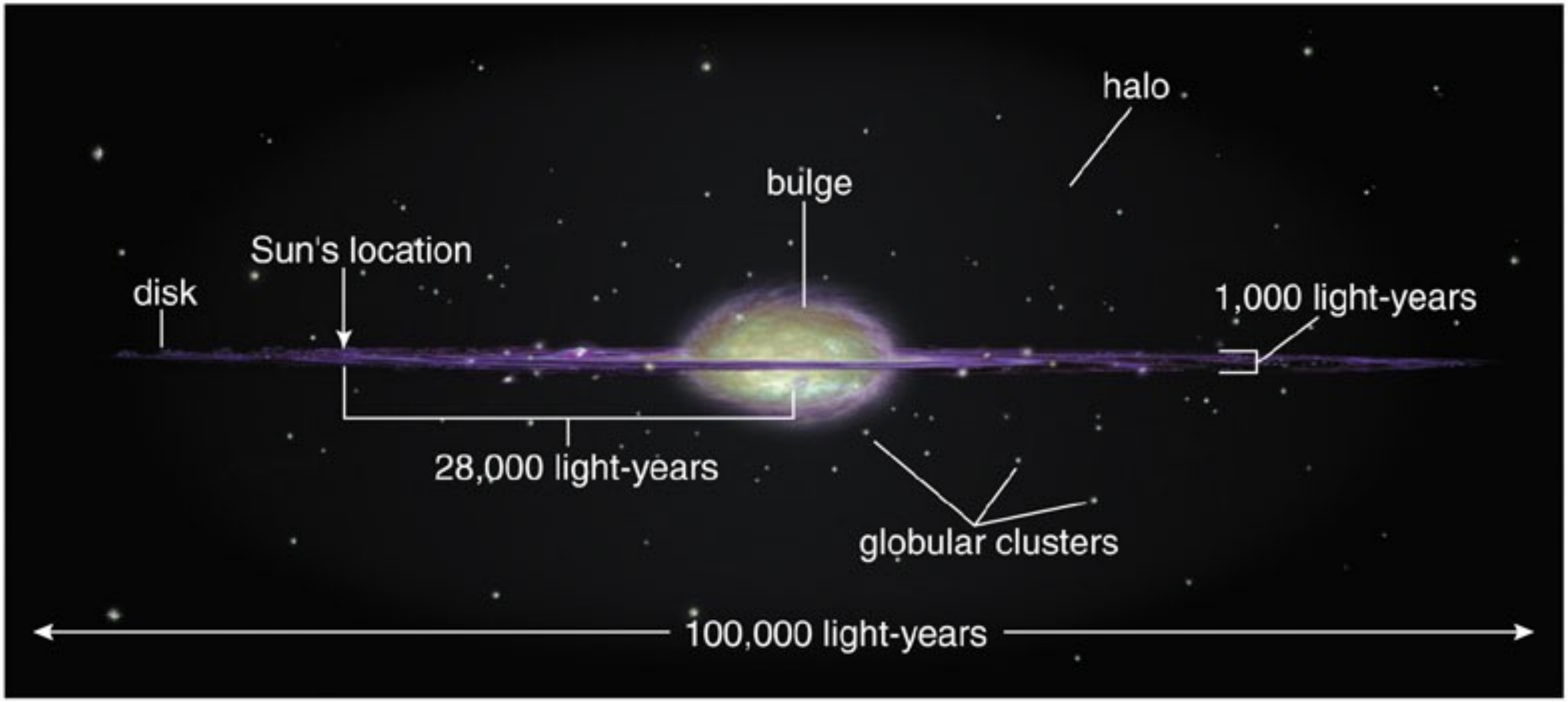
# Open clusters

- Open clusters (galactic clusters) contain $10^2$ to $10^4$ stars, not centrally concentrated.
- The clusters are confined to plane of the galaxy.
- Stars are young, and often have lots of metals (recall a “metal” is any element beyond hydrogen and helium).

M1:1 the “Wild Duck” open cluster in Scutum.

H and Chi Persei

M35 and NCG
2158 in Gemini


halo
bulge
Sun's location
disk
1,000 light-years
28,000 light-years
globular clusters
100,000 light-years

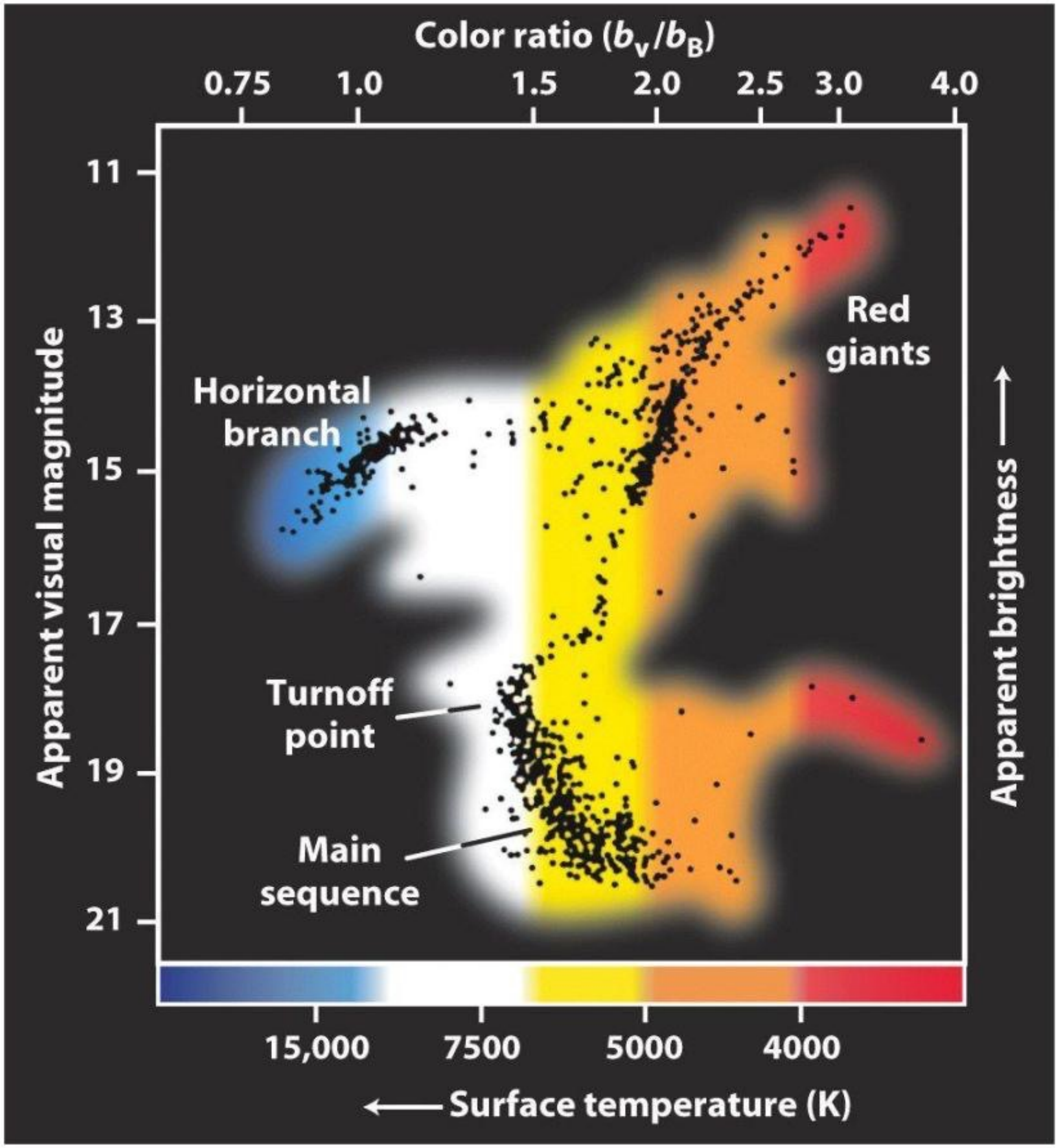
# Globular clusters

- Globular clusters contain $10^5$ to $10^6$ stars, centrally concentrated.
- Found in the halo of the galaxy.
- The stars are old with low metallicity.
- Provide an important, lower limit to the age of the Universe.

M10

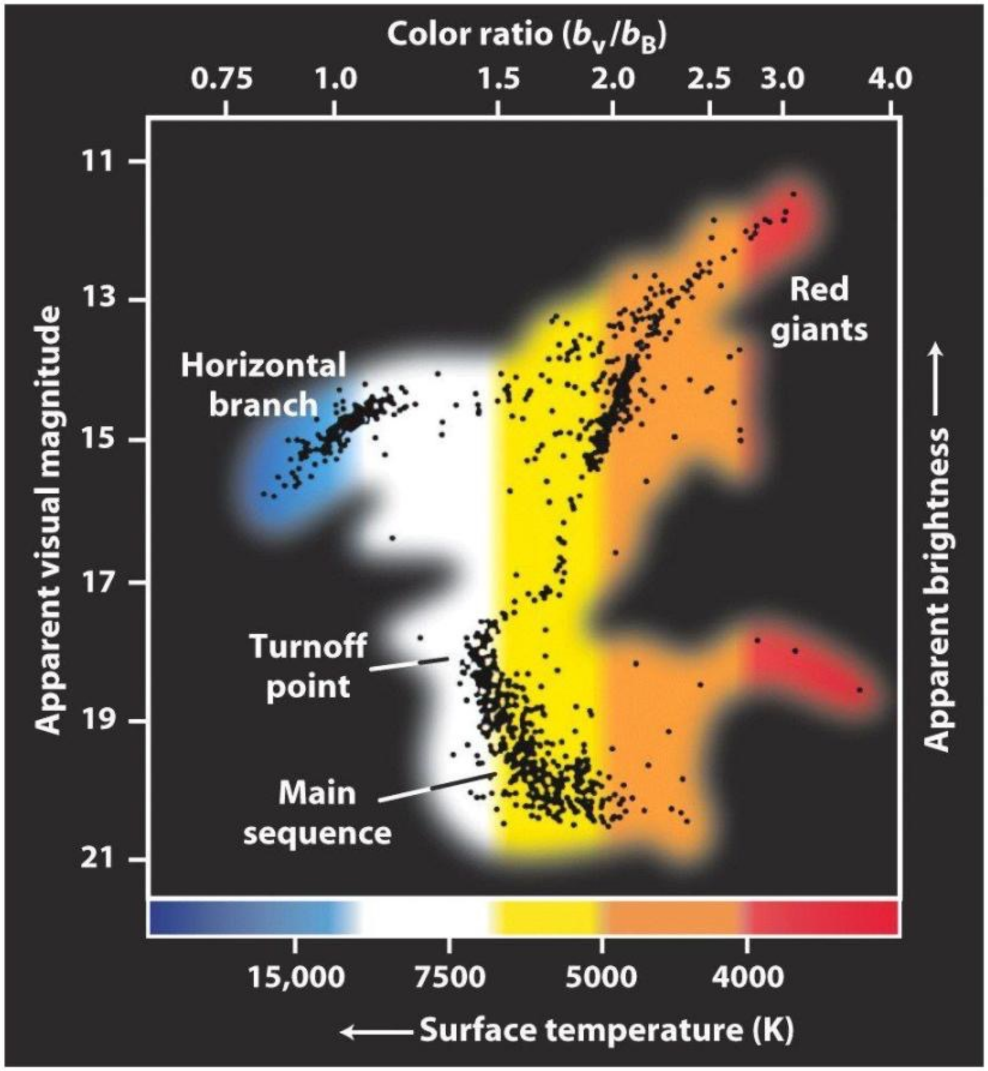
M80

Typical globular cluster H-R diagram. Note low turnoff point, and many red giants. Age?

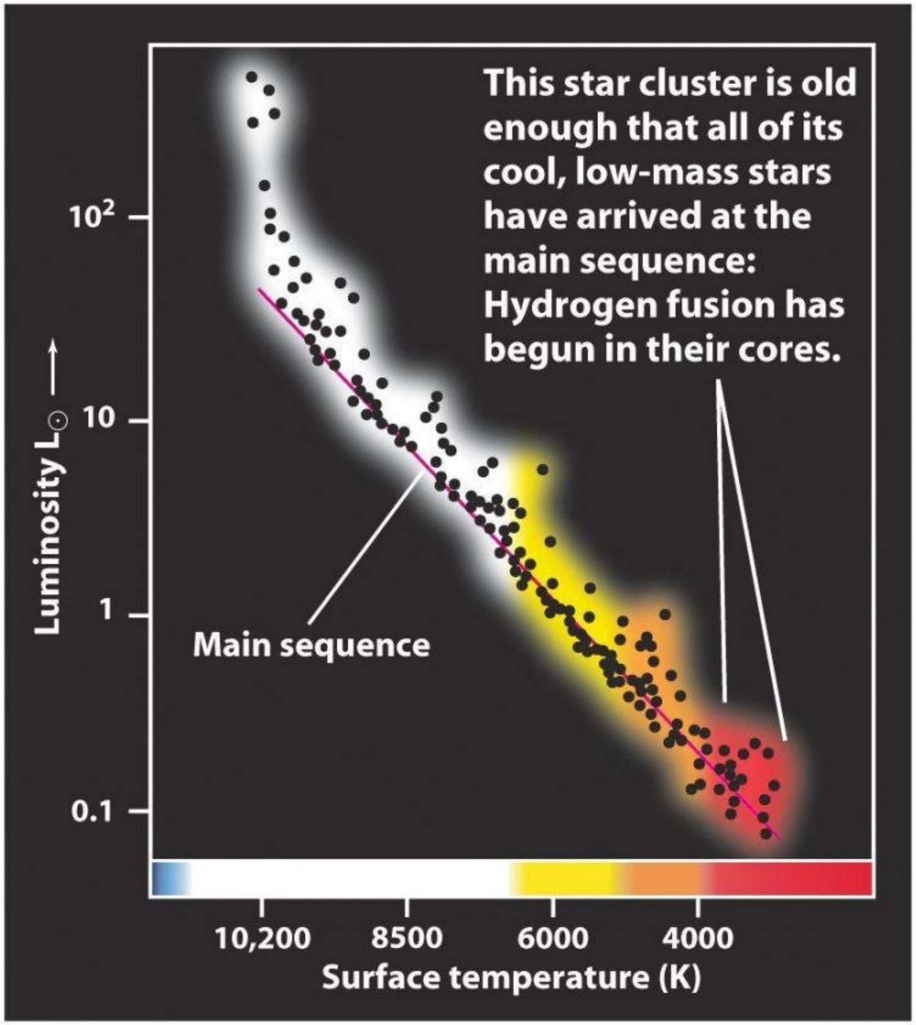


# Compare to open cluster H-R diagram

Globular cluster

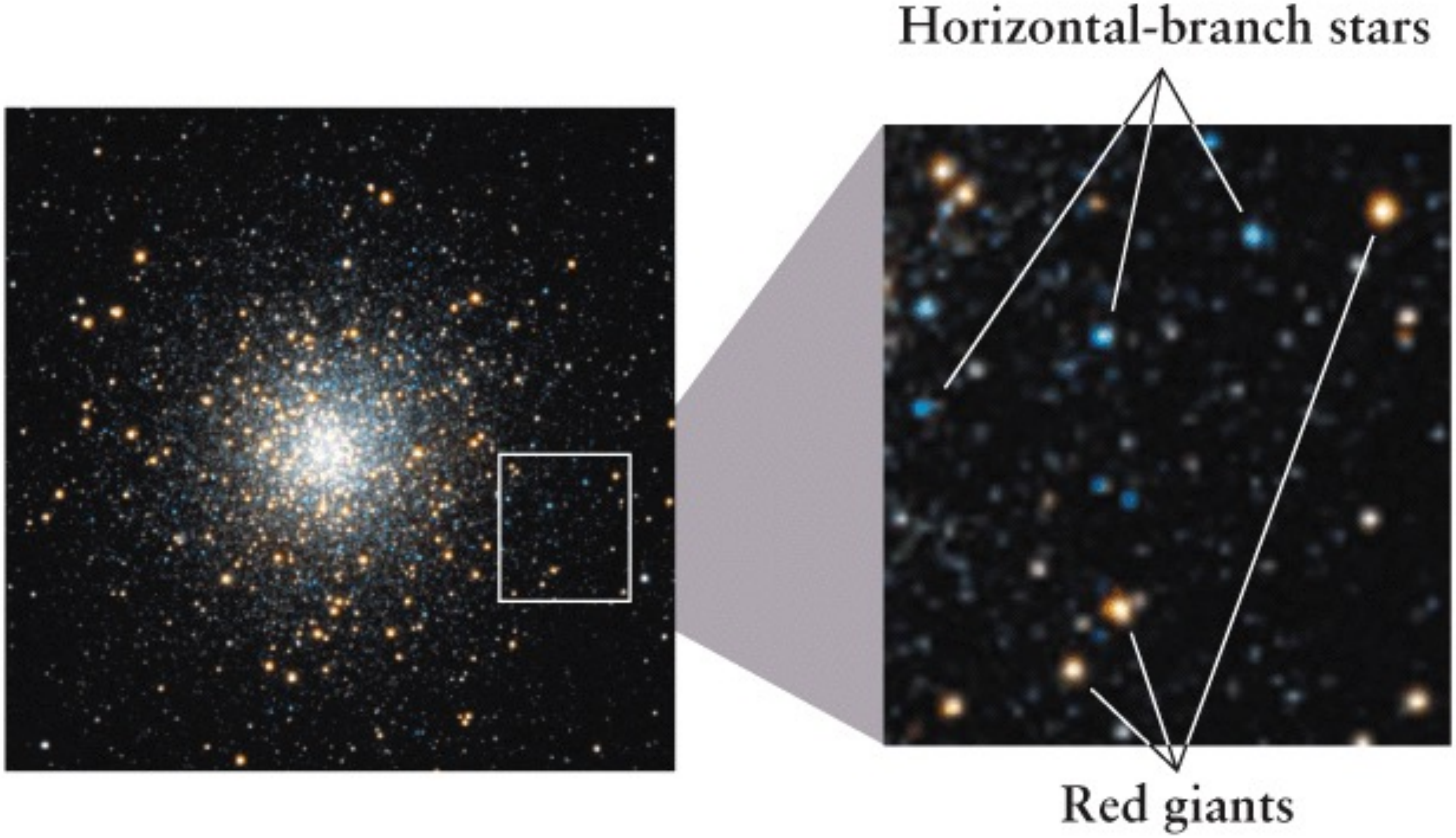


Open cluster



An H-R diagram of the stars in the Pleiades

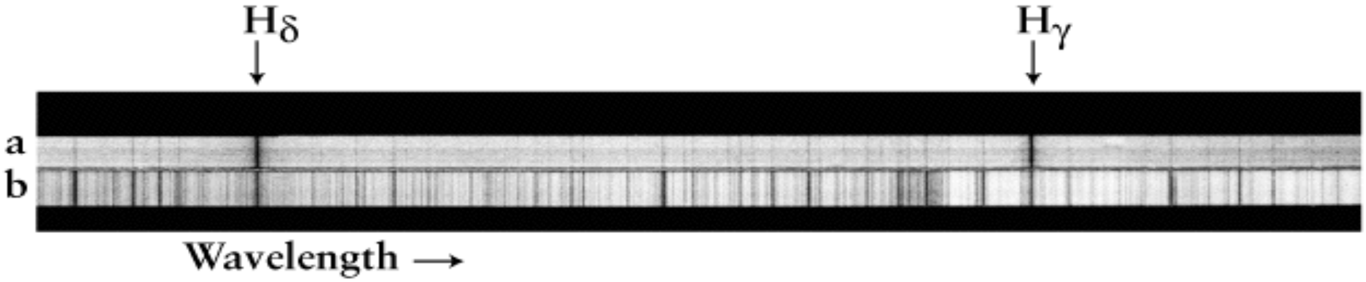
M10 again: note that some stars are blue: these are not young stars, they are stars from an even later stage on the evolutionary sequence.



# Stellar populations

Two basic types of stars – a young class and an old class.

- *Population I* – young, in disk of galaxy, metal-rich, many in open clusters.
- *Population II* – old , avoid disk (in halo), metal-poor, many in globular clusters.

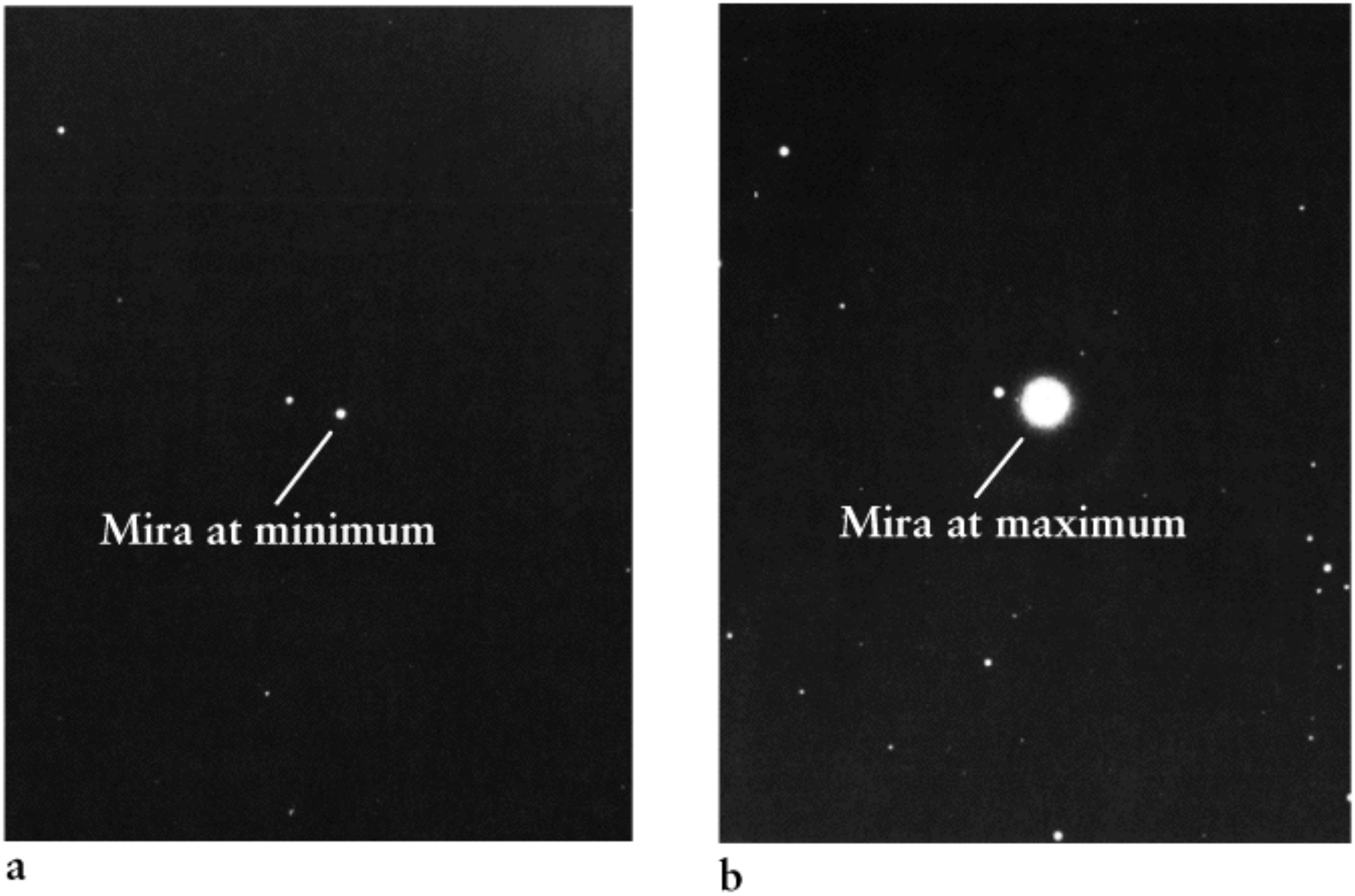


A has low metallicity, B has high metallicity.

- Earlier stars formed out of "cleaner" gas (Pop II).
- Later generations formed out of gas which the first stars "polluted" with heavier elements they created (Pop I).

*More on this when we discuss how the Milky Way galaxy formed…*

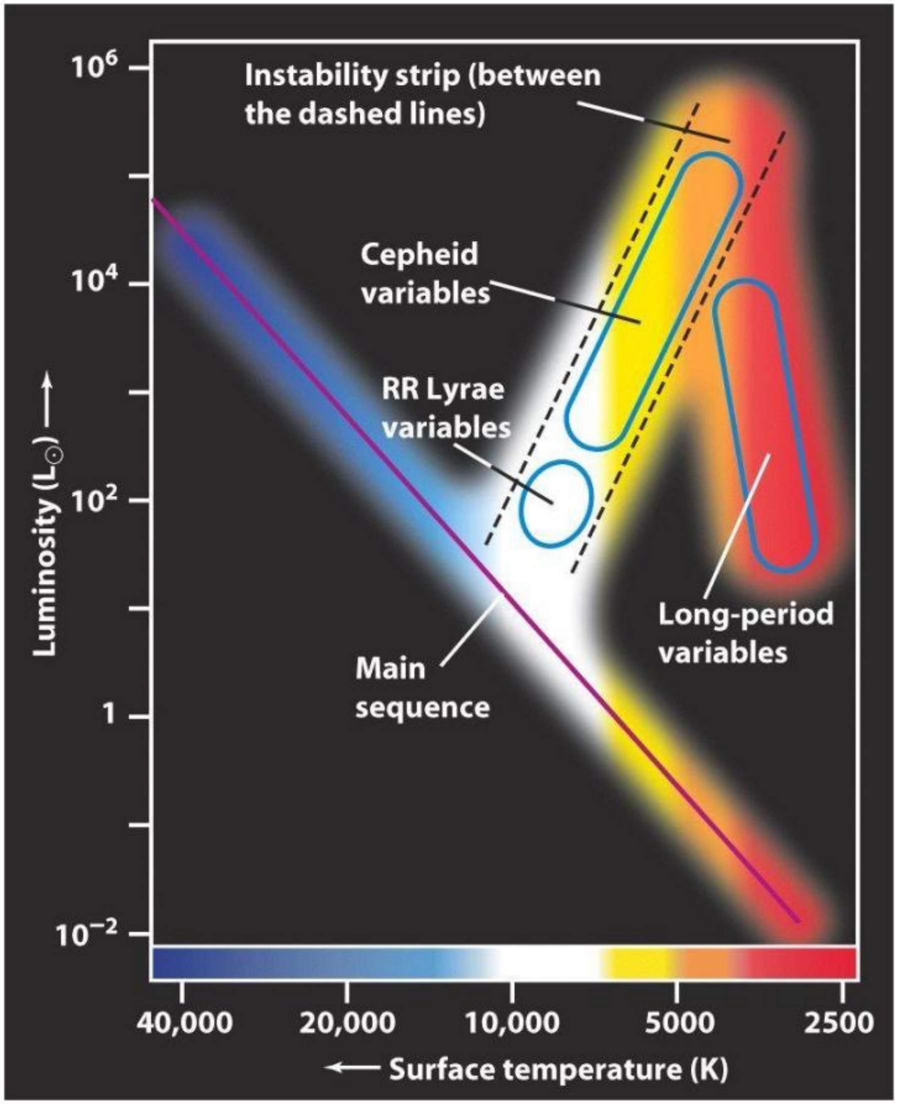
# Variable stars



Some evolved stars vary in brightness. Mira variables are long period variables: red giants varying in brightness by a factor of ~100 over a timescale of months/years.

# Intrinsic variability

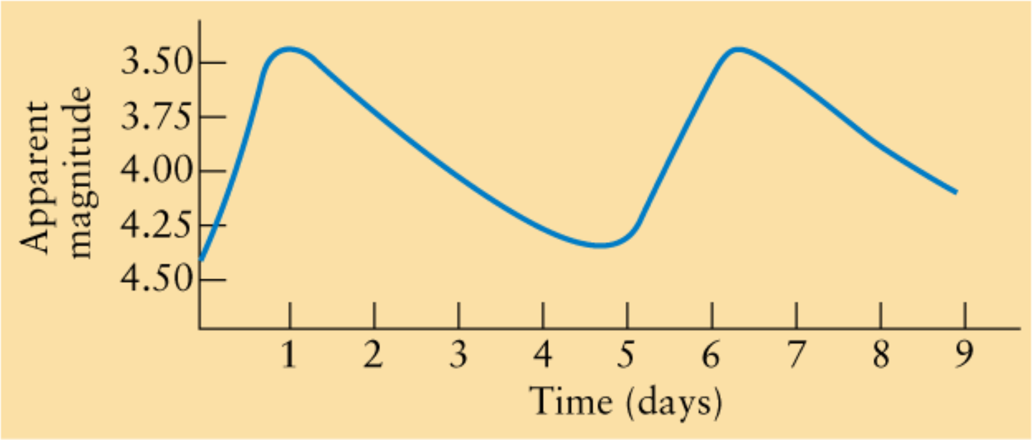
- Those that vary in brightness as a result of conditions within the star itself.
- Found in the *instability strip*. Any star within these portions of the H-R diagram will become unstable to pulsations.
- The different regions produce different kinds of observed phenomena.
- Stars may go through these stages several times during their lives.



# Cause of pulsations

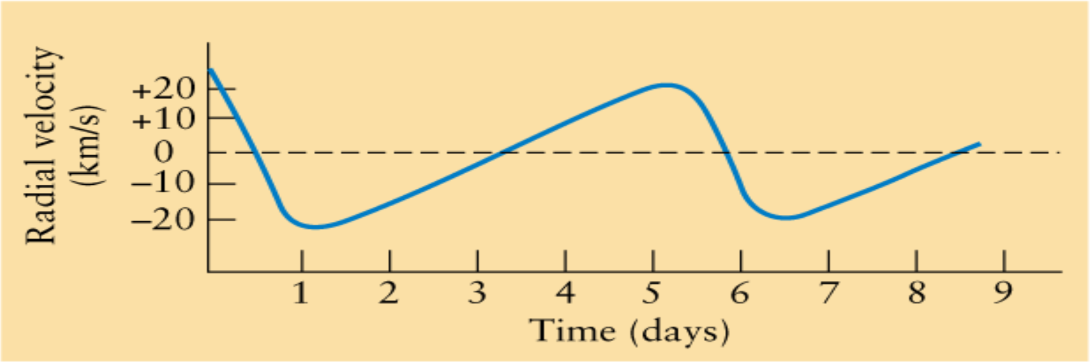
- Stars are variable because they are unstable in one way or another: they lack hydrostatic equilibrium beneath surface.
- Miras are not well understood, but other, more periodically varying stars are better understood, like the Cepheids:
- The ionization zone of He lies at a distance from the center of the star, close to the surface.
- When He gas is ionized, it is opaque to radiation, thus effectively absorbing photons, trapping the heat.
- Radiation will push the surface layer outward, and cooling will begin.
- As the gas cools, it will recombine. Neutral He is transparent, ceasing the outward push and layers fall back as a result of gravity.
- Heating of those layers causes the process to repeat.

# How to study variable stars



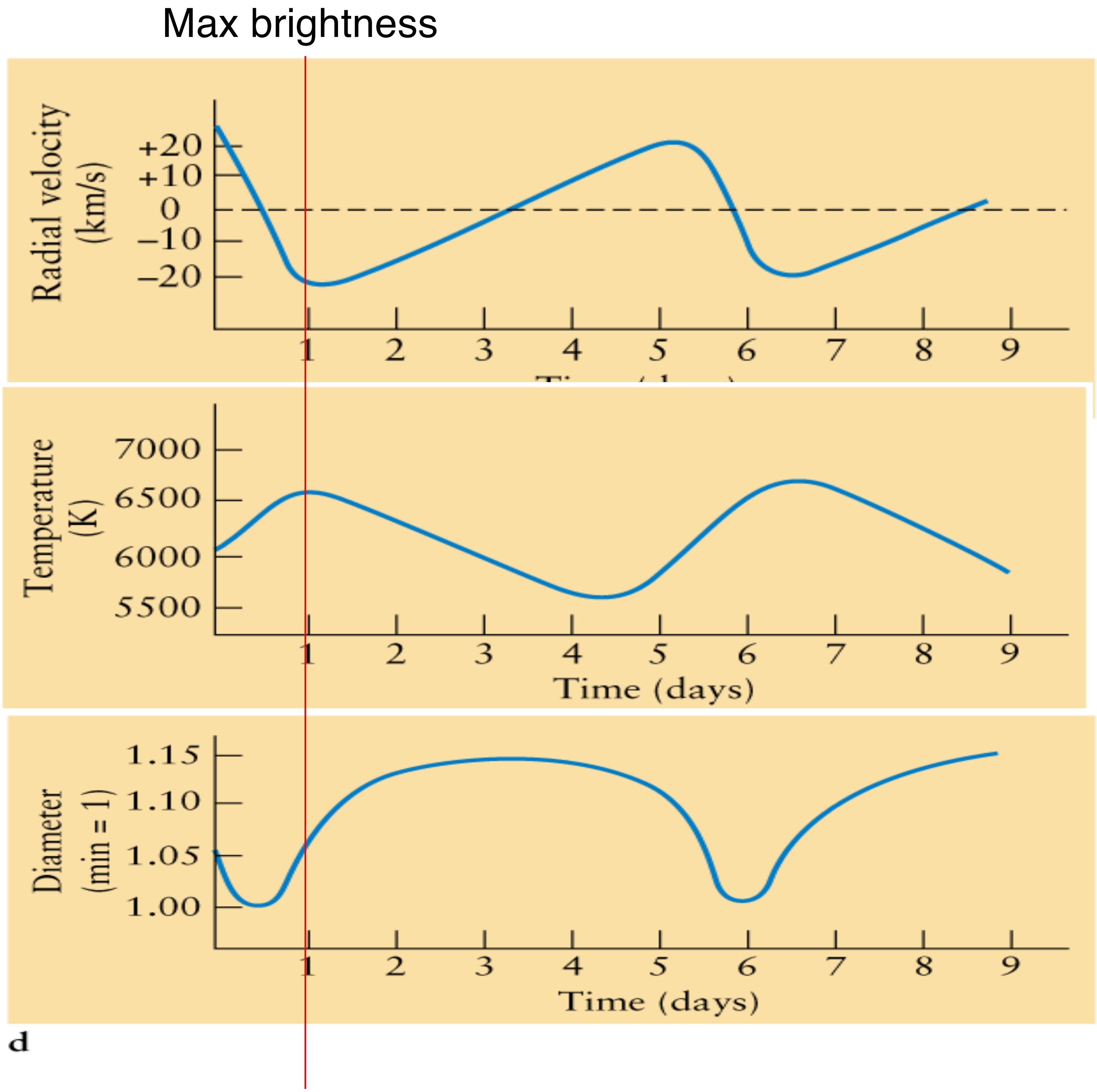
a

We use lightcurves, which show the brightness versus time for the star.



b

We can also look at the periodic change of other properties, such as the radial velocity, surface temperature, and size.



At max brightness, the star expands most rapidly. As it cools, the outer layers will start falling back onto the star.

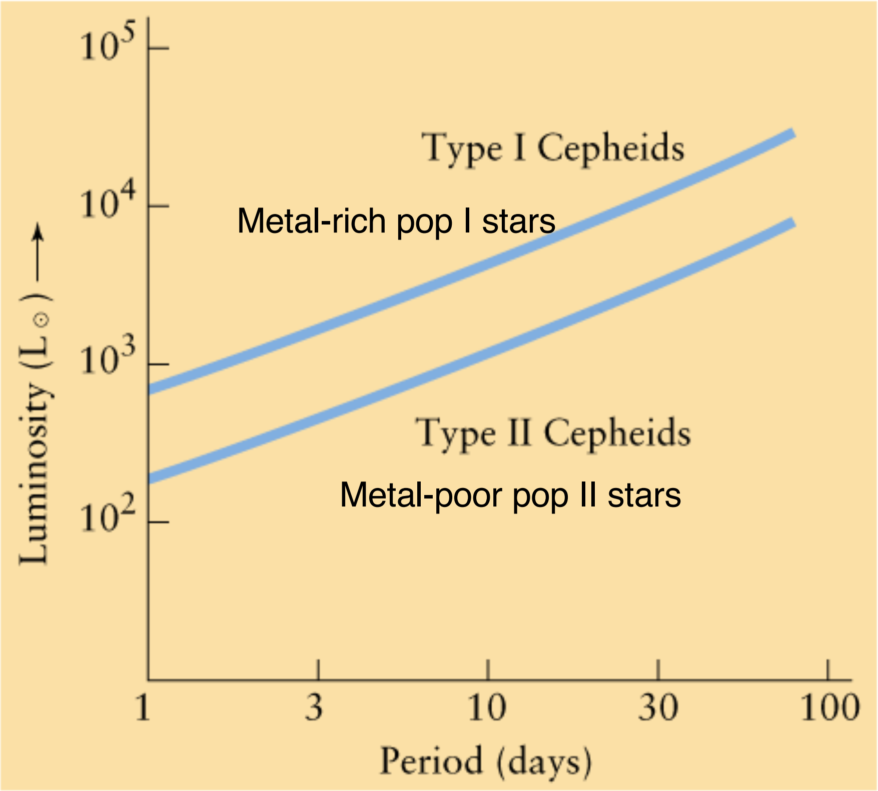
The surface temperature will vary with the brightness.

The star reaches its minimum size *before* maximum brightness, since it will take a little time to transport the radiation to the surface. A *time lag*.

# Distance indicators

- Variable stars like Cepheids, and RR Lyrae stars can be used as distance indicators. How?
- The exhibit a relation between their period and their luminosity.

  => if we can measure the period of the star, then we know its luminosity (or absolute magnitude).



The period-luminosity (P/L) relationship for Cepheids

Type I and II Cepheids behave differently because they have different abundances of heavy elements in their atmospheres, affecting the opacity.

- The P/L relationship for RR Lyrae stars is trivial: all have *M*=+0.5.
- For Cepheids, the relation is fitted by:

$$M_{<V>} = -2.81 \log_{10} P_d - 1.43$$

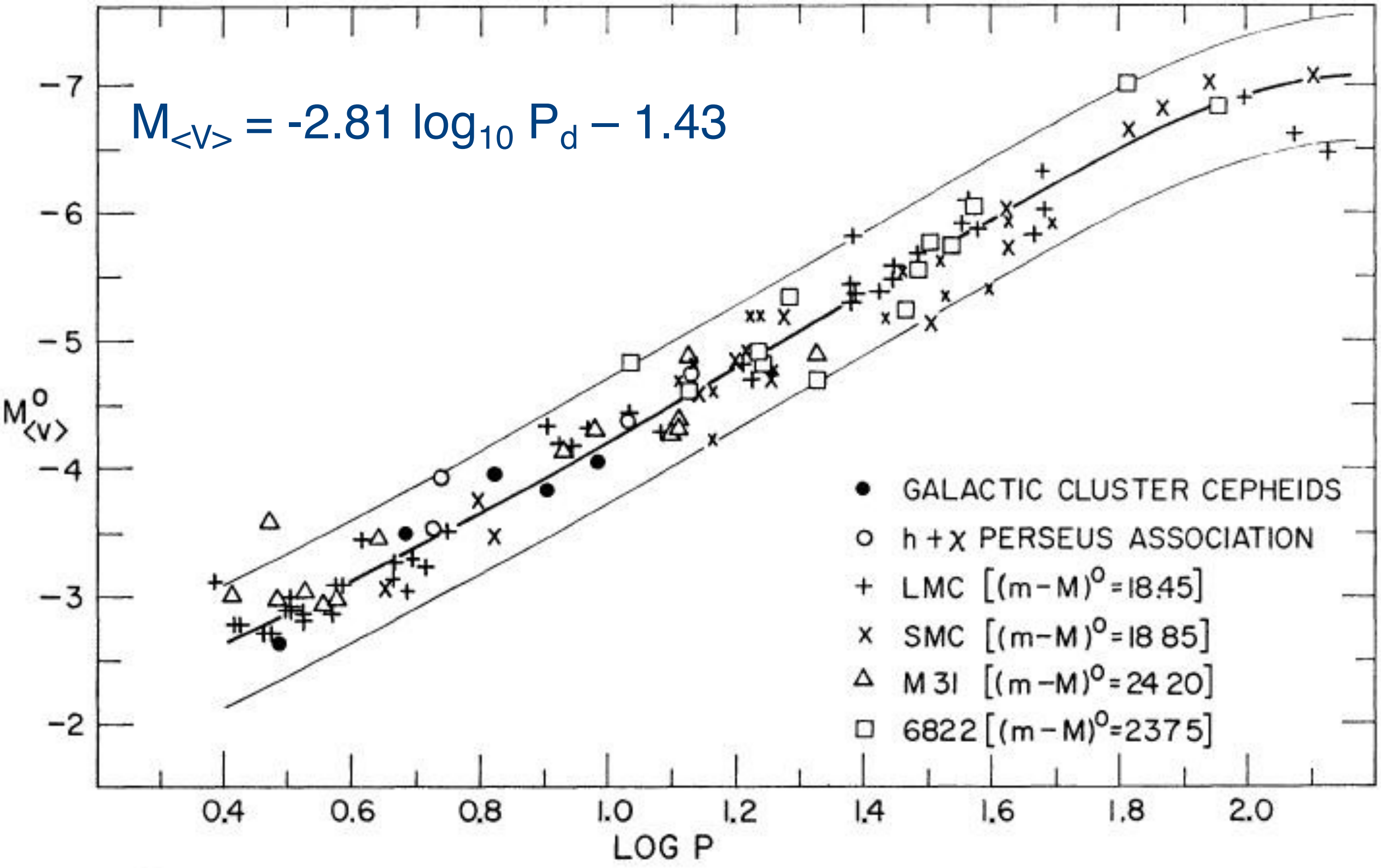
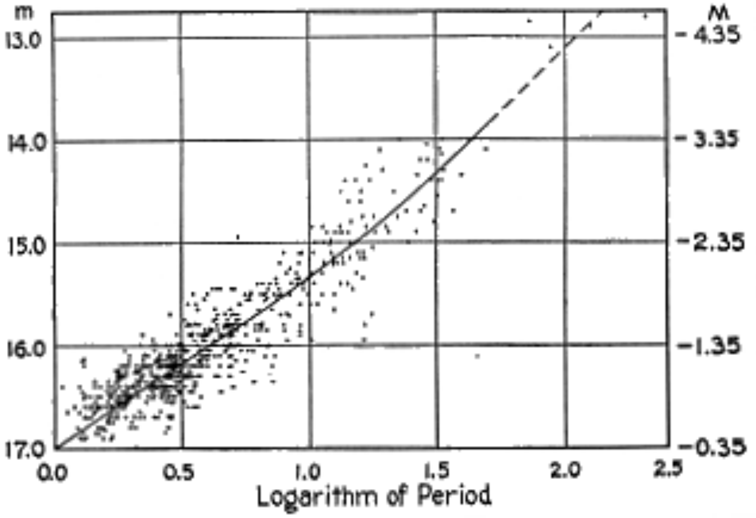


FIG. 1.—The composite period-luminosity relation at mean intensity in *B* and *V* wavelengths derived from the sources indicated at the lower right. The absolute calibration was made by using the nine Cepheids of the galactic system shown as open and filled circles. The photographic data from the SMC are plotted with smaller crosses than the Gascoigne and Kron photoelectric data.

- Knowing *L* or *M*, we can calculate the distance. Apparent magnitude (*m*) is always easy.

$$m - M = 5\log(d) - 5$$

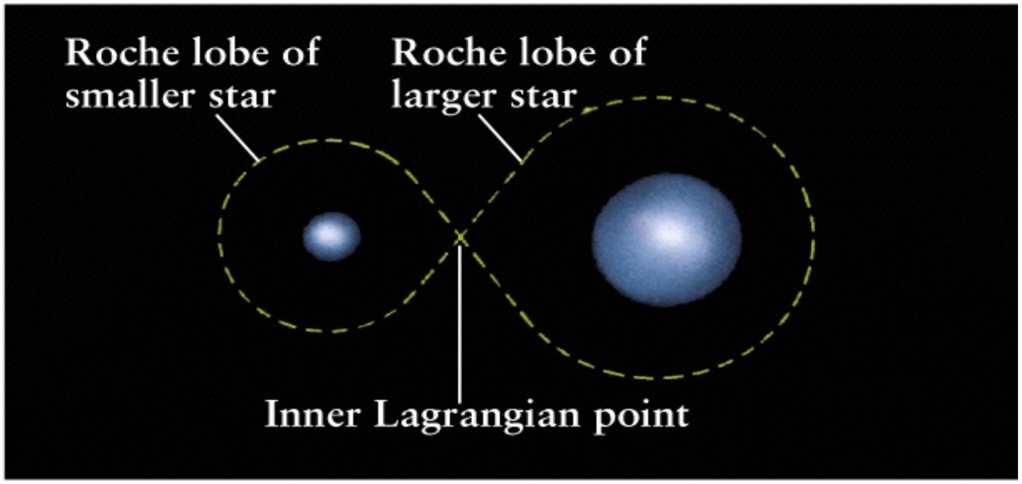
- Important relation: Cepheids and RR Lyrae stars are giant and thus very luminous. We can see them as individual stars in other galaxies.



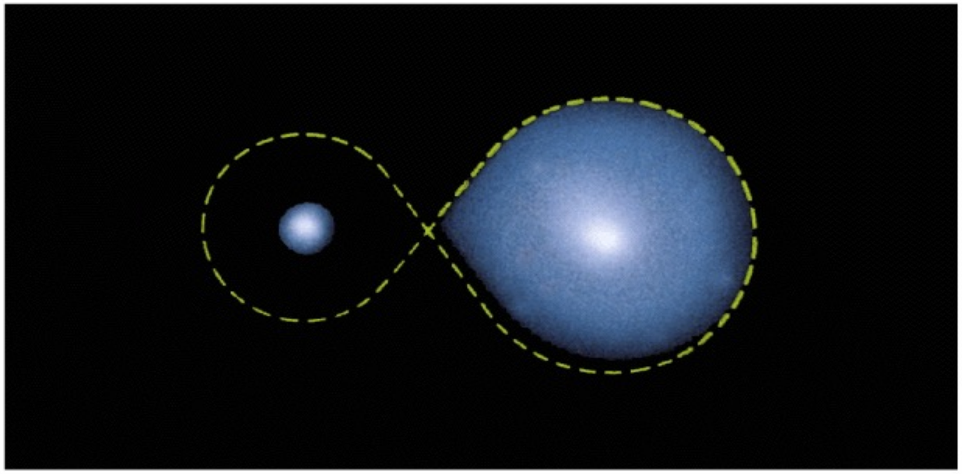
Cepheids in the Small Magellanic Cloud

# Mass transfer can affect stellar evolution

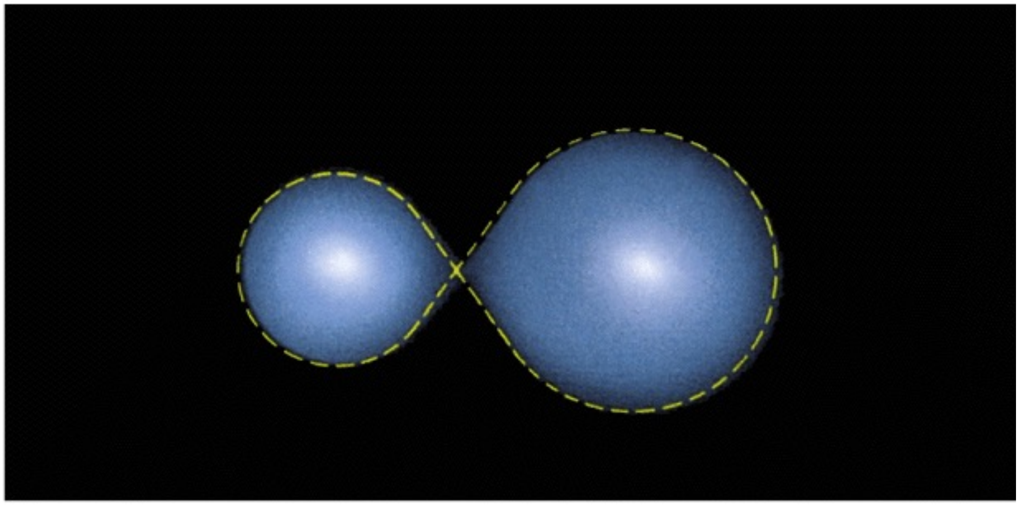
- Close binary systems - some binary systems are so close they are in contact.



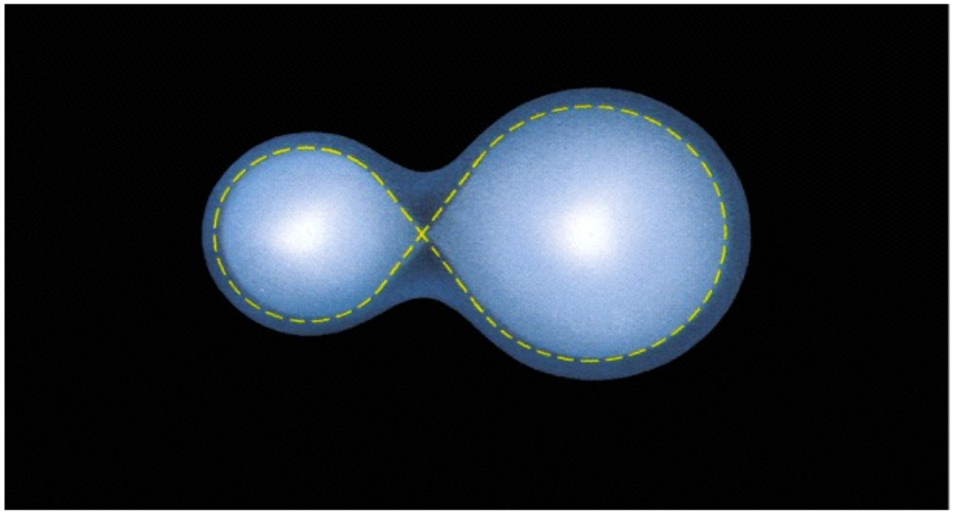
a Detached binary



b Semi-detached binary

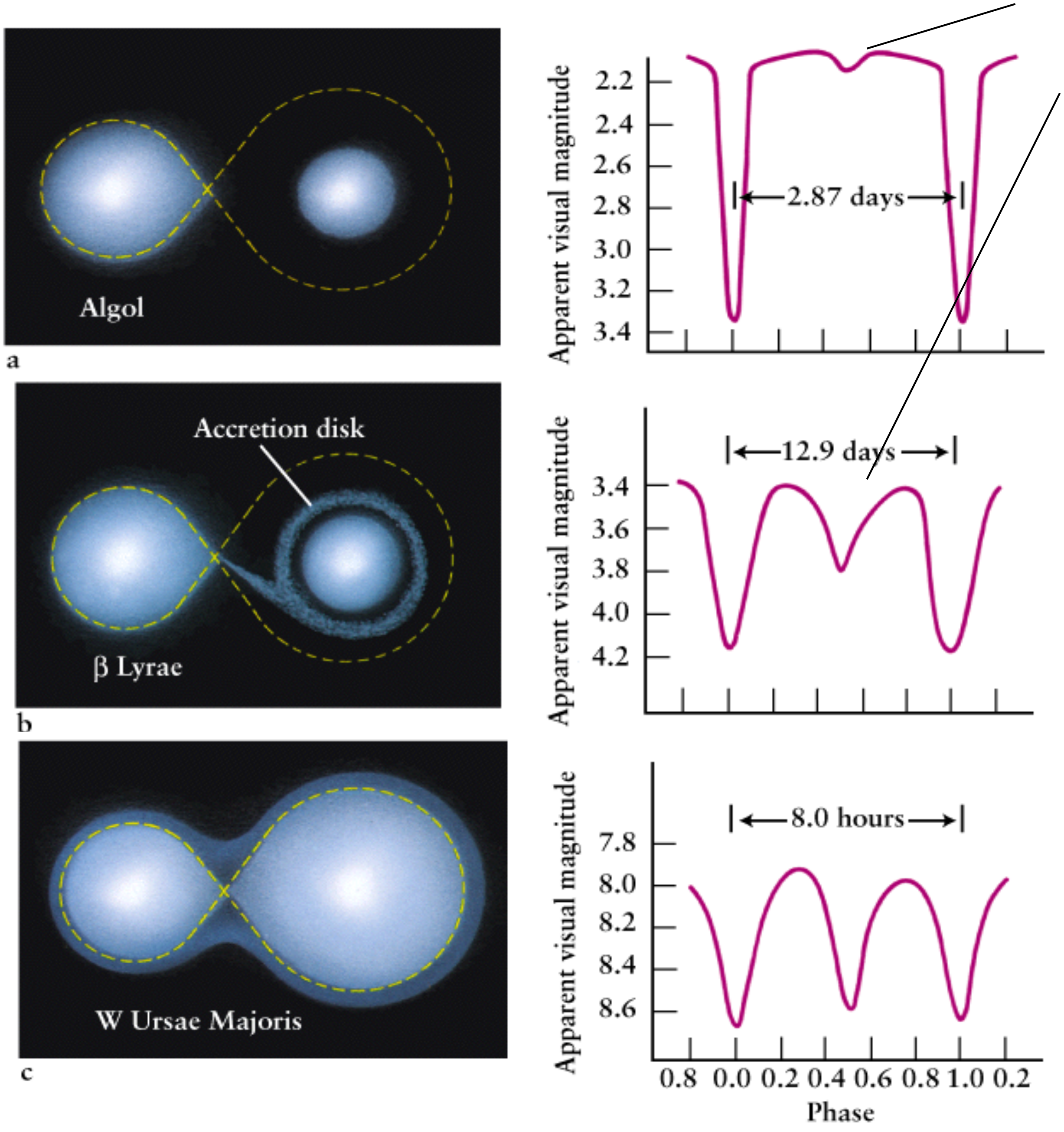


c Contact binary



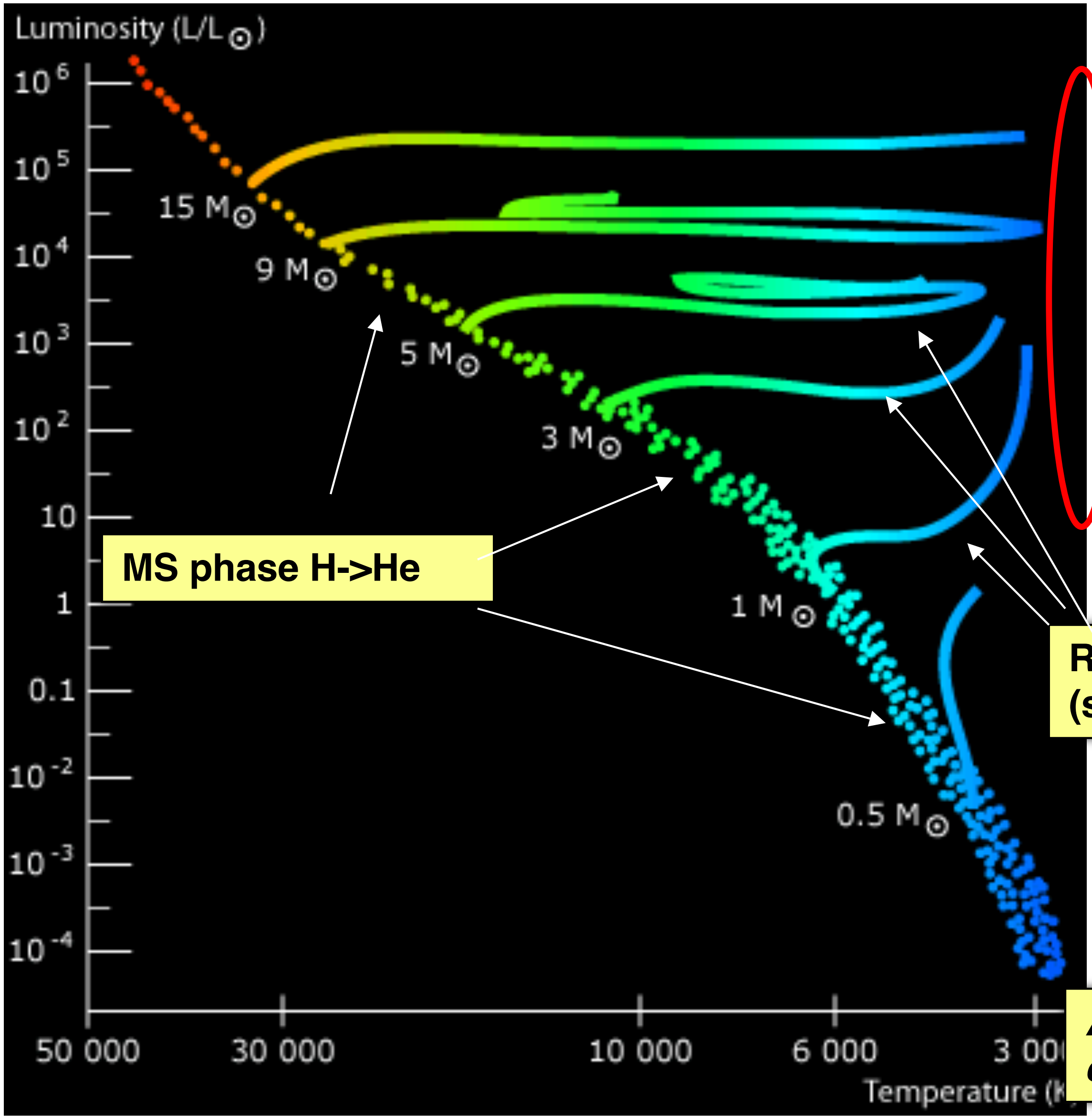
d Overcontact binary

Gas may flow from one star to another in close systems. This can alter the standard evolutionary pattern.



Small star eclipses large one

# Stellar evolution so far



**MS phase H->He**

**Different energy sources during different stages in the star's evolution**

**Protostar phase (KH contraction)**

**RGB phase (shell H->He)**

***And remember: more massive stars evolve faster during all stages***