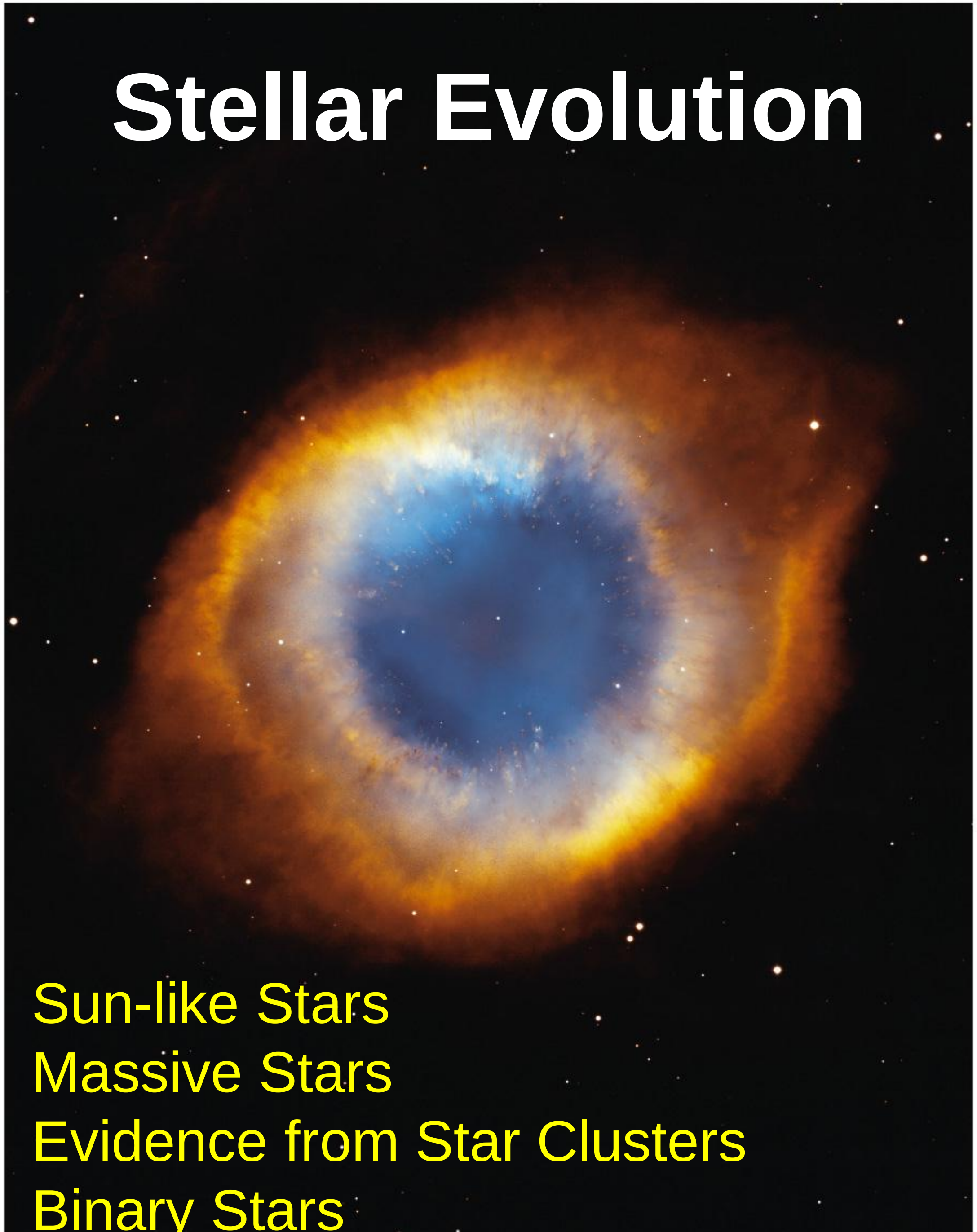
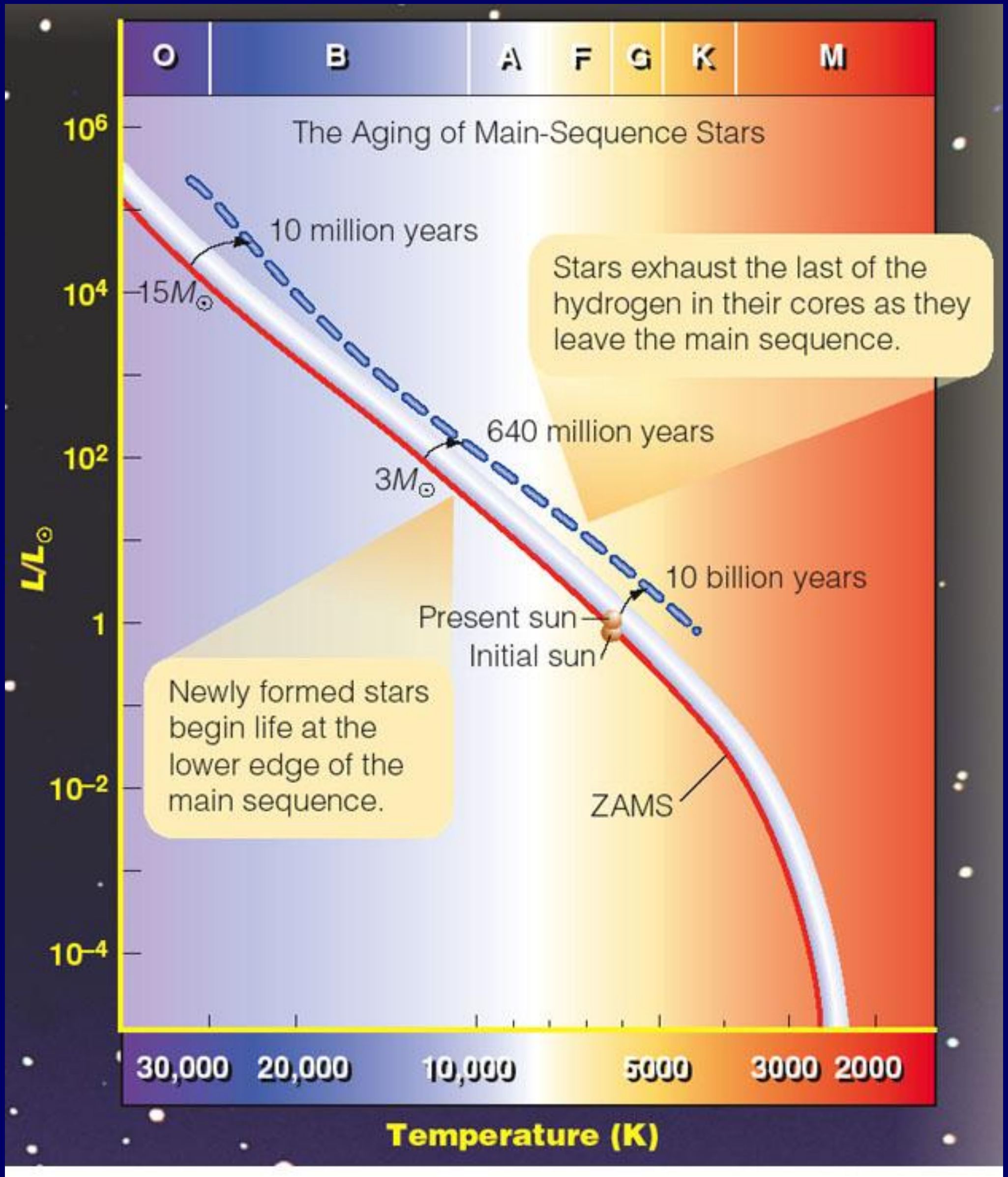
Stellar Evolution



Sun-like Stars
Massive Stars
Evidence from Star Clusters
Binary Stars

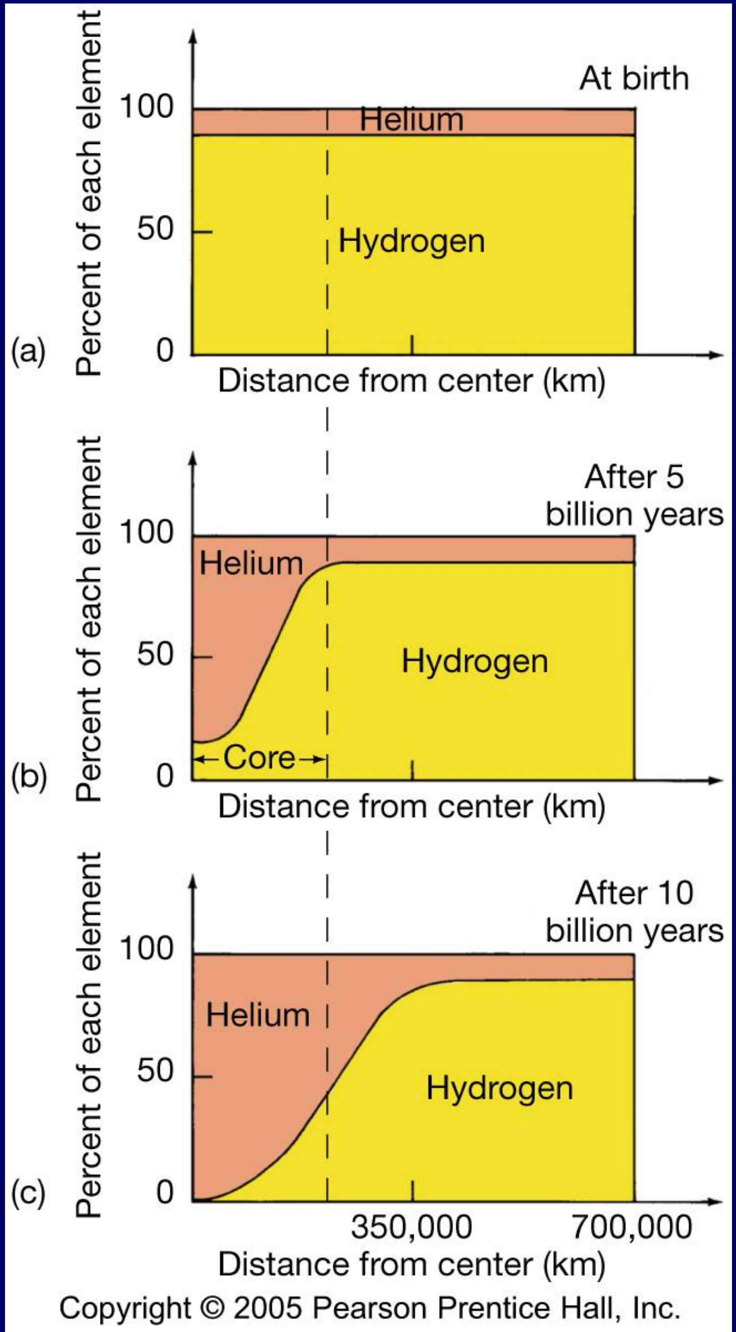
The Life of Main-Sequence Stars



- **Stars gradually exhaust their hydrogen fuel.**
- **In the process of aging, they gradually become brighter and a little cooler.**
- **They evolve from zero-age main sequence (ZAMS) moving up and slightly to the right on the H-R diagram.**

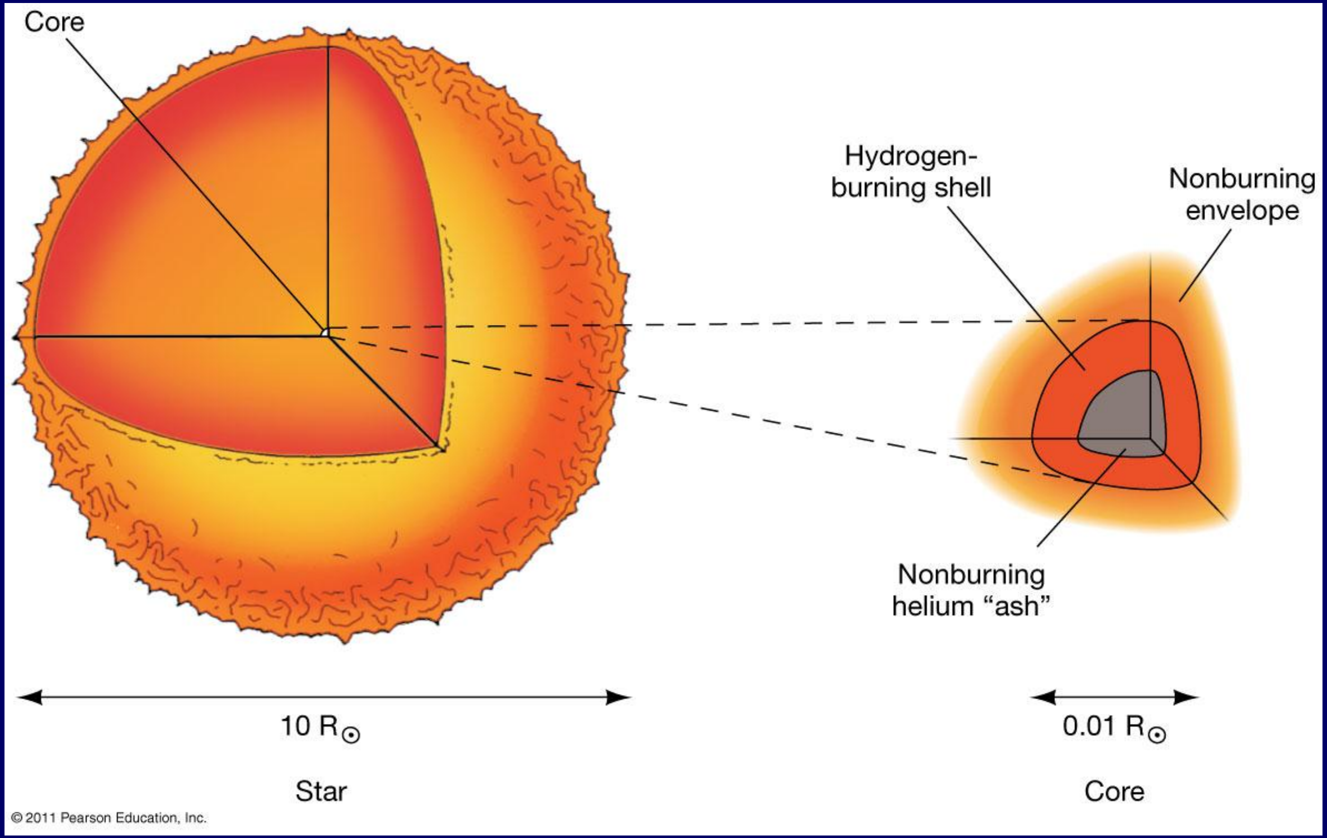
Evolution of a Sun-like Star

Even while on the main sequence, the composition of a star's core is changing. Hydrogen decreases while helium increases.

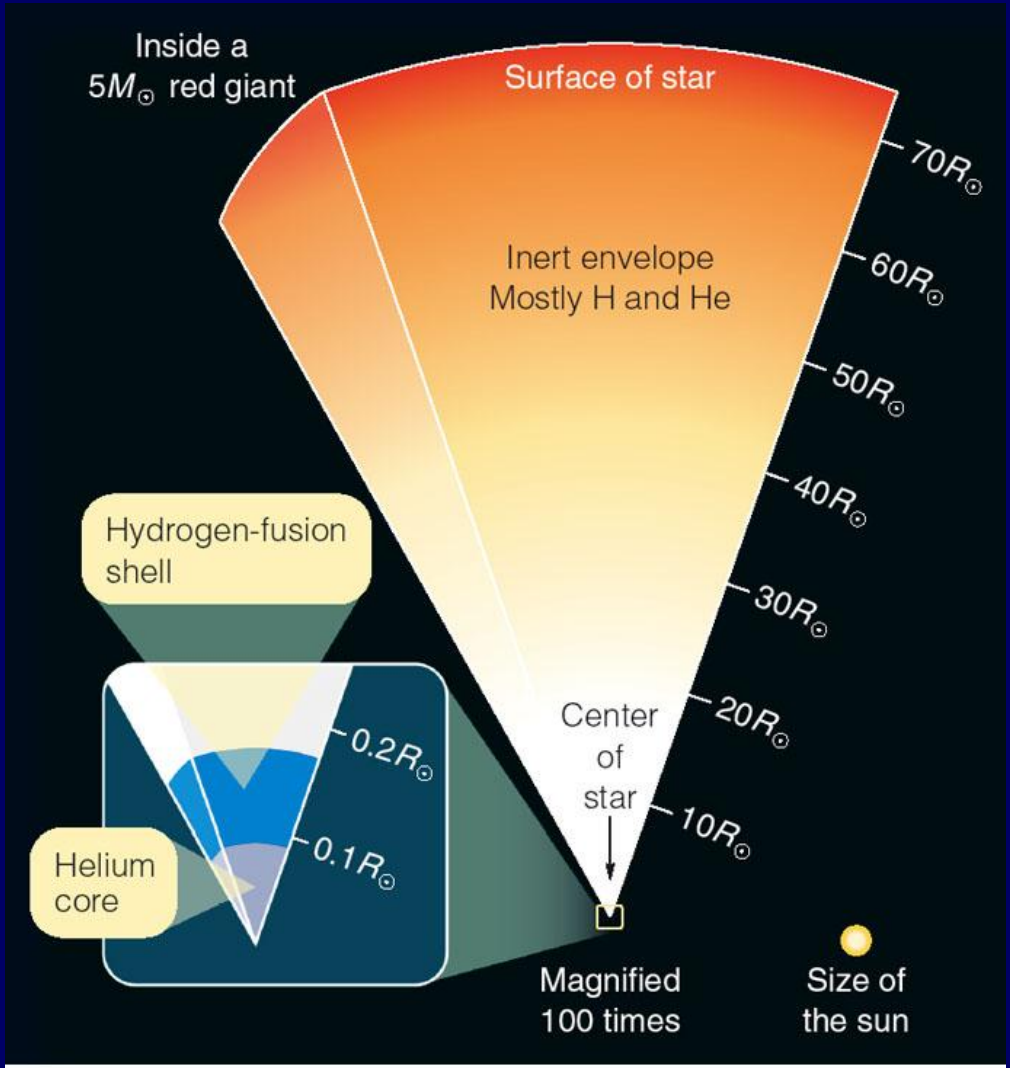


Evolution of a Sun-like Star

- As the fuel in the core is used up, the core **contracts**
- When the fuel is used up the core begins to **collapse** because the source of thermal pressure is no longer there.
- Hydrogen begins to fuse outside the core in a shell, which is called **hydrogen shell burning**.



Evolution off the Main Sequence: Expansion into a Red Giant



- **Hydrogen in the core is completely converted into He:**

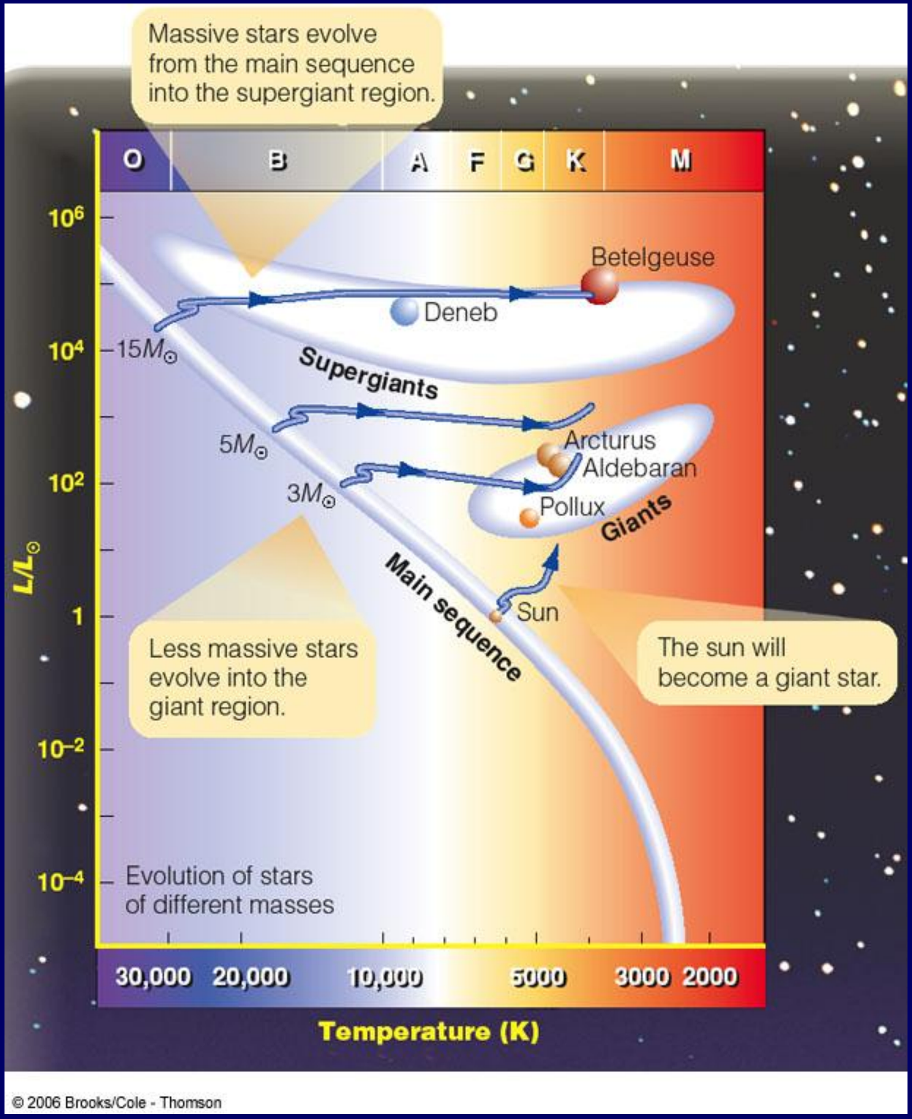
  ⇒ "Hydrogen burning" (*i.e.* fusion of H into He) ceases in the core.

- **H burning continues in a shell around the core.**
- **He core + H-burning shell produces heat that increases pressure causing the mass above the shell to expand**

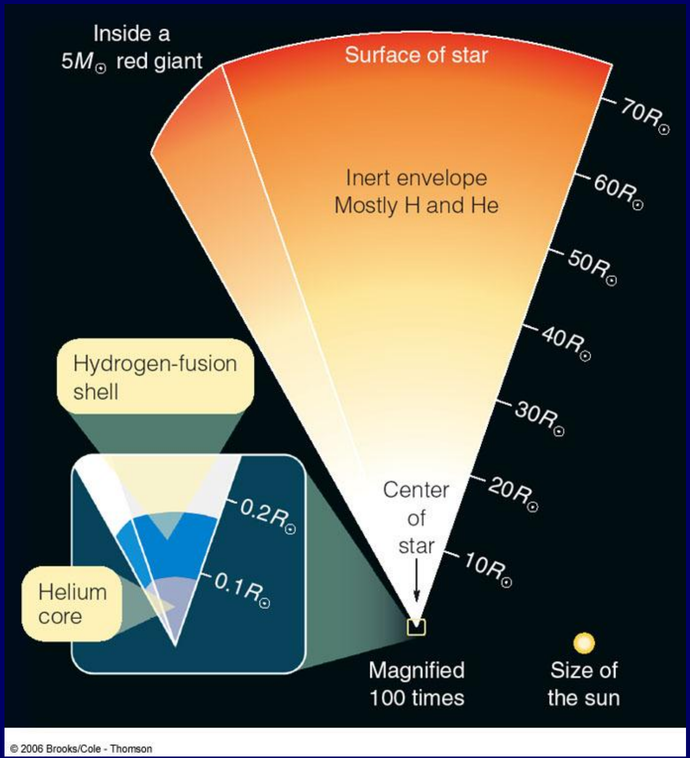
  ⇒ Expansion and cooling of the outer layers of the star

⇒ Red Giant

Expansion onto the Giant Branch

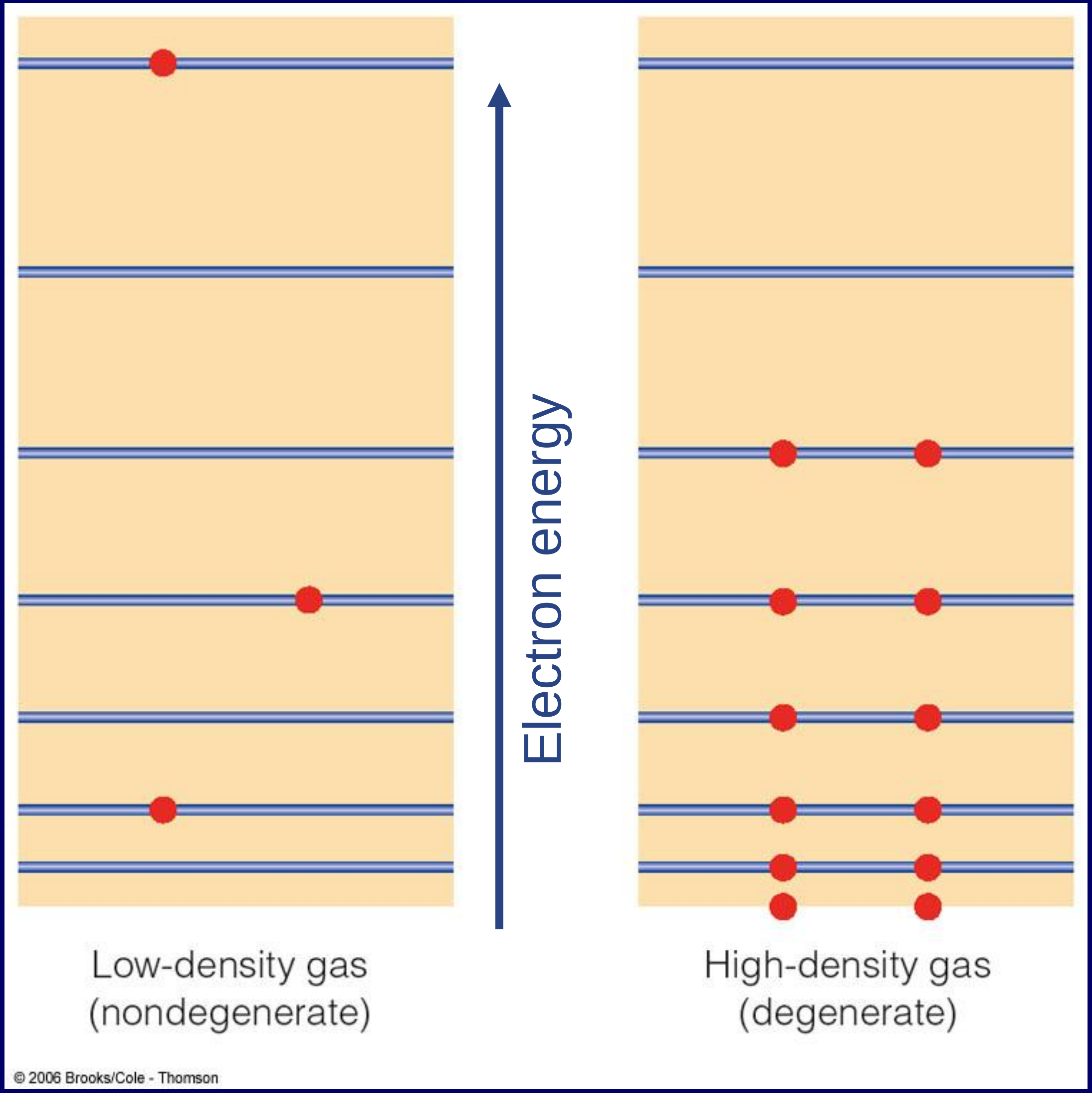


- **Expansion and surface cooling during the phase of an inactive He core and a H-burning shell**



Sun will expand beyond Earth's orbit!

Degenerate Matter



- **Matter in the He core has no energy source left.**

  ⇒ Not enough thermal pressure to resist and to balance gravity even though the core heats up from gravitational energy.
- **In stars < 2.5 $m_{\odot}$, matter assumes a new state, called**

  degenerate matter
- **Pressure in the degenerate core comes from electrons that cannot be packed arbitrarily close together (Pauli exclusion principle) and they have low energies.**

Evolution of a Sun-like Star

Stages of a star leaving the Main Sequence:

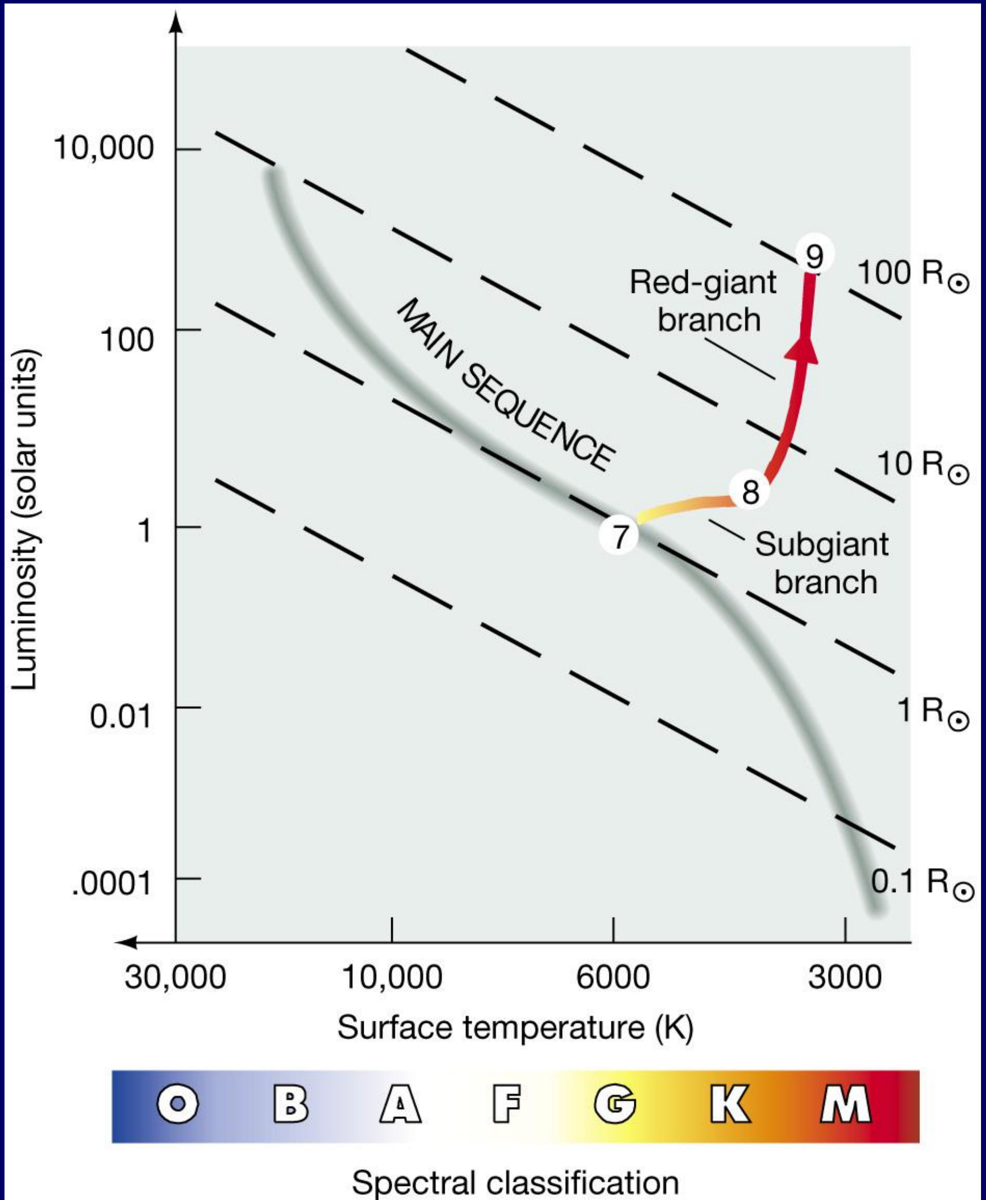
TABLE 20.1 Evolution of a Sun-like Star

Stage	Approximate Time to Next Stage (Yr)	Central Temperature (10^6 K)	Surface Temperature (K)	Central Density (kg/m^3)	Radius (km)	Radius (solar radii)	Object
7	10^{10}	15	6000	10^5	7×10^5	1	Main-sequence star
8	10^8	50	4000	10^7	2×10^6	3	Subgiant branch
9	10^5	100	4000	10^8	7×10^7	100	Helium flash
10	5×10^7	200	5000	10^7	7×10^6	10	Horizontal branch
11	10^4	250	4000	10^8	4×10^8	500	Asymptotic-giant branch
12	10^5	300	100,000	10^{10}	10^4	0.01	Carbon core
		—	3000	10^{-17}	7×10^8	1000	Planetary nebula*
13	—	100	50,000	10^{10}	10^4	0.01	White dwarf
14	—	Close to 0	Close to 0	10^{10}	10^4	0.01	Black dwarf

* *Values refer to the envelope.*

Evolution of a Sun-like Star

- The Sun moves off the main sequence on the H–R diagram to the red giant stage (8 to 9)
- As the core continues to shrink, the outer layers of the star expand and cool.
- It is now a red giant, extending out as far as the orbit of Mercury.
- Despite its cooler temperature, its luminosity increases enormously due to its large size.



Evolution of a Sun-like Star

Helium fusion

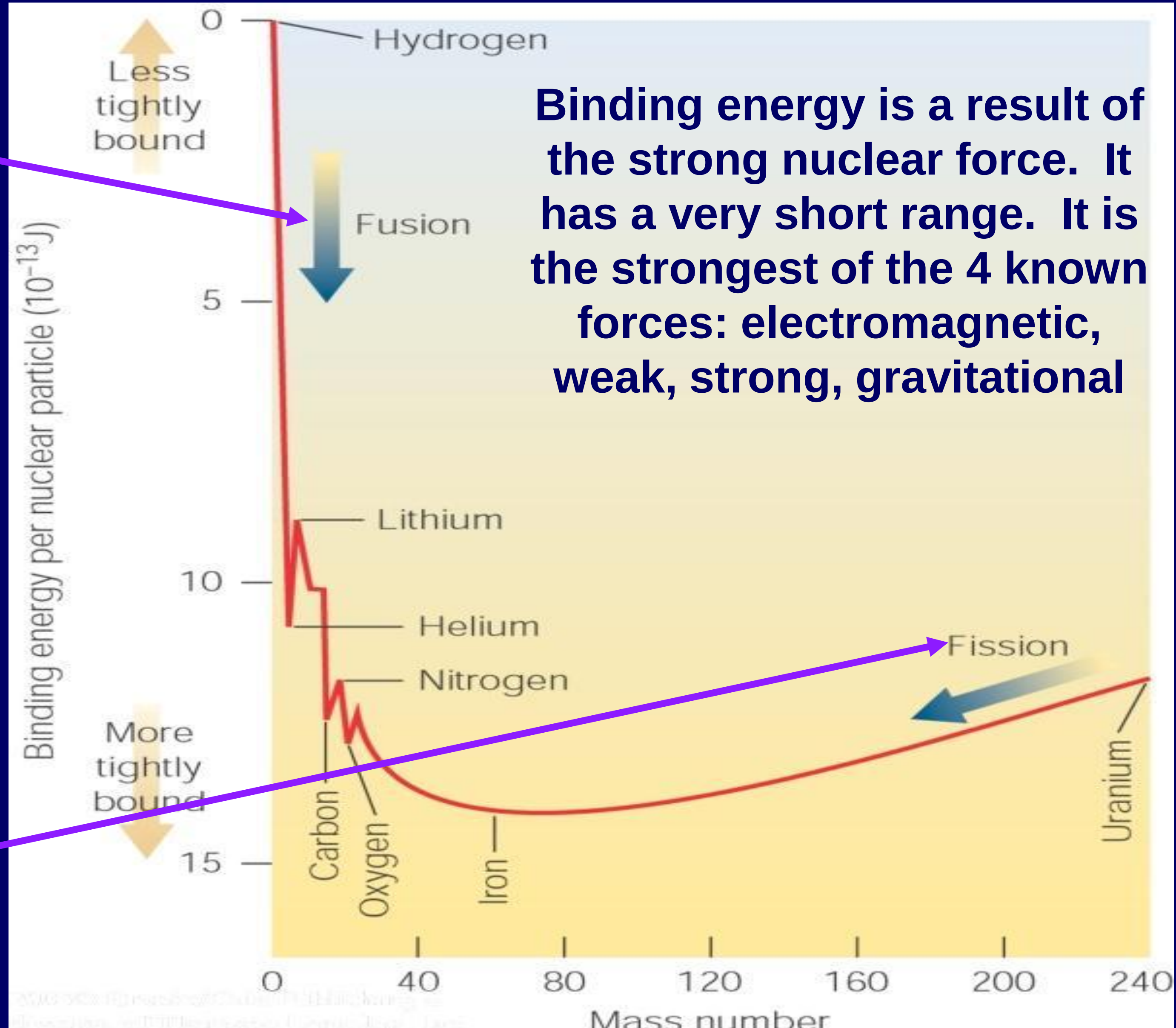
Once the core temperature has risen to 10^8 K, the helium in the core starts to fuse, through the triple-alpha process:

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be} + \text{energy}$$
$$^{8}\mathrm{Be} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \text{energy}$$

The ^{8}Be nucleus is highly unstable, and will decay in about 10^{-12} s unless an alpha particle fuses with it first. This is why high temperatures and densities are necessary.

Energy Production

- **Nuclear fusion can produce energy up to the production of iron;**
- **For elements heavier than iron, energy is gained by nuclear fission.**

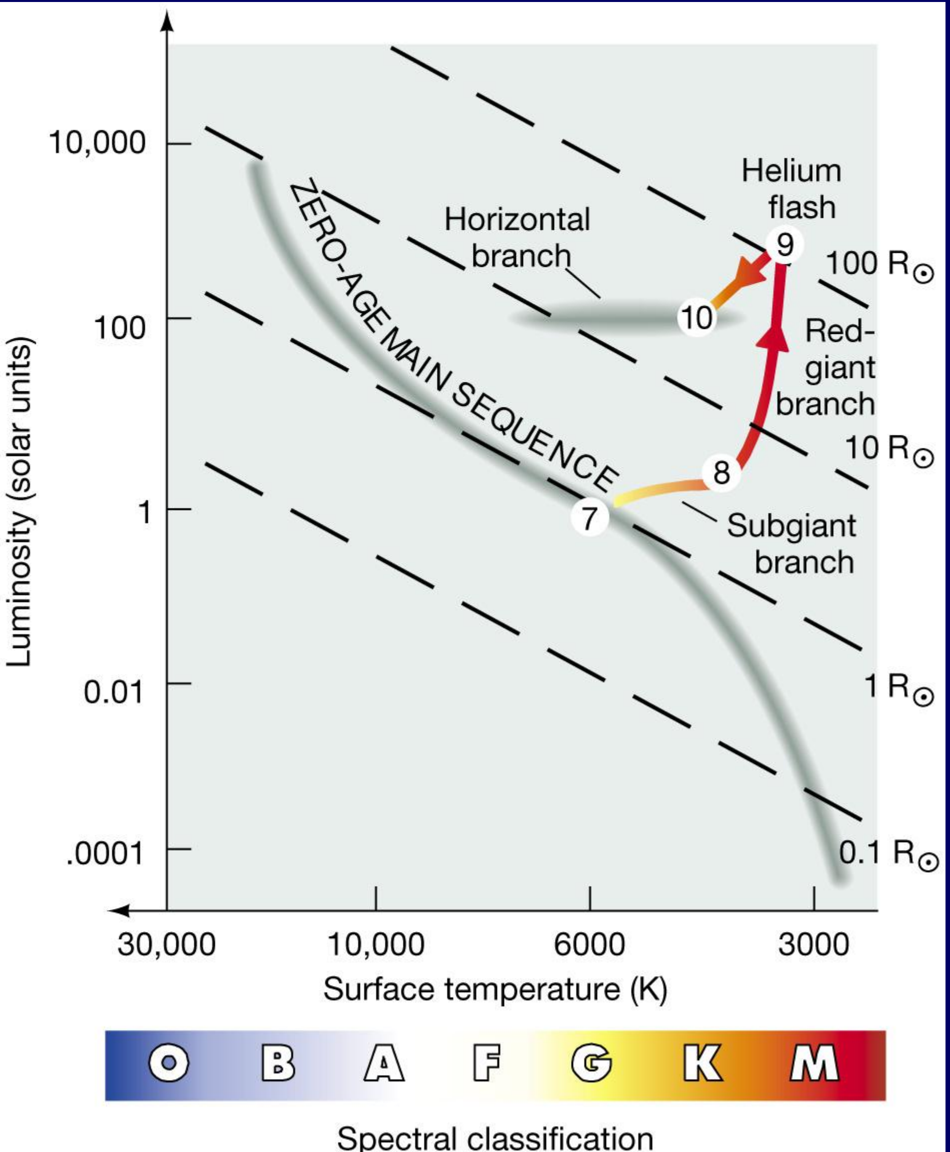


Binding energy is a result of the strong nuclear force. It has a very short range. It is the strongest of the 4 known forces: electromagnetic, weak, strong, gravitational

Evolution of a Sun-like Star

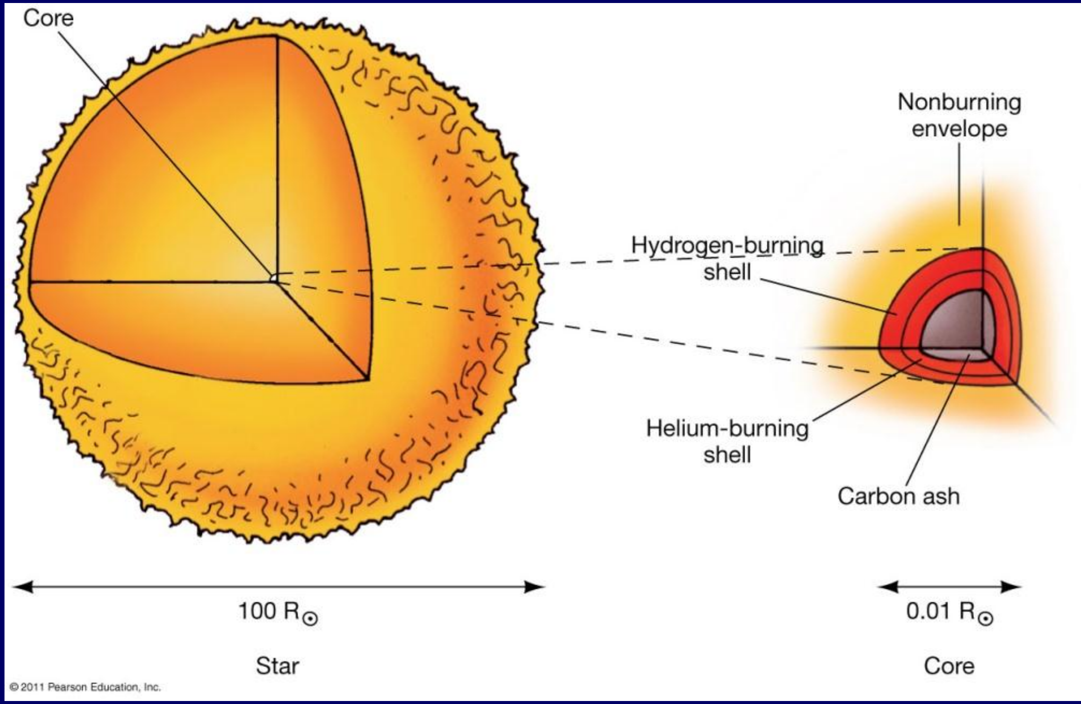
The Helium Flash:

- The pressure within the helium core is almost totally due to "electron degeneracy" – two electrons cannot be in the same quantum state, so the core cannot contract beyond a certain point.
- This pressure is almost independent of temperature – when the helium starts fusing, the pressure cannot adjust.
- Helium begins to fuse extremely rapidly; within hours the enormous energy output is over.
- The star once again reaches equilibrium with steady helium fusion (Stage 10).



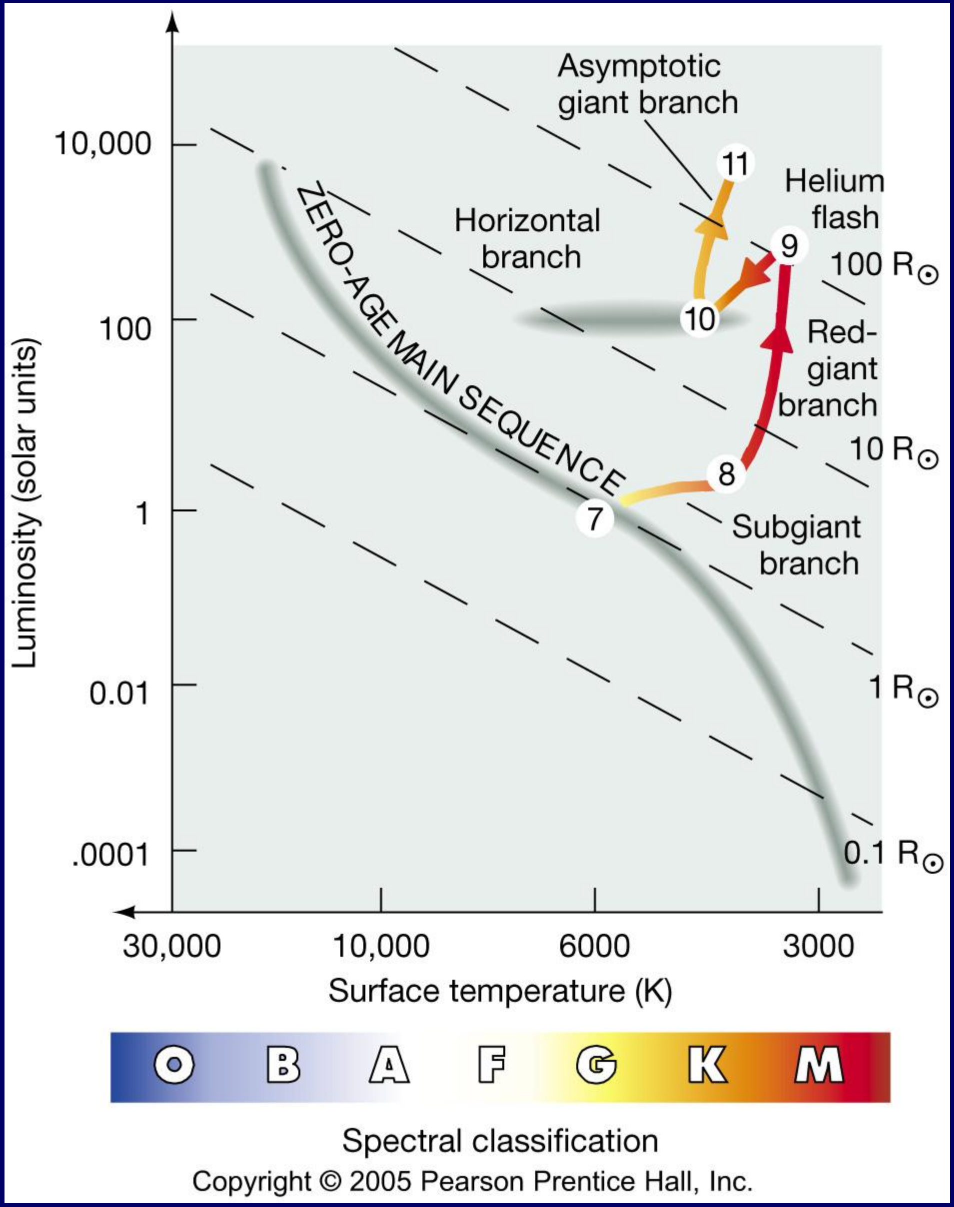
Evolution of a Sun-like Star

- After the helium flash, the radius decreases, but the star remains a giant on the **horizontal branch**.
- As the helium in the core fuses to carbon, the core becomes hotter and hotter, and the helium burns faster and faster.
- When the helium is exhausted, the star is now similar to its condition just as it left the main sequence, except now there are **two shells**: a **hydrogen-burning shell** and a **helium-burning shell**.



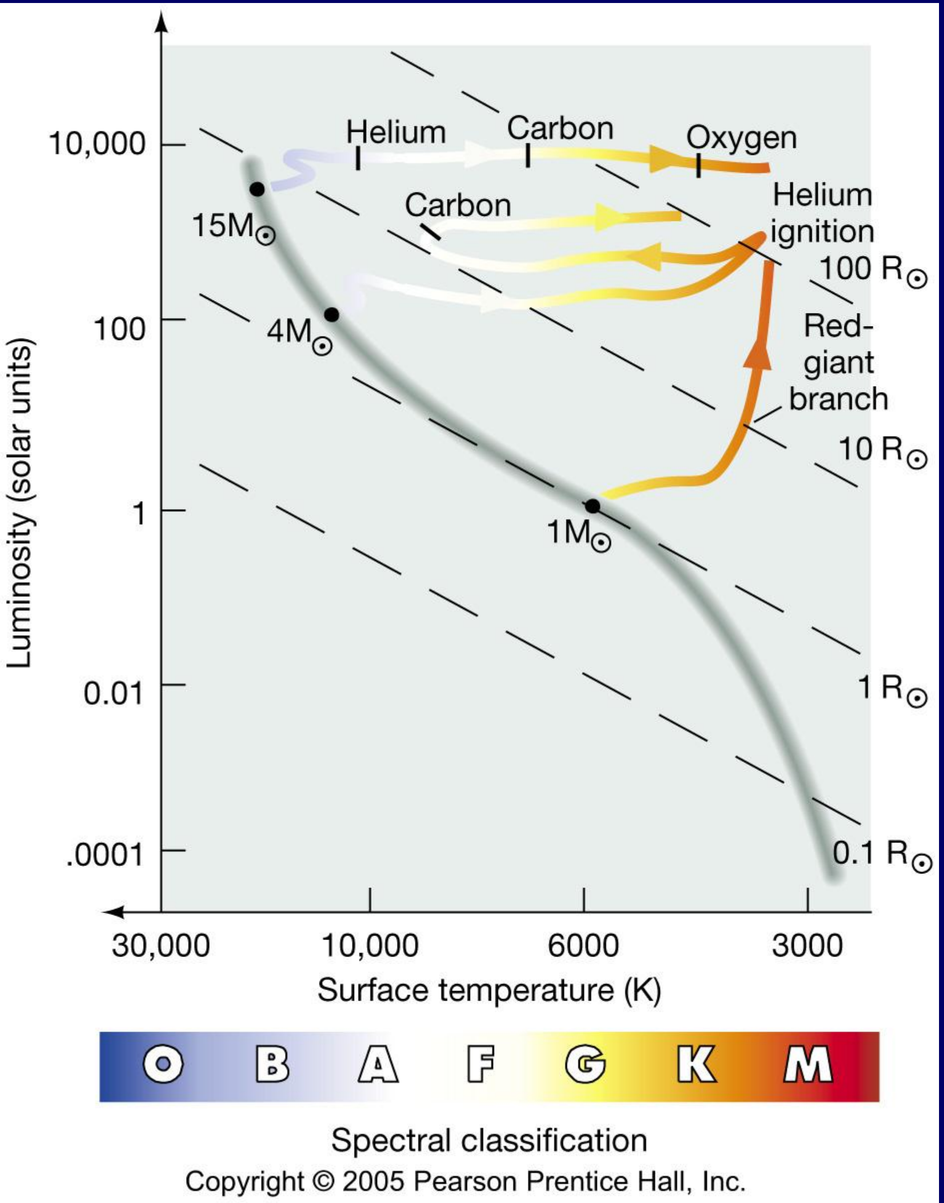
Evolution of a Sun-like Star

- The star expands in radius for the second time (10 to 11).
- A 1 $m_{\odot}$ star is about to enter its last stage.



Evolution of Stars More Massive than the Sun

It can be seen from this H–R diagram that stars more massive than the Sun follow very different paths when leaving the main sequence

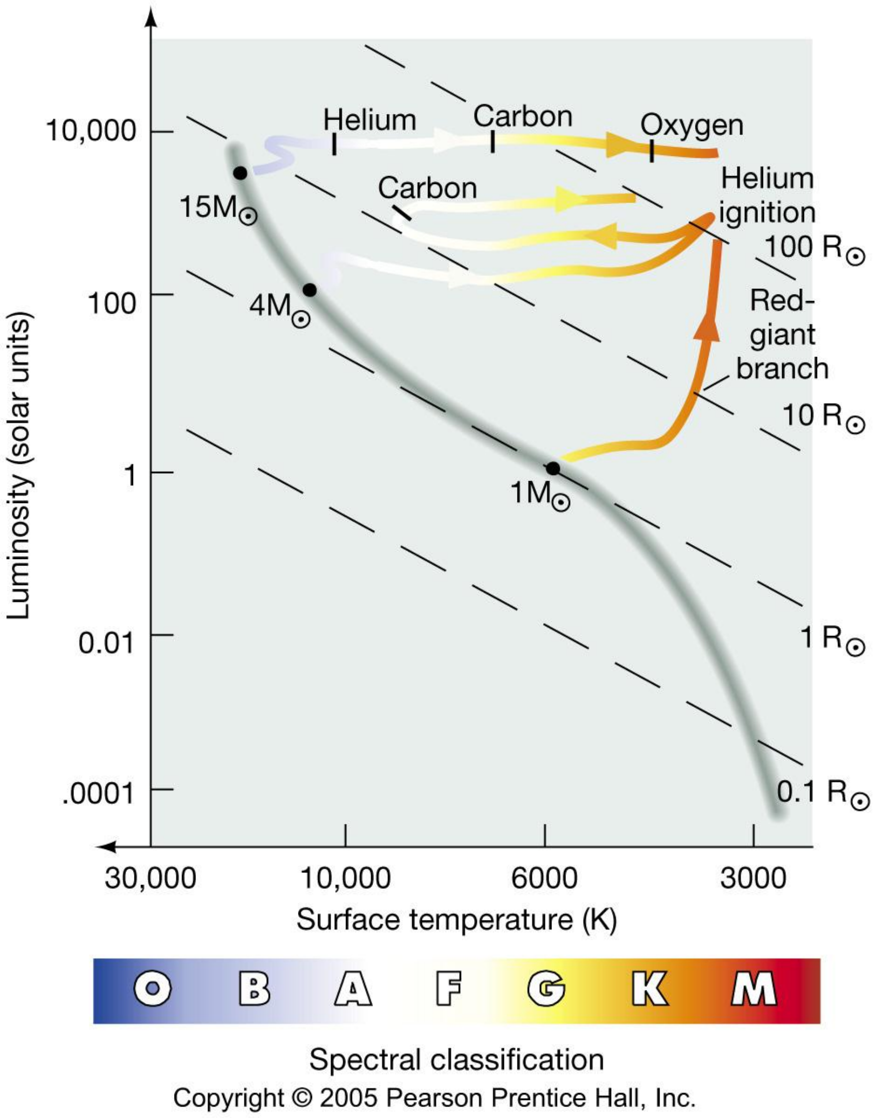


Evolution of Stars More Massive than the Sun

- High-mass stars, like all stars, leave the main sequence when there is no more hydrogen fuel in their cores.
- The first few events are similar to those in lower-mass stars.
    1. A hydrogen shell and a collapsing core.
    2. Followed by a core burning helium to carbon, surrounded by helium- and hydrogen-burning shells.

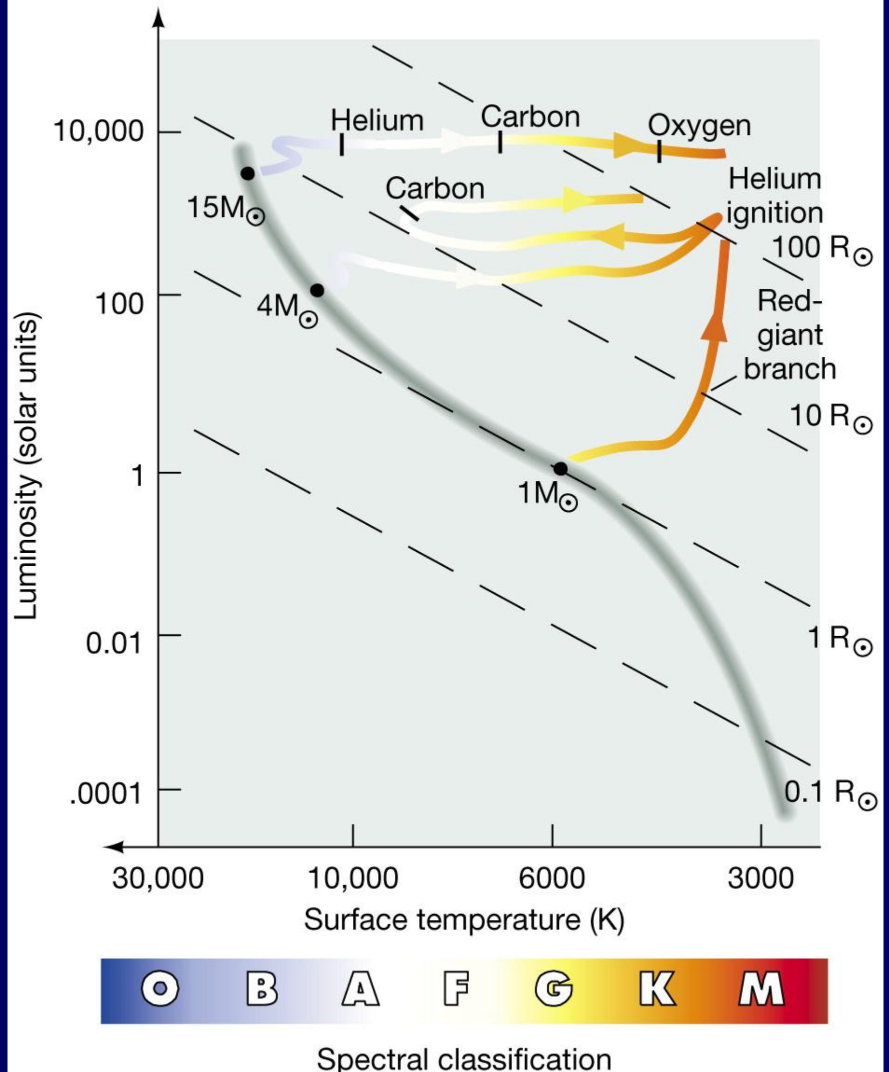
Evolution of Stars More Massive than the Sun

- **Stars with masses more than 2.5 $m_{\odot}$ do not experience a helium flash because the core does not become degenerate. Helium burning starts gradually.**
- **A 4 $m_{\odot}$ star makes no sharp moves on the H–R diagram – it moves smoothly back and forth.**



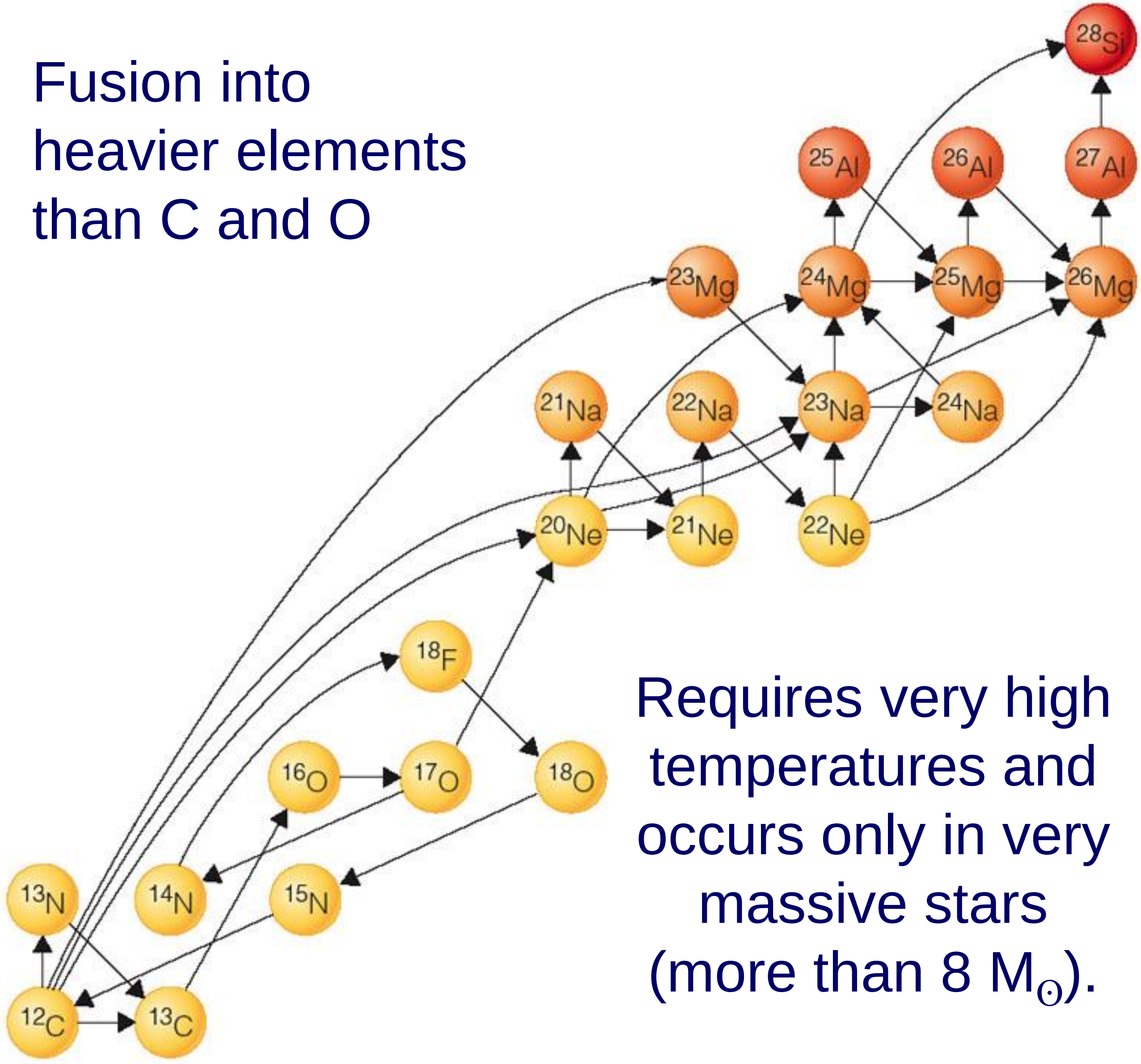
Evolution of Stars More Massive than the Sun

- A star of more than 8 $m_{\odot}$ can fuse elements far beyond carbon in its core, leading to a very different fate.
- Its path across the H–R diagram is essentially a straight line – it stays at just about the same luminosity as it cools off.
- Eventually the star dies in a violent explosion called a supernova.



Fusion into Heavier Elements

Fusion into heavier elements than C and O



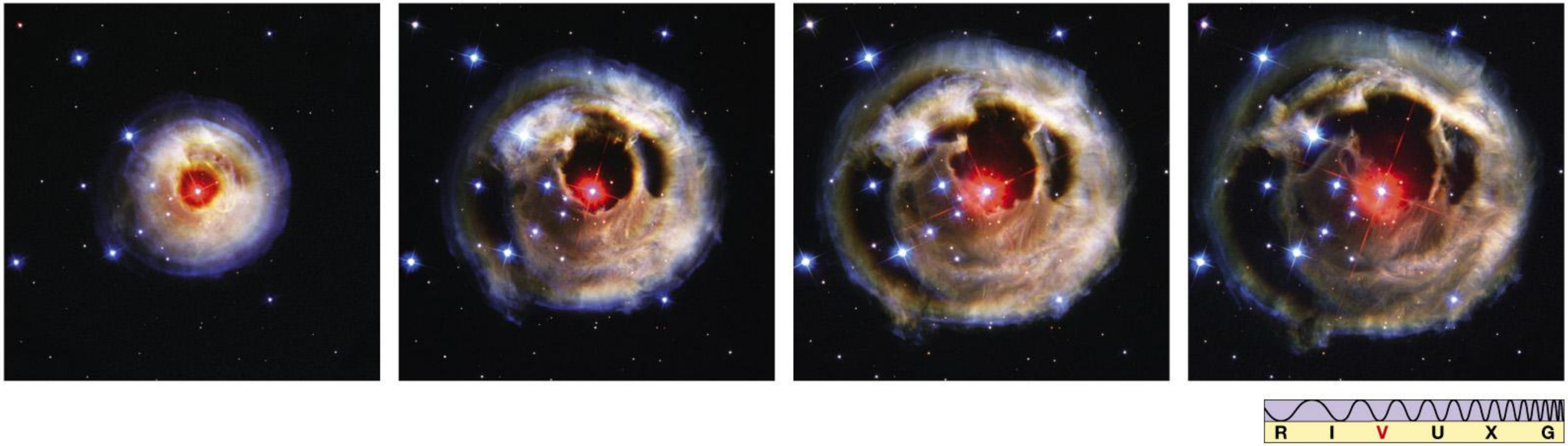
Requires very high temperatures and occurs only in very massive stars (more than 8 $M_{\odot}$).

Mass Loss from Giant Stars

- All stars lose mass by some form of stellar wind. The most massive stars have the strongest winds; O- and B-type stars can lose a tenth of their total mass this way in only a million years.
- These stellar winds hollow out cavities in the interstellar medium surrounding giant stars.

Mass Loss from Giant Stars

The sequence below, of actual *Hubble* images, shows a very unstable red giant star as it emits a burst of light, illuminating the dust around it



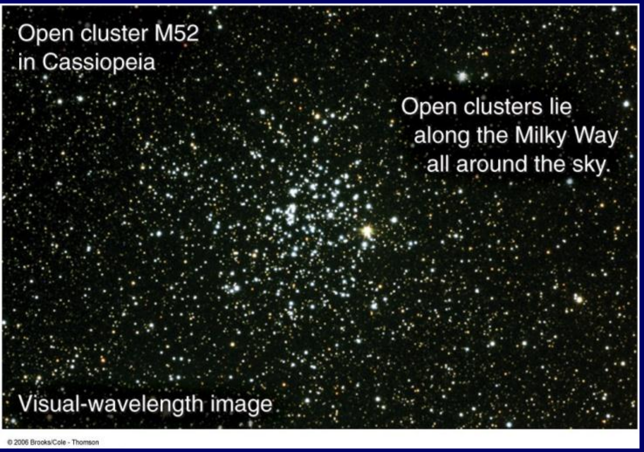
Evidence for Stellar Evolution: Star Clusters

Stars in a star cluster all have approximately the same age!

More massive stars evolve more quickly than less massive ones.

If you put all the stars of a star cluster on a H-R diagram, the most massive stars (upper left) will be missing!

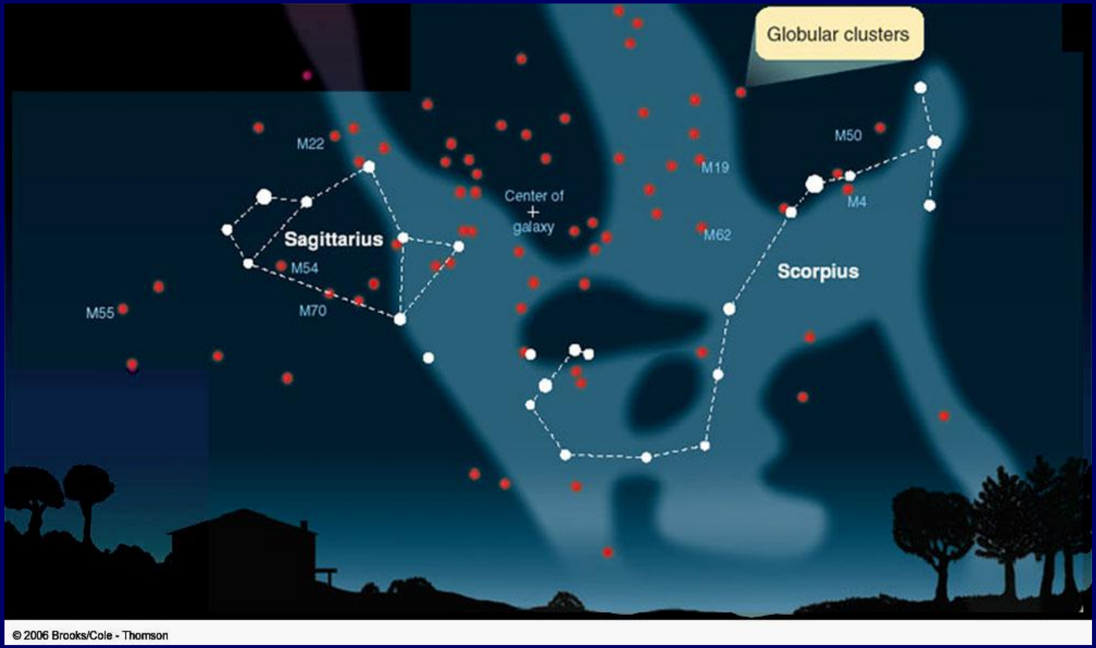
Star Clusters

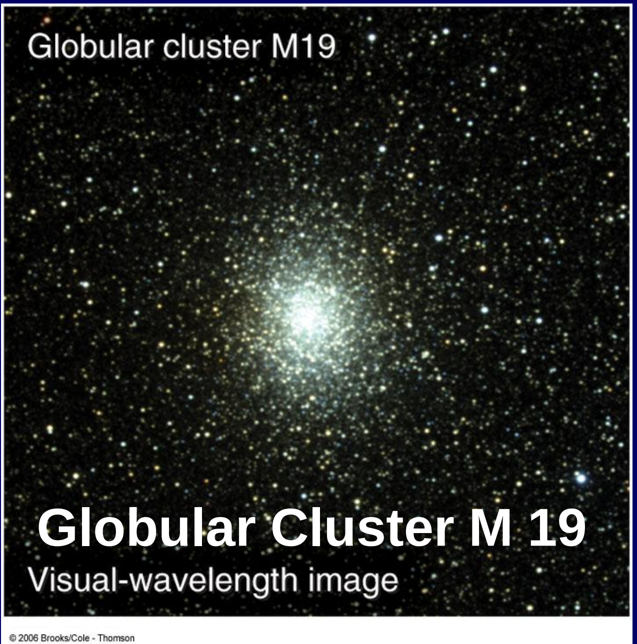


Open cluster M 52

Two types of star clusters:

1. **Open clusters** = young clusters of recently formed stars within the disk of the Galaxy



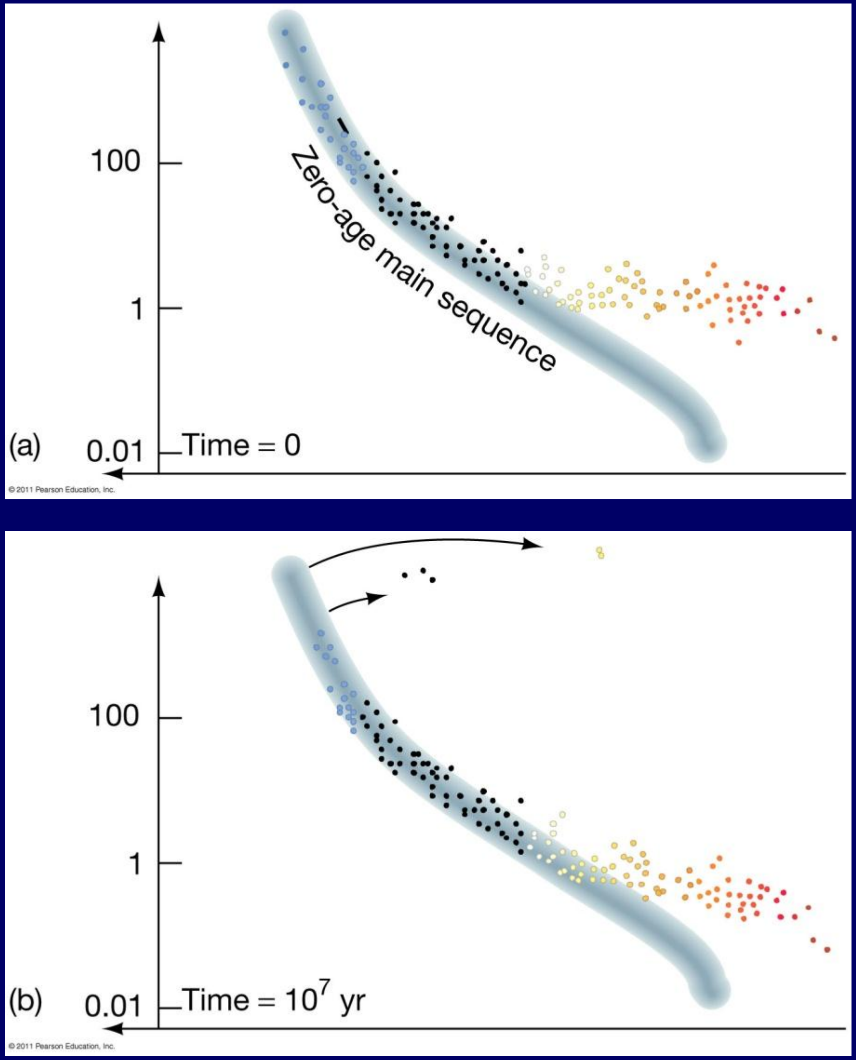


2. **Globular clusters** = old, centrally concentrated star clusters; mostly in a halo around the galaxy and near the galactic center

Globular Clusters

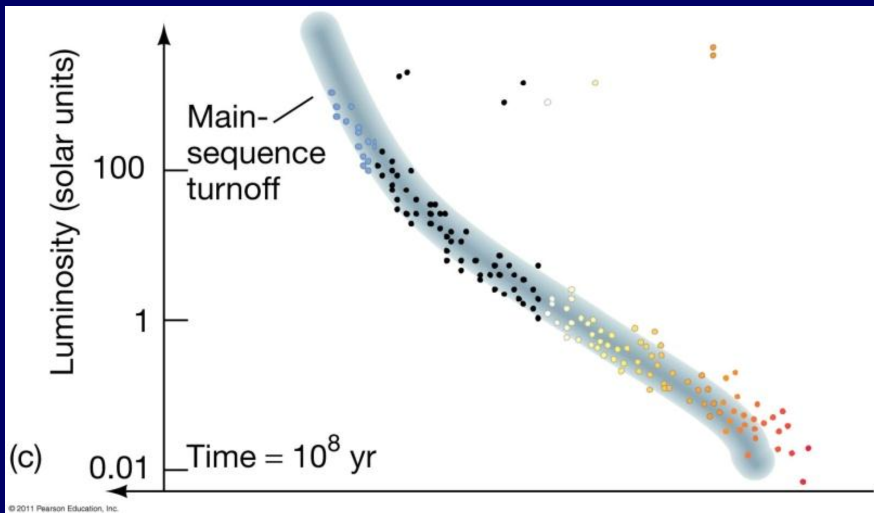
- **Dense clusters of 50,000 – a million stars**
- **Old (~11 billion years), lower-main-sequence stars**
- **~200 globular clusters in our galaxy**

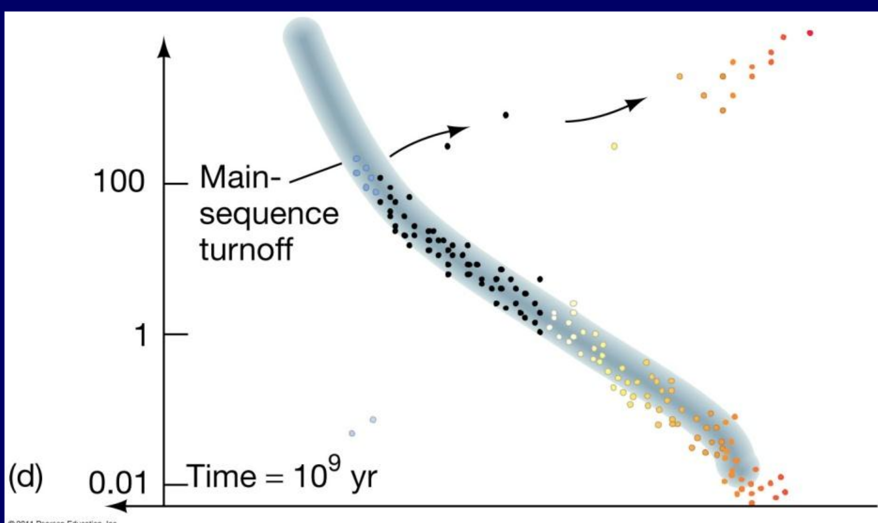
Observing Stellar Evolution in Star Clusters



- The following series of H–R diagrams shows how stars of the same age, but different masses, appear as the cluster as a whole ages.
- After 10^7 years, some of the most massive stars have already left the main sequence, while many of the least massive have not even reached it yet.
- Note that the lowest mass bodies are still proto-stars.

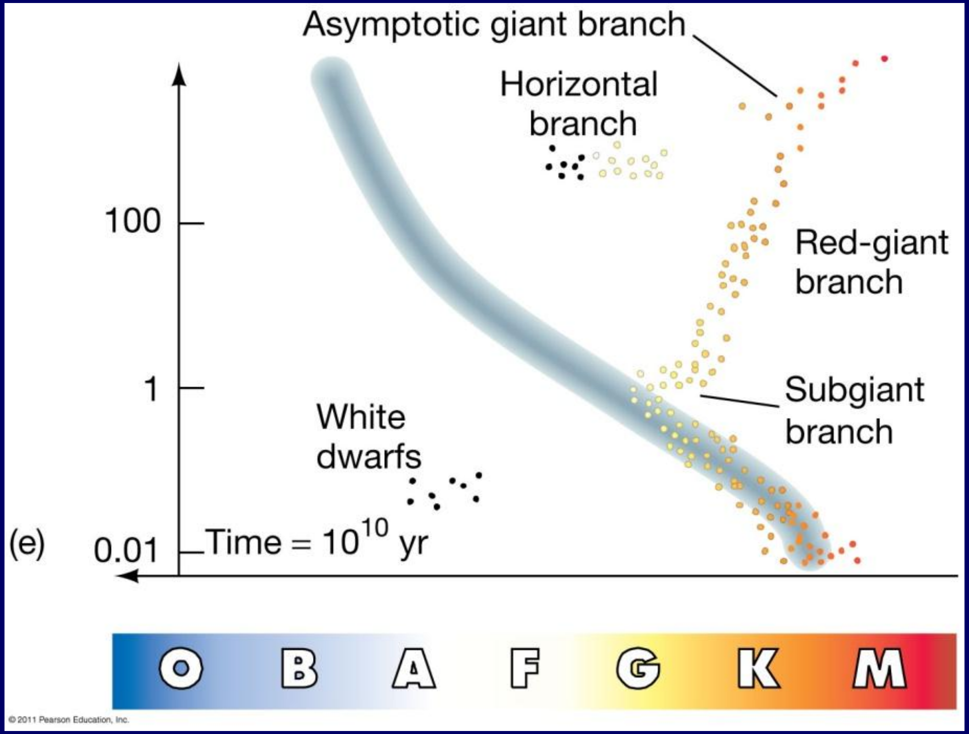
Observing Stellar Evolution in Star Clusters





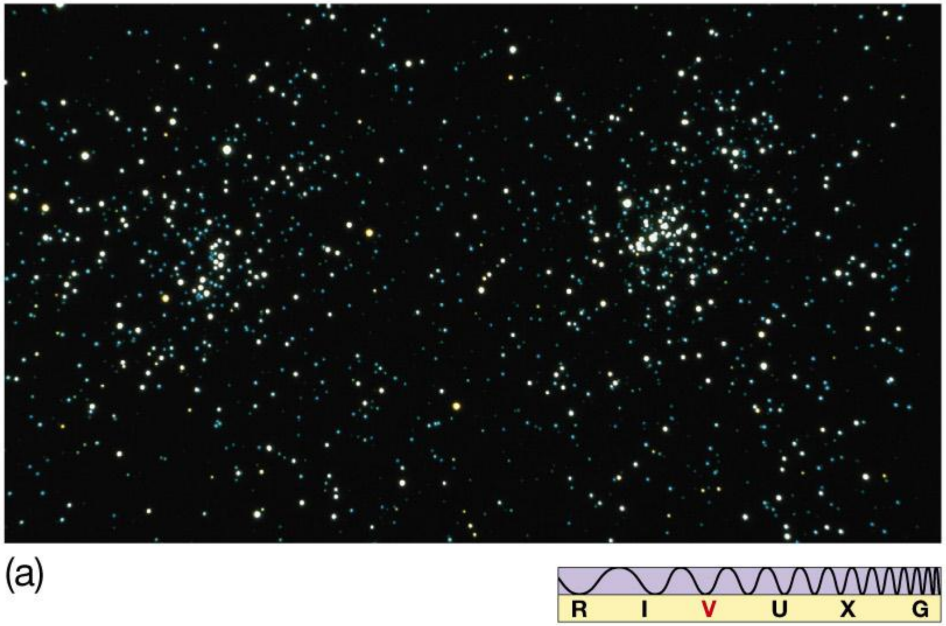
- **After 10^8 years, a distinct main-sequence turnoff begins to develop. Yet, most of the highest-mass stars are still on the main sequence.**
- **After 10^9 years, the main-sequence turnoff is much clearer.**

Observing Stellar Evolution in Star Clusters

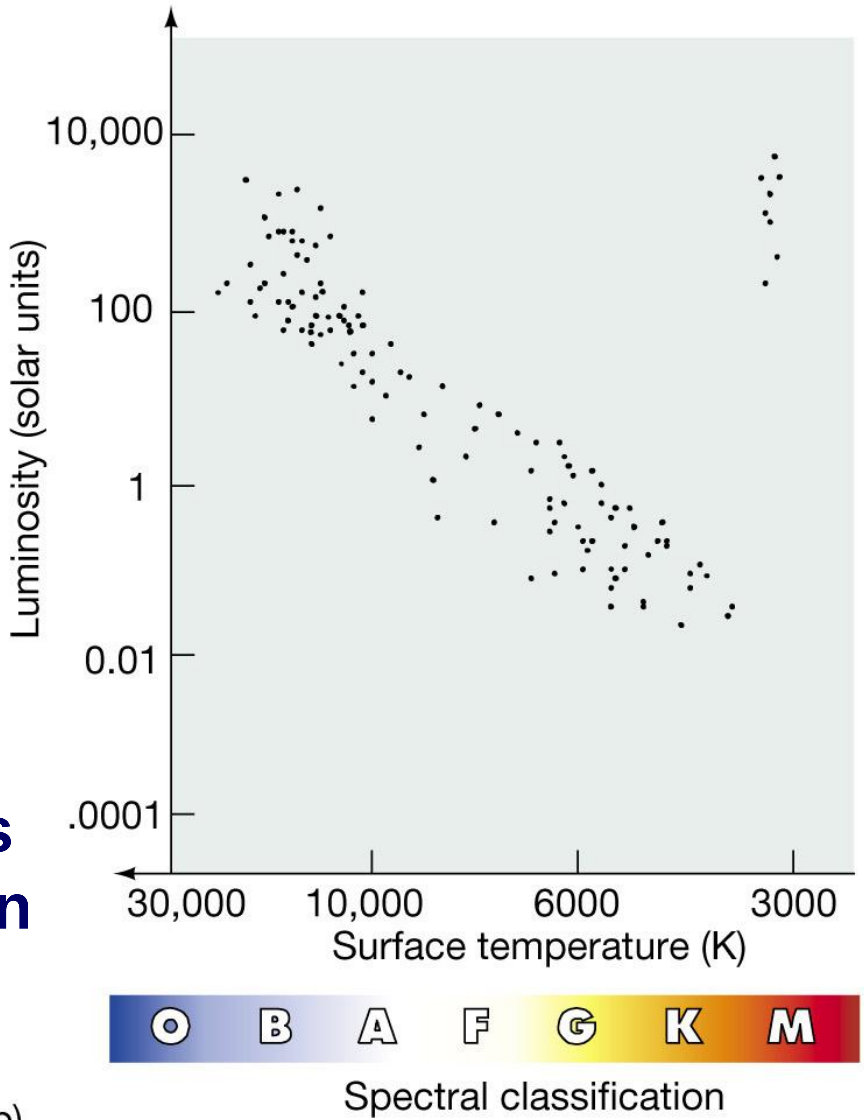


- After 10^{10} years, a number of features are evident:
  - The subgiant, red-giant, asymptotic giant, and horizontal branches are all clearly populated.
  - White dwarfs, solar-mass stars in their last phases, also appear.

Observing Stellar Evolution in Star Clusters



(a)

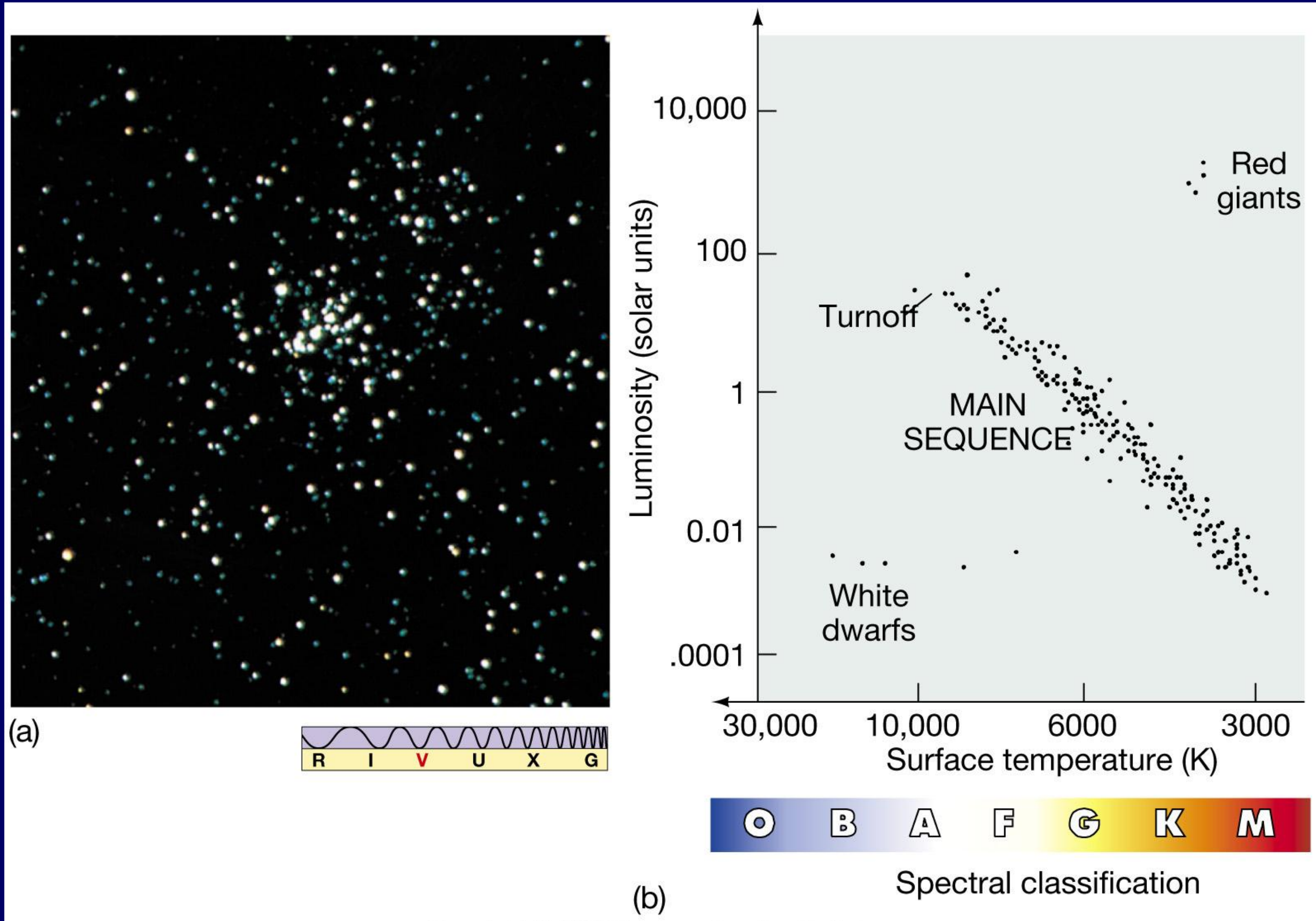


(b)

This double cluster, h and χ Persei, must be quite young – its H–R diagram is that of a newborn cluster. Its age cannot be more than about 10^7 years.

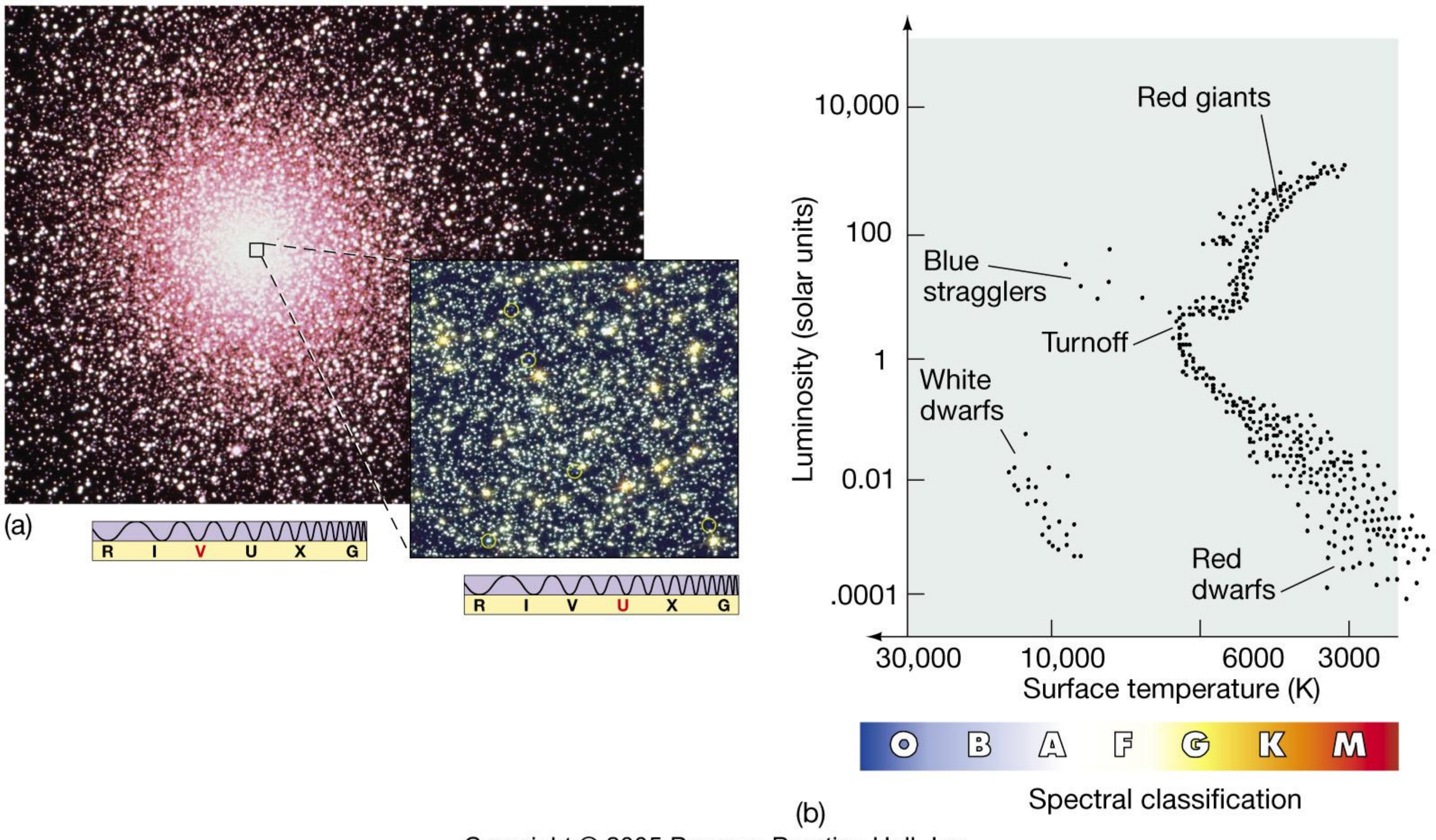
Observing Stellar Evolution in Star Clusters

- The **Hyades cluster** is also rather young
- Its main-sequence turnoff indicates an age of about 6×10^8 years.



Observing Stellar Evolution in Star Clusters

This globular cluster, 47 Tucanae, is about 1–1.2 x 10^{10} years old, much older than the previous examples.

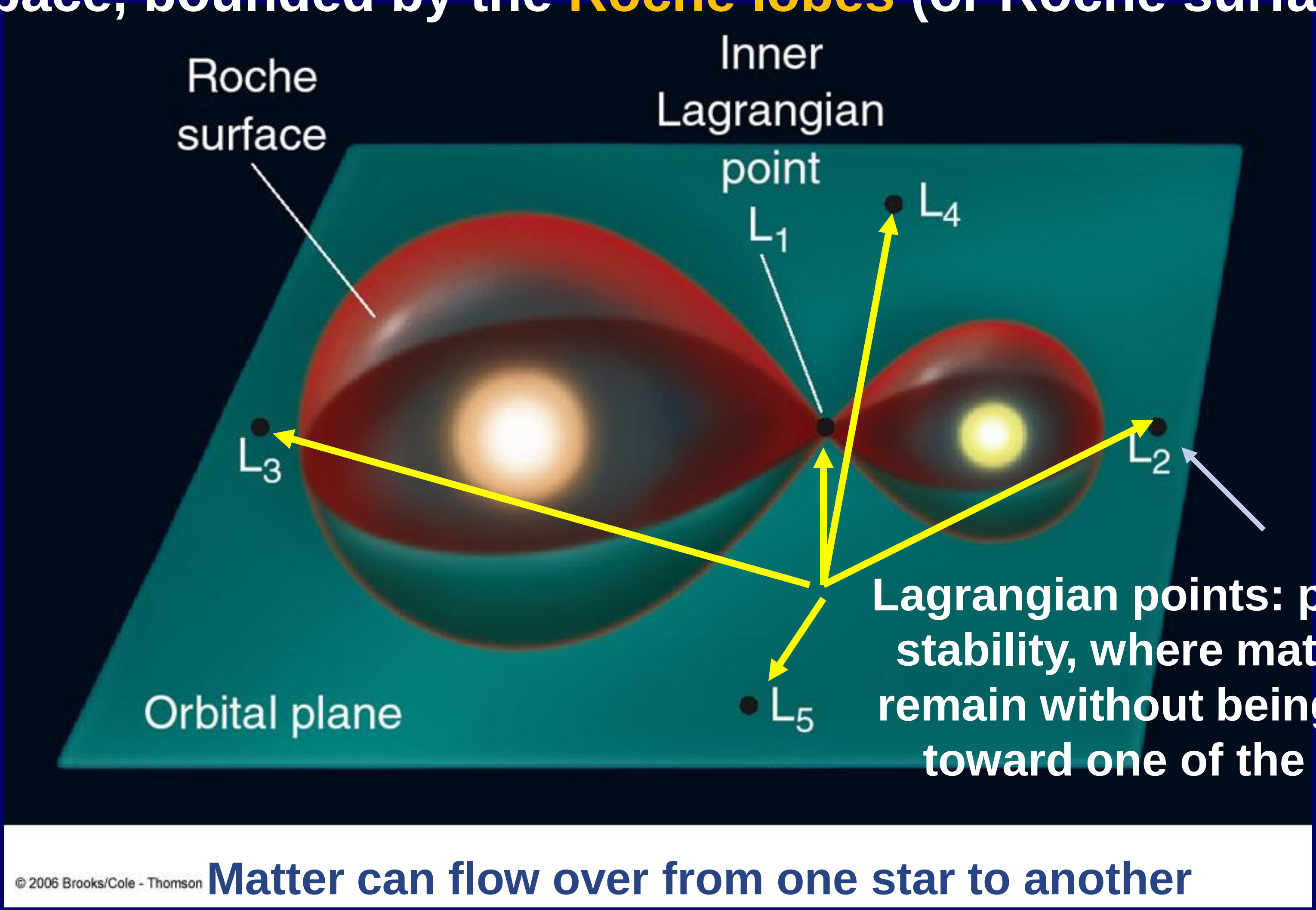


The Evolution of Close Binary-Star Systems

- If stars in a binary-star system are relatively widely separated, their evolution proceeds as it would if they were not companions.
- If they are close enough for their Roche lobes to be in contact, it is possible for material to transfer from one star to another, leading to unusual evolutionary paths. These are called close binary systems.

Mass Transfer in Close Binary Stars

In a binary system, each star controls a finite region of space, bounded by the Roche lobes (or Roche surfaces).

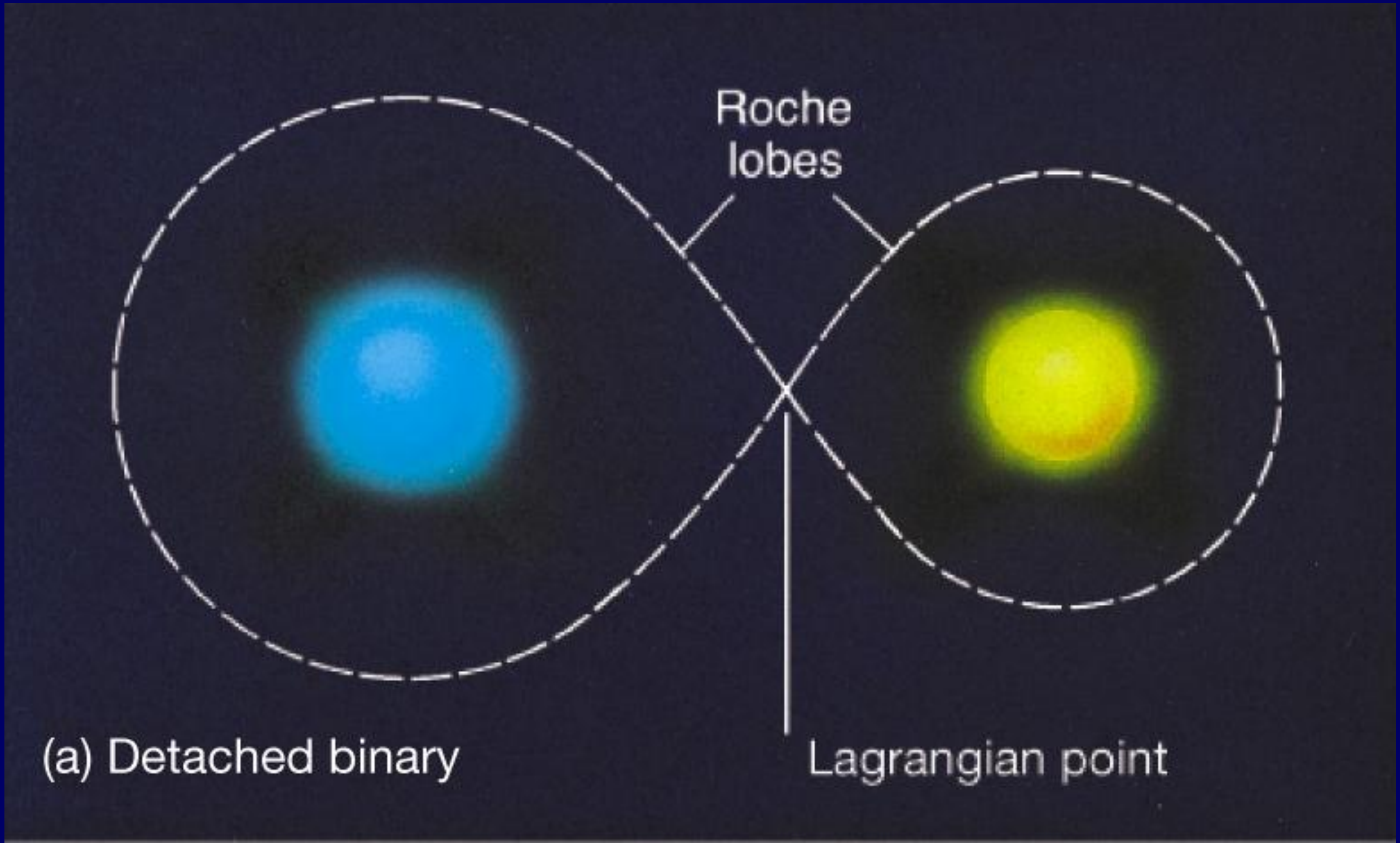


Lagrangian points: points of stability, where matter can remain without being pulled toward one of the stars.

Matter can flow over from one star to another through the inner Lagrange point L_1.

The Evolution of Close Binary-Star Systems

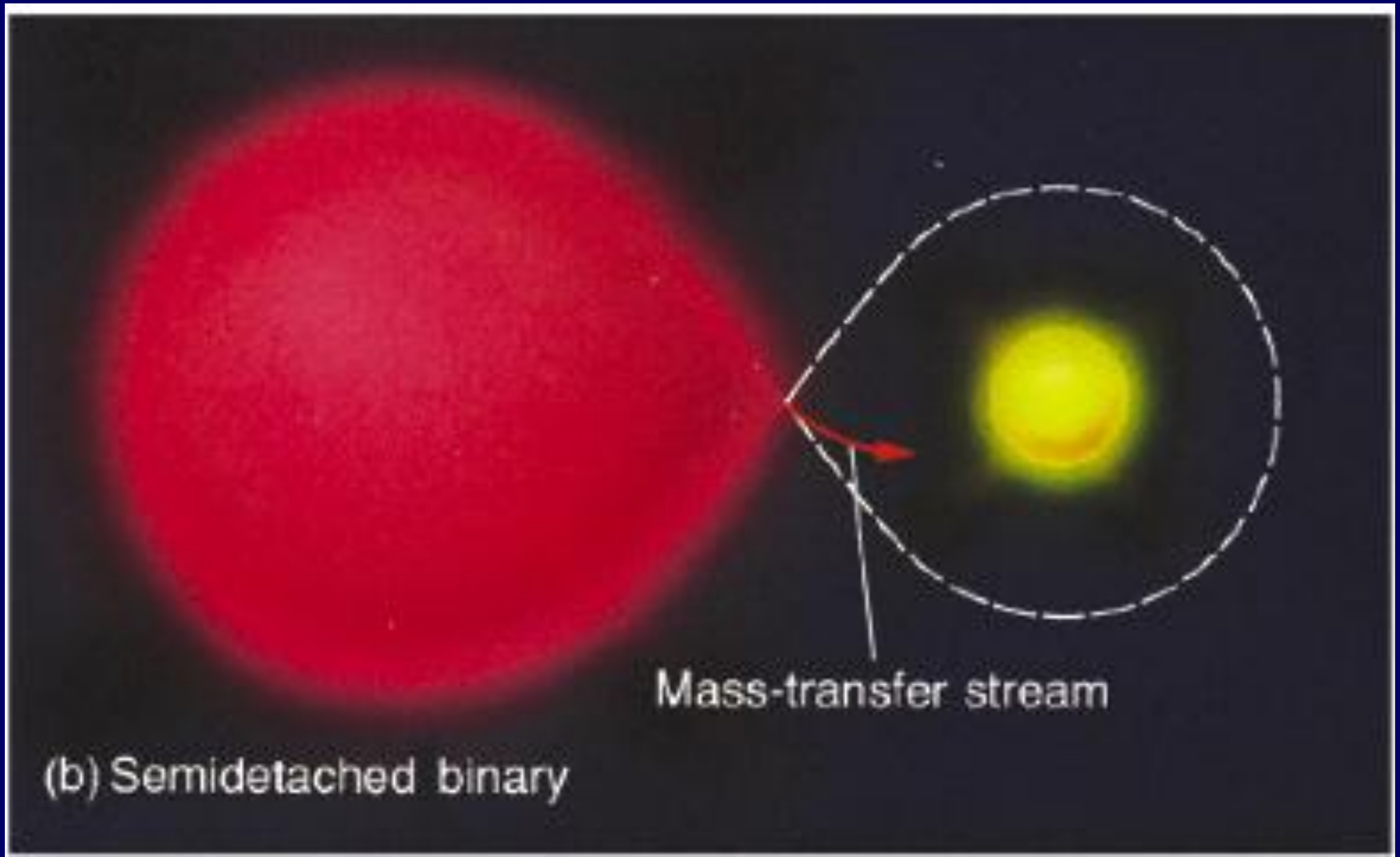
- There are **different types of close binary-star systems**, depending on the evolutionary state of the stars.
- In a **detached binary**, neither star fills its own Roche lobe. This term is also used for stars whose Roche lobes do not touch.



(a) Detached binary

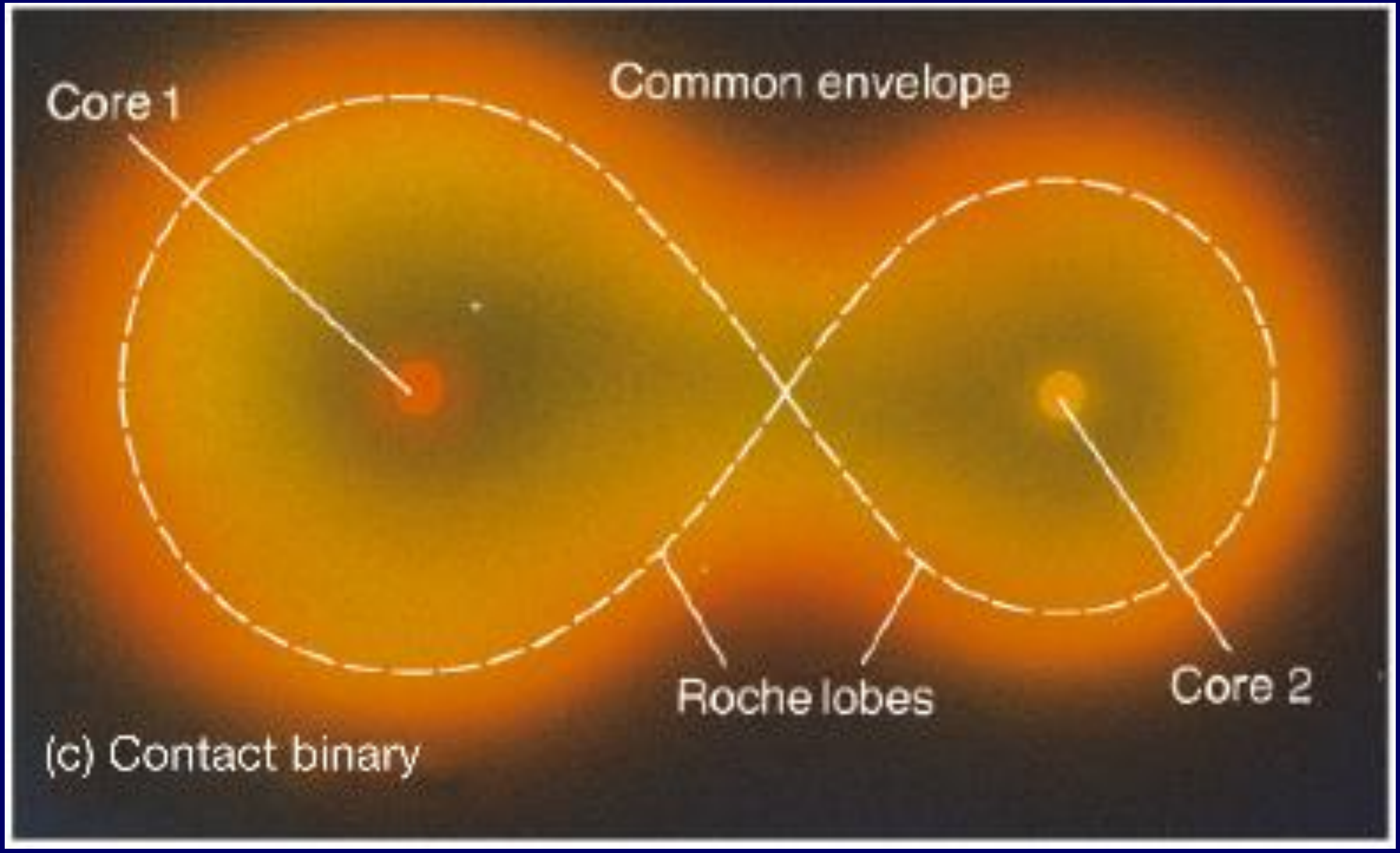
The Evolution of Close Binary-Star Systems

- In a semidetached binary, one star fills its Roche lobe and can transfer mass to the other star. This will alter the evolution of both stars compared to isolated stars.



The Evolution of Close Binary-Star Systems

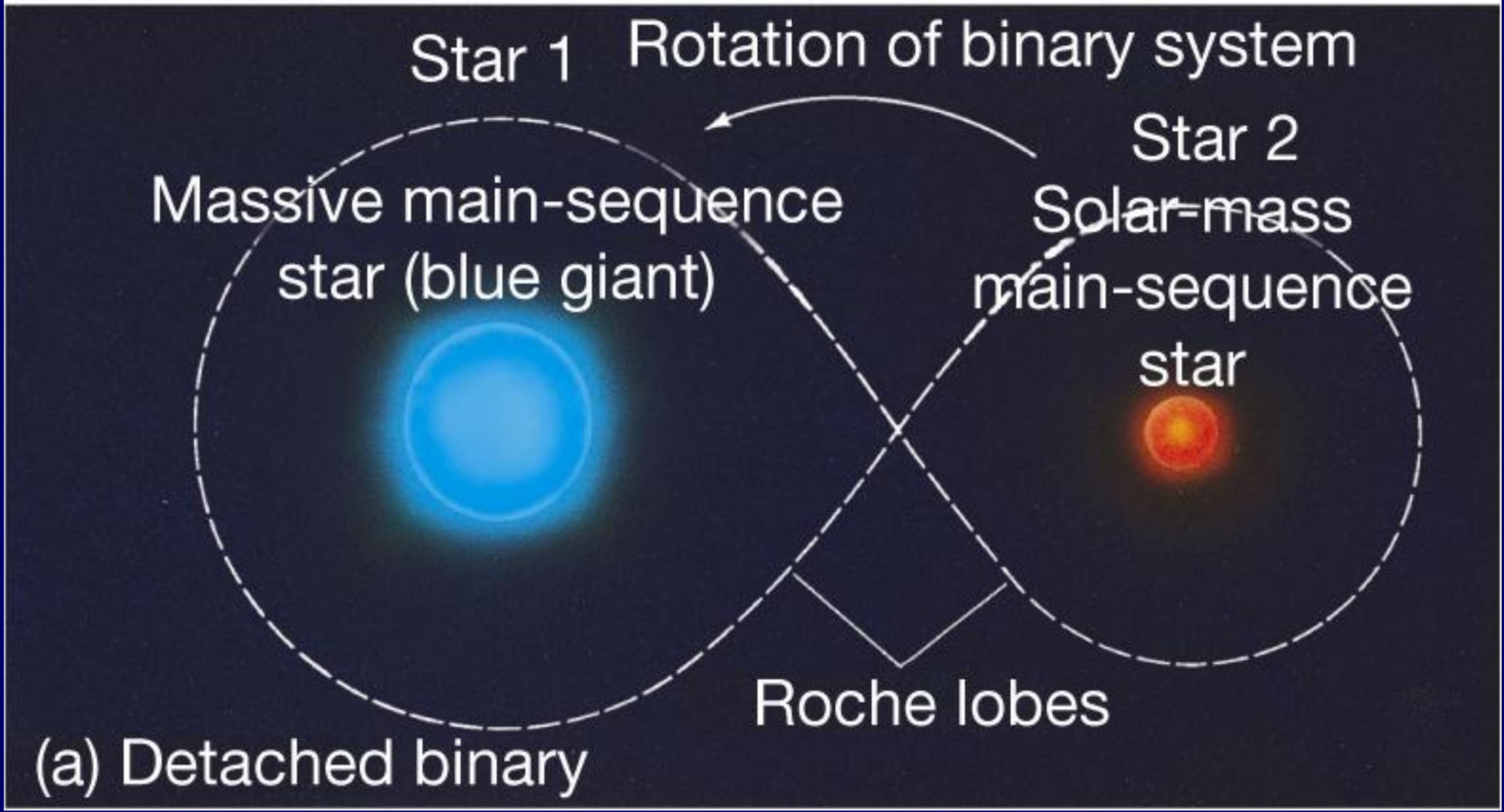
- In a **contact binary**, much of the mass is shared between the two stars and their volumes overlap.



The Evolution of Close Binary-Star Systems

- As the stars evolve, the type of binary system can evolve as well. This is the **Algol system**.

a) It is thought to have begun as a **detached binary**.



(a) Detached binary

The Evolution of Close Binary-Star Systems

Algol system

b) As the blue-giant star enters its red-giant phase, it expands to the point where mass transfer occurs.

c) Eventually enough mass is accreted onto the smaller star that it becomes a blue giant, leaving the other star as a red subgiant.