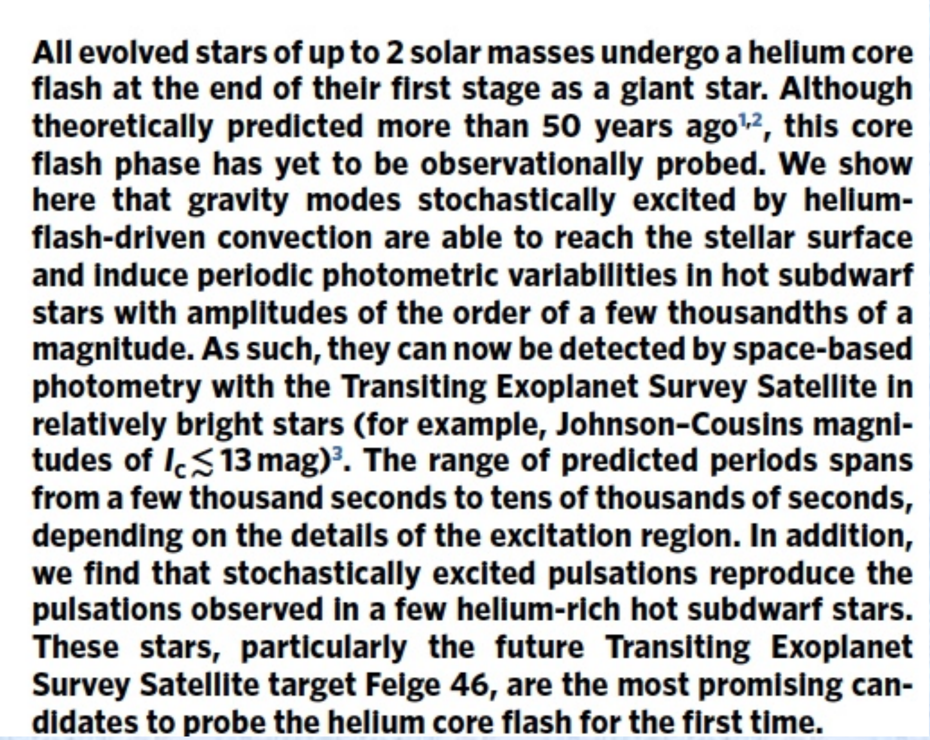
Astronomy 1 – Fall 2019

Asteroseismic signatures of the helium core flash

M. M. Miller Bertolami[1,2*], T. Battich[1,2], A. H. Córsico[1,2], J. Christensen-Dalsgaard[3,4] and L. G. Althaus[1,2]



All evolved stars of up to 2 solar masses undergo a helium core flash at the end of their first stage as a giant star. Although theoretically predicted more than 50 years ago[1,2], this core flash phase has yet to be observationally probed. We show here that gravity modes stochastically excited by helium-flash-driven convection are able to reach the stellar surface and induce periodic photometric variabilities in hot subdwarf stars with amplitudes of the order of a few thousandths of a magnitude. As such, they can now be detected by space-based photometry with the Transiting Exoplanet Survey Satellite in relatively bright stars (for example, Johnson–Cousins magnitudes of $I_C \lesssim 13$ mag)[3]. The range of predicted periods spans from a few thousand seconds to tens of thousands of seconds, depending on the details of the excitation region. In addition, we find that stochastically excited pulsations reproduce the pulsations observed in a few helium-rich hot subdwarf stars. These stars, particularly the future Transiting Exoplanet Survey Satellite target Feige 46, are the most promising candidates to probe the helium core flash for the first time.

News Flash (2019 September):

Observing a very brief phase of stellar evolution.

He core flash shakes a star, inducing detectable variations in its brightness.

Lecture 11; November 13, 2019

Previously on Astro-1

- The Main-Sequence is a mass sequence
- High mass stars live fast and die young
- Stars form in clouds of cold gas, collapsing under gravitational instability
- Protostars are heated by gravitational collapse and often form disks and jets around them

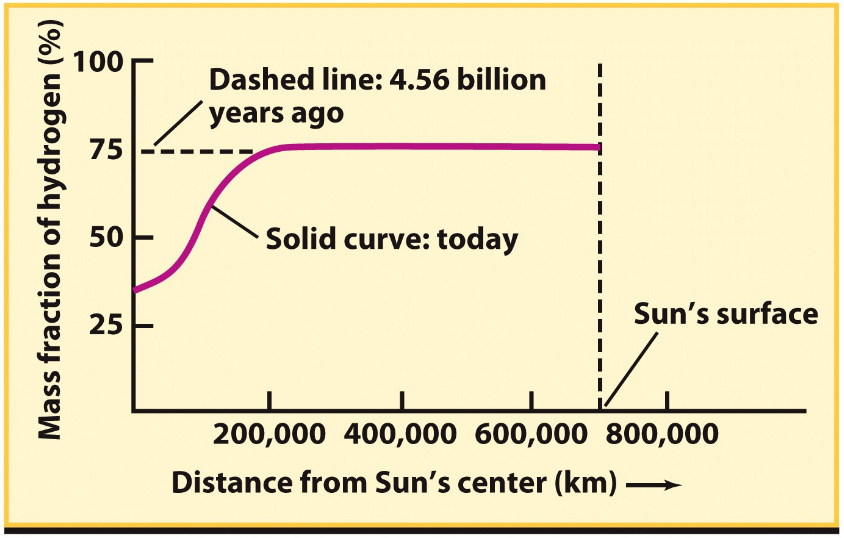
Today on Astro-1

- Stars on the Main Sequence burn H in their core
- After the Main Sequence
- How one finds the age of a star cluster
- How one finds the distance to a pulsating star
- Mass transfer between stars

Why Do Stars Evolve?

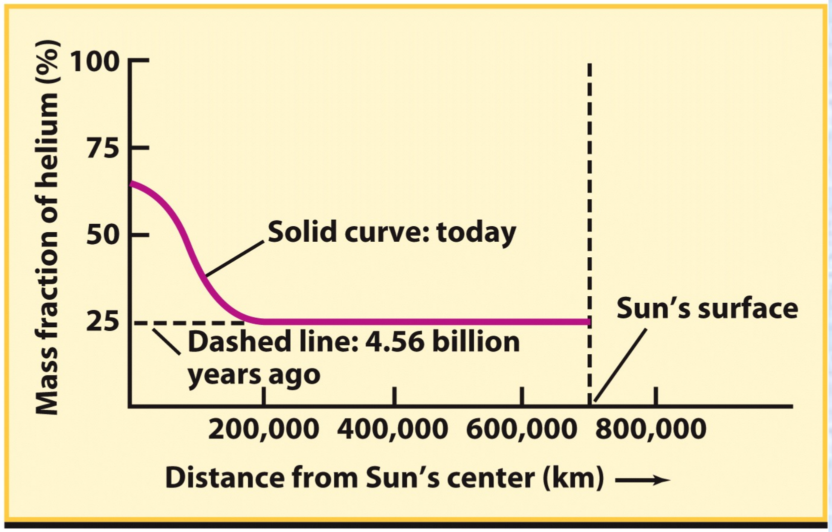
1. On the Main Sequence

- The conversion of 4 H into ^{4}He reduces the number of particles bouncing around to provide pressure.
- The core must contract.



Hydrogen in the Sun's interior

Figure 19-1a
Universe, Tenth Edition
© 2014 W. H. Freeman and Company



Helium in the Sun's interior

Figure 19-1b
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

As a star ages,
it continually tries
to establish
a new equilibrium…

Luminosity and radius
both change

Moral:

when a star’s core contracts,
- the star’s luminosity increases
- the star’s outer layers expand and cool

Conversely,

when a star’s core expands,
- the star’s luminosity decreases
- the star’s outer layers contract and heat up

What is happening in the Sun's core?

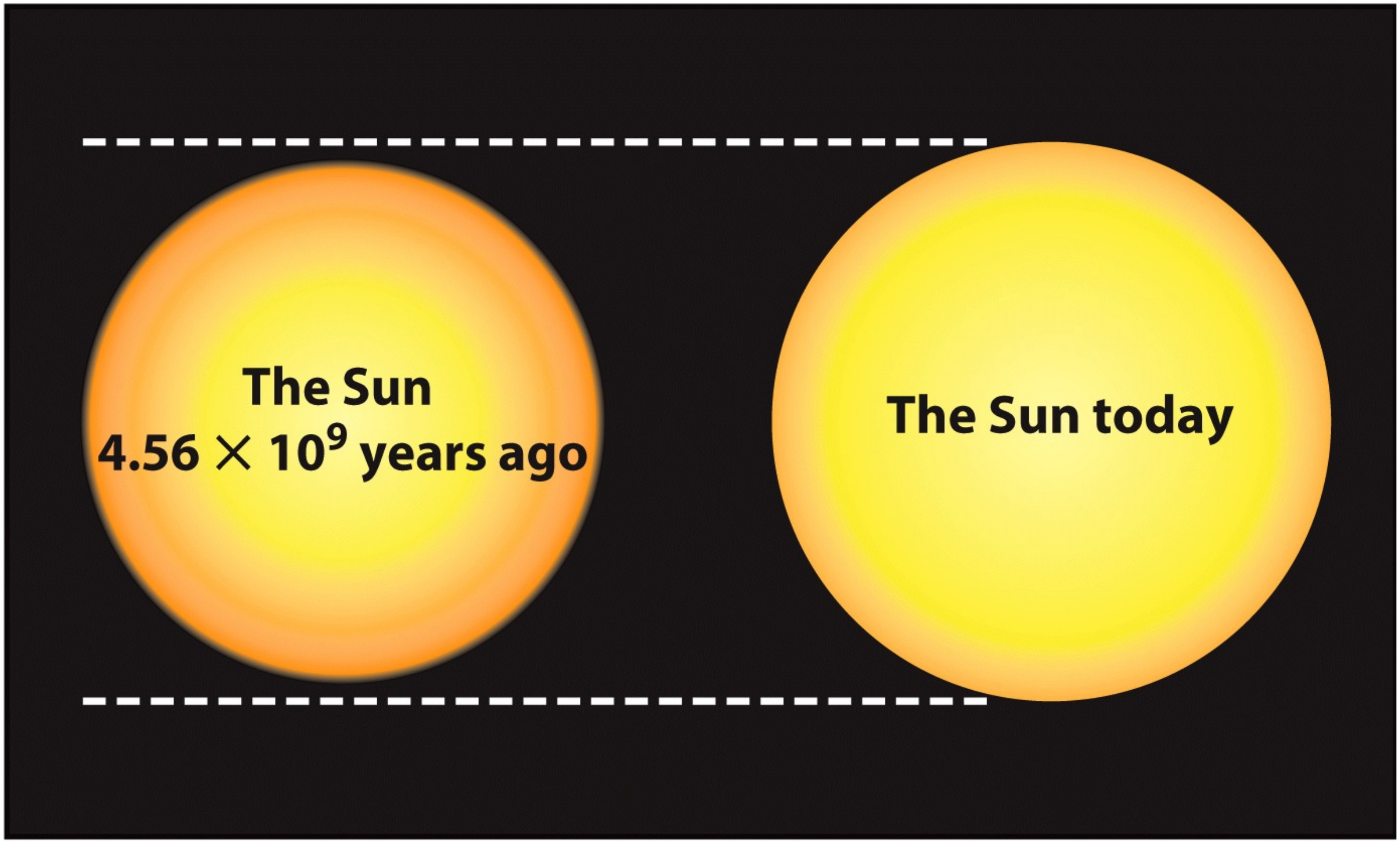


Figure 19-2
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

All Main Sequence Stars Burn H in their Core

- We learned that the Sun converts hydrogen to helium via the proton-proton chain.
- There is another chain of reactions which also converts hydrogen to helium. We call it the CNO cycle.
- The CNO cycle is the primary source of energy generation in main sequence stars more massive than about 1.5 solar masses.

Why Do Stars Evolve?

2. After the Main Sequence

- They consumed all their hydrogen fuel.

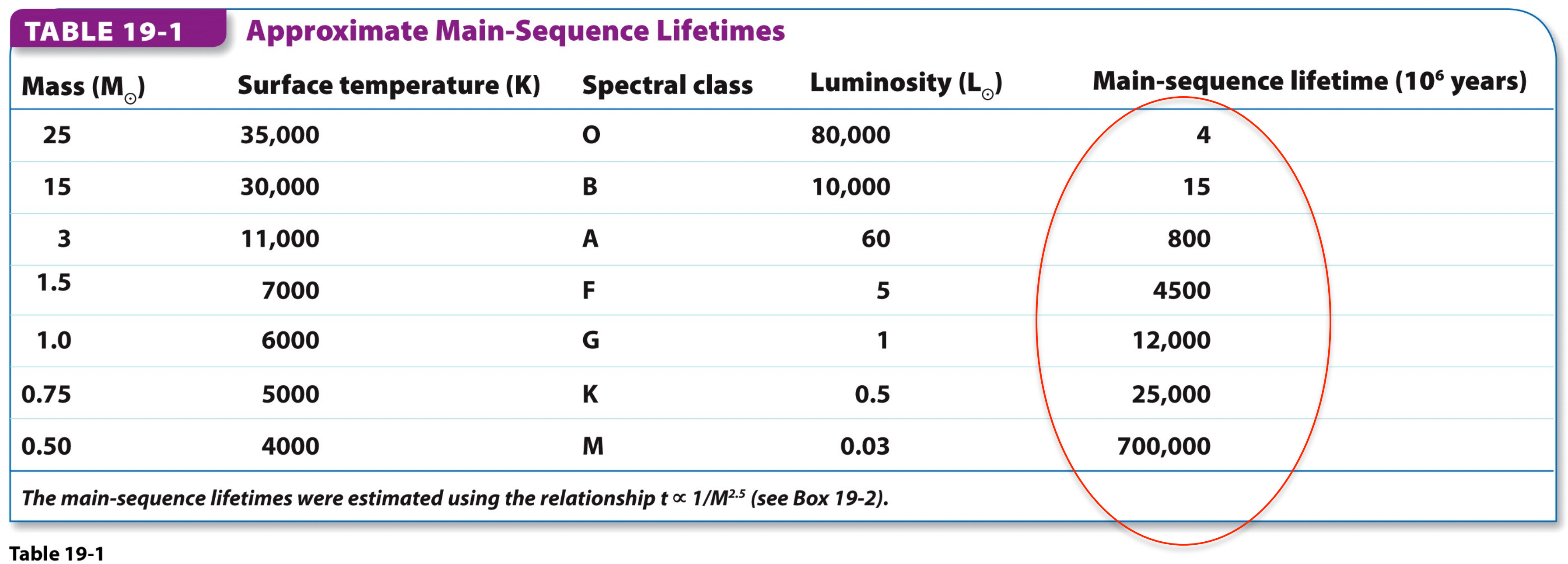


TABLE 19-1 Approximate Main-Sequence Lifetimes

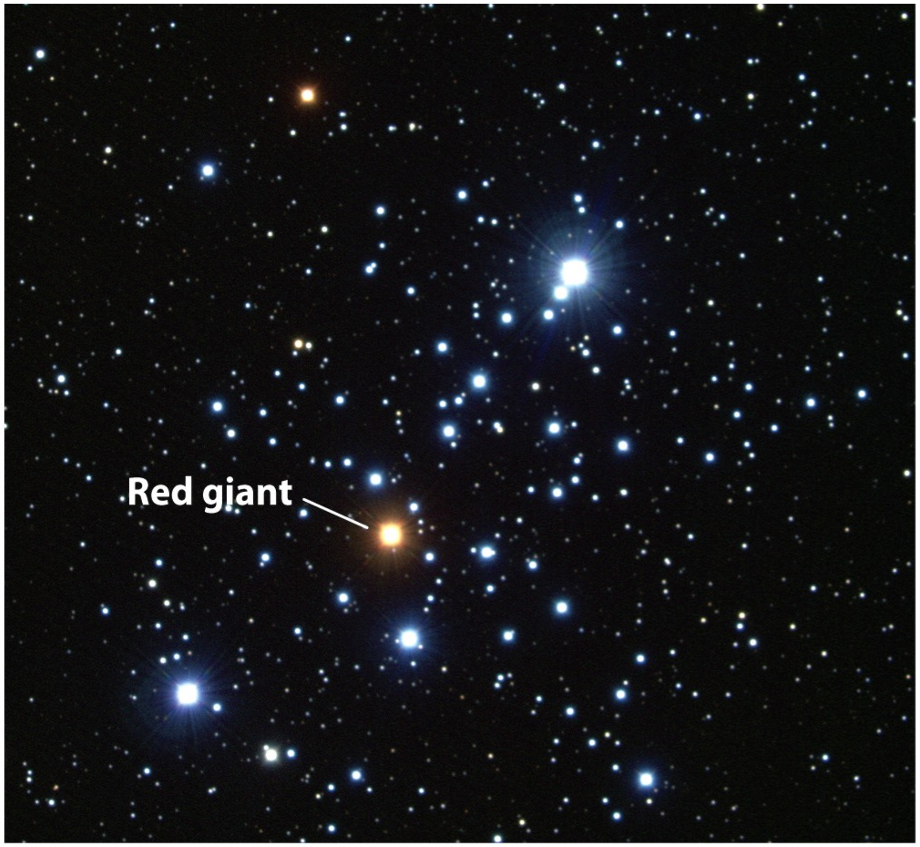
Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetime (10^6 years)
25	35,000	O	80,000	4
15	30,000	B	10,000	15
3	11,000	A	60	800
1.5	7000	F	5	4500
1.0	6000	G	1	12,000
0.75	5000	K	0.5	25,000
0.50	4000	M	0.03	700,000

The main-sequence lifetimes were estimated using the relationship $t \propto 1/M^{2.5}$ (see Box 19-2).

Table 19-1
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

Red Giants

Red Giants Burn H in a Shell

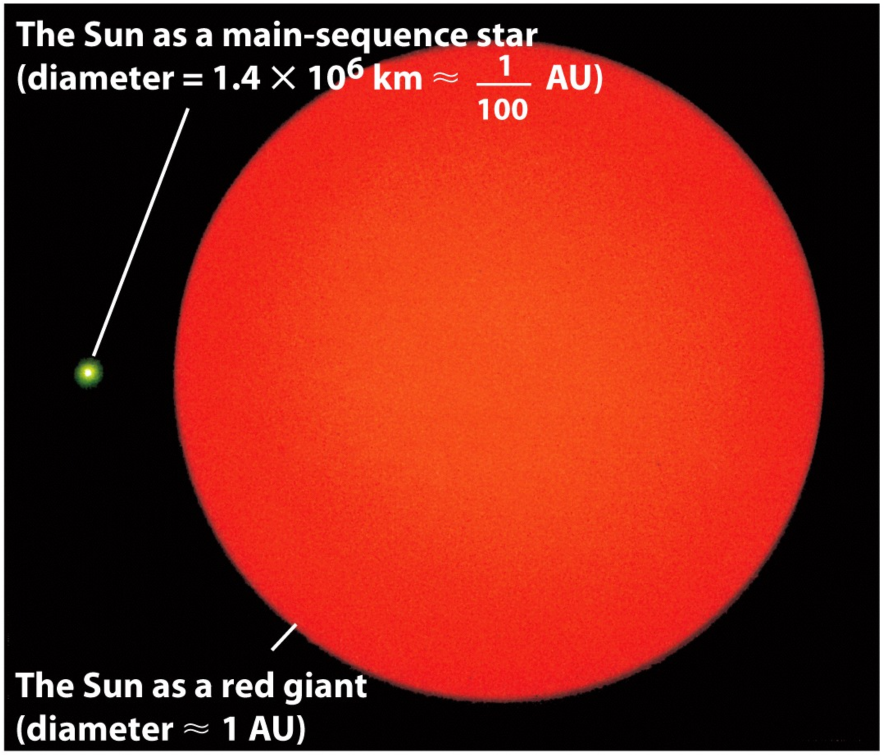


A red giant star in the star cluster M103

Figure 19-4b
Universe, Tenth Edition
NOAO/Science Source

- Core starts to cool when fusion ceases.
- Heat flows outward from the contraction.
- Fusion ignites in a shell around the He core.

The Sun will grow by a factor of 100 in radius during shell H burning.



The Sun today and as a red giant

Figure 19-4a
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

- Shell burning adds more He to core.
- Core contracts and heats up as it gains mass.
- The increased core pressure and the shell’s luminosity expand the outer layers.
- The expansion cools the outer layers.

HW6 (11.19.46): Why do red giants lose mass easily?

Stars less than 0.4 M_0 never become red giants.

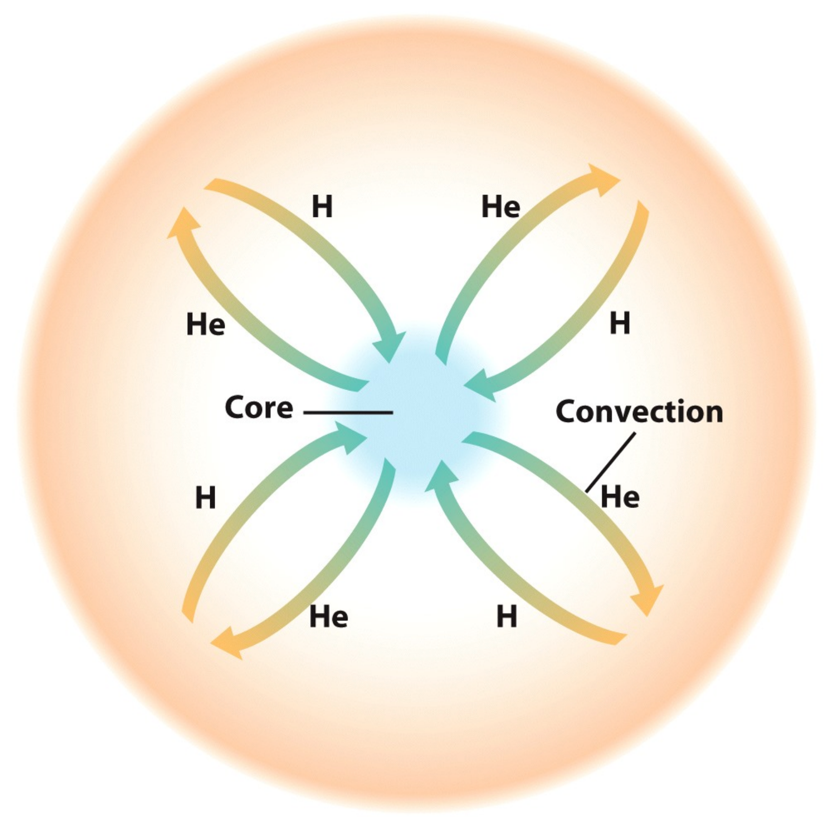


Figure 19-3
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

- Convection brings new fuel to the core.
- Left with a sphere of Helium after more than 700 Gyr.
- Red dwarfs

When the Sun Becomes a Red Giant

… in about 4 x 10^9 years, it will grow bigger and become redder. How does these affect its luminosity?

- $L(\text{now}) = 4\pi R^2(\text{now}) \times \sigma\, T^4(\text{now})$
- $L(\text{RG}) = 4\pi R^2(\text{RG}) \times \sigma\, T^4(\text{RG})$
- $L(\text{RG}) / L(\text{now}) = [R(\text{RG}) / R(\text{now})]^2 \times [T(\text{RG}) / T(\text{now})]^4$
- **$L(\text{RG}) / L(\text{now}) = [100]^2 \times [3800/5800]^4 \approx 2 \times 10^3$**

Outer Planets Could Warm Up

- The higher energy flux will warm up the outer planets.
- At a distance, d, from the Sun, the energy flux becomes

$$F(d) = L / 4\pi d^2.$$

- So the solar flux at Jupiter will be 2000 times higher than it is today.
- The outer planets will heat up.

Models Predict the Habitable Zone Shifts Outward

- And gradually reaches 10-50 AU as the Sun grows brighter

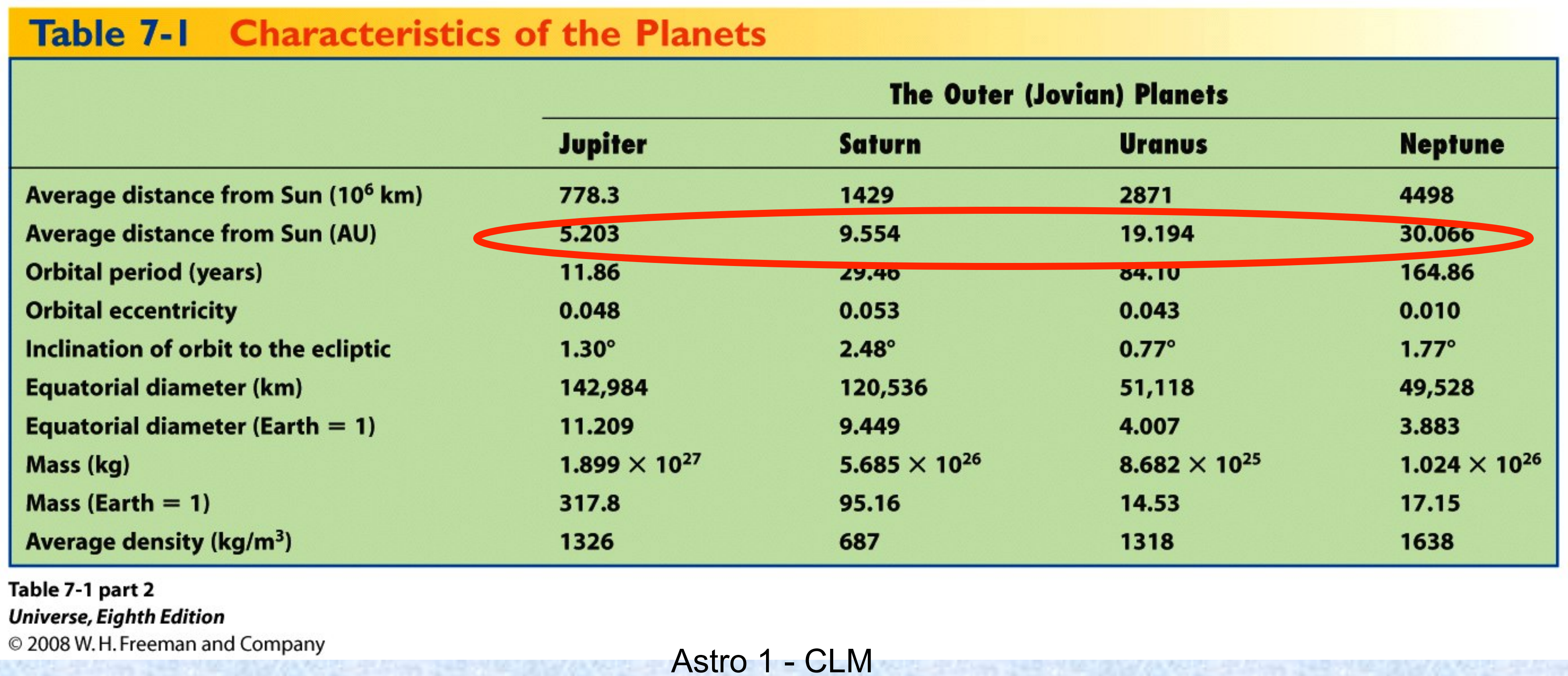


Table 7-1 Characteristics of the Planets

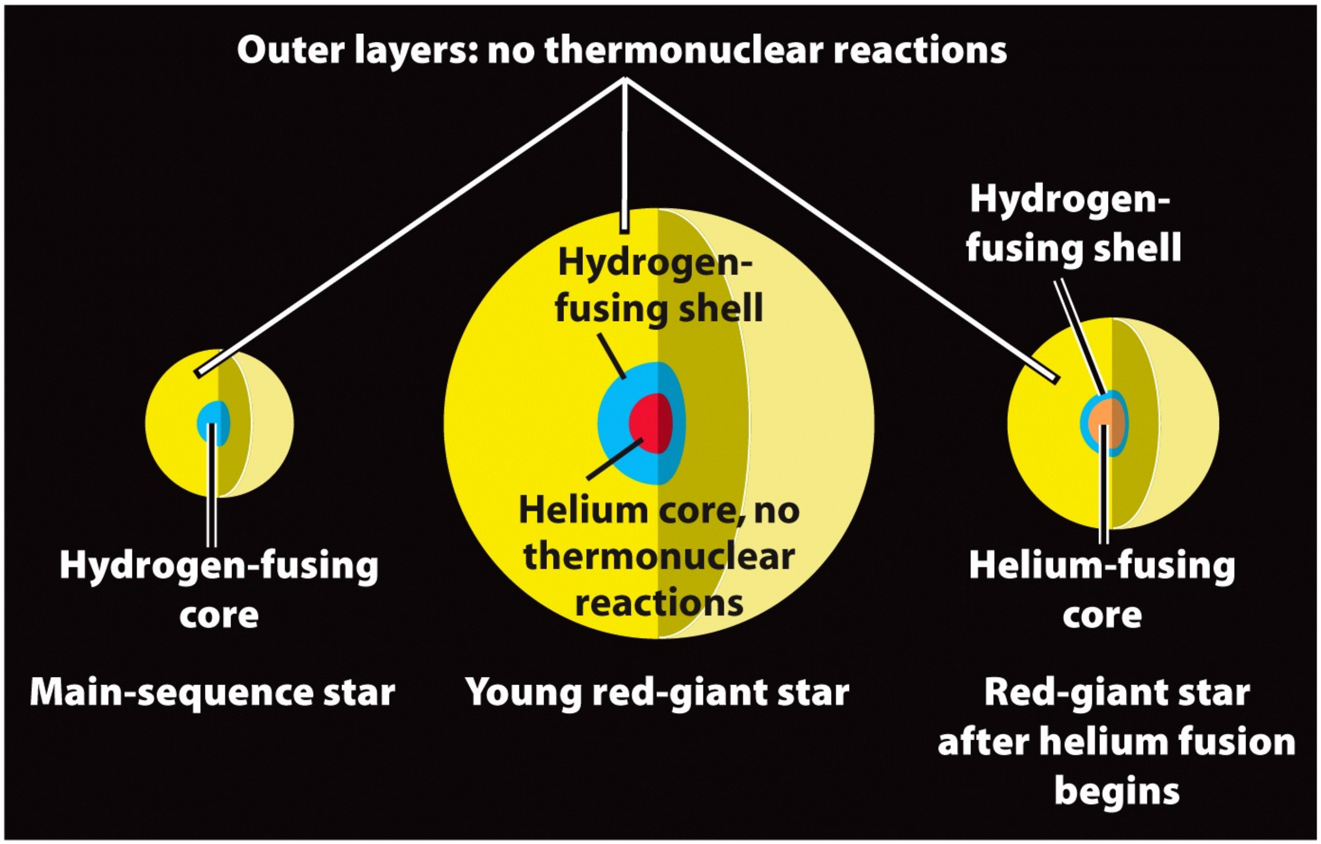
	The Outer (Jovian) Planets			
	Jupiter	**Saturn**	**Uranus**	**Neptune**
Average distance from Sun (10^6 km)	778.3	1429	2871	4498
Average distance from Sun (AU)	5.203	9.554	19.194	30.066
Orbital period (years)	11.86	29.46	84.10	164.86
Orbital eccentricity	0.048	0.053	0.043	0.010
Inclination of orbit to the ecliptic	1.30°	2.48°	0.77°	1.77°
Equatorial diameter (km)	142,984	120,536	51,118	49,528
Equatorial diameter (Earth = 1)	11.209	9.449	4.007	3.883
Mass (kg)	1.899×10^{27}	5.685×10^{26}	8.682×10^{25}	1.024×10^{26}
Mass (Earth = 1)	317.8	95.16	14.53	17.15
Average density (kg/m^3)	1326	687	1318	1638

Table 7-1 part 2
Universe, Eighth Edition
© 2008 W. H. Freeman and Company

But not all these worlds have an equal chance to support life

- Saturn, Neptune, and Uranus may not be affected that much. "Hot Jupiters" in other planetary systems seem to hold onto their gaseous atmospheres despite their proximity to a star. Life as we know it is unlikely to appear on gaseous planets.
- In the journal *Astrobiology*, Alan Stern argues that Neptune's moon Triton, Pluto, and its moon Charon, and perhaps other Kuiper Belt Objects will have the best chances for life. These bodies are rich in organic chemicals, and the heat of the red giant sun will melt their icy surfaces into oceans.
- How long will the Sun remain a red giant? Then what?

Helium Fusion Requires Higher Temperatures than H Fusion

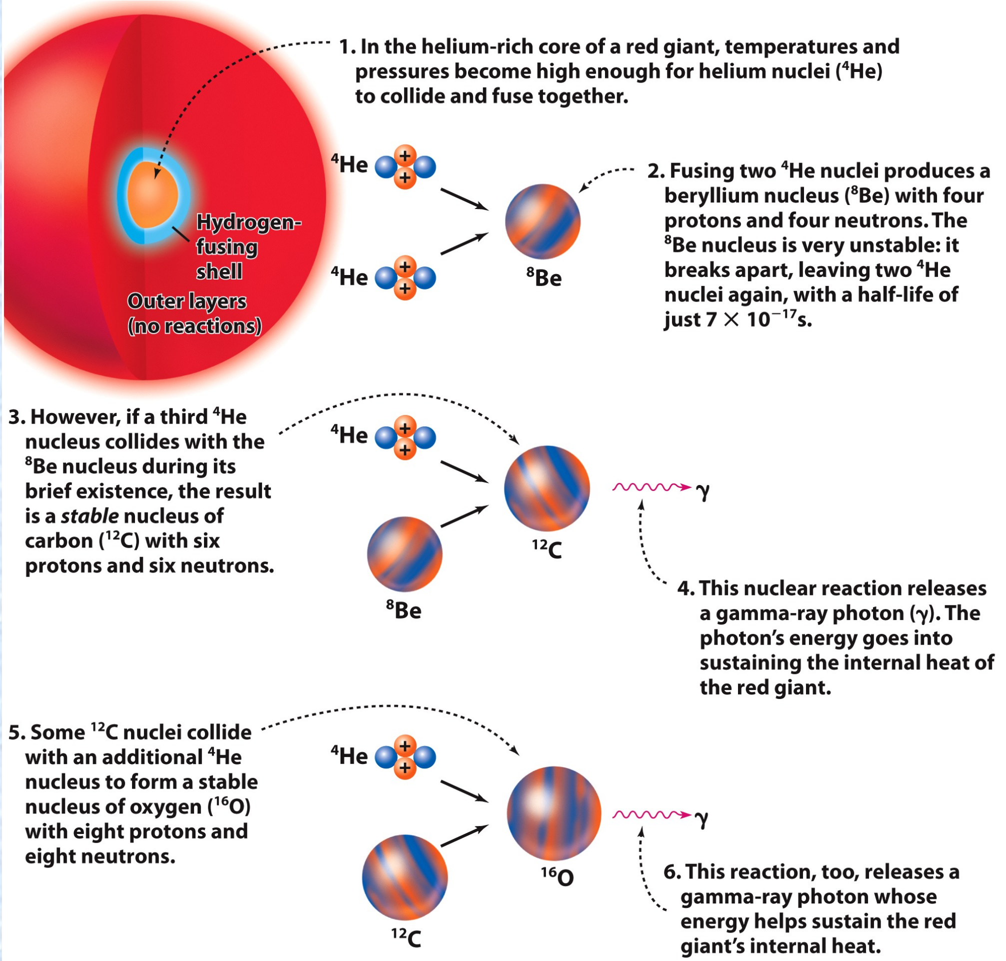


(a)

Figure 19
Universe,
© 2014 W.

HW6 (11.19.12): Why???

Three ^{4}He Nuclei Make ^{12}C. Add a Fourth and Make ^{16}O.

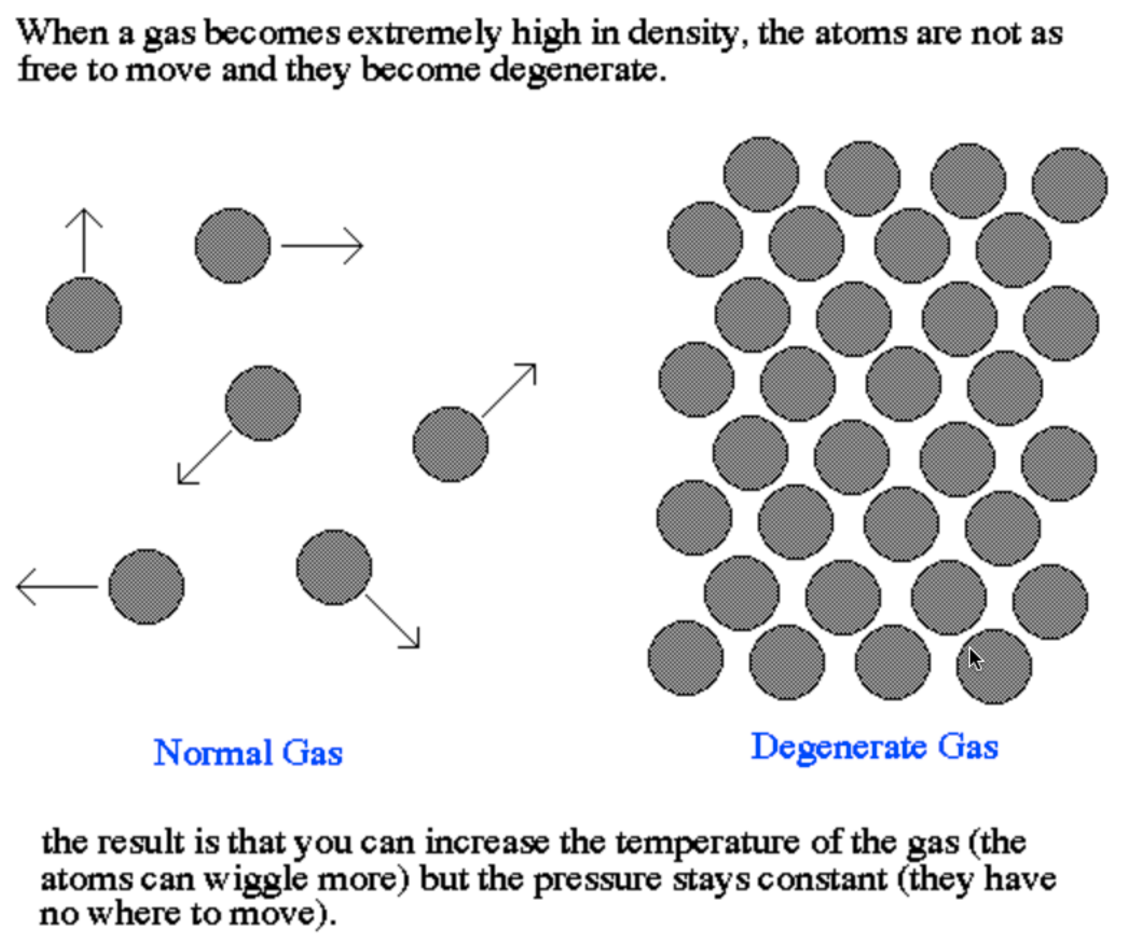


1. In the helium-rich core of a red giant, temperatures and pressures become high enough for helium nuclei (^{4}He) to collide and fuse together.
2. Fusing two ^{4}He nuclei produces a beryllium nucleus (^{8}Be) with four protons and four neutrons. The ^{8}Be nucleus is very unstable: it breaks apart, leaving two ^{4}He nuclei again, with a half-life of just 7×10^{-17}s.
3. However, if a third ^{4}He nucleus collides with the ^{8}Be nucleus during its brief existence, the result is a *stable* nucleus of carbon (^{12}C) with six protons and six neutrons.
4. This nuclear reaction releases a gamma-ray photon (γ). The photon's energy goes into sustaining the internal heat of the red giant.
5. Some ^{12}C nuclei collide with an additional ^{4}He nucleus to form a stable nucleus of oxygen (^{16}O) with eight protons and eight neutrons.
6. This reaction, too, releases a gamma-ray photon whose energy helps sustain the red giant's internal heat.

Cosmic Connections 19
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

Degeneracy Pressure

- Closely packed electrons resist compression.


When a gas becomes extremely high in density, the atoms are not as free to move and they become degenerate.

the result is that you can increase the temperature of the gas (the atoms can wiggle more) but the pressure stays constant (they have no where to move).

Degeneracy Pressure

- Comes from Quantum Mechanics
  (Pauli Exclusion Principle)
- Pressure rises independent of temperature.
- Think of adding electrons to a constant volume. The energy goes up with each addition because the lower levels are full.

$$P = \frac{2}{3}\frac{E_{\mathrm{tot}}}{V} = \frac{2}{3}\frac{\hbar^2 k_{\mathrm{F}}^5}{10\pi^2 m_{\mathrm{e}}} = \frac{(3\pi^2)^{2/3}\hbar^2}{5m_{\mathrm{e}}}\rho_N^{5/3}$$

Degeneracy Pressure

- Closely packed electrons resist compression.
- Pressure rises independent of temperature.
- At high enough temperatures, the electrons lose their degeneracy. Explosive situation.

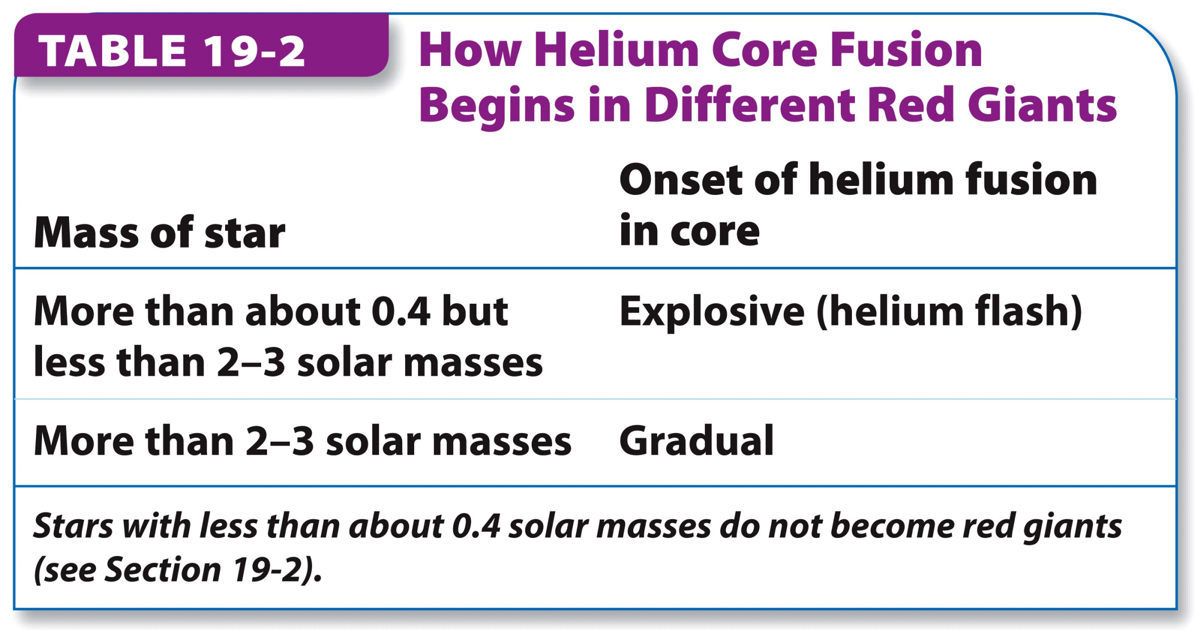


TABLE 19-2 **How Helium Core Fusion Begins in Different Red Giants**

Mass of star	Onset of helium fusion in core
More than about 0.4 but less than 2–3 solar masses	Explosive (helium flash)
More than 2–3 solar masses	Gradual

Stars with less than about 0.4 solar masses do not become red giants (see Section 19-2).

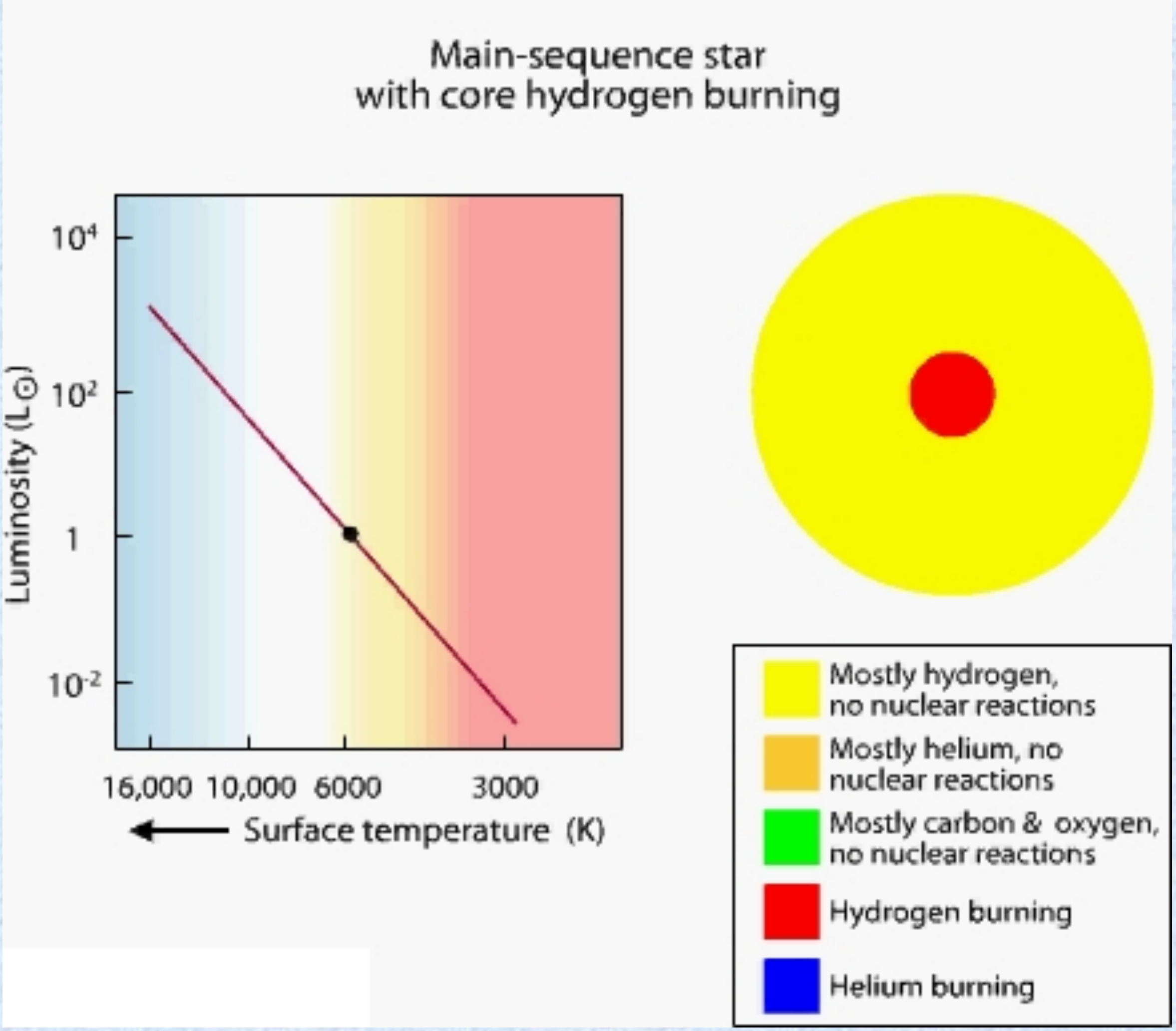
Table 19-2
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

Evolution of a 1 M_0 Star: A Time-Lapse Movie

Evolution of a star like the Sun

Main–sequence star (core H fusion) Stage 1:

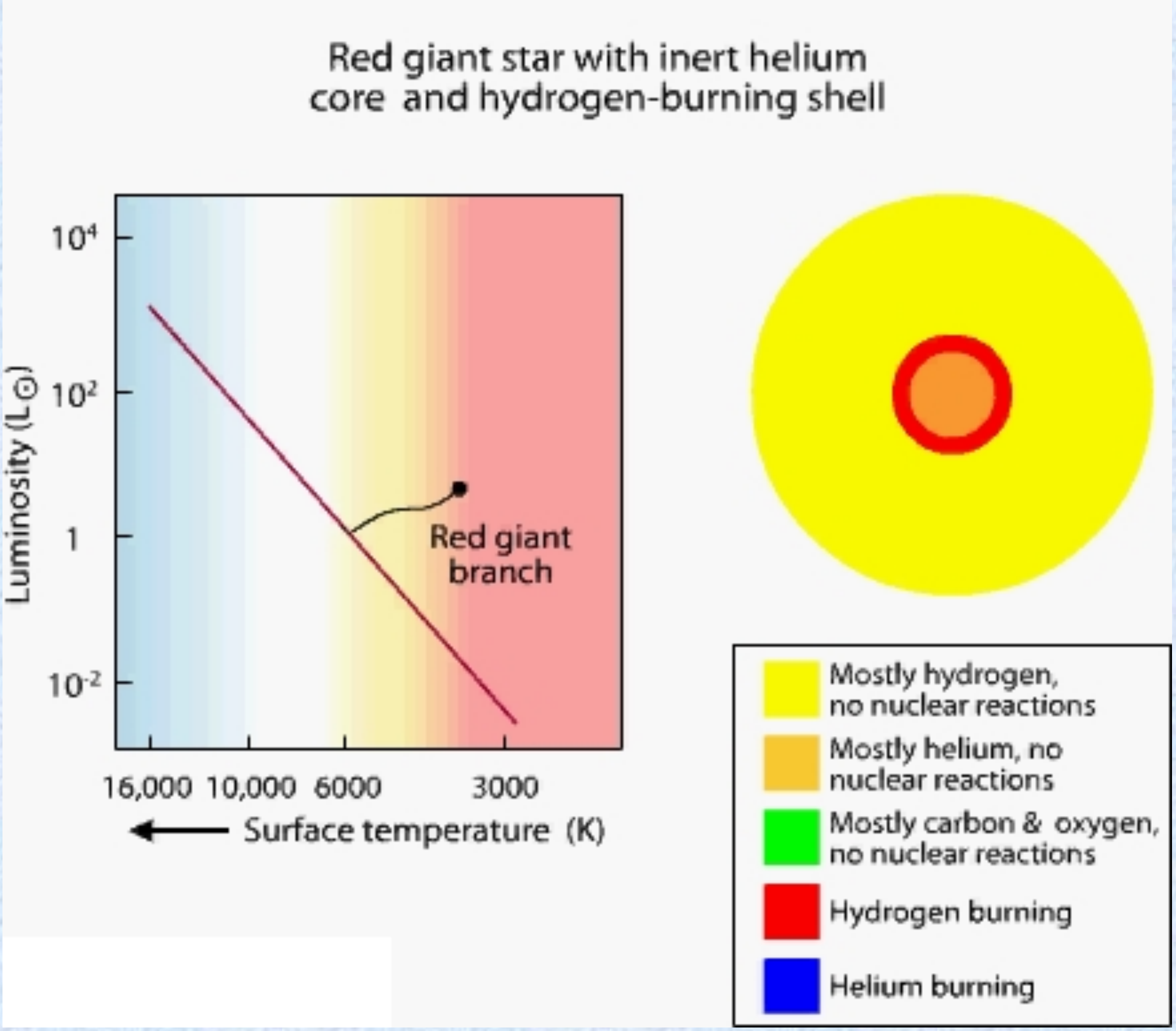
H = hydrogen
He = helium
C = carbon
O = oxygen


Main-sequence star with core hydrogen burning

Evolution of a star like the Sun

Stage 1:
Main–sequence star (core H fusion)
Stage 2:
Red giant
(shell H fusion)

H = hydrogen
He = helium
C = carbon
O = oxygen

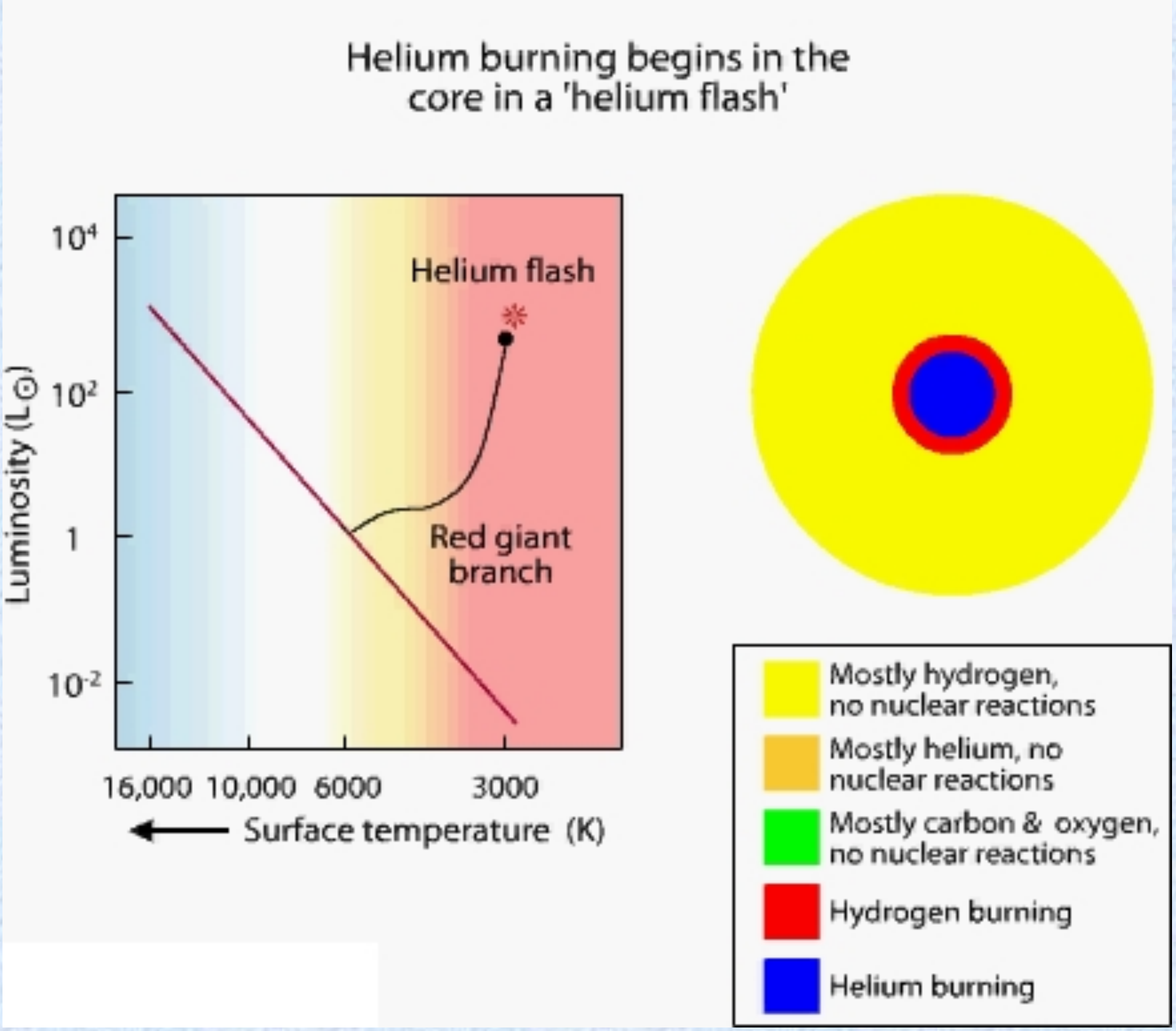


Red giant star with inert helium core and hydrogen-burning shell

Evolution of a star like the Sun

Stage 1:
Main–sequence star (core H fusion)
Stage 2:
Red giant
(shell H fusion)
Stage 3: He core fusion begins

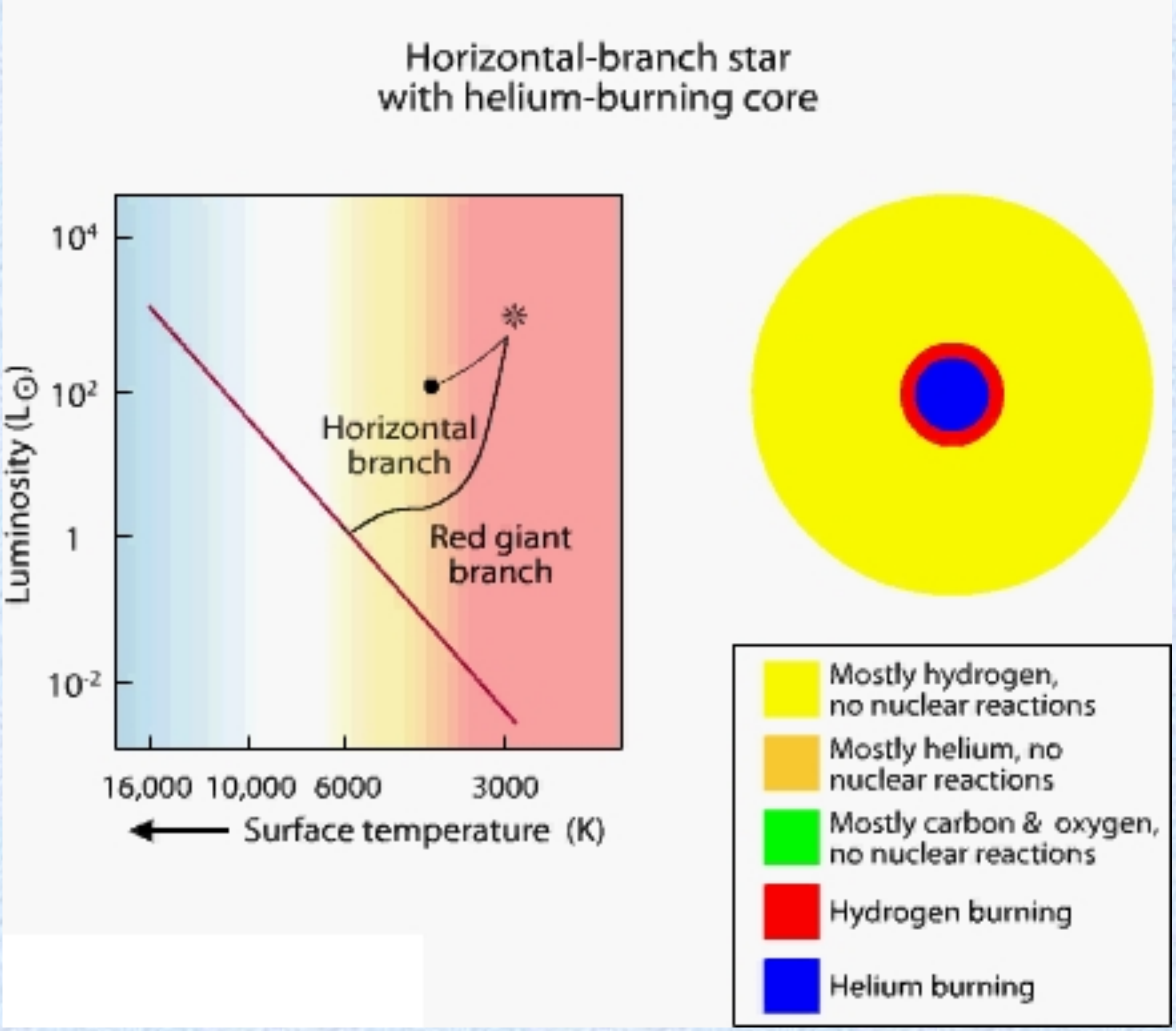
H = hydrogen
He = helium
C = carbon
O = oxygen



Evolution of a star like the Sun

Stage 1:
Main–sequence star (core H fusion)
Stage 2:
Red giant
(shell H fusion)
Stage 3: He core fusion begins
Stage 4:
Horizontal branch
(core He fusion)

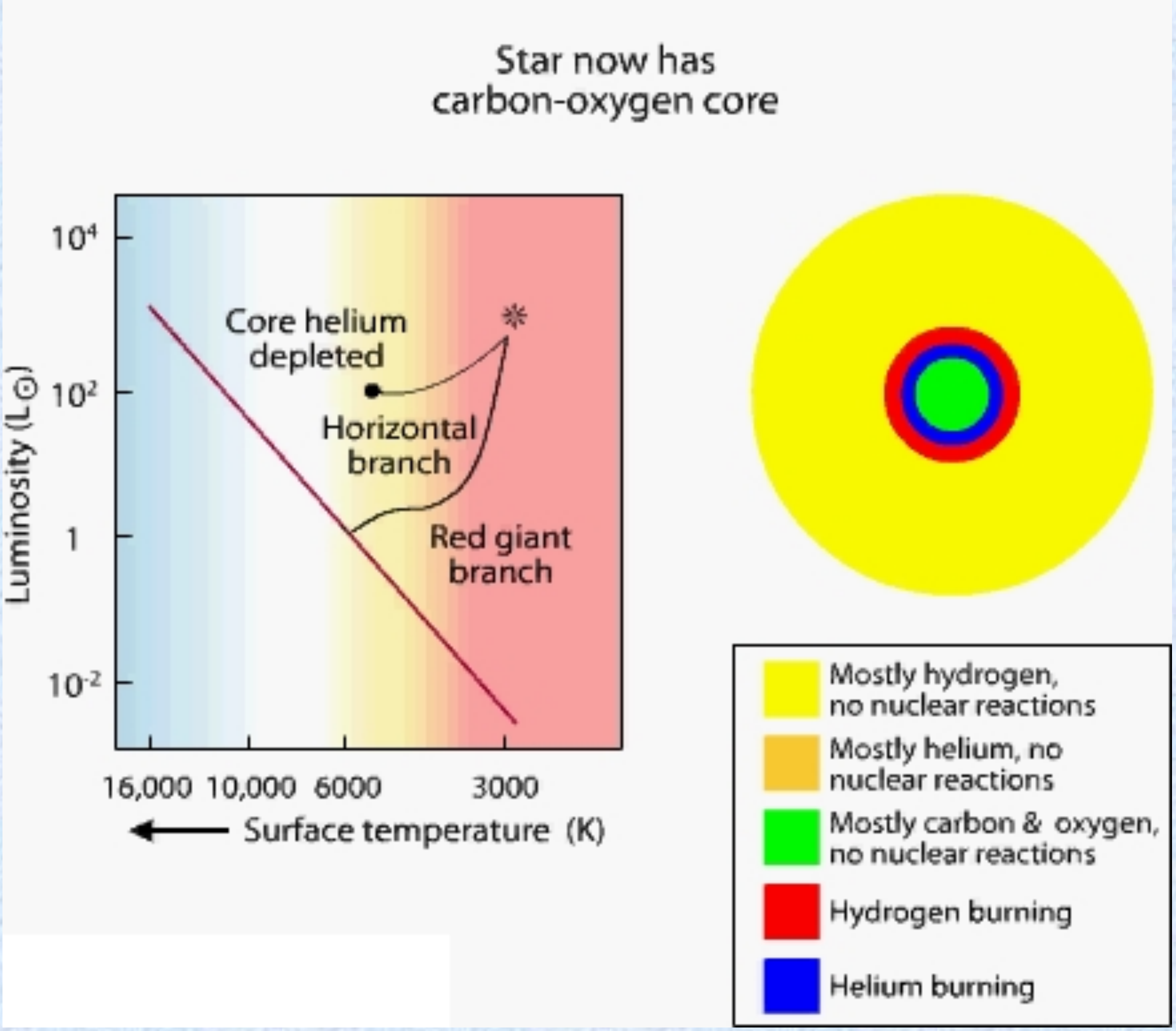
H = hydrogen
He = helium
C = carbon
O = oxygen



Evolution of a star like the Sun

Stage 1:
Main–sequence star (core H fusion)
Stage 2:
Red giant
(shell H fusion)
Stage 3: He core fusion begins
Stage 4:
Horizontal branch
(core He fusion)
Stage 5: C-O core

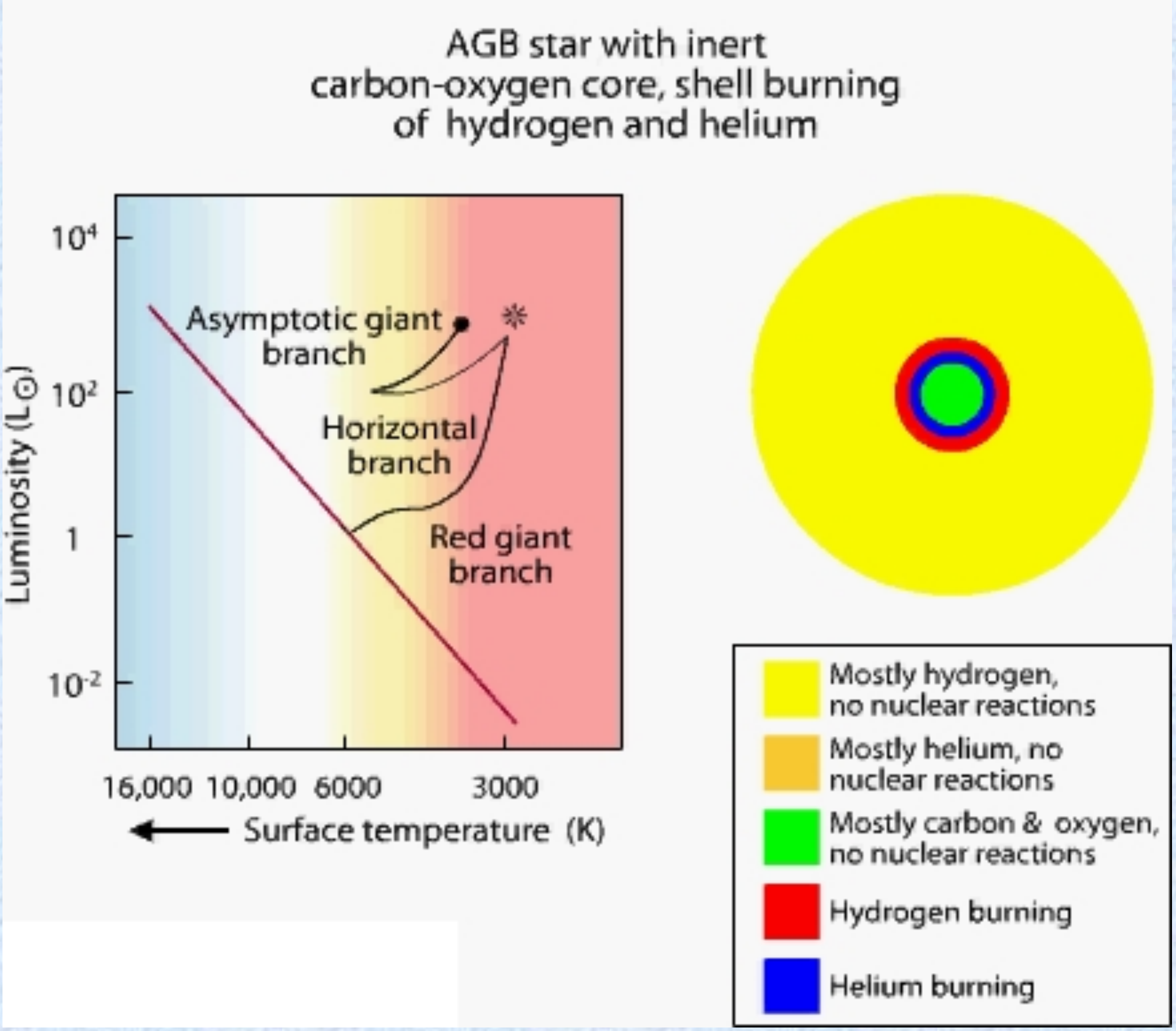
H = hydrogen
He = helium
C = carbon
O = oxygen



Evolution of a star like the Sun

Stage 1:
Main–sequence star (core H fusion)
Stage 2:
Red giant
(shell H fusion)
Stage 3: He core fusion begins
Stage 4:
Horizontal branch
(core He fusion)
Stage 5: C-O core
Stage 6:
Asymptotic giant branch
(shell H & He fusion)

H = hydrogen
He = helium
C = carbon
O = oxygen


AGB star with inert carbon-oxygen core, shell burning of hydrogen and helium

Horizontal-branch stars are stars that have left the main sequence. Inside such stars

A. no fusion is occurring in the core, and hydrogen fusion is occurring in a shell around the core.

B. both core helium fusion and shell hydrogen fusion are taking place.

C. helium fusion is occurring in the core, and there is no hydrogen fusion.

D. both core hydrogen fusion and shell helium fusion are taking place.

Horizontal-branch stars are stars that have left the main sequence. Inside such stars

A. no fusion is occurring in the core, and hydrogen fusion is occurring in a shell around the core.

B. both core helium fusion and shell hydrogen fusion are taking place.

C. helium fusion is occurring in the core, and there is no hydrogen fusion.

D. both core hydrogen fusion and shell helium fusion are taking place.

Star Clusters & Stellar Populations

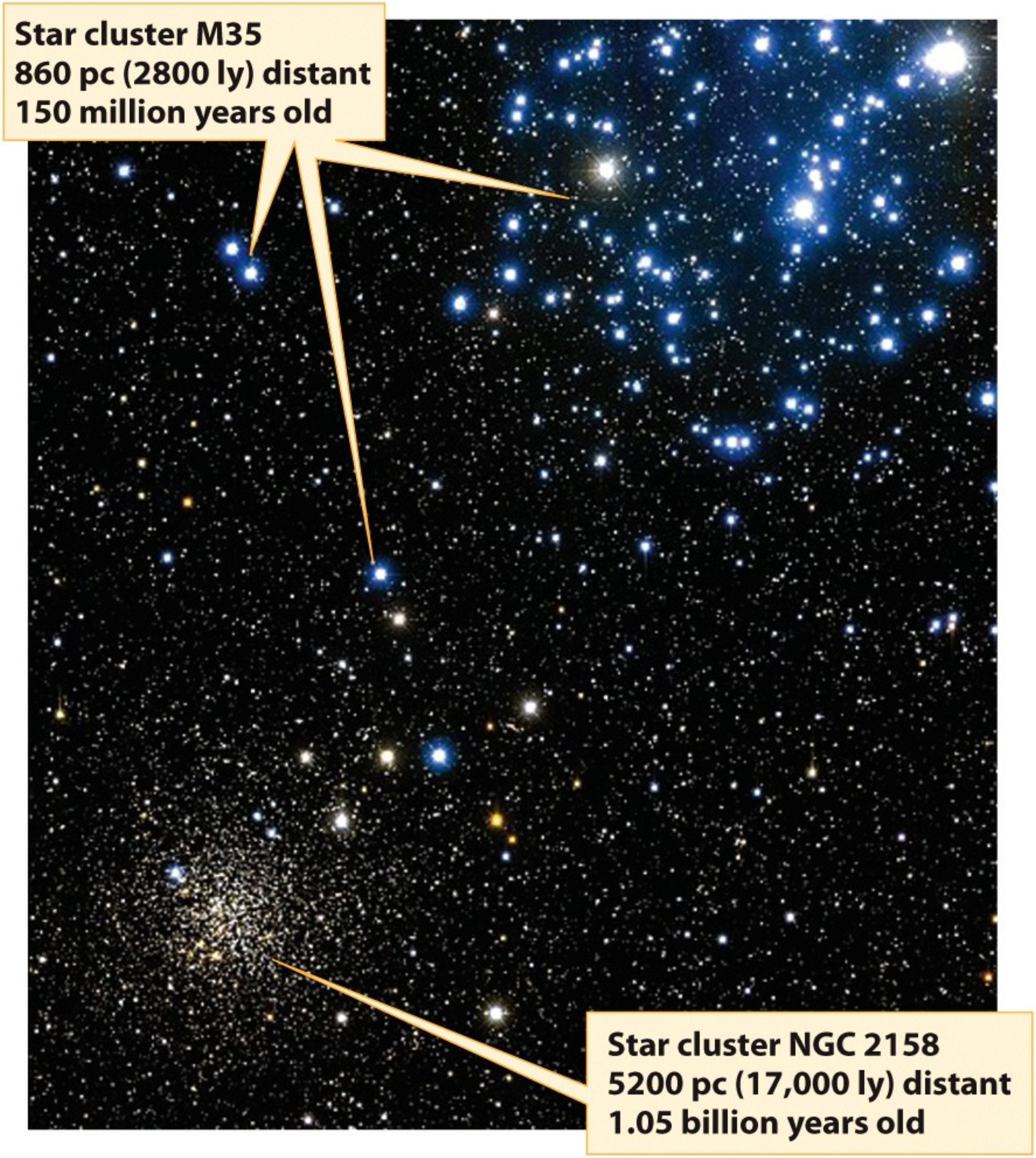


Figure 19-11
Universe, Tenth Edition
Jean-Charles Cuillandre (CFHT), © 2001 CFHT

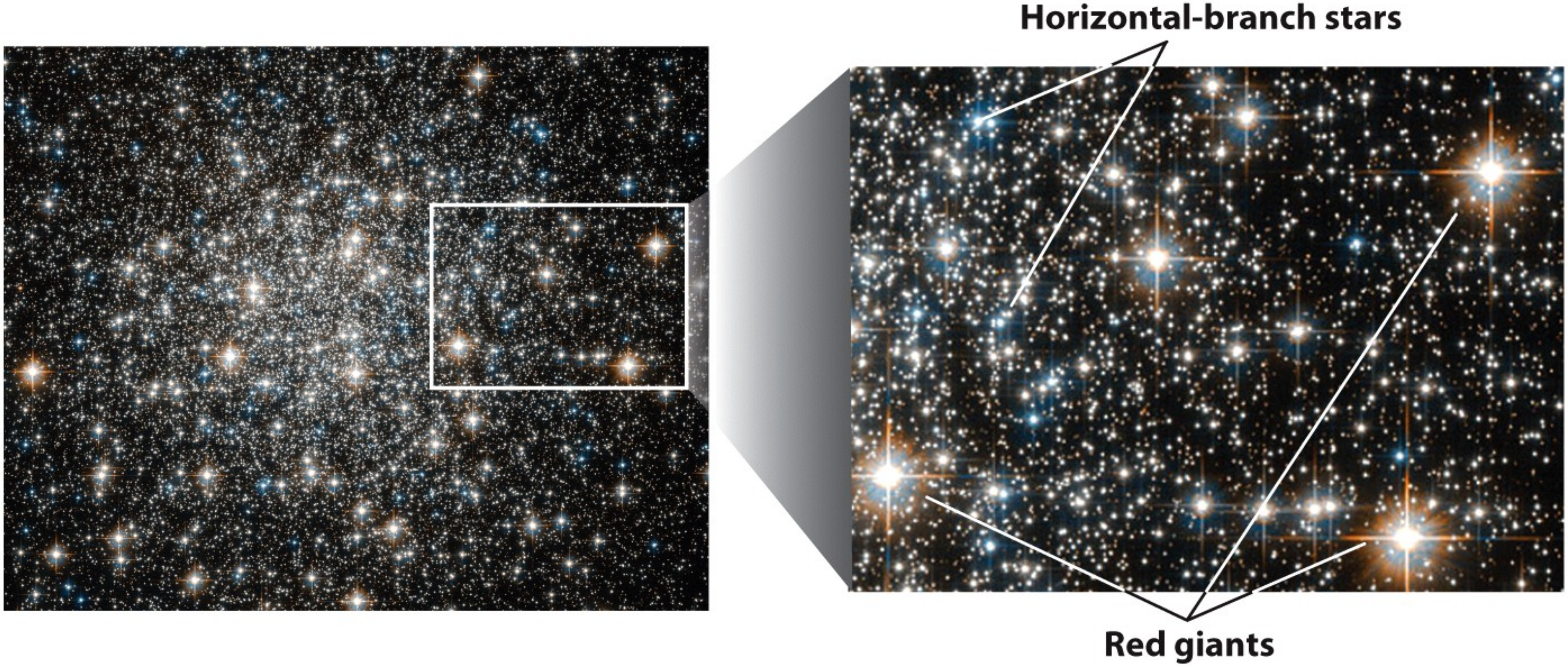
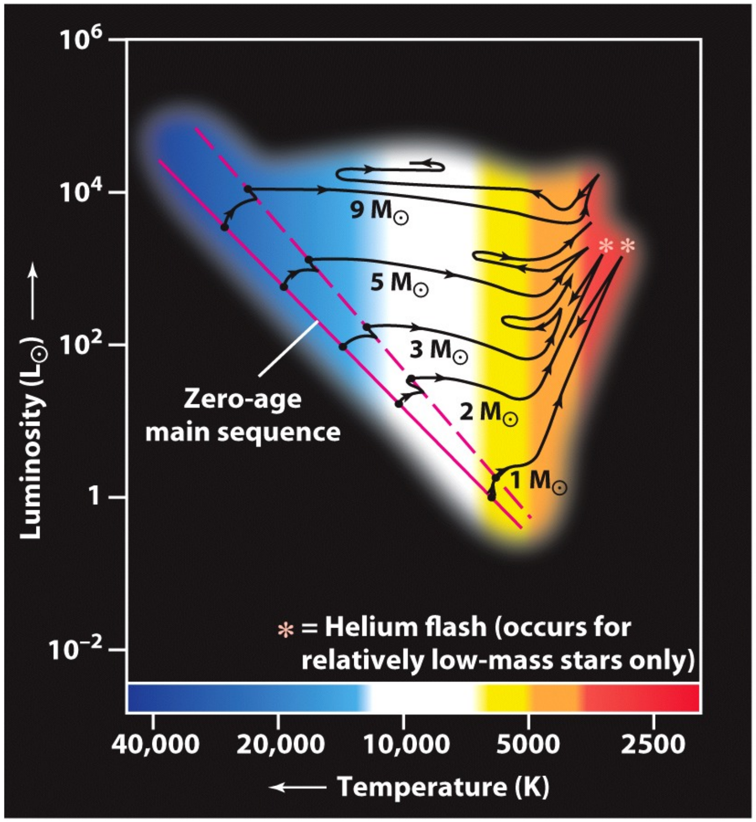


Figure 19-12
Universe, Tenth Edition
ESA/Hubble & NASA

Evolution Tracks in HR Diagram Depend on Stellar Mass



Post–main-sequence evolutionary tracks of five stars with different mass

Figure 19-9a
Universe, Tenth Edition
© 2014 W. H. Freeman and Company [Adapted from I. Iben]

- The stars in a cluster are coeval; i.e., they have the same age.
- We can their location in an HR diagram to estimate the age of the star cluster.

Evolution of a Star Cluster.
1. Joining the Main Sequence

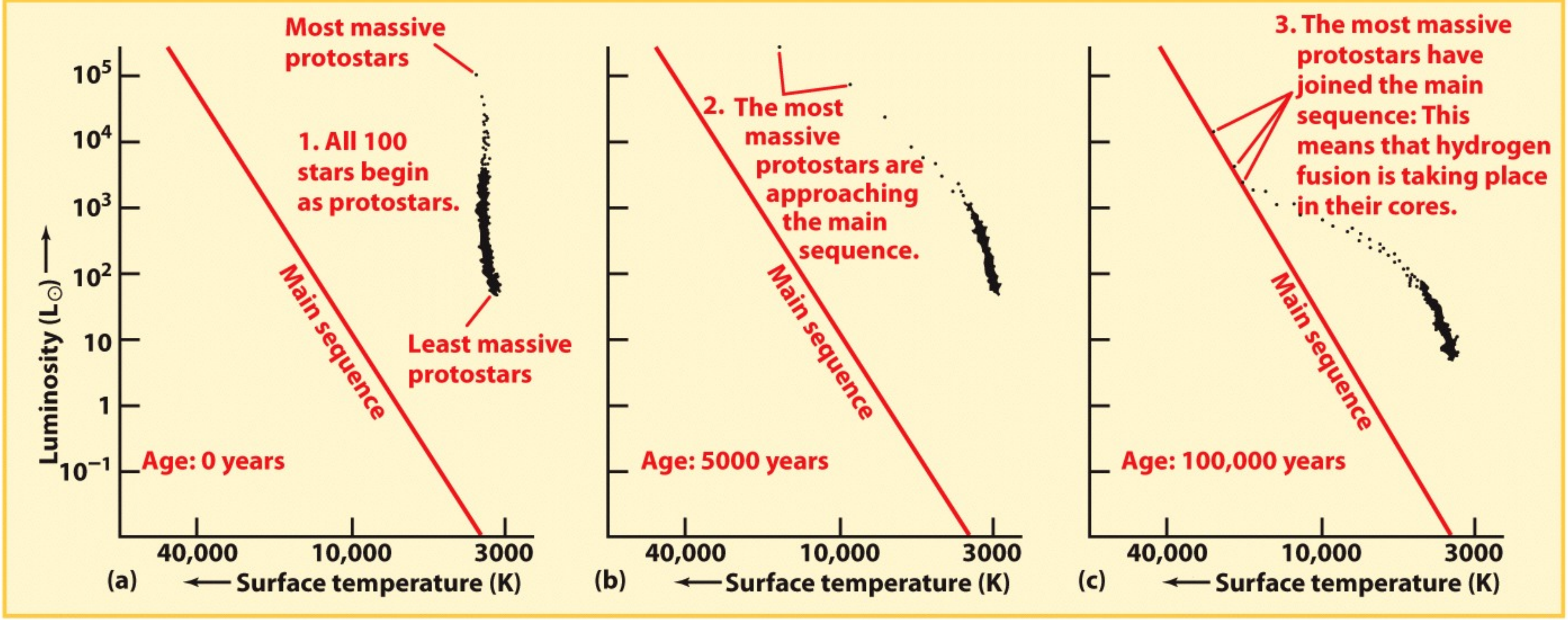


Figure 19-10 part 1

Universe, Tenth Edition

© 2014 W. H. Freeman and Company [Adapted from R. Kippenhahn]

Evolution of a Star Cluster.

2. The Main Sequence Turn Off

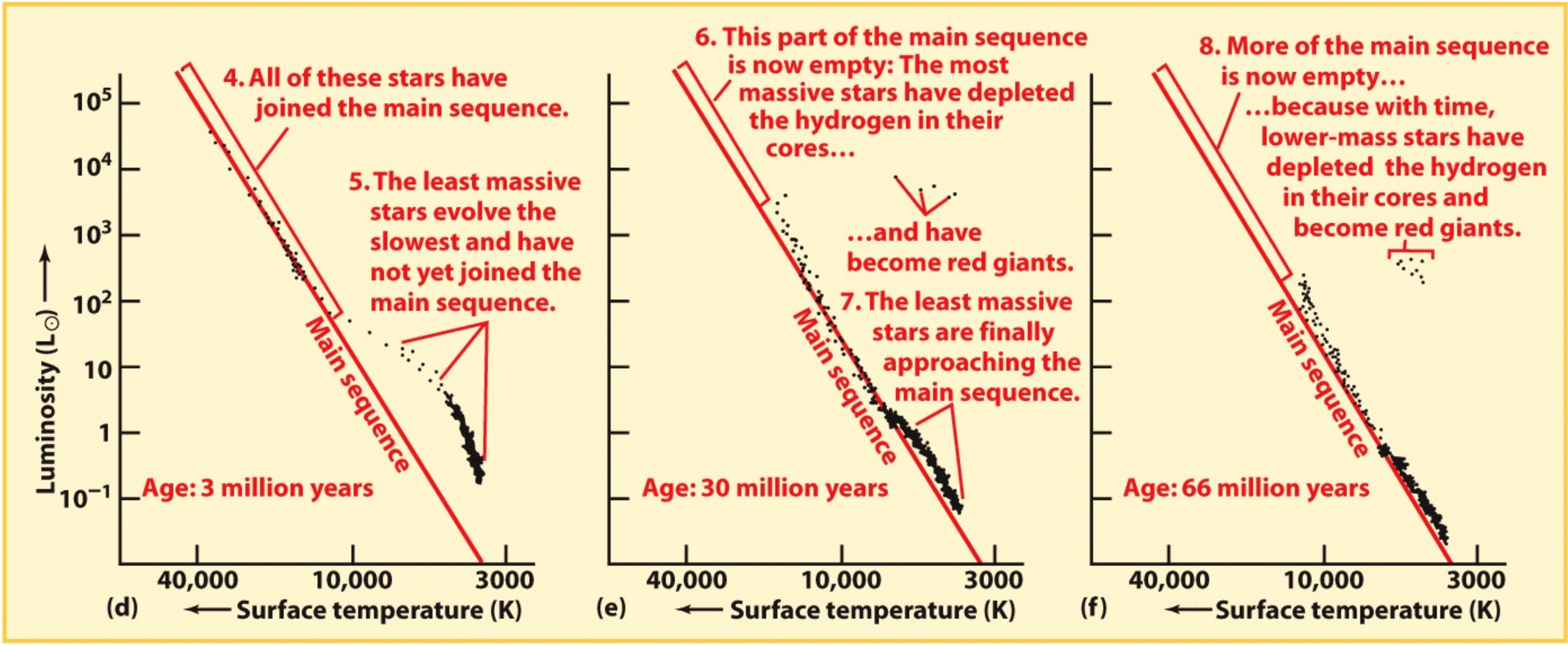


Figure 19-10 part 2
Universe, Tenth Edition
© 2014 W. H. Freeman and Company [Adapted from R. Kippenhahn]

Evolution of a Star Cluster.
3. Oldest Clusters

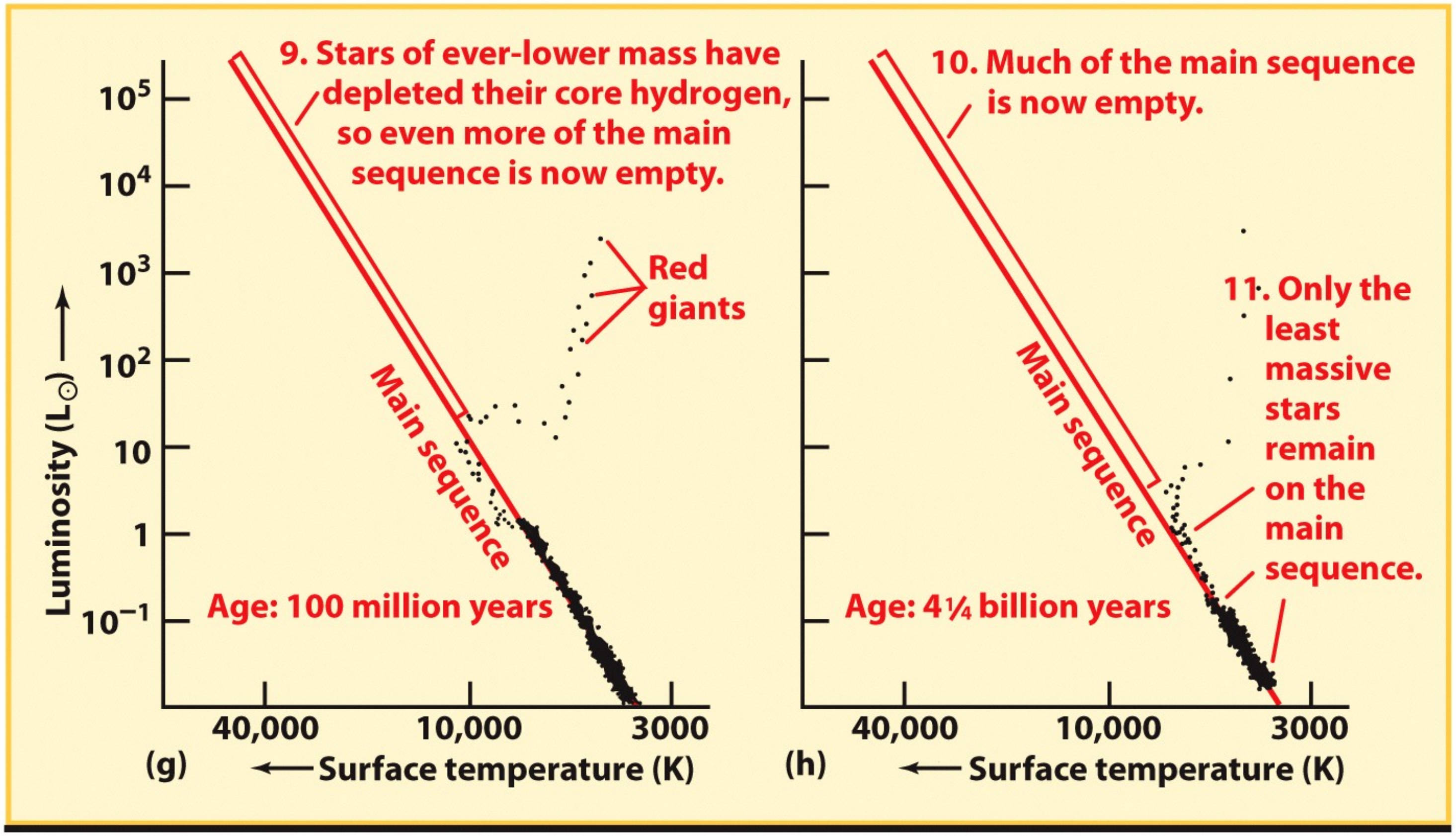


Figure 19-10 part 3

Universe, Tenth Edition

© 2014 W. H. Freeman and Company [Adapted from R. Kippenhahn]

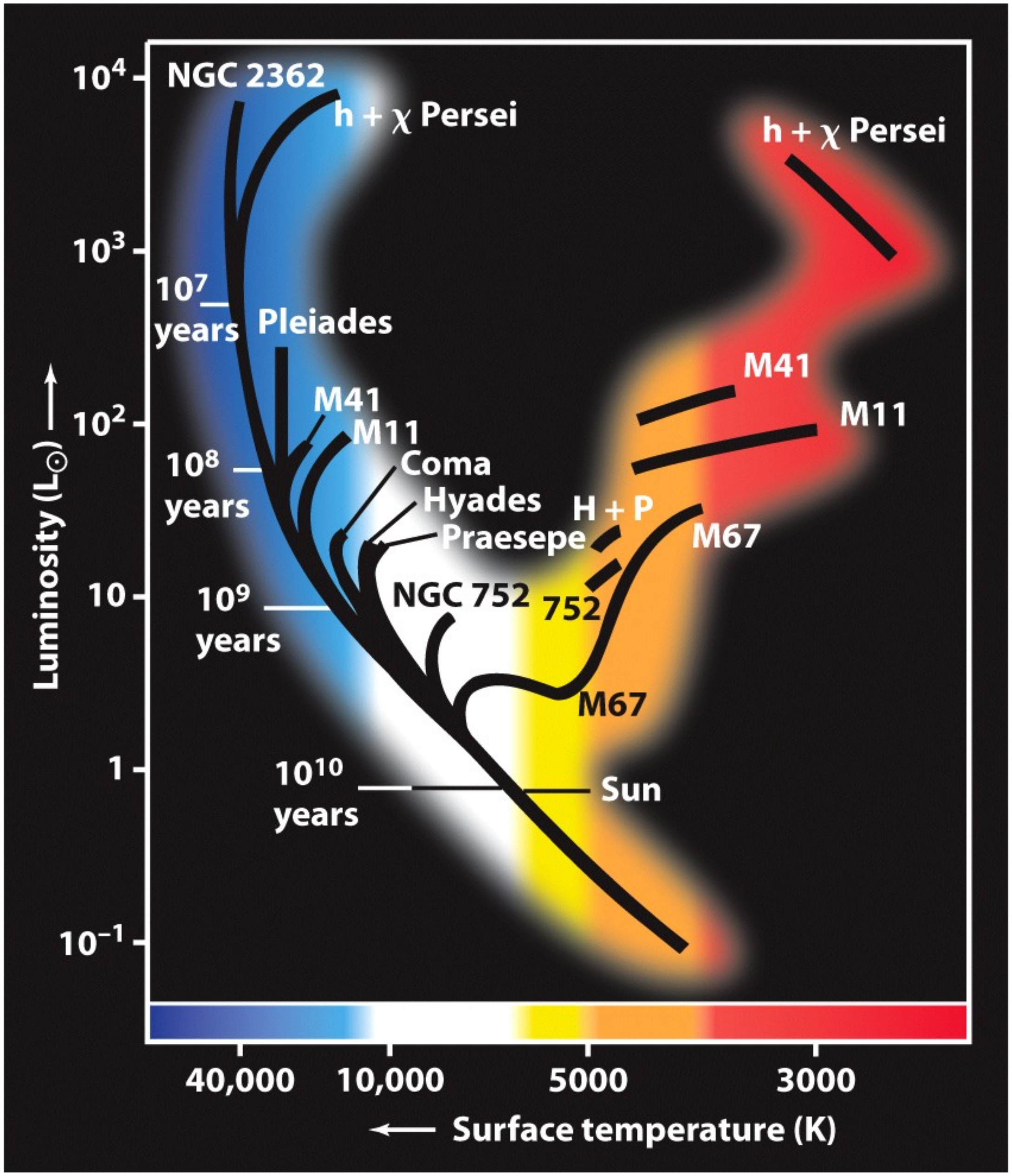


Figure 19-14
Universe, Tenth Edition
© 2014 W. H. Freeman and Company [Adapted from A. Sandage]

Variable Stars

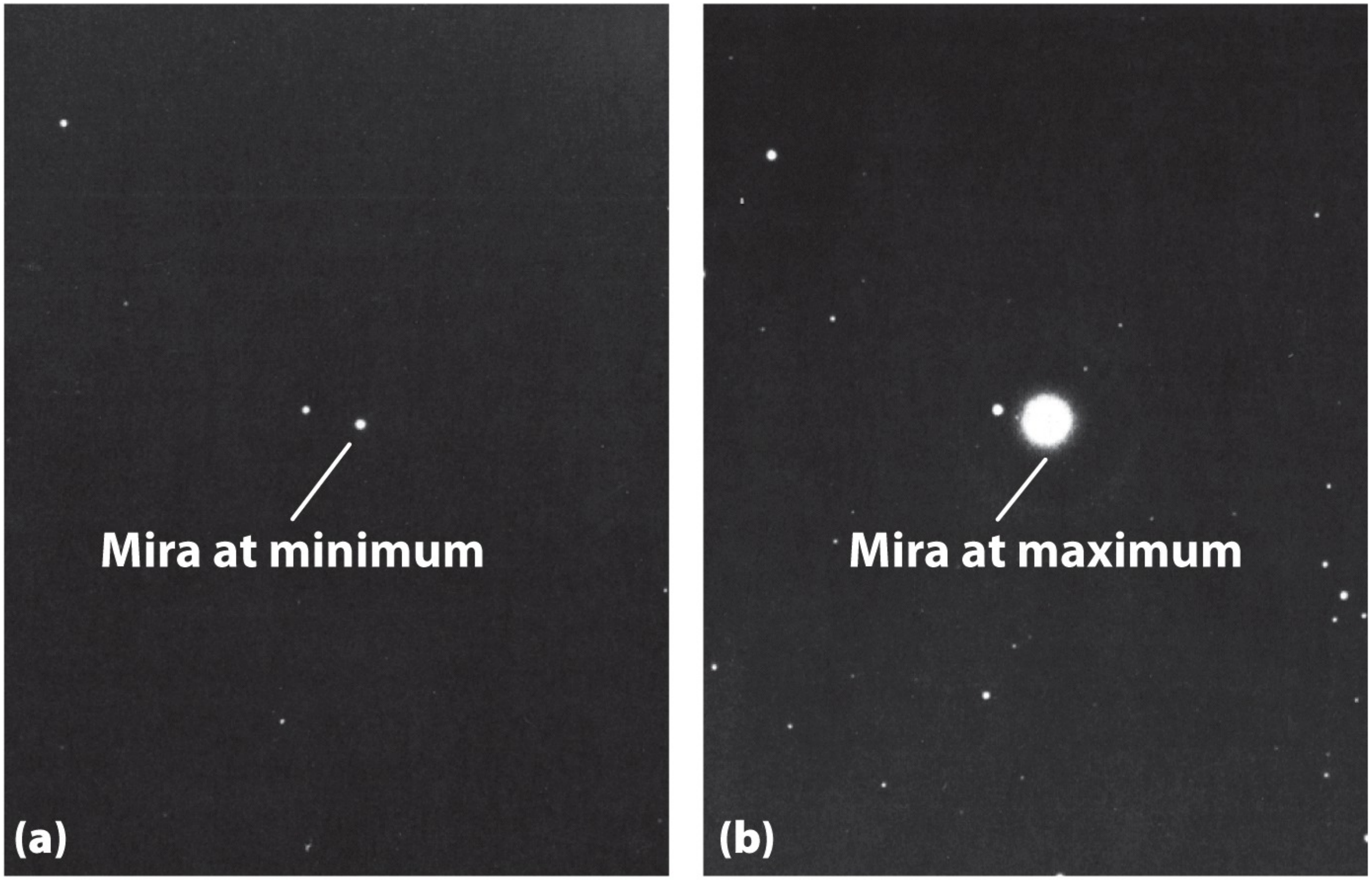


Figure 19-16
Universe, Tenth Edition
Lowell Observatory

The Instability Strip in the HRD

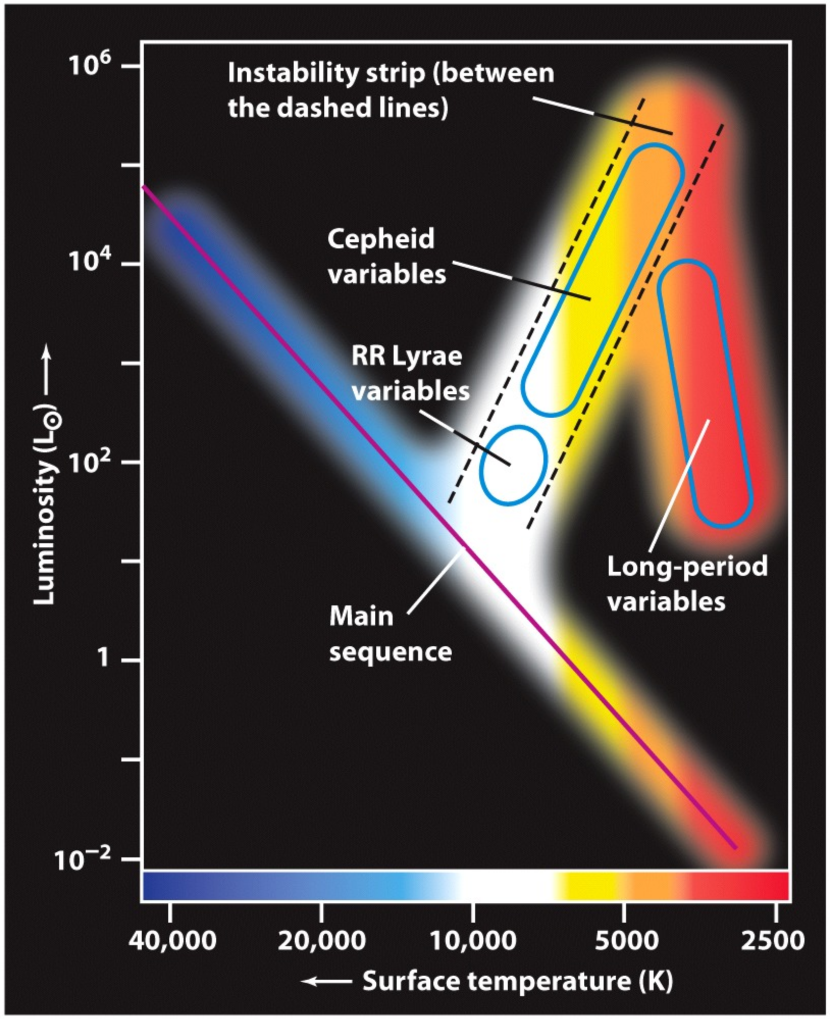
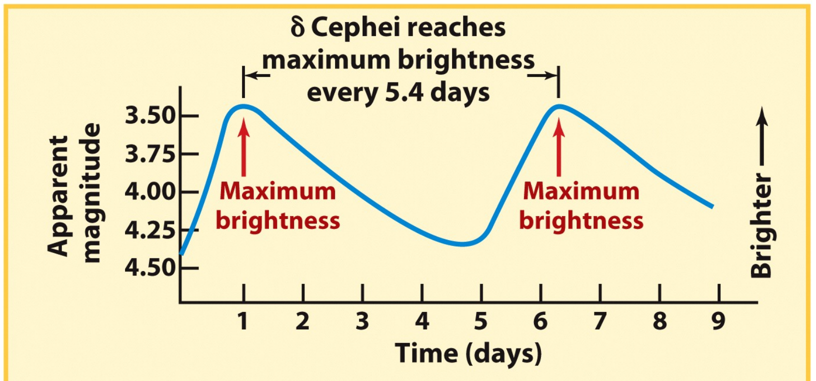


Figure 19-17
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

This graph shows the light curve of δ Cephei. The average period of this variable star is about

A. 1 day
B. 3.5 days
C. 4.4 days
D. 5.4 days
E. 6.4 days

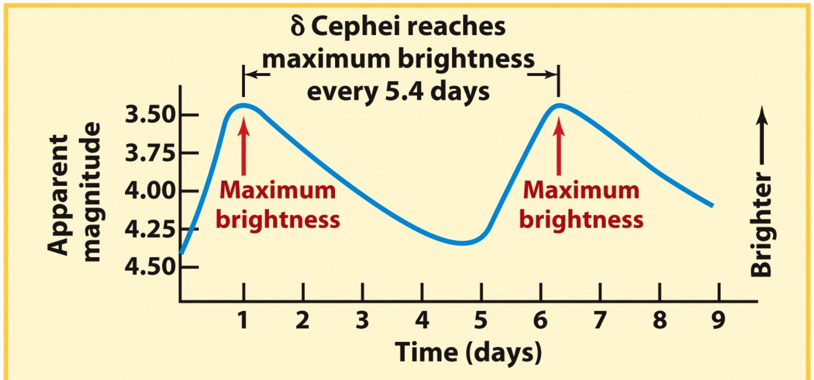


The light curve of δ Cephei (a graph of brightness versus time)

Figure 19-18a
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

This graph shows the light curve of δ Cephei. The average period of this variable star is about

A. 1 day
B. 3.5 days
C. 4.4 days
D. 5.4 days
E. 6.4 days



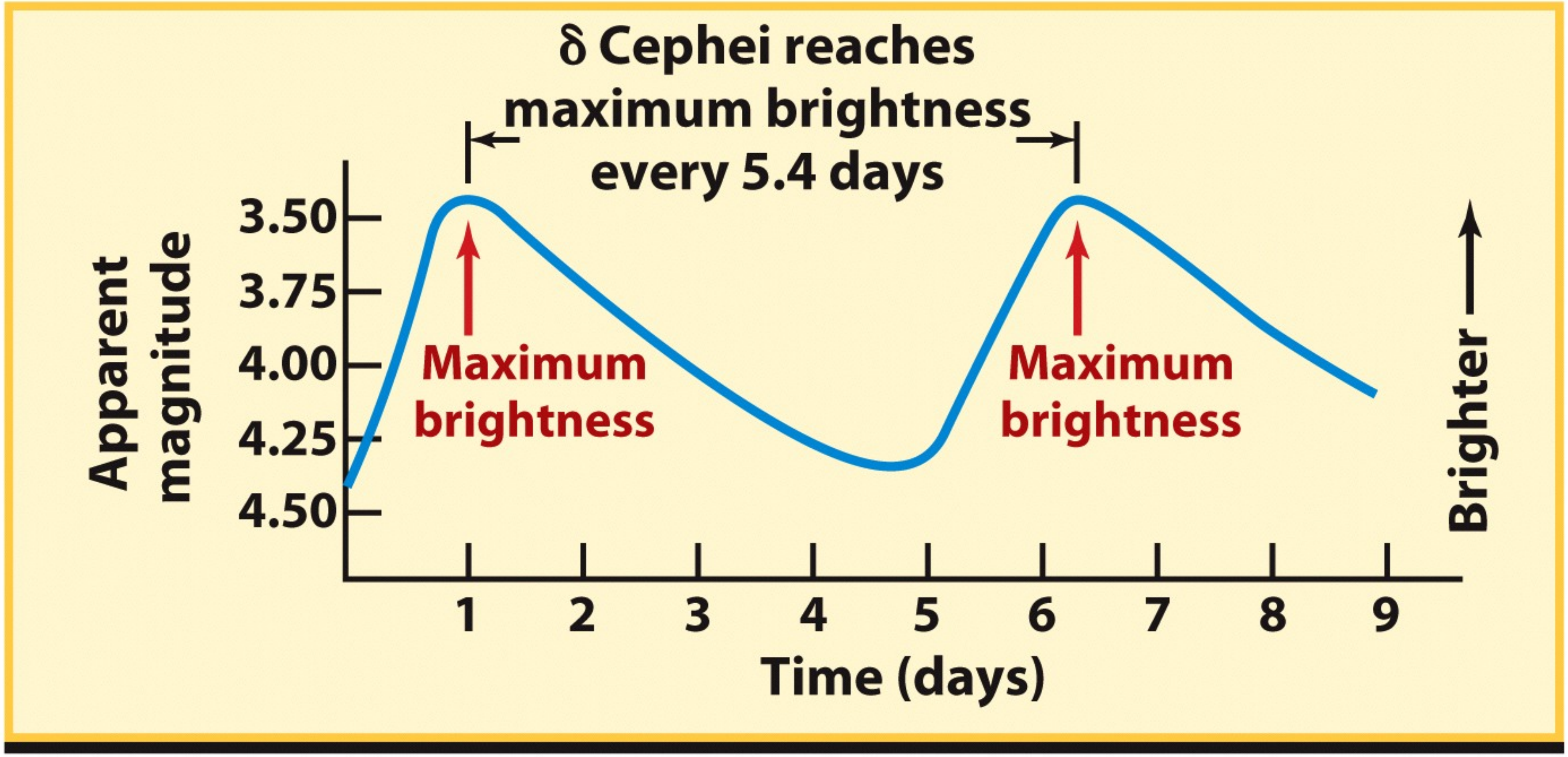
The light curve of δ Cephei (a graph of brightness versus time)

Figure 19-18a
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

HW6 (11.19.35) : Given the average apparent brightness of δ Cephei, find its distance.

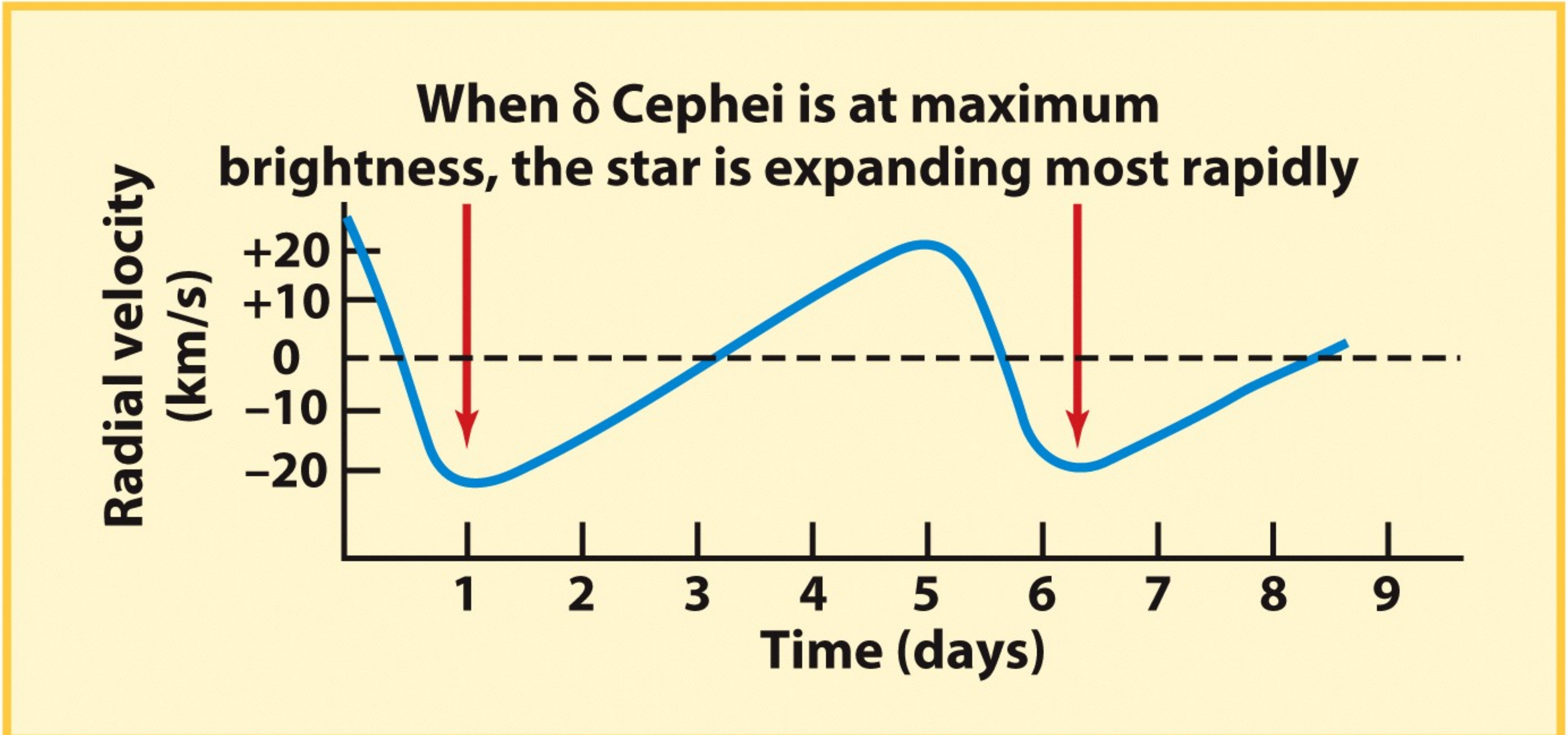
A19.10

The Pulsation of Cepheid Variables



The light curve of δ Cephei (a graph of brightness versus time)

Figure 19-18a
Universe, Tenth Edition
© 2014 W. H. Freeman and Company



When δ Cephei is at maximum brightness, the star is expanding most rapidly

Radial velocity versus time for δ Cephei (positive: star is contracting; negative: star is expanding)

Figure 19-18b
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

Cepheids pulsate because the star is more opaque when compressed than when expanded.

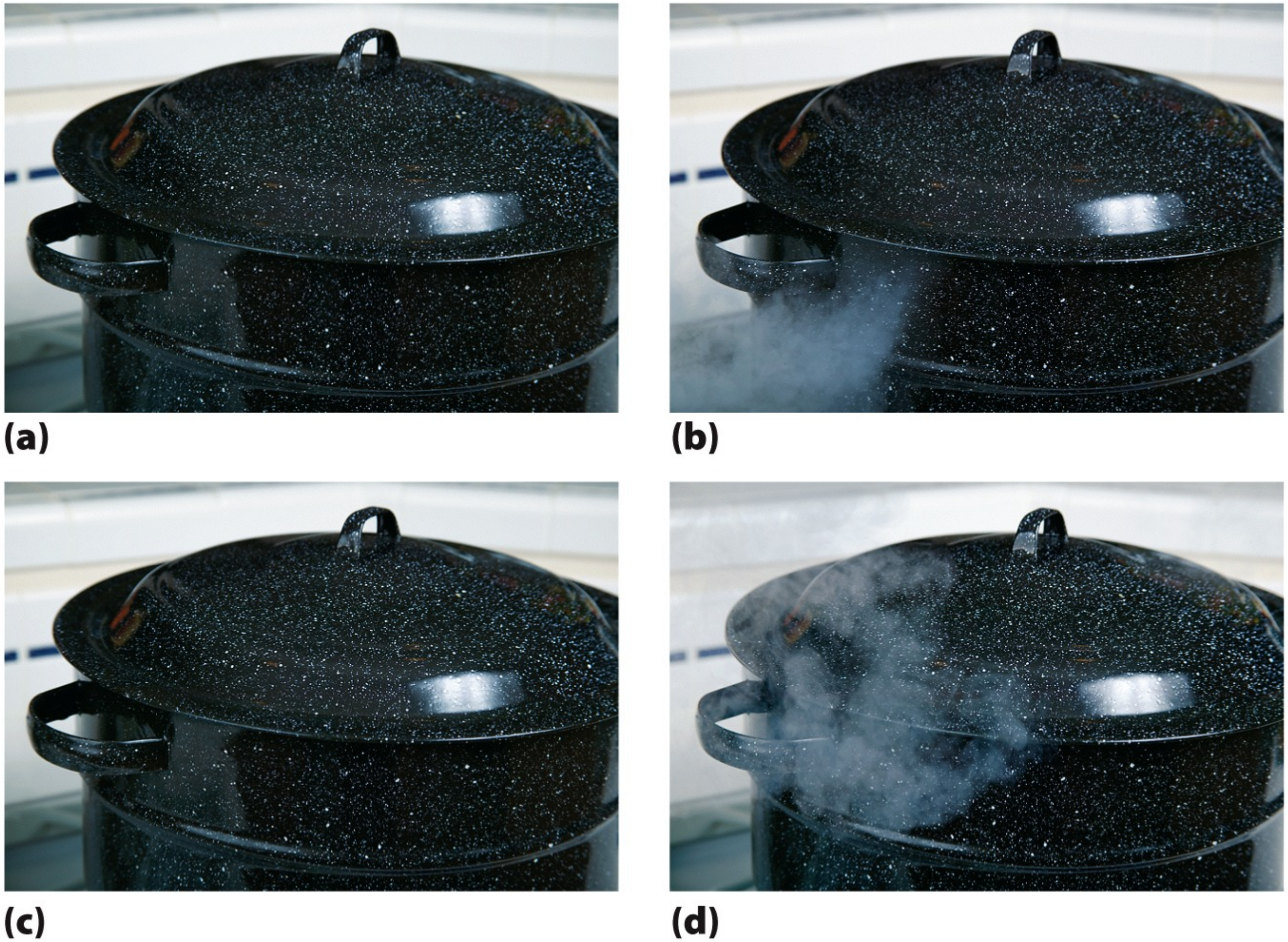
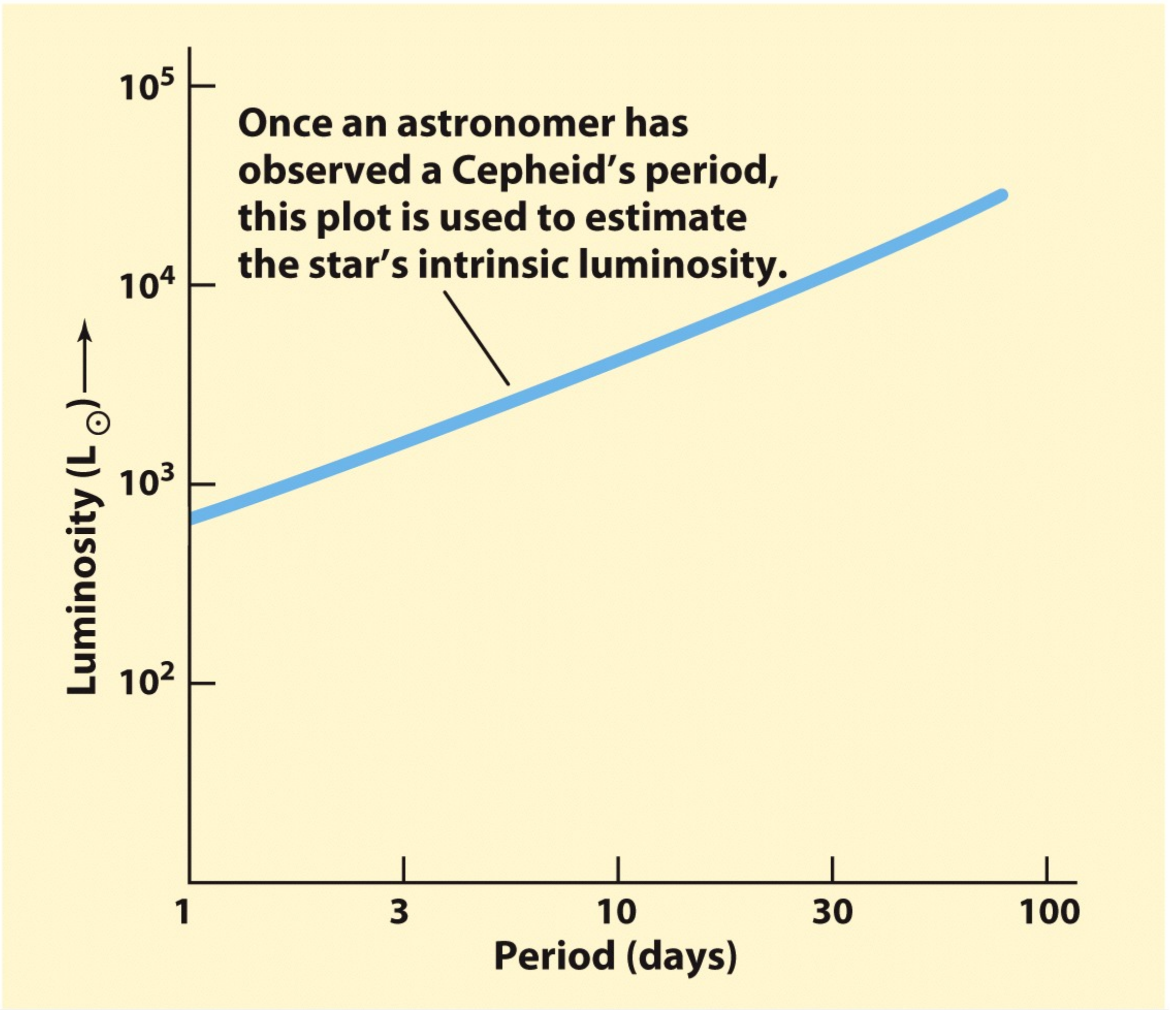


Figure 19-19
Universe, Tenth Edition
Janet Horton

Cepheid Period-Luminosity Relation



Once an astronomer has observed a Cepheid’s period, this plot is used to estimate the star’s intrinsic luminosity.

Figure 19-20
Universe, Tenth Edition
© 2014 W. H. Freeman and Company [Adapted from H. C. Arp]

A certain star has 100 times the luminosity of the Sun and a surface temperature of 3500 K. What type of star is it?

A. A high-mass main-sequence star
B. A low-mass main-sequence star
C. A red giant
D. A red dwarf
E. A white dwarf

A certain star has 100 times the luminosity of the Sun and a surface temperature of 3500 K. What type of star is it?

A. A high-mass main-sequence star
B. A low-mass main-sequence star
C. A red giant
D. A red dwarf
E. A white dwarf

Cepheid variable stars are very luminous and can be observed over very large distances. Why are such stars important to astronomers?

A. They confirm the theory of nuclear fusion as the energy source for stars.
B. They can be used as distance indicators because their luminosity can be determined from their period.
C. Such stars are unstable and are about to become supernovae.
D. Their age can be determined directly from their period.
E. They are always found in binary systems.

Summary

- The minimum mass of a star is about 0.08 M_0; less massive bodies do not get hot enough to fuse H nuclei into He.
- The maximum mass of a star is about 100 M_0; more massive bodies are unstable.
- The Main Sequence lifetimes of stars range from a few million years to much longer than the age of the Universe.
- Stars move up the RGB when their core is contracting and the luminosity of the H burning shell is growing.
- The main sequence turn off measured for a star cluster indicates the stellar mass of the most massive stars still burning H in their cores, thereby implying the cluster age.
- Pauli exclusion principle and electron degeneracy pressure
- Production of C and O in He-burning stars
- The luminosity of Cepheid stars increases with their period. Hence they are useful indicators of distance.