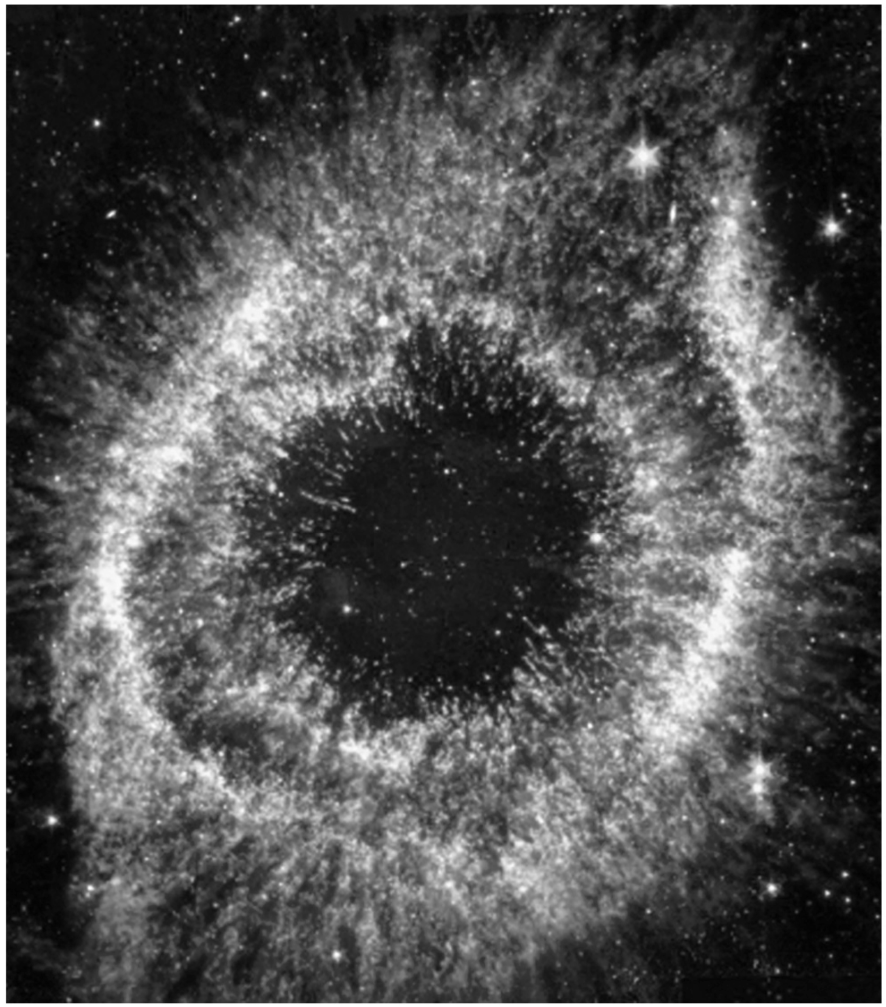
Chapter 12
Stellar Evolution



Units of Chapter 12

Leaving the Main Sequence

Evolution of a Sun-like Star

The Death of a Low-Mass Star

Evolution of Stars More Massive than the Sun

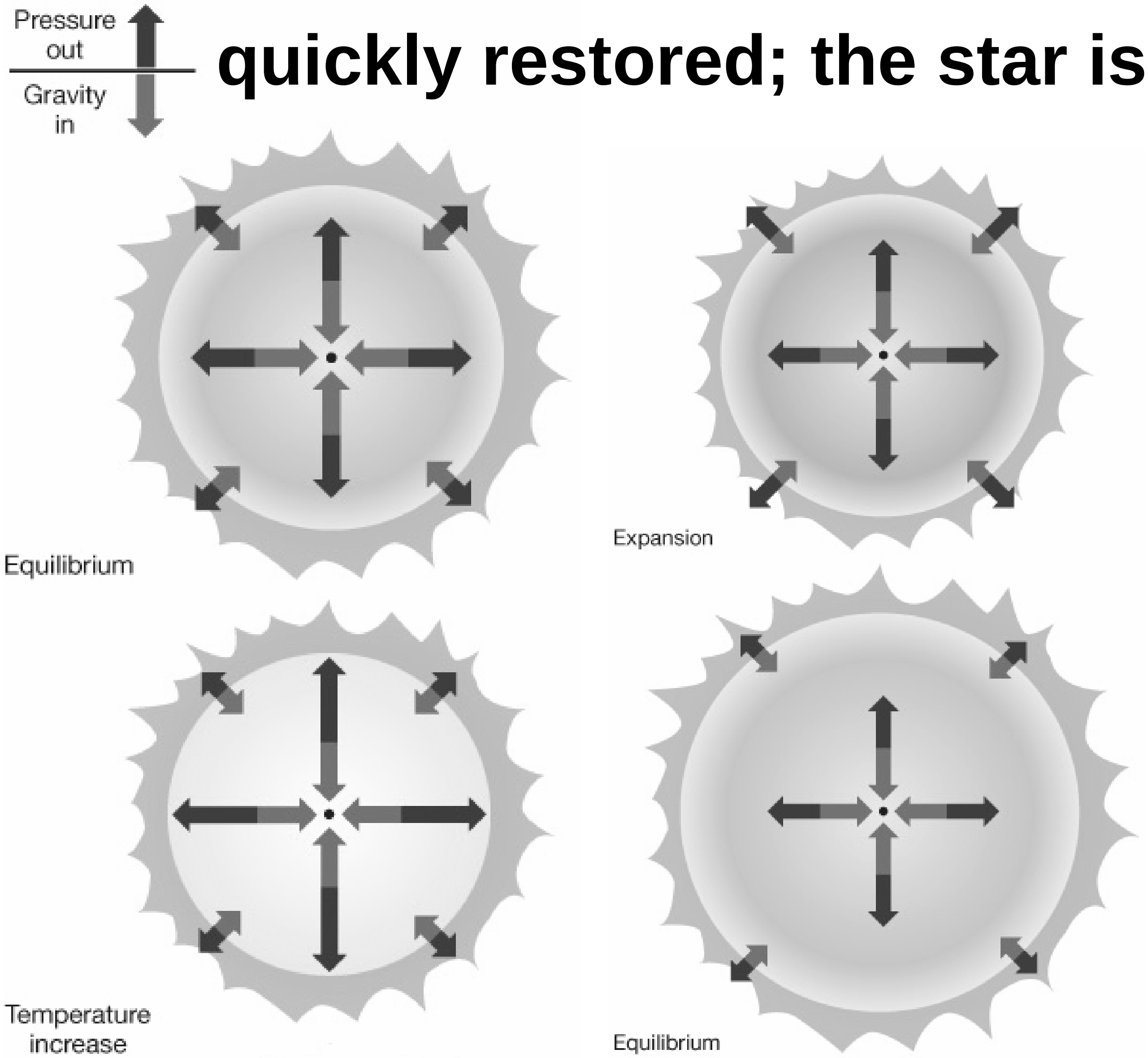
Supernova Explosions

Observing Stellar Evolution in Star Clusters

The Cycle of Stellar Evolution

12.1 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:



12.1 Leaving the Main Sequence

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

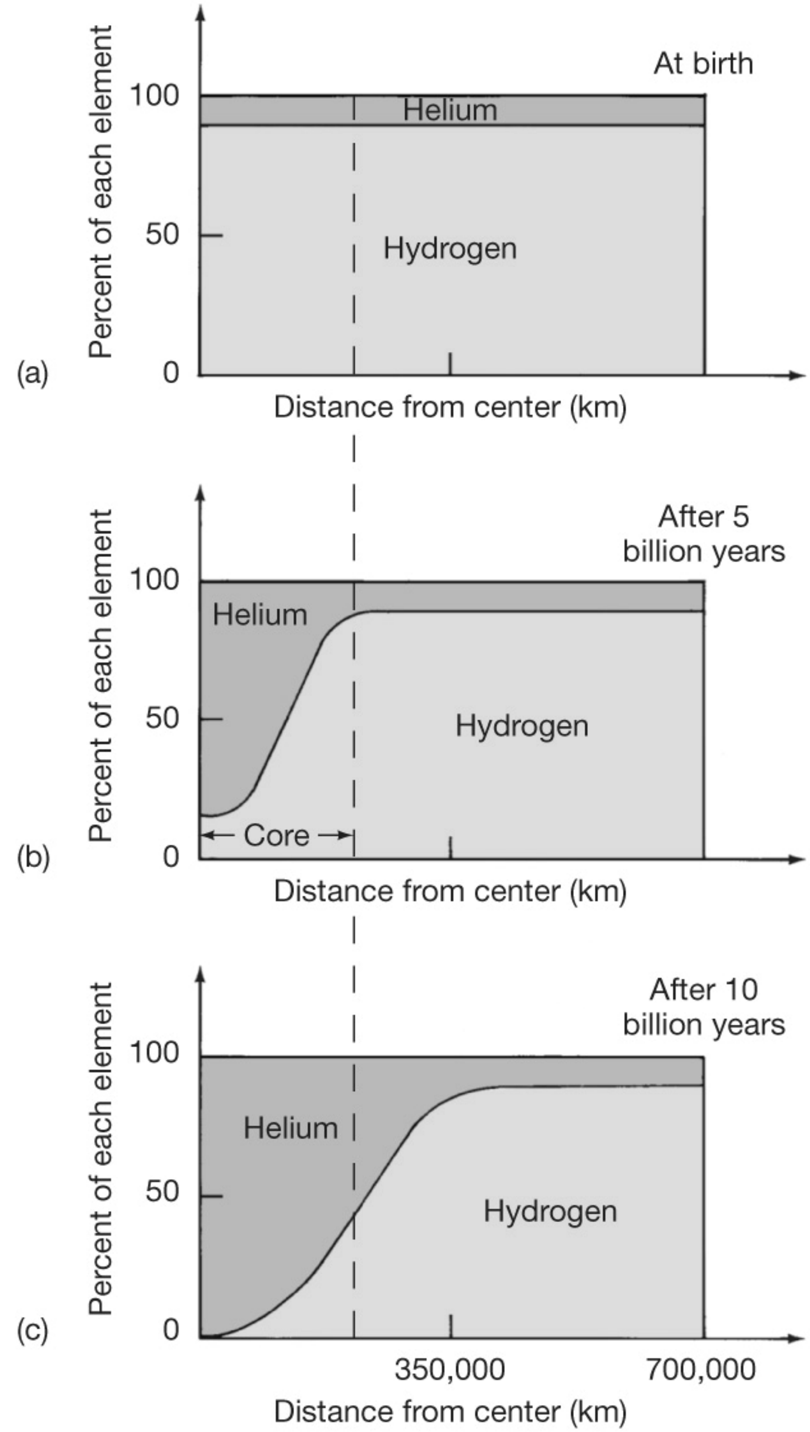
Its evolution from then on depends very much on the mass of the star:

Low-mass stars go quietly

High-mass stars go out with a bang!

12.2 Evolution of a Sun-like Star

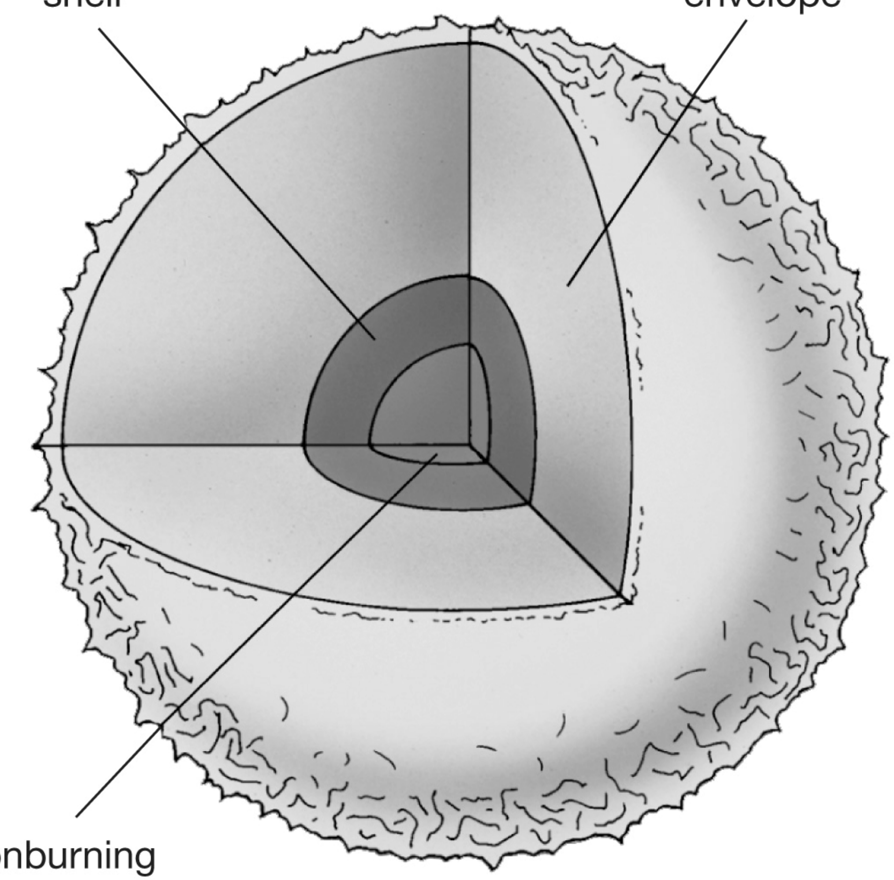
Even while on the Main Sequence, the composition of a star's core is changing:



12.2 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:



12.2 Evolution of a Sun-like Star

Stages of a star leaving the Main Sequence:

TABLE 12.1 Evolution of a Sun-like Star

STAGE	APPROX. TIME TO NEXT STAGE (yr)	CENTRAL TEMPERATURE (K)	SURFACE TEMPERATURE (K)	CENTRAL DENSITY (kg/m^3)	RADIUS (km)	RADIUS (solar radii)	OBJECT
7	10^{10}	1.5×10^7	6,000	10^5	7×10^5	1	Main-sequence star
8	10^8	5×10^7	4,000	10^7	2×10^6	3	Subgiant
9	10^5	10^8	4,000	10^8	7×10^7	100	Red giant/Helium flash
10	5×10^7	2×10^8	5,000	10^7	7×10^6	10	Horizontal branch
11	10^4	2.5×10^8	4,000	10^8	4×10^8	500	Red giant (AGB)
	10^5	3×10^8	100,000	10^{10}	10^4	0.01	Carbon core
12	—	—	3,000	10^{-17}	7×10^8	1,000	Planetary nebula*
13	—	10^8	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 in columns 2–7 refer to the envelope.

12.2 Evolution of a Sun-like Star

Stage 9: The Red-Giant Branch

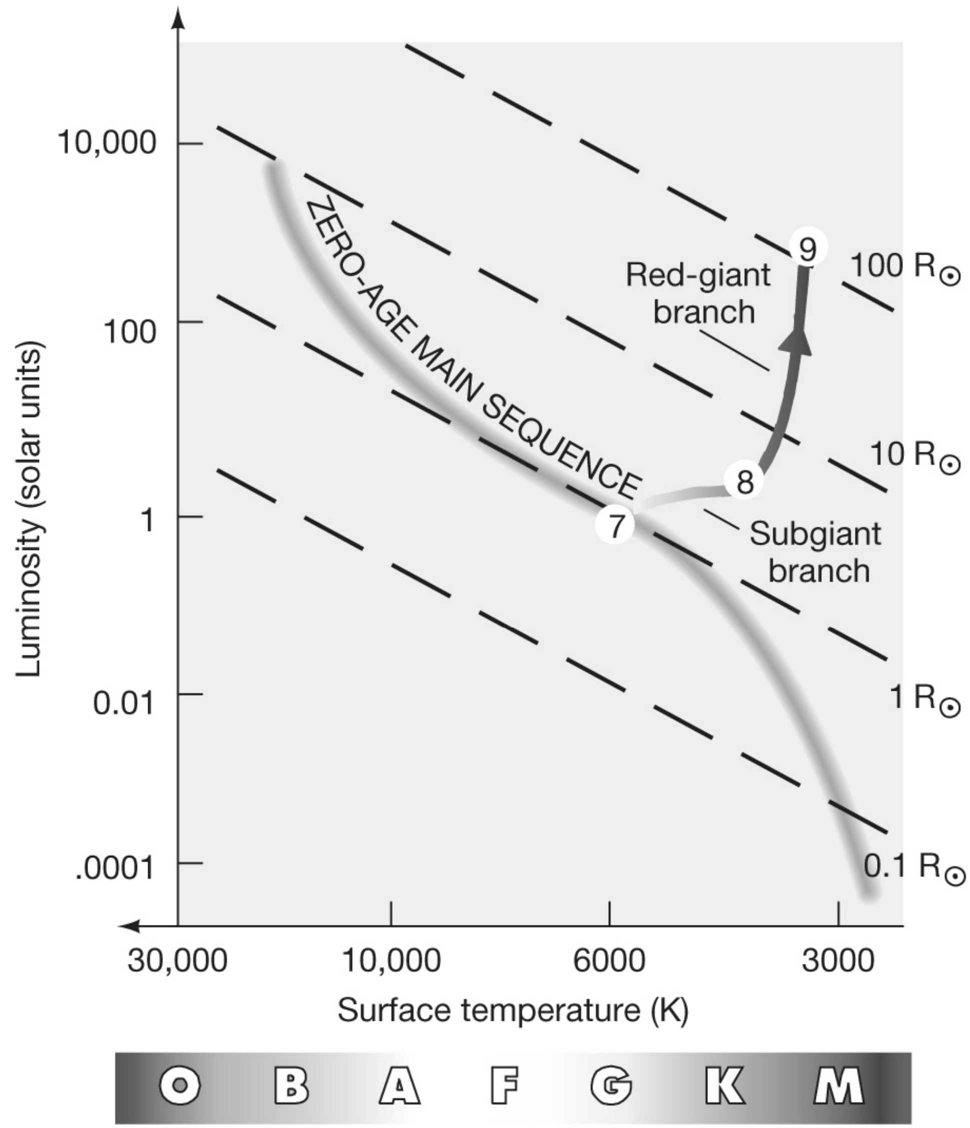
As the core continues to shrink, the outer layers of the star expand and cool.

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.

12.2 Evolution of a Sun-like Star

The red giant stage on the H-R diagram:



12.2 Evolution of a Sun-like Star

Stage 10: Helium fusion

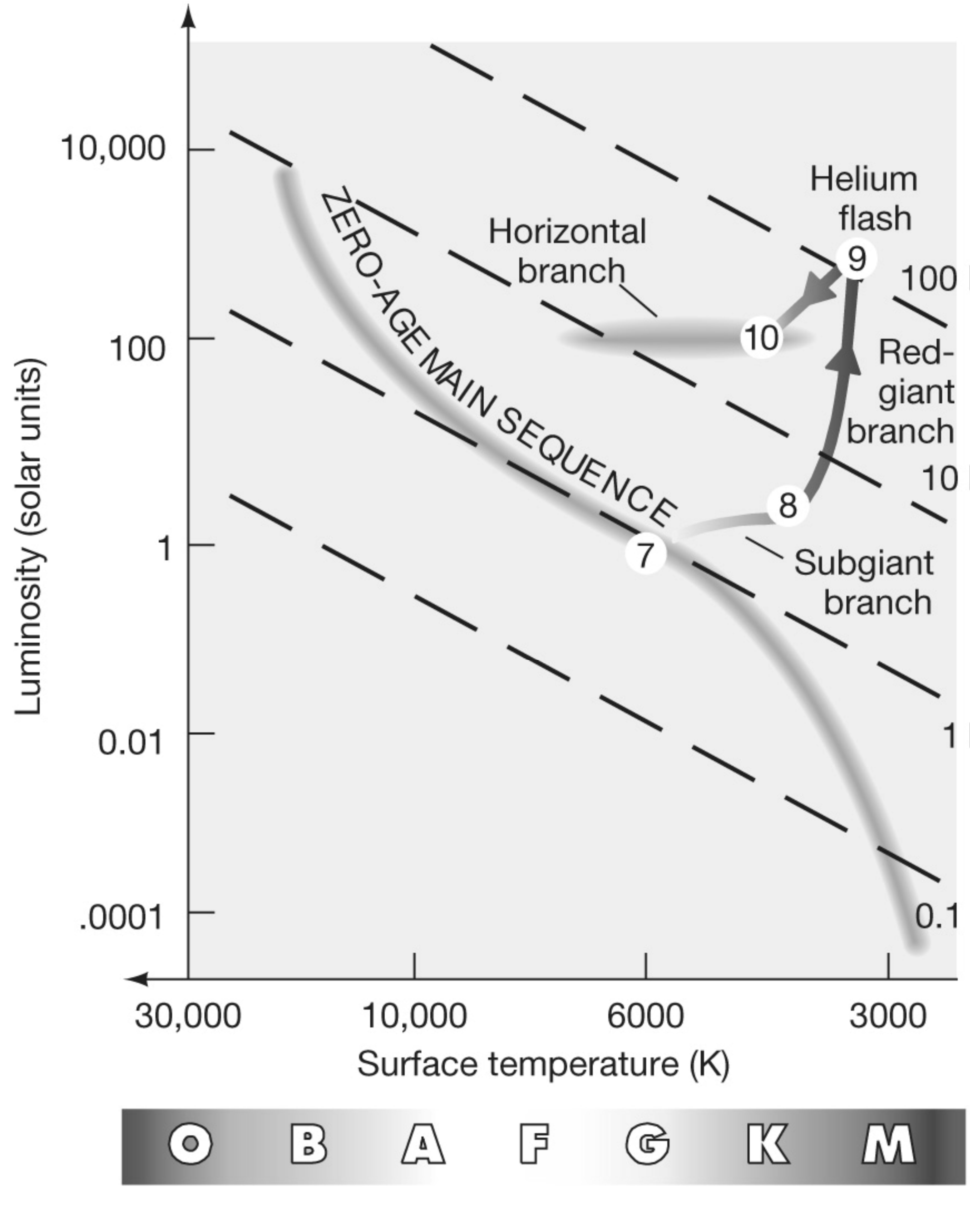
Once the core temperature has risen to 100,000,000 K, the helium in the core starts to fuse.

The helium flash:

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

12.2 Evolution of a Sun-like Star

Stage 10 on the H-R diagram:

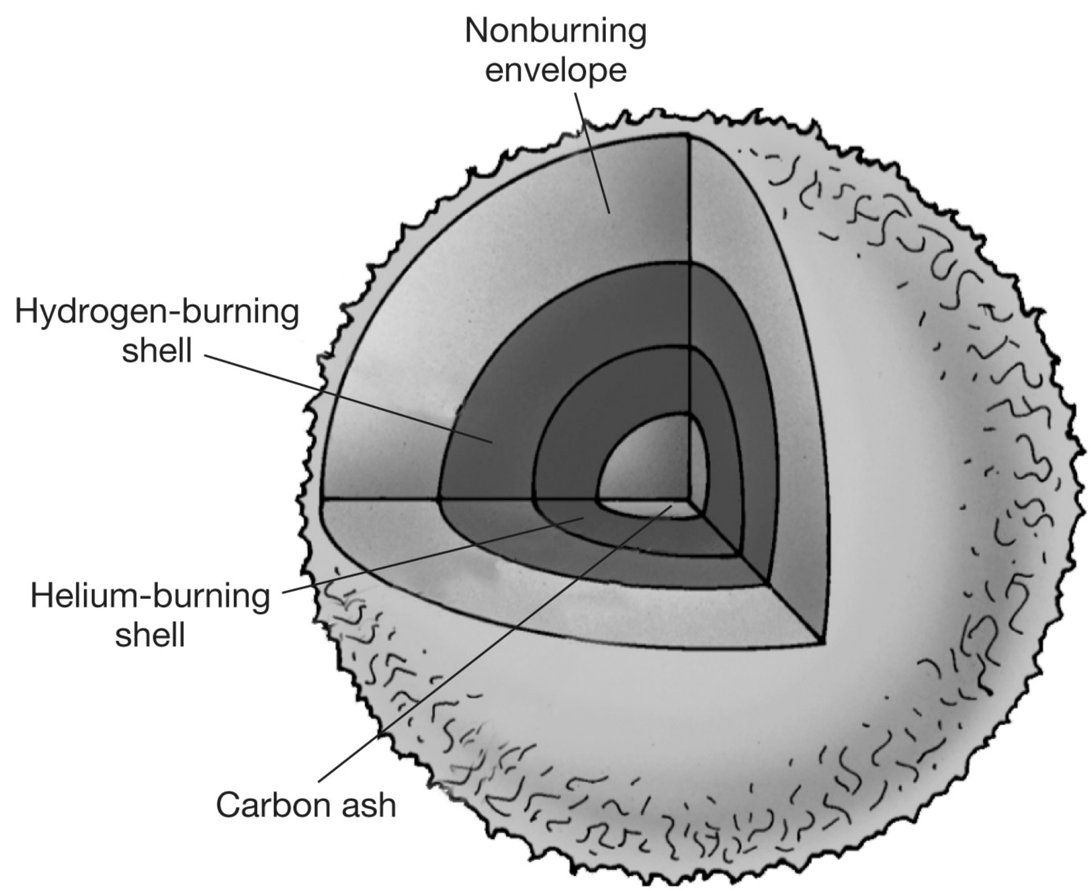


12.2 Evolution of a Sun-like Star

Stage 11: Back to the giant branch

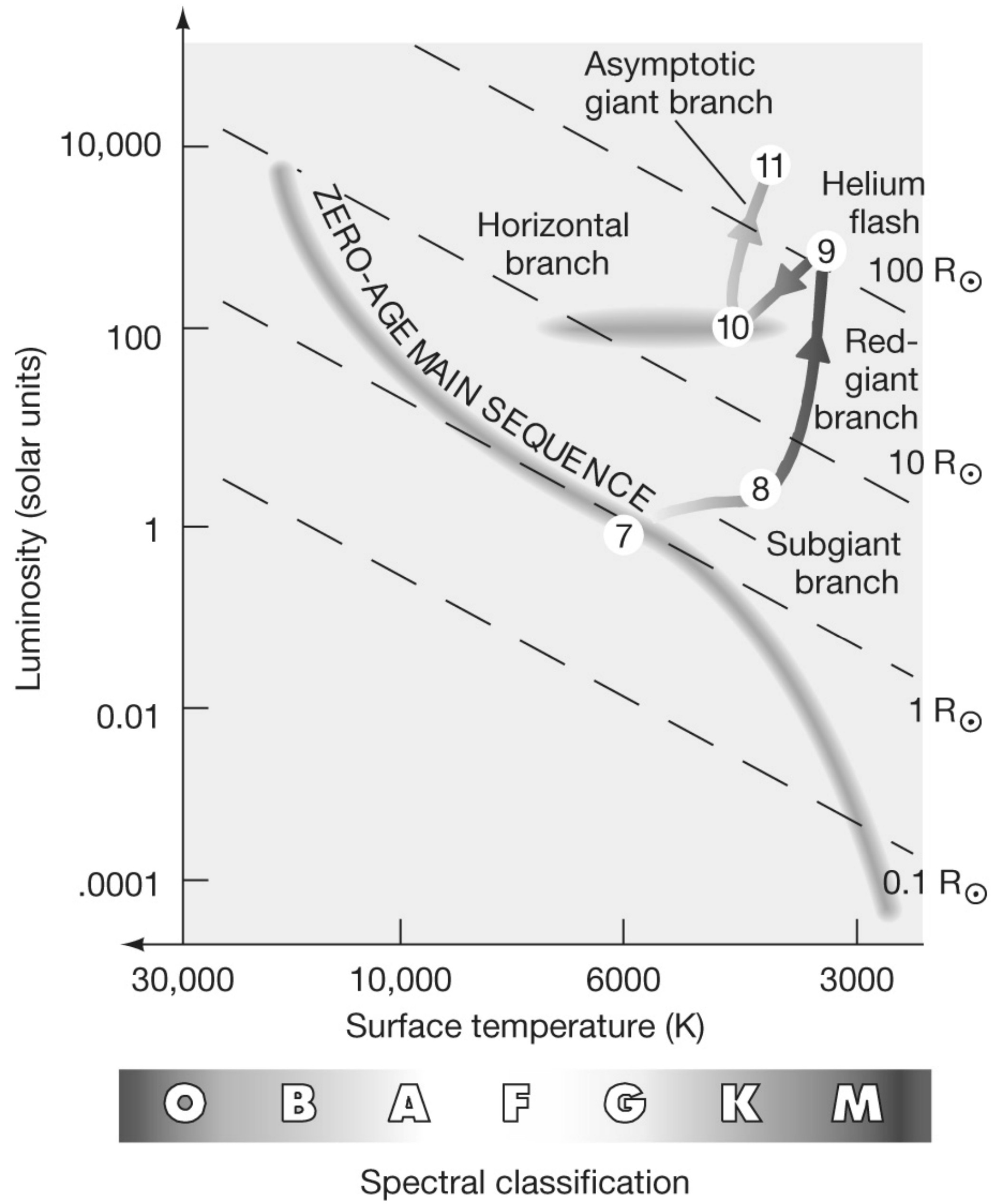
As the helium in the core fuses to carbon, the core becomes hotter and hotter, and the helium burns faster and faster.

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



12.2 Evolution of a Sun-like Star

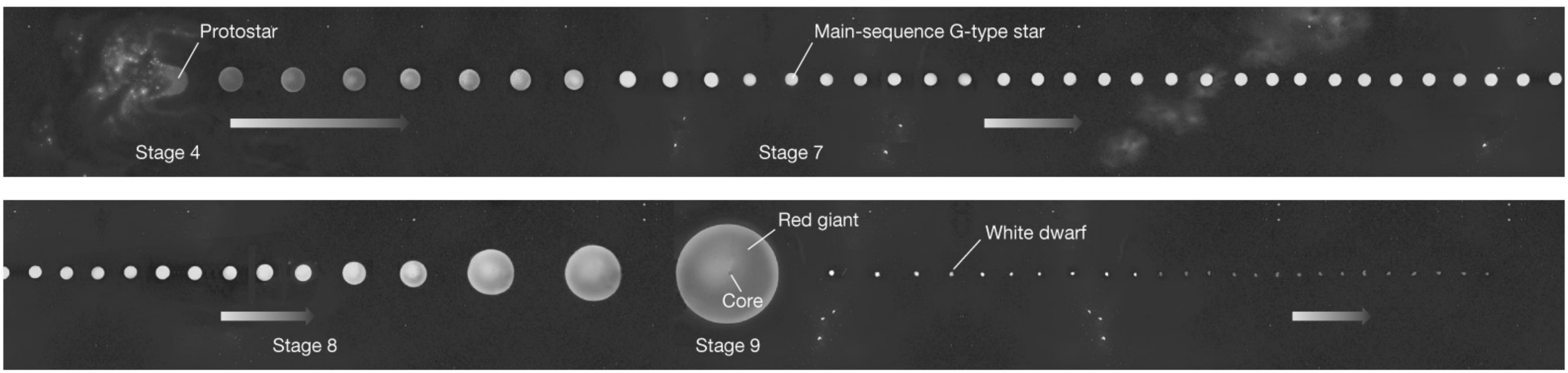
The star has become a red giant for the second time:



12.3 The Death of a Low-Mass Star

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

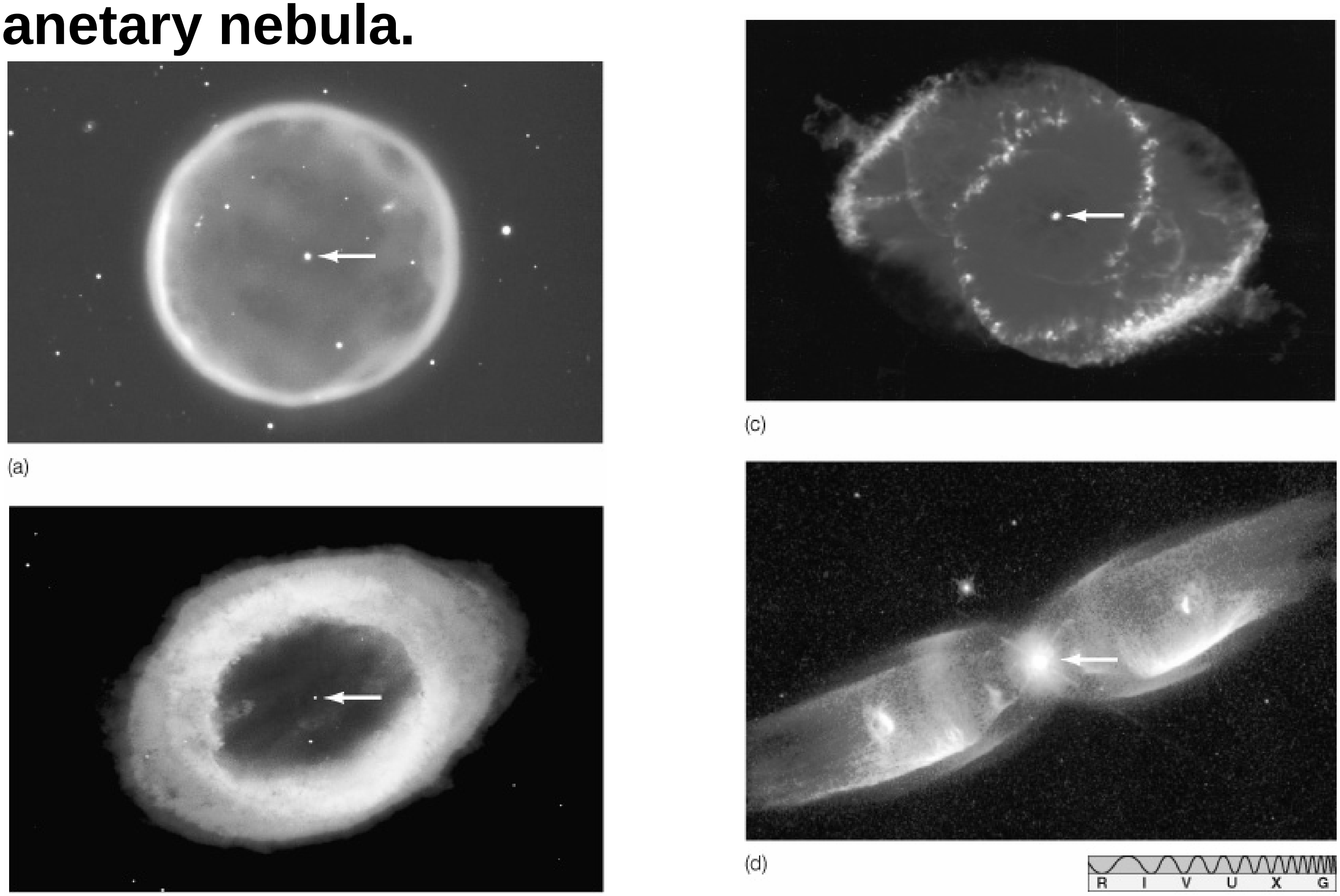
Such stars never become hot enough for fusion past carbon to take place.



12.3 The Death of a Low-Mass Star

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

Meanwhile, the outer layers of the star expand to form a planetary nebula.



12.3 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.**

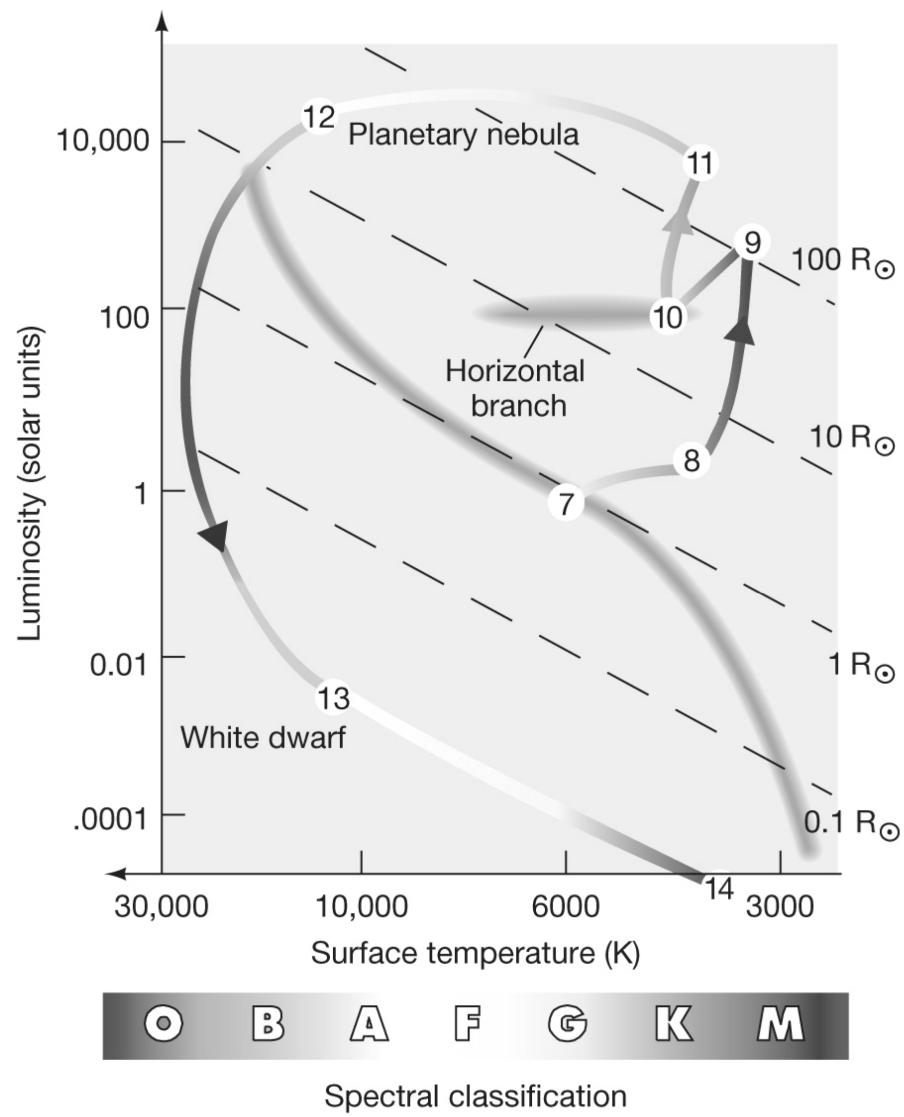
The envelope is called a planetary nebula, even though it has nothing to do with planets – early astronomers viewing the fuzzy envelope thought it resembled a planetary system.

12.3 The Death of a Low-Mass Star

Stages 13 and 14: White and black dwarfs

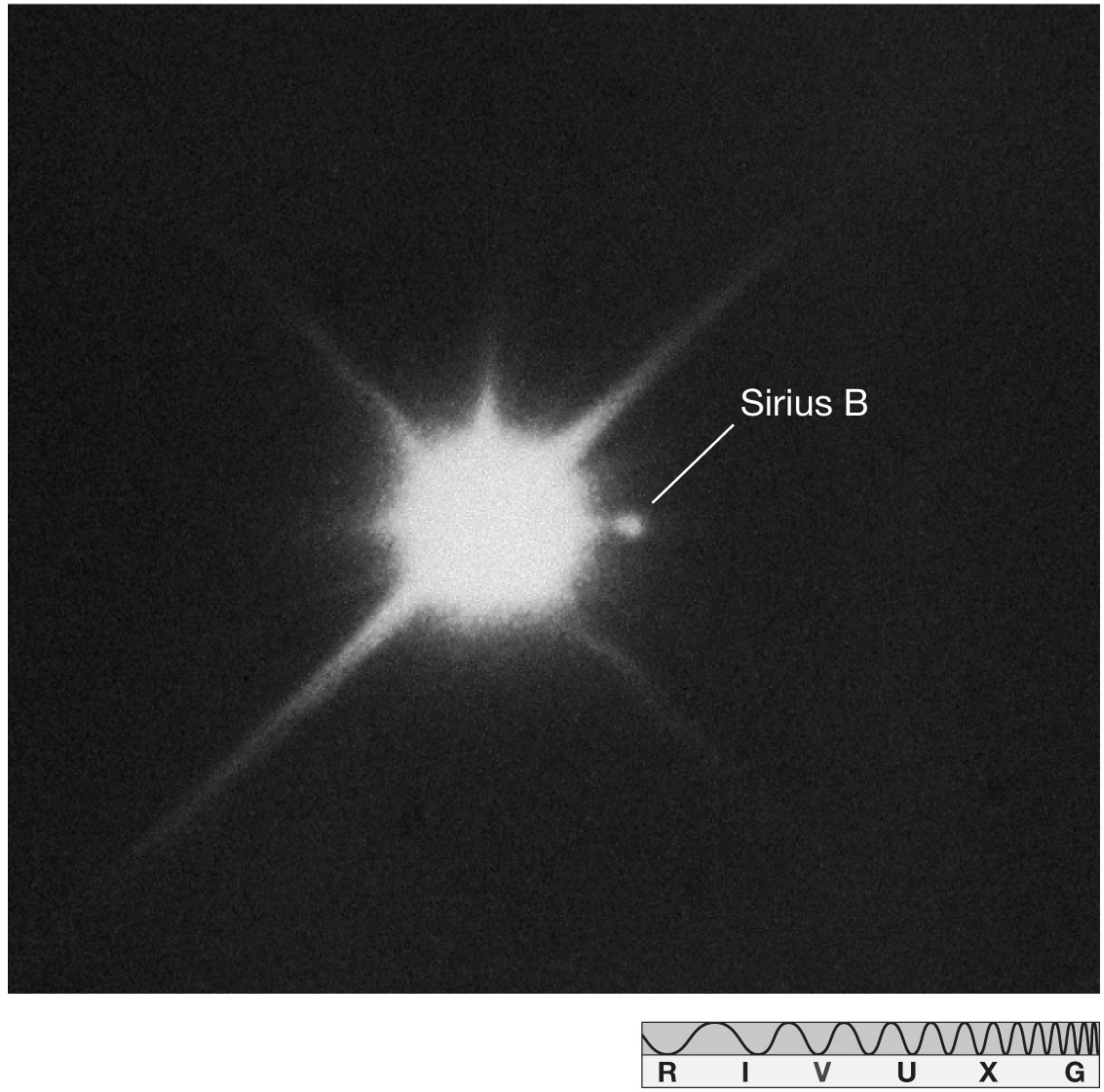
Once the nebula has gone, the remaining core is extremely dense and extremely hot, but quite small.

It is luminous only due to its high temperature.



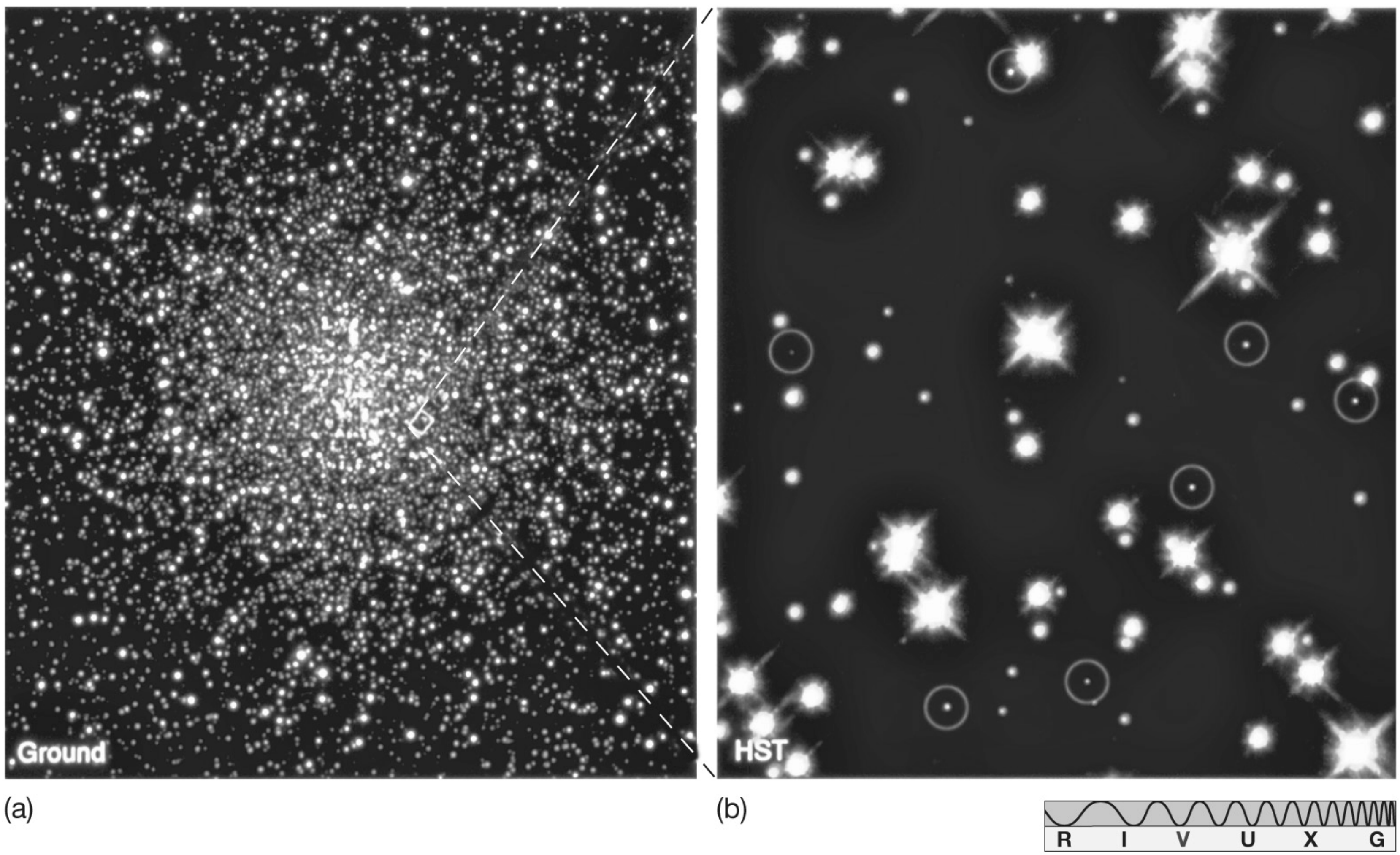
12.3 The Death of a Low-Mass Star

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



12.3 The Death of a Low-Mass Star

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

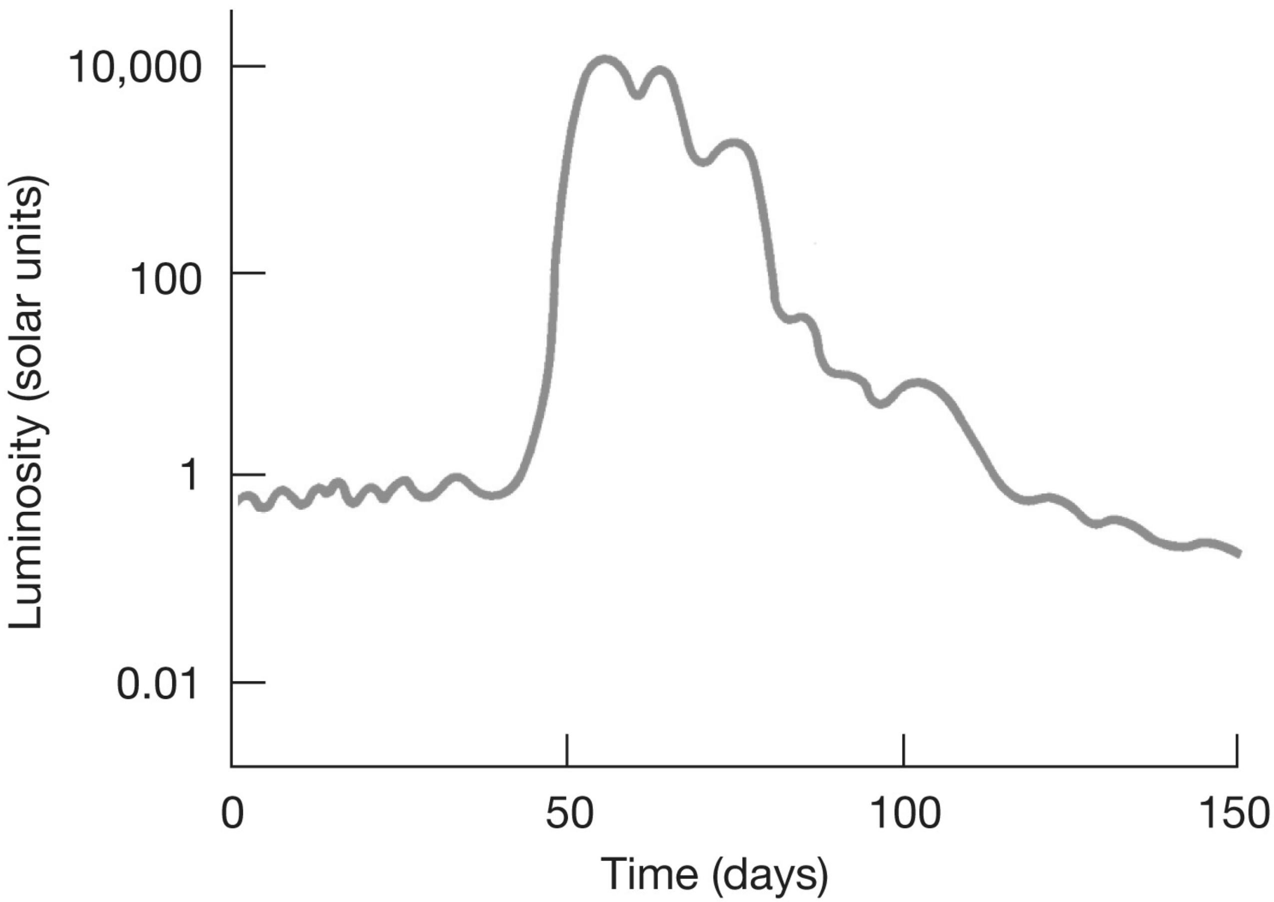


12.3 The Death of a Low-Mass Star

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

12.3 The Death of a Low-Mass Star

A nova is a star that flares up very suddenly and then returns slowly to its former luminosity:



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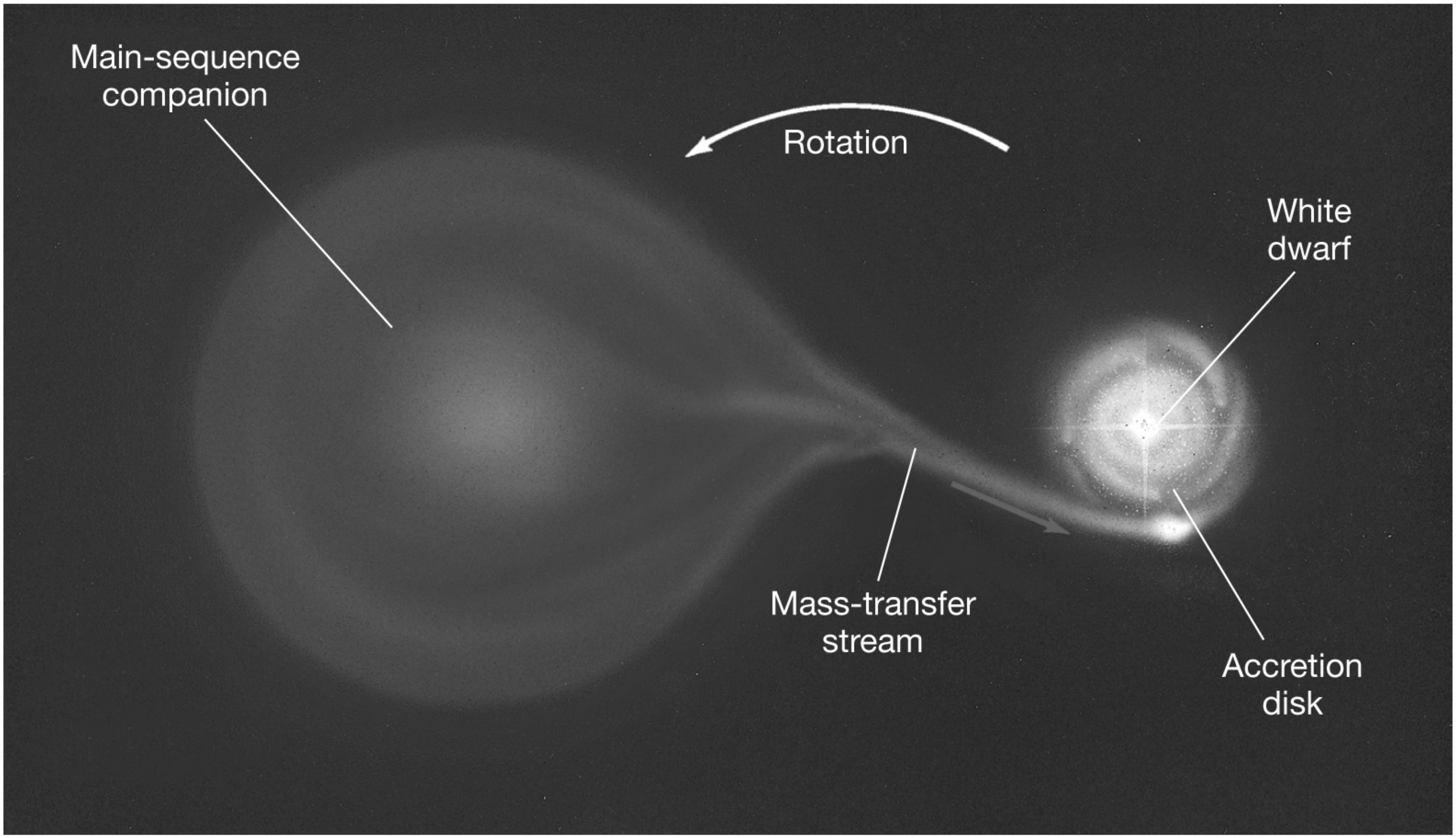
12.3 The Death of a Low-Mass Star

A white dwarf that is part of a semidetached binary system can undergo repeated novas:



12.3 The Death of a Low-Mass Star

Material falls onto the white dwarf from its main-sequence companion.

When enough material has accreted, fusion can reignite very suddenly, burning off the new material.

Material keeps being transferred to the white dwarf, and the process repeats.