Stellar Evolution

Guiding Questions

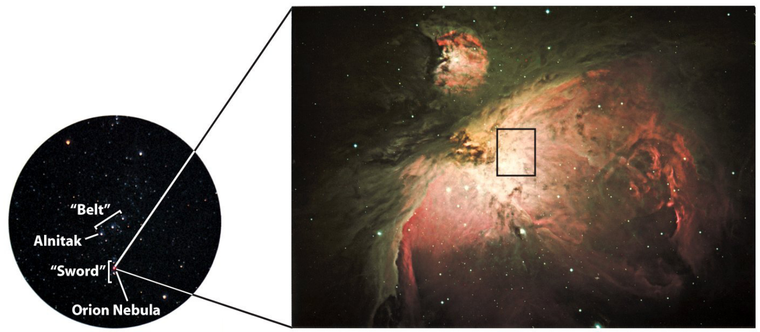
1. Why do astronomers think that stars evolve?
2. What kind of matter exists in the spaces between the stars?
3. What steps are involved in forming a star like the Sun?
4. When a star forms, why does it end up with only a fraction of the available matter?
5. What do star clusters tell us about the formation of stars?
6. Where in the Galaxy does star formation take place?
7. How can the death of one star trigger the birth of many other stars?

Stars Evolve

- Stars shine by thermonuclear reactions
- They have a finite life span, because the hydrogen fuel will be exhausted
- A year to a star is like a second to a human
- To understand the evolution of stars, the approach is to piece together the information gathered for many stars that are at different evolution stages

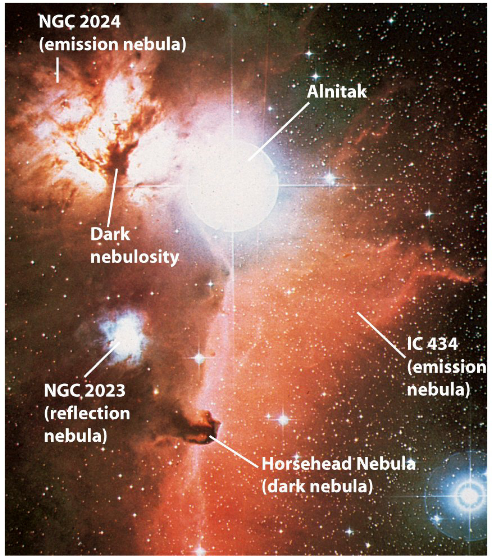
Interstellar Medium and Nebulae

- The space between stars is filled with a thin gas and dust particles
- Interstellar gas and dust pervade the Galaxy
- Nebula: a cloud of concentrated interstellar gas and dust; 10^4 to 10^9 particles per cubic centimeter



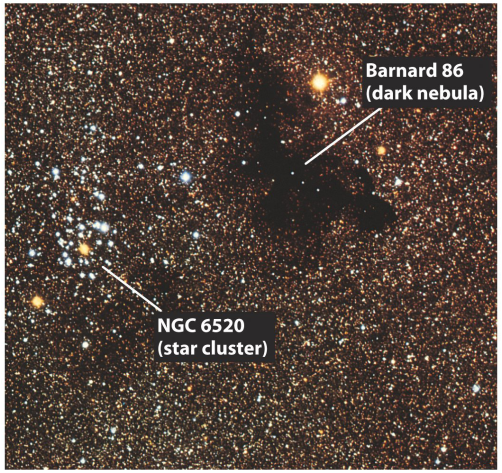
(a) A wide-angle view of Orion. (b) A closeup of the Orion Nebula.

Emission Nebula or H II region

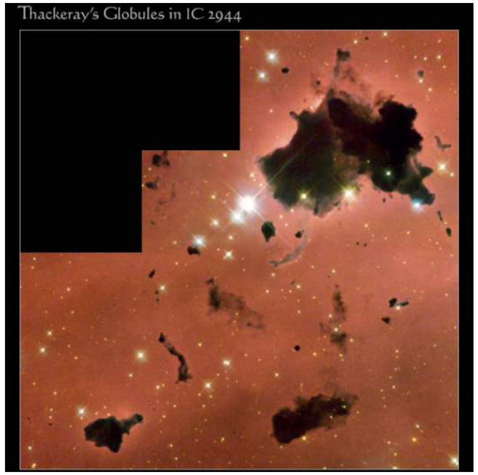


- Emission nebulae are glowing clouds of gas
- They are found near hot, luminous stars of spectral types O and B
- They are powered by ultraviolet light that they absorb from nearby hot stars
- They are composed of ionized hydrogen atoms; the so called H II region.
- They emit light through a process called recombination: free electrons get back to form neutron hydrogen; similar to fluorescence
- They glow red (Hα emission)

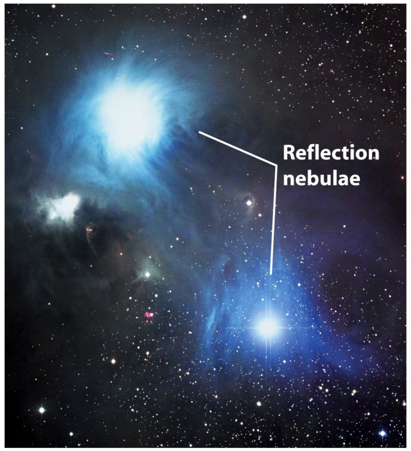
Dark Nebula



- Dark nebulae are so dense that they are opaque
- They appear as dark blobs against a background of distant stars



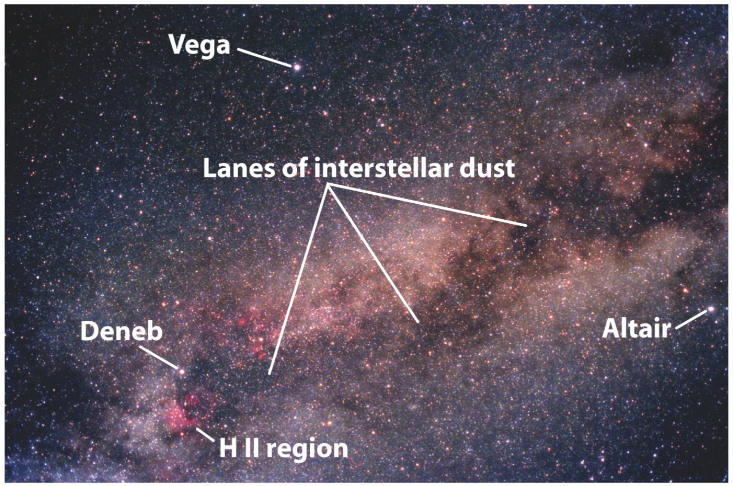
Reflection Nebulae: dust scattering



- Reflection nebulae are produced when starlight is reflected from dust grains in the interstellar medium, producing a characteristic bluish glow
- Short wavelength blue lights are scattered more efficient that red lights

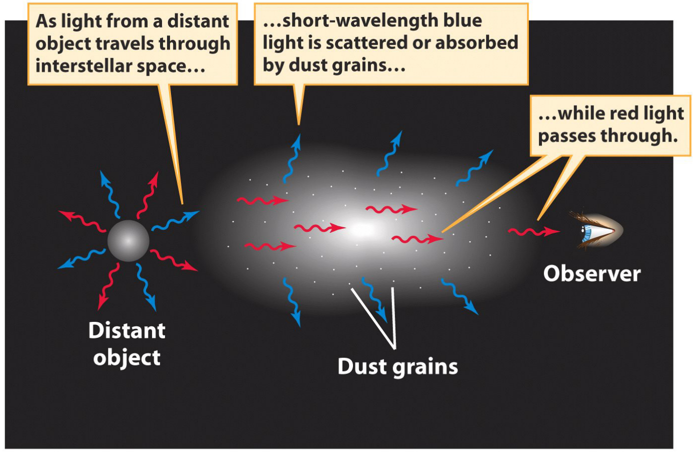
Interstellar Extinction

- Remote stars seem to be dimmer than would be expected from their **distance alone**



Interstellar Reddening

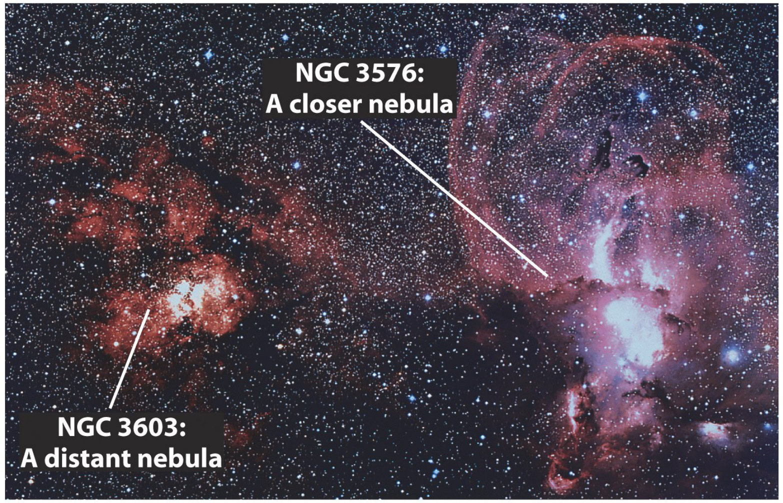
- Remote stars are also reddned as they pass through the interstellar medium, because the blue component of their star light is scattered and absorbed by interstellar dust



How dust causes interstellar reddening

Interstellar Reddening

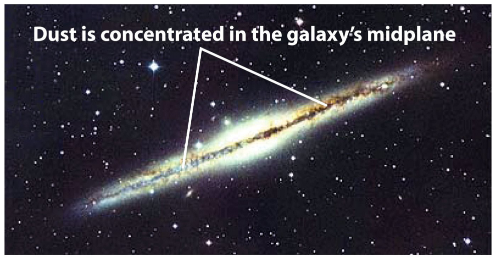
- Reddening depends on distance; the more distant, the redder



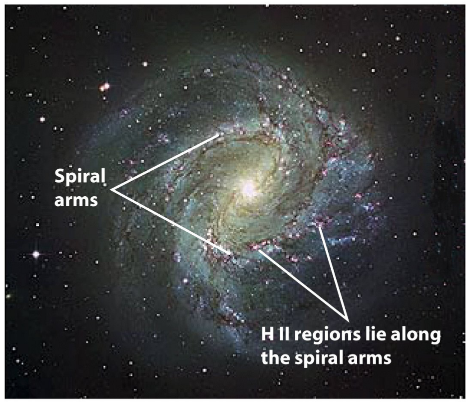
Reddening depends on distance

Distribution of Interstellar Gas and Dust

- The interstellar gas and dust are confined to the plane of the galaxy



We see spiral galaxy NGC 891 nearly edge-on

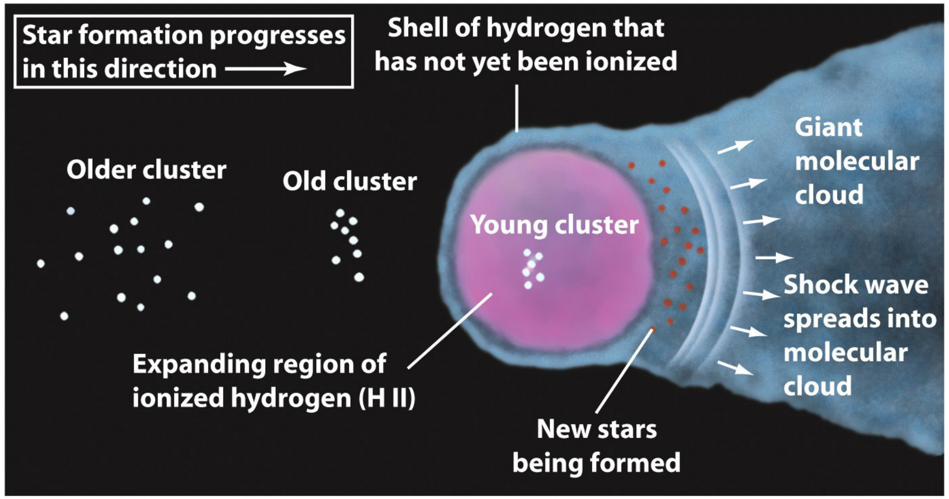


We see spiral galaxy M83 nearly face-on

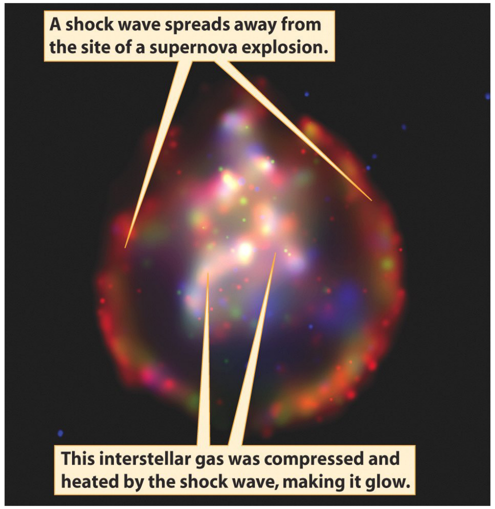
Trigger of Star Birth: Shock Waves from O and B Stars

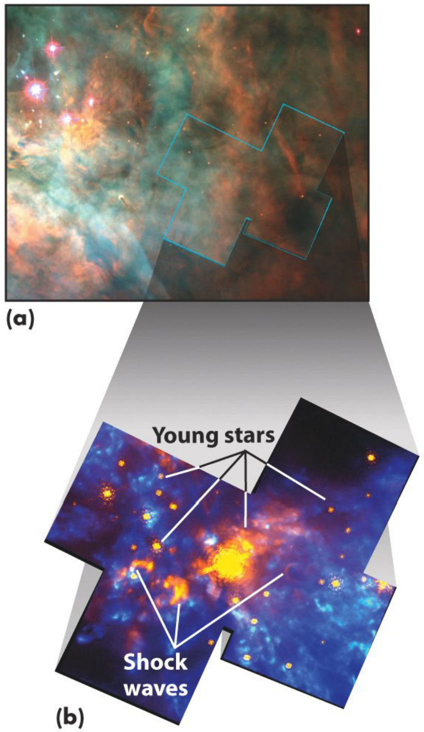
- The most massive protostars to form out of a dark nebula rapidly become main sequence O and B stars
- They emit strong ultraviolet radiation that ionizes hydrogen in the surrounding cloud, thus creating the reddish emission nebulae called H II regions
- Ultraviolet radiation and stellar winds from the O and B stars at the core of an H II region create **shock waves** that move outward through the gas cloud, compressing the gas and triggering the formation of more protostars nearby

Trigger of Star Birth: Shock Waves from O and B Stars



Trigger of Star Birth: Shock Waves from Supernovae Explosion

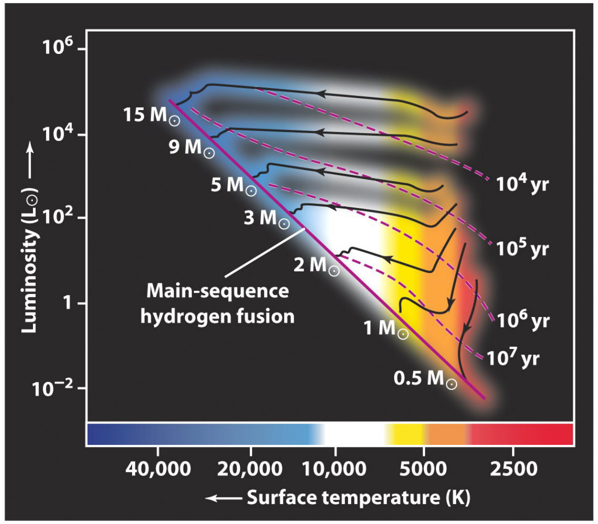




Protostars form in cold, dark nebulae

- Protostar: the clump formed from dense and cold nebula under gravitational contraction
- As a protostar grows by the gravitational accretion of gases, Kelvin-Helmholtz contraction causes it to heat and begin glowing

Protostars evolve into main-sequence stars



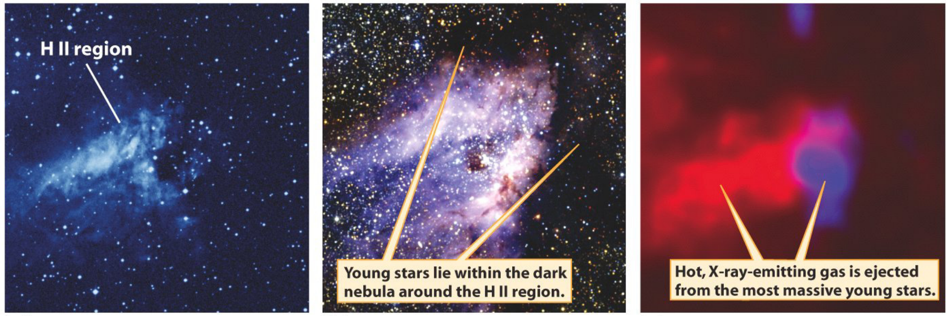
- A protostar's relatively low temperature and high luminosity place it in the upper right region on an H-R diagram
- Further evolution of a protostar causes it to move toward the main sequence on the H-R diagram
- When its core temperatures become high enough to ignite steady hydrogen burning, it becomes a main sequence star

Stellar Evolution Rate

- Greater mass, contracts and heats more rapidly, and hydrogen fusion begins earlier
- Greater mass, greater pressure and temperature in the core
- If protostar less than 0.08 Msun, it can never develop the temperature and pressure to start the hydrogen fusion
- Such "failed" stars end up as brown dwarfs, which shines faintly by Kelvin-Helmholtz contraction

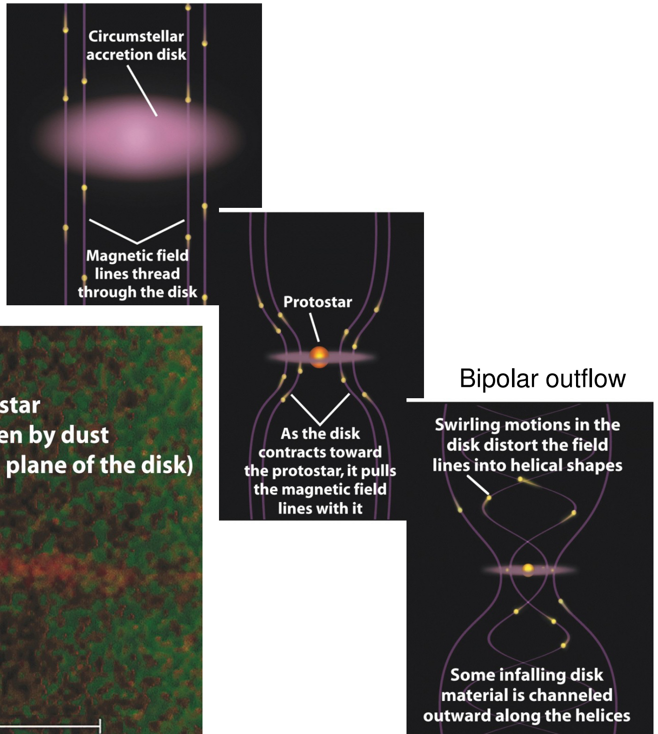
During the birth process, stars both gain and lose mass

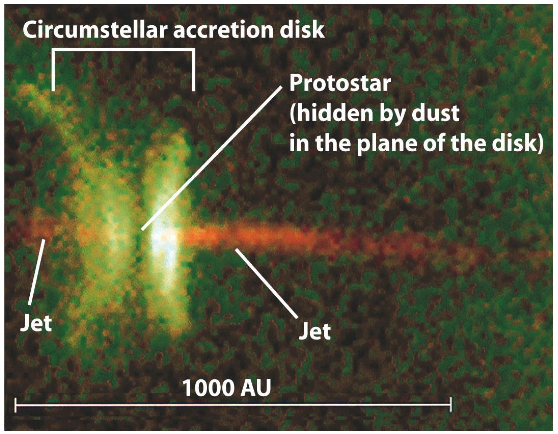
- In the final stages of pre–main-sequence contraction, when thermonuclear reactions are about to begin in its core, a protostar may eject large amounts of gas into space. Low-mass stars that vigorously eject gas are called T Tauri stars (age ~ 1 million year)

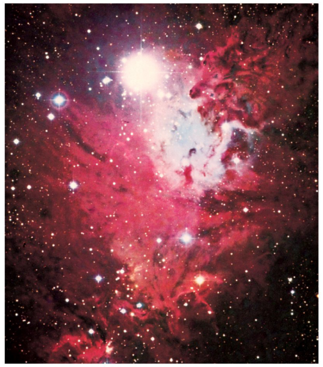


(a) Visible-light image **(b)** False-color infrared image **(c)** False-color X-ray image

A circumstellar accretion disk provides material that a young star ejects as jets






The star cluster NGC 2264


The Pleiades star cluster

Young Star Clusters

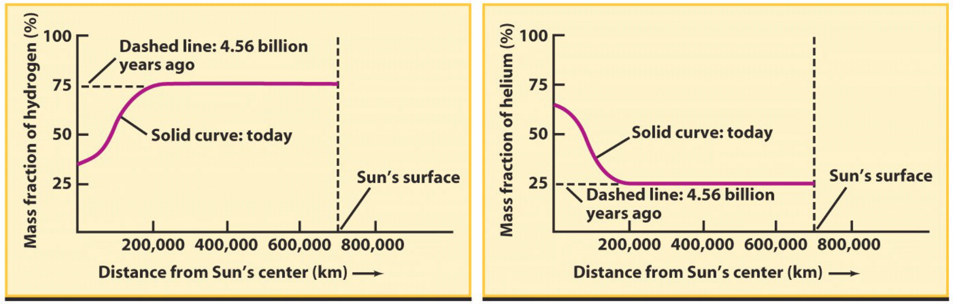
- Newborn stars may form a star cluster
- Stars are held together in such a cluster by gravity
- Occasionally a star moving more rapidly than average will escape from such a cluster
- A stellar association is a group of newborn stars that are moving apart so rapidly that their gravitational attraction for one another cannot pull them into orbit about one another

Guiding Questions

1. How will our Sun change over the next few billion years?
2. Why are red giants larger than main-sequence stars?
3. Do all stars evolve into red giants at the same rate?
4. Why do some giant stars pulsate in and out?

The Sun: 4.5 billion years old

- The Sun has been a main-sequence star for 4.56 billion years, and at the core
  - Hydrogen depleted by about 35%
  - Helium amount increased
- The Sun should remain in main sequence for another 7 billion years
- The Sun or 1 Msun star has a main sequence lifetime of 12 billion years



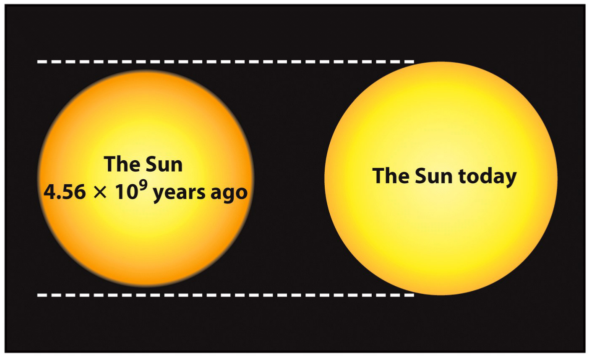
(a) Hydrogen in the Sun's interior (b) Helium in the Sun's interior

The Sun: 4.5 billion years old

During a star's main-sequence lifetime, the star expands somewhat and undergoes a modest increase in luminosity

Over 4.5 billion years, the Sun

- Become 40% more luminous
- Has grown in radius by 6%



A star's lifetime on the main sequence

- The duration of the lifetime depends on two factors
  1. the amount of hydrogen at the core, ~ mass
  2. the rate at which the hydrogen is consumed, ~ luminosity

Because the mass-luminosity relation: $L \sim M^{3.5}$

- The duration $T \sim$ mass/burning rate $\sim M/M^{3.5} \sim 1/M^{2.5}$
- As a ratio of two stars $T_1/T_2=(M_2/M_1)^{2.5}$
- Question: T = 12 billion years for 1 Msun star, what T for 10 Msun star?

  $Tsun/T = (1/10)^{2.5}$

  Or T = 38 million years for a 10 Msun star

A star's lifetime on the main sequence

- O star, 25 Msun, 4 million years
- G star, 1 Msun, 12 billion years
- M star, 0.50 Msun, 700 billion year

table 21-1 **Approximate Main-Sequence Lifetimes**

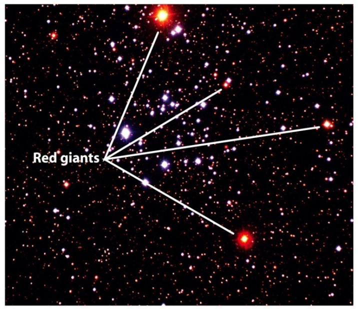
Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetime (10^6 years)
25	35,000	O	80,000	4
15	30,000	B	10,000	15
3	11,000	A	60	800
1.5	7000	F	5	4500
1.0	6000	G	1	12,000
0.75	5000	K	0.5	25,000
0.50	4000	M	0.03	700,000

The main-sequence lifetimes were estimated using the relationship $t \propto 1/M^{2.5}$ (see Box 21-2).

After Main Sequence, star becomes a red giant

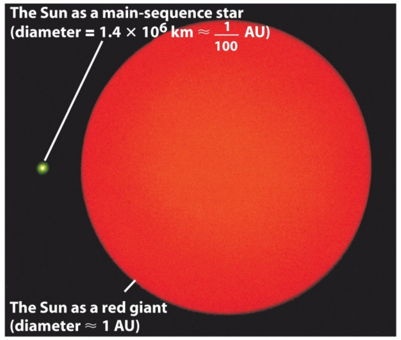
- Hydrogen fusion ceases at the core
- Core contracts, and temperature increases
- Shell hydrogen fusion occurs just outside the core
- Shell hydrogen fusion works its way outward in the star and adds more helium into the core; core becomes hotter
- Shell hydrogen fusion occurs at a greater rate
- Outer layers expands because of the increased energy flow
- A main sequence star is now gradually becoming a red giant star

Red Giants



Red giant stars in the star cluster M50

- Giant: it is very luminous because of its large size.
- Red: it is red due to its low surface temperature
- Surface temperature drops as a result of gas expansion in the outer layer



The Sun today and as a red giant

- The Sun → red giant (after ~ 7 billion years)
- 100 times larger
- 2000 times brighter
- Temperature drop to 3500 K

Red Giants: core Helium fusion

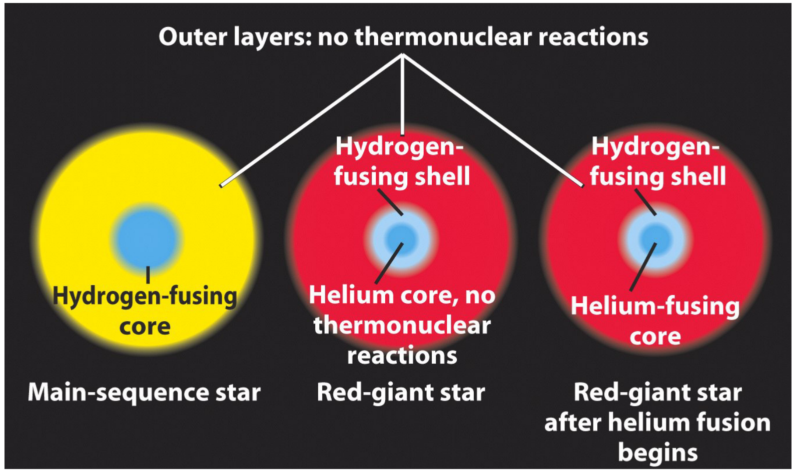
- With time, more helium "ash" adds into the core
- Core contracts more and becomes even hotter
- When the central temperature reaches 100 million K (10^8 K), helium fusion ignites inside the core
- Helium fusion process, also called the **triple alpha process**, converts helium to carbon:

  $3\ ^4He \rightarrow\ ^{12}C + \text{energy}$
- Or form stable Oxygen

  $^{12}C +\ ^4He \rightarrow\ ^{16}O + \text{energy}$
- (note: helium nucleus called alpha particle)

Summary of Stellar Evolution

- Main sequence: core hydrogen fusion
- Red giant (stage 1): shell hydrogen fusion
- Red giant (stage 2): shell hydrogen fusion + core helium fusion



Ignition of Helium Fusion

- In a more massive red giant, helium fusion begins gradually
- In a less massive red giant (< 3 Msun), the ignition of helium fusion begins suddenly, in a process called helium flash, which lasts seconds

table 21-2 How Helium Core Fusion Begins in Different Red Giants

Mass of star	Onset of helium burning in core
Less than 2–3 solar masses	Explosive (helium flash)
More than 2–3 solar masses	Gradual

Helium Flash

- In low-mass star, the compressed core is not an ideal gas, instead it is in an **electron-degeneracy** state
- **Electron-degeneracy**: the electrons are so closely packed that they can not be further compressed. The core of a low-mass star becomes eventually being supported by degenerate-electron pressure
- Degenerate-electron pressure is independent of temperature. As helium fusion ignites in the core, temperature rises, but pressure does not rise. Helium fusion rate rises exponentially, which results in helium flash
- During the brief time of helium flash, the core is extremely bright (10^{11} Lsun). When the temperature becomes very high, electron in the core is not degenerate any more; the core becomes an ideal gas (=> stable He fusion in the core)

After ignition of helium fusion

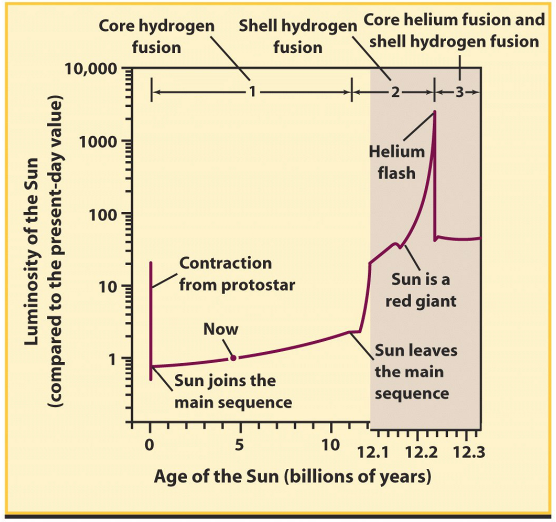
The core settles down to a steady state of helium fusion

A red giant enters into the stage of "**Horizontal Branch**" in the H-R diagram

- **Red giant becomes less luminous and smaller, but hotter.** The core is in a steady state:
  - Temperature increases, core expands
  - Core expands, temperature decreases
- Shell hydrogen fusion rate drops that lead to a lower luminosity
- Red-giant star shrinks because of less energy output
- The giant become hotter at surface as it compresses

Summary Evolution of the Sun

- Protostar: ~ 10 M yrs
- Main sequence: core hydrogen fusion, 12 billion years
- Red Giant (before helium flash): shell hydrogen burning; 250 million years
- Red Giant (after helium flash): core helium fusion and shell hydrogen burning; 100 million years
- Death (become a white dwarf): helium in the core exhausted

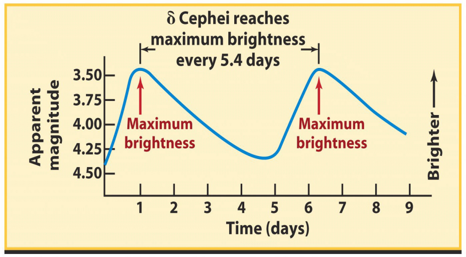


Two populations of Stars

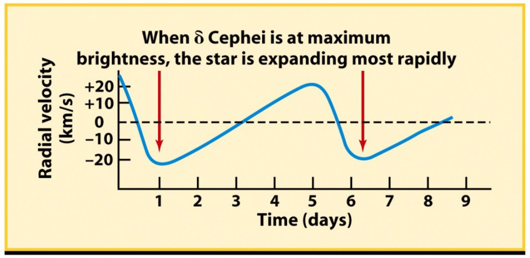
Population I	Population II
rich in metal absorption lines e.g., the Sun	poor in metal absorption lines
Metal rich	Metal poor
Second or later generation stars	First generation stars
	Generate metals at the core, and expel them into interstellar medium upon death

Cepheid Stars

- Brightness varies cyclically in time scale of days
- Brightness changes because the outer envelope cyclically expands and contracts



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



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

Doppler Effect