Chapter 20
Stellar Evolution (20.1-20.3)

Units of Chapter 20

20.1 Leaving the Main Sequence

20.2 Evolution of a Sun-Like Star

XXThe CNO Cycle

20.3 The Death of a Low-Mass Star

XXLearning Astronomy from History

Try to review at this point.

20.4 Evolution of Stars More Massive than the Sun

XXMass Loss from Giant Stars

20.5 Observing Stellar Evolution in Star Clusters

OMIT: 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. And when we observe large numbers of stars, we are looking at stars borne at different times in the 10Gyr history of our Galaxy, so they are in different phases of evolution.

Observation of stars in star clusters help, by giving us a look at stars that were all born at the same time. However we use the observations, *our interpretation must rely heavily on theoretical calculations of the evolution of stars of various masses.*

20.1 Leaving the Main Sequence

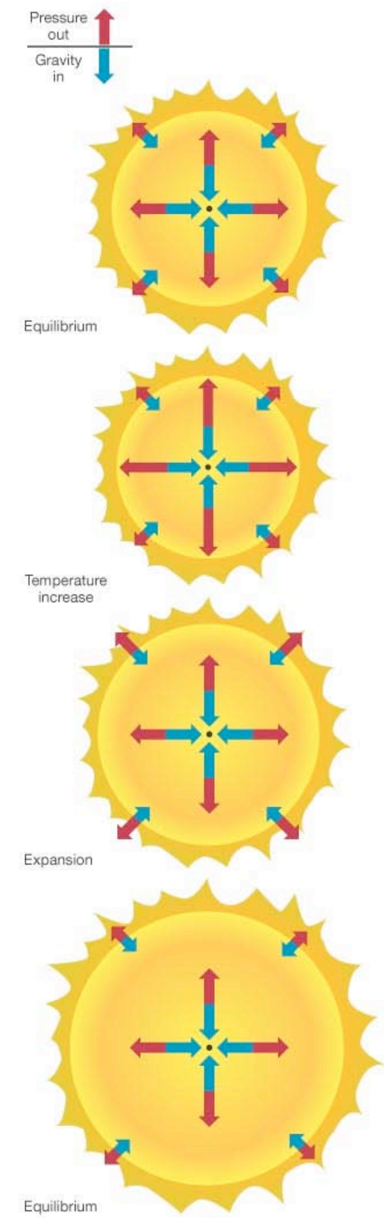
During its stay on the Main Sequence, any fluctuations in a star's condition are quickly restored; the star is in equilibrium.

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!

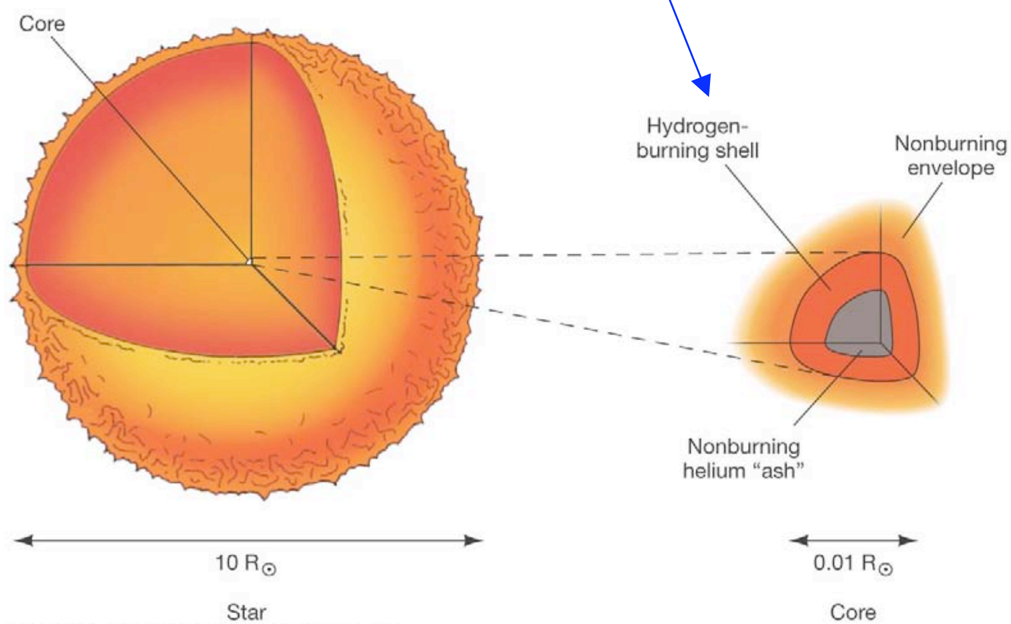


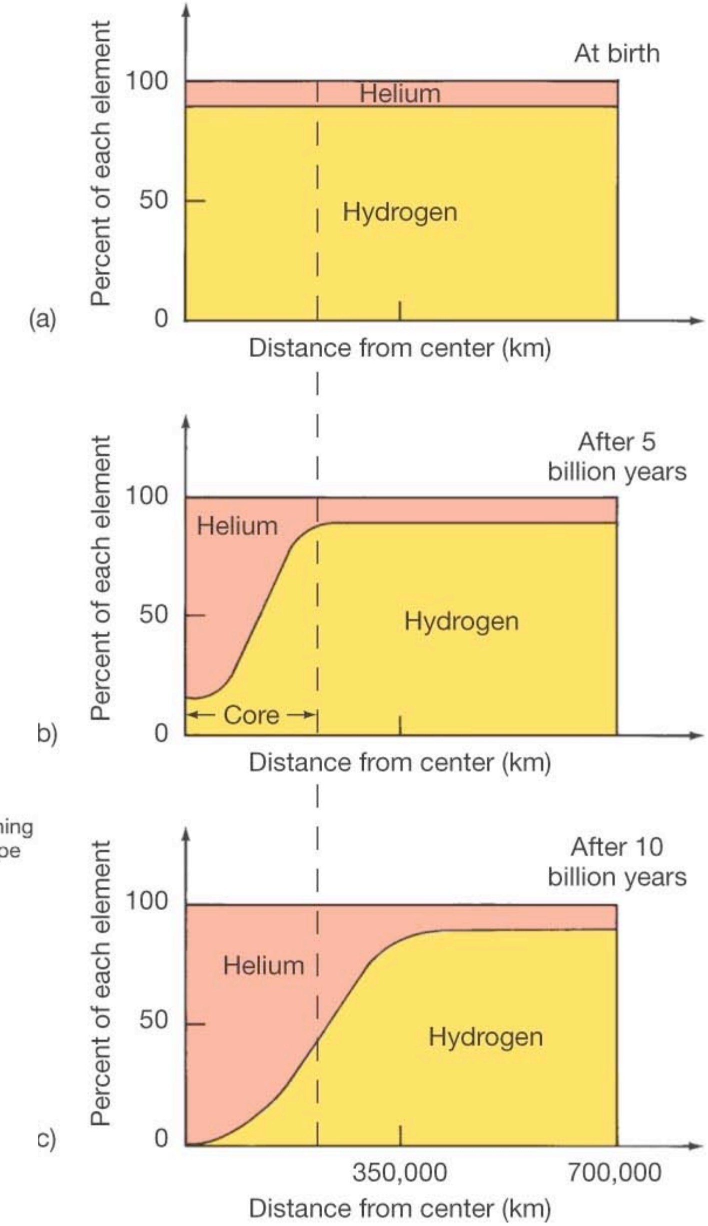
20.2 Evolution of a Sun-like Star

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

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:

You Should be able to describe what is happening at each of these stages, in the core and in the envelope, as well as place it in the H-R diagram. However you don't have to know these numbers.

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/m³)	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

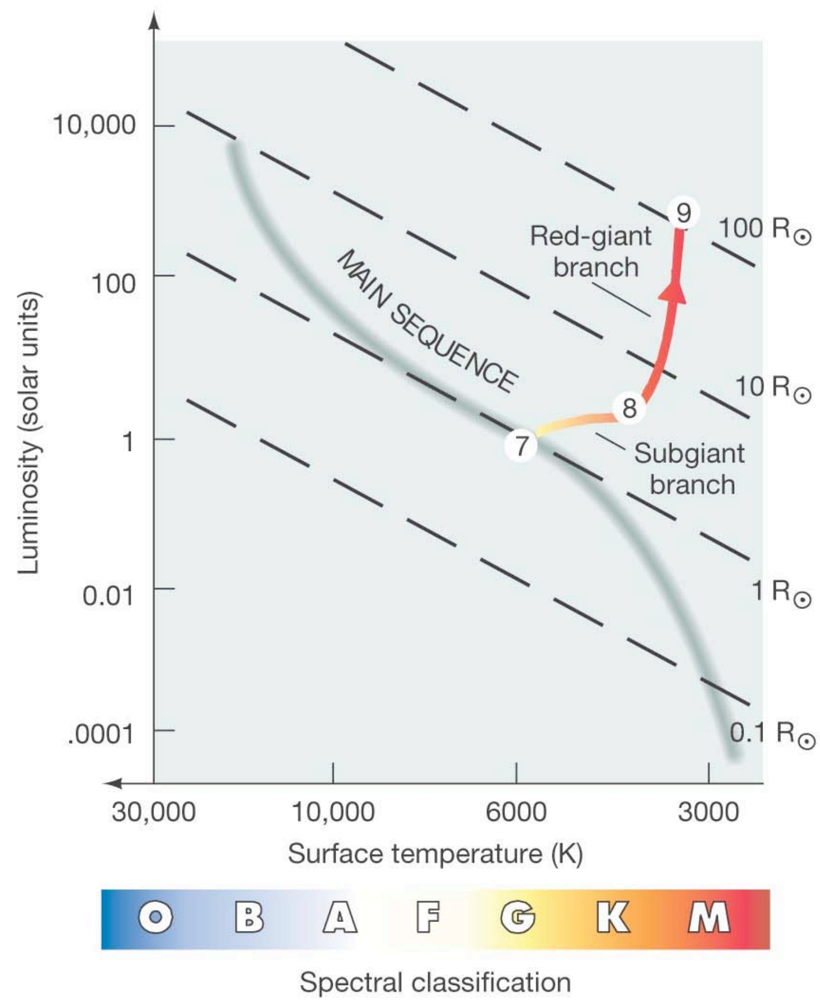
Stage 9: The Red-Giant Branch

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.

The **red giant** stage on the H-R diagram:



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.

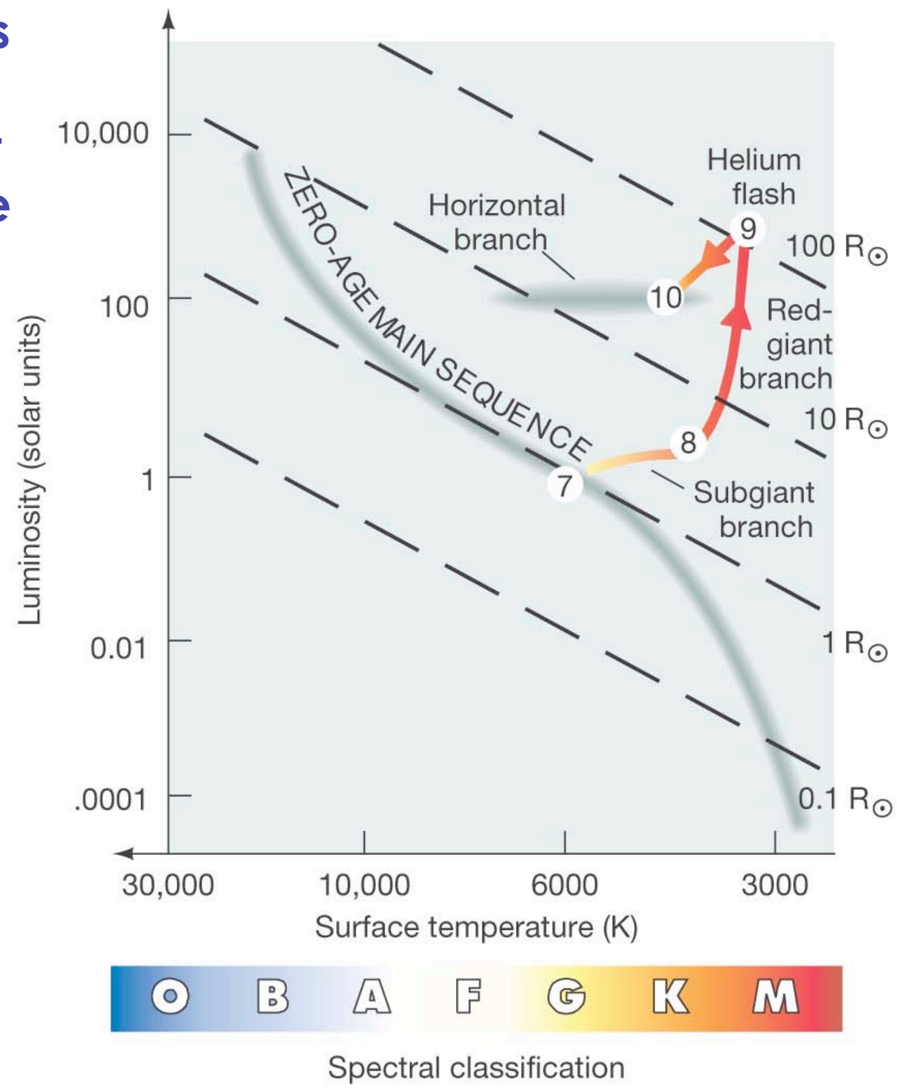
20.2 Evolution of a Sun-Like Star

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.

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

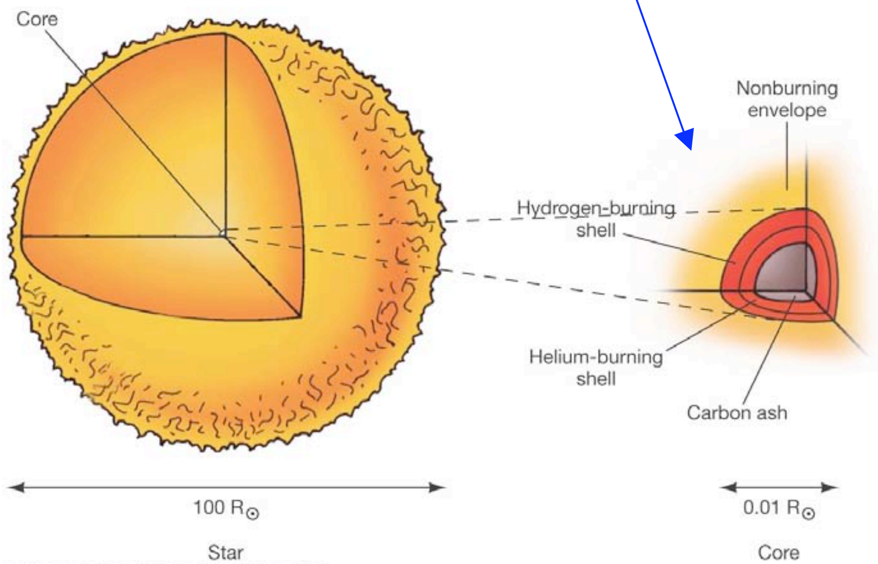


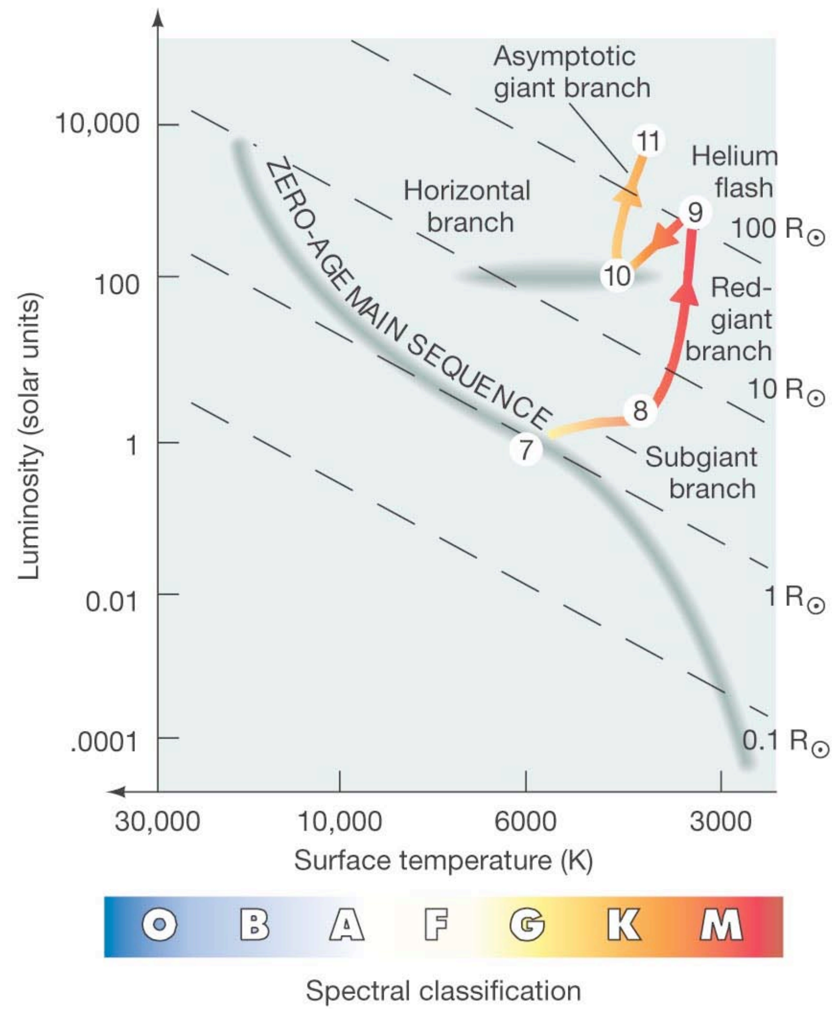
20.2 Evolution of a Sun-Like Star

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:





The star has become a **red giant** for the second time

More Precisely 20-1: The CNO Cycle

The proton–proton cycle is not the only path stars take to fuse hydrogen to helium. At higher temperatures, the CNO cycle occurs:

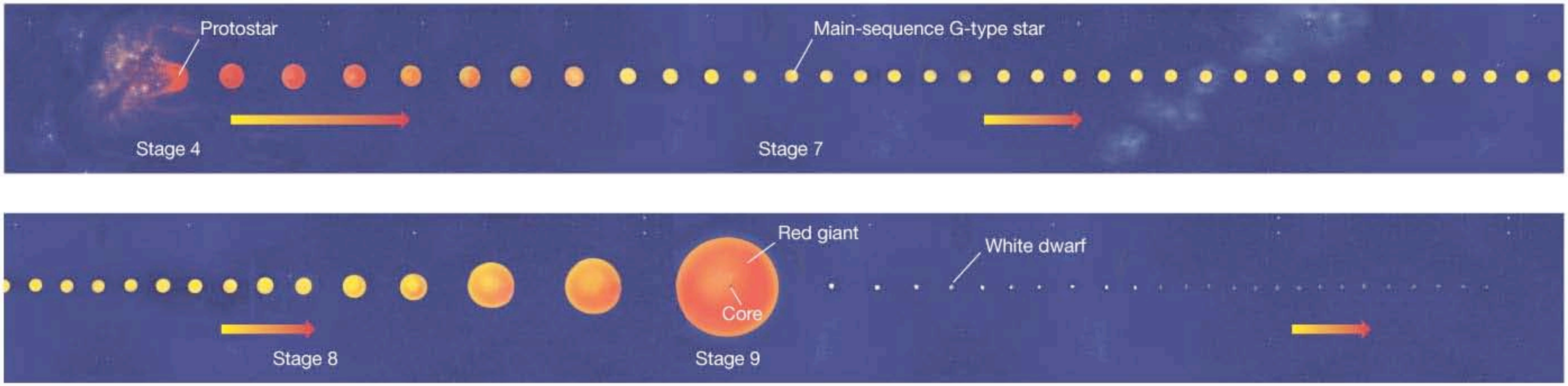
$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \text{energy}$$
$$^{13}N \rightarrow {}^{13}C + \text{positron} + \text{neutrino}$$
$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \text{energy}$$
$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \text{energy}$$
$$^{15}O \rightarrow {}^{15}N + \text{positron} + \text{neutrino}$$
$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He$$

In stars more massive than the Sun, whose core temperatures exceed 20,000,000 K, the CNO process is dominant.

20.3 The Death of a Low-Mass Star

This graphic shows the entire **evolution** of a Sun-like star. Use it as a review device. Try to describe each of the phases shown.

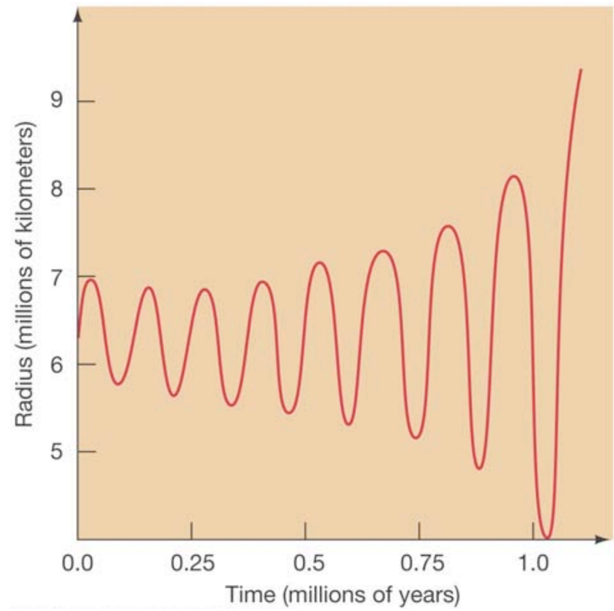
Low mass stars like the sun never become hot enough for fusion past **carbon** to take place.

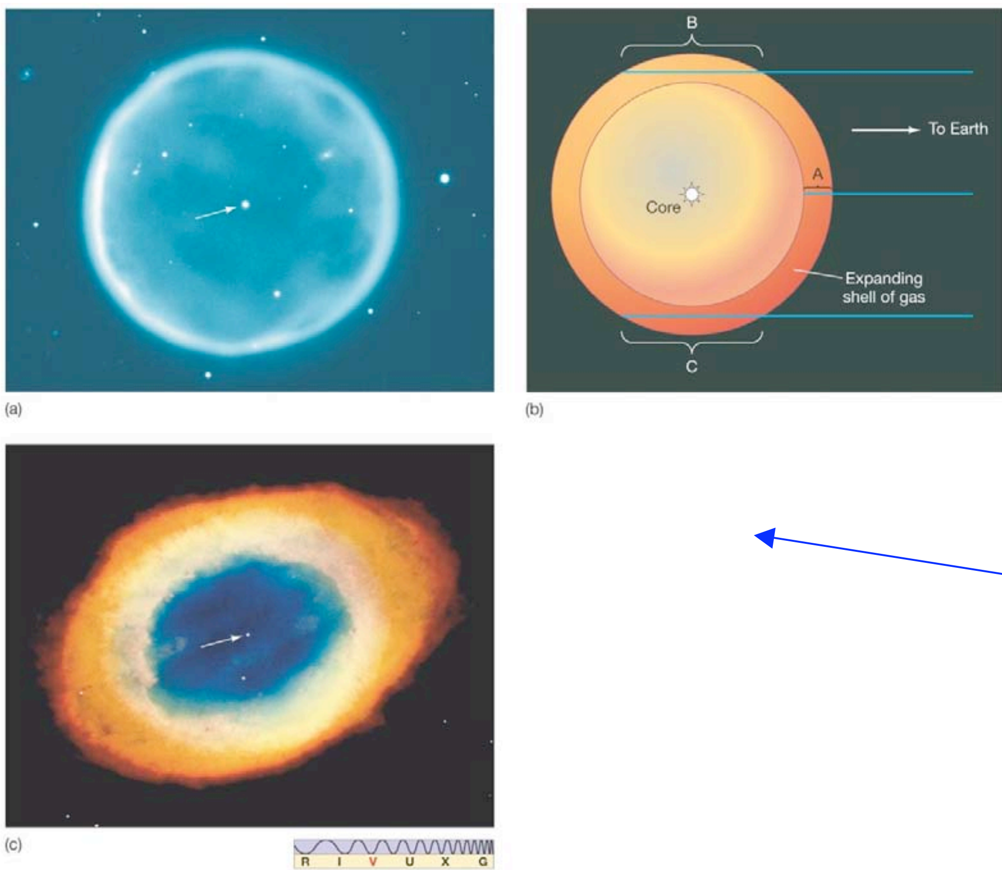


20.3 The Death of a Low-Mass Star

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.





(a) (b) (c)

The ejected envelope expands into interstellar space, forming a "planetary nebula." (No planet is involved!)

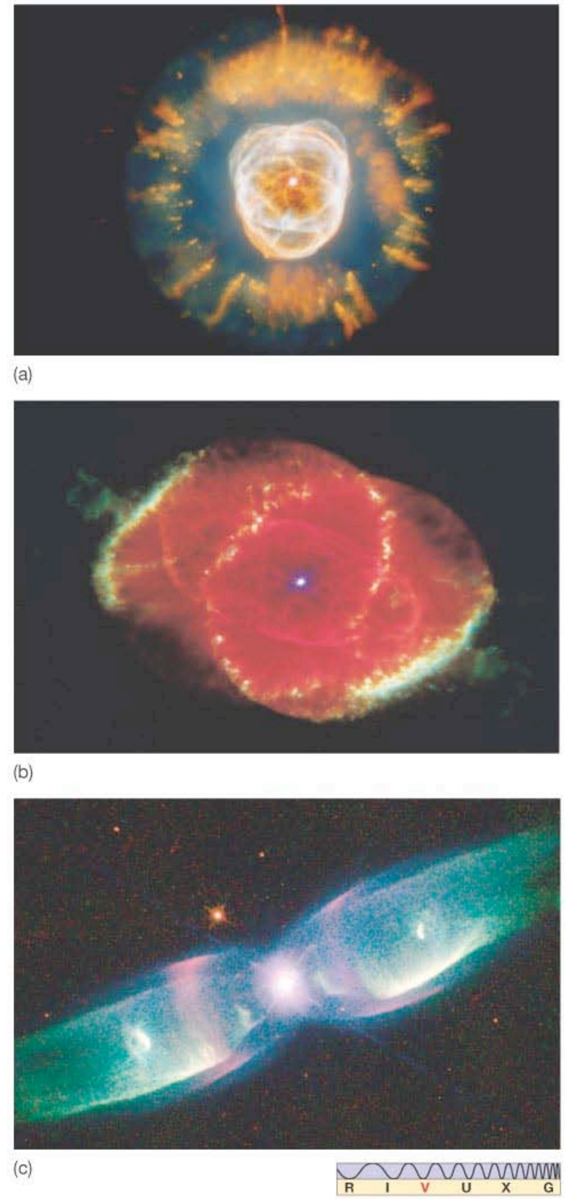
20.3 The Death of a Low-Mass Star

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.

Planetary nebulae can have many shapes:



(a) (b) (c)

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

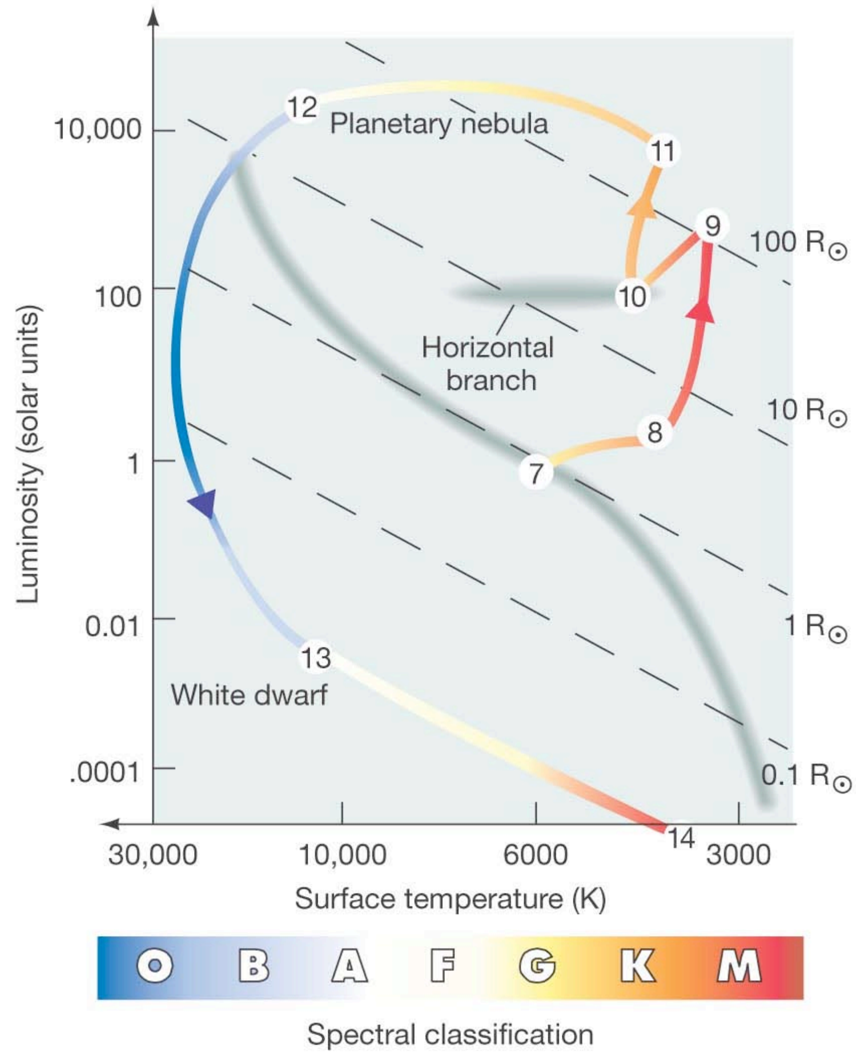
20.3 The Death of a Low-Mass Star

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.

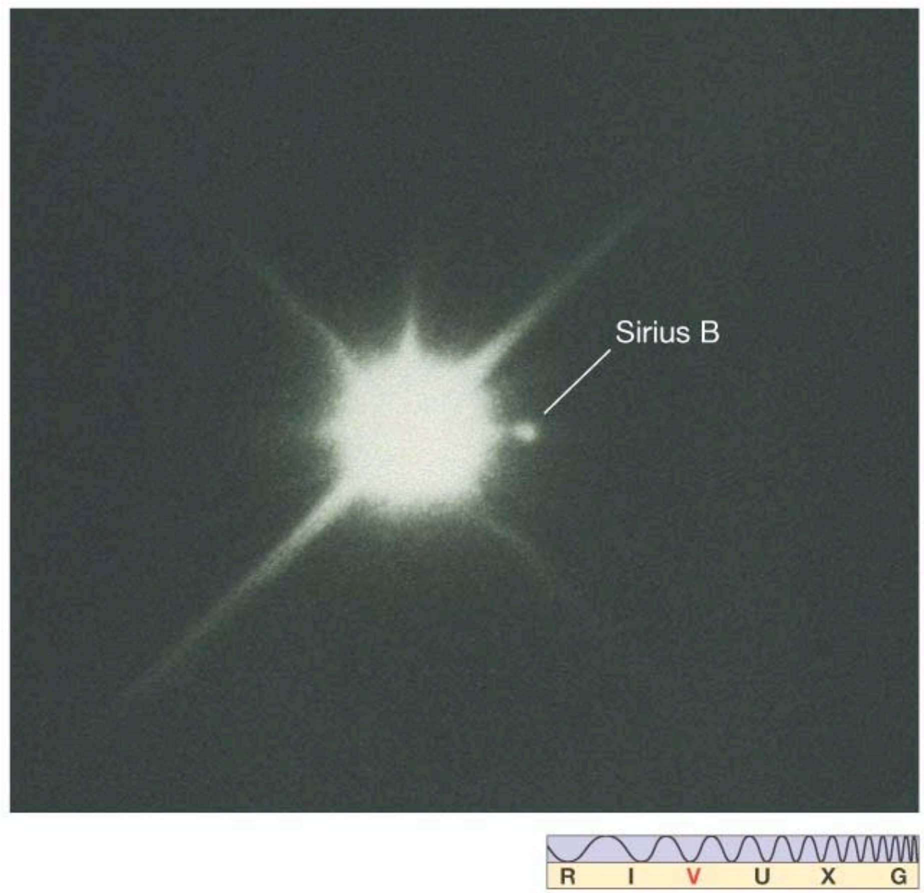
When observed, this remnant cores is called a "white dwarf."

It is **luminous** only due to its high temperature. It will spend the rest of its life radiating away its internal supply of heat, gradually fading into invisibility.



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:

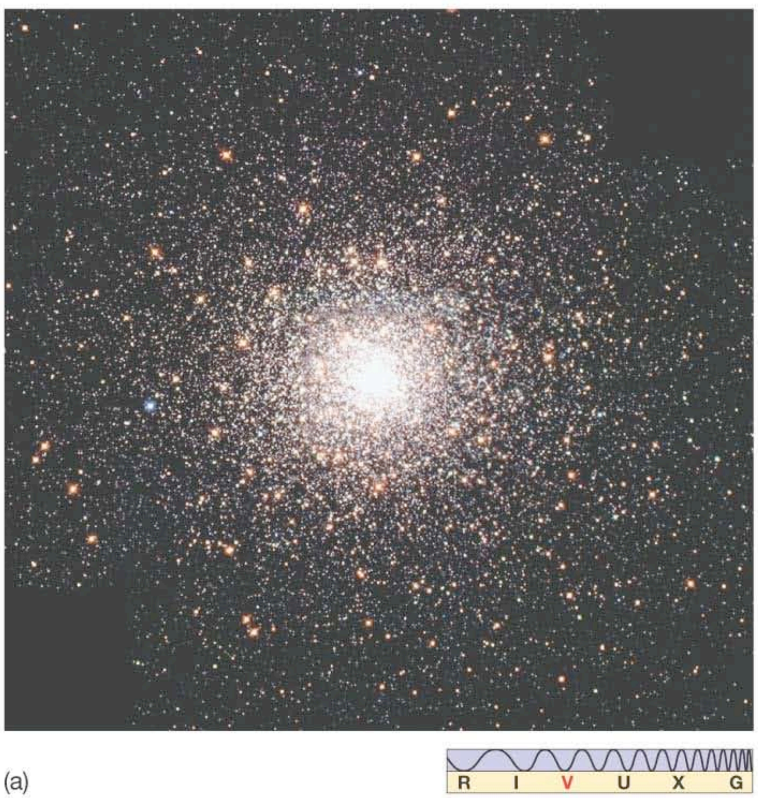


As the **white dwarf** cools, its size does not change significantly; it simply gets **dimmer** and dimmer, and finally ceases to glow.

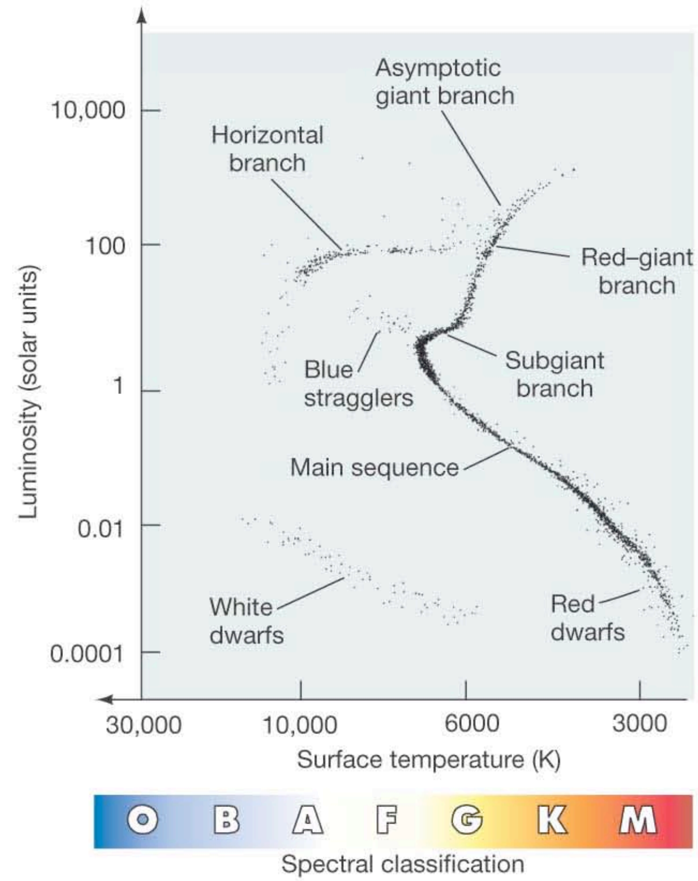
20.3 The Death of a Low-Mass Star

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

The "**blue stragglers**" in this 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.



(a)



(b)

Next we move on to the evolution of more massive stars, whose lives are quite a bit different, especially near the end…