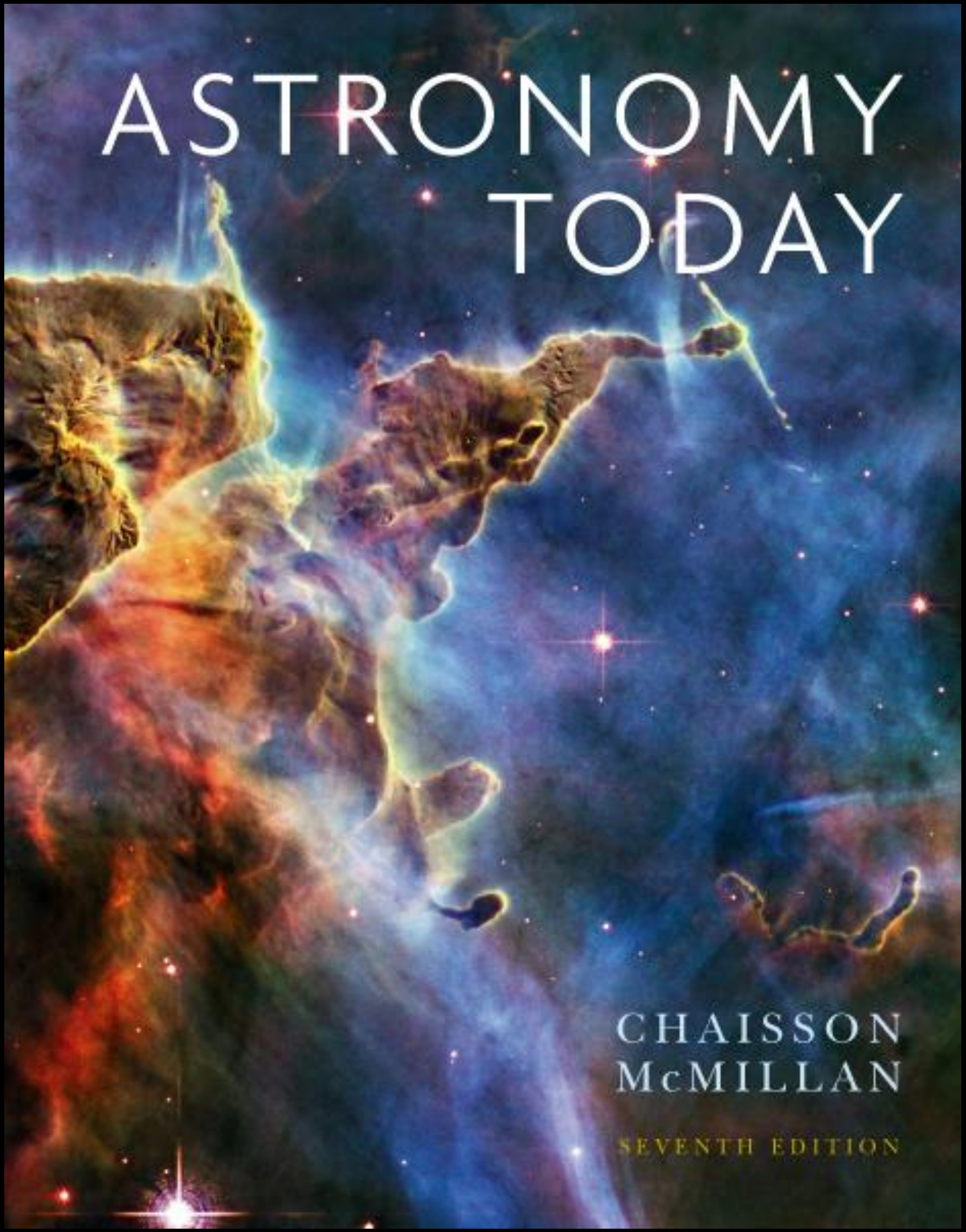


Lecture Outlines

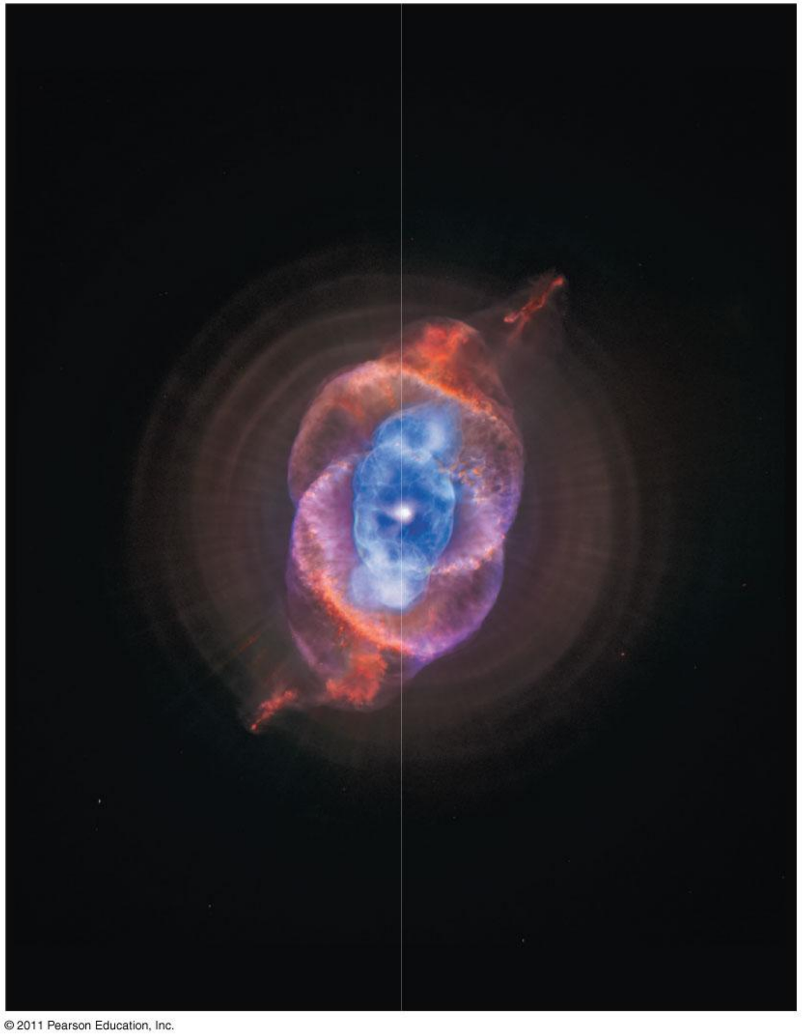
Chapter 20

Astronomy Today

7th Edition

Chaisson/McMillan

Chapter 20
Stellar Evolution



Units of Chapter 20

20.1 Leaving the Main Sequence

20.2 Evolution of a Sun-Like Star

20.3 The Death of a Low-Mass Star

Learning Astronomy from History

20.4 Evolution of Stars More Massive than the Sun

Mass Loss from Giant Stars

20.5 Observing Stellar Evolution in Star Clusters

20.6 The Evolution of Binary-Star Systems

20.1 Leaving the Main Sequence

We cannot observe a single star going through its whole life cycle; even short-lived stars live too long for that.

Observation of stars in star clusters gives us a look at stars in all stages of evolution; this allows us to construct a complete picture.

20.1 Leaving the Main Sequence

During its stay on the Main Sequence, any fluctuations in a star's condition are quickly restored; the star is in equilibrium

20.1 Leaving the Main Sequence

Eventually, as hydrogen in the core is consumed, the star begins to leave the Main Sequence

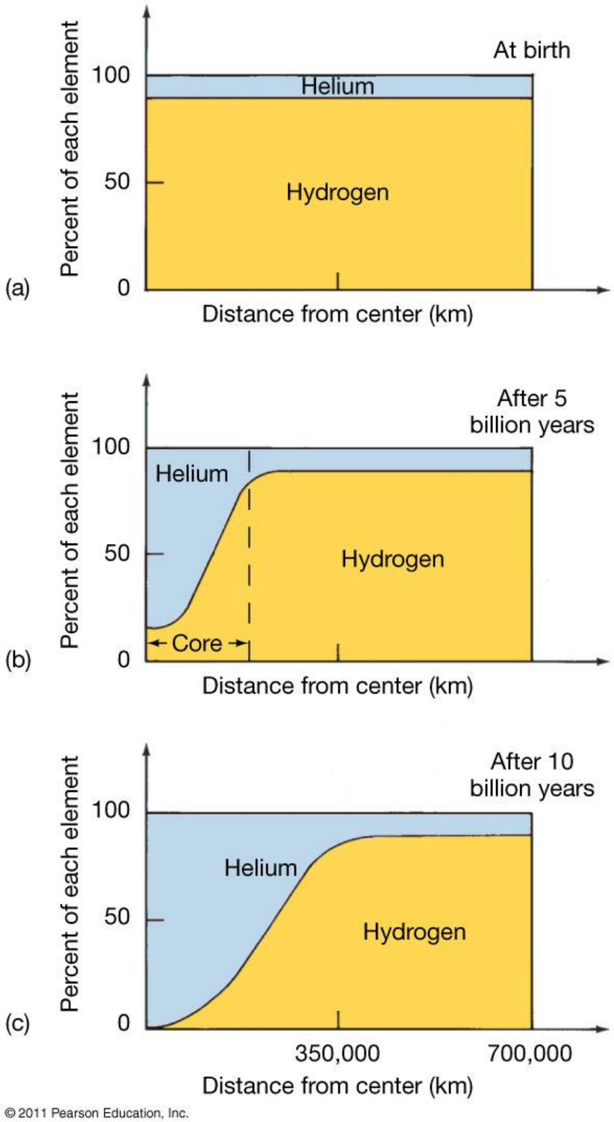
Its evolution from then on depends very much on the mass of the star:

Low-mass stars go quietly

High-mass stars go out with a bang!

20.2 Evolution of a Sun-like Star

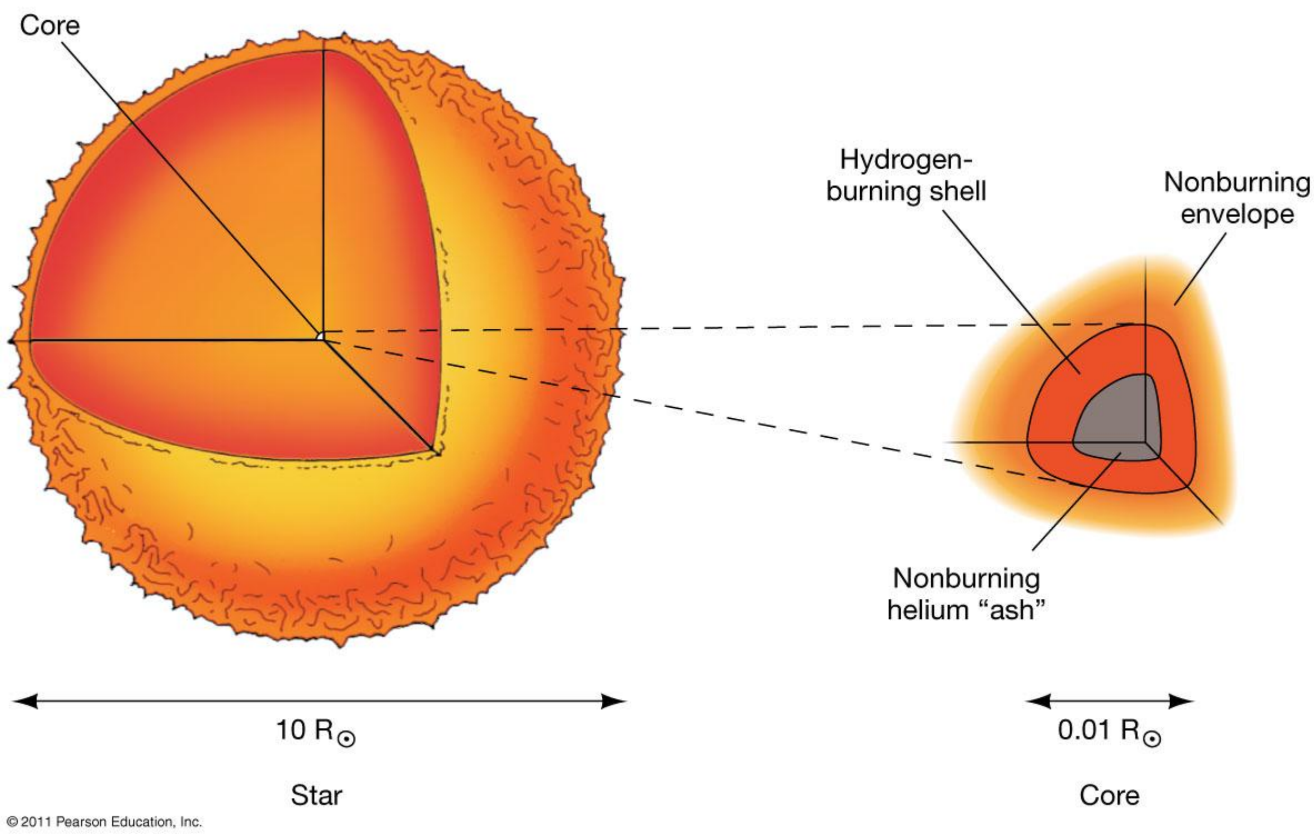
Even while on the Main Sequence, the composition of a star's core is changing



20.2 Evolution of a Sun-Like Star

As the fuel in the core is used up, the core contracts; when it is used up the core begins to collapse.

Hydrogen begins to fuse outside the core:



20.2 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.*

20.2 Evolution of a Sun-Like Star

Stage 9: The Red-Giant Branch

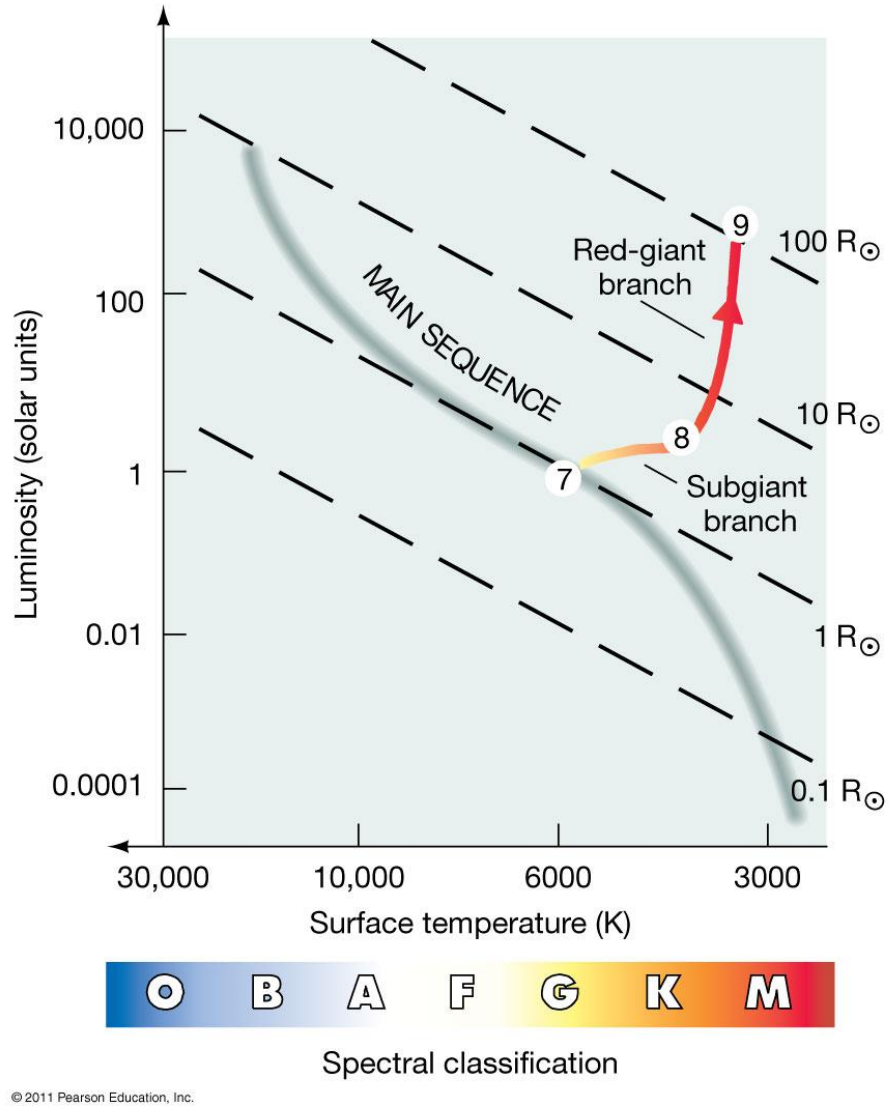
As the core continues to shrink, the outer layers of the star expand and cool.

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.

20.2 Evolution of a Sun-like Star

The red giant stage on the H-R diagram:



20.2 Evolution of a Sun-Like Star

Stage 10: Helium fusion

Once the core temperature has risen to 100,000,000 K, the helium in the core starts to fuse, through a three-alpha process:

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

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

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.

20.2 Evolution of a Sun-Like Star

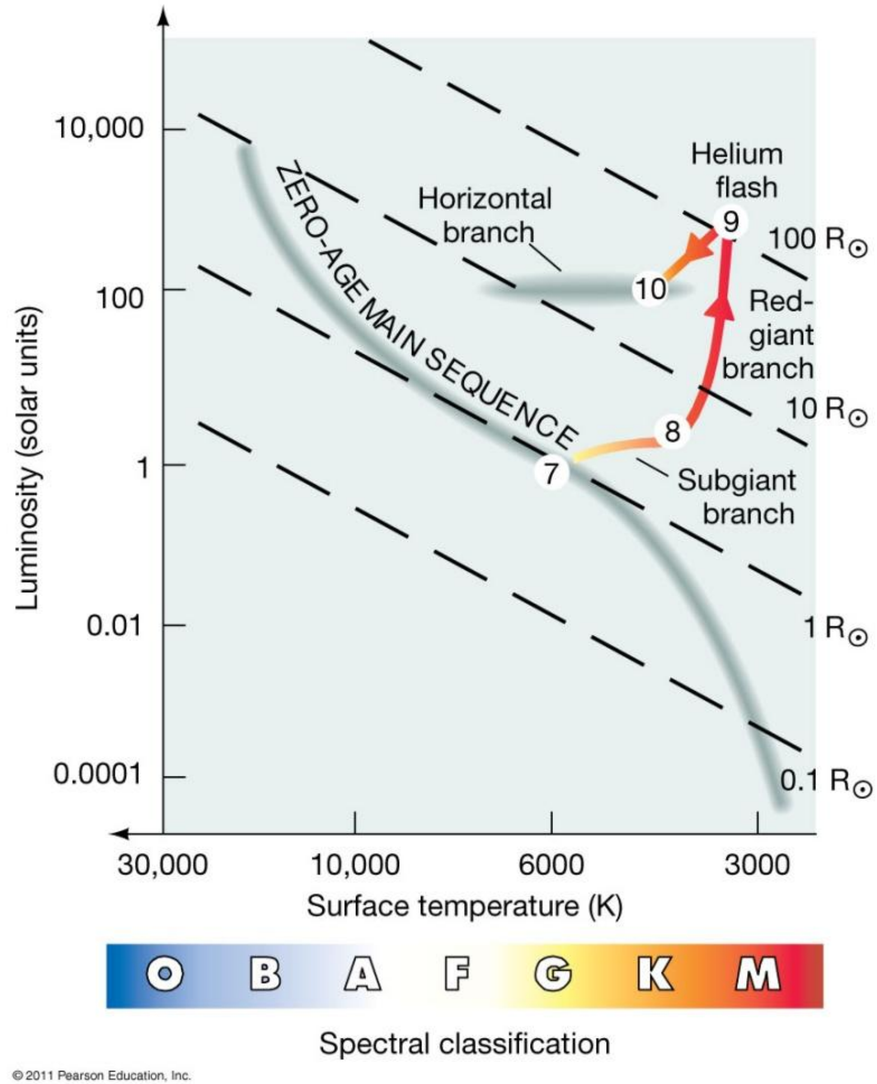
The helium flash:

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.

20.2 Evolution of a Sun-Like Star

Helium begins to fuse extremely rapidly; within hours the enormous energy output is over, and the star once again reaches equilibrium

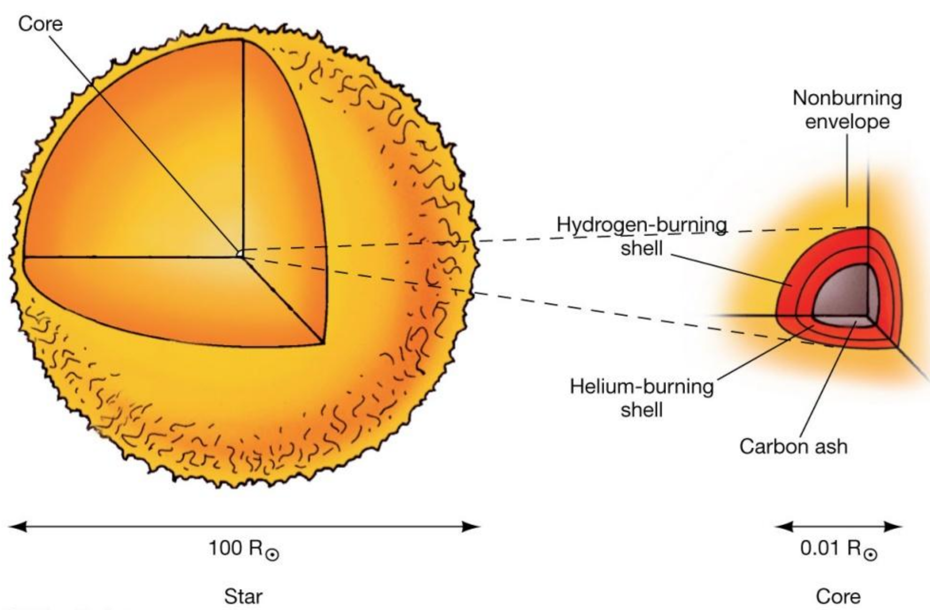


20.2 Evolution of a Sun-Like Star

Stage 11: Back to the giant branch

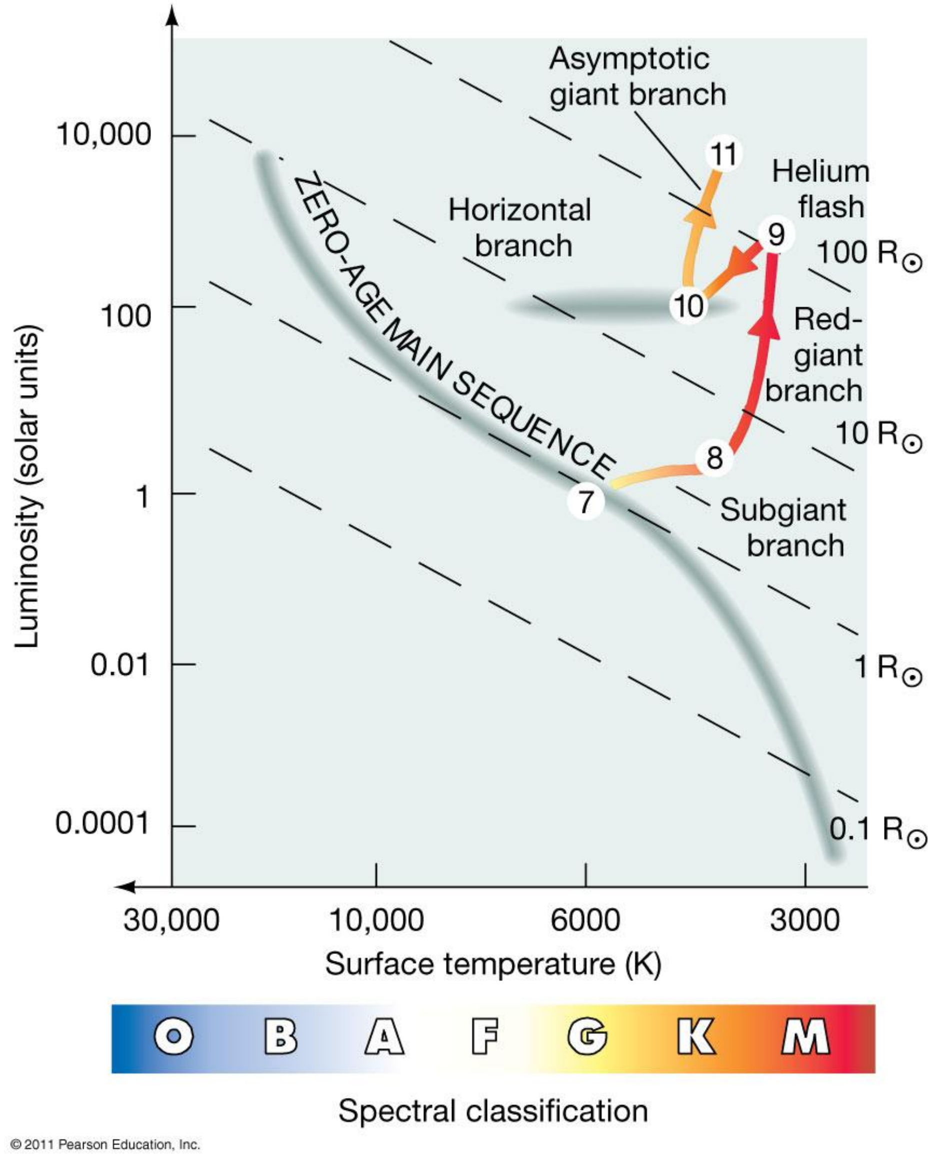
As the helium in the core fuses to carbon, the core becomes hotter and hotter, and the helium burns faster and faster.

The star is now similar to its condition just as it left the Main Sequence, except now there are two shells:



20.2 Evolution of a Sun-Like Star

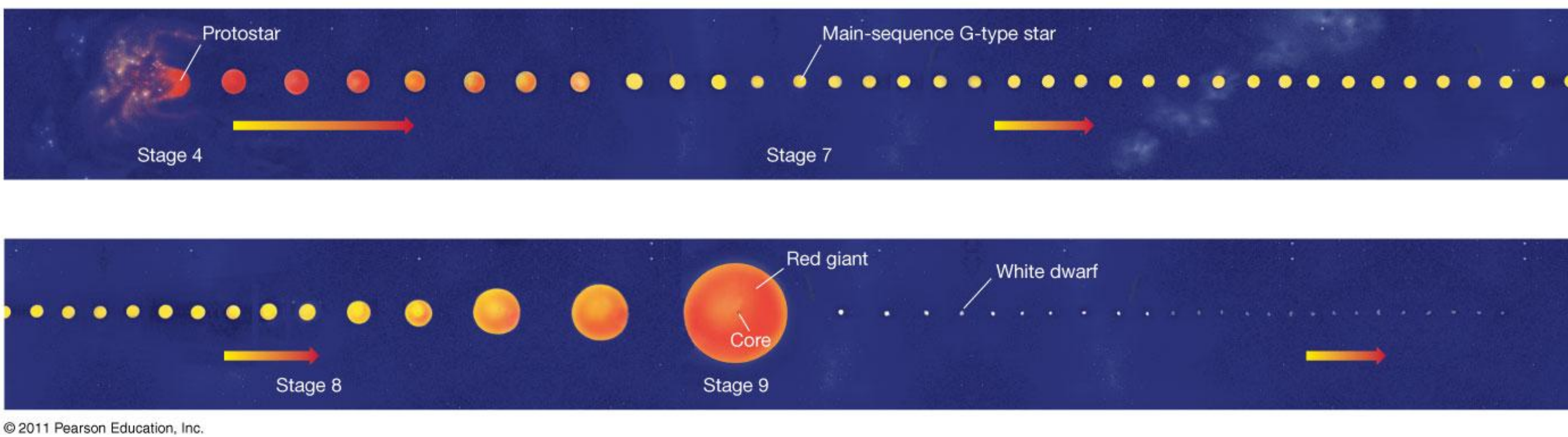
The star has become a red giant for the second time



20.3 The Death of a Low-Mass Star

This graphic shows the entire evolution of a Sun-like star.

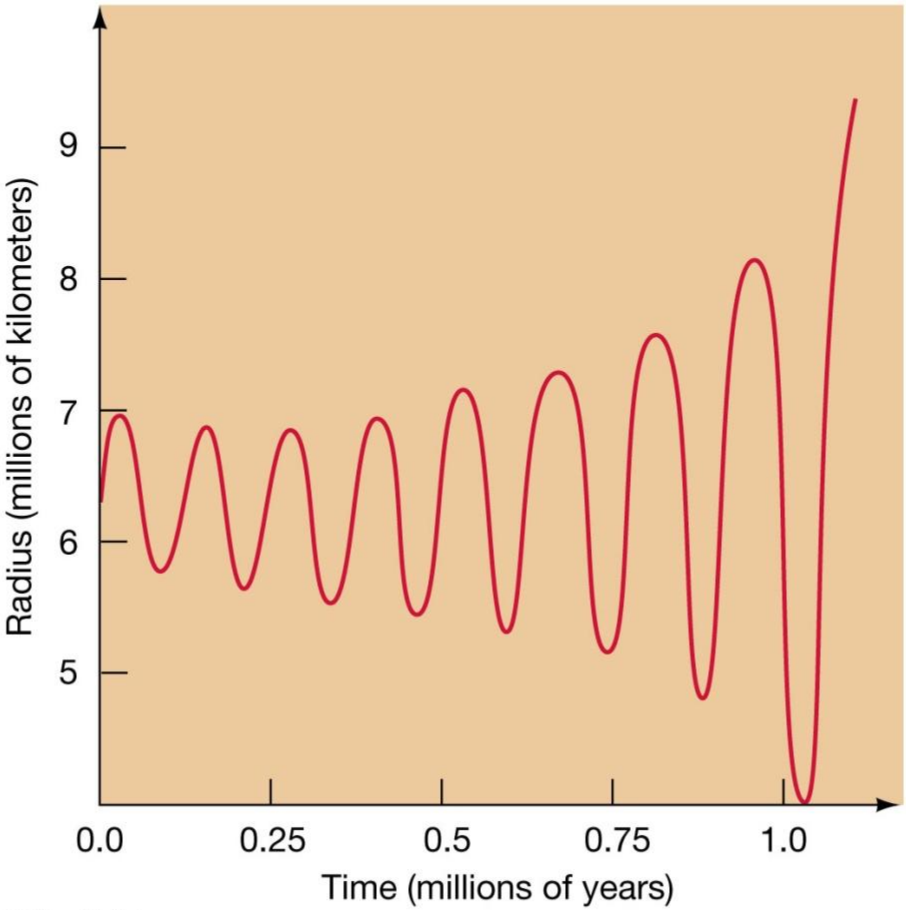
Such stars never become hot enough for fusion past carbon to take place.



20.3 The Death of a Low-Mass Star

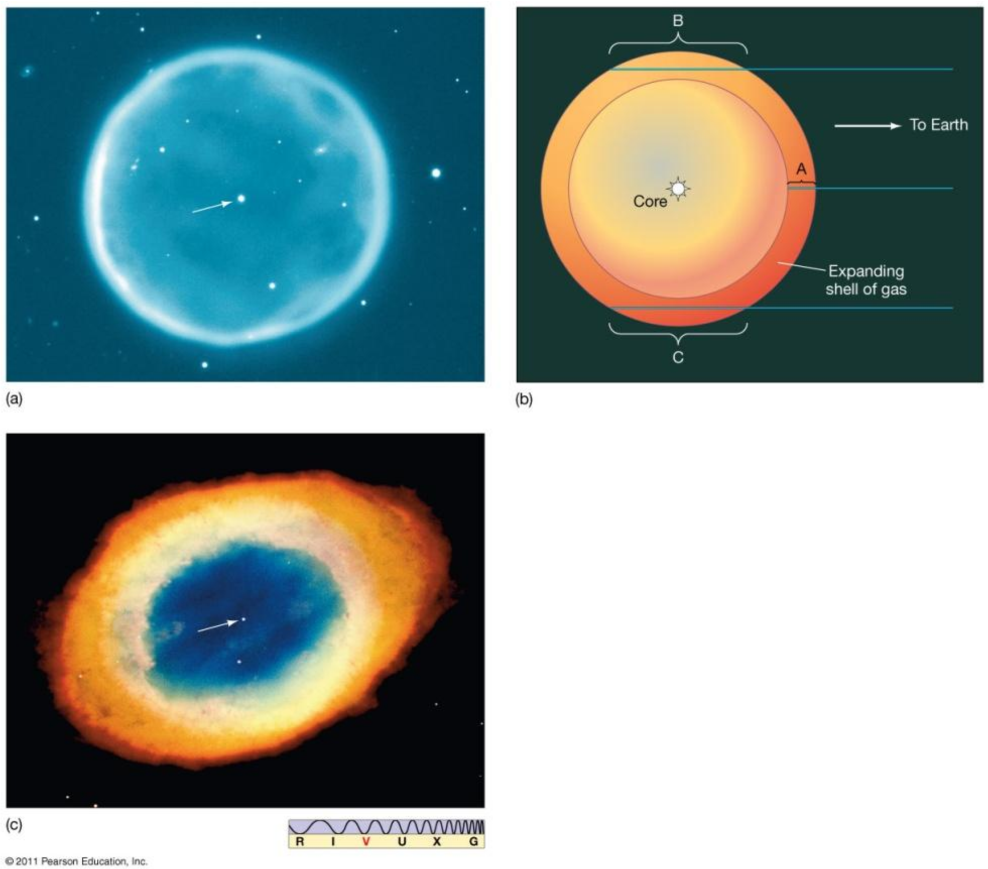
There is no more outward fusion pressure being generated in the core, which continues to contract.

The outer layers become unstable and are eventually ejected.



20.3 The Death of a Low-Mass Star

The ejected envelope expands into interstellar space, forming a planetary nebula.



20.3 The Death of a Low-Mass Star

The star now has two parts:

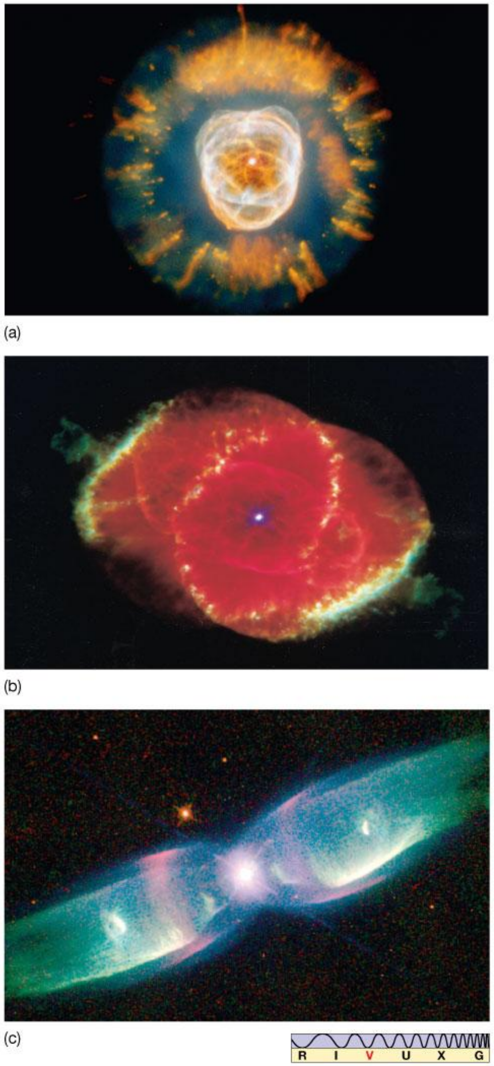
- A small, extremely dense carbon core
- An envelope about the size of our solar system.

The envelope is called a planetary nebula, even though it has nothing to do with planets—early astronomers viewing the fuzzy envelope thought it resembled a planetary system.

20.3 The Death of a Low-Mass Star

Planetary nebulae can have many shapes:

As the dead core of the star cools, the nebula continues to expand and dissipates into the surroundings.

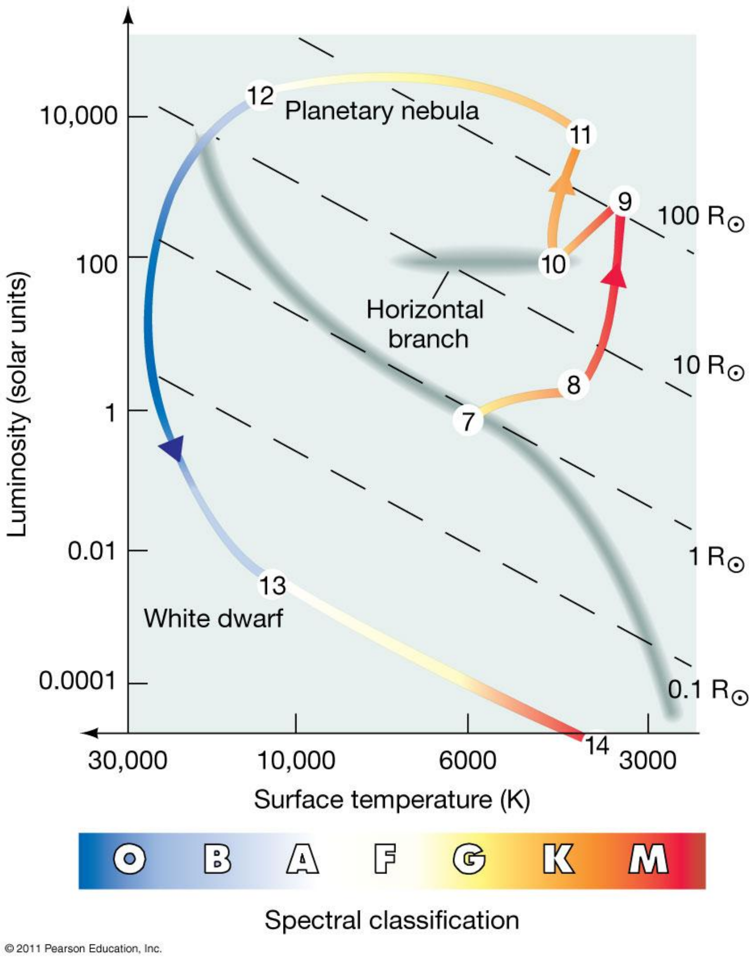


20.3 The Death of a Low-Mass Star

Stages 13 and 14: White and black dwarfs

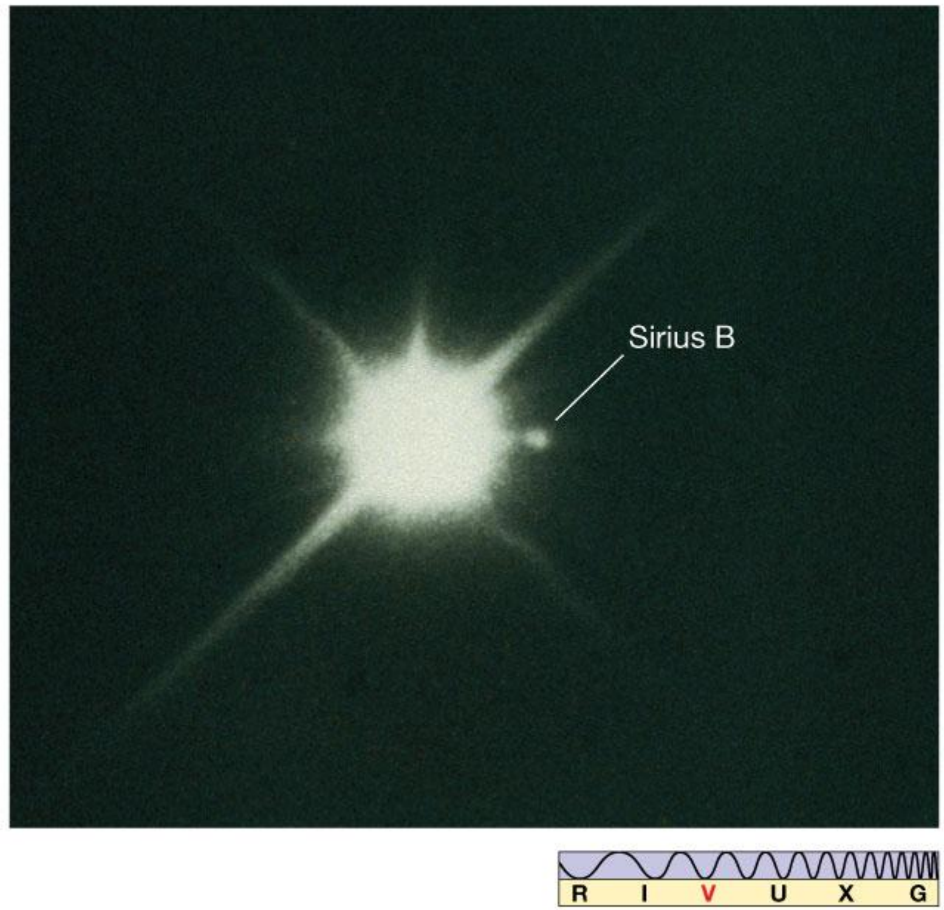
Once the nebula has gone, the remaining core is extremely dense and extremely hot, but quite small.

It is luminous only due to its high temperature.



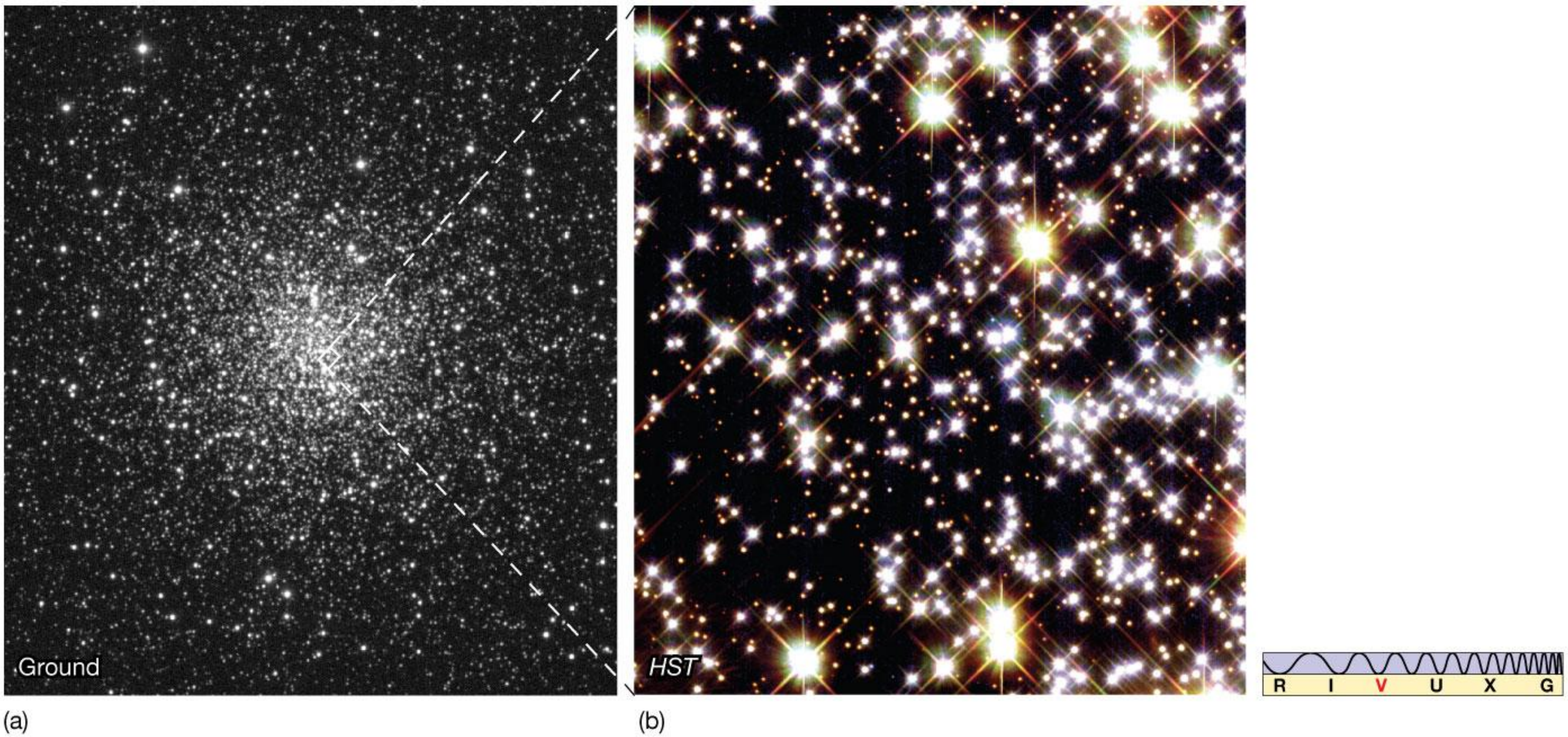
20.3 The Death of a Low-Mass Star

The small star Sirius B is a white-dwarf companion of the much larger and brighter Sirius A:



20.3 The Death of a Low-Mass Star

The Hubble Space Telescope has detected white dwarf stars in globular clusters:

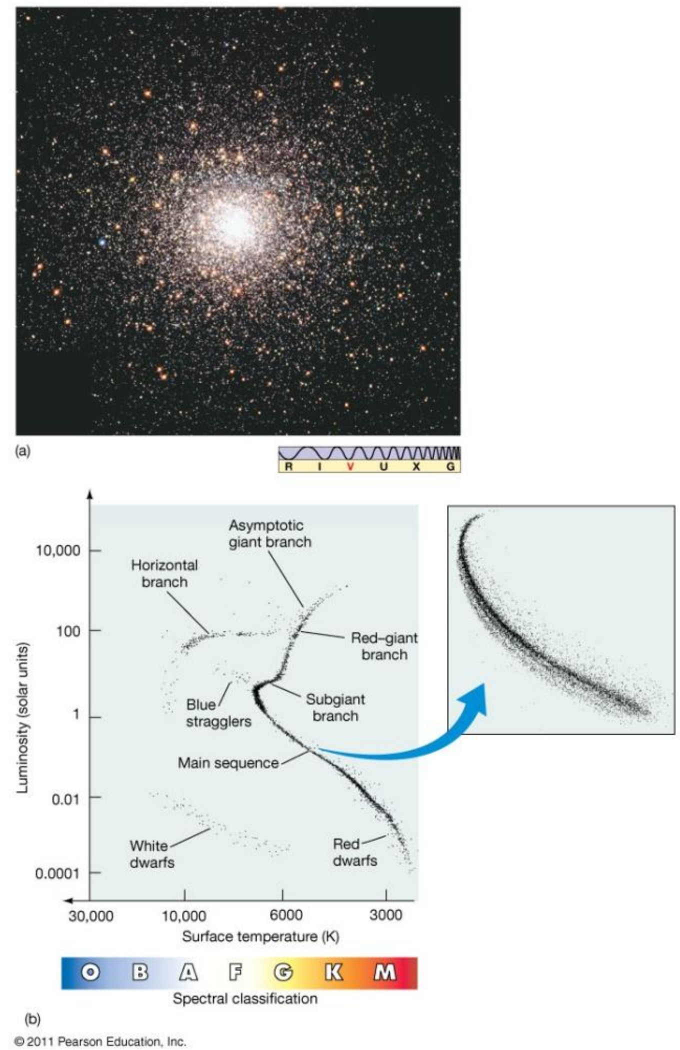


20.3 The Death of a Low-Mass Star

As the white dwarf cools, its size does not change significantly; it simply gets dimmer and dimmer, and finally ceases to glow.

20.3 The Death of a Low-Mass Star

This outline of stellar formation and extinction can be compared to observations of star clusters. Here a globular cluster:



20.3 The Death of a Low-Mass Star

The "blue stragglers" in the previous H-R diagram are not exceptions to our model; they are stars that have formed much more recently, probably from the merger of smaller stars.

Discovery 20-1: Learning Astronomy from History

Sirius is the brightest star in the northern sky and has been recorded throughout history. But there is a mystery!

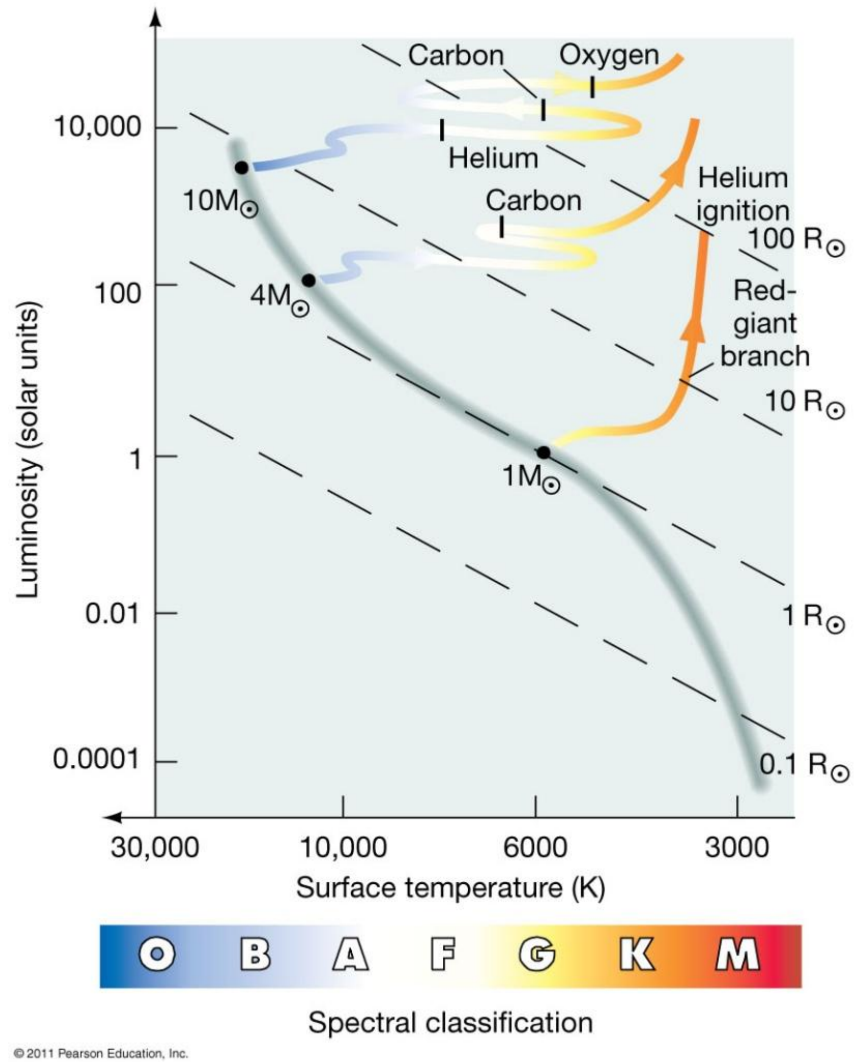
All sightings recorded between about 100 BCE and 200 CE describe it as being red—it is now blue-white. Why?

Could there have been an intervening dust cloud? (Then where is it?)

Could its companion have been a red giant? (It became a white dwarf very quickly, then!)

20.4 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



20.4 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—first a hydrogen shell, then a core burning helium to carbon, surrounded by helium- and hydrogen-burning shells.

20.4 Evolution of Stars More Massive than the Sun

Stars with masses more than 2.5 solar masses do not experience a helium flash—helium burning starts gradually.

A 4-solar-mass star makes no sharp moves on the H-R diagram—it moves smoothly back and forth.

20.4 Evolution of Stars More Massive than the Sun

A star of more than 8 solar masses 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.

20.4 Evolution of Stars More Massive than the Sun

In summary:

TABLE 20.3 End Points of Evolution for Stars of Different Masses

Initial Mass (Solar Masses)	**Final State**
less than 0.08	(hydrogen) brown dwarf
0.08–0.25	helium white dwarf
0.25–8	carbon–oxygen white dwarf
8–12 (approx.)*	neon–oxygen white dwarf
greater than 12*	supernova (Chapter 21)

* *Precise numbers depend on the (poorly known) amount of mass lost while the star is on, and after it leaves, the main sequence.*

Discovery 20-2: Mass Loss from Giant Stars

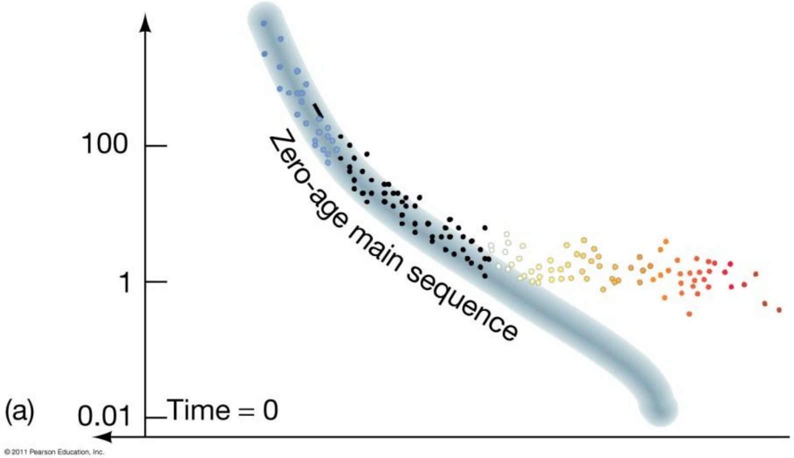
All stars lose mass via some form of stellar wind. The most massive stars have the strongest winds; O- and B-type stars can lose a tenth of their total mass this way in only a million years.

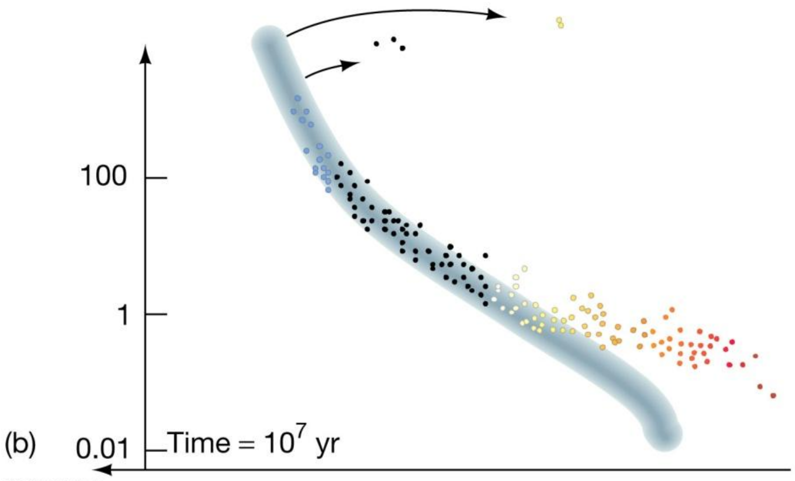
These stellar winds hollow out cavities in the interstellar medium surrounding giant stars.

Discovery 20-2: 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:

20.5 Observing Stellar Evolution in Star Clusters

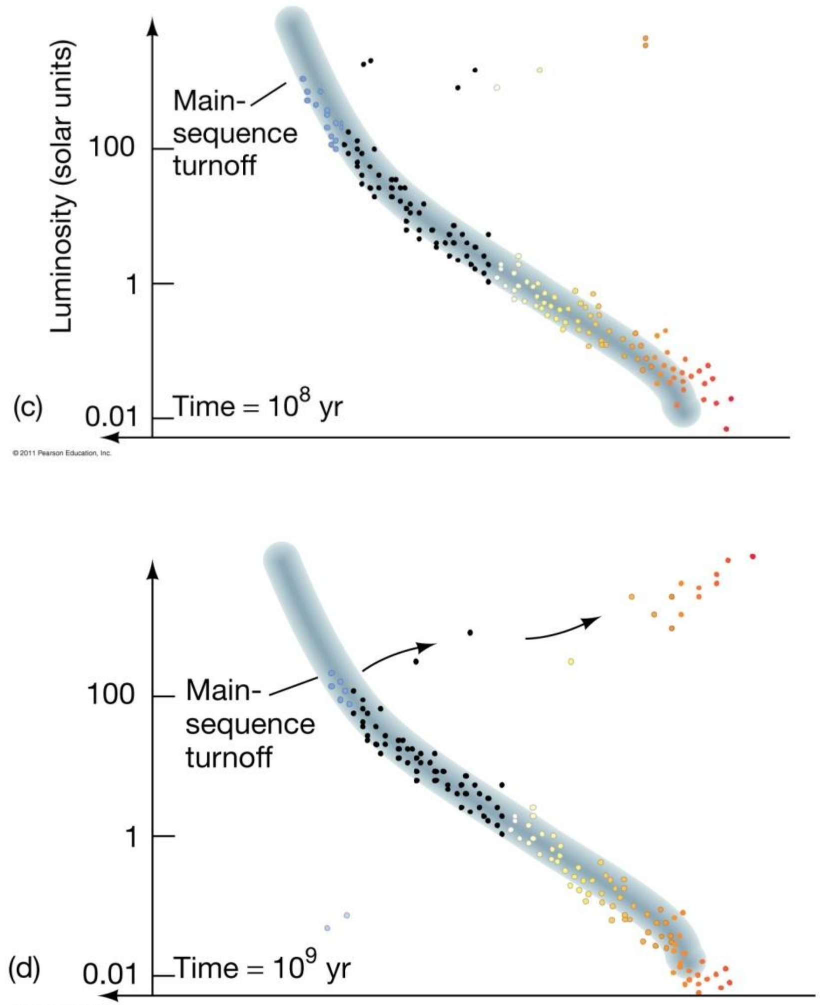




The following series of H-R diagrams shows how stars of the same age, but different masses, appear as the whole cluster ages.

After 10 million years, the most massive stars have already left the Main Sequence, while many of the least massive have not even reached it yet.

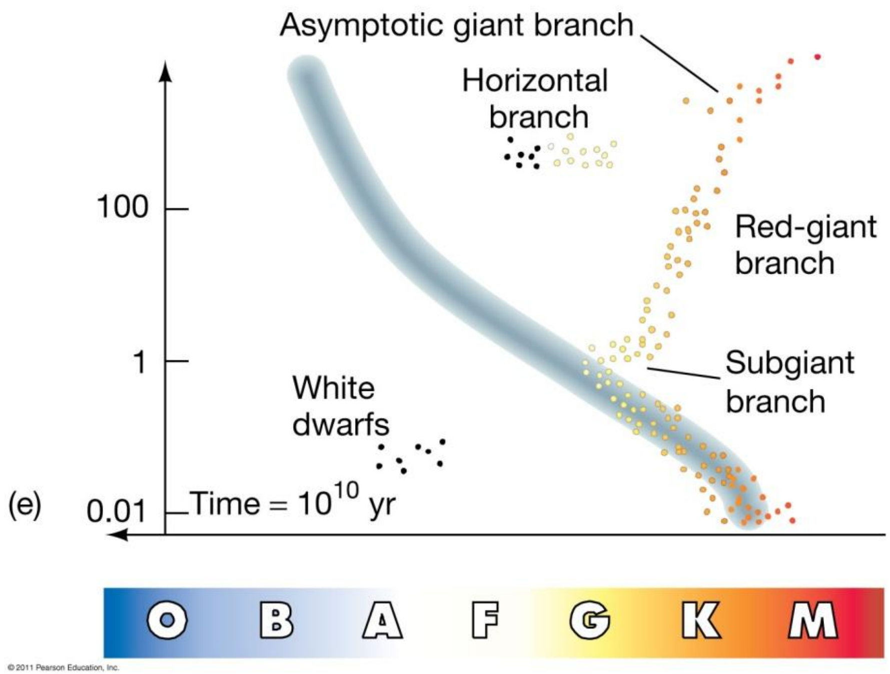
20.5 Observing Stellar Evolution in Star Clusters



After 100 million years, a distinct main-sequence turnoff begins to develop. This shows the highest-mass stars that are still on the Main Sequence.

After 1 billion years, the main-sequence turnoff is much clearer.

20.5 Observing Stellar Evolution in Star Clusters



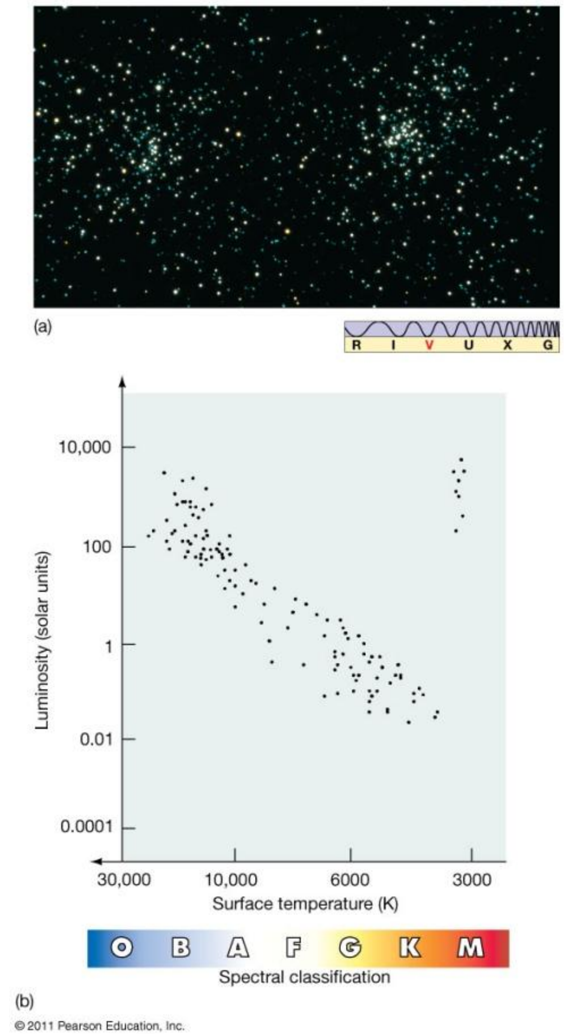
After 10 billion years, a number of features are evident:

The red-giant, subgiant, asymptotic giant, and horizontal branches are all clearly populated.

White dwarfs, indicating that solar-mass stars are in their last phases, also appear.

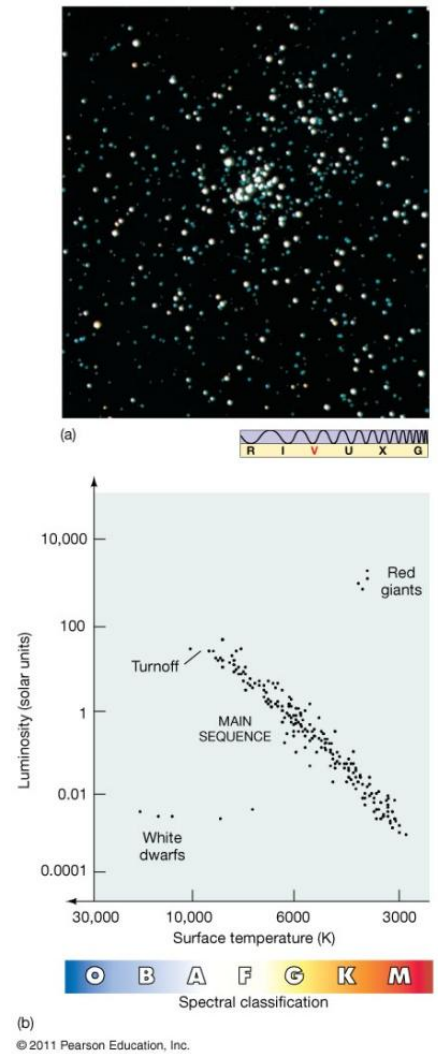
20.5 Observing Stellar Evolution in Star Clusters

This double cluster, h and chi Persei, must be quite young—its H-R diagram is that of a newborn cluster. Its age cannot be more than about 10 million years.



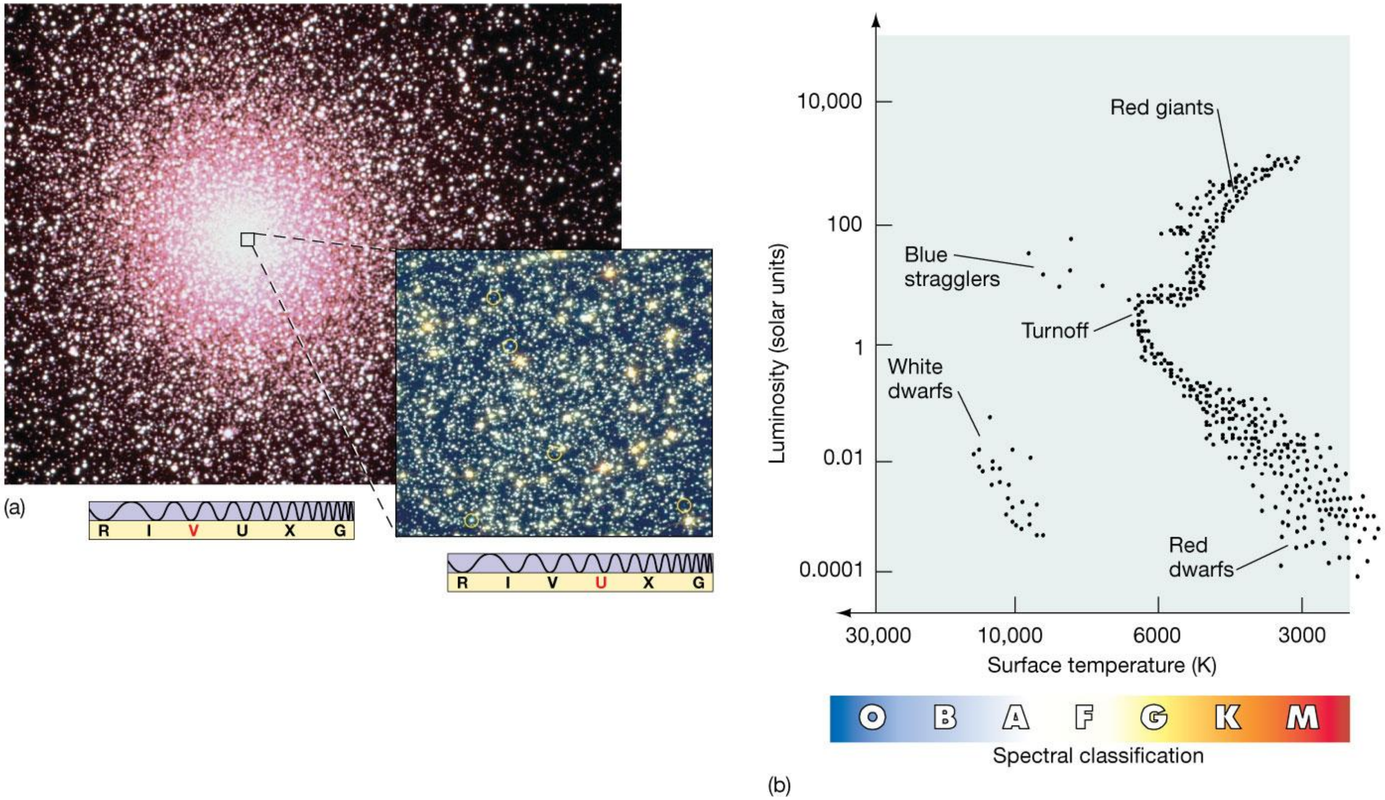
20.5 Observing Stellar Evolution in Star Clusters

The Hyades cluster, shown here, is also rather young; its main-sequence turnoff indicates an age of about 600 million years.



20.5 Observing Stellar Evolution in Star Clusters

This globular cluster, 47 Tucanae, is about 10–12 billion years old, much older than the previous examples:



20.6 The Evolution of Binary-Star Systems

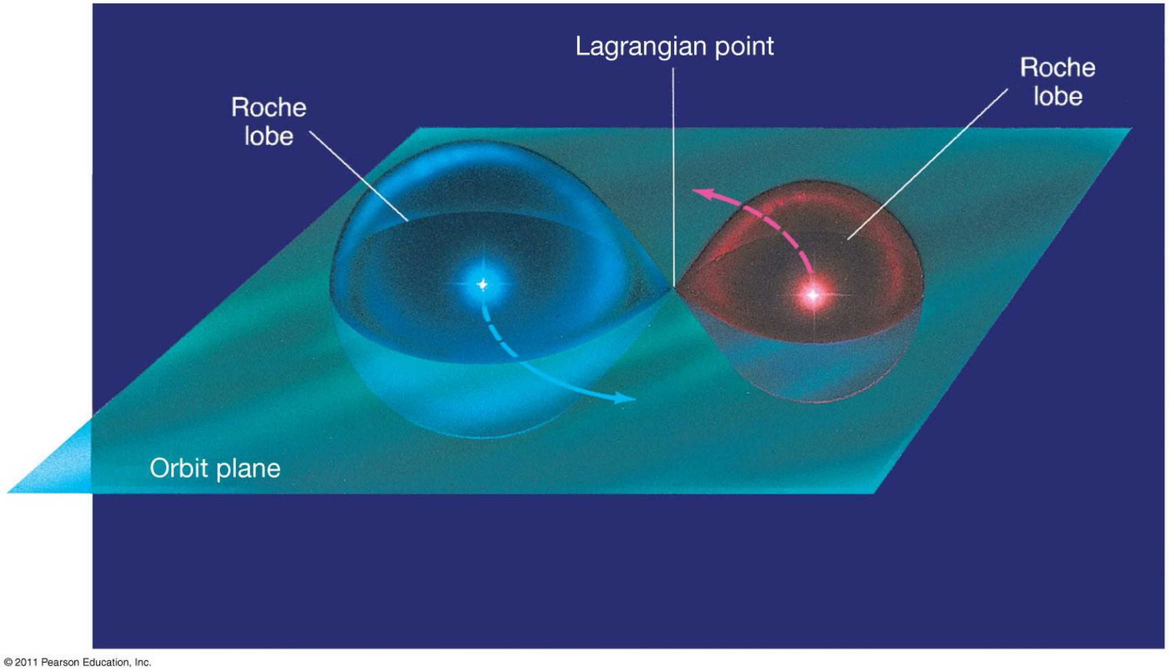
If the stars in a binary-star system are relatively widely separated, their evolution proceeds much as it would have if they were not companions.

If they are closer, it is possible for material to transfer from one star to another, leading to unusual evolutionary paths.

20.6 The Evolution of Binary-Star Systems

Each star is surrounded by its own Roche lobe; particles inside the lobe belong to the central star.

The Lagrangian point is where the gravitational forces are equal.



20.6 The Evolution of Binary-Star Systems

There are different types of binary-star systems, depending on how close the stars are.

In a detached binary, each star has its own Roche lobe.

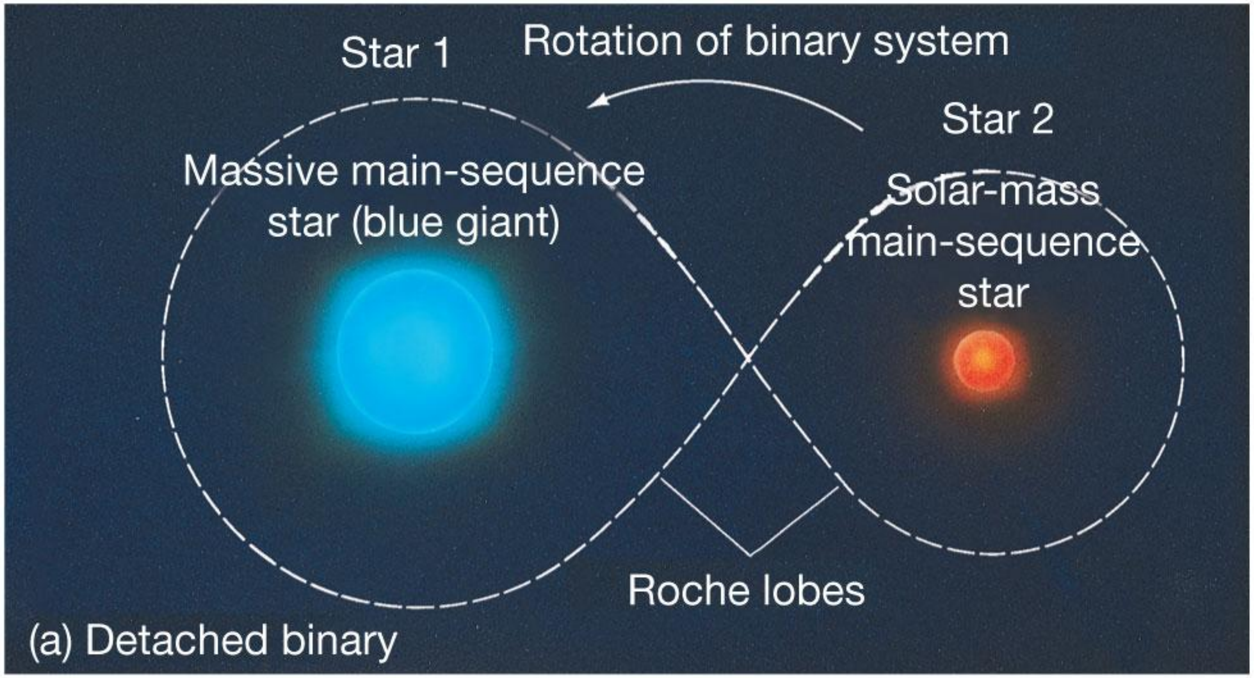
In a semidetached binary, one star can transfer mass to the other.

In a contact binary, much of the mass is shared between the two stars.

20.6 The Evolution of Binary-Star Systems

As the stars evolve, their binary system type can evolve as well. This is the Algol system:

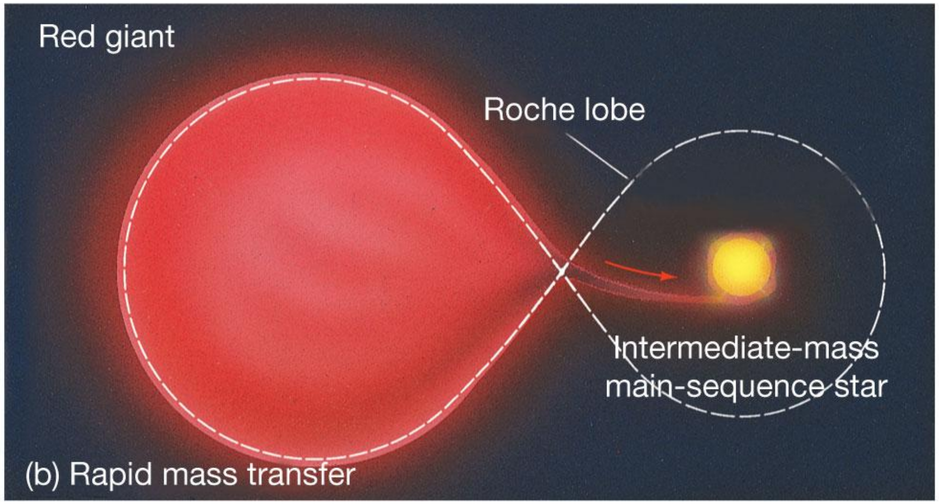
It is thought to have begun as a detached binary

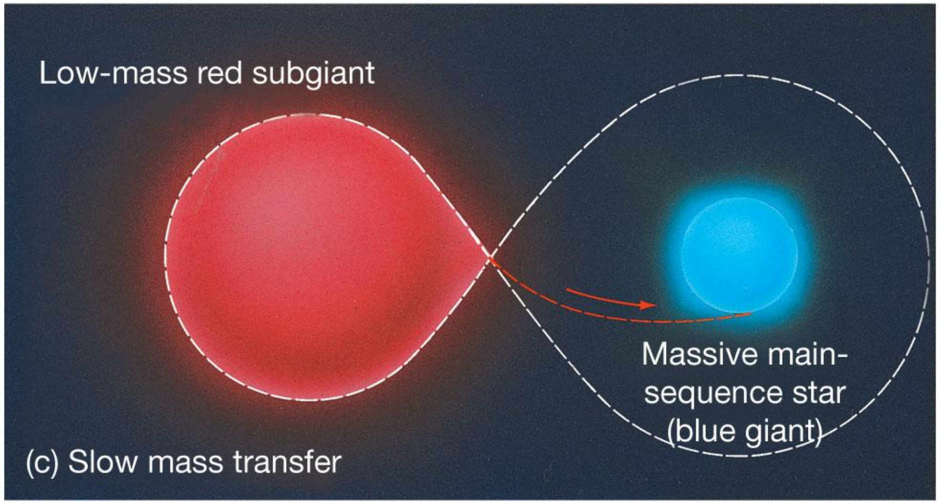


20.6 The Evolution of Binary-Star Systems

As the blue-giant star entered its red-giant phase, it expanded to the point where mass transfer occurred (b).

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





Summary of Chapter 20

- Stars spend most of their life on the Main Sequence
- When fusion ceases in the core, it begins to collapse and heat. Hydrogen fusion starts in the shell surrounding the core.
- The helium core begins to heat up; as long as the star is at least 0.25 solar masses, the helium will get hot enough that fusion (to carbon) will start.
- As the core collapses, the outer layers of the star expand and cool.

Summary of Chapter 20 (cont.)

- In Sun-like stars, the helium burning starts with a helium flash before the star is once again in equilibrium.
- The star develops a nonburning carbon core, surrounded by shells burning helium and hydrogen.
- The shell expands into a planetary nebula, and the core is visible as a white dwarf.
- The nebula dissipates, and the white dwarf gradually cools off.

Summary of Chapter 20 (cont.)

- High-mass stars become red supergiants, and end explosively.
- The description of stars' birth and death can be tested by looking at star clusters, whose stars are all the same age but have different masses.
- Stars in binary systems can evolve quite differently due to interactions with each other.