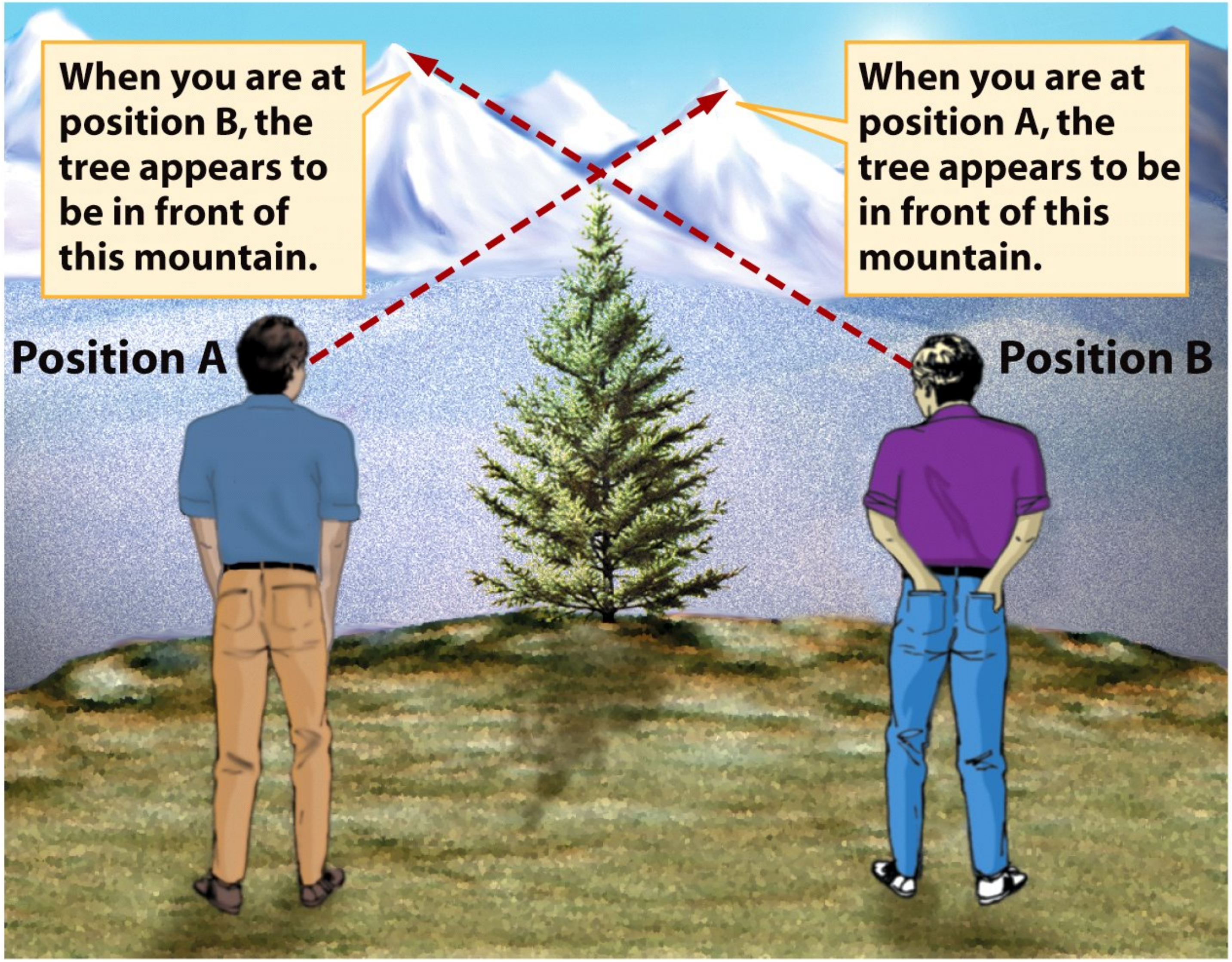
1. The Nature of the Stars

Guiding Questions

1. How far away are the stars?
2. What evidence do astronomers have that the Sun is a typical star?
3. What is meant by a "first-magnitude" or "second magnitude" star?
4. Why are some stars red and others blue?
5. What are the stars made of?
6. As stars go, is our Sun especially large or small?
7. What are giant, supergiant, and white dwarf stars?
8. How do we know the distances to really remote stars?
9. Why are binary star systems important in astronomy?
10. How can a star's spectrum show whether it is actually a binary star system?
11. What do astronomers learn from stars that eclipse each other?

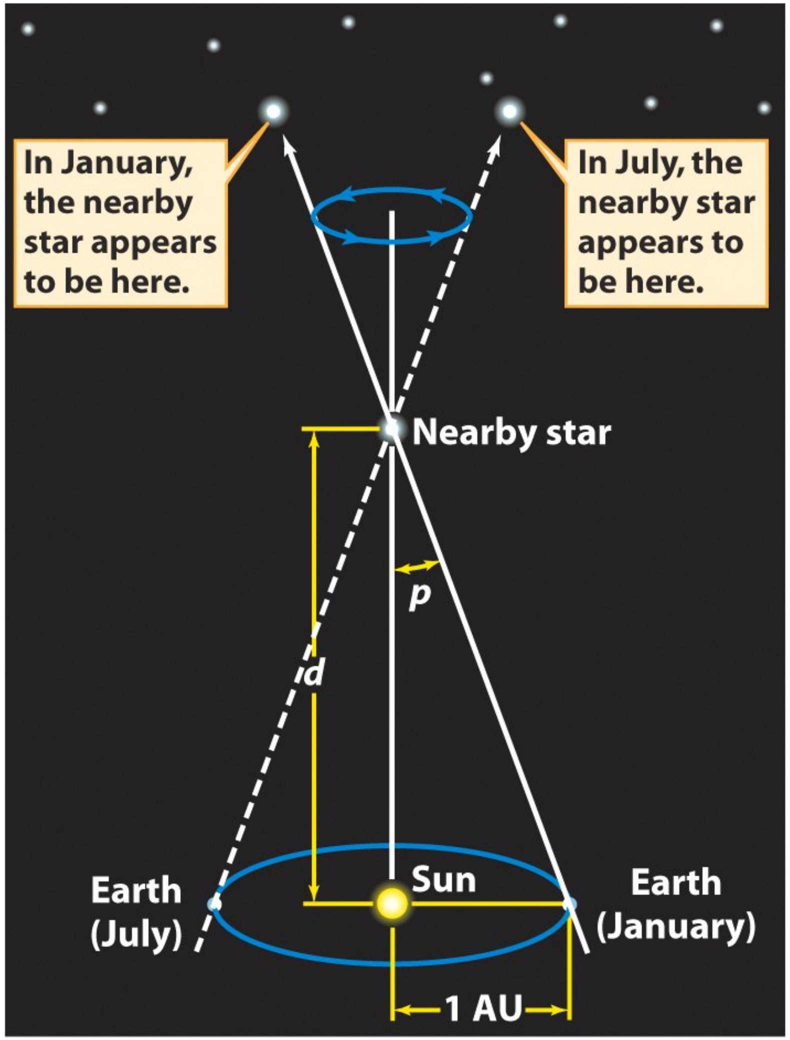
Parallax

- The apparent displacement of a nearby object against a distant fixed background from two different viewpoints.



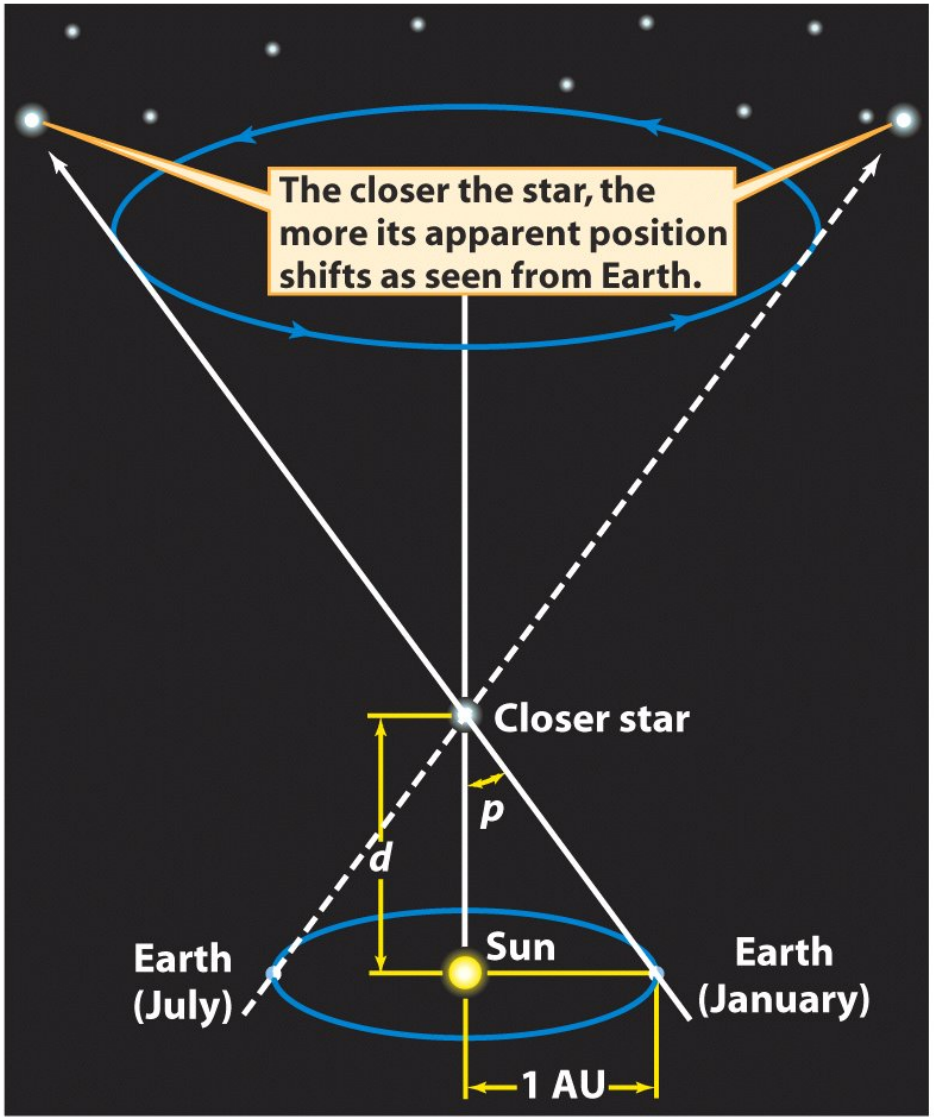
Stellar Parallax

- The apparent position shift of a star as the Earth moves from one side of its orbit to the other (the largest separation of two viewpoints possibly from the Earth)



Parallax of a nearby star

Stellar Parallax



Parallax of an even closer star

Stellar Parallax and Distance

Relation between a star's distance and its parallax

$$d = \frac{1}{p}$$

d = distance to a star, in parsecs

p = parallax angle of that star, in arcseconds

1 pc = 3.26 ly

1 pc = 206,265 AU = 3.09 X 10^{13} km

- Distances to the nearer stars can be determined by parallax, the apparent shift of a star against the background stars observed as the Earth moves along its orbit

Once a star's distance is known ….. Luminosity and brightness

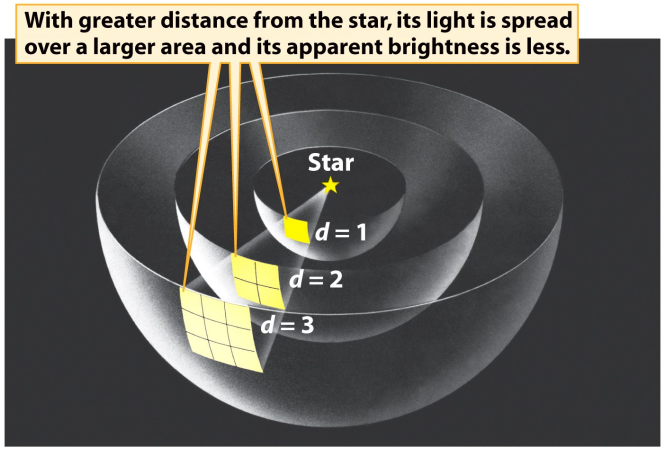
Inverse-square law relating apparent brightness and luminosity

$$b = \frac{L}{4\pi d^2}$$

b = apparent brightness of a star's light, in W/m^2

L = star's luminosity, in W

d = distance to star, in meters



- A star's luminosity (total light output), apparent brightness, and distance from the Earth are related by the inverse-square law
- If any two of these quantities are known, the third can be calculated

Stellar Parallax

- **All known star have parallax angles less than one arcsec (1”), m**eaning their distance more than 1 parsec (pc)
- Stellar parallaxes can only be measured for stars within a few hundred parsecs

- The closest star Proxima Centauri has a parallax angle of 0.772 arcsec
- d=1/p => d=1/(0.772 arcsec) => d =1.30 pc
- d = 1.30 pc => d = 4.24 ly
- Therefore, the closest star is 4.24 light years away

Luminosity, Brightness and Distance

Determining a star's luminosity from its apparent brightness

$$\frac{L}{L_\odot} = \left(\frac{d}{d_\odot}\right)^2 \frac{b}{b_\odot}$$

$L/L_\odot$ = ratio of the star's luminosity to the Sun's luminosity

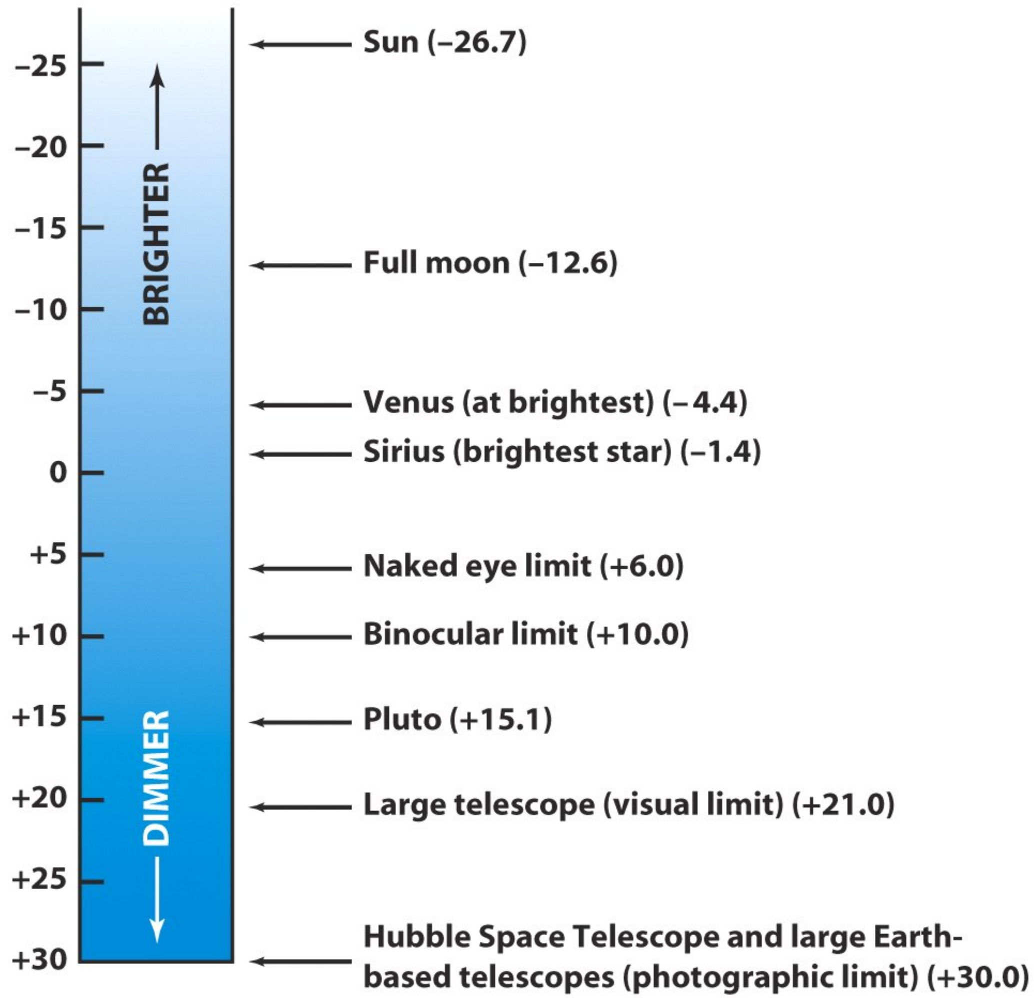
$d/d_\odot$ = ratio of the star's distance to the Earth-Sun distance

$b/b_\odot$ = ratio of the star's apparent brightness to the Sun's apparent brightness

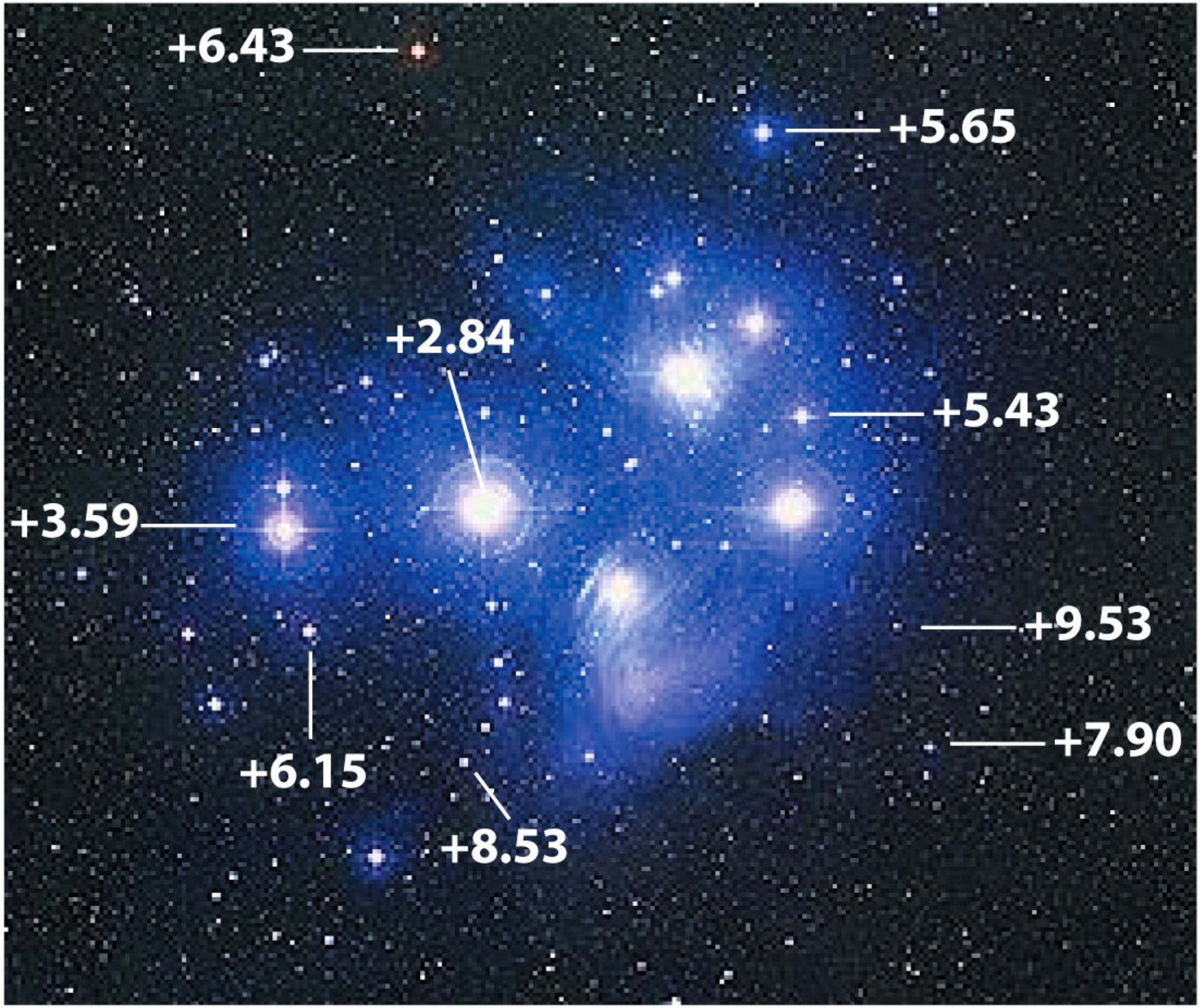
- Many visible stars turn out to be more luminous than the Sun

Magnitude Scale to Denote brightness

- **Apparent magnitude** scale is a traditional way to denote a star's apparent brightness (~ 200 B.C. by Greek astronomer Hipparchus)
- First magnitude, the brightest
- Second magnitude, less bright
- Sixth magnitude, the dimmest one human naked eyes see



Some apparent magnitudes



Apparent magnitudes of stars in the Pleiades

七姊妹星團

Apparent Magnitude and Absolute Magnitude

- **Apparent magnitude** is a measure of a star's apparent brightness as seen from Earth
  - the magnitude depends on the distance of the star

- **Absolute magnitude** is the apparent magnitude a star would have if it were located exactly 10 parsecs (32.6 lyr) from Earth
  - This magnitude is independent of the distance
  - One way to denote the intrinsic luminosity of a star in the unit of magnitude

- The Sun's apparent magnitude is -26.7
- The Sun absolute magnitude is +4.8

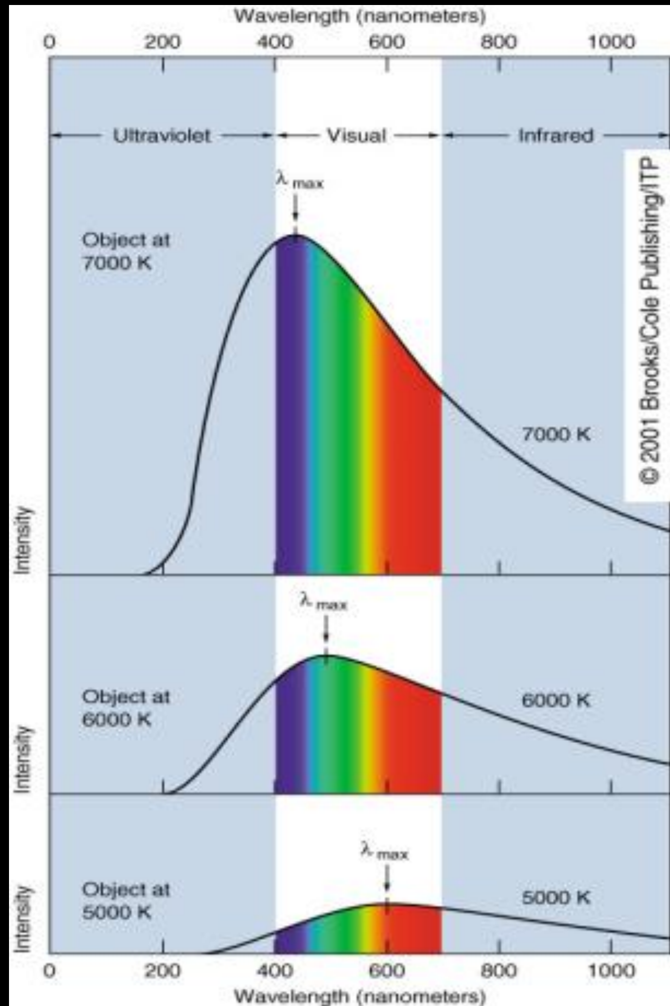
Scale of Magnitude

- The first magnitude star is 100 times brighterthan the sixth magnitude star
- A magnitude difference of 1 corresponds to a factor of 2.512 in brightness
- Magnitude difference of 5 corresponds to a factor of 100 in brightness

Blackbody radiation

A blackbody reflects no light. When it is kept at temperature T, it emits EM-waves from each unit area of the surface with a spectrum given by,

$$I(\lambda) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda k_B T} - 1}$$



$$\text{Total power/(unit area)} = \int_0^\infty I(\lambda)\,d\lambda = \sigma T^4$$

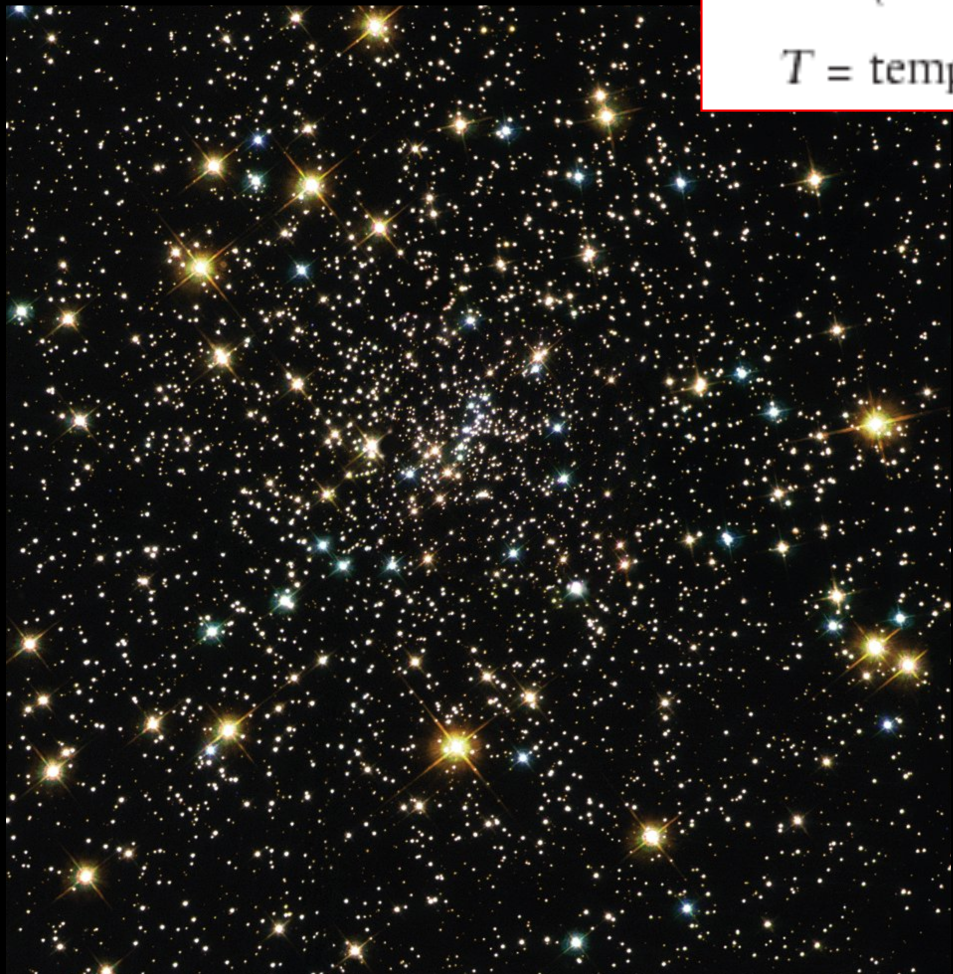
where $\sigma = 5.67 \times 10^{-8}\ \mathrm{W/(m^2K^4)}$

A star's color depends on its surface temperature

$$\lambda_{max} = \frac{0.0029 \text{ K m}}{T}$$

λ_{max} = wavelength of maximum emission of the object (in meters)

T = temperature of the object (in kelvins)



Wien's Law

A star's color depends on its surface temperature

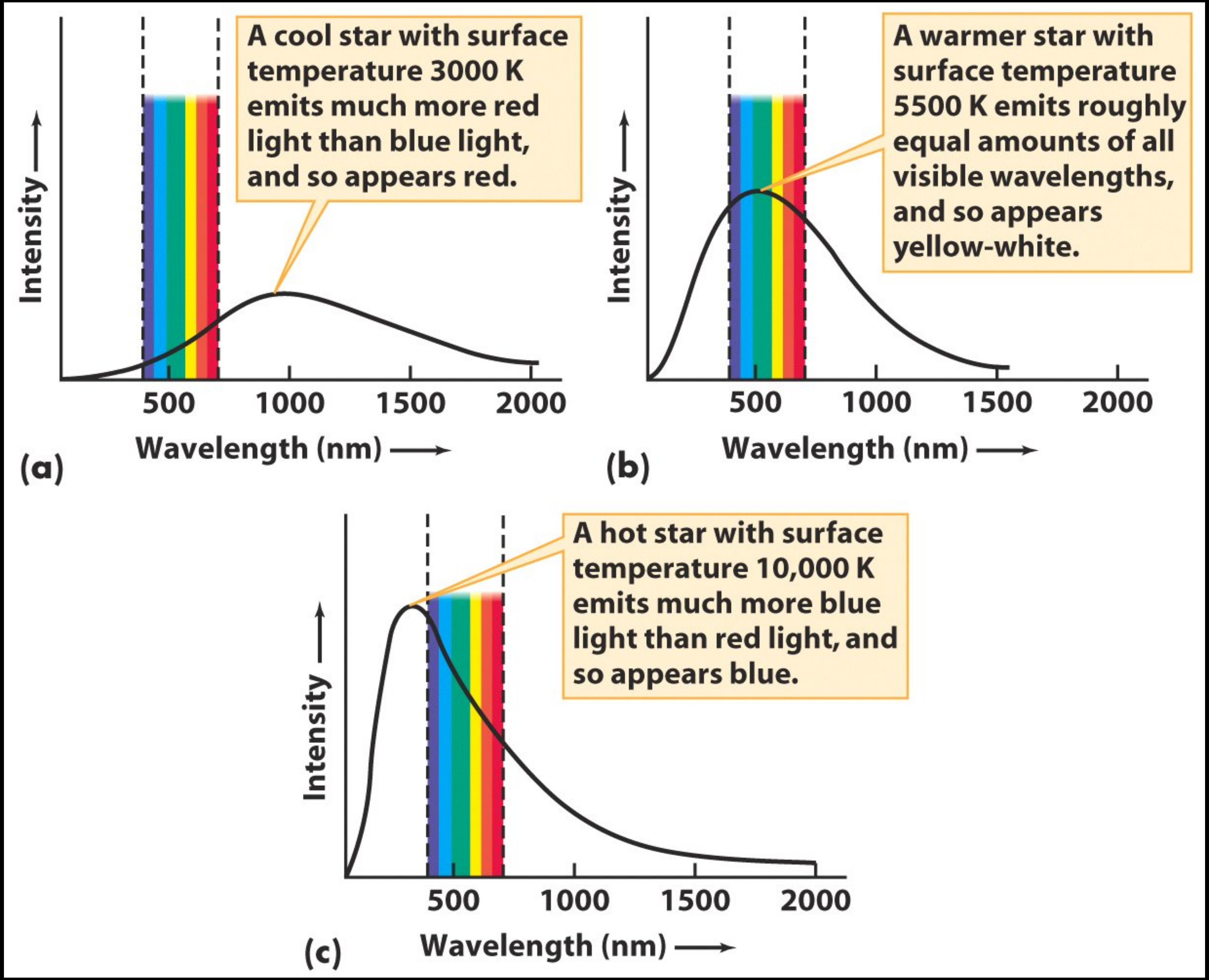
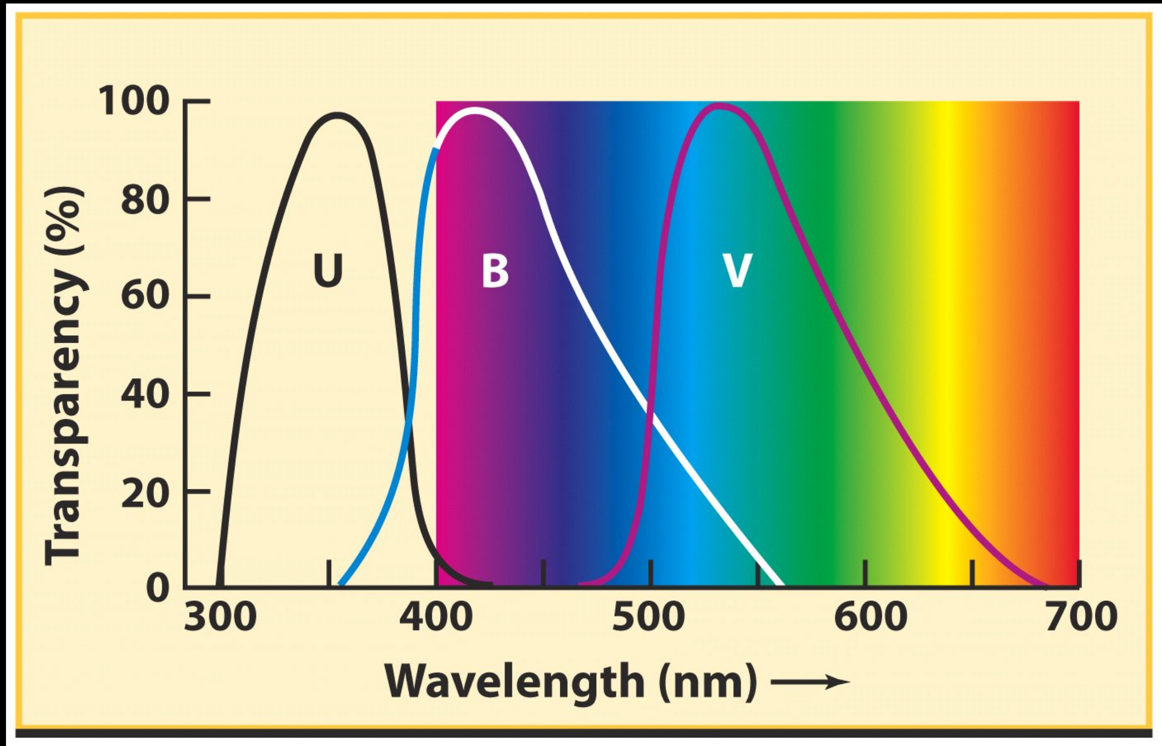


table 19-1 Colors of Selected Stars

Star	Surface temperature (K)	b_V/b_B	b_B/b_U	Apparent color
Bellatrix (γ Orionis)	21,500	0.81	0.45	Blue
Regulus (α Leonis)	12,000	0.90	0.72	Blue-white
Sirius (α Canis Majoris)	9400	1.00	0.96	Blue-white
Megrez (δ Ursae Majoris)	8630	1.07	1.07	White
Altair (α Aquilae)	7800	1.23	1.08	Yellow-white
Sun	5800	1.87	1.17	Yellow-white
Aldebaran (α Tauri)	4000	4.12	5.76	Orange
Betelgeuse (α Orionis)	3500	5.55	6.66	Red

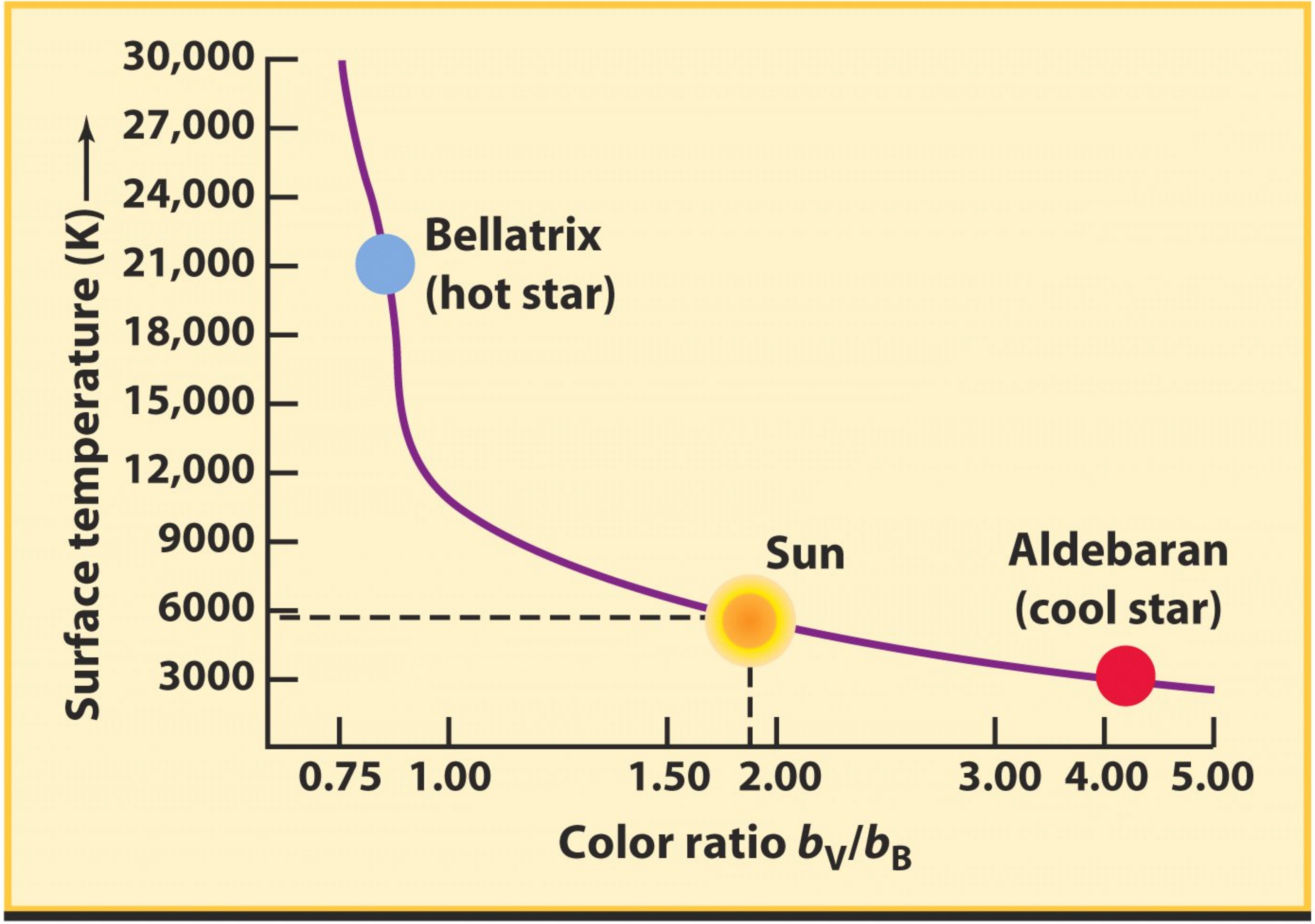
Source: J.-C. Mermilliod, B. Hauck, and M. Mermilliod, University of Lausanne.

Photometry, Filters and Color Ratios



- **Photometry** measures the apparent brightness of a star
- **Standard filters**, such as U (Ultraviolet), B (Blue) and V (Visual, yellow-green) filters,
- **Color ratios** of a star are the ratios of brightness values obtained through different filters
- These ratios are a good measure of the star's **surface temperature;** this is an easy way to get temperature

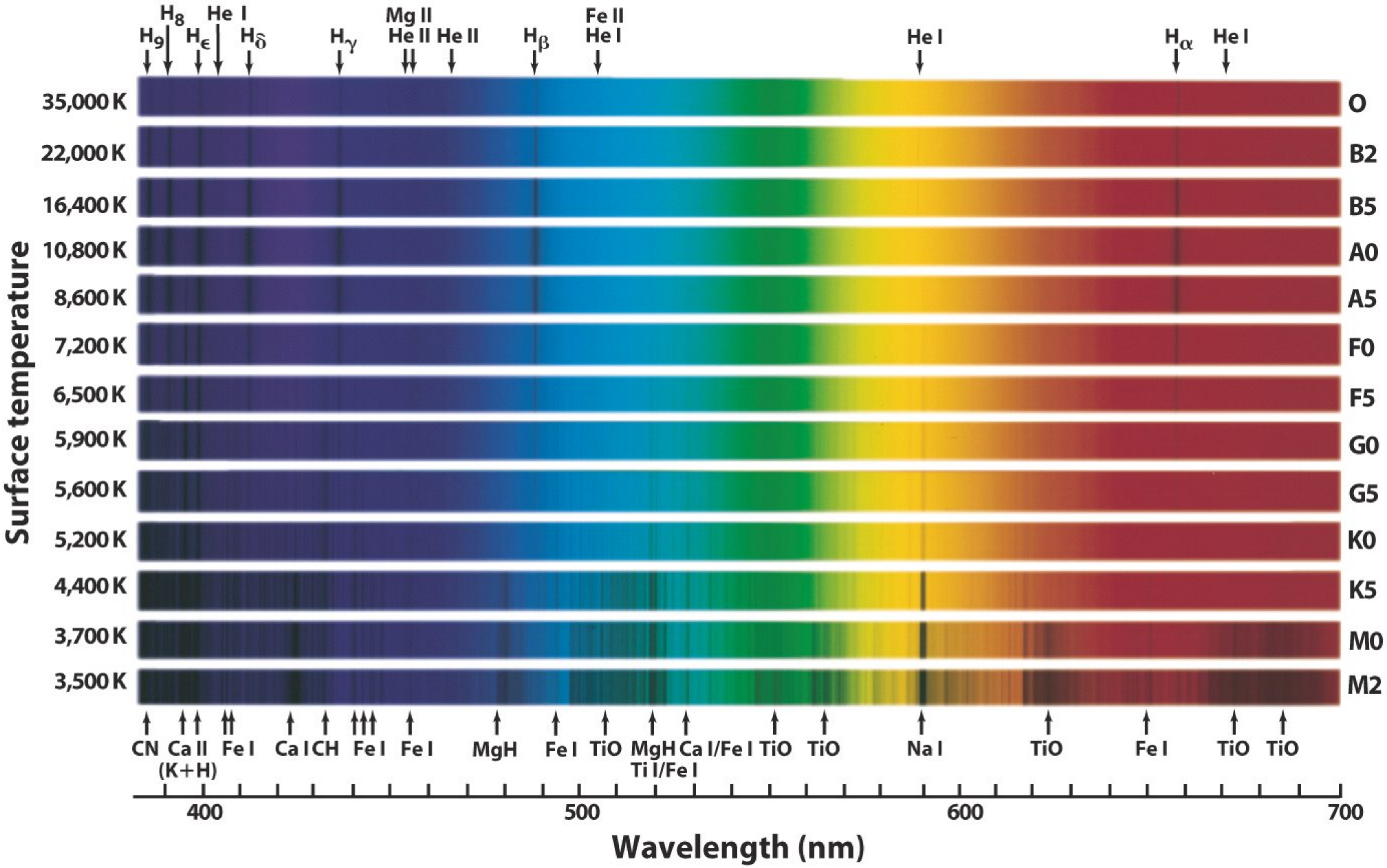
Surface temperature and Color Ratio



The spectra reveal more about stars

- Stellar spectroscopy
- Stars are classified into different spectral types according to the strength or weakness of the hydrogen Balmer lines in the star's spectrum

Stellar Spectrum

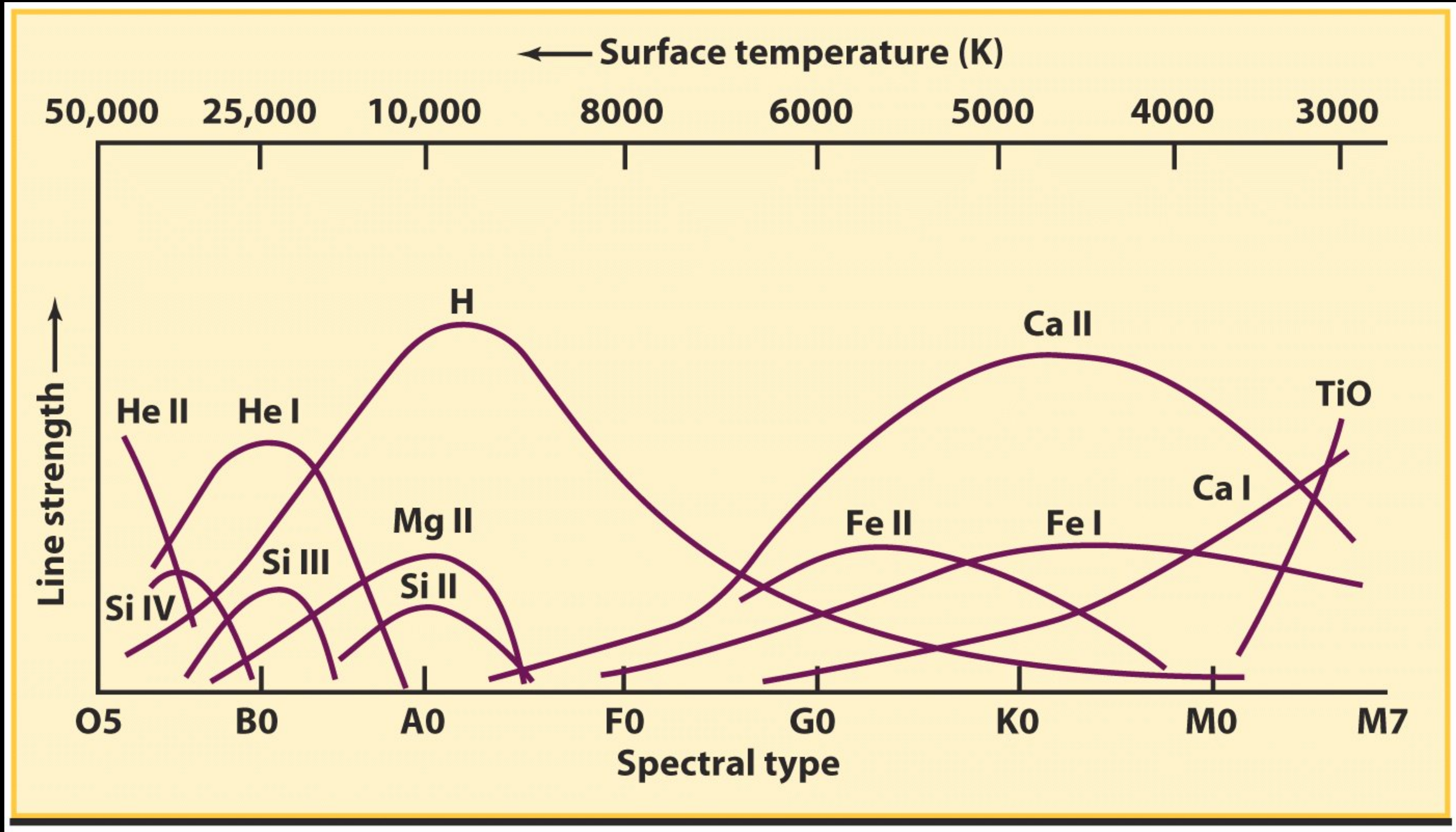


- E.g., Balmer lines: Hydrogen lines of transition from higher orbits to n=2 orbit; Hα (orbit 3 -> 2) at 656 nm

Classic Spectral Types

- **O B A F G K M**
- (**O**h, **B**e **A** **F**ine **G**irl, **K**iss **M**e!) (mnemonic)
- Spectral type is directly related to surface temperature
- From O to M, the temperature decreases
- O type, the hottest, blue color, Temp ~ 25000 K
- M type, the coolest, red color, Temp ~ 3000 K
- Sub-classes, e.g. B0, B1…B9, A0, A1…A9
- The Sun is a G2 type of star (temp. 5800 K)

Classic Spectral Types



The spectral class and type of a star is directly related to its surface temperature: O stars are the hottest and M stars are the coolest

More Types: Brown dwarf stars

table 19-2 The Spectral Sequence

Spectral class	Color	Temperature (K)	Spectral lines	Examples
O	Blue-violet	30,000–50,000	Ionized atoms, especially helium	Naos (ζ Puppis), Mintaka (δ Orionis)
B	Blue-white	11,000–30,000	Neutral helium, some hydrogen	Spica (α Virginis), Rigel (β Orionis)
A	White	7500–11,000	Strong hydrogen, some ionized metals	Sirius (α Canis Majoris), Vega (α Lyrae)
F	Yellow-white	5900–7500	Hydrogen and ionized metals such as calcium and iron	Canopus (α Carinae), Procyon (α Canis Minoris)
G	Yellow	5200–5900	Both neutral and ionized metals, especially ionized calcium	Sun, Capella (α Aurigae)
K	Orange	3900–5200	Neutral metals	Arcturus (α Boötis), Aldebaran (α Tauri)
M	Red-orange	2500–3900	Strong titanium oxide and some neutral calcium	Antares (α Scorpii), Betelgeuse (α Orionis)
L	Red	1300–2500	Neutral potassium, rubidium, and cesium, and metal hydrides	Brown dwarf Teide 1
T	Red	below 1300	Strong neutral potassium and some water (H_2O)	Brown dwarf Gliese 229B

- Most brown dwarfs are in even cooler spectral classes called L and T
- Unlike true stars, brown dwarfs are too small to sustain thermonuclear fusion

Luminosity, Radius, and Surface Temperature

$$L = 4\pi R^2 \sigma T^4$$

L = star's luminosity, in watts

R = star's radius, in meters

σ = Stefan-Boltzmann constant = 5.67×10^{-8} W m^{-2} K^{-4}

T = star's surface temperature, in kelvins

- Reminder: Stefan-Boltzmann law states that a blackbody radiates electromagnetic waves with a total energy flux (Total power per unit area) *F* directly proportional to the fourth power of the Kelvin temperature *T* of the object:

$$\text{Total power/(unit area)} = \int_0^\infty I(\lambda)\,d\lambda = \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8}$ W/(m^{2}K^4)

Luminosity, Radius, and Surface Temperature

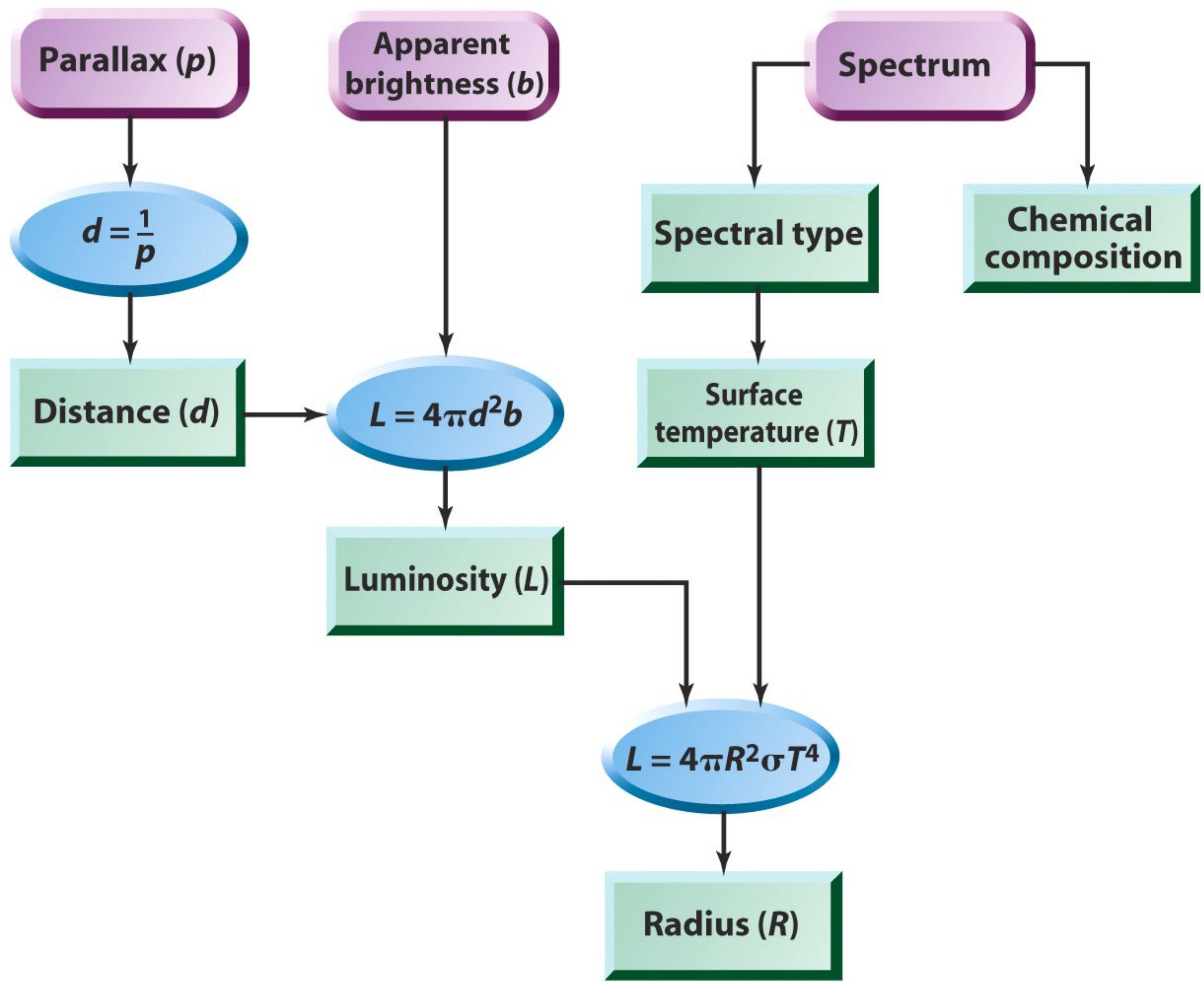
- A more luminous star could be due to
  - Larger size (in radius)
  - Higher Surface Temperature

- Example: The first magnitude reddish star Betelgeuse is 60,000 time more luminous than the Sun and has a surface temperature of 3500 K, what is its radius (in unit of the solar radius)?

R = 670 Rs (radius of the Sun)

A Supergiant star

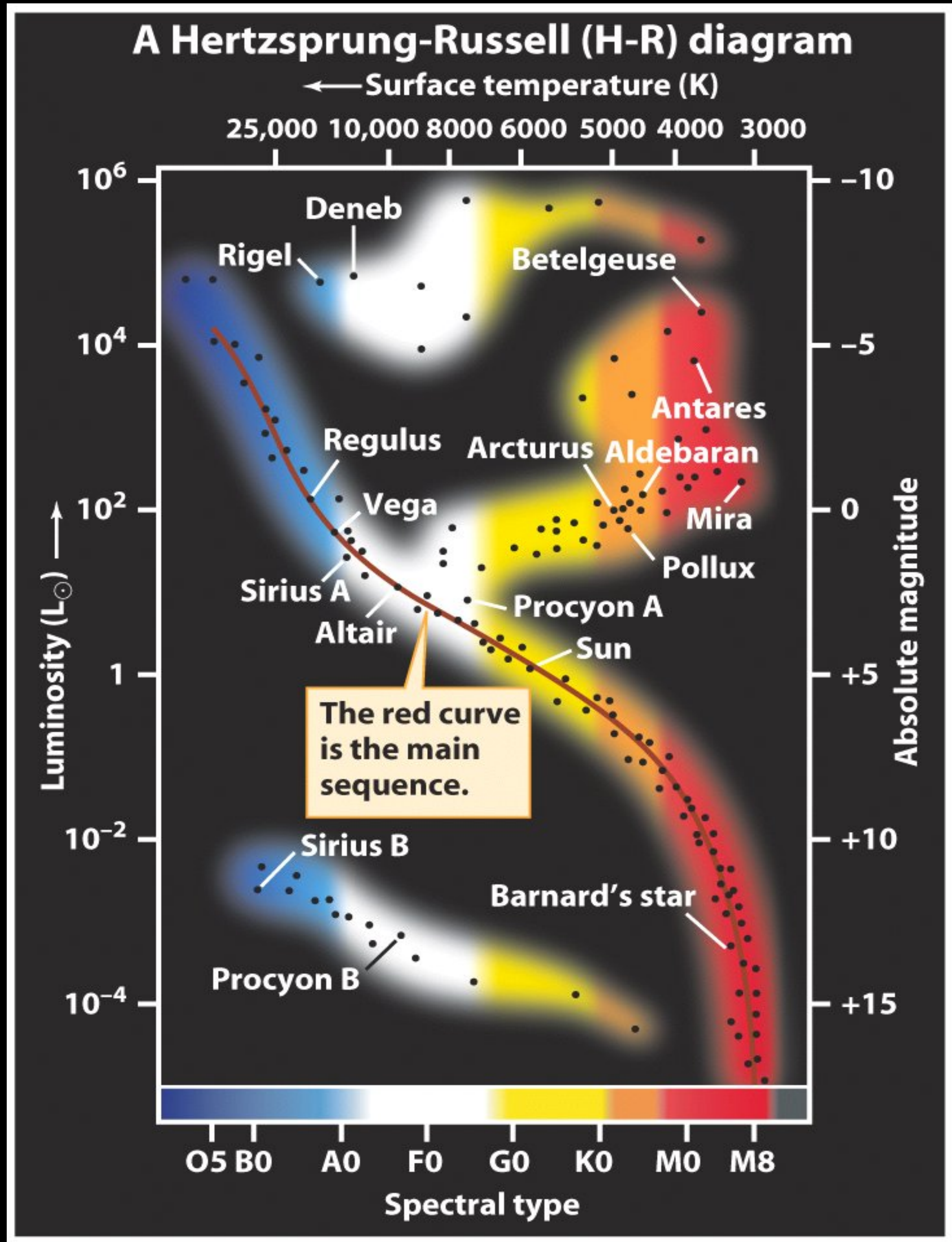
Finding Key Properties of Nearby Stars



Hertzsprung-Russell (H-R) diagrams reveal the patterns of stars

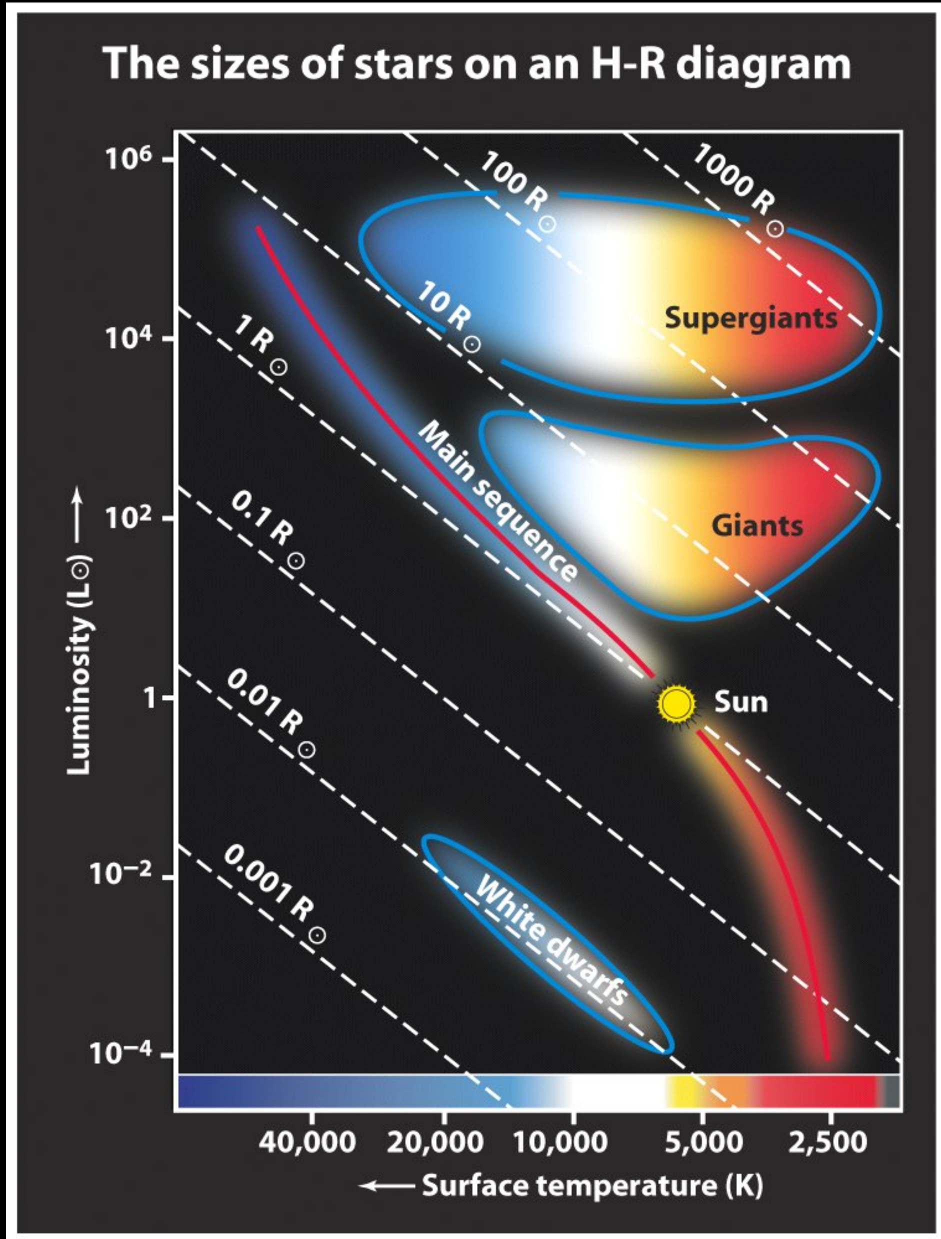
- The H-R diagram is a graph plotting the absolute magnitudes of stars against their spectral types—or, equivalently, their luminosities against surface temperatures

- There are patterns



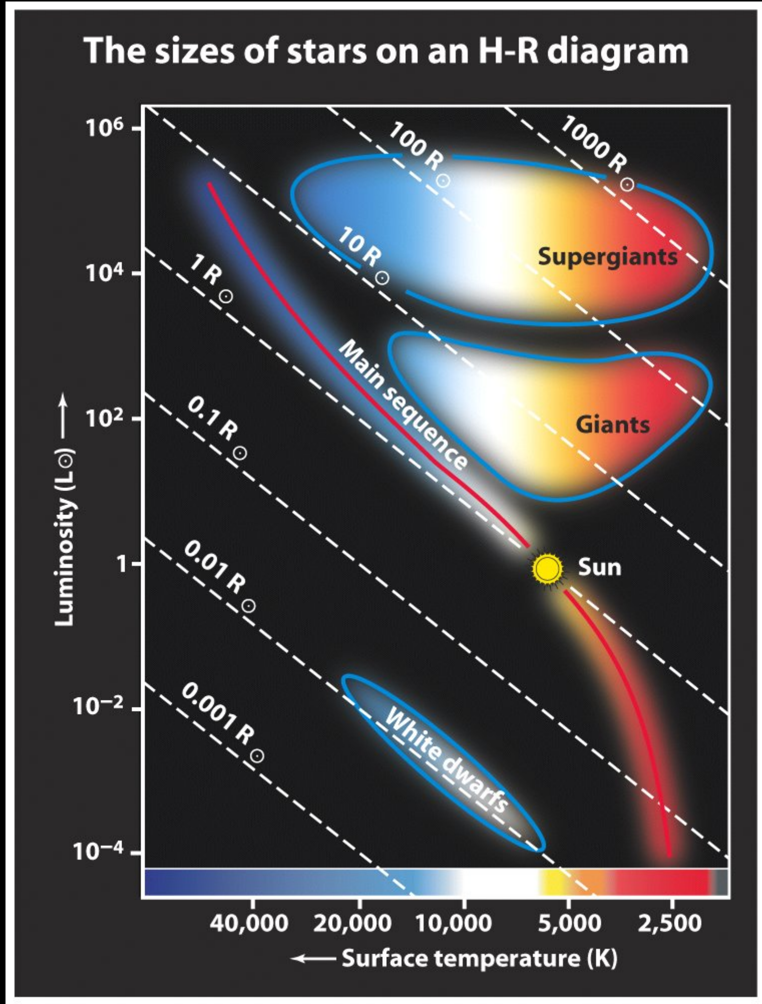
Hertzsprung-Russell (H-R) diagram
the patterns of stars

- The size can be denoted (dotted lines)
  0.001 Rs
  To
  1000 Rs



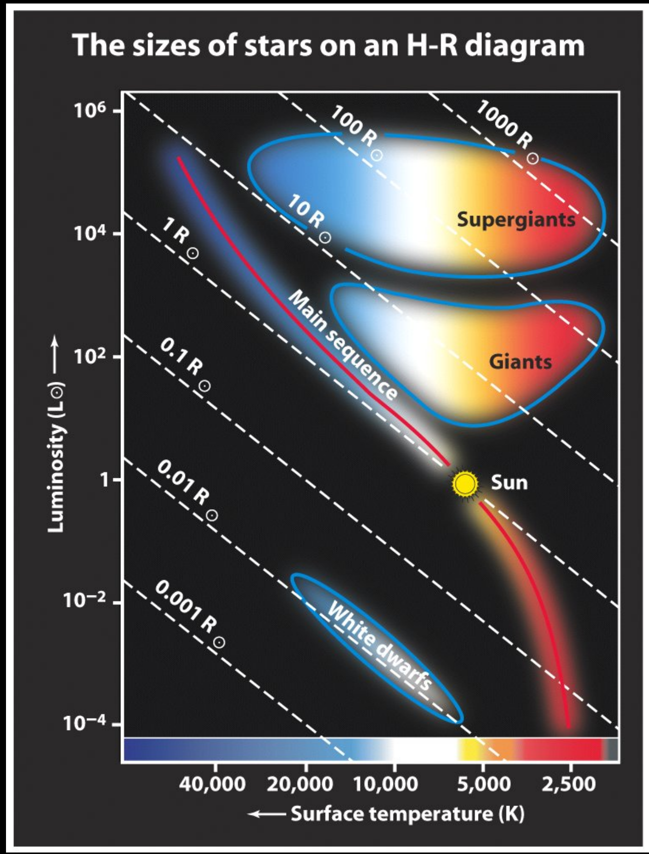
Hertzsprung-Russell (H-R) diagram
the patterns of stars

- Main Sequence: the band stretching diagonally from top-left (high luminosity and high surface temperature) to bottom-right (low luminosity and low surface temperature)
  - 90% stars in this band
  - The Sun is one of main sequence stars
  - Hydrogen burning as energy source



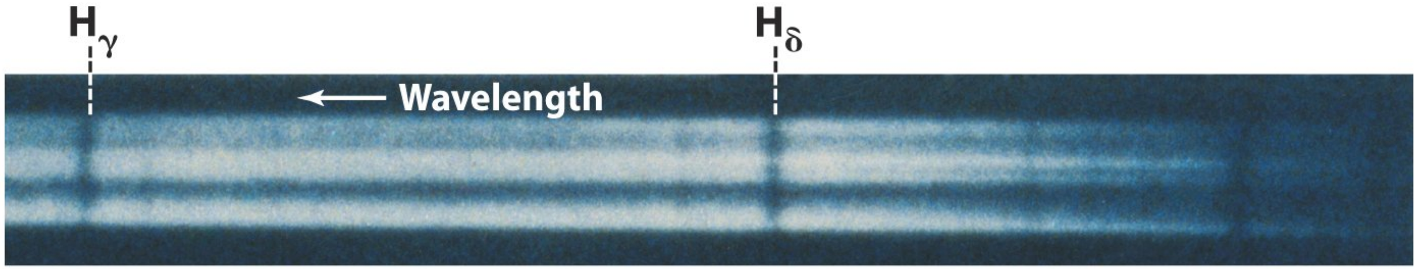
Hertzsprung-Russell (H-R) diagram
the patterns of stars

- Main Sequence
- Giants
  - upper- right side
  - Luminous (100 – 1000 Lsun)
  - Cool (3000 to 6000 K)
  - Large size (10 – 100 Rsun)
- Supergiants
  - Most upper-right side
  - Luminous (10000 - 100000 Lsun)
  - Cool (3000 to 6000 K)
  - Huge (1000 Rsun)
- White Dwarfs
  - Lower-middle
  - Dim (0.01 Ls)
  - Hot (10000 K)
  - Small (0.01 Rs)

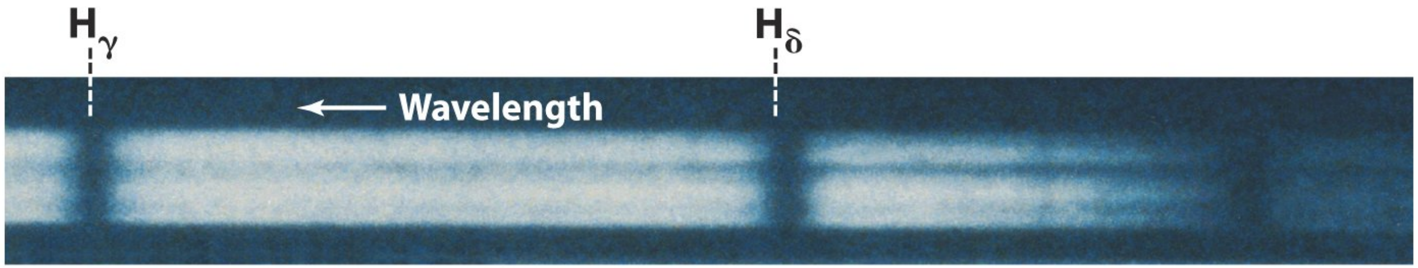


Spectroscopic Parallax

- The presence of spectral lines are used to determine the spectral type of a star, thus the surface temperature
- In addition, by carefully examining the spectral lines, e.g., the width or profile of lines, astronomers can determine the luminosity of a star
- The greater the luminosity, the narrower the spectral line



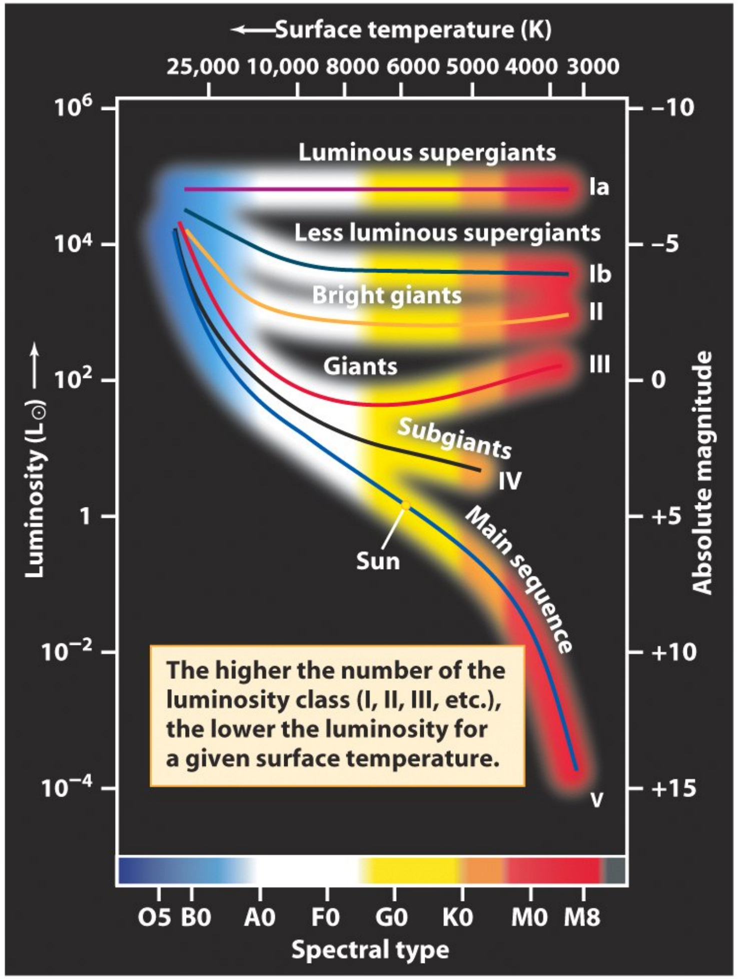
(a) A supergiant star has a low-density, low-pressure atmosphere: its spectrum has narrow absorption lines



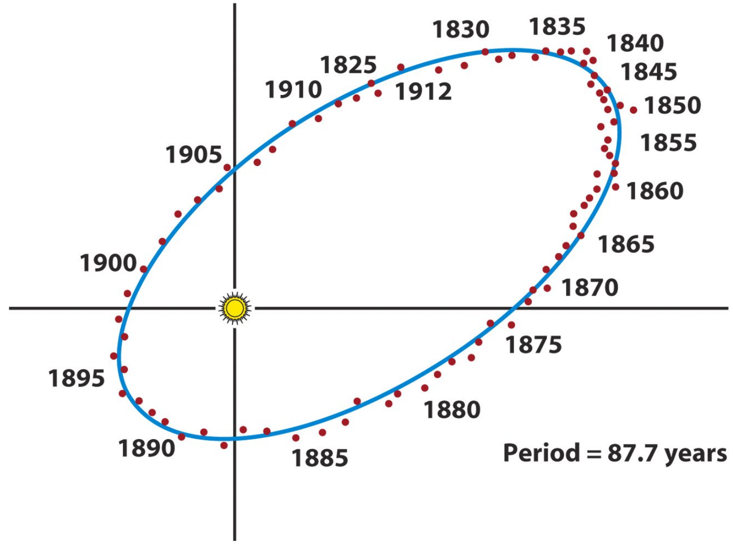
(b) A main-sequence star has a denser, higher-pressure atmosphere: its spectrum has broad absorption lines

Spectroscopic Parallax

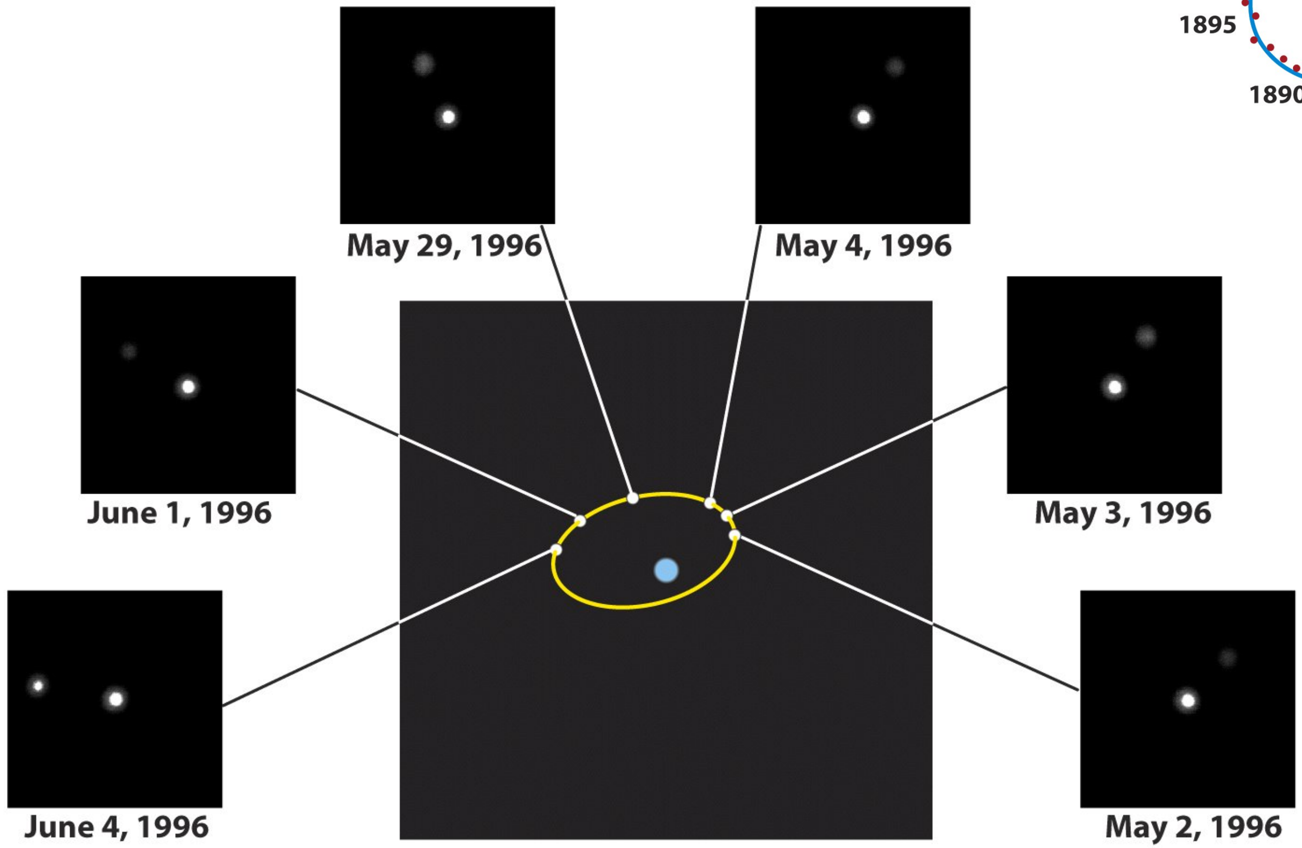
- Using luminosity inferred from spectrum, the star' s distance can be calculated using the inverse square law.
- **This method can apply for remote stars**, e.g., millions parsec away
- By contrary, stellar parallex is only for stars within a few hundred parsec



A way to obtain the MASS of stars
Binary Star System



Period: ~ 80 days

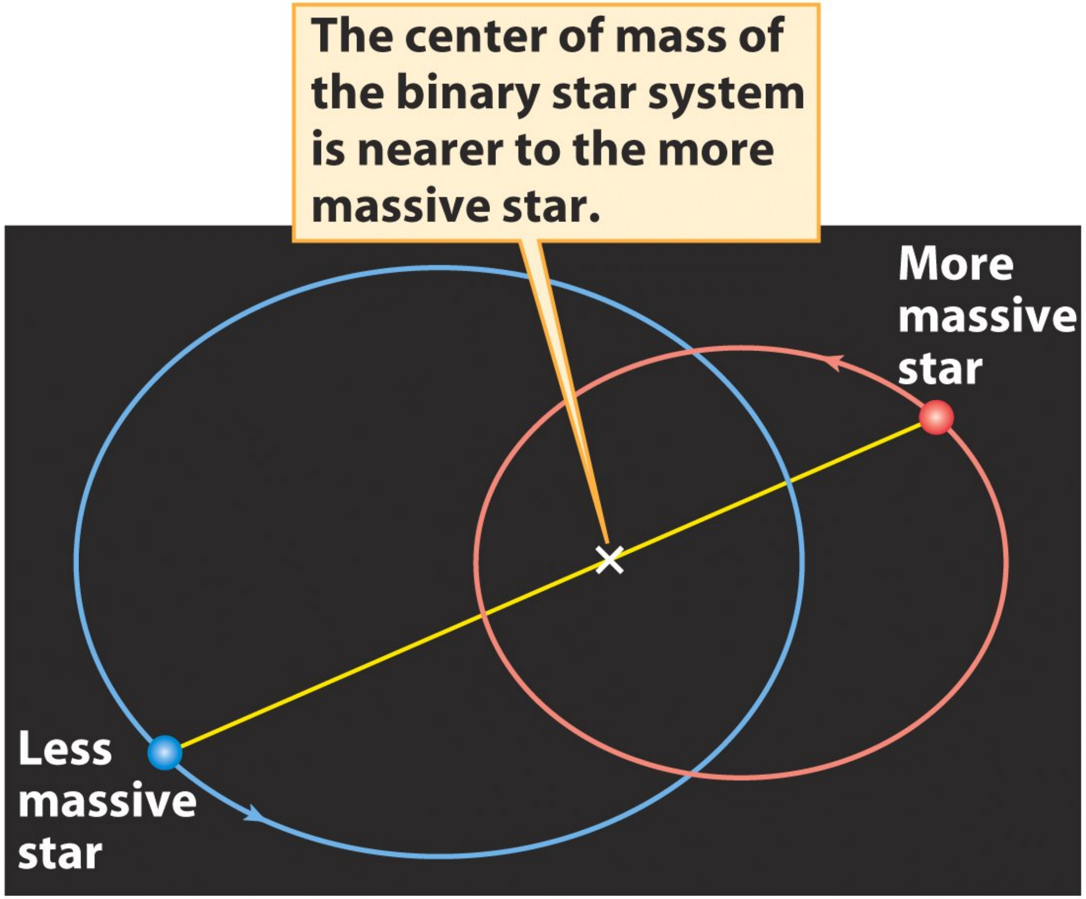


Binary Stars

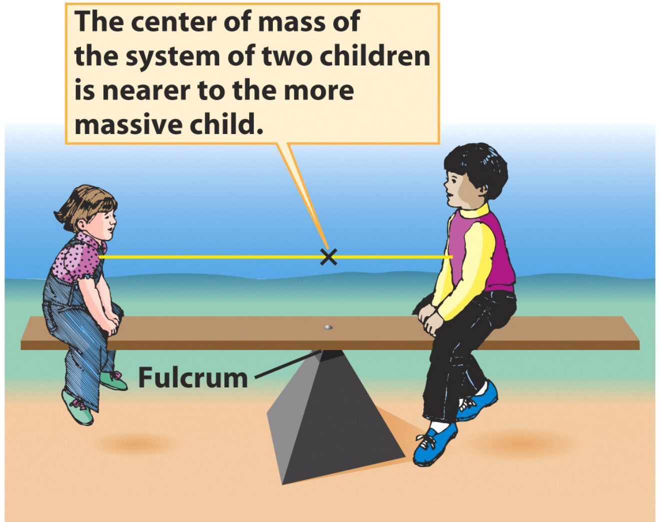
- Binary stars are two stars which are held in orbit around each other by their mutual gravitational attraction, are surprisingly common
- **Visual binaries:** those that can be resolved into two distinct star images by a telescope
- Each of the two stars in a binary system moves in an elliptical orbit about the center of mass of the system

Binary Stars

•Each of the two stars in a binary system moves in an elliptical orbit about the **center of mass** of the system



A binary star system



A "binary system" of two children

Two-body problem

Binary star systems: stellar masses

- The masses can be computed from measurements of the orbital period and orbital size of the system
- The mass ratio of M1 and M2 is inversely proportional to the distance of stars to the center of mass

$$M_1 + M_2 = \frac{a^3}{P^2}$$

M_1, M_2 = masses of two stars in binary system, in solar masses

a = semimajor axis of one star's orbit around the other, in AU

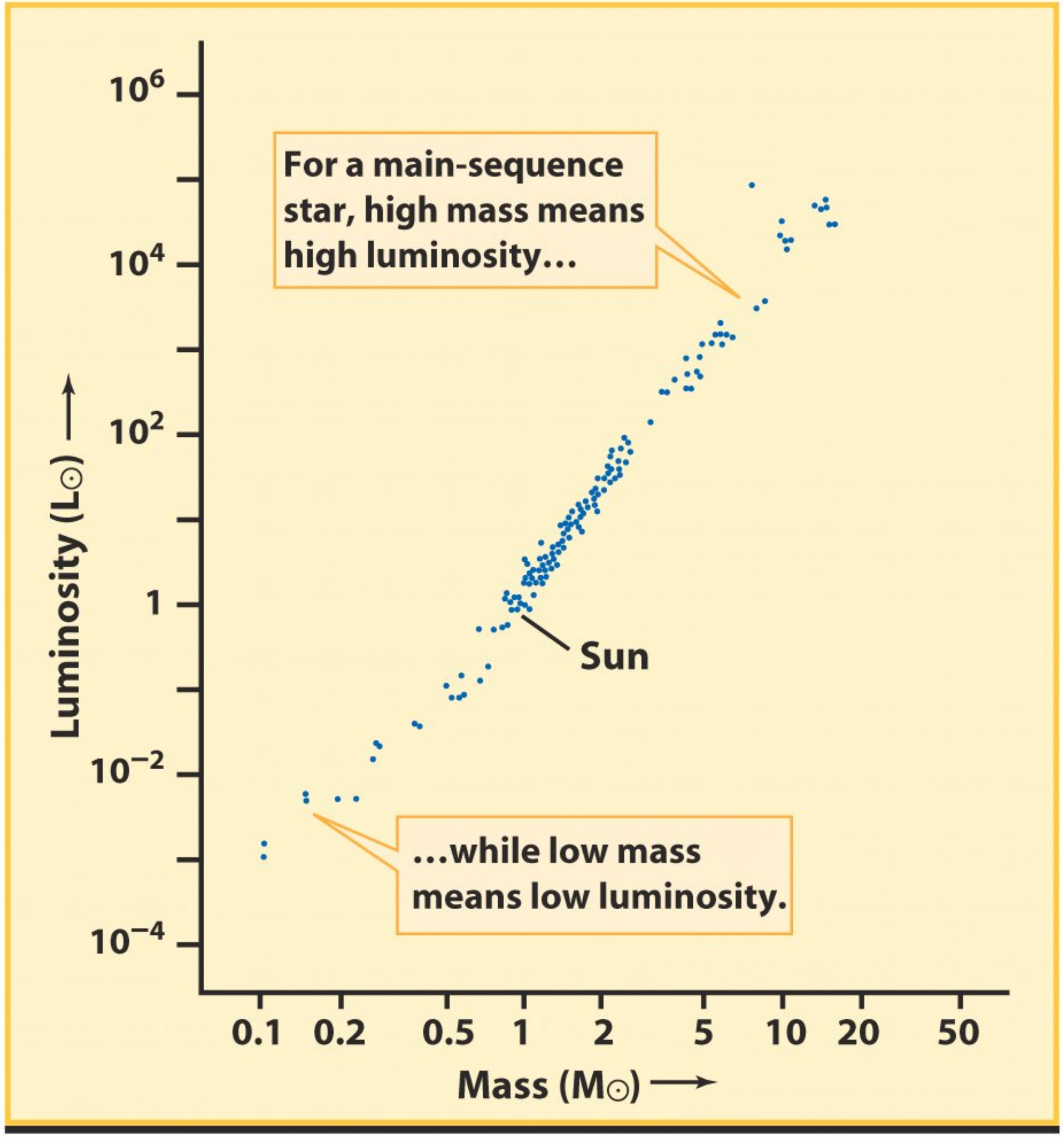
P = orbital period, in years

- This formula is a generalized format of Kepler's 3rd law
- When M1+M2 = 1 M_{sun}, it reduces to

$$a^3 = P^2$$

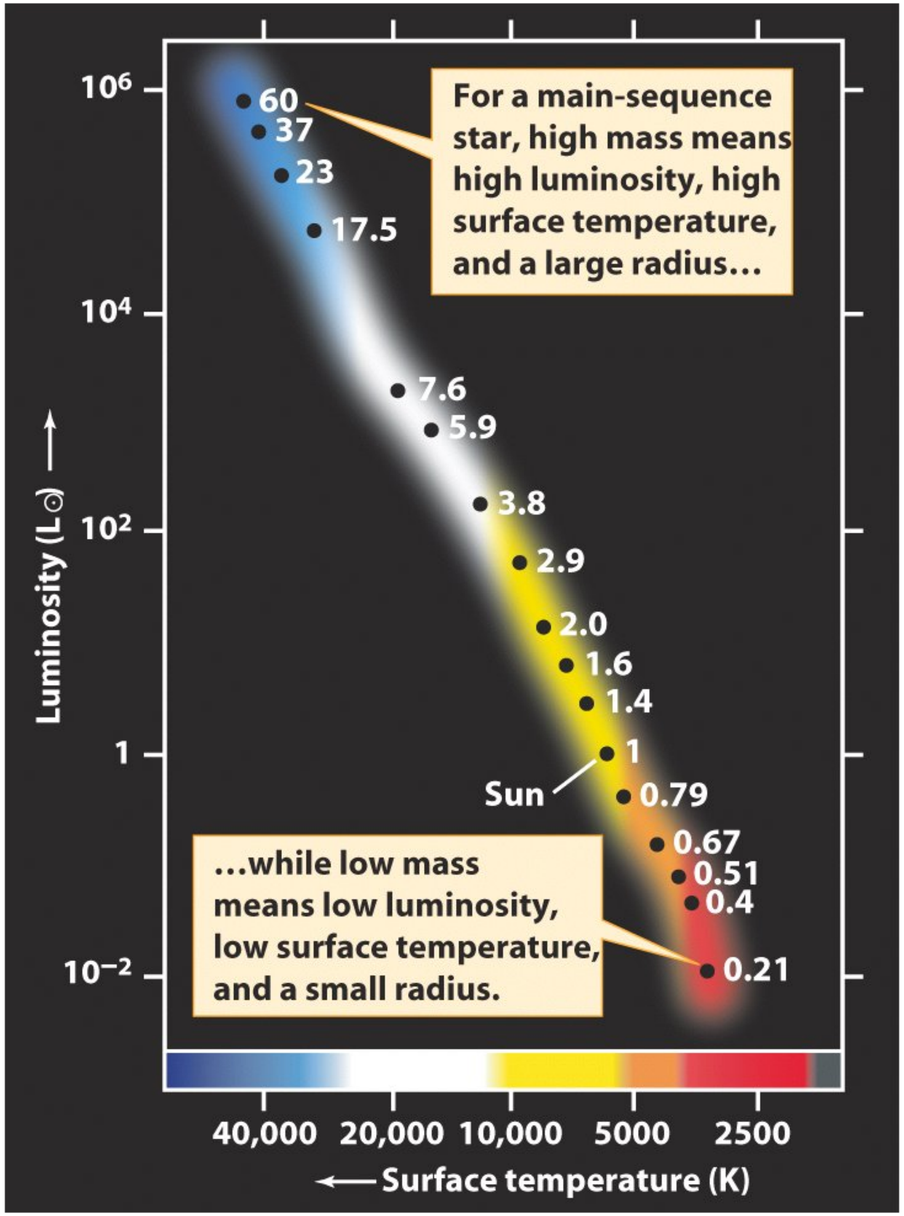
Mass-Luminosity Relation for Main-Sequence Stars

- The greater the mass of a main-sequence star, the greater its luminosity

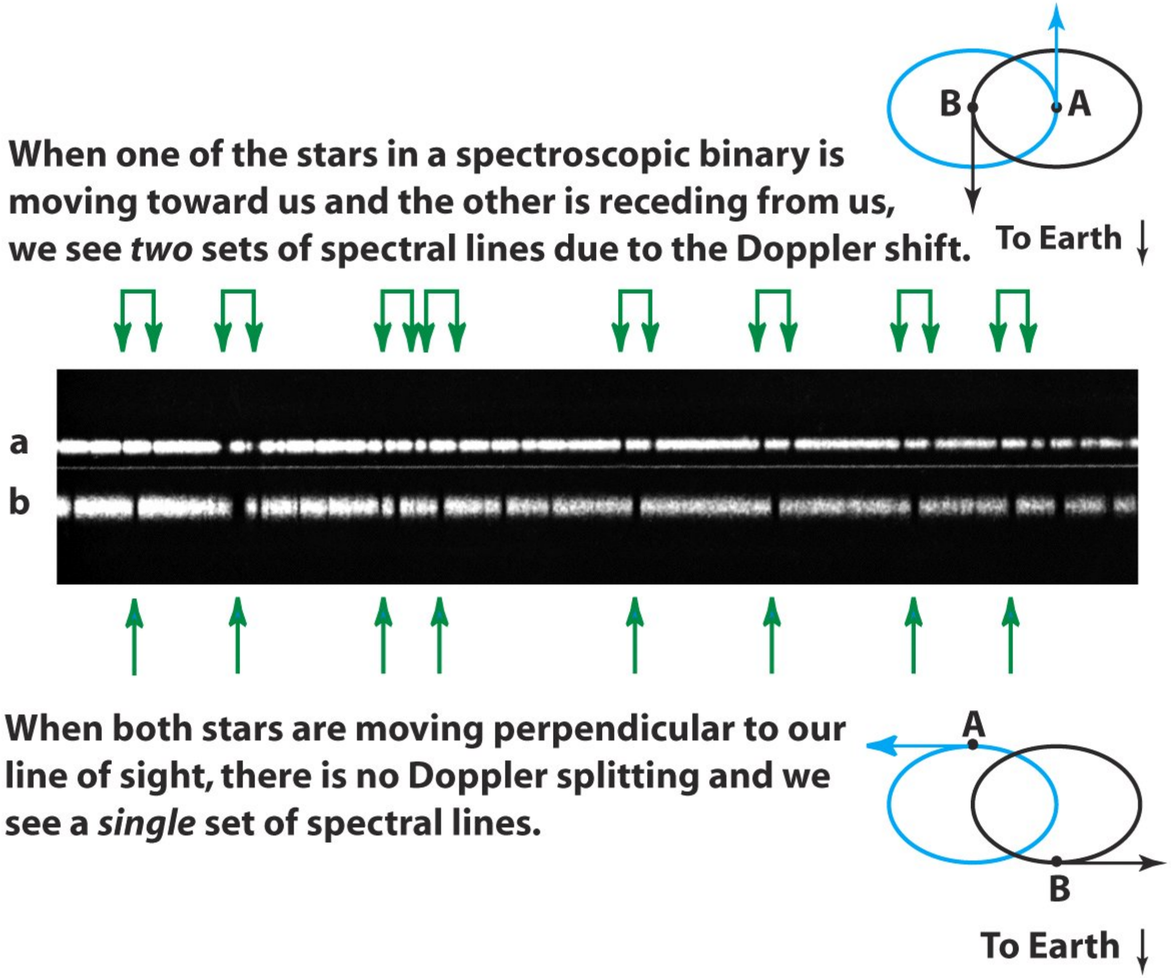


Mass-Luminosity Relation for Main-Sequence Stars

- Masses from 0.2 $M_{\odot}$
- to 60 $M_{\odot}$
- The greater the mass
- The greater the luminosity
- The greater the surface temperature
- The greater the radius

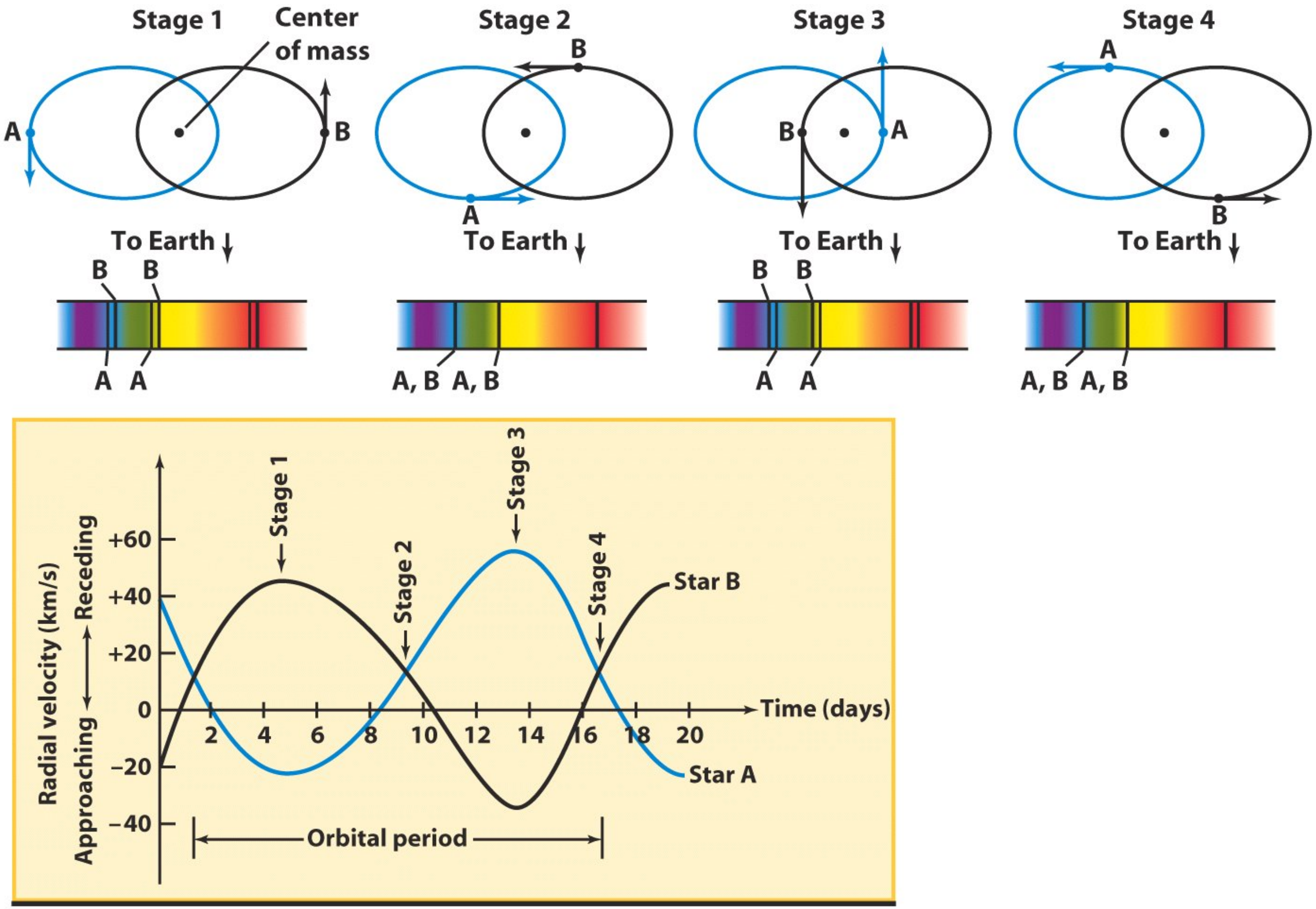


Spectroscopic binary



- Some binaries can be detected and analyzed, even though the system may be so distant or the two stars so close together that the two star images cannot be resolved
- A **spectrum binary** appears to be a single star but has a spectrum with the absorption lines for two distinctly different spectral types
- A **spectroscopic binary** has spectral lines that shift back and forth in wavelength
- This is caused by the **Doppler effect**, as the orbits of the stars carry them first toward then away from the Earth

Spectroscopic binary



2. The Birth of Stars

Guiding Questions

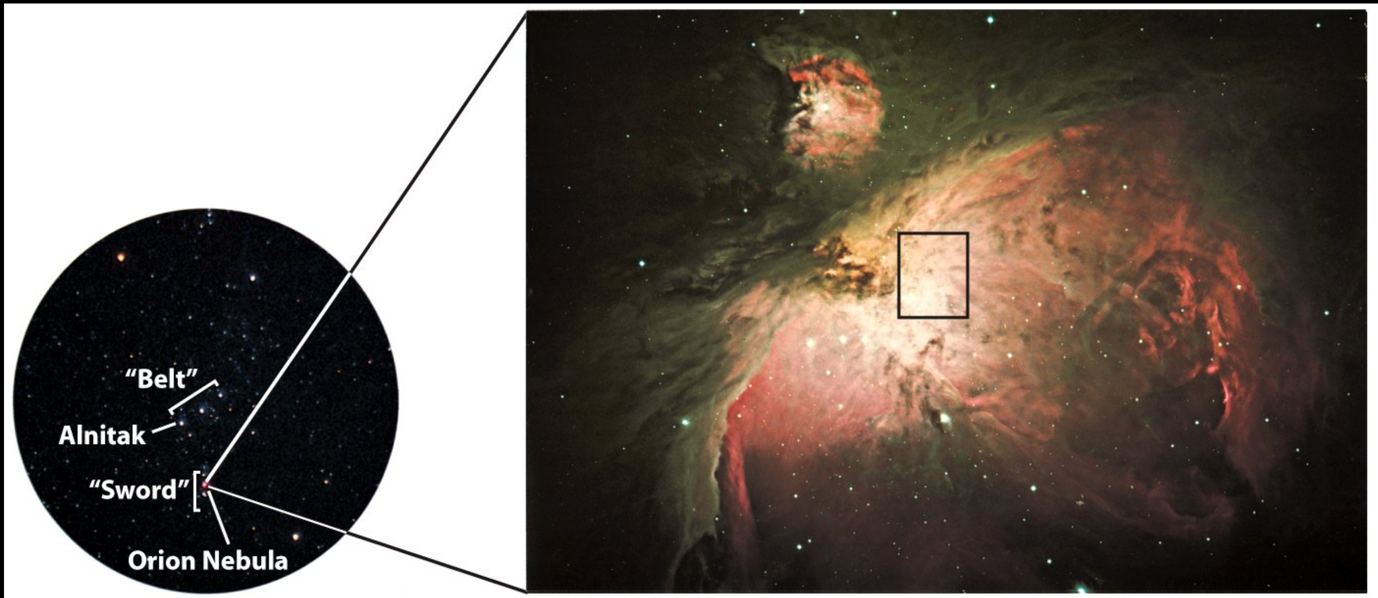
1. Why do astronomers think that stars evolve?
2. What kind of matter exists in the spaces between the stars?
3. In what kind of nebulae do new stars form?
4. What steps are involved in forming a star like the Sun?
5. When a star forms, why does it end up with only a fraction of the available matter?
6. What do star clusters tell us about the formation of stars?
7. Where in the Galaxy does star formation take place?
8. 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

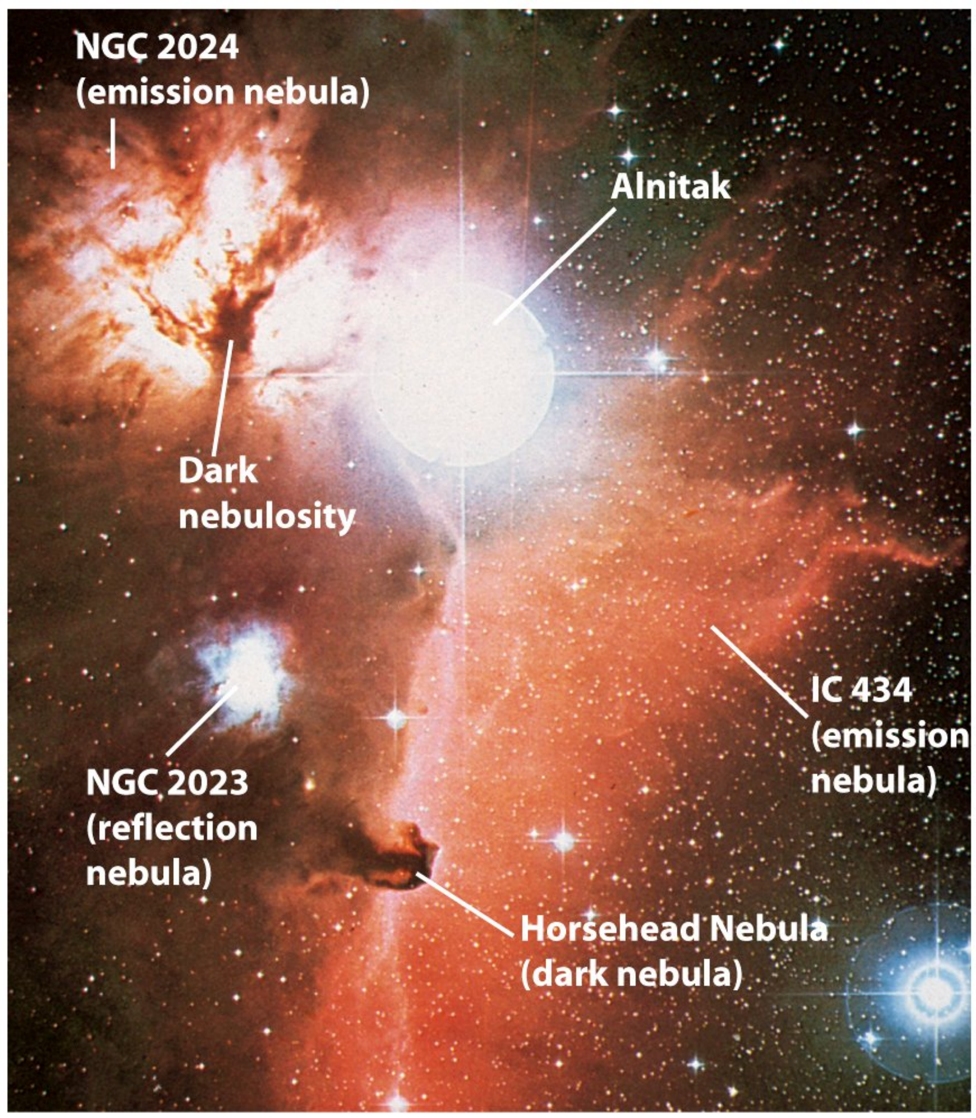
Interstellar Medium and Nebulae

- 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



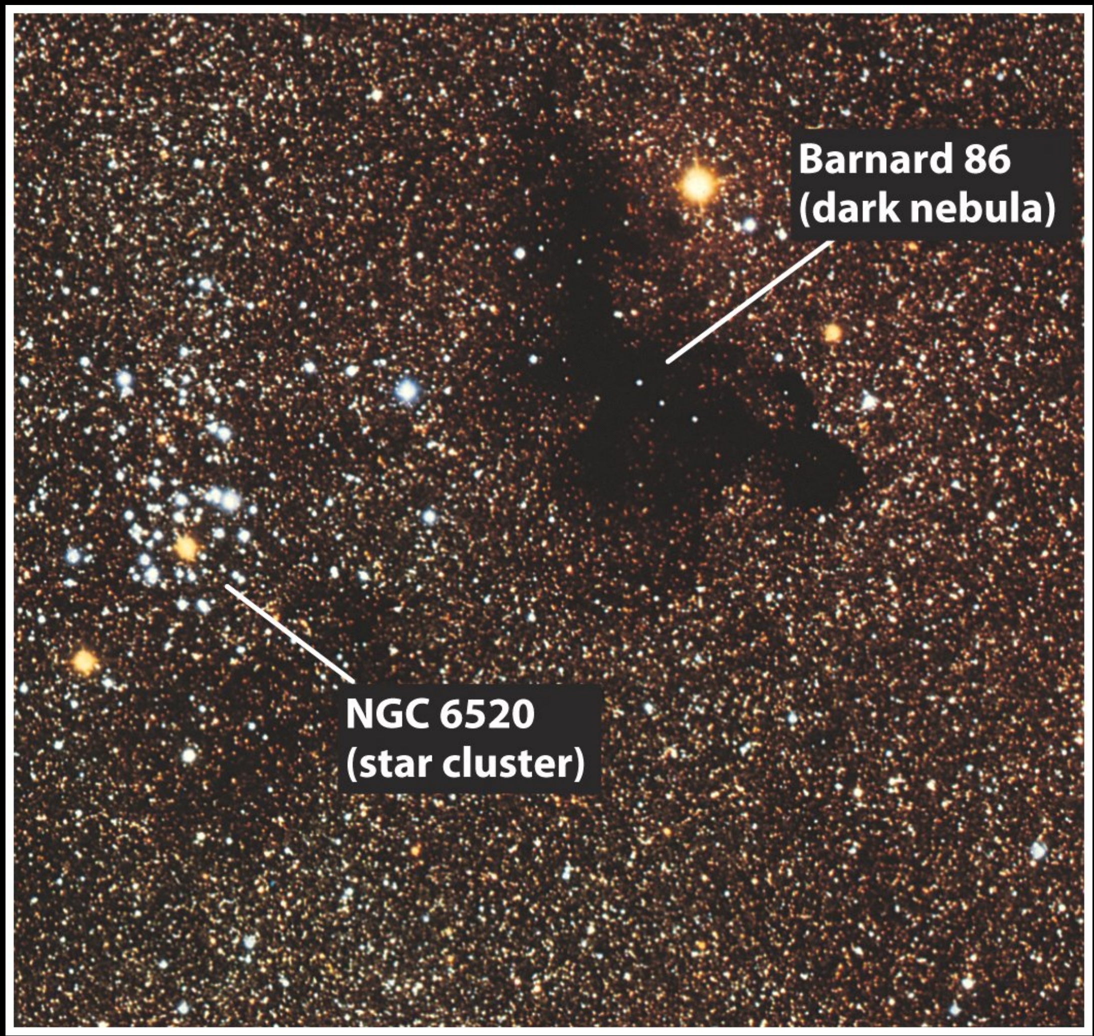
(a) A wide-angle view of Orion. (b) A closeup of the Orion Nebula.

Emission Nebula or H II region



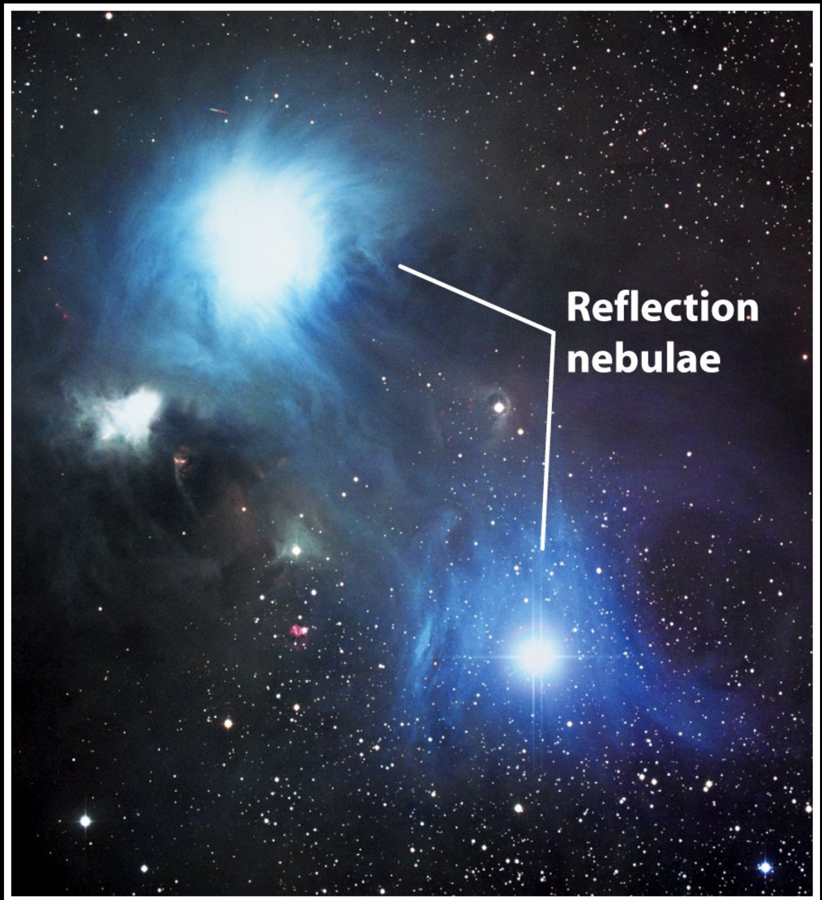
- Emission nebulae are glowing clouds of gas
- They are found near hot, luminous stars of spectral types O and B
- They are powered by ultraviolet light that they absorb from nearby hot stars
- They are composed of ionized hydrogen atoms; the so called H II region.
- They emit light through a process 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

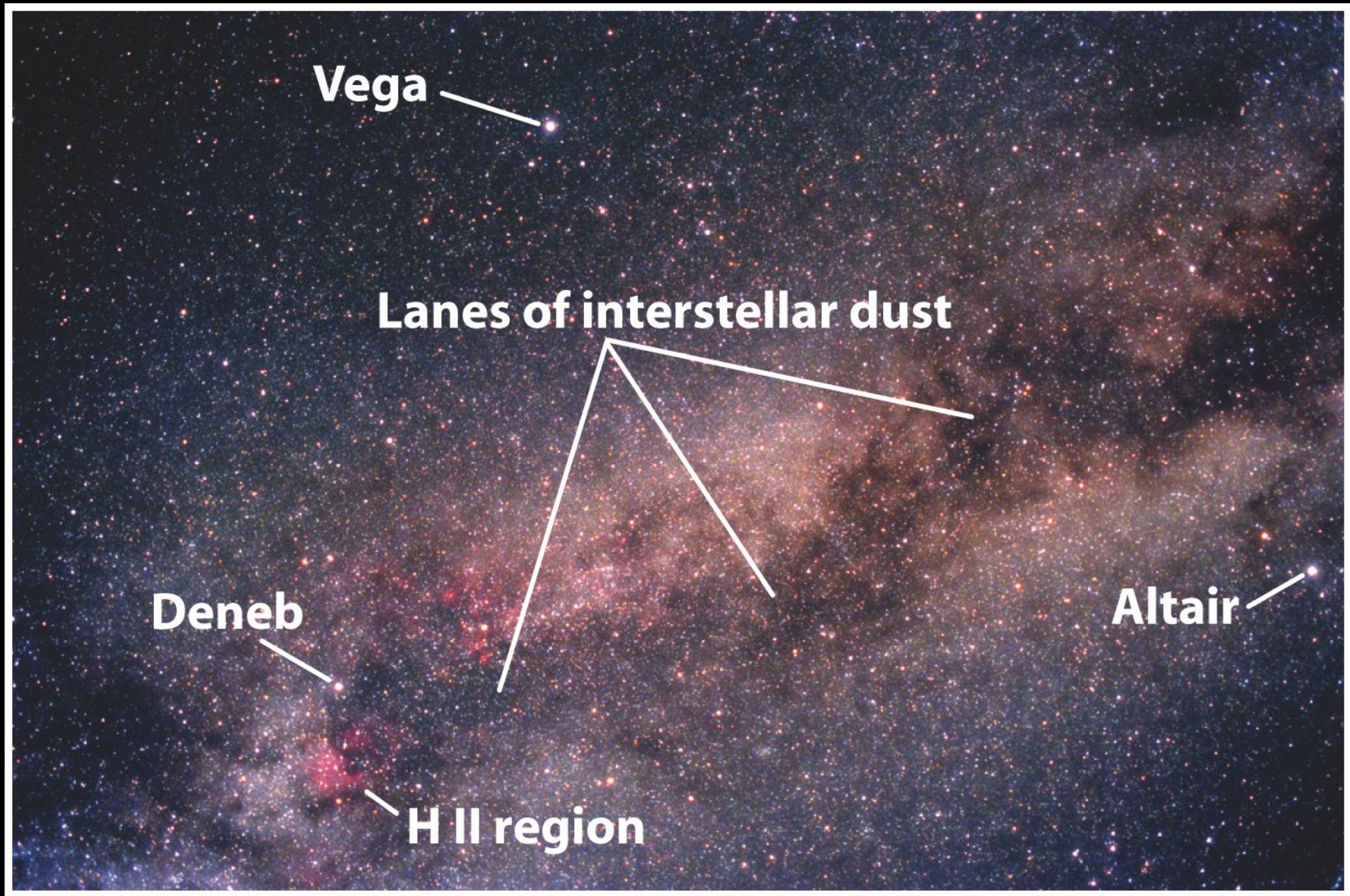
Reflection Nebulae: dust scattering



- 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 (like our blue sky)

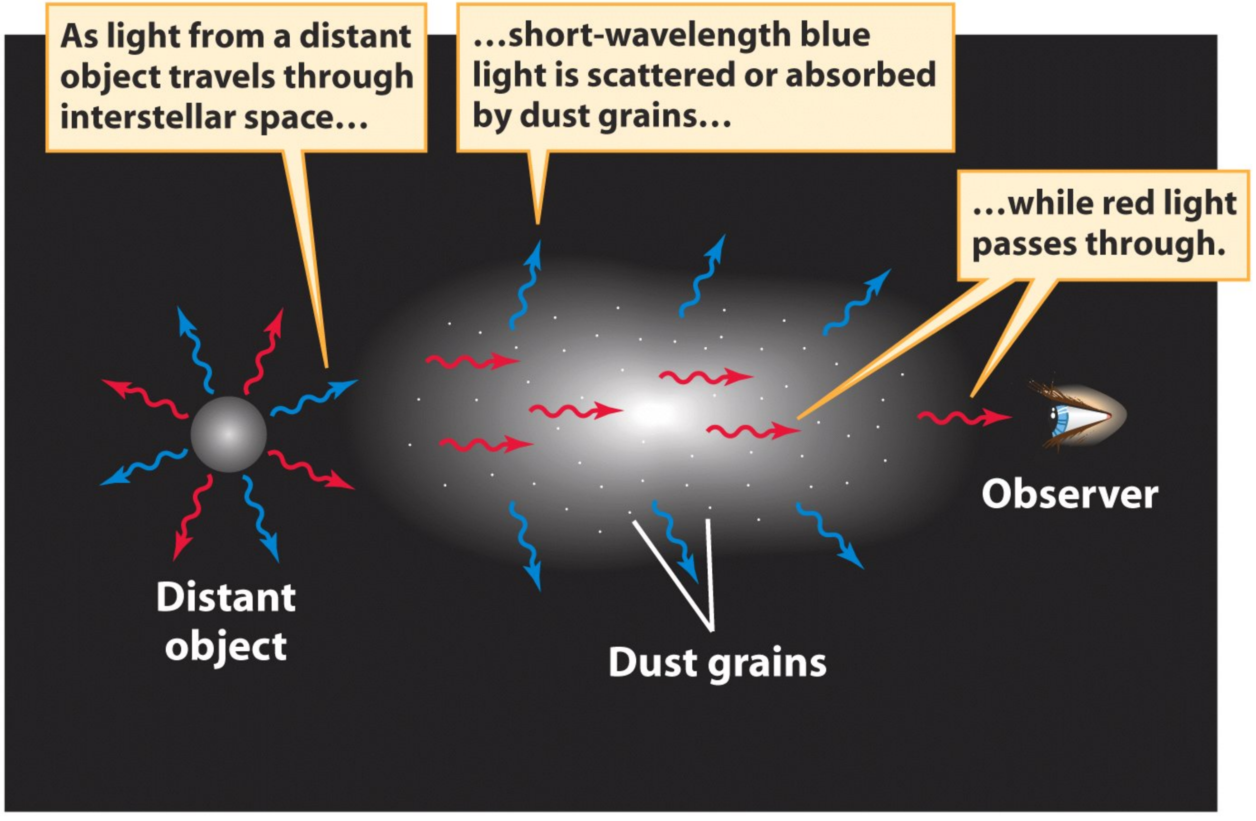
Interstellar Extinction

- 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

Rayleigh scattering

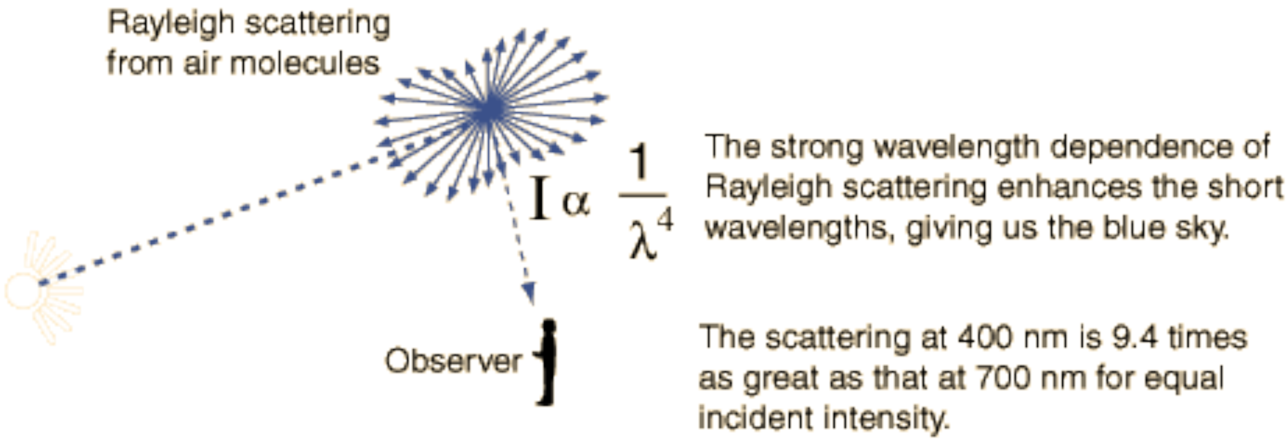
Atmospheric composition: N_2 (78%), O_2 (21%), Ar (1%)

Size of N_2 molecule: 0.31 nm

Size of O_2 molecule: 0.29 nm

Size of Ar molecule: 0.3 nm

Visible wavelengths ~400-700 nm

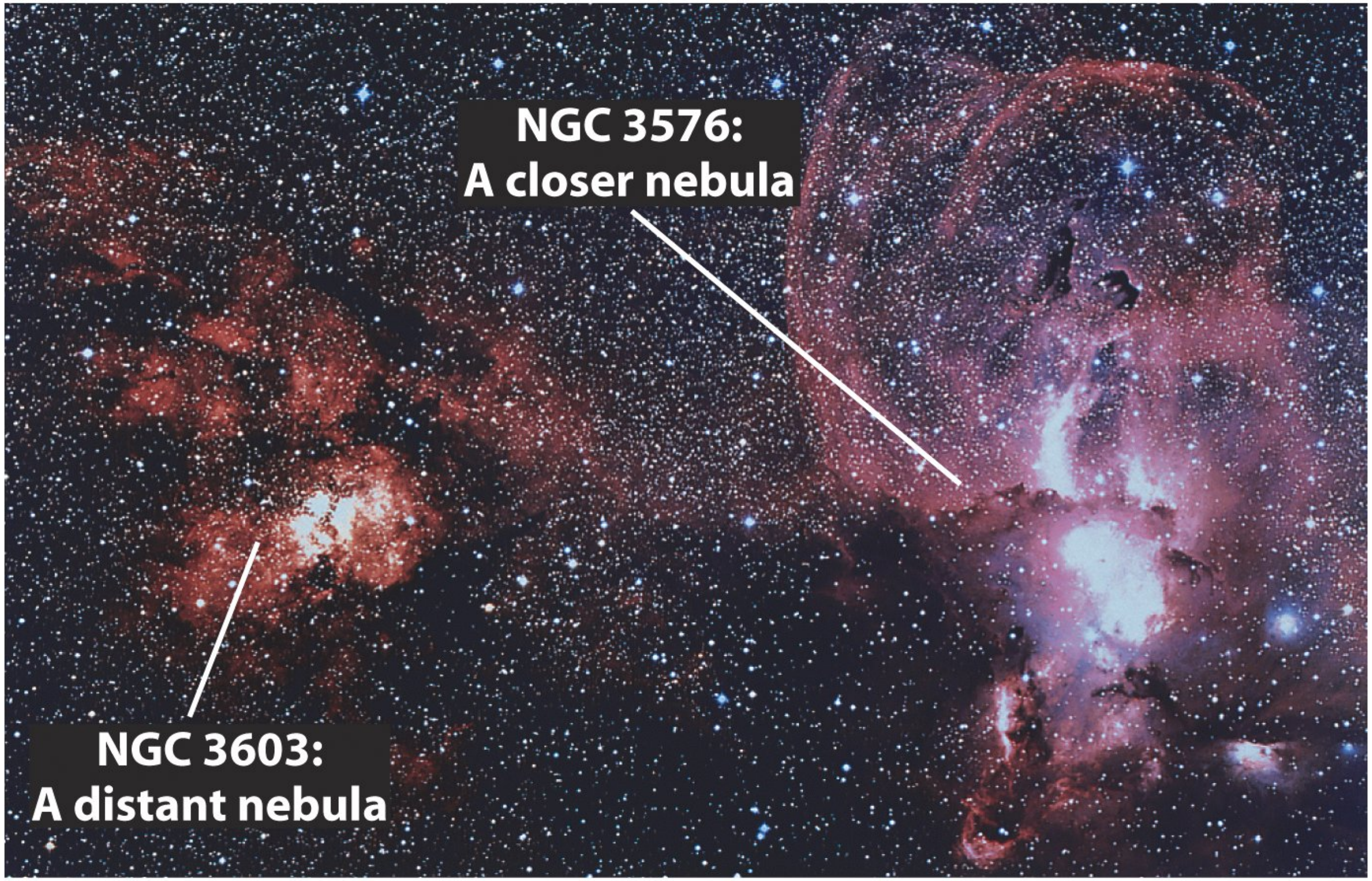


- Scattering of light off air molecules is called Rayleigh Scattering
- Involves particles much smaller than the wavelength of incident light
- Responsible for the blue color of clear sky

Rayleigh scattering

Interstellar Reddening

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

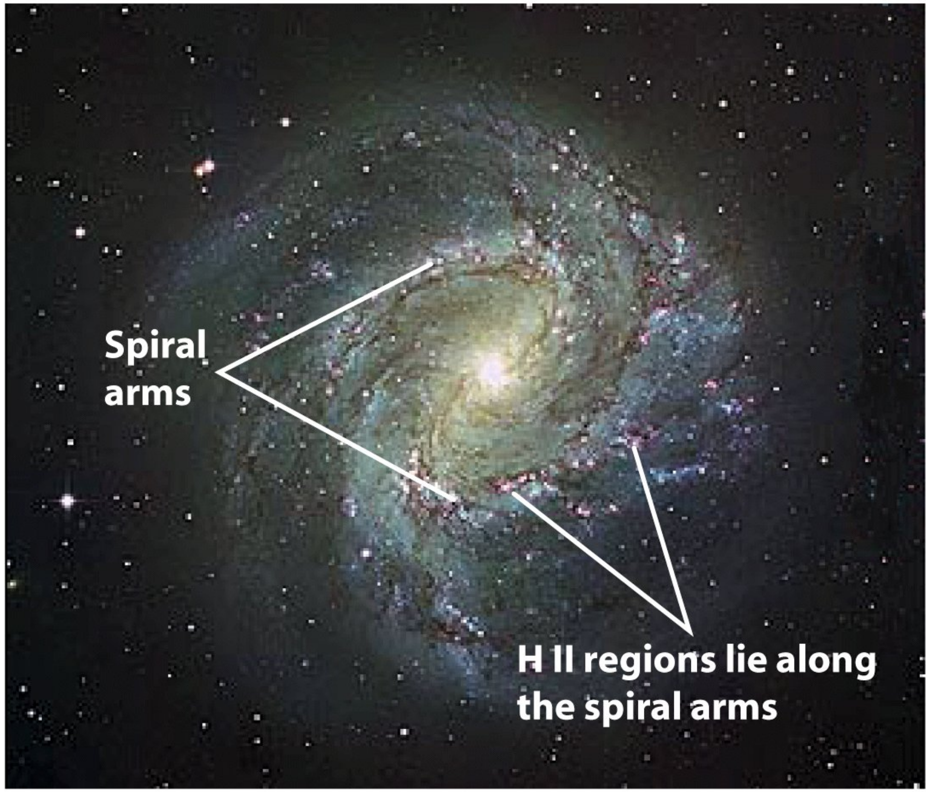


Reddening depends on distance

Distribution of Interstellar Gas and Dust

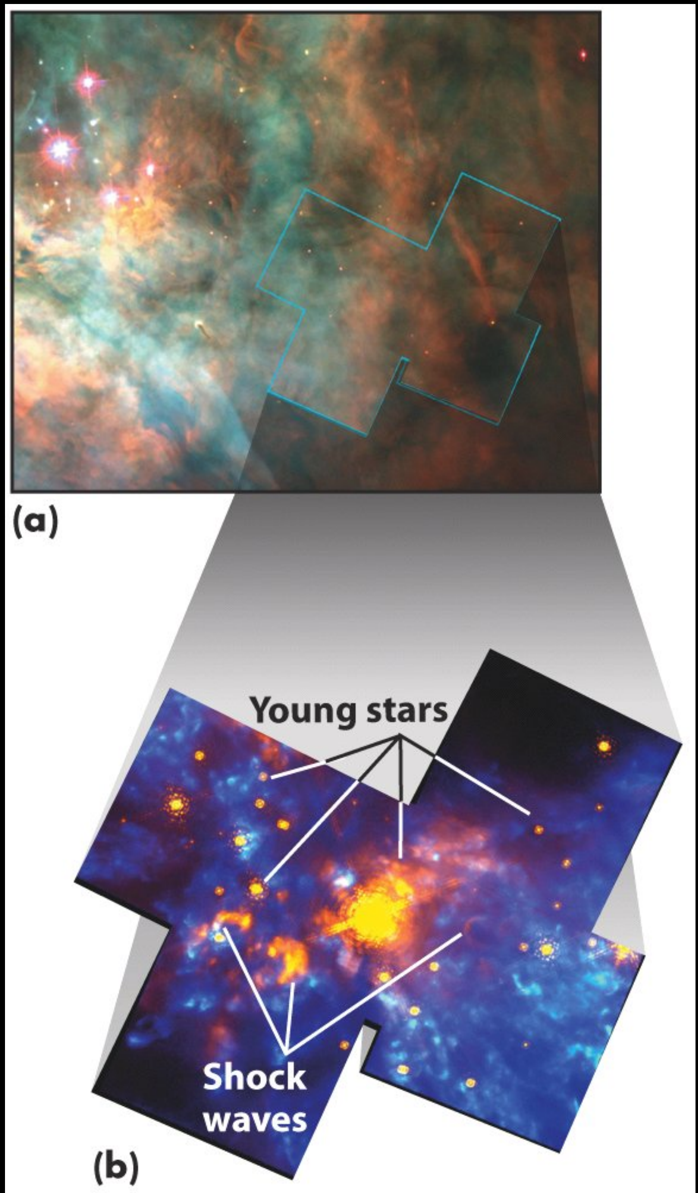
- The interstellar gas and dust are confined to the plane of the galaxy

We see spiral galaxy NGC 891 nearly edge-on



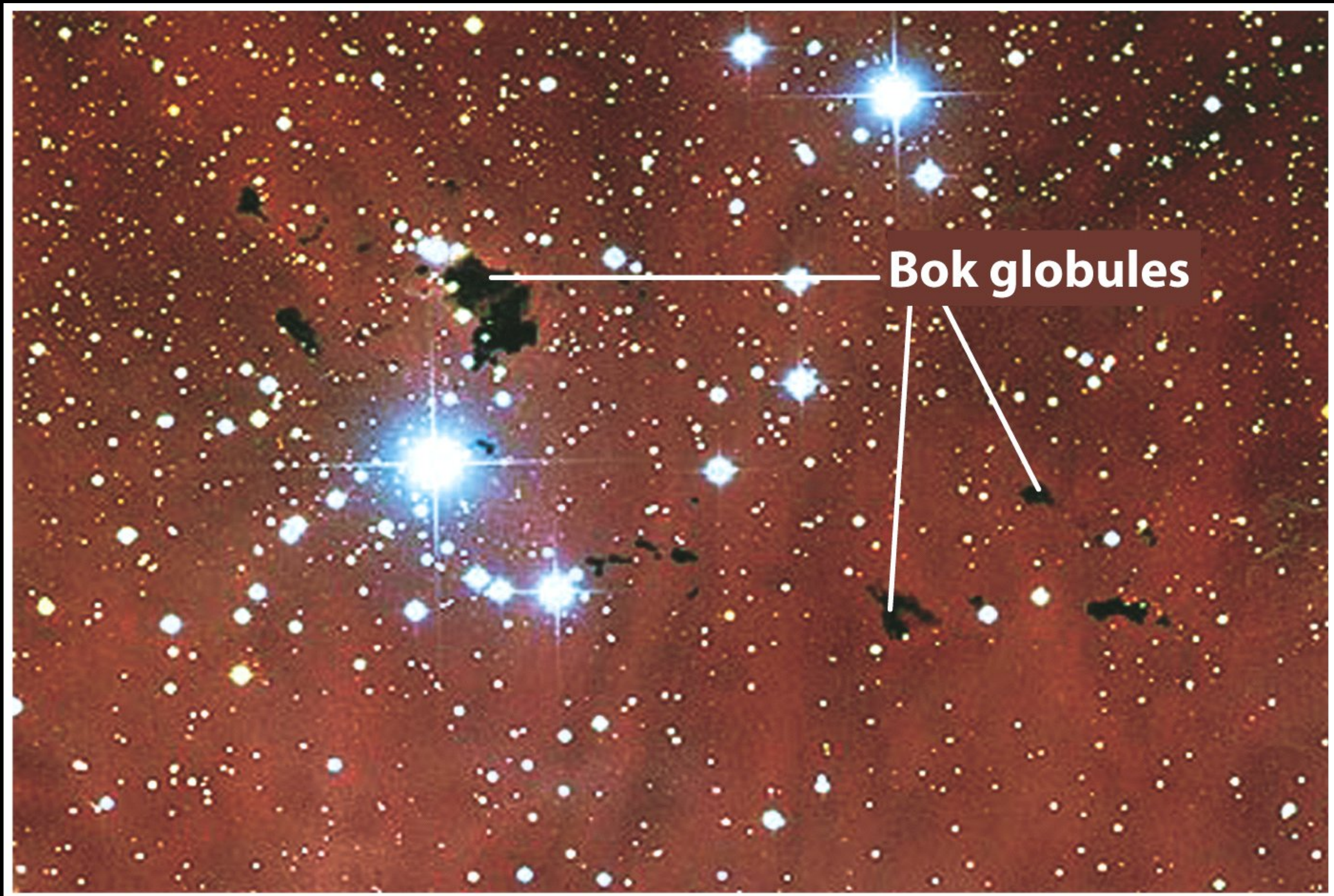
We see spiral galaxy M83 nearly face-on

Protostars form in cold, dark nebulae



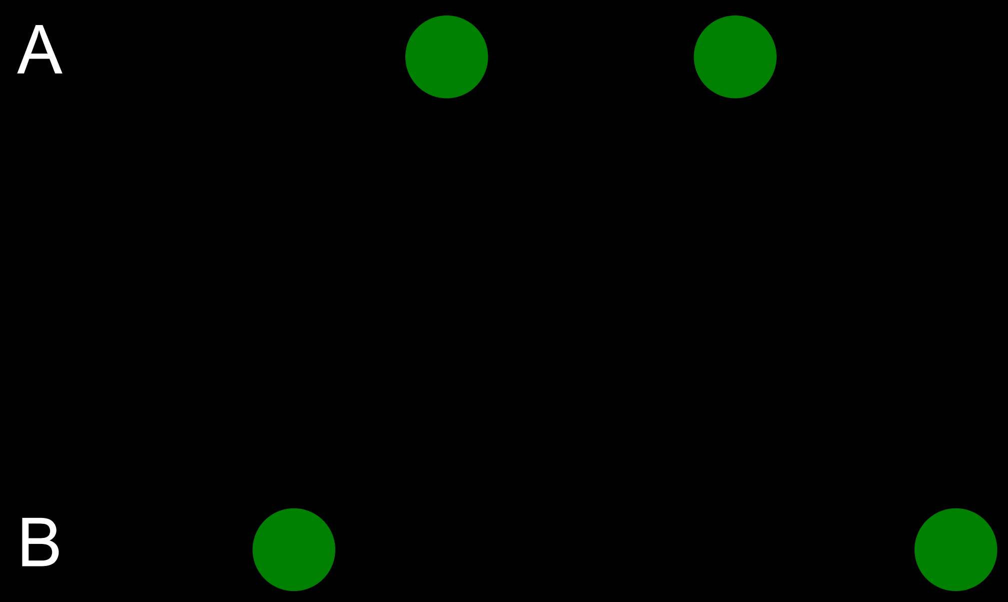
- Protostar: the clump formed from dense and cold nebula under gravitational contraction
- The protostar contracts, because the pressure inside is too low to support all the mass.
- As a protostar grows by the gravitational accretion of gases, Kelvin-Helmholtz contraction causes it to heat and begin glowing

Protostars form in cold, dark nebulae



Gravitational collapse

Which configuration has more potential energy?



Potential energy due to gravity

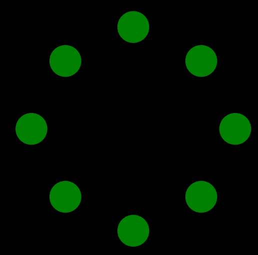
$$F = G\frac{m_1 m_2}{r^2}$$

$$U = -\int F(x)dx = -G\frac{m_1 m_2}{r}$$

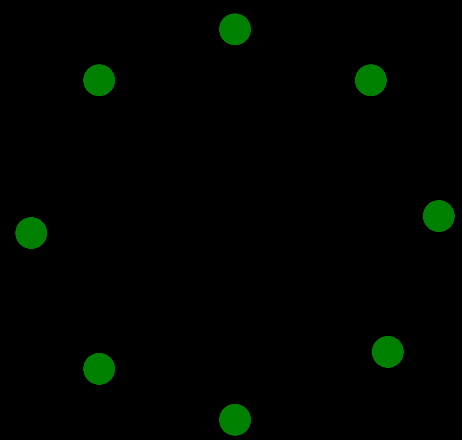
Gravitational collapse

Which configuration has more potential energy?

A



B



Potential energy due to gravity

Sphere of mass *M* and radius *R*

$$\boxed{U = -\frac{3}{5} G \frac{M^2}{R}}$$

Gravitational potential energy is released as sphere shrinks

Gravitation binding energy of a sphere

The gravitational binding energy of a sphere with radius R is found by imaging that it is pulled apart by successively moving spherical shells to infinity, and finding the total energy needed.

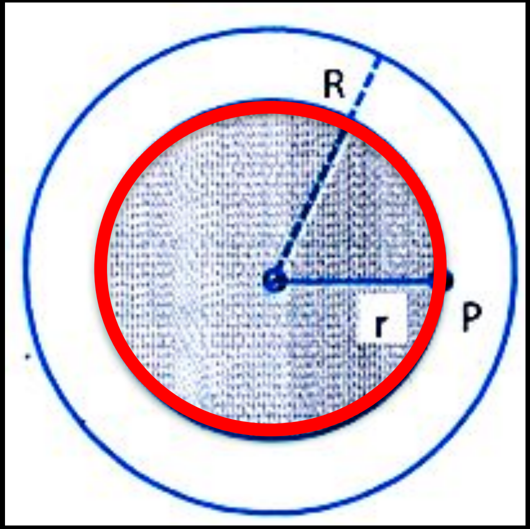
$$m_{\text{shell}} = 4\pi r^2 dr \times \rho \qquad \text{and} \qquad m_{\text{interior}} = \frac{4}{3}\pi r^3 \times \rho$$

The required energy for a shell

$$dU = -G\frac{m_{\text{shell}} m_{\text{interior}}}{r}$$

$$\Rightarrow U = -G\int dU = -G\int_0^R \frac{\left(4\pi r^2 dr\rho\right)\left(\frac{4}{3}\pi r^3\rho\right)}{r}$$

$$= -G\frac{16}{15}\pi^2\rho^2 R^5 = -\frac{3}{5}\frac{GM^2}{R}$$



Gravitational collapse

- How much energy is released when 1 $M_{\odot}$ of material collapses from a radius of 10 $R_{\odot}$ to 1 $R_{\odot}$?

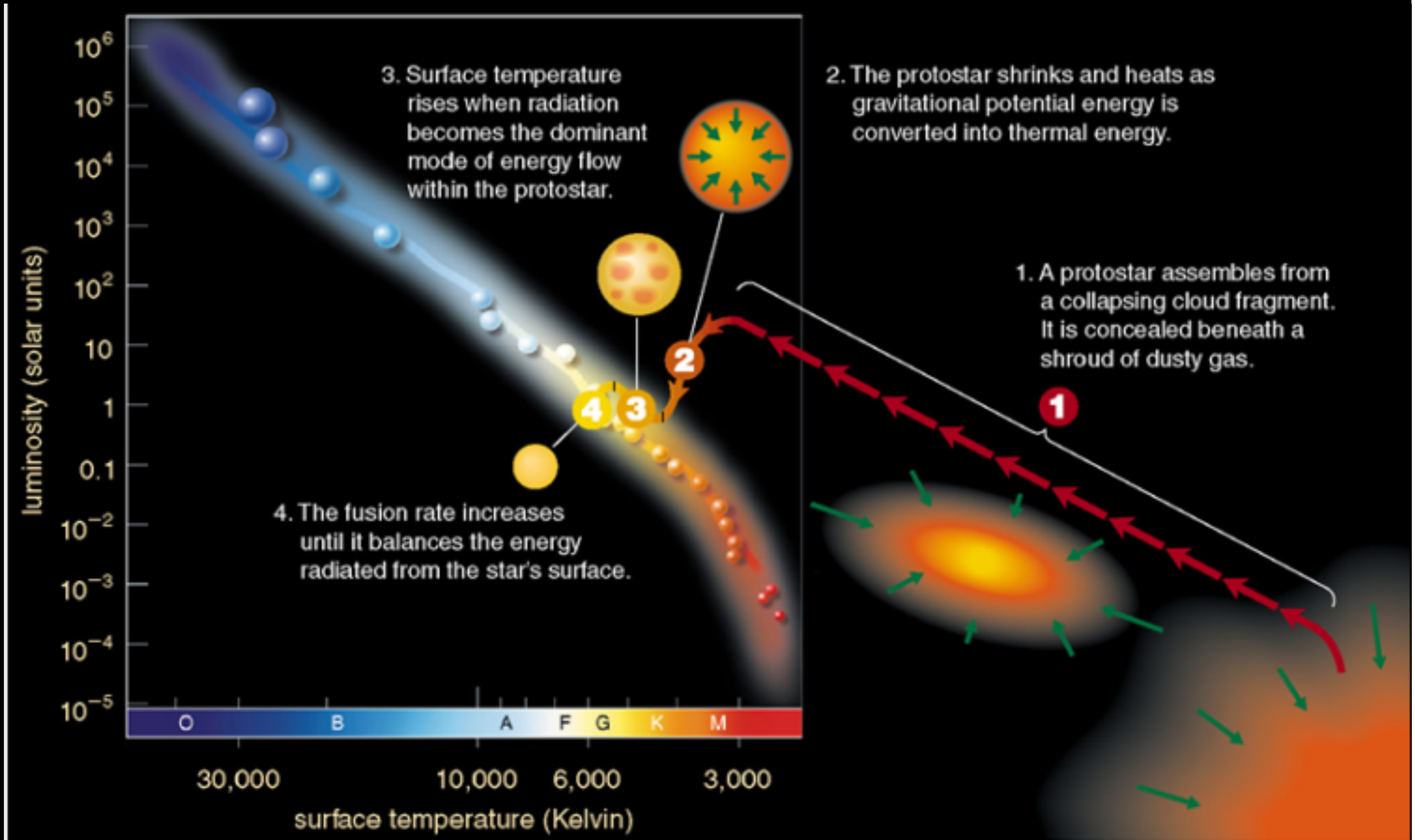
Gravitational collapse

- About 2×10^{41} J of energy is released when 1 $M_\odot$ of material collapses from a radius of 10 $R_\odot$ to 1 $R_\odot$. This collapse takes about 10-20 million years. The luminosity is:

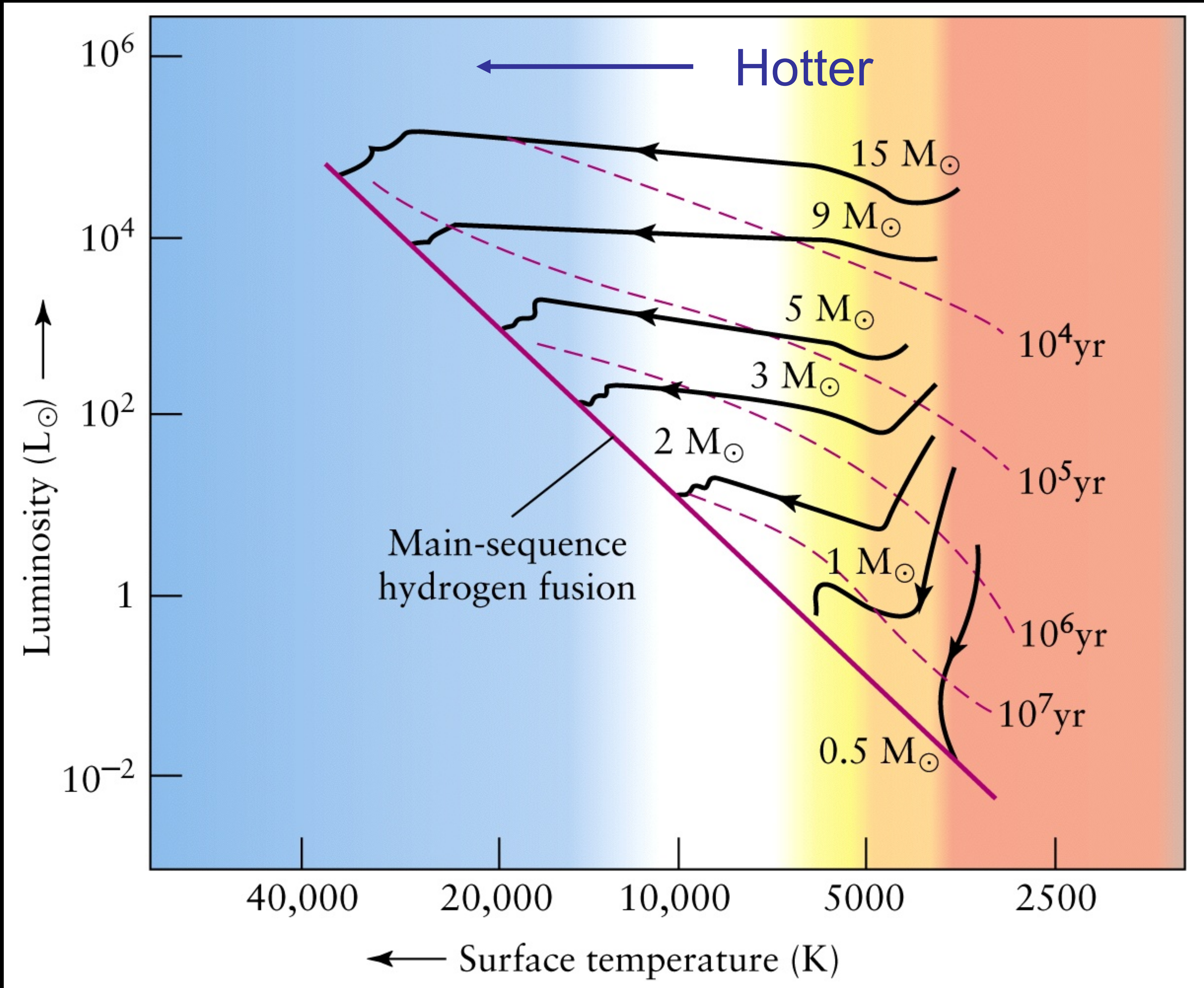
$$L = \frac{\Delta E}{T} = \frac{2\times10^{41}\,\mathrm{J}}{3\text{-}6\times10^{14}\,\mathrm{s}} = 3-7\times10^{26}\,\mathrm{W} = 1\text{-}2L_\Theta$$

- Size of cloud?
- Temperature of cloud?

Cloud collapse to star: on HR diagram



Protostars on the HR diagram

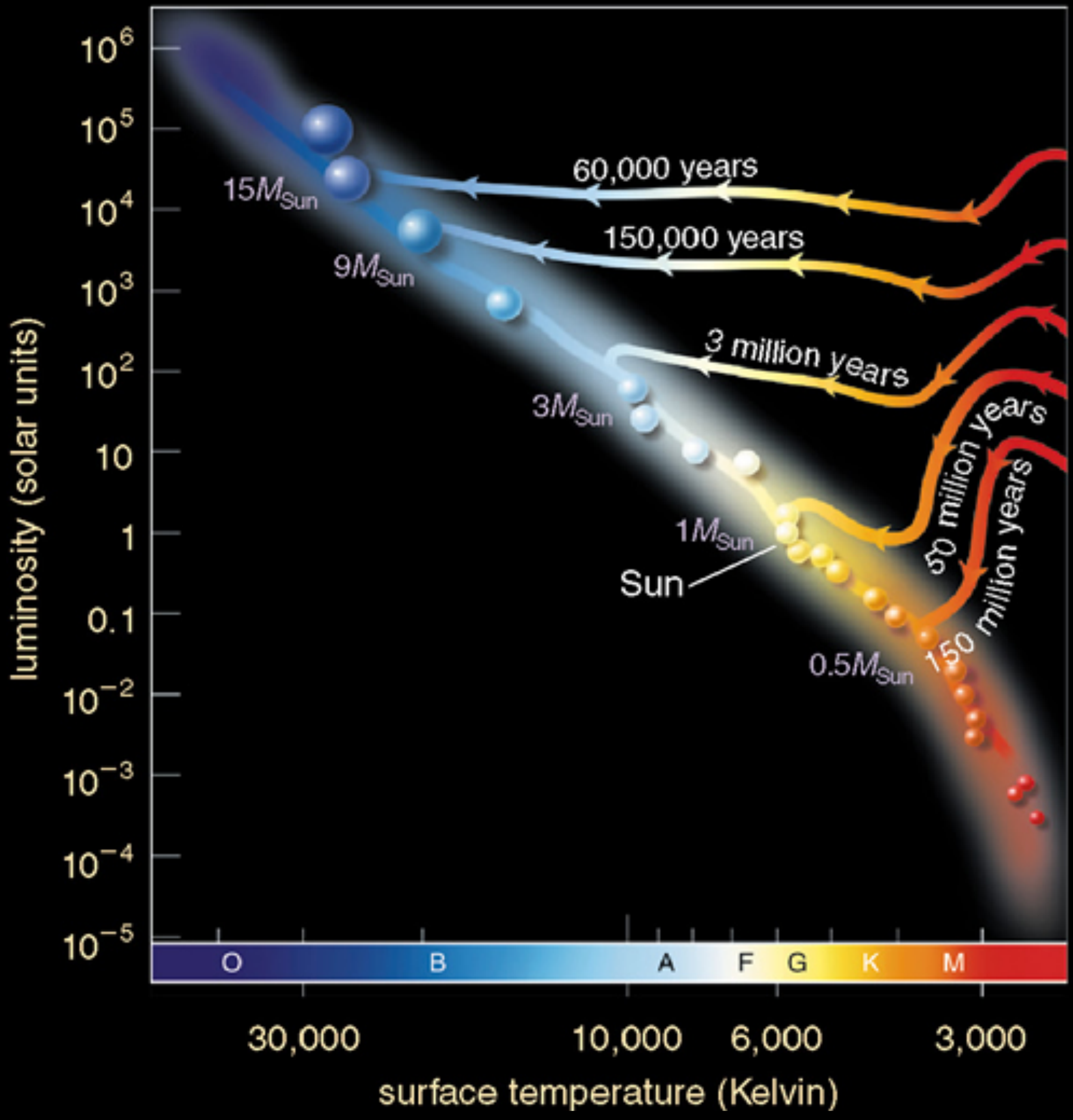


Why does temperature increase as star contracts?

- Note that luminosity remains constant.
- To produce constant luminosity as radius decreases, need increase in temperature

$$L \propto R^2 T^4 \longrightarrow T \propto \frac{L^{1/4}}{R^{1/2}}$$

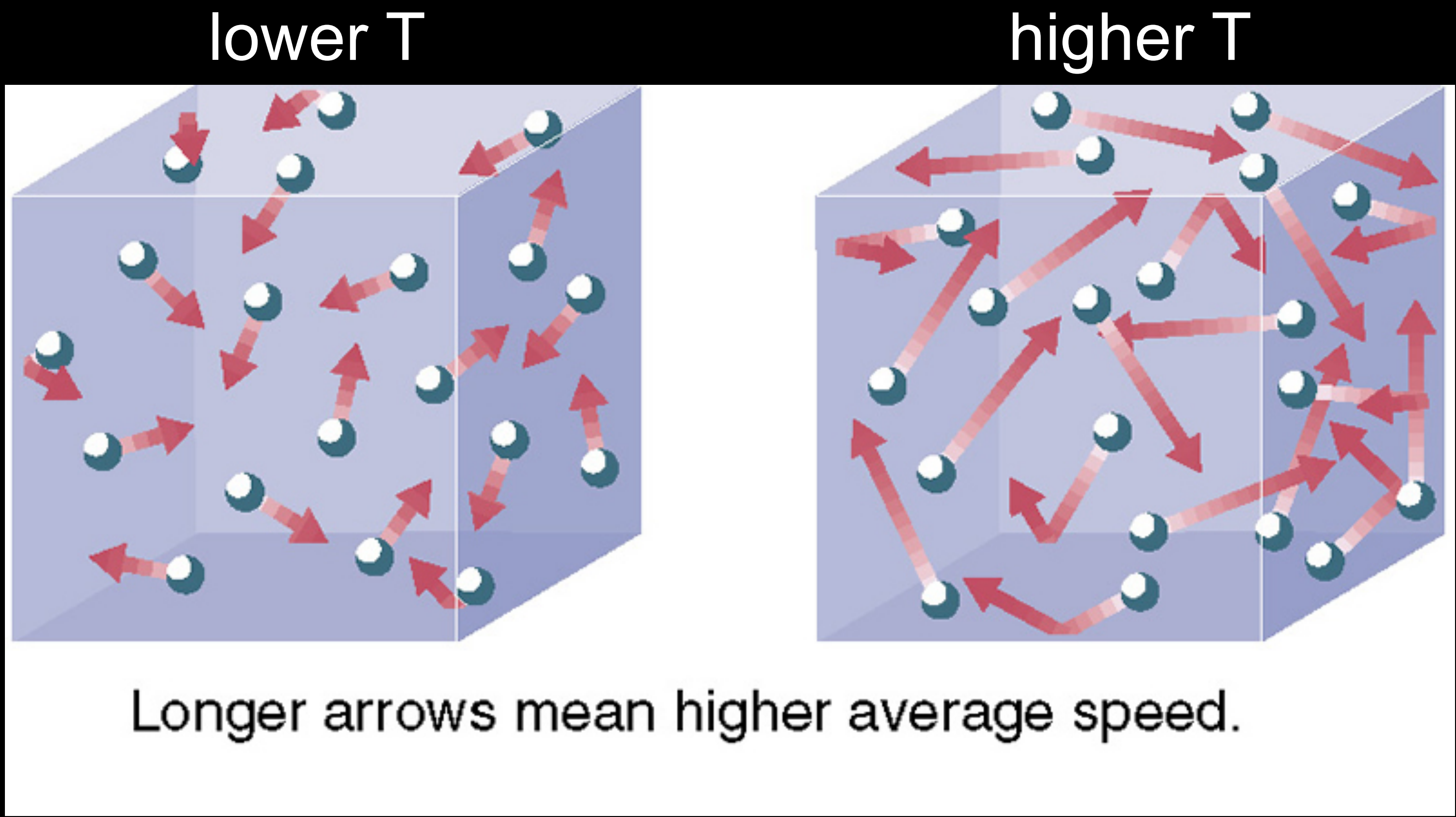
More massive stars form faster



Which clouds will collapse?

- Gravitational force causes objects to collapse.
- What keeps objects from collapsing?
- In the solar system, the motion of the planets keeps them from falling in to the Sun.
- In a gas, the random motions of the gas atoms can support the gas against gravity.

Temperature



- Temperature is proportional to the <u>average</u> kinetic energy per molecule

$$K = \frac{1}{2}mv^2 = \frac{3}{2}kT$$

k = Boltzmann constant = 1.38×10^{-23} J/K = 8.62×10^{-5} eV/K

Energy of gas cloud

Gravitational potential energy:

Sphere of mass *M* and radius *R*

$$U = -\frac{3}{5} G \frac{M^2}{R}$$

Kinetic energy of *N* atoms

$$K = N \frac{3}{2} kT = \frac{M}{m_H} \frac{3}{2} kT$$

Energy of gas cloud

$$E = \frac{M}{m_H}\frac{3}{2}kT - \frac{3}{5}G\frac{M^2}{R}$$

If $E < 0$ then gas cloud collapses

If $E > 0$ then gas cloud can support itself

Density of gas cloud is n

$$M = \frac{4}{3}\pi R^3 n \cdot m_H$$

Critical size of gas cloud

$$E = \frac{3kT}{2m_H} M - \frac{3G}{5}\left(\frac{4\pi n m_H}{3}\right)^{1/3} M^{5/3}$$

By increasing the mass, we can always cause the gravity to dominate so that the gas cloud collapses.

Critical size and mass are called the Jean's length and mass

$$R_J = \sqrt{\frac{15kT}{8\pi G m_H^2 n}} \qquad M_J = 18 M_\Theta \sqrt{\frac{T^3}{n}}$$

T in Kelvin, n in atoms/cm^3

Critical size of gas cloud

If we have a cloud at T = 100 K and n = 1 cm^{-3}, how large pieces does it fragment into?

$$M_J = 18 M_\Theta \sqrt{\frac{T^3}{n}} = 18 M_\Theta \sqrt{\frac{100^3}{1}} \approx 18000 M_\Theta$$

Therefore, such clouds will typically form a group of stars rather than a single star. Stars are generally found in groups, called star clusters or OB associations, depending on the type of stars.

Critical size of gas cloud

If we have a cloud at T = 30 K and n = 300 cm^{-3}, how large pieces does it fragment into?

$$M_J = 18 M_\Theta \sqrt{\frac{T^3}{n}} = 18 M_\Theta \sqrt{\frac{30^3}{300}} \approx 170 M_\Theta$$

Therefore, such clouds will typically form a group of stars rather than a single star. Stars are generally found in groups, called star clusters or OB associations, depending on the type of stars.

Critical size of gas cloud

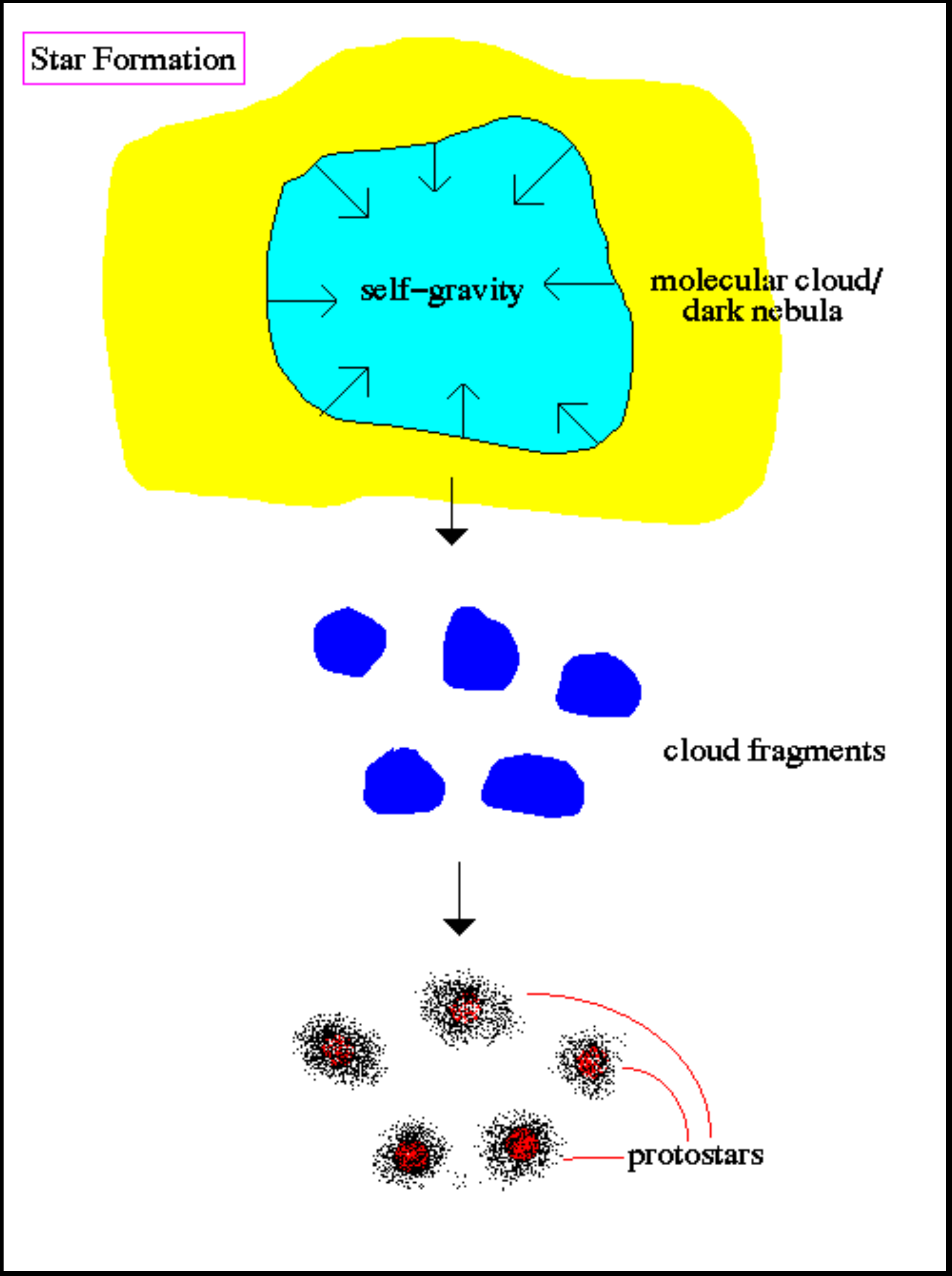
The dense cores can reach n = 300,000 cm^{-3}, how large pieces do they fragment into?

$$M_J = 18 M_\Theta \sqrt{\frac{T^3}{n}} = 18 M_\Theta \sqrt{\frac{30^3}{300{,}000}} \approx 5.4 M_\Theta$$

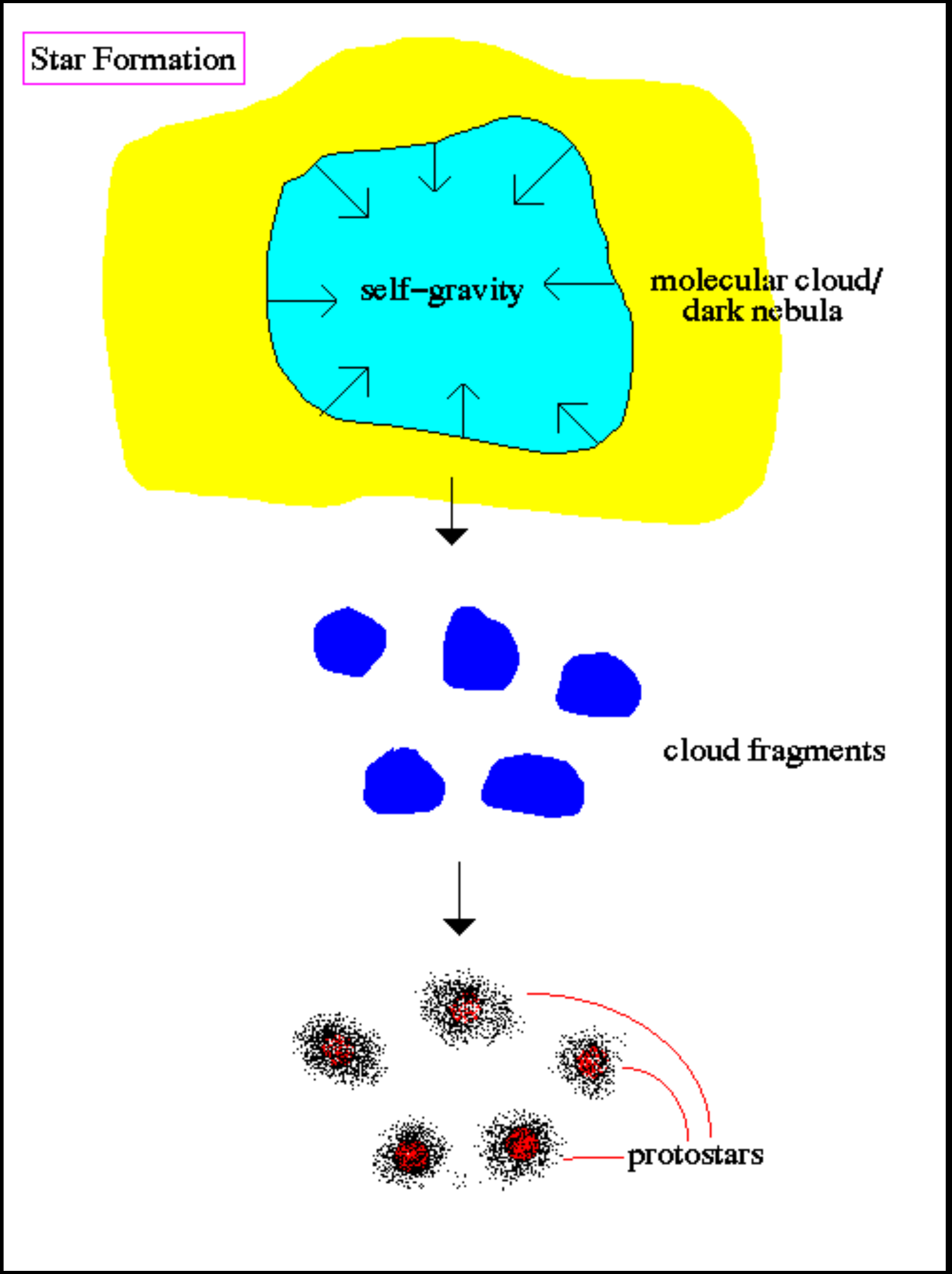
Therefore, the dense cores fragment into individual stars.

Protostars form by collapse of molecular clouds

- Clouds must form **dense** and **cold** clumps or <u>cores</u> to collapse
- Typically, multiple stars will form from one gas cloud

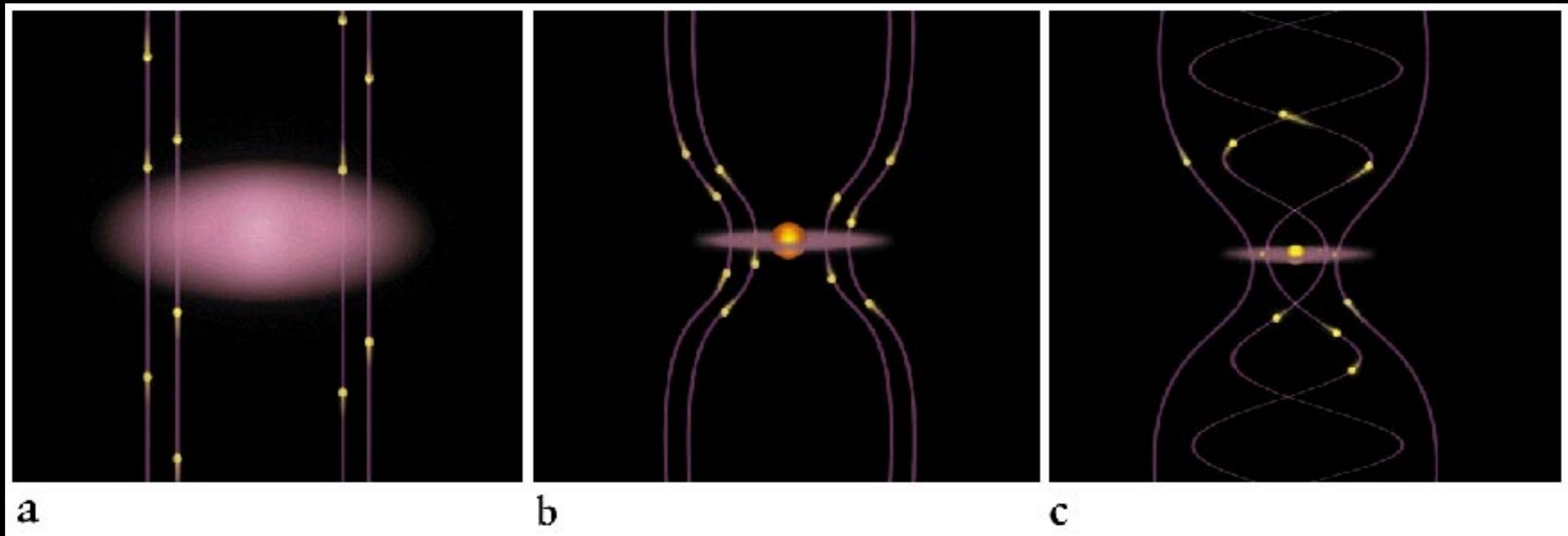


- As the gas/dust falls in, it picks up speed and energy. It is slowed by friction and the energy is converted to heat.
- As long as the protostar is transparent, the heat can be radiated away.
- When the protostar becomes so dense it is opaque, then the heat starts to build up, the pressure increases, and the rapid collapse slows.



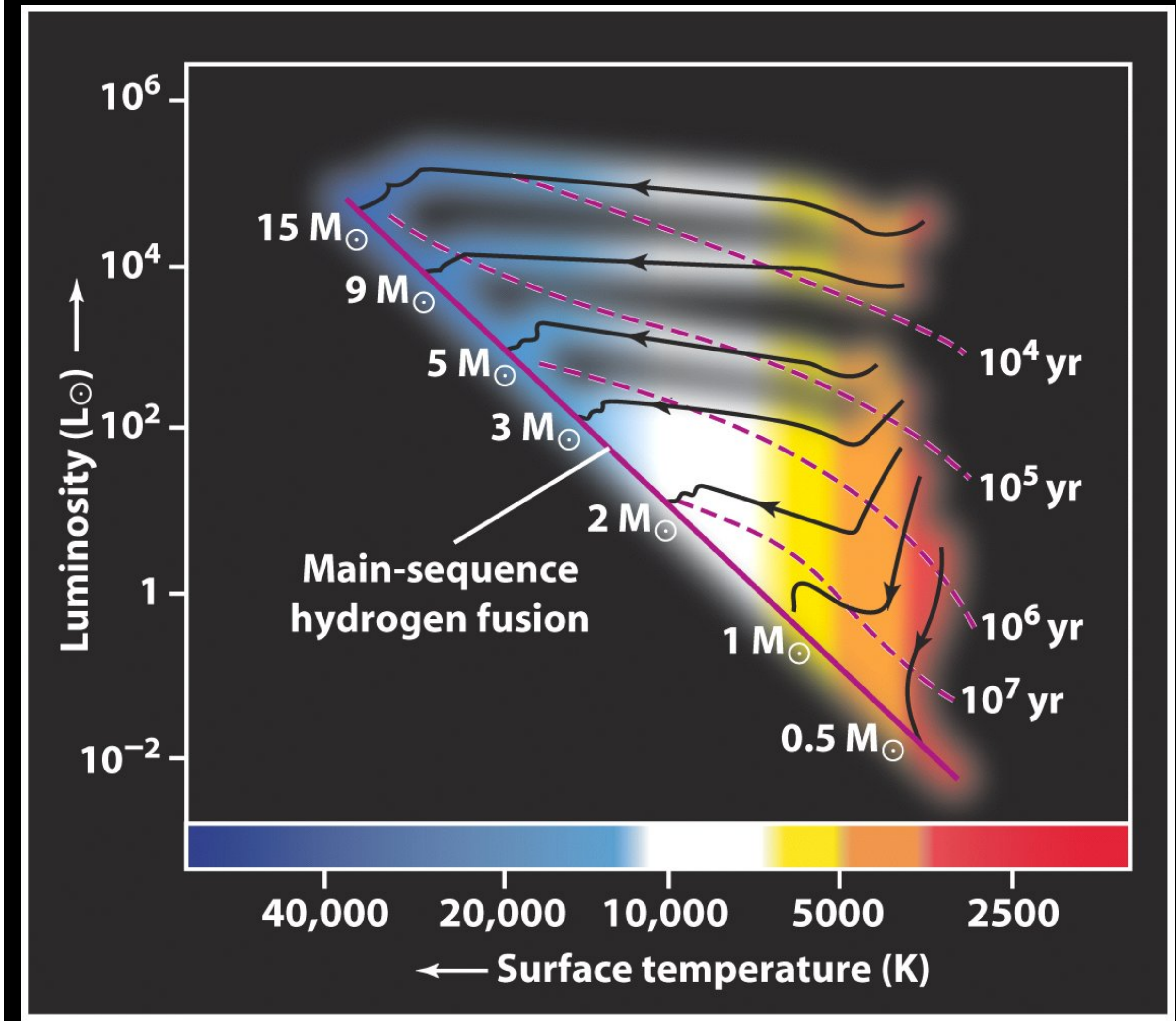
- Gas in the cloud keeps falling onto the **protostar**.
- The collapsing gas tends to start rotating around the protostar as it falls in forming a disk and a jet.
- Eventually, the protostar develops a wind, like the solar wind but much stronger. This out flowing wind stops the in falling matter.
- The protostar keeps contracting under it own gravity. The protostar is powered by gravity via contraction - not by fusion.
- The protostar becomes a star when it has contracted so much that it is dense and hot enough to begin nuclear fusion.

During the birth process, stars both gain and lose mass



Magnetic field lines are pulled toward the protostar as material is attracted to the protostar. The swirling motions of the disk material distort the field into helical shapes and some of in-falling disk material is channeled outward along these lines.

Protostars evolve into main-sequence stars



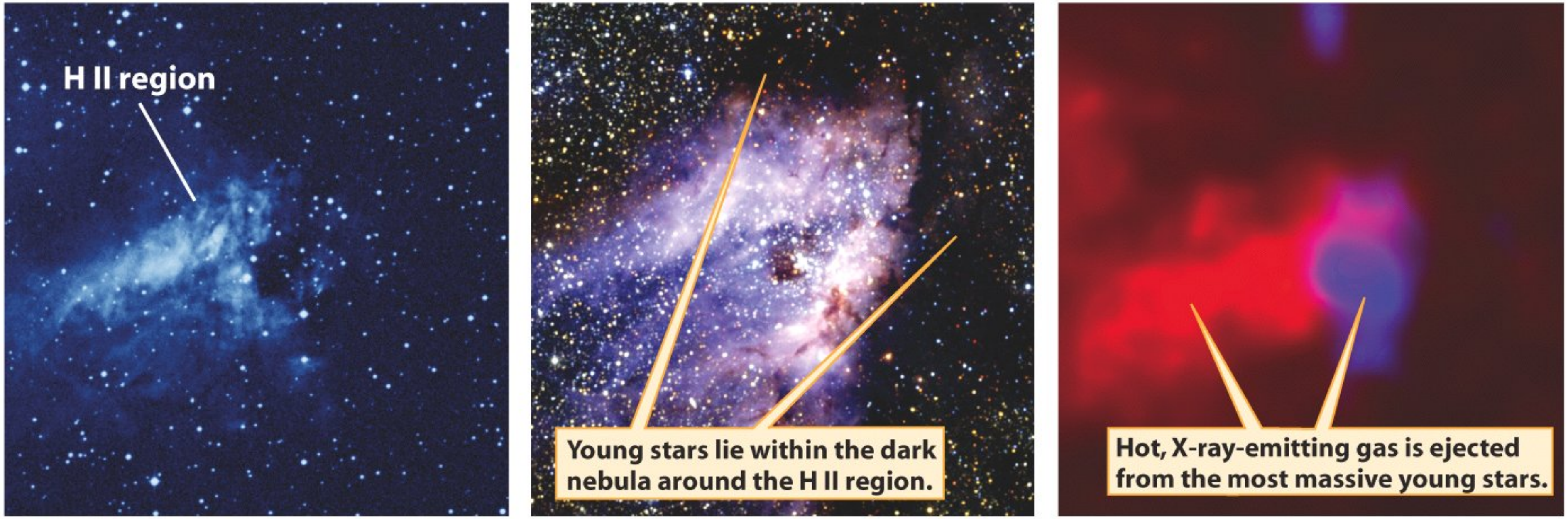
- A protostar's relatively low temperature and high luminosity place it in the upper right region on an H-R diagram
- Further evolution of a protostar causes it to move toward the main sequence on the H-R diagram
- When its core temperatures become high enough to ignite steady hydrogen burning, it becomes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

The more massive the protostar, the more rapidly it evolves

- 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

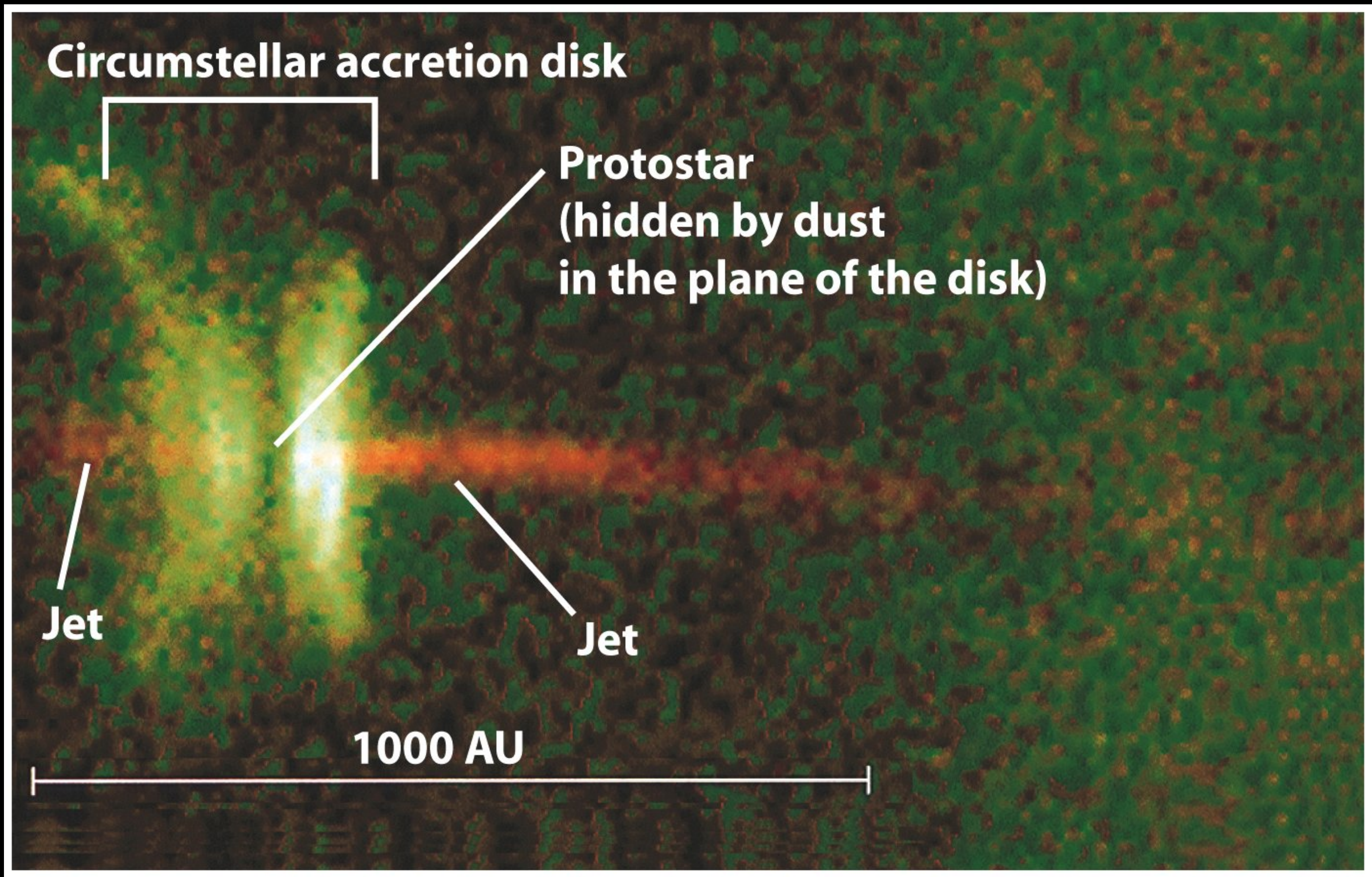
During the birth process, stars both gain and lose mass

- 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)

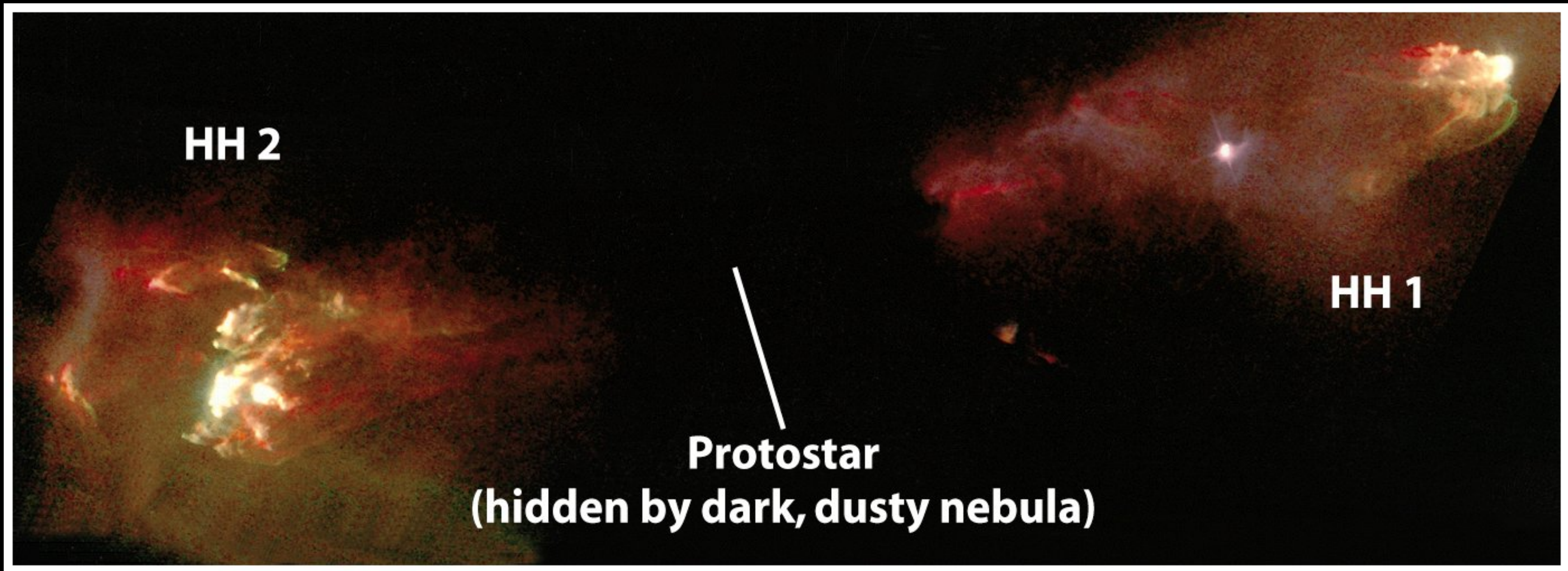


(a) Visible-light image (b) False-color infrared image (c) False-color X-ray image

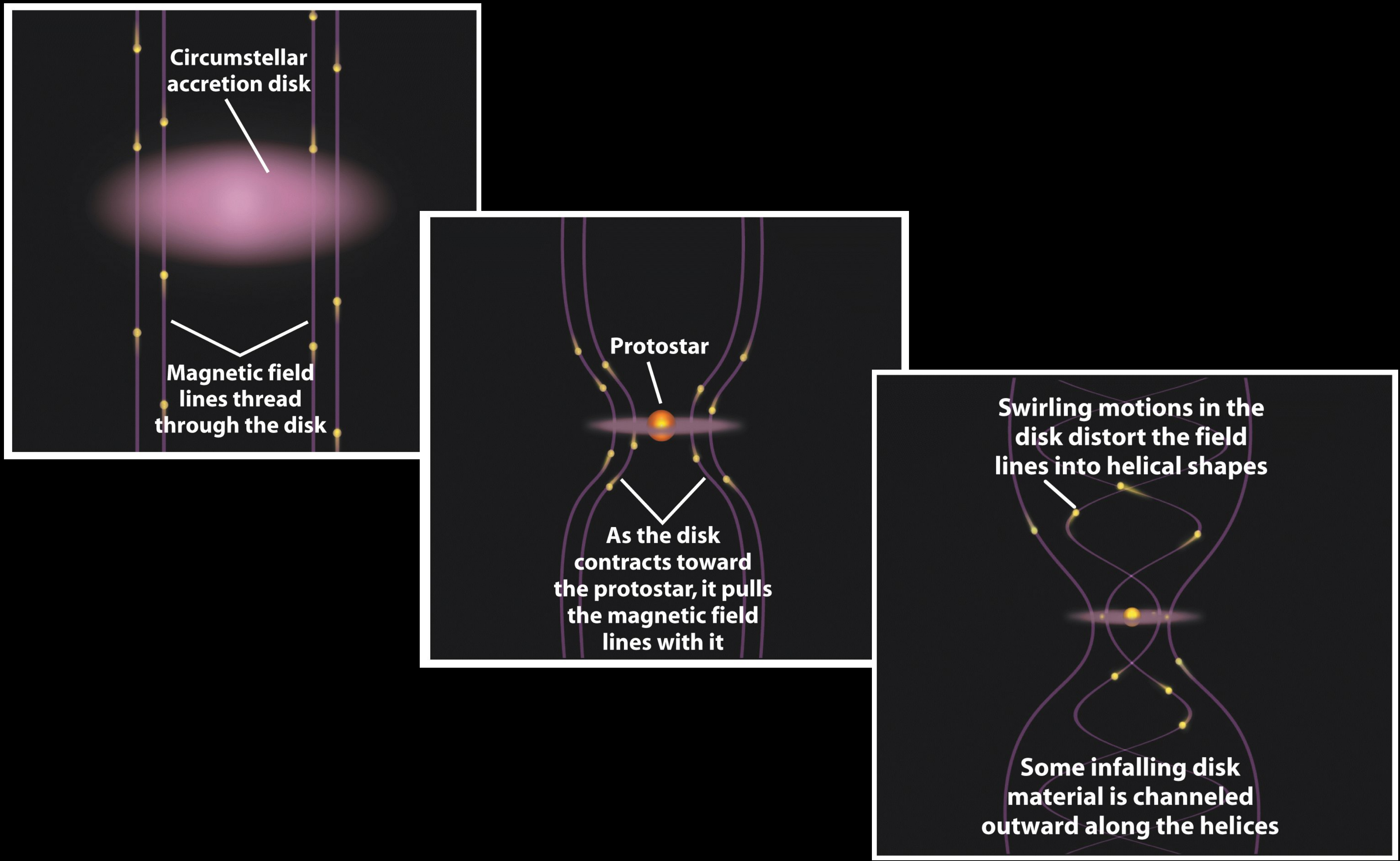
Jets: A circumstellar accretion disk provides material that a young star ejects as jets



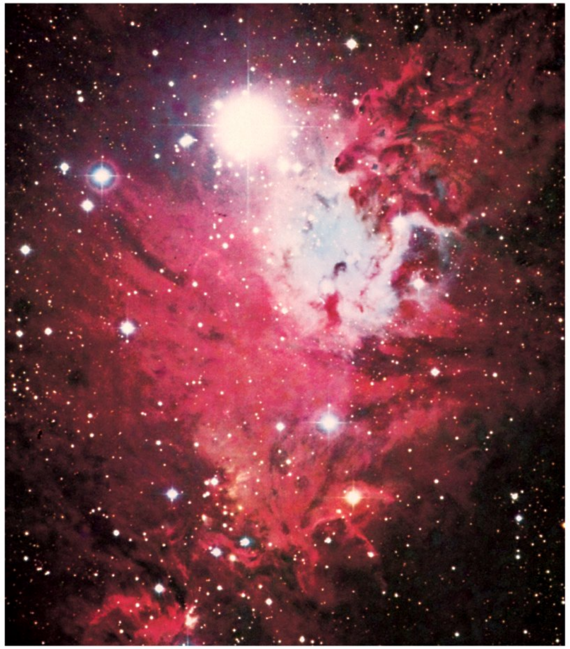
Jets: Clumps of glowing gas are sometimes found along these jets and at their ends



A Magnetic Model for Jets (Bipolar Outflow)



Young Star Clusters



The star cluster NGC 2264

The Pleiades star cluster

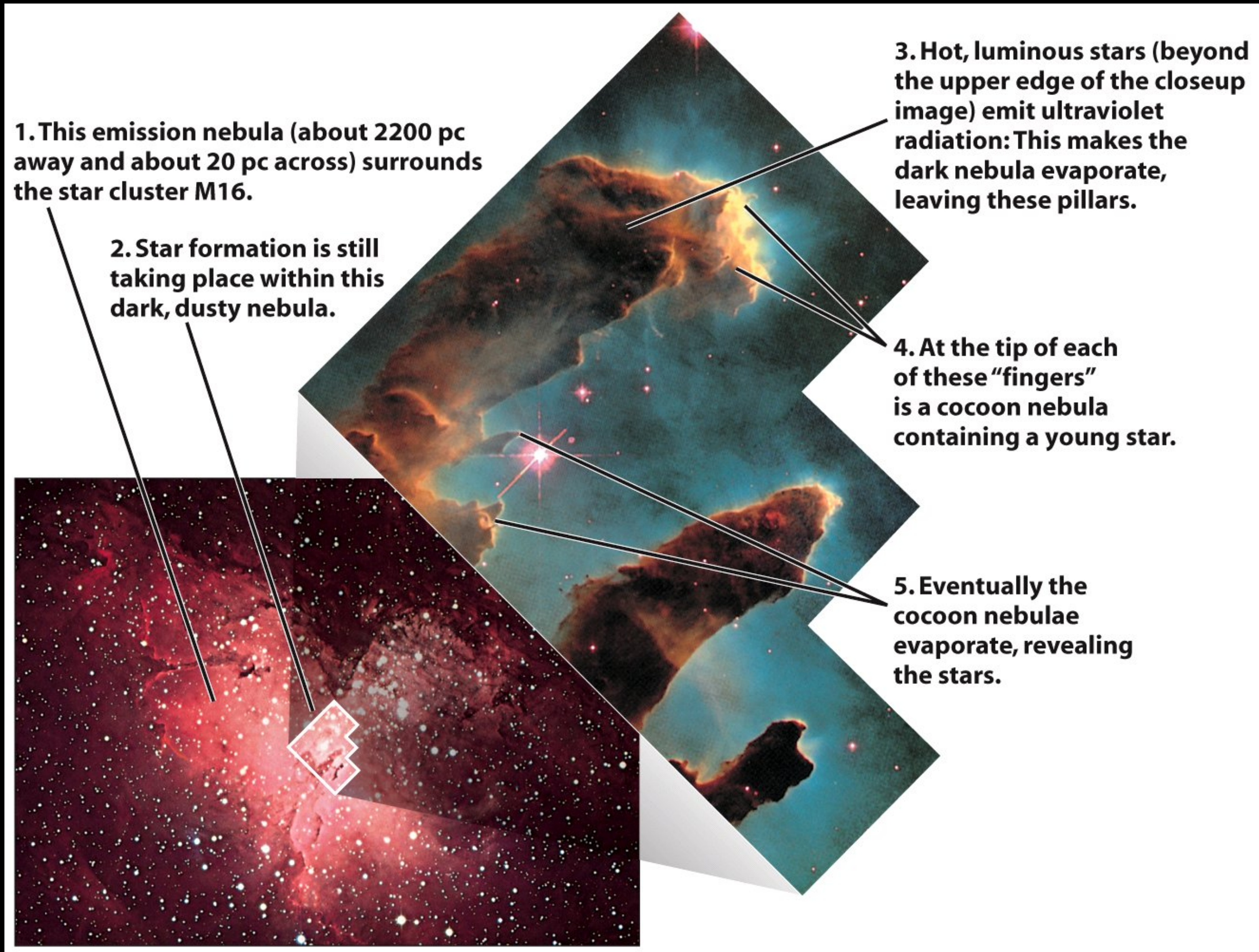
- Newborn stars may form a star cluster
- Stars are held together in such a cluster by gravity
- Occasionally a star moving more rapidly than average will escape, or "evaporate," from such a cluster
- A stellar association is a group of newborn stars that are moving apart so rapidly that their gravitational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

Young Star Cluster with an HII Region

- High-mass protostars becomes hot,ultraluminous stars of spectral types O and B
- Ultraviolet radiation from these exposed young stars ionize the surrounding interstellar medium to produce H II region, or emission nebula

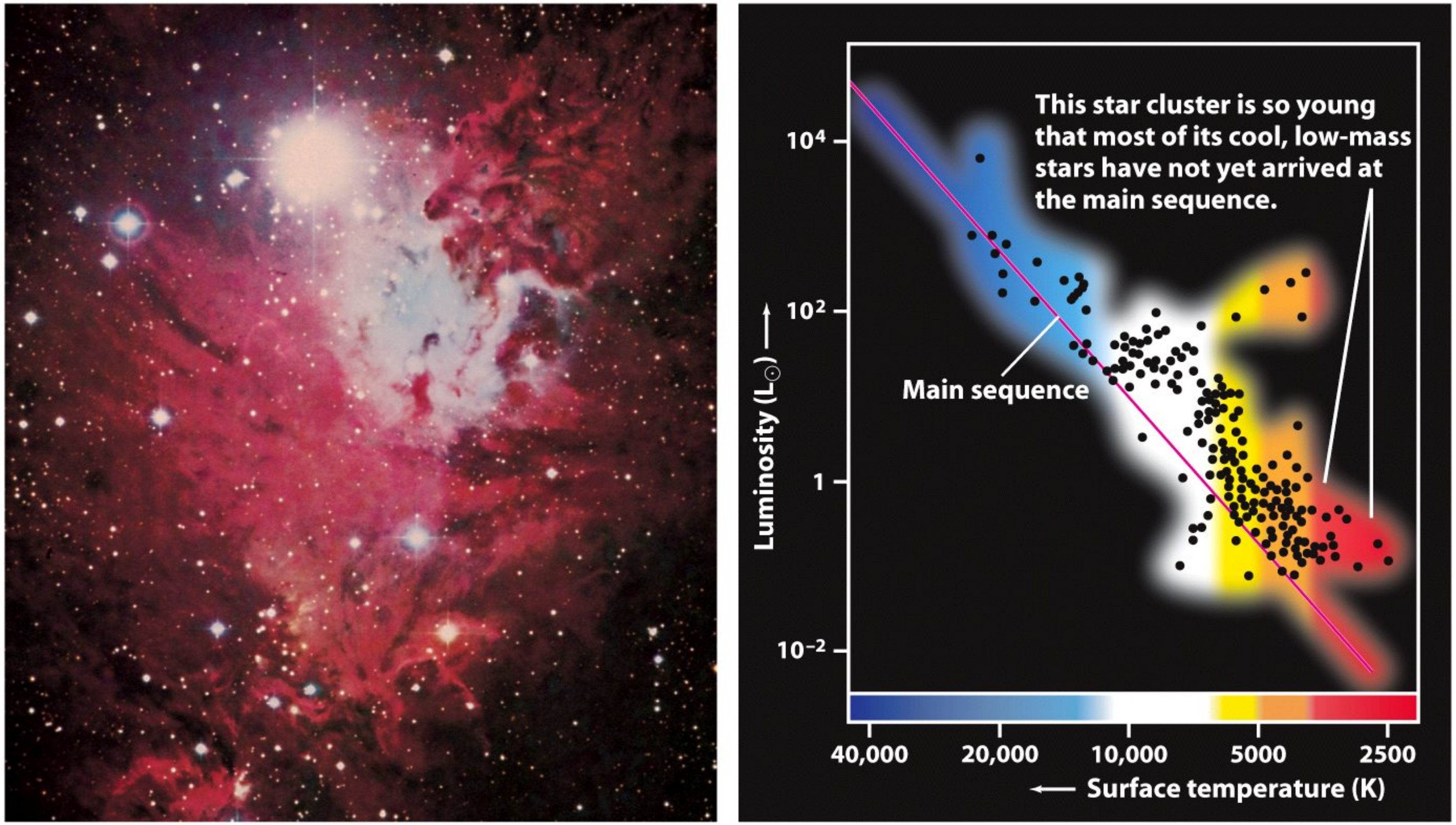
Young Star Cluster with an HII Region

- When the most massive protostars have reached the main sequence, other low-mass protostars are still evolving nearby within their dusty cocoons.



Young Star Cluster and its H-R diagram

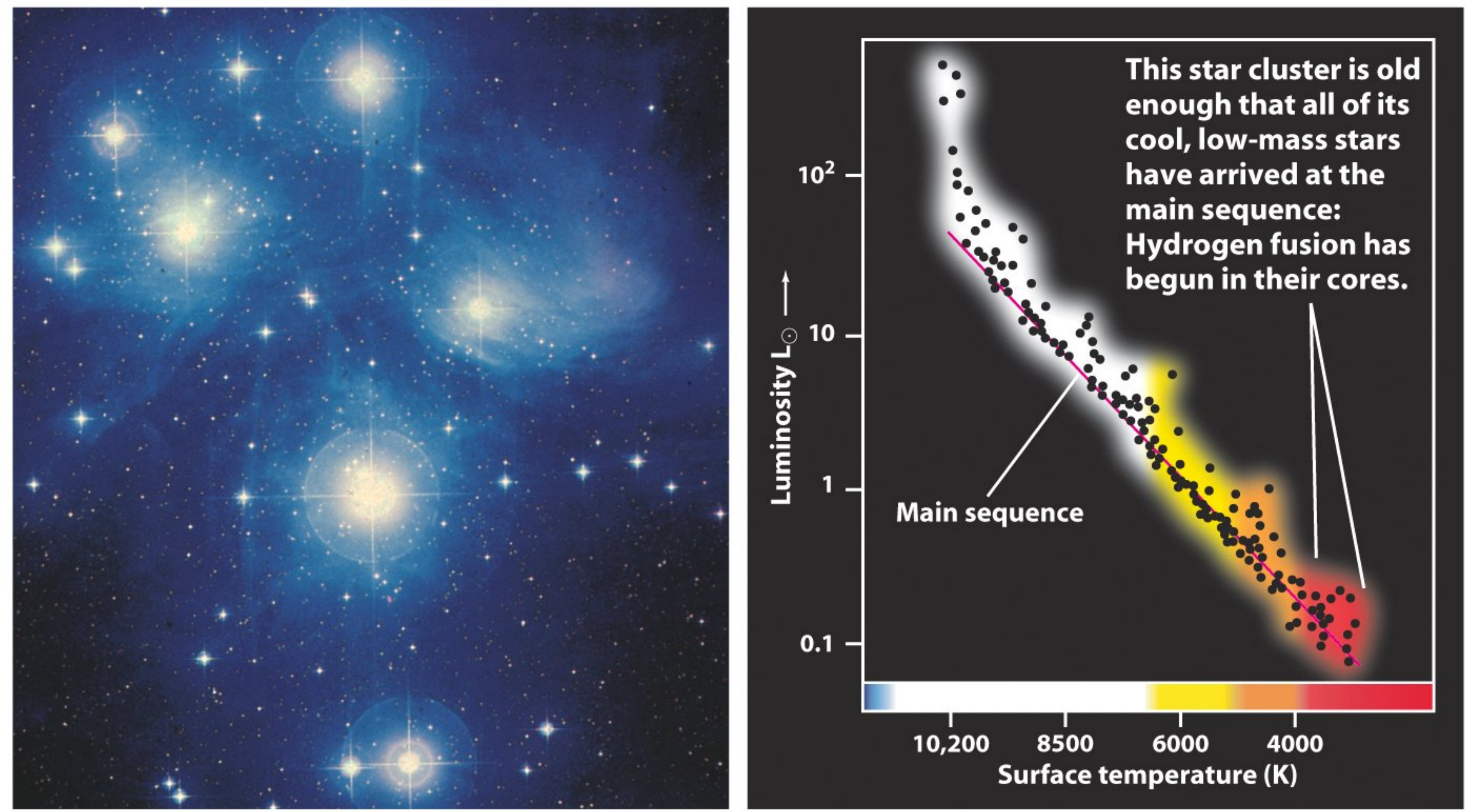
- NGC 2264, ~ 2 million year old
- Most of its cool, low-mass stars have not yet arrived at the main sequence



(a) The star cluster NGC 2264 (b) An H-R diagram of the stars in NGC 2264

Older Star Cluster and its H-R diagram

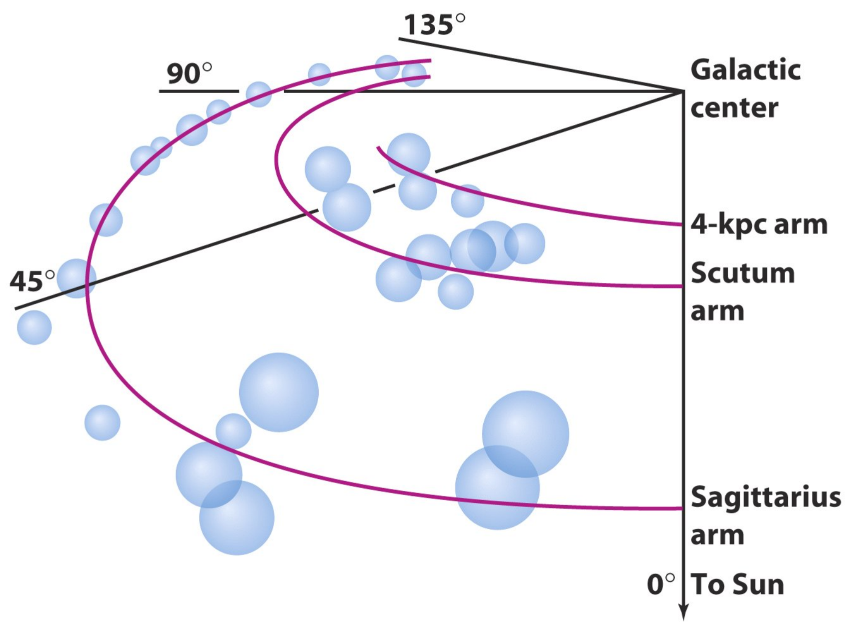
- Plleiades, ~ 50 million year old
- Almost all stars arrived at the main



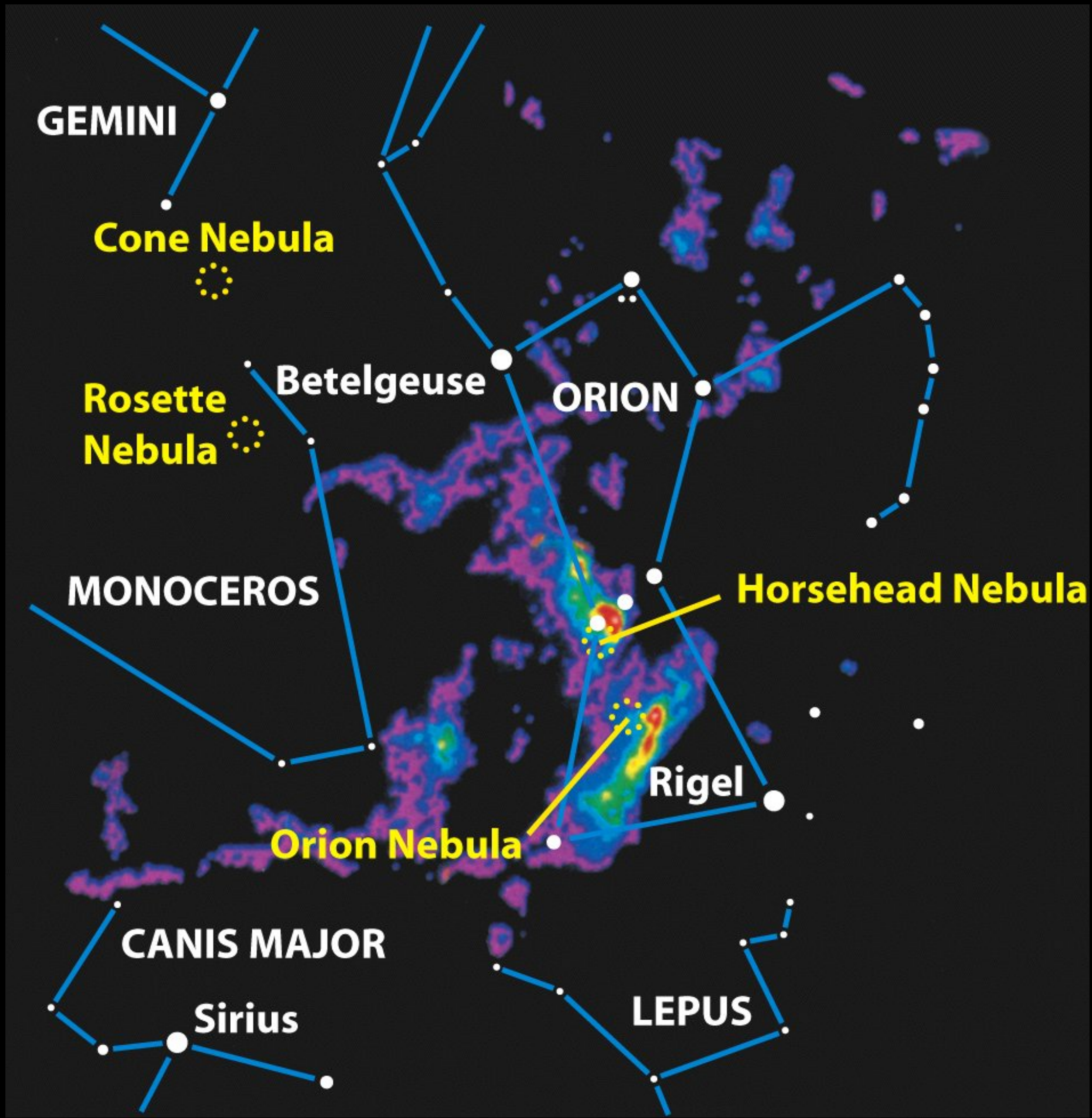
(a) The Pleiades star cluster (b) An H-R diagram of the stars in the Pleiades

Giant Molecular Clouds

- How do the star-forming dark nebulae distribute in our galaxy?
- Distant dark nebulae are hard to observe, because they do not emit visible light
- However, dark nebulae can be detected using microwave observation, because the molecules in nebulae emit at millimeter wavelengths
- Giant molecular clouds are immense nebular so cold that their constituent atoms can form molecules.
- Giant molecular clouds are found in the spiral arms of our Galaxy.



Giant Molecular Clouds and Star-forming Regions

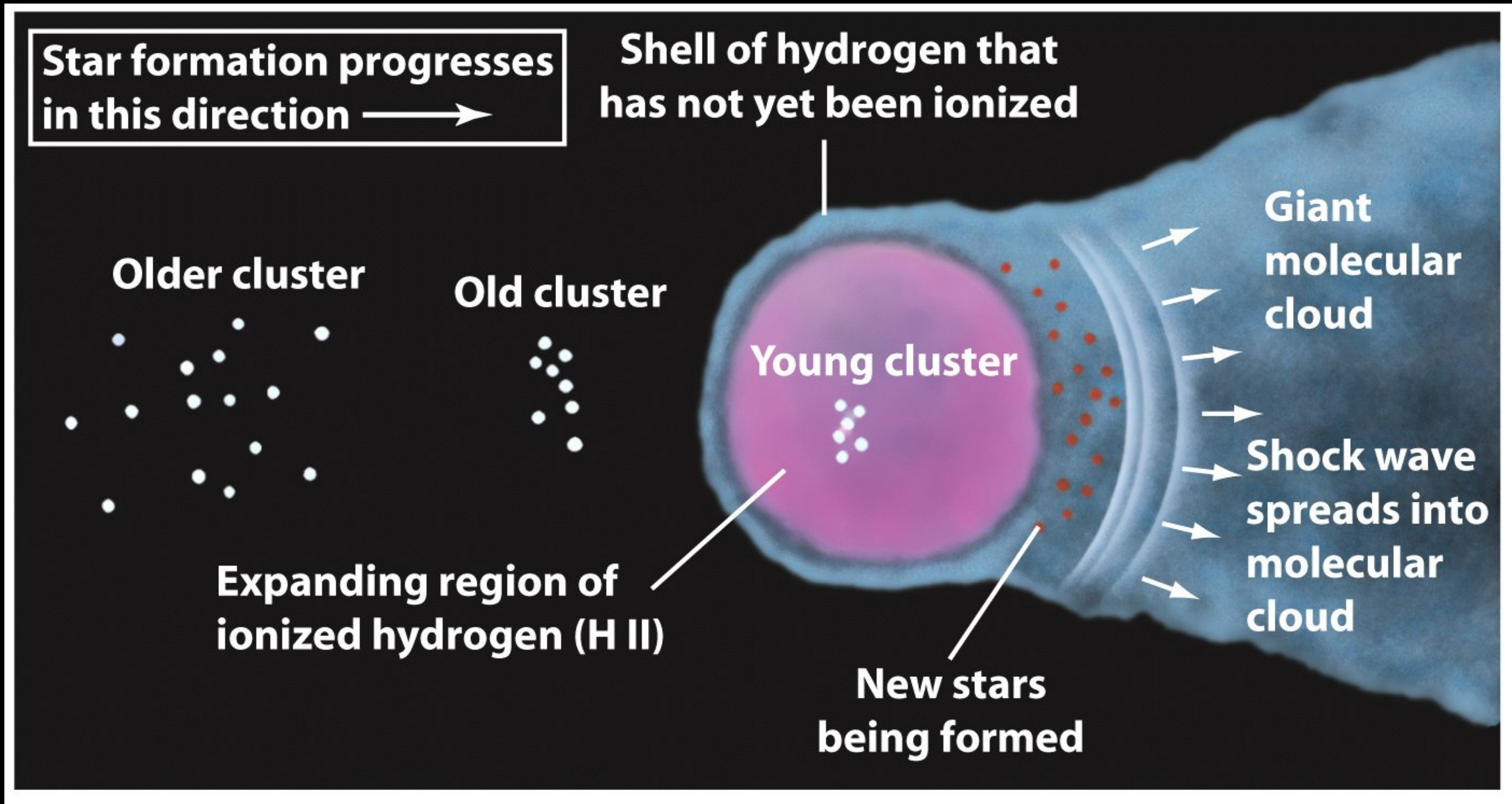


- Star-forming regions appear when a giant molecular cloud is compressed
- This can be caused by the cloud's passage through one of the spiral arms of our Galaxy, by a supernova explosion, or by other mechanisms

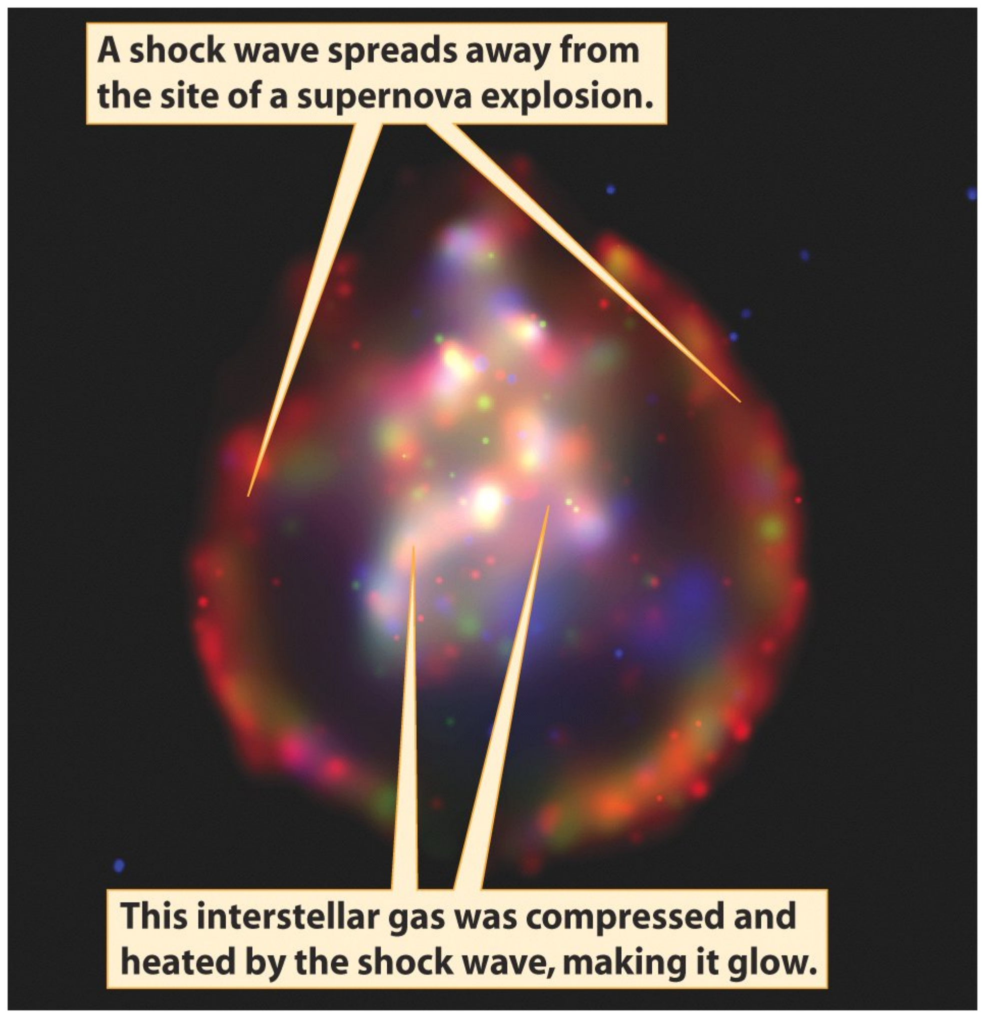
Trigger of Star Birth: Shock Waves from O and B Stars

- 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



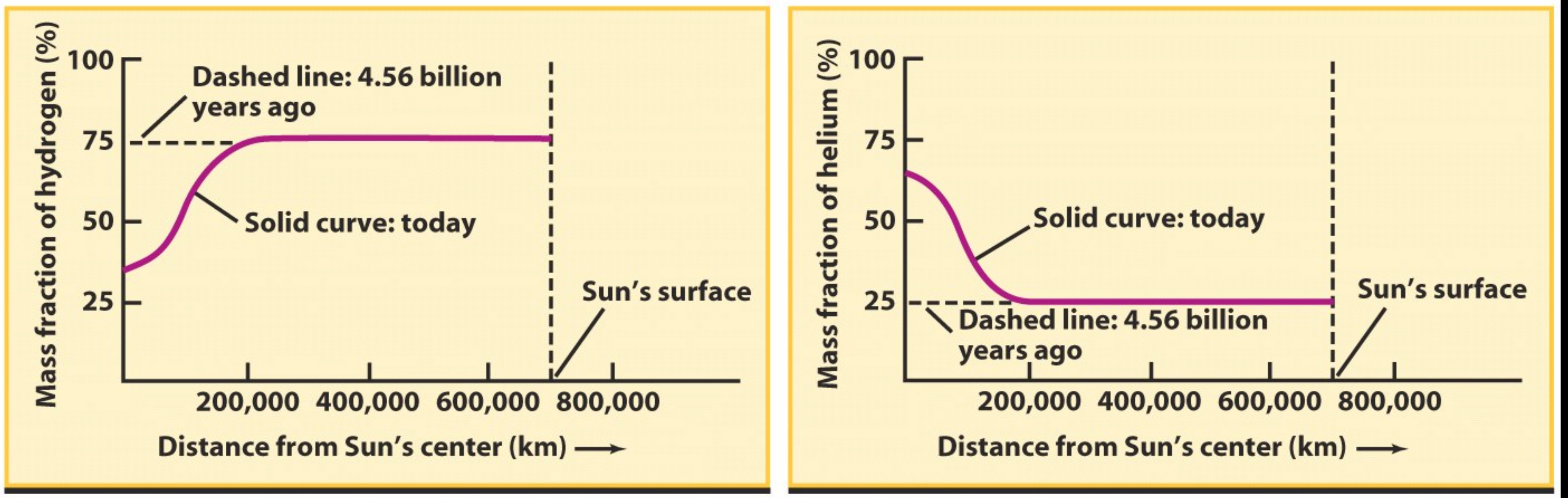
3. Stellar Evolution: After the Main Sequence

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. How do we know that many stars lived and died before our Sun was born?
5. Why do some giant stars pulsate in and out?
6. Why do stars in some binary systems evolve in unusual ways?

The Sun: 4.5 billion years old

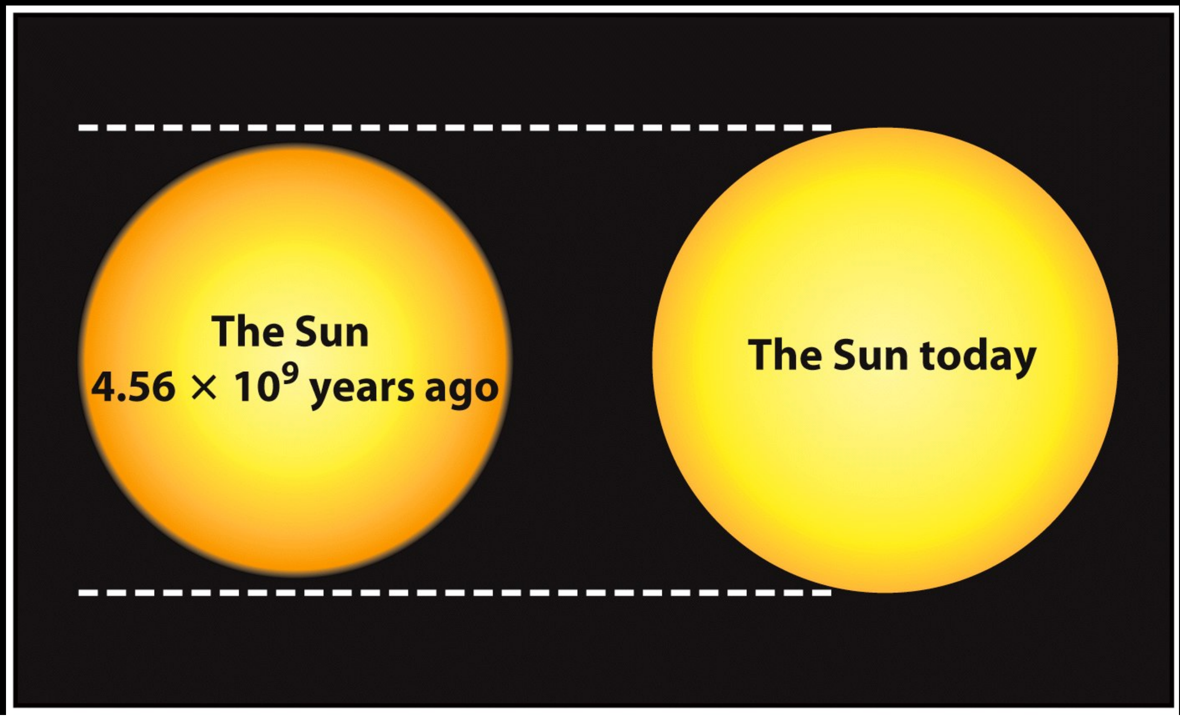
- The Sun has been a main-sequence star for 4.56 billion years, and at the core
  - Hydrogen depleted by about 35%
  - Helium amount increased
- The Sun should remain in main sequence for another 7 billion years
- The Sun or 1 Msun star has a main sequence lifetime of 12 billion years



(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 $T \sim M/M^{3.5} \sim 1/M^{2.5}$

- Question: T = 12 billion years for 1 Msun star, what T for 10 Msun star?

  $T / T_{sun} = 1/(10^{2.5}) = 1/316$

  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 --- core hydrogen fusion ceases

Core hydrogen fusion ceases when the hydrogen has been exhausted in the core of a main-sequence star

This leaves a core of nearly pure helium

The core shrinks under self-gravitation due to the loss of hydrostatic equilibrium

The core becomes hotter

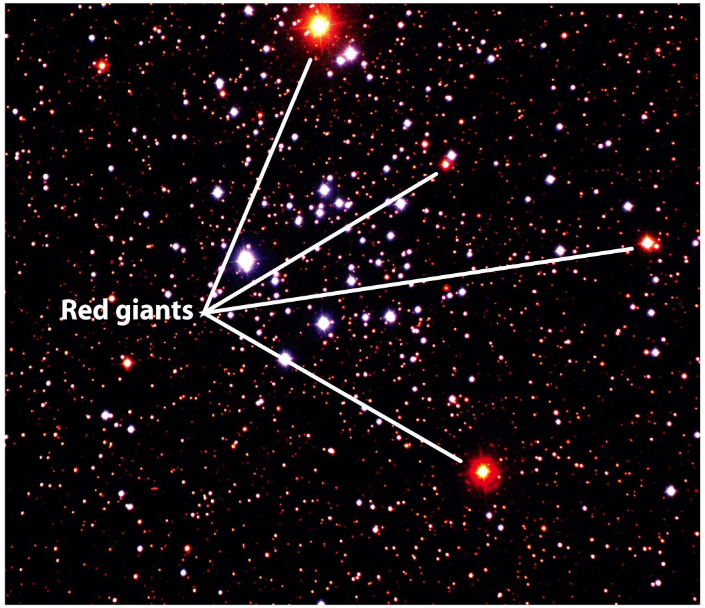
For 1 Msun star, over hundreds of million years

- Core compressed to one-third of its original size
- Temperature increases to 100 million K (from 15 MK)

After Main Sequence:
1. Hydrogen fusion ceases at the core
2. a 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

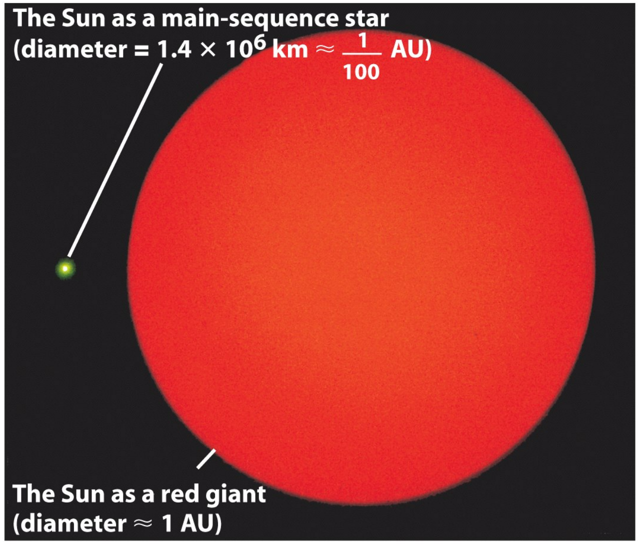
Red Giants



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



The Sun today and as a red giant

Red Giants (the next evolution stage): 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:

$$3\ {}^{4}He \rightarrow {}^{12}C + \text{energy}$$

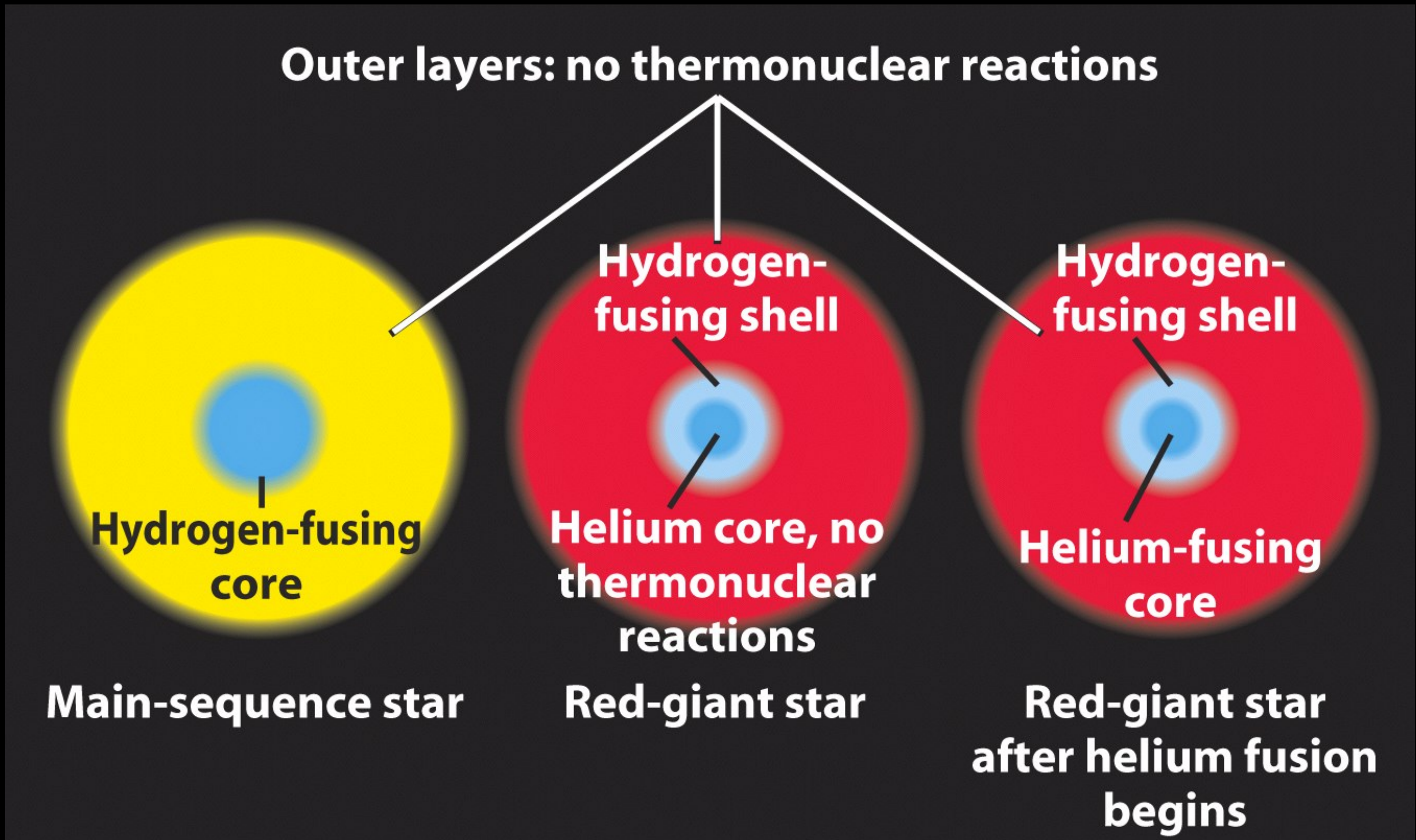
- Or form stable Oxygen

$${}^{12}C + {}^{4}He \rightarrow {}^{16}O + \text{energy}$$

- (note: helium nucleus called alpha particle)

Summary of Stellar Evolution (remind)

- 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 the core

- 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 (cont.)

- 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, due to the **Pauli exclusion principle**
  - **E.g., electrons in a piece of metal on the Earth**
- **Pauli exclusion principle: two particles can not occupy the same quantum state; in other words, can not have two things at the same place at the same time**
- 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 Flash

- In the degenerate-electron core, temperature rises exponentially, because of no "safety valve" of an ideal gas
- 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
- The core expands, and cools, terminating the helium flash
- 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: After ignition of helium fusion,

Red giant becomes less luminous and smaller, but hotter

After the ignition of helium fusion, the core expands and enters the steady state of helium fusion

The core is in a steady state: no contraction and no temperature rising

The ideal gas of the core serves as the "safety valve" that leads to the steady state of the core:

- 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

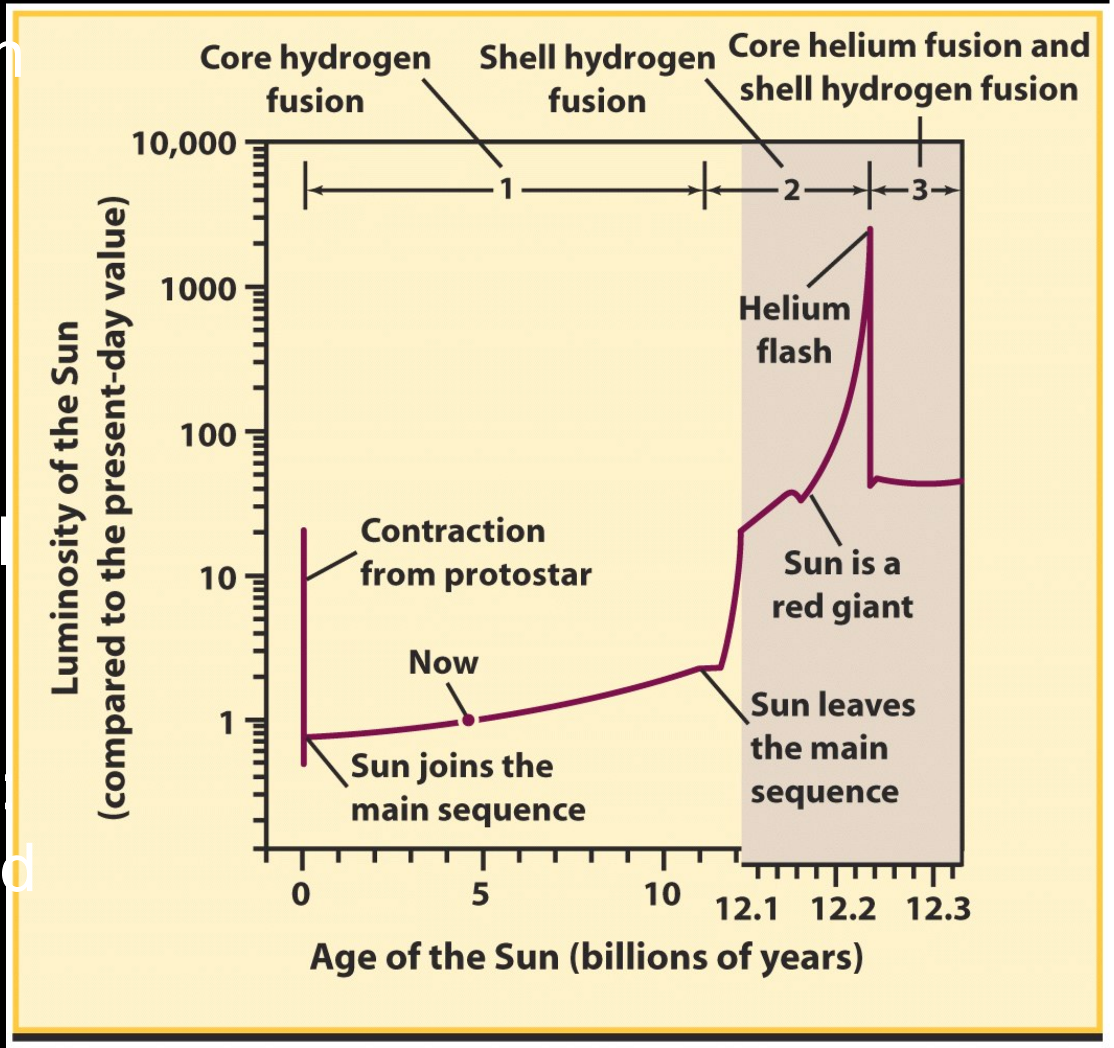
Protostar: ~ 10 M yrs

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

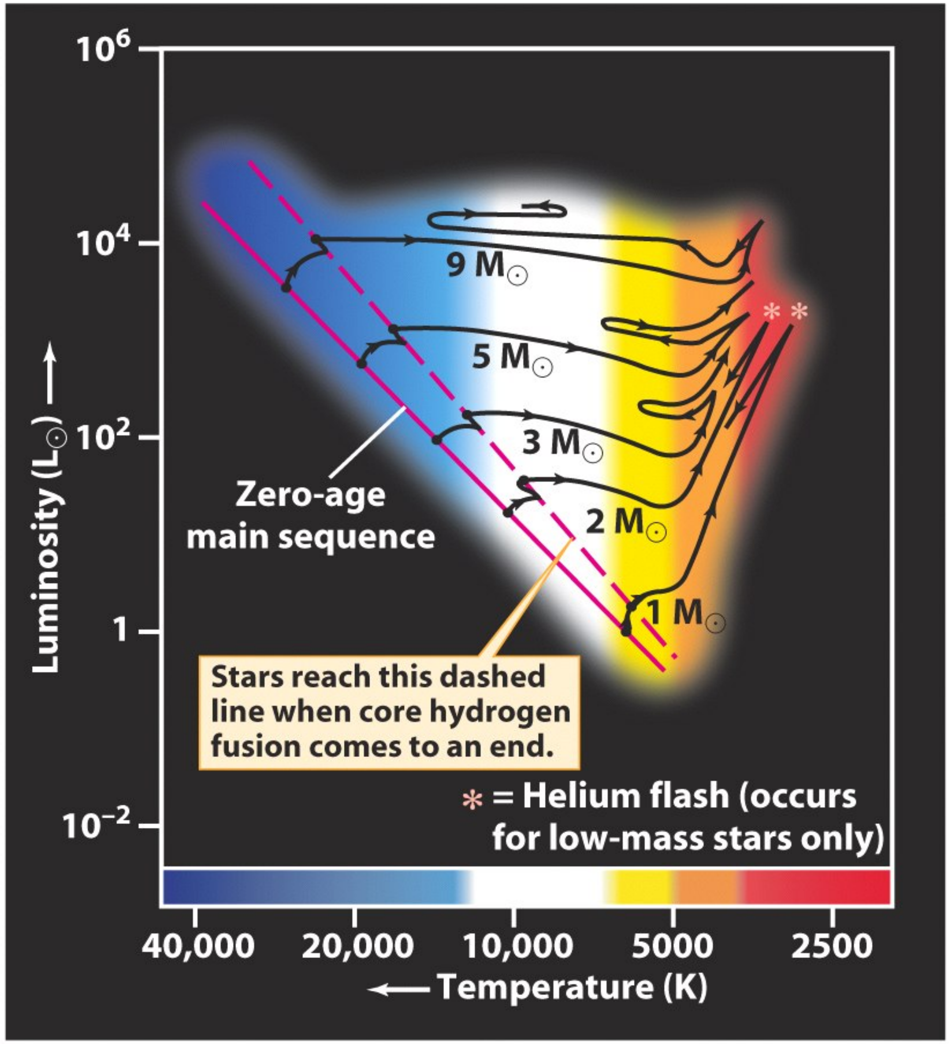
Death (become a white dwarf): helium in the core exhausted



ZAMS (Zero-age Main Sequence Star)

ZAMS (zero-age main sequence, the solid line): stars have just arrived at the main sequence
With time of hydrogen fusion, core shrinks, star **slowly** expand and gradually becomes brighter

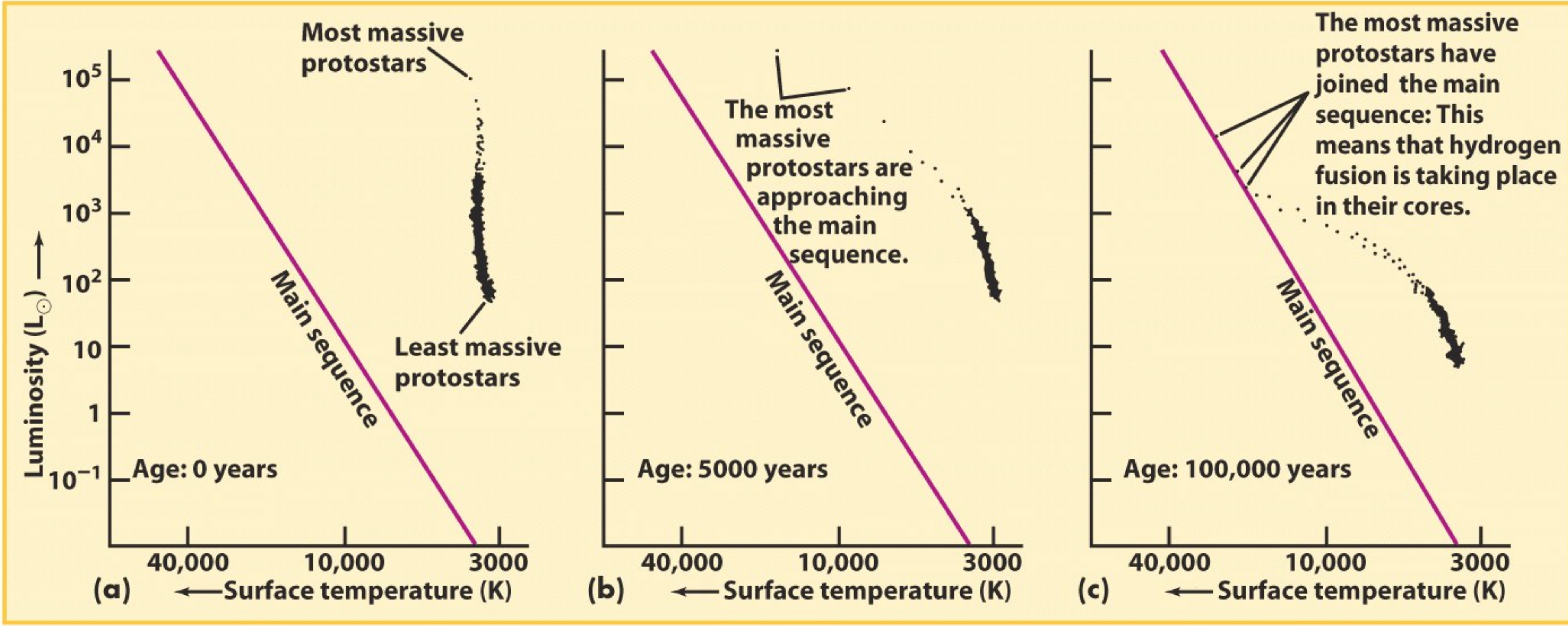
As a result, **main sequence is a broad band rather than a narrow line**



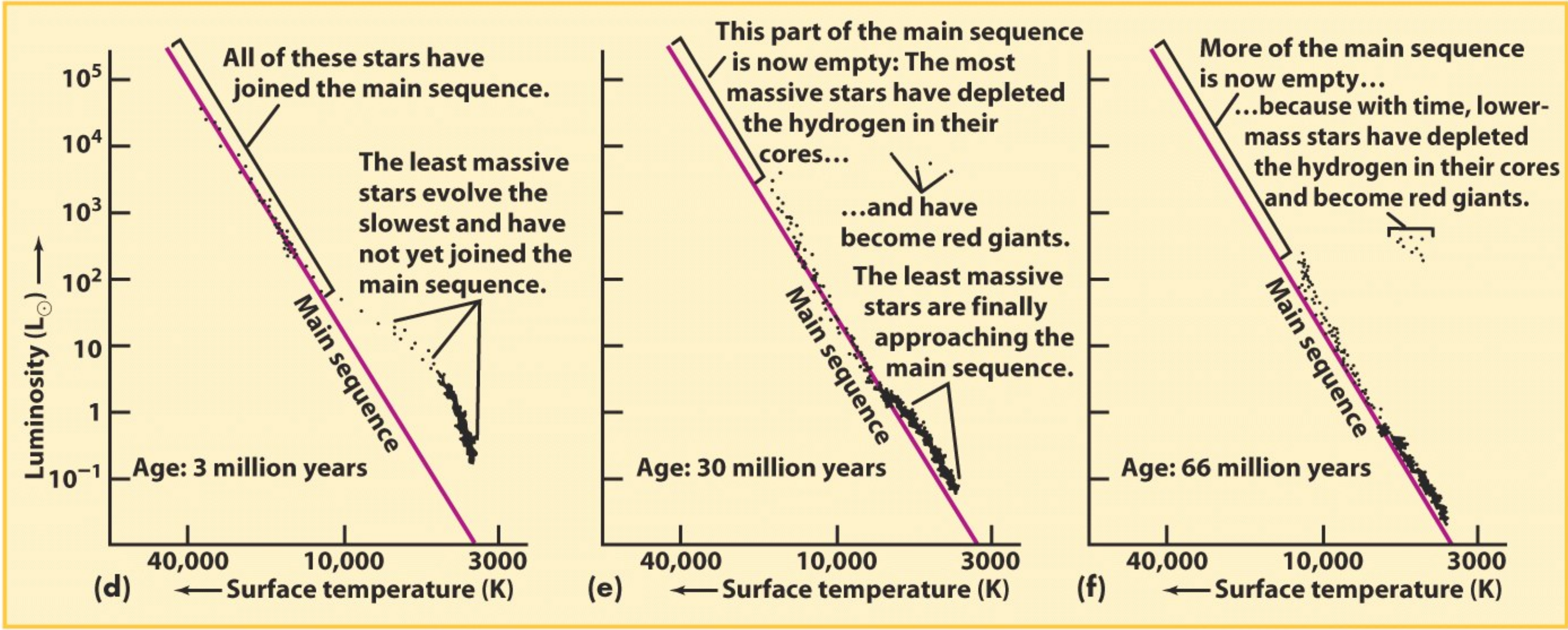
Post–main-sequence evolutionary tracks of five stars with different mass

H-R Diagram: Cluster Evolution

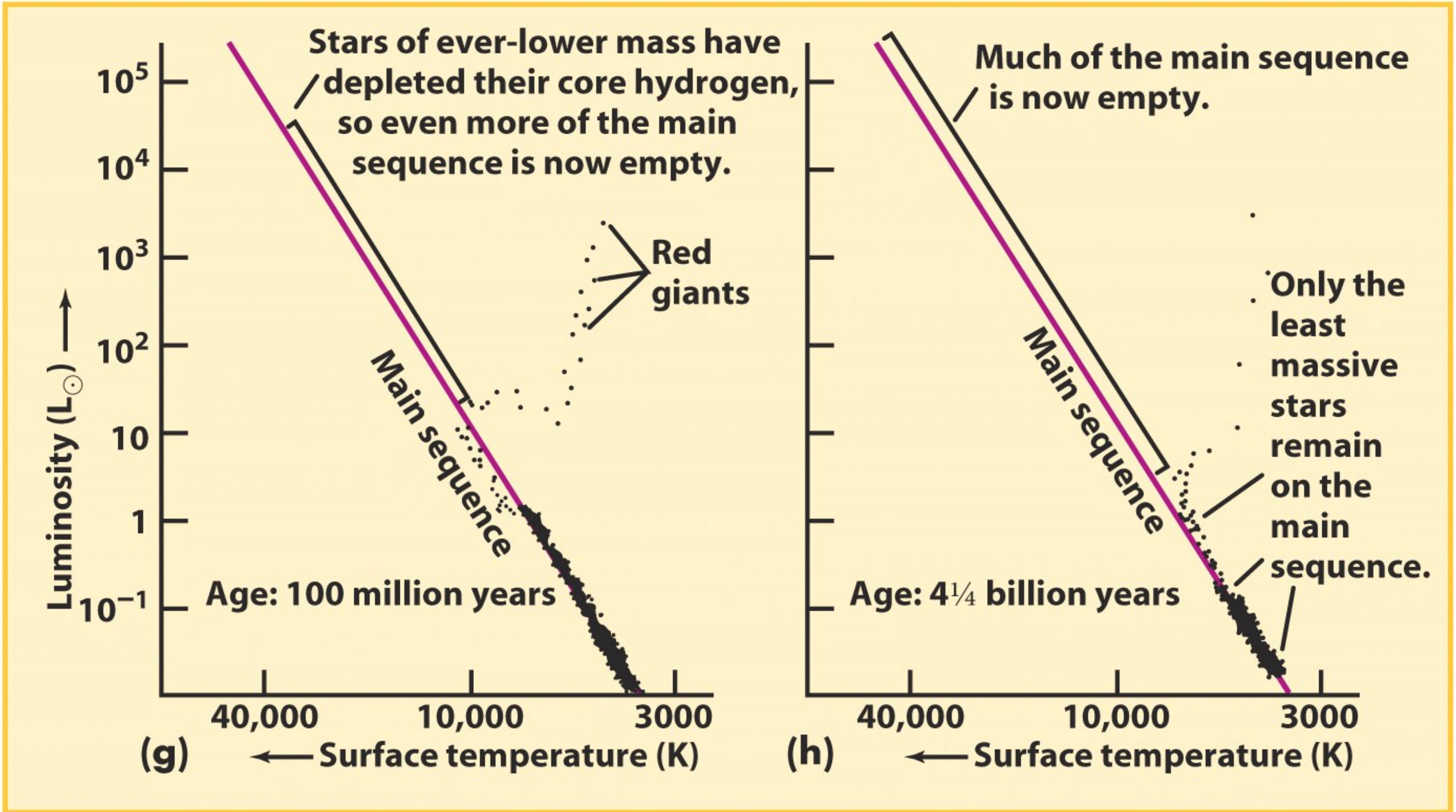
100 protostars stars with different mass start to evolve at the same time: computer-simulate the evolution of a star cluster



H-R diagram: Cluster Evolution

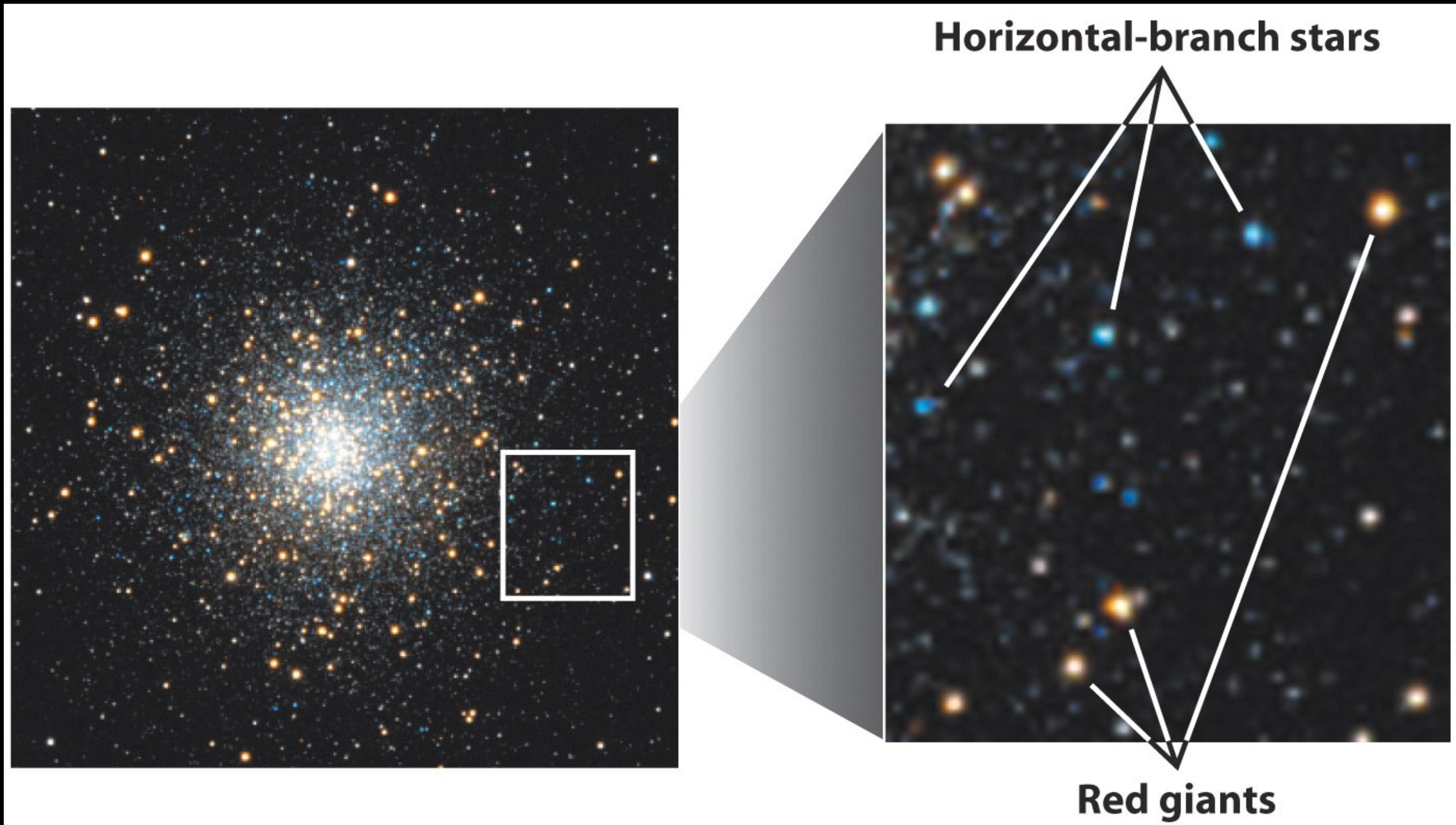


H-R diagram: cluster evolution



Old cluster: contains many post-main-sequence stars, such as red giants

A typical cluster contains up to 1 million stars within 100 parsec across



H-R diagram for Globular Cluster M55

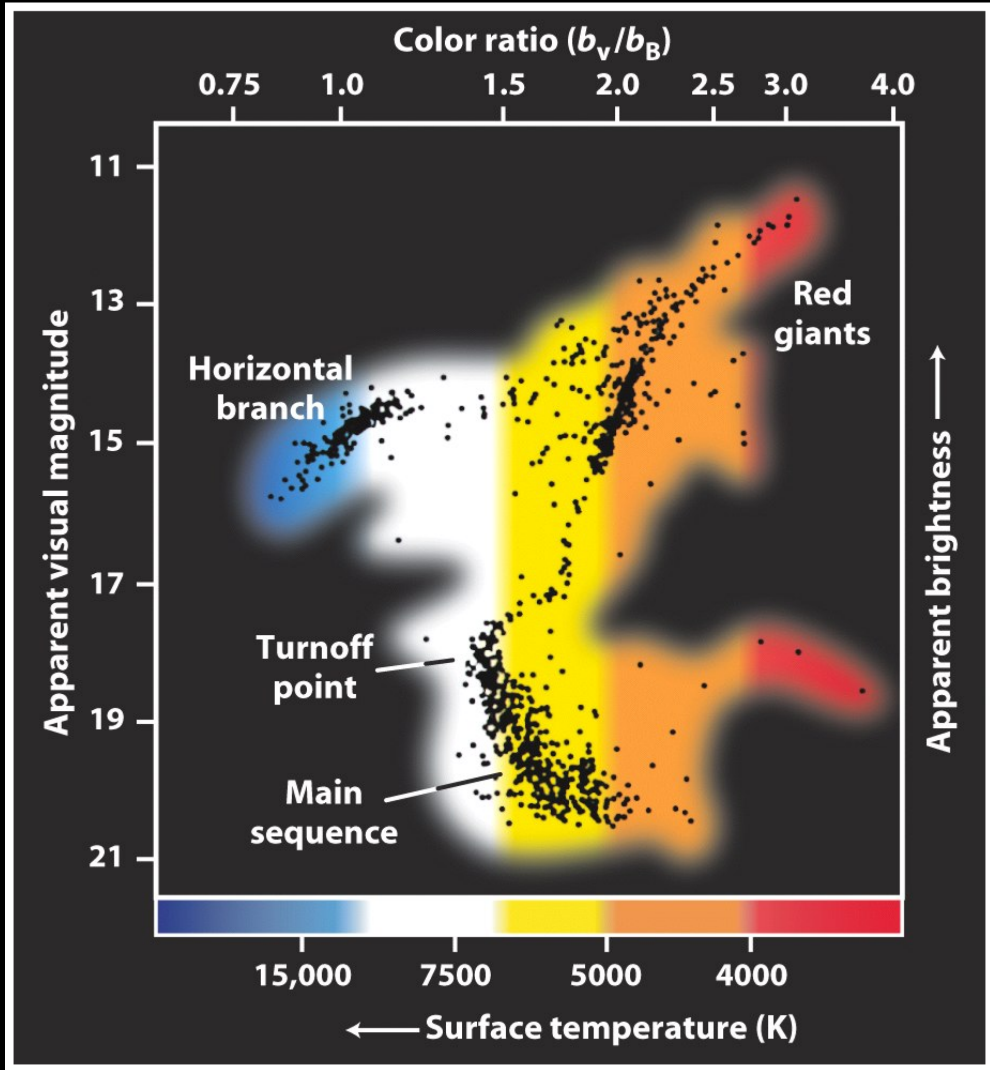
Apparent magnitude is equivalent to the absolute magnitude, because all stars are at the same distance

The magnitude-color diagram is equivalent to the H-R diagram

Turnoff point: top of the surviving portion of the main sequence

Turnoff points indicates the age of the cluster

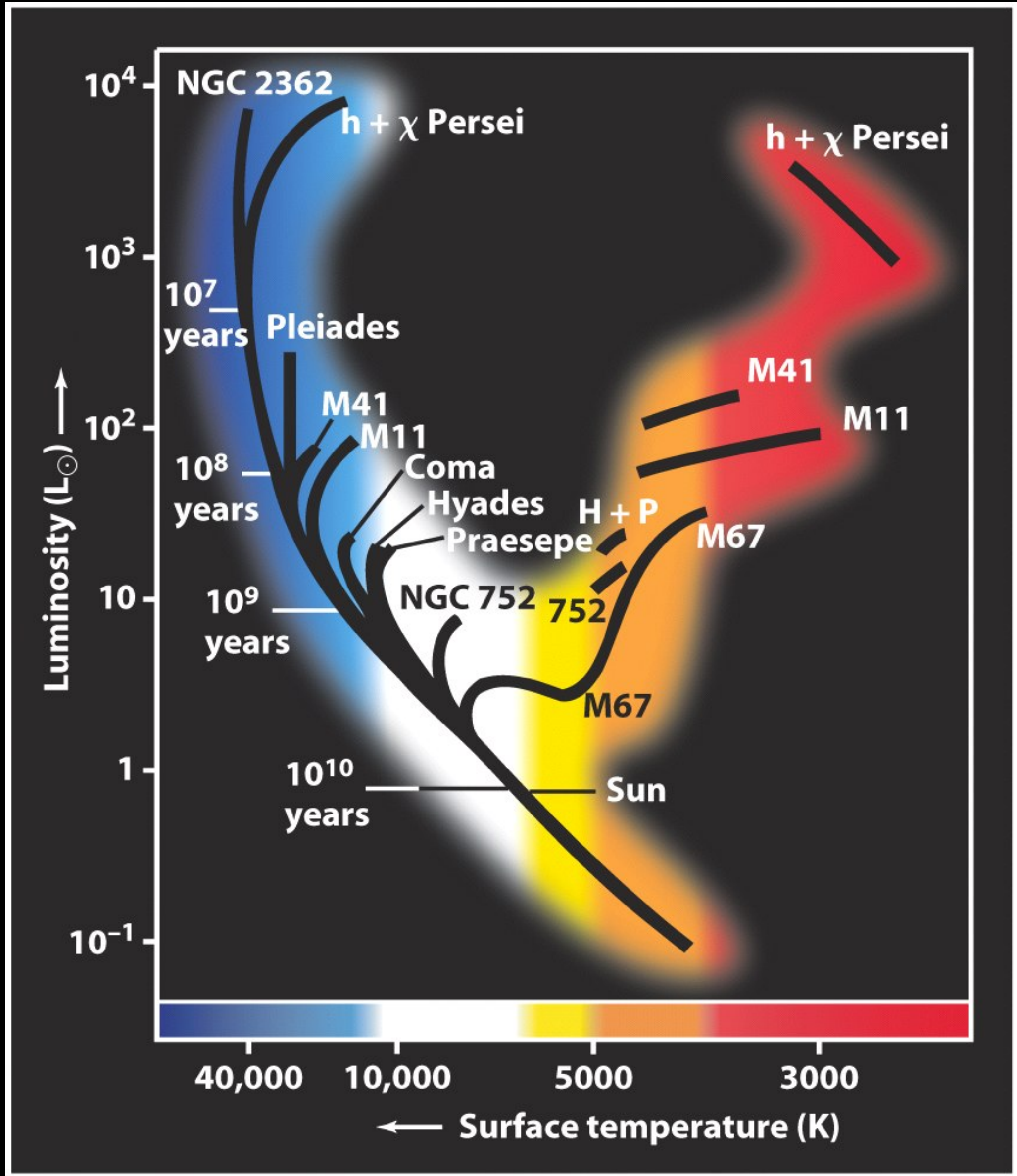
M55 is 12 billion years old



Horizontal Branch are stars post-helium-flash with both core helium fusion and shell hydrogen fusion

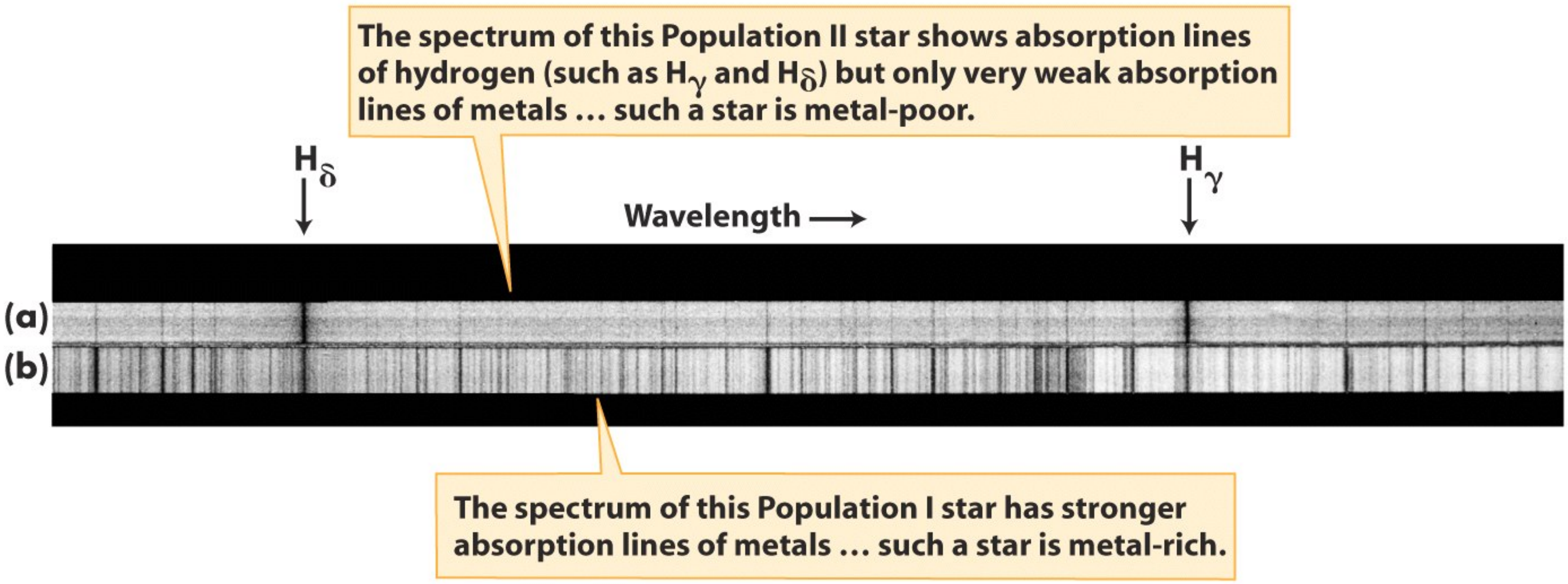
Turnoff points for different star clusters

Turnoff Points indicate the ages of these observed star clusters

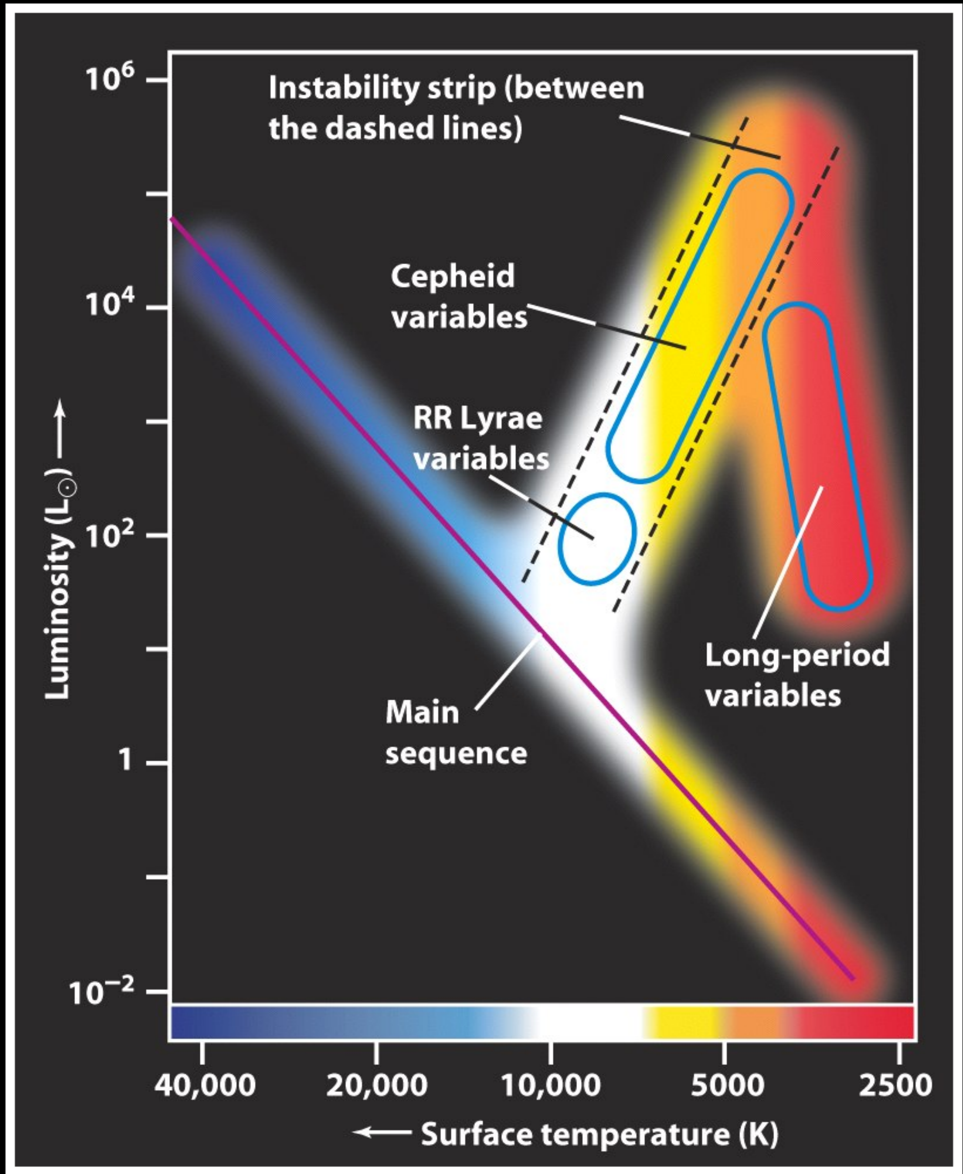


Two populations of Stars

- Stellar evolution produces two distinct population of stars: population I and population II.
- Population I shows many metal lines, rich of metals
- Population II shows only hydrogen lines, lacking of metals
- Metals in astronomy denote any elements other than hydrogen and helium



Many stars pulsate when they evolve into the instability strip

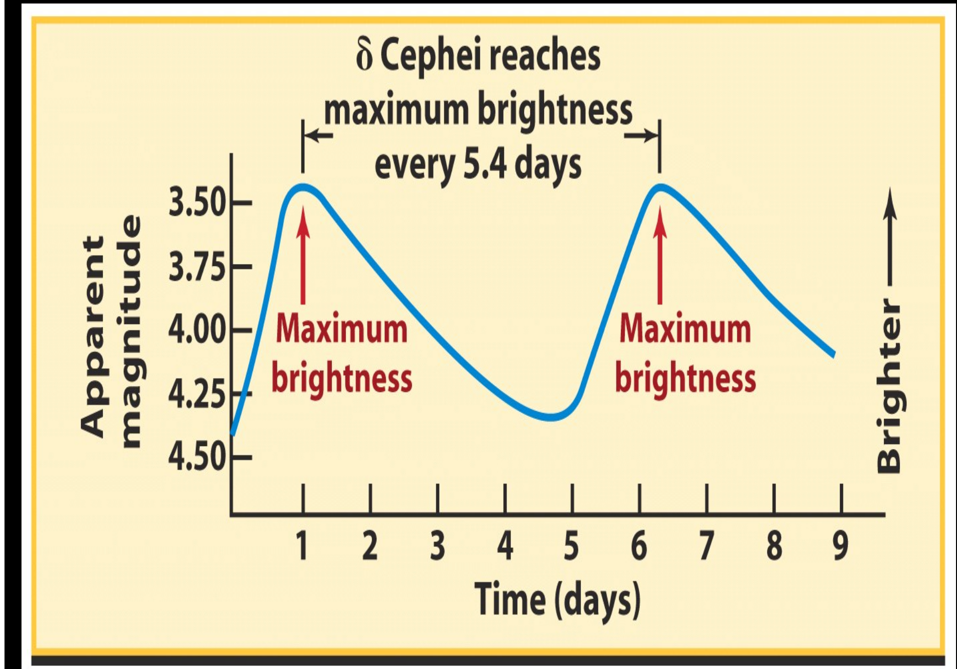


- Instability strip lies between the main sequence and the red giant region
- Cepheid variables are high-mass pulsating variables
- RR Lyrae variables are low-mass, metal-poor pulsating variables with short periods
- Long-period variable stars also pulsate but in a fashion that is less well understood

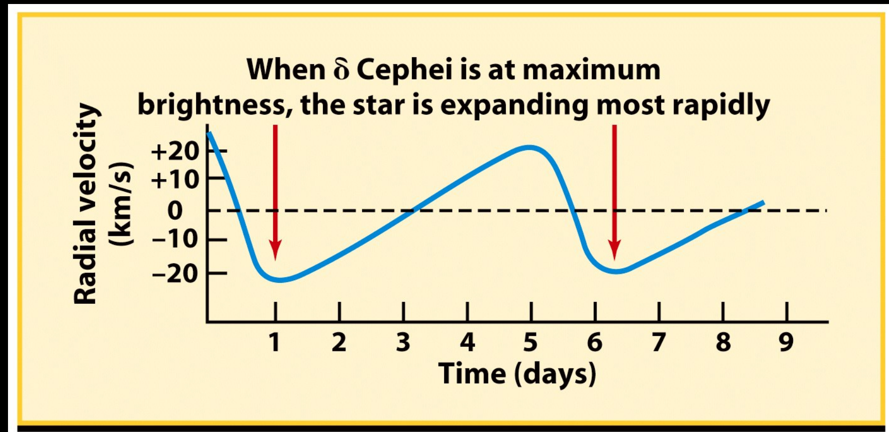
Cepheid Stars

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

Cepheid pulsates because a star is more opaque when compressed than when expanded

When the envelope contracts, compression ionizes the helium, and make the atmosphere opaque

An opaque atmosphere traps heat, increases temperature and this internal pressure

Increased internal pressure pushes the envelope expands

As envelope expands, ionized helium recombines with electron and becomes neutral

The atmosphere becomes more transparent, and let releases the trapped energy

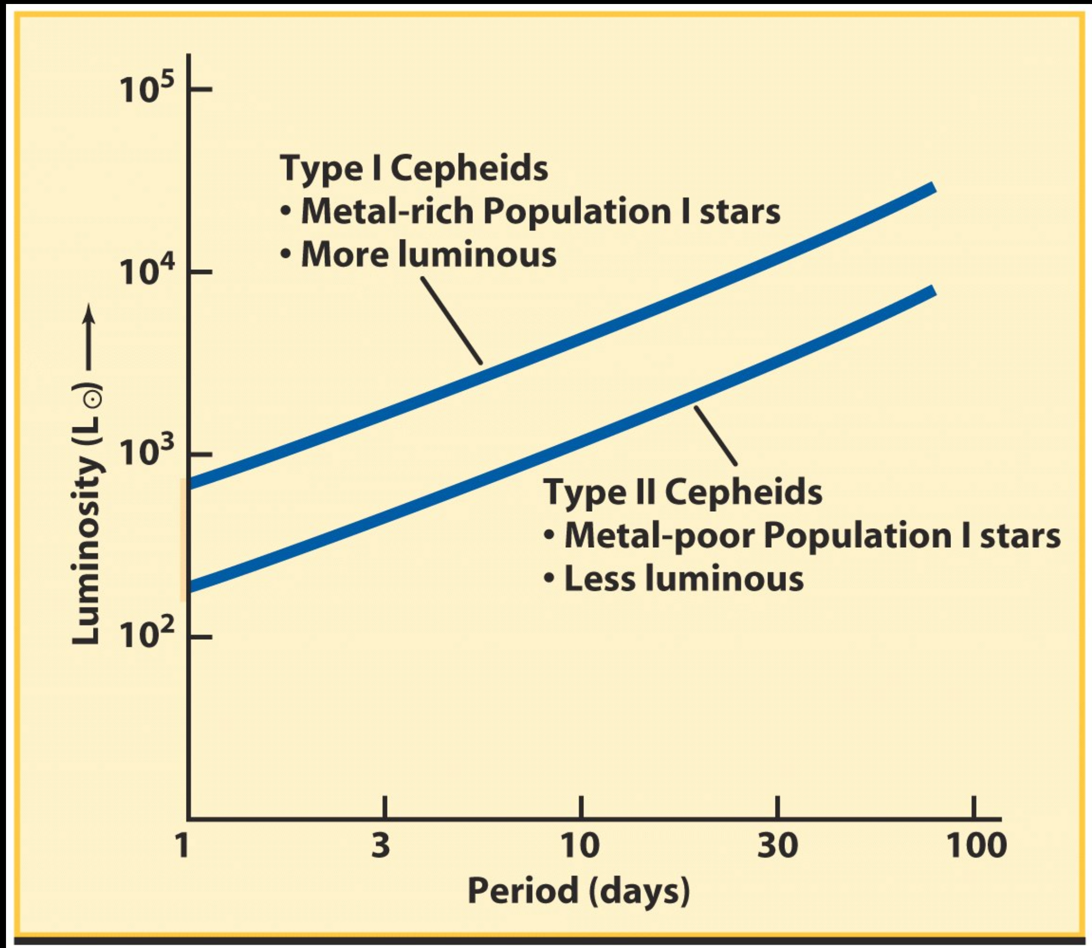
Temperature and pressure drops, and the envelope starts to contract again.

Cepheid Stars: Period-Luminosity Relation

There is good correlation between Cepheid Periods and Luminosity Brightness

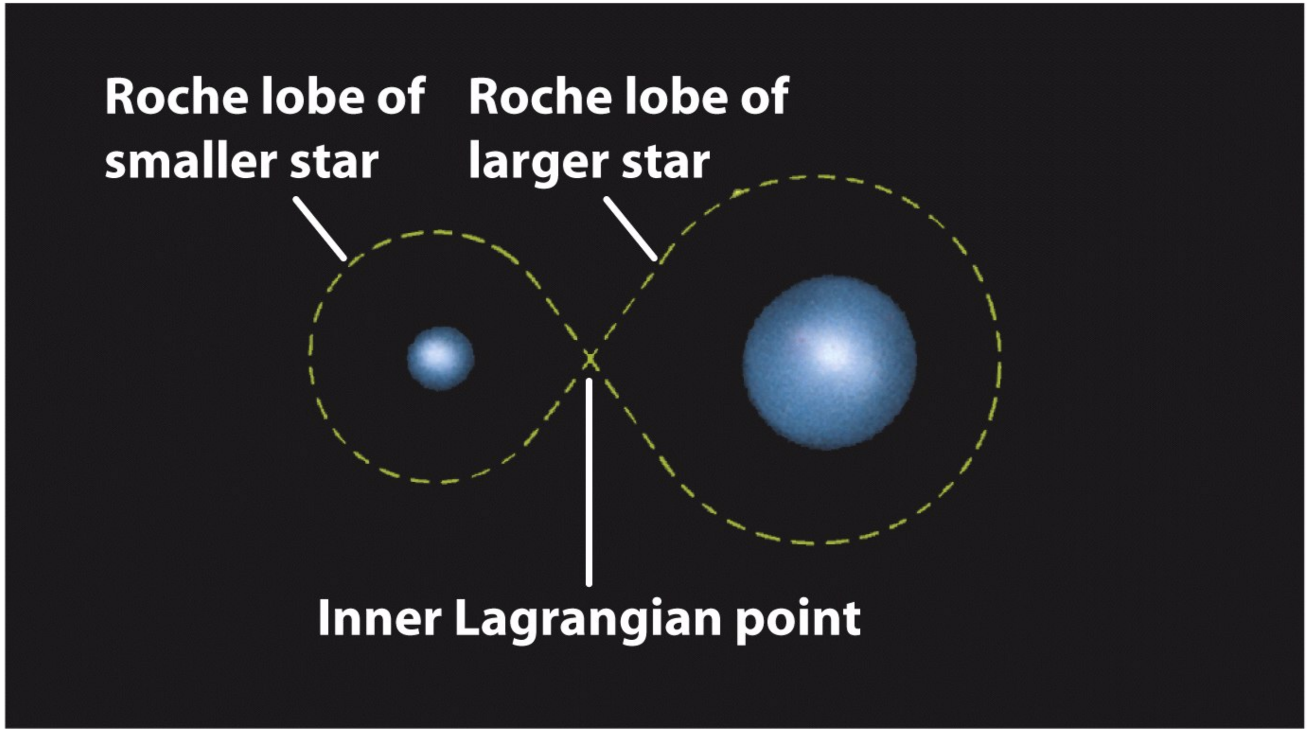
The longer the period, the greater the luminosity

Cepheid stars are very useful in determining distance to remote galaxies



Binary Star Systems: Roche Lobe

- Mass transfers in a close binary system
- The transfer affects the evolution of the stars involved
- **Roche lobe:** mass within the lobe is bound by gravity, but mass outside the lobe will leak to the companion star



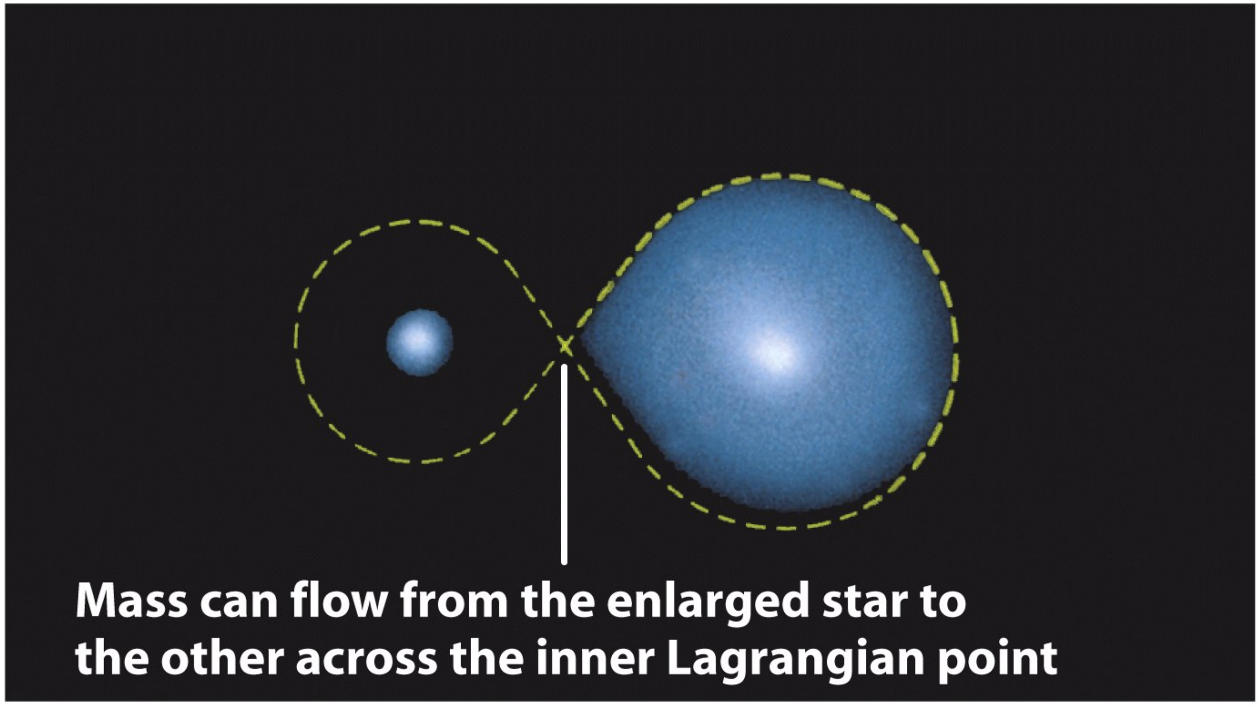
Detached binary: Neither star fills its Roche lobe.

Mass transfer

When one star evolves and becomes a red giant, it may fill the Roche Lobe

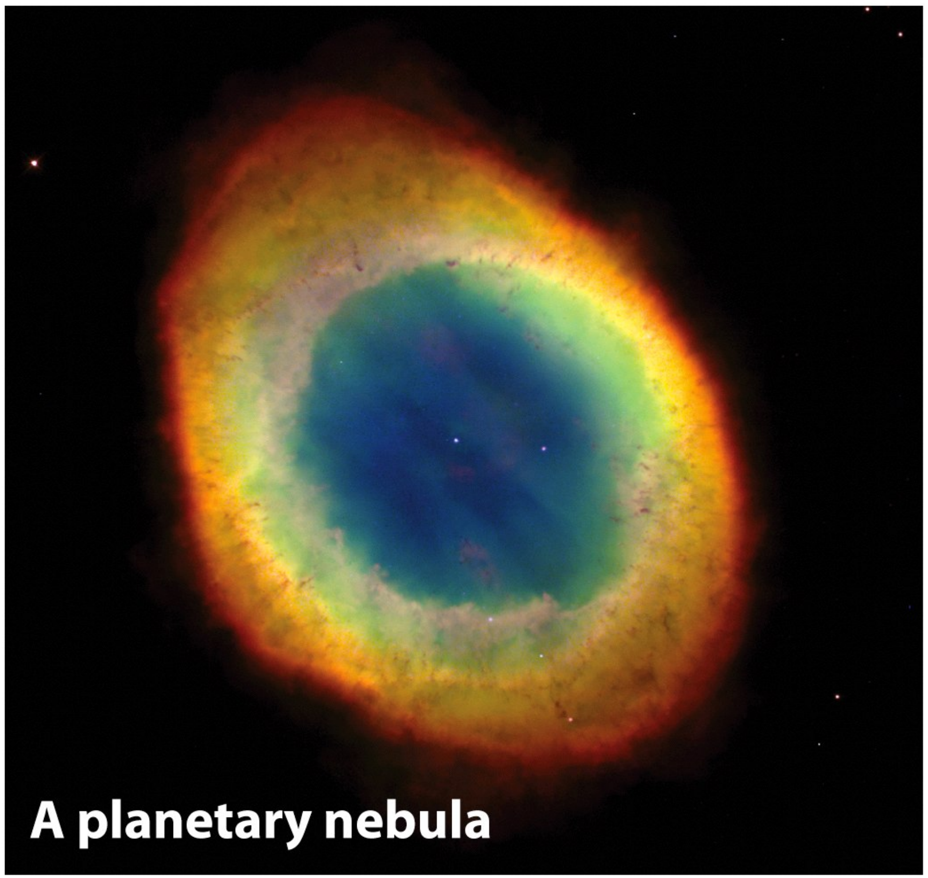
Mass will flow across the inner **Lagrangian point**, a kind of balance point in the binary system

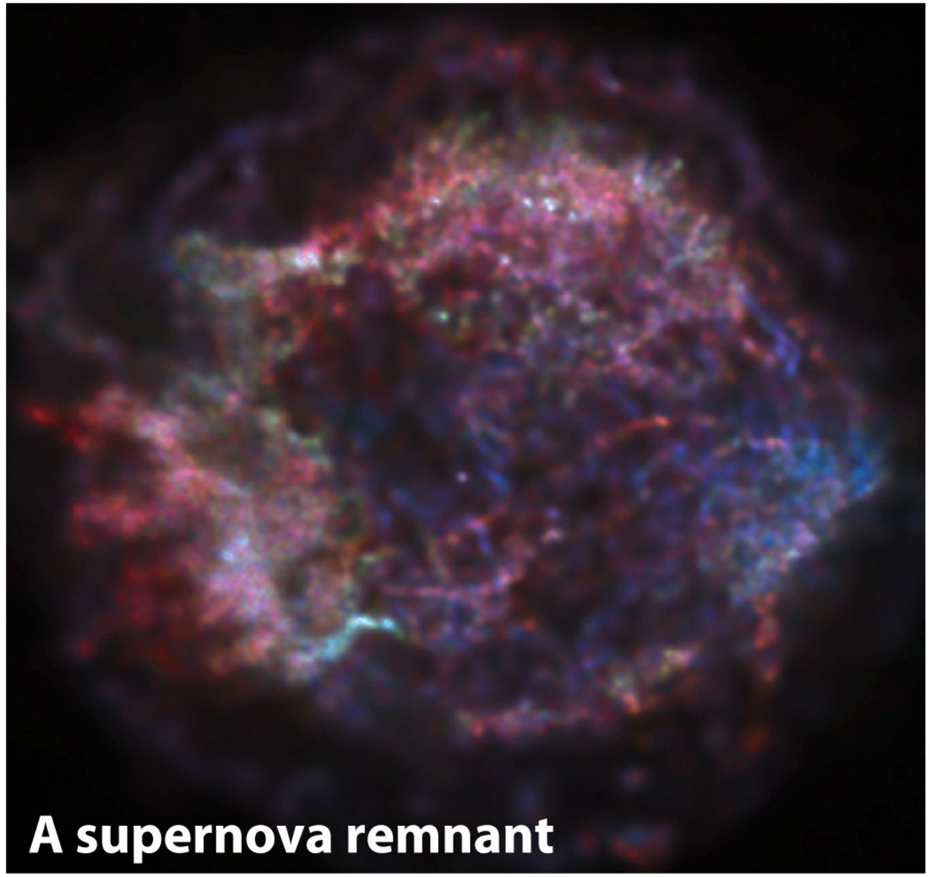
The bloated star loses mass, and companion star gains mass



Semi-detached binary: One star fills its Roche lobe.

4. Stellar Evolution: The Deaths of Stars

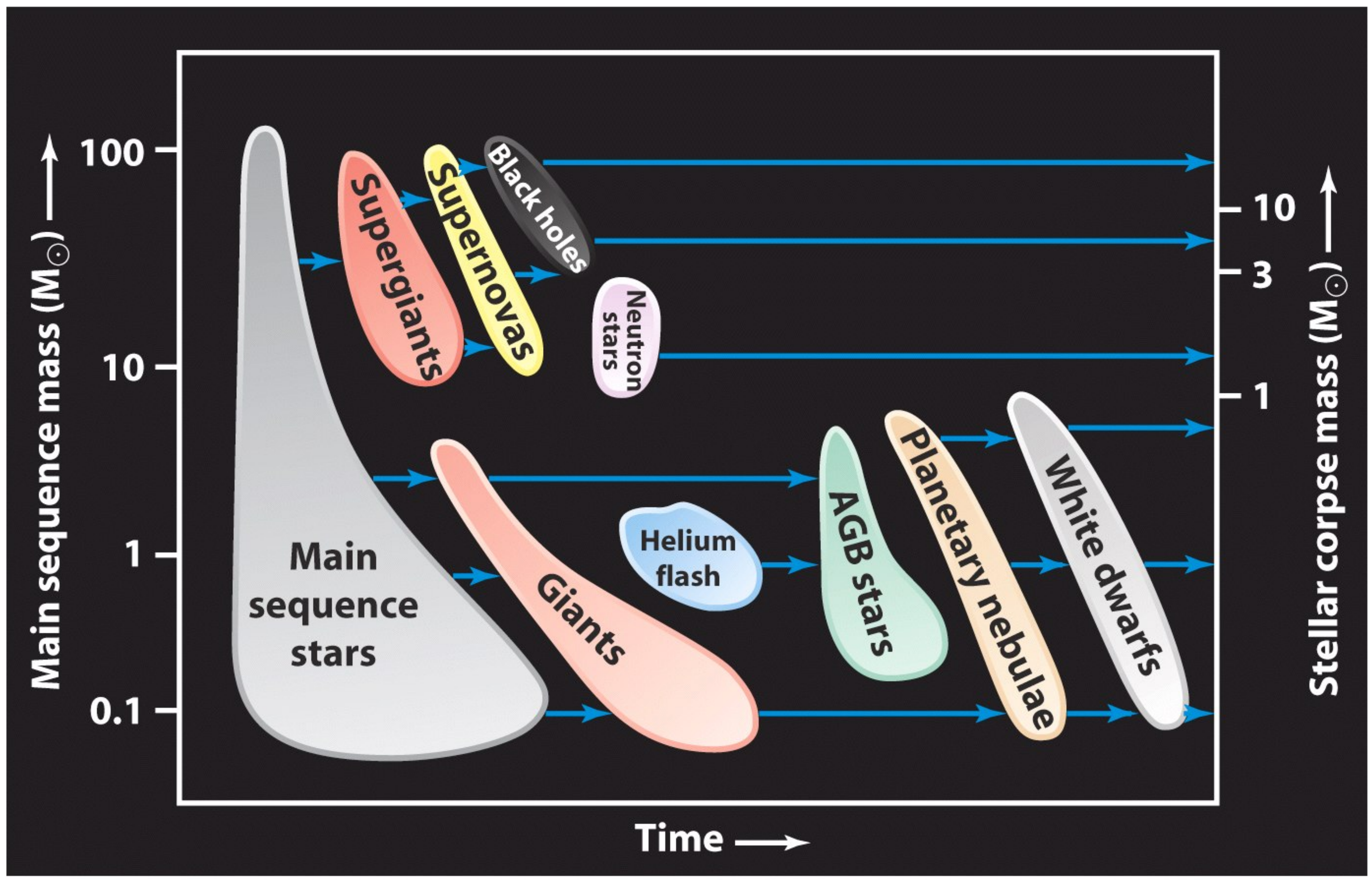




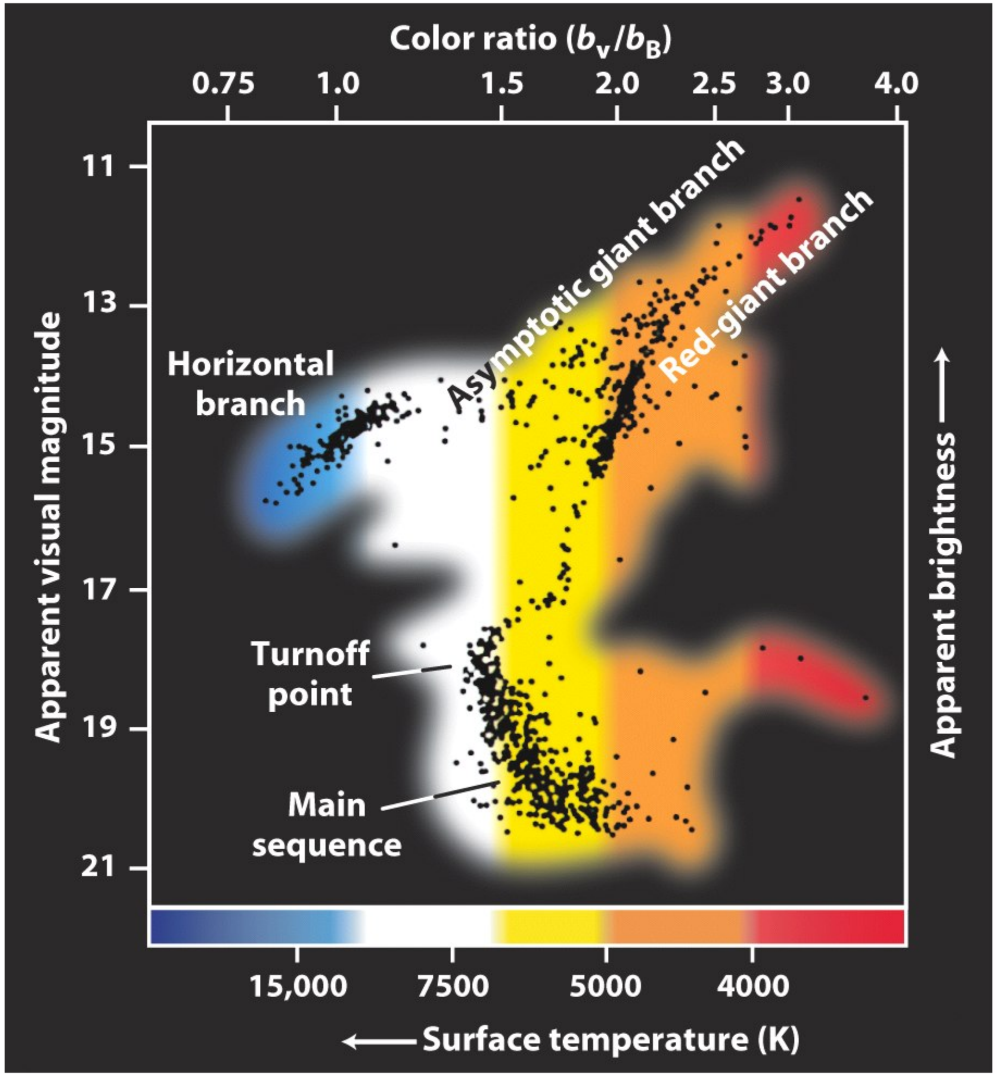
Guiding Questions

1. What kinds of nuclear reactions occur within a star like the Sun as it ages?
2. Where did the carbon atoms in our bodies come from?
3. What is a planetary nebula, and what does it have to do with planets?
4. What is a white dwarf star?
5. Why do high-mass stars go through more evolutionary stages than low-mass stars?
6. What happens within a high-mass star to turn it into a supernova?
7. Why was SN 1987A an unusual supernova?
8. What was learned by detecting neutrinos from SN 1987A?
9. How do white dwarf stars give rise to certain types of supernovae?
10. What vestiges are left after a supernova explosion?

Pathways of Stellar Evolution

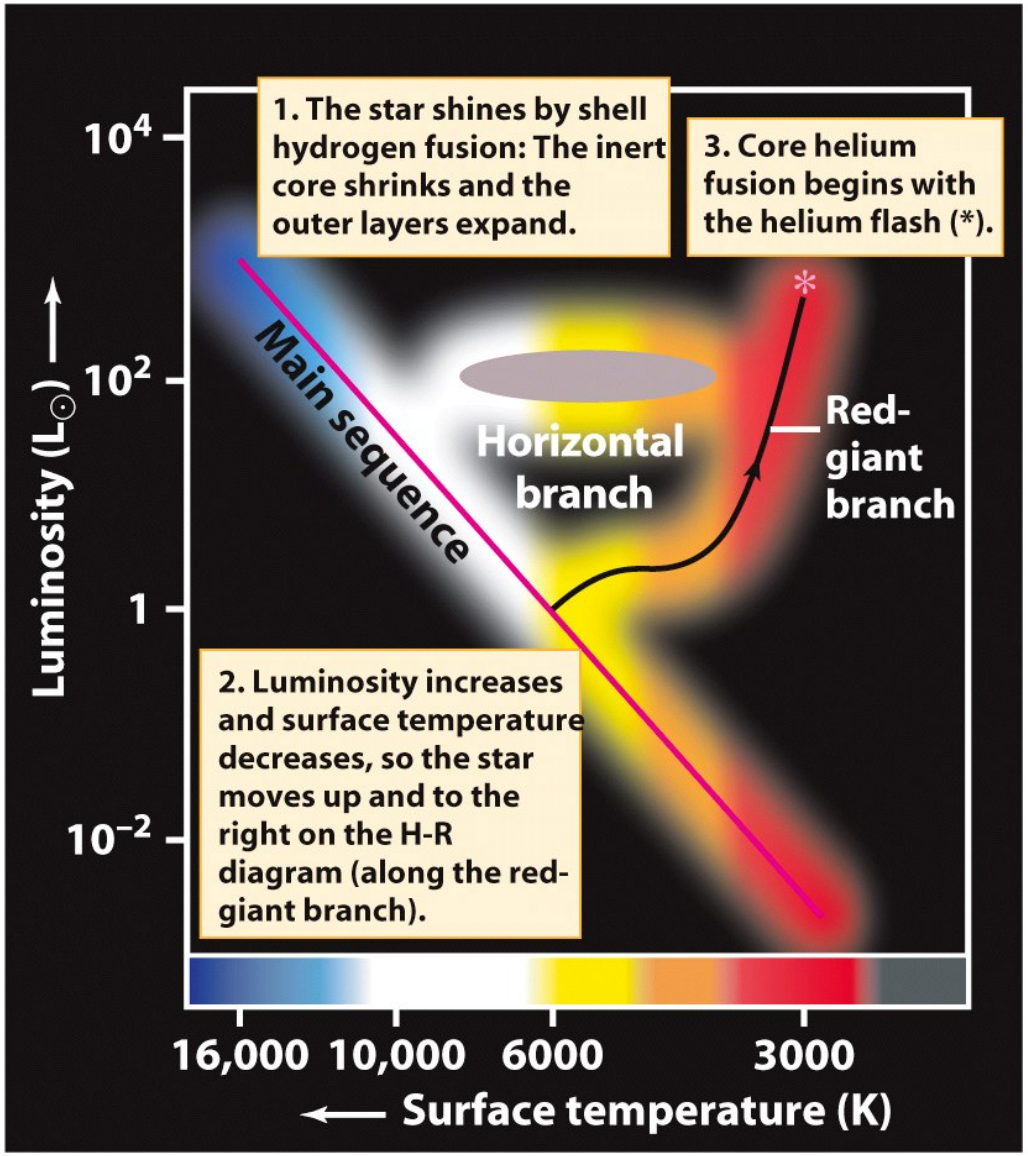


Low-mass stars: two red-giant stages



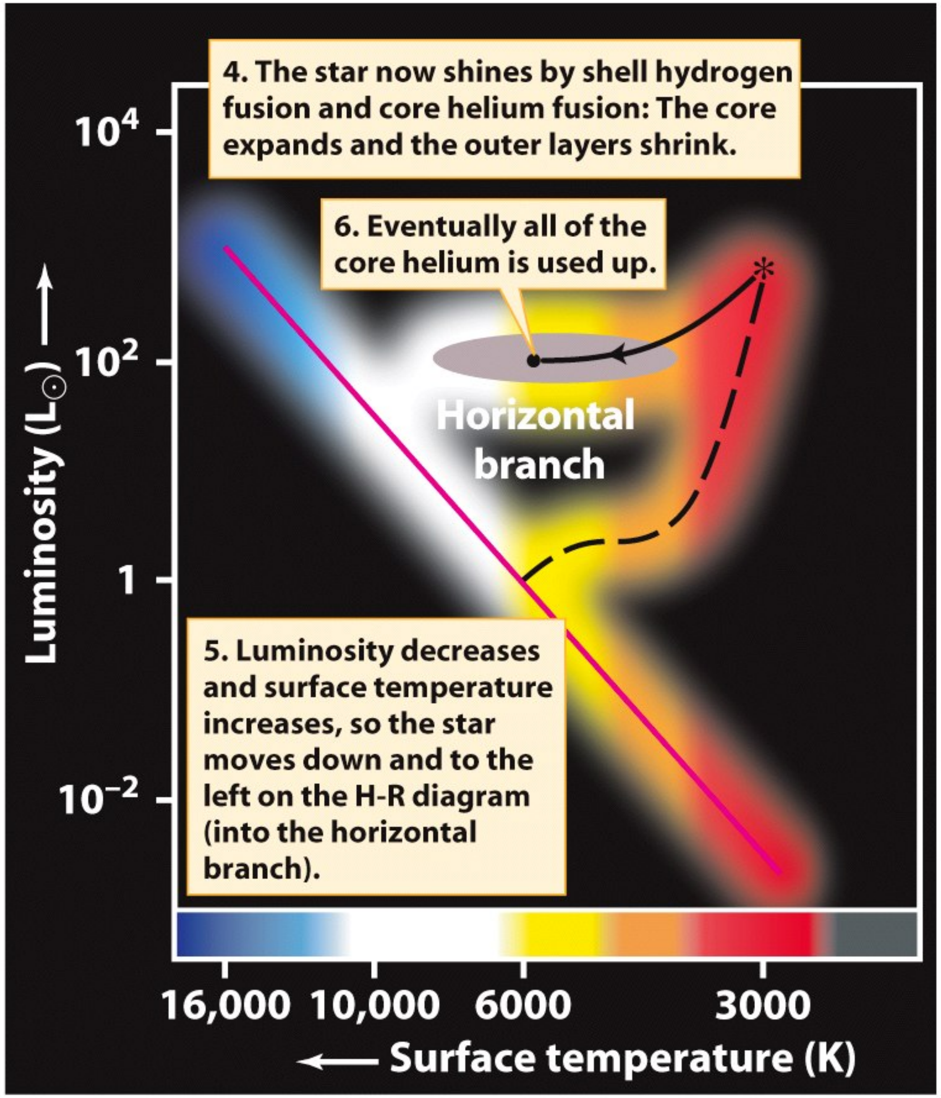
- A low-mass star (< 4 Msun at main sequence, e.g., the Sun)
  - a **red giant** when shell hydrogen fusion begins
  - a **horizontal-branch** star when core helium fusion begins
  - an **asymptotic giant branch (AGB)** star when the helium in the core is exhausted and shell helium fusion begins

Low-mass stars: two red-giant stages



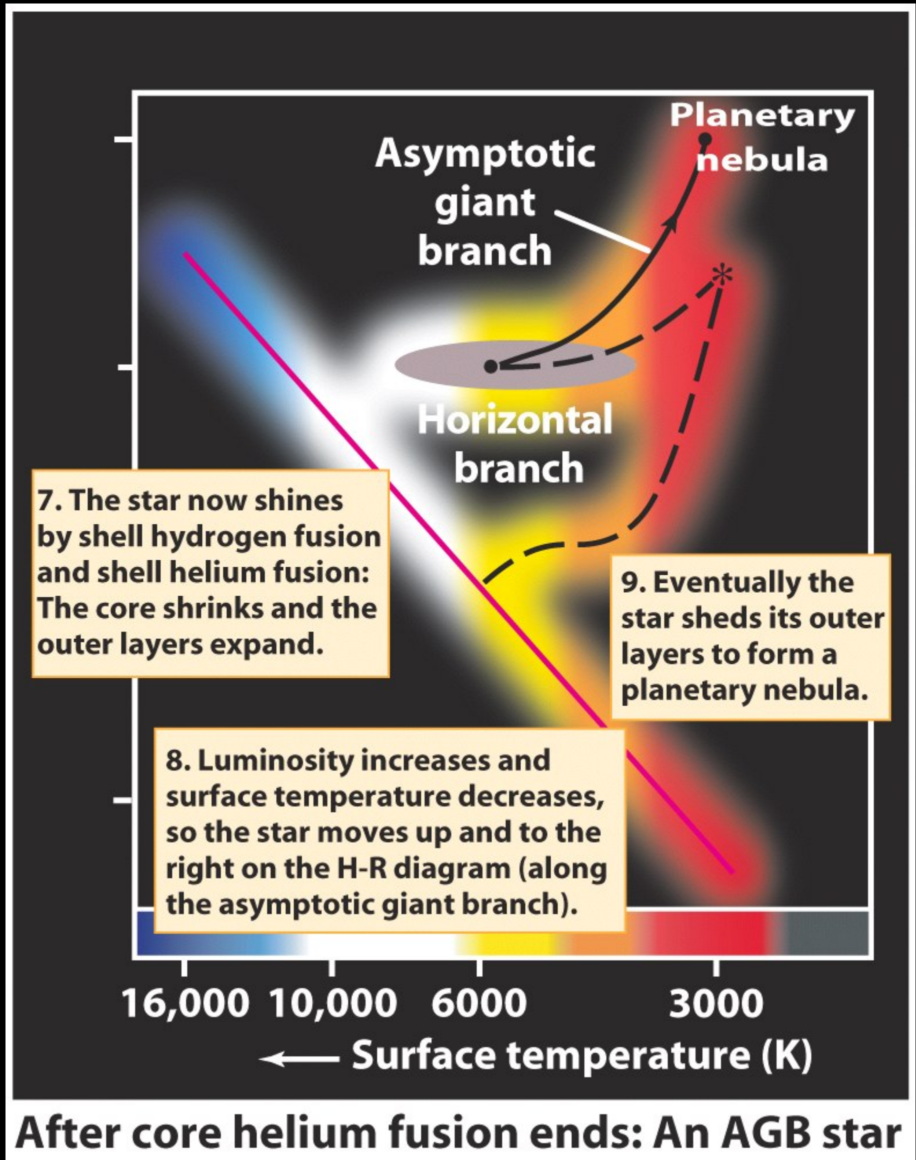
Before the helium flash: A red-giant star

Low-mass stars: two red-giant stages



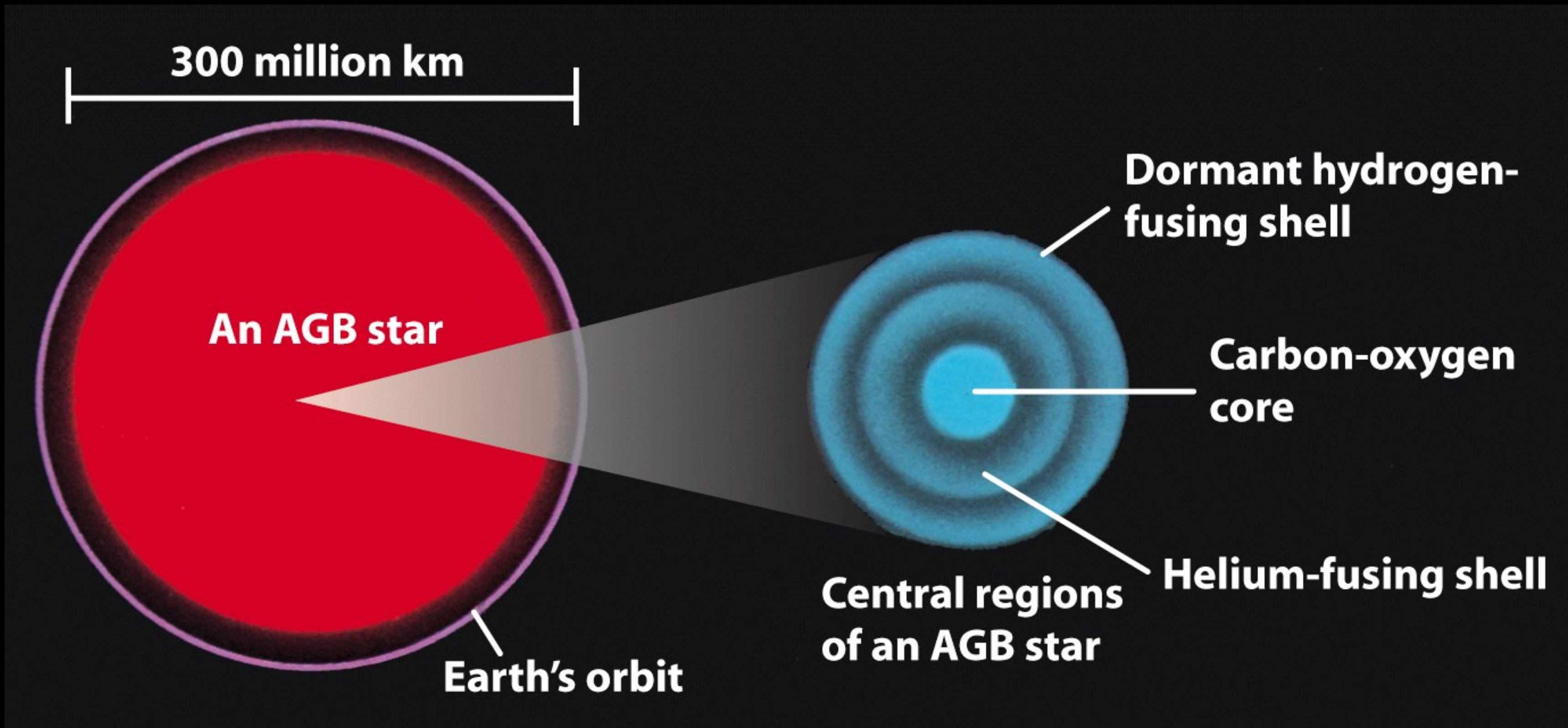
After the helium flash: A horizontal-branch star

Low-mass stars: two red-giant stages



AGB star: Structure

- Thermonuclear reaction in the helium fusion shell is so fast that star's luminosity is thousands of times Lsun
- The size of the star is about 200 Rsun
- But the size of the core is only the size of the Earth

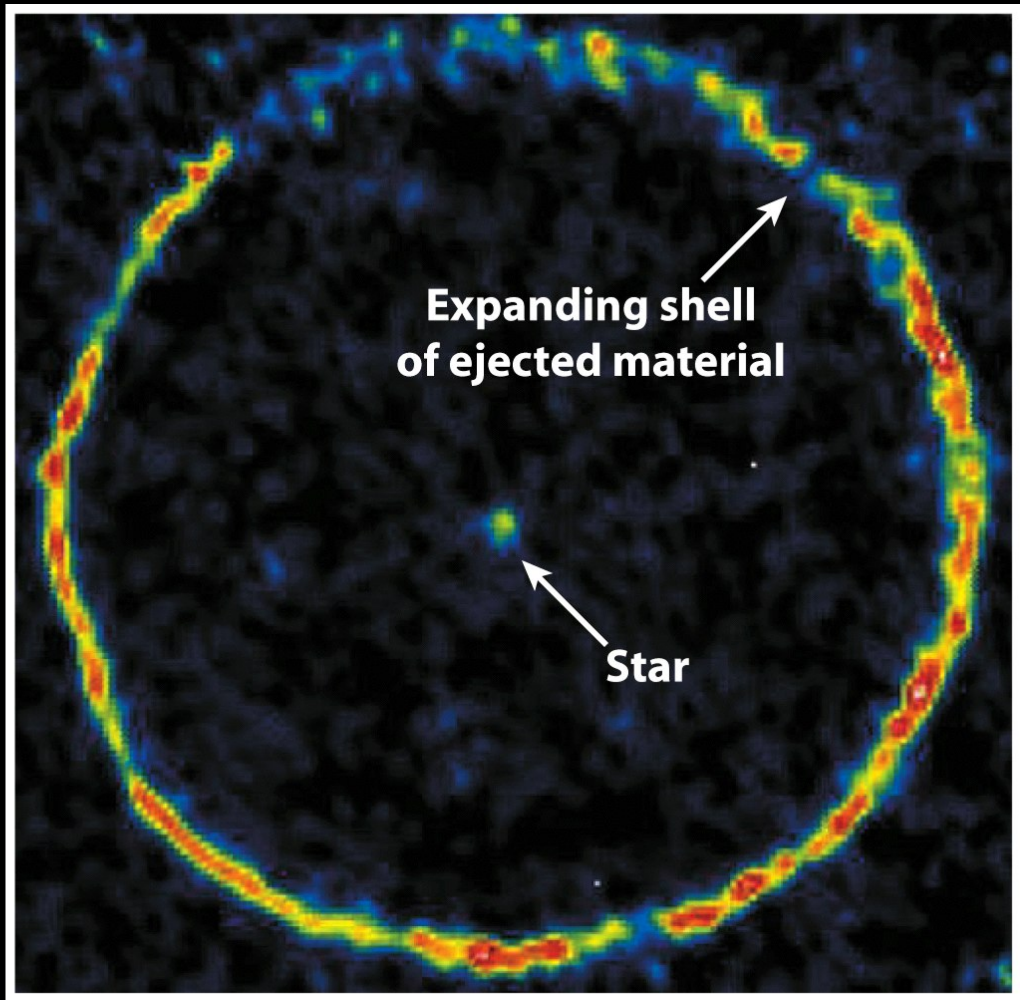


AGB star: Convection

- Convection occurs over a larger portion of its volume
- It takes heavy elements formed in the star's interior and distributes them throughout the star
- AGB star is also called **Carbon Star**
- AGB star has strong stellar wind, losing mass at very high rate
- AGB star enriches interstellar medium with carbon, and some oxygen and nitrogen
- Most of carbons in our body are likely from early-generation AGB stars nearby

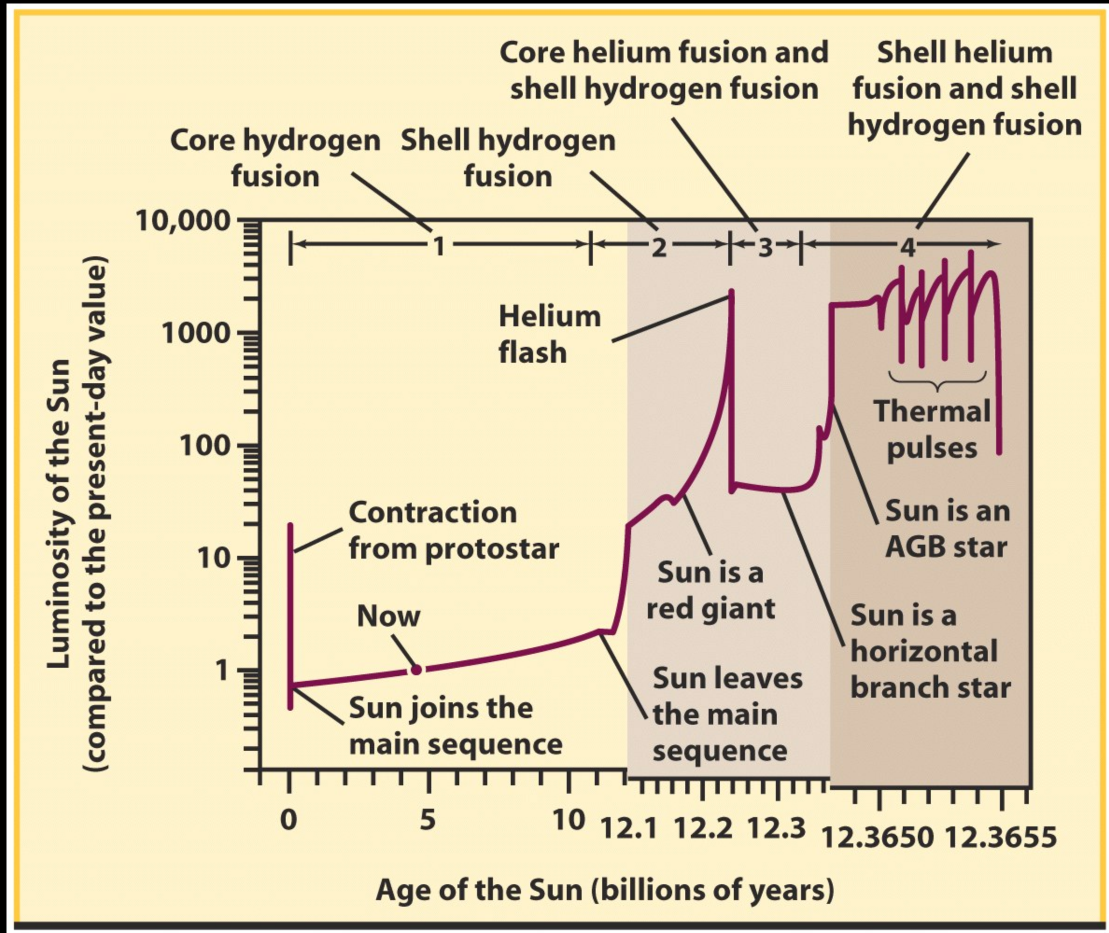
AGB star →Planetary Nebula

- An aging AGB star gently sheds away its outer layers
- The expanding outer layers become **Planetary Nebula**,
- Planetary Nebula has nothing to do planets



Planetary nebulae: Creation

- In AGB star, helium shell continuously gains mass from surrounding hydrogen fusion shell
- Helium shell contracts and ignites helium flash
- Helium flash creates a strong thermal pulse, which ejects a shell of material into space
- Thermal pulse through helium flash can occur several times
- Eventually, the entire shell of an AGB star is shed away and becomes nebula



Planetary nebulae

Planetary nebulae

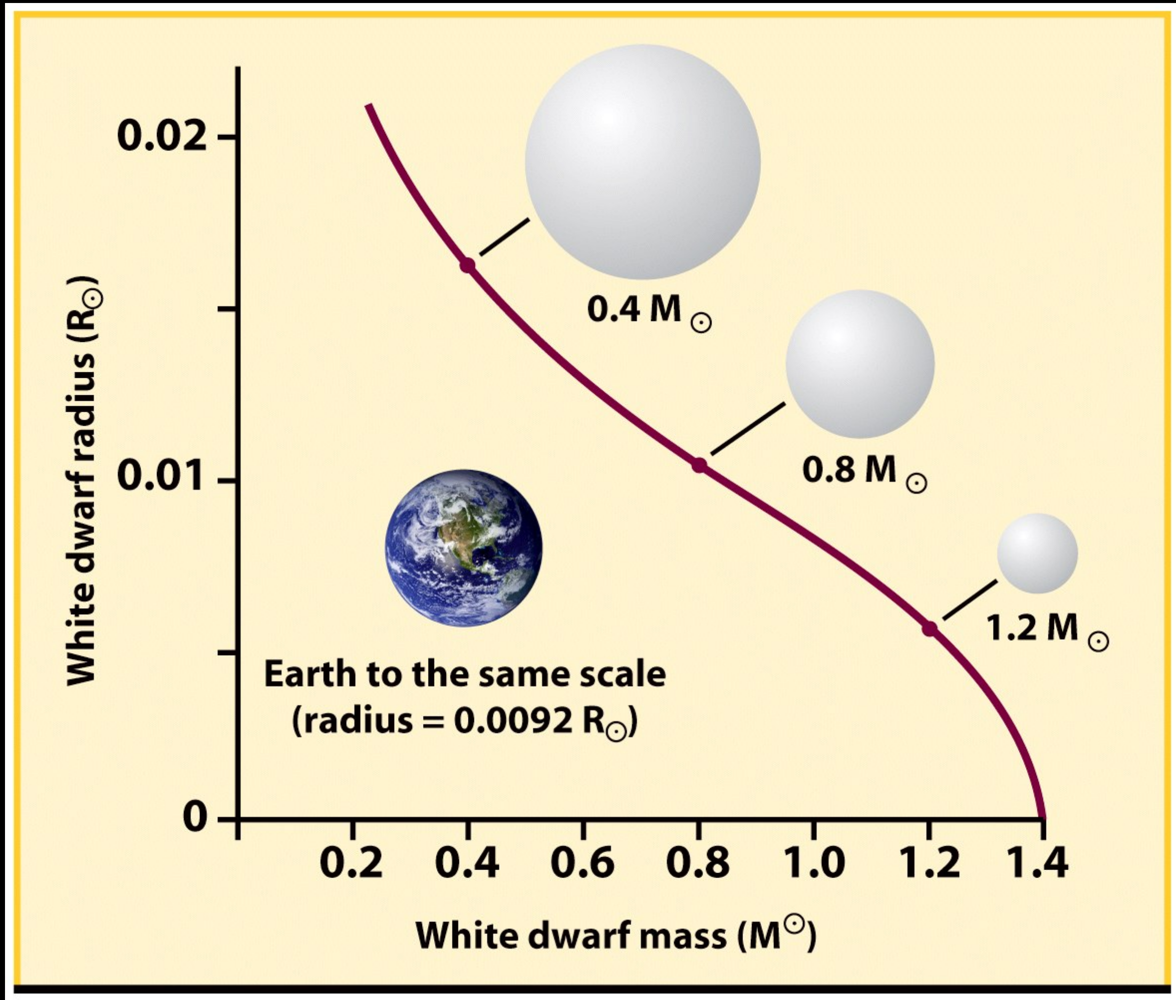
- Planetary Nebula expands at a speed ~20 km/s
- Reaches a size about 1 light year in 10, 000 year
- The propelling force is the radiation pressure caused by intense ultraviolet emission from the central core, acting upon dust grains in the nebula
- Dust grains condense out from the cooling nebula gas, because of the existence of heavy elements, such as carbon

Burned-out core becomes white dwarf

- In the exposed stellar core (after the shedding of the outer shell), no further nuclear reactions take place
- It becomes a dense sphere about the size of the Earth and is called a white dwarf
- It is so dense that electrons are degenerate
- The degenerate-electron pressure supports the star against further collapse
- It glows from thermal radiation; as the sphere cools, it becomes dimmer
- A cool white dwarf is a giant diamond made of crystallized carbon
- One teaspoon white dwarf matter weighs about 5.5 tons, or density $10^9 kg/m^3$

White Dwarf Star

- The more massive a white dwarf, the stronger the gravitation, and the smaller the size
- Mass of White Dwarf can not exceed 1.4 Msun



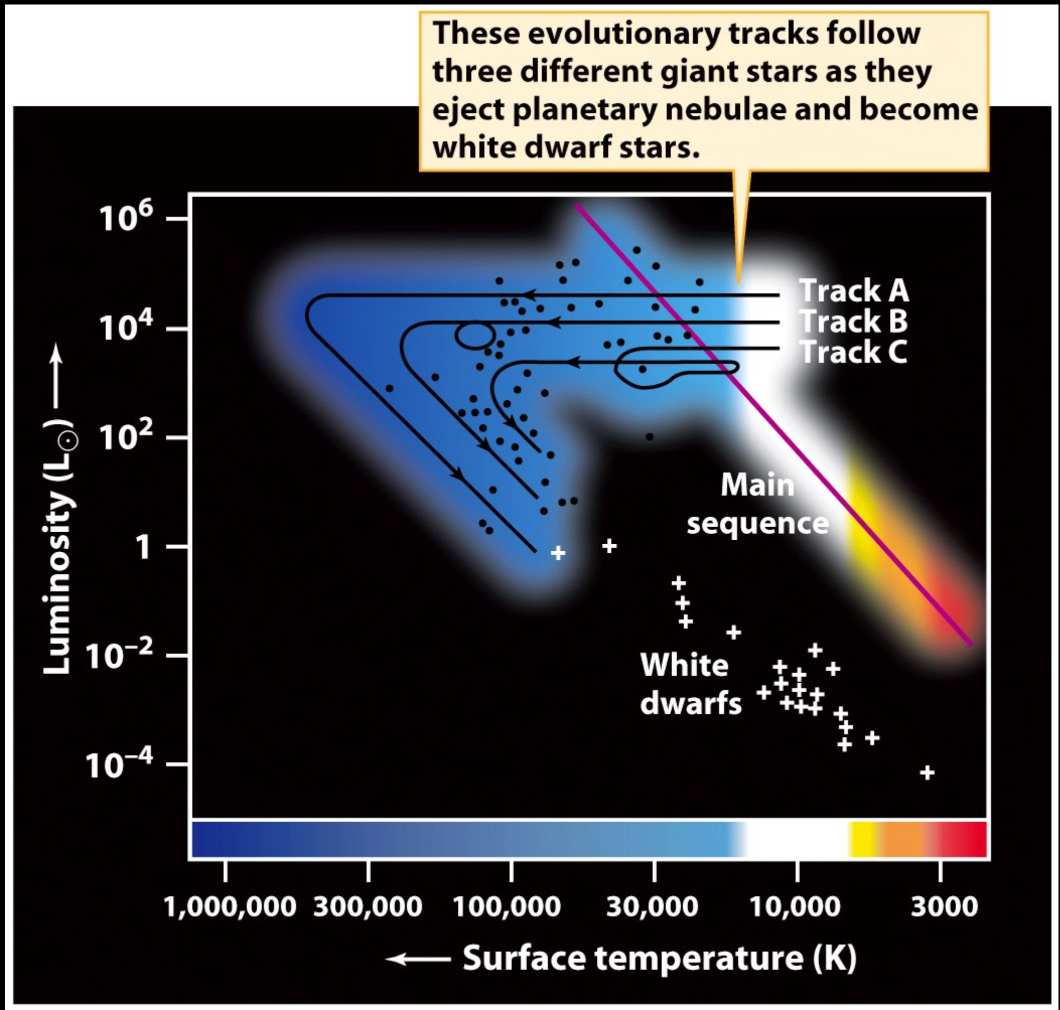
Chandrasekhar Limit: 1.4 Ms

- The upper limit of the mass a white dwarf can have
- The limit is **1.4 Msun**
- Beyond this limit, the degenerate electron pressure can no longer hold the gravitation contraction

- ----→ more exotic objects

White Dwarf Star

- A, main sequence mass 3.0 Msun, white dwarf mass 1.2 M_{sun}
- B, main sequence mass 1.5 Msun, white dwarf mass 0.8 M_{sun}
- C, main sequence mass 0.8 Msun, white dwarf mass 0.6 M_{sun}



High Mass Stars (>3 Msun)

- A low mass star (< 3 Msun) follows the evolution track of
  1. Main sequence
  2. Red Giant -→ Horizontal Branch -→ AGB star
  3. Planetary Nebula
  4. White Dwarf

– But, a high mass star (>3 Msun) has different evolution
  1. Main
  2. Supergiant
  3. Supernova
  4. Neutron star or black hole

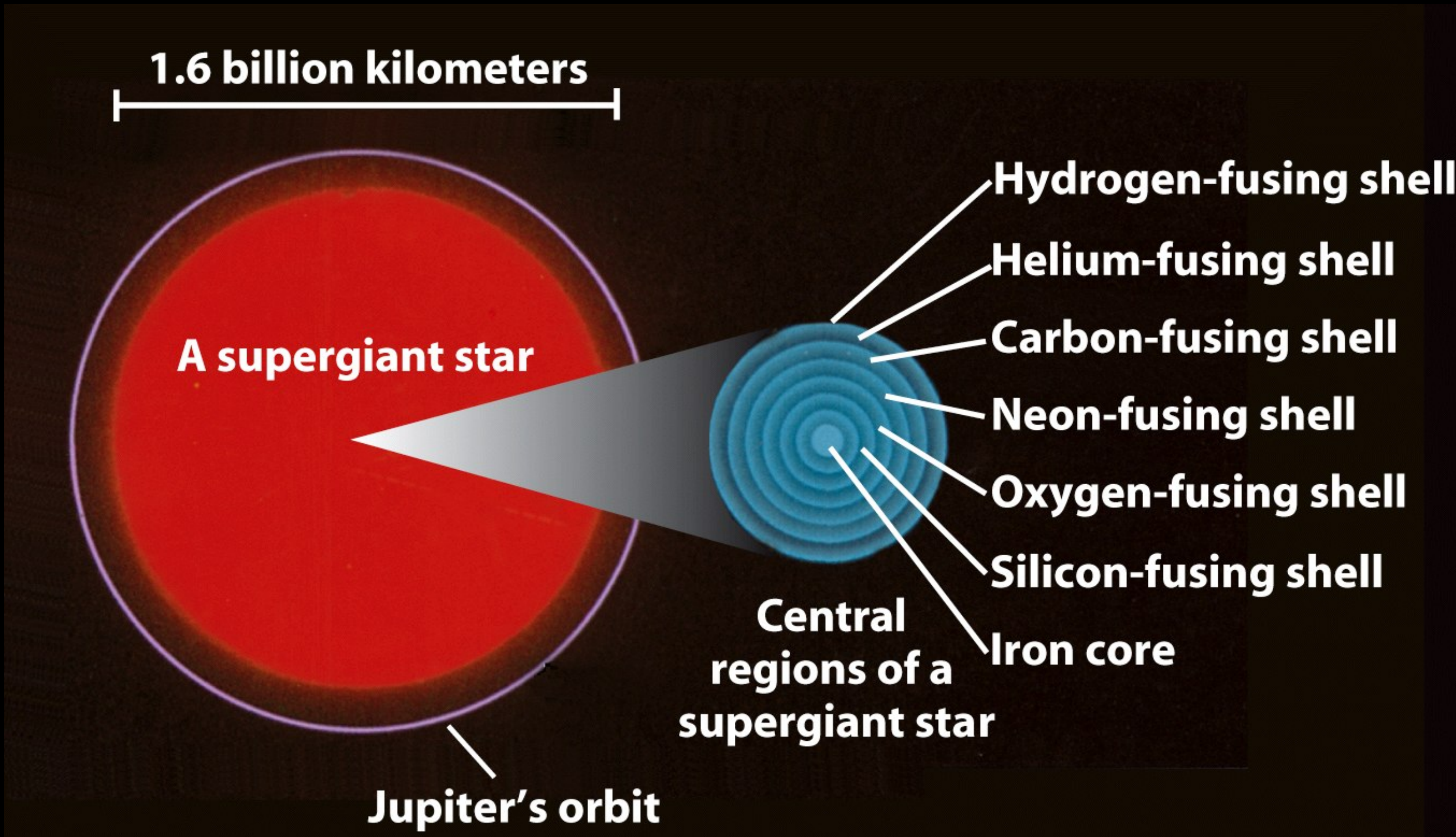
High-mass stars create heavy elements in their cores

- Unlike a low-mass star, a high mass star undergoes an extended sequence of thermonuclear reactions in its core and shells
- These include carbon (^{12}C) fusion, neon (^{20}Ne) fusion, oxygen (^{16}O) fusion, and silicon (^{28}Si) fusion

table 22-1 Evolutionary Stages of a 25-$M_\odot$ Star

Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	¼ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

Supergiant and its onion core



- In the last stages of its life, a high-mass star has an iron-rich core surrounded by concentric shells hosting the various thermonuclear reactions
- The sequence of thermonuclear reactions stops here, because the formation of elements heavier than iron requires an input of energy rather than causing energy to be released

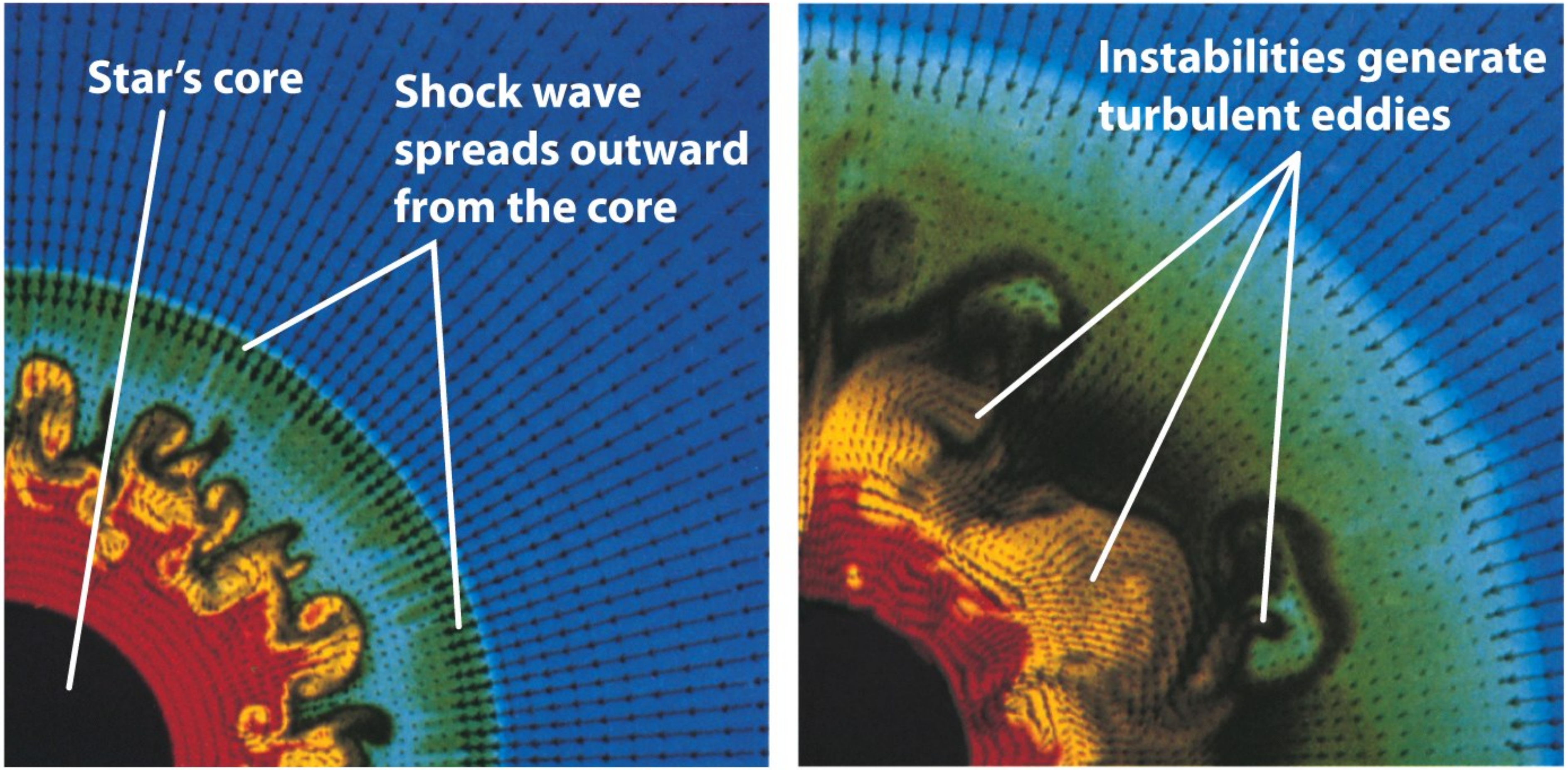
Supernova explosions

- Once the iron core is formed, the core contracts very rapidly (in less 1 second, from Earth size to city size)
- Temperature skyrockets to 5 billion Kelvin
- Photodisintegration: high energy photons break the iron nuclei to helium nuclei
- Electron combines with proton to form neutrons
- During the combining process, it produces neutrinos that carry energy away
- The core ends up as all neutron, with nuclear density (10^{17} km/m^3)
- The degenerate neutron pressure suddenly halts the core contract
- The outer core bounce back and sends a powerful wave of pressure
- The pressure wave becomes a powerful shock wave as it go outwards, and expel most stellar material outward
- Shock wave produces a series of nuclear reaction, the only place elements heavier than iron (such as silver, gold) are produced in the universe

Supernova explosions

- A high-mass star dies in a violent cataclysm in which its core collapses and most of its matter is ejected into space at high speeds
- The luminosity of the star increases suddenly by a factor of around 10^8 during this explosion, producing a **supernova**
- The matter ejected from the supernova, moving at supersonic speeds through interstellar gases and dust, glows as a nebula called a **supernova remnant**

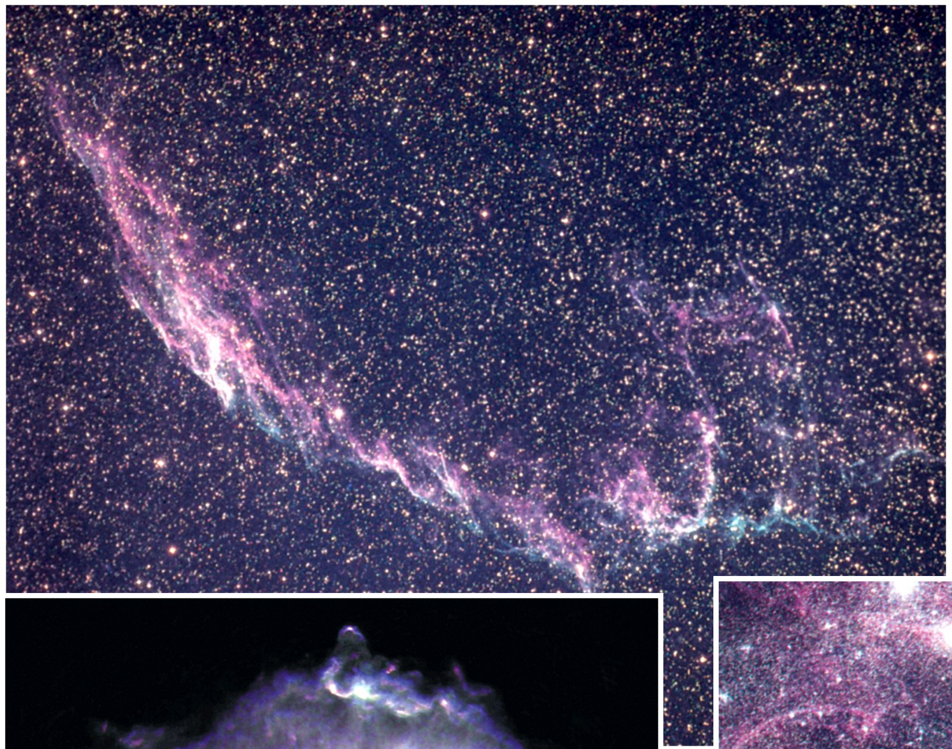
Supernova explosions

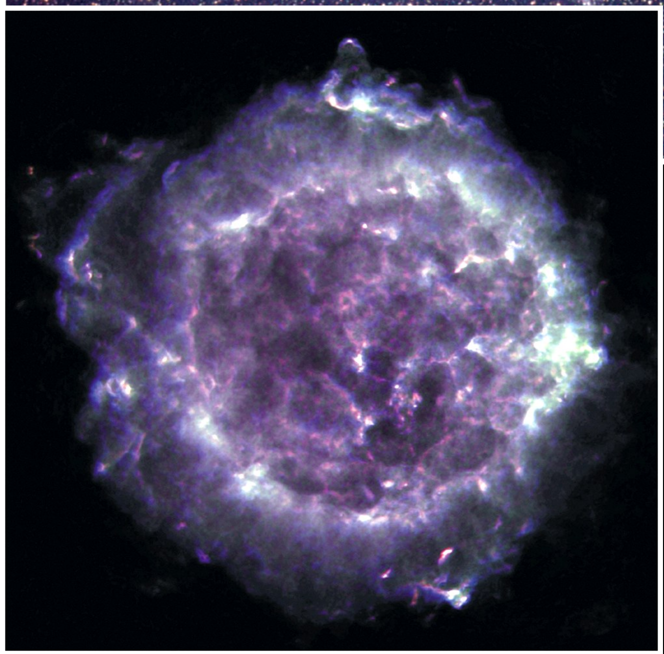


(a) 10 milliseconds after the core "bounce"

(b) 20 milliseconds after the core "bounce"

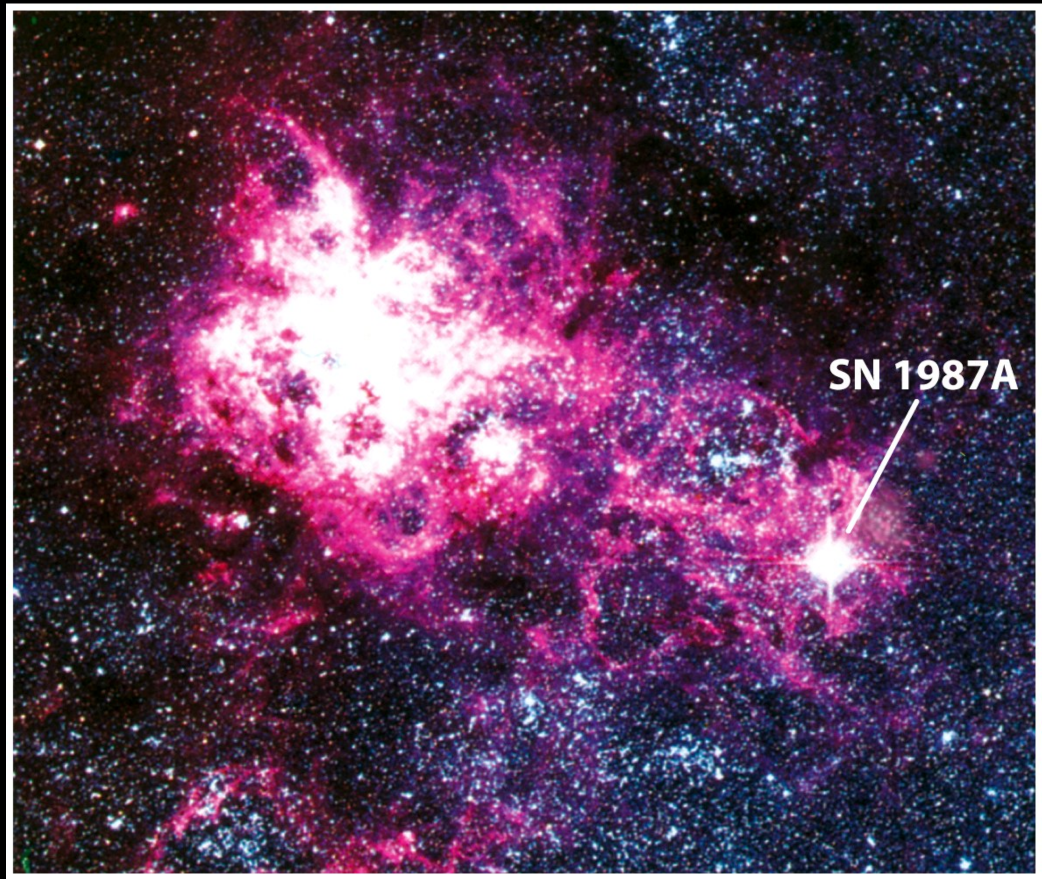
Supernova Remnants





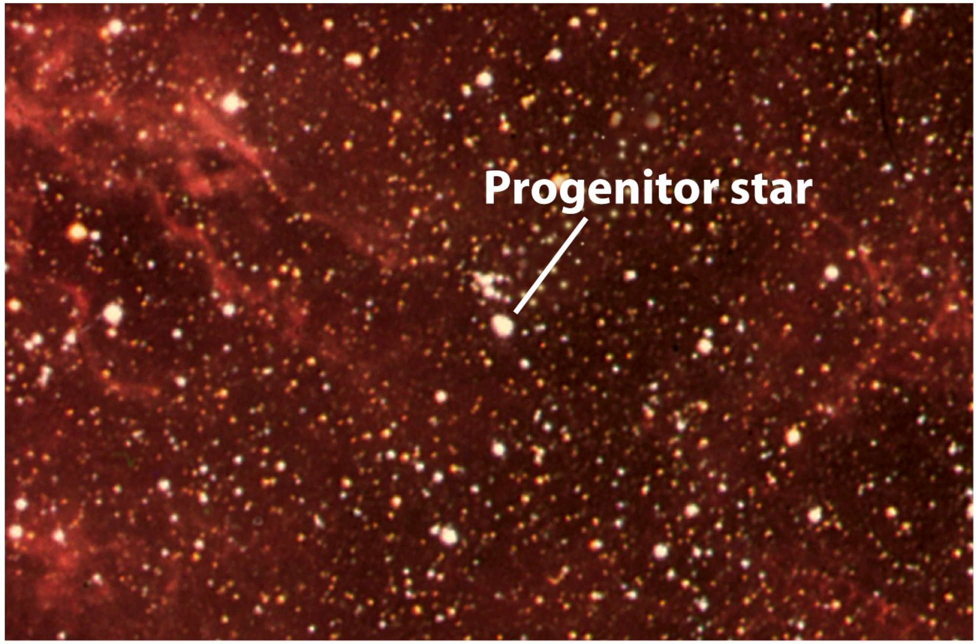
SN1987 A: the best observed SN

- Occurred on Feb. 23, 1987
- 50,000 PC away in a huge HII region (or emission nebula) in Large Magellanic Cloud (LMC)

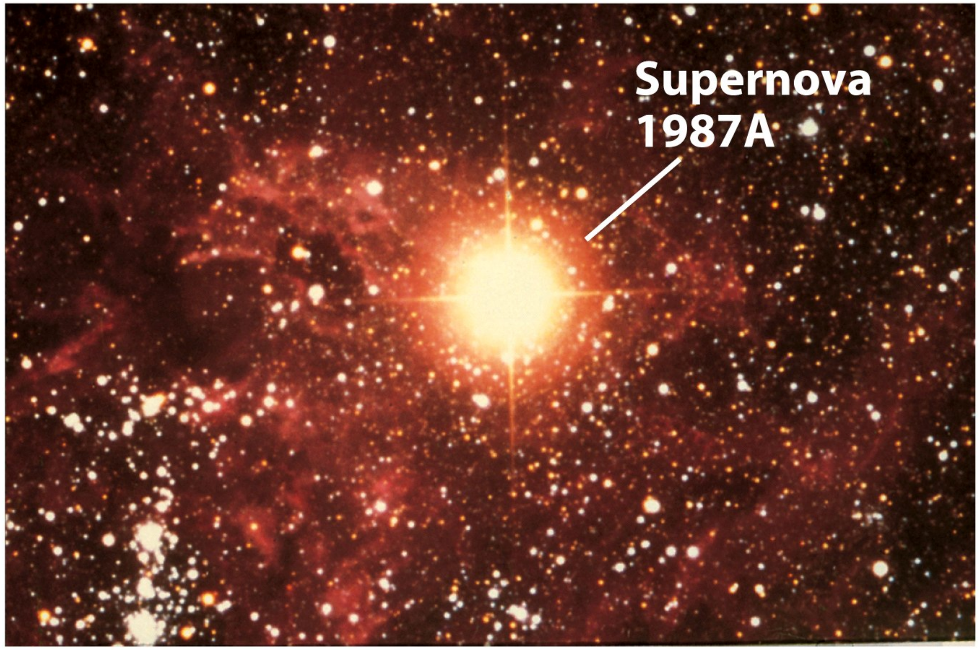


SN1987 A: the best observed SN

- Progenitor star: blue B3 I supergiant
- Could see it with naked eyes right after the explosion

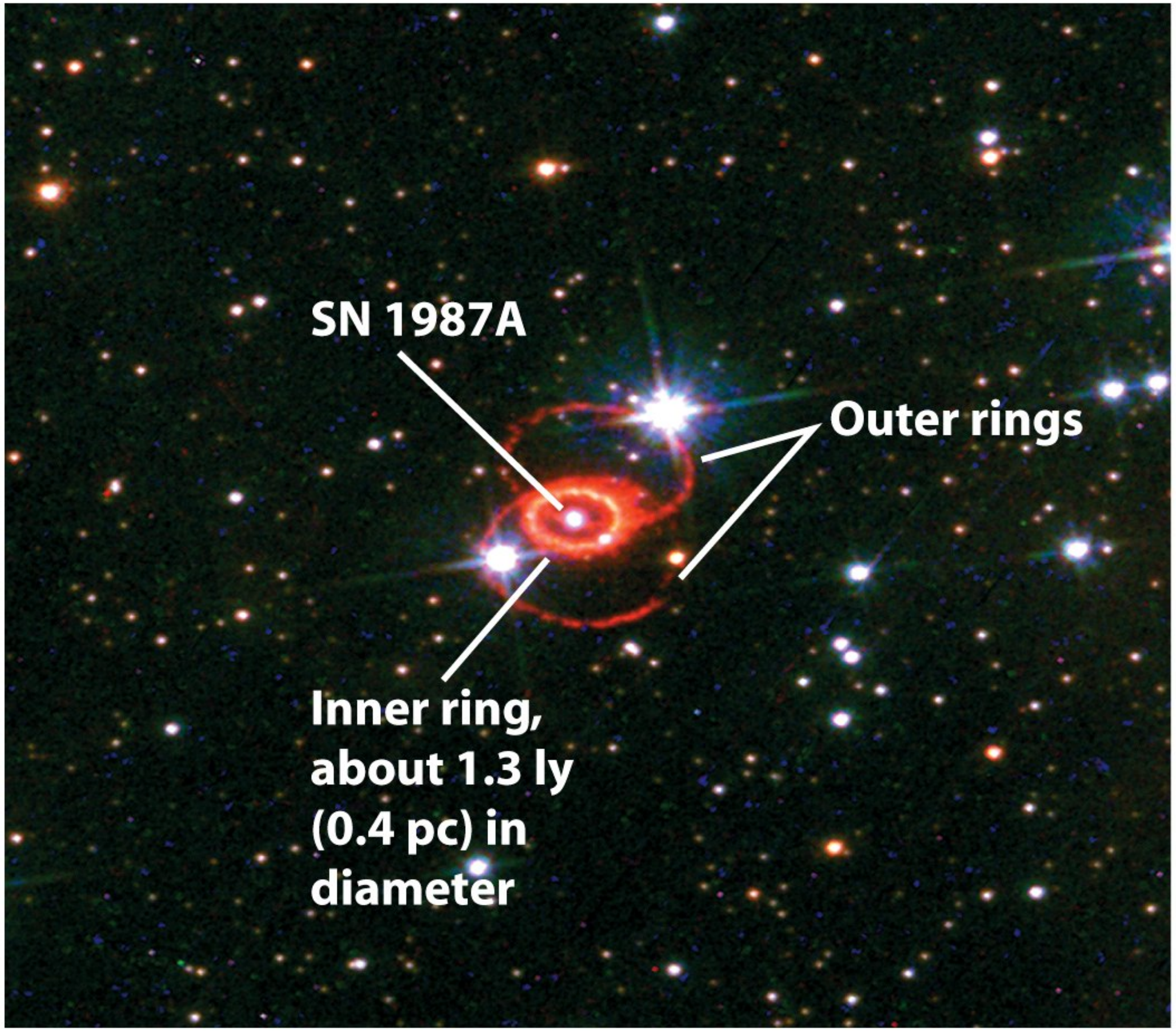


Before the star exploded



After the star exploded

SN1987 A: the best observed SN



Supernova 1987A seen in 1996

SN 1987A: Neutrinos were detected

- More than 99% of the energy from such a supernova is emitted in the form of neutrinos from the collapsing core
- Neutrino energy 10^{46} Joules, 100 times as much energy as Sun has emitted in its entire history
- Neutrinos arrive 3 hours before the first SN light was seen
- **The 3-hour delay is due to the propagation time of the shock wave from the core to the surface of the supergiant**

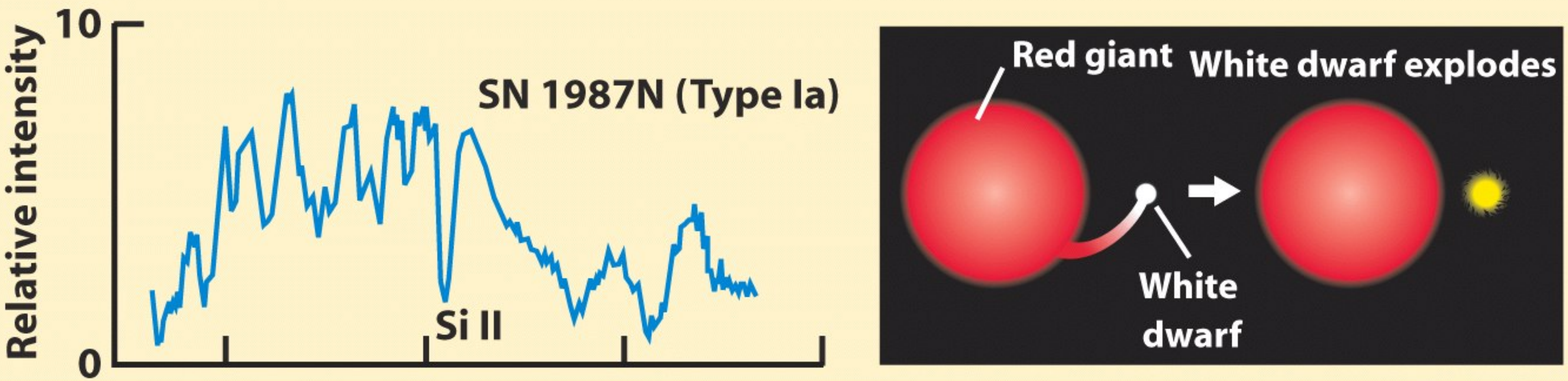
Different Types of Supernovae

- **Type 1 supernova**: no hydrogen lines
  - **Type 1a supernova**: explosion of white dwarf in a closed binary system; mass accumulation exceeds the critical mass and ignites the carbon fusion at the core
  - **Type 1b supernova**: core collapse of massive star with hydrogen shell lost before
  - **Type 1c supernova:** core collapse of massive star with both hydrogen and helium shells lost before
- **Type 2 supernova**: strong hydrogen lines
  - core collapse of massive star with hydrogen shell largely intact

Type Ia supernovae are those produced by accreting white dwarfs in close binaries

(a) Type Ia supernova

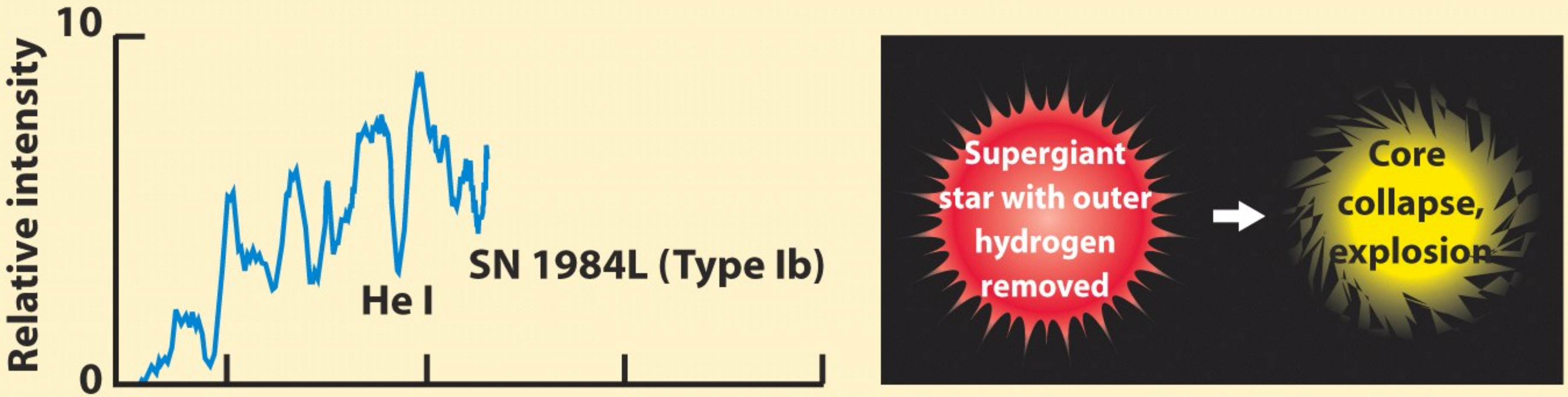
- The spectrum has no hydrogen or helium lines, but does have a strong absorption line of ionized silicon (Si II).
- Produced by runaway carbon fusion in a white dwarf in a close binary system (the ionized silicon is a by-product of carbon fusion).



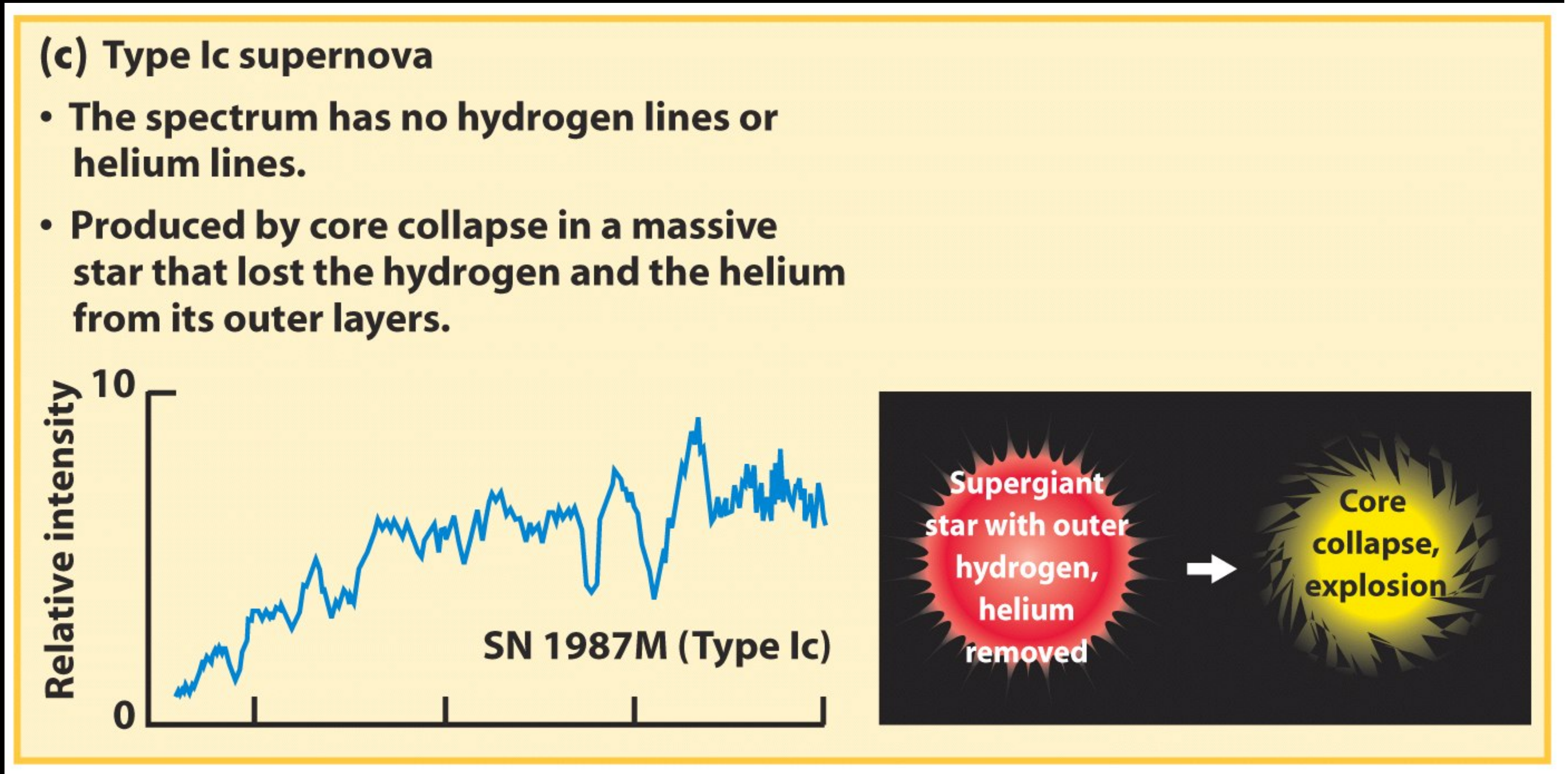
Type Ib supernovae occur when the star has lost a substantial part of its hydrogen shell

(b) Type Ib supernova

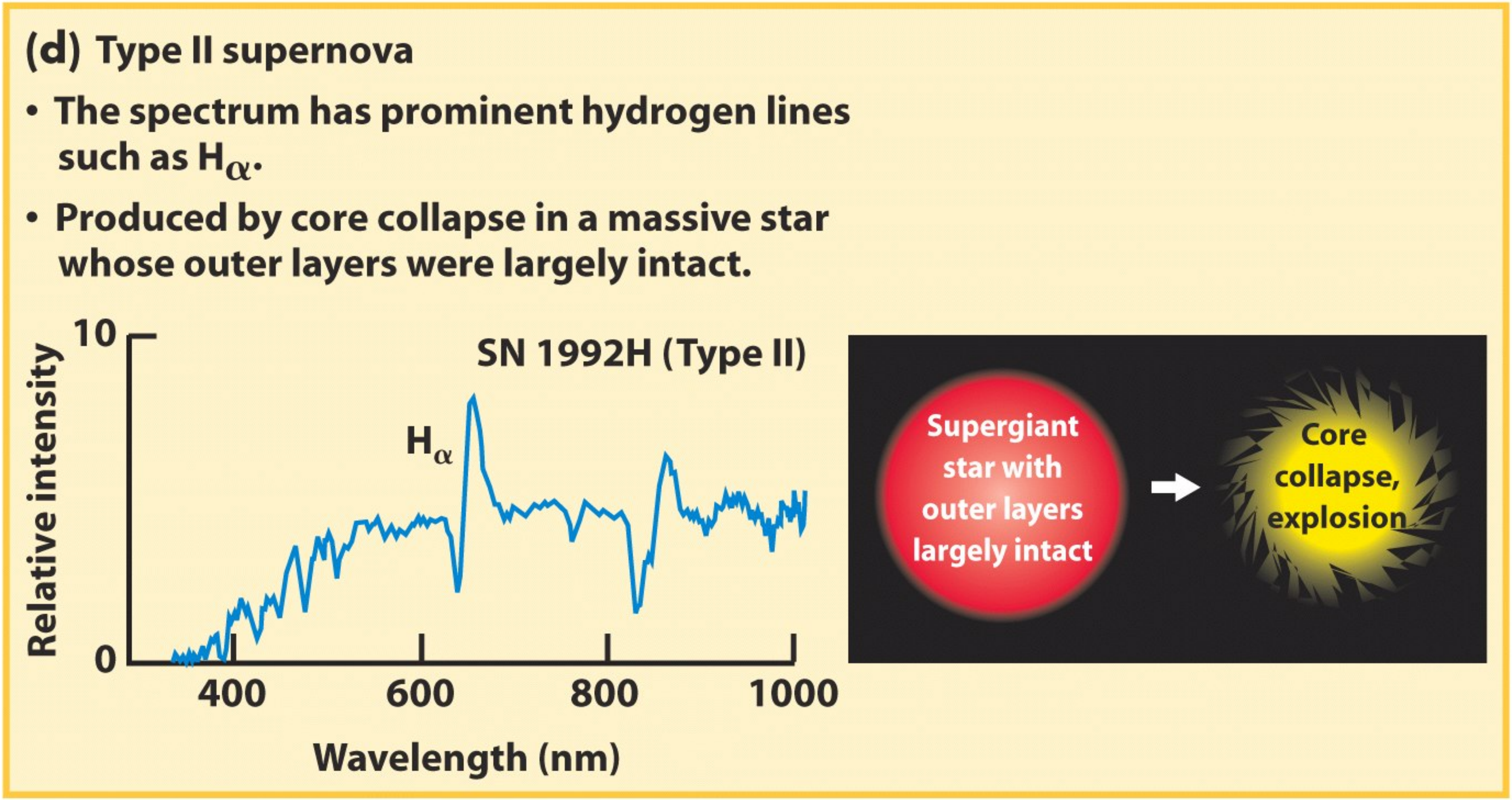
- **The spectrum has no hydrogen lines, but does have a strong absorption line of un-ionized helium (He I).**
- **Produced by core collapse in a massive star that lost the hydrogen from its outer layers.**



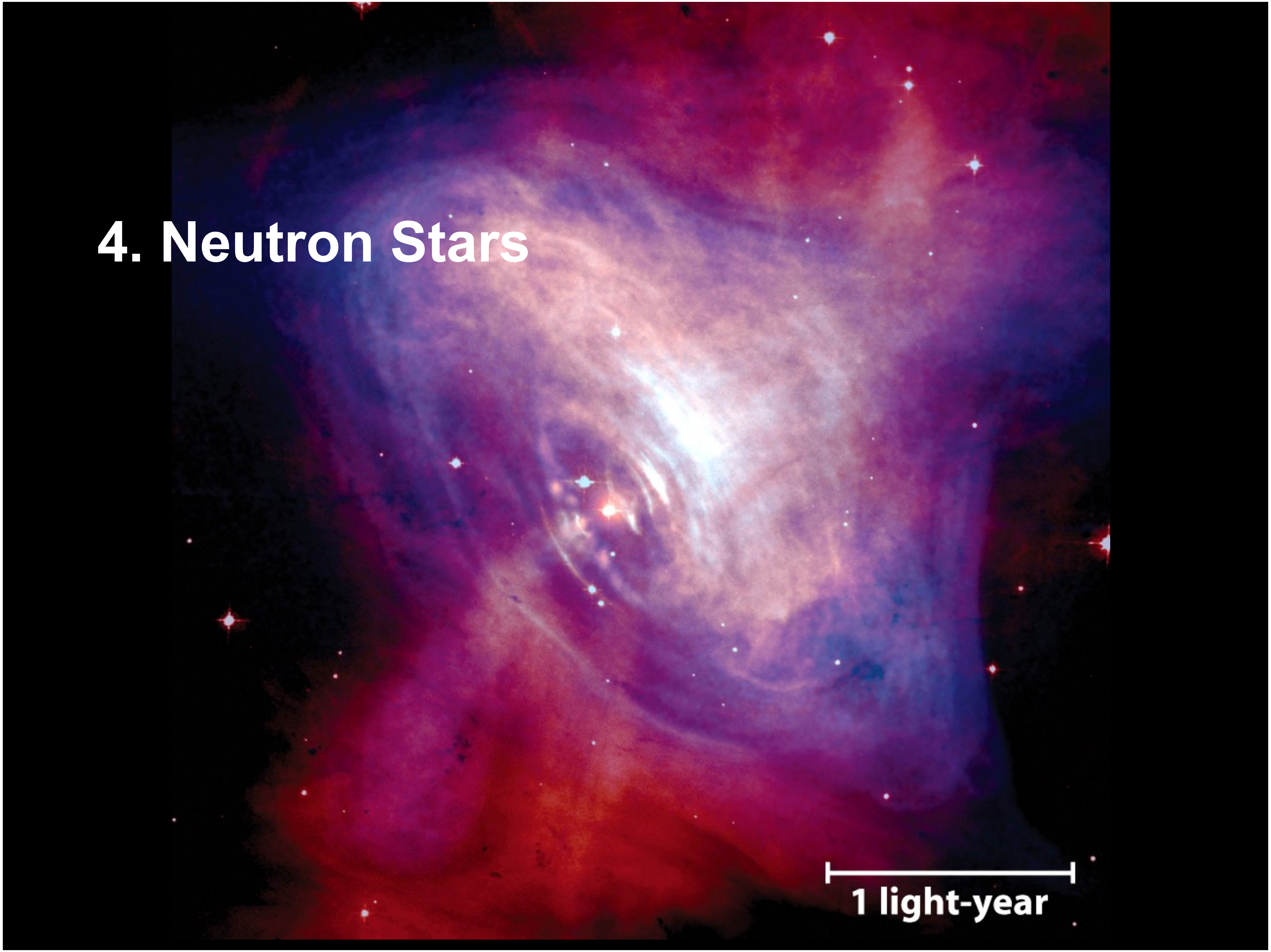
Type Ic supernovae occur when the star has lost a substantial part of both its hydrogen shell and helium shell



Type II supernovae are created by the deaths of massive stars



4. Neutron Stars



Guiding Questions

1. What led scientists to the idea of a neutron star?
2. What are pulsars, and how were they discovered?
3. How did astronomers determine the connection between pulsars and neutron stars?
4. How can a neutron star supply energy to a surrounding nebula?
5. What are conditions like inside a neutron star?
6. How are some neutron stars able to spin several hundred times per second?
7. Why do some pulsars emit fantastic amounts of X rays?
8. Are X-ray bursters and novae similar to supernovae?
9. How massive can a neutron star be?

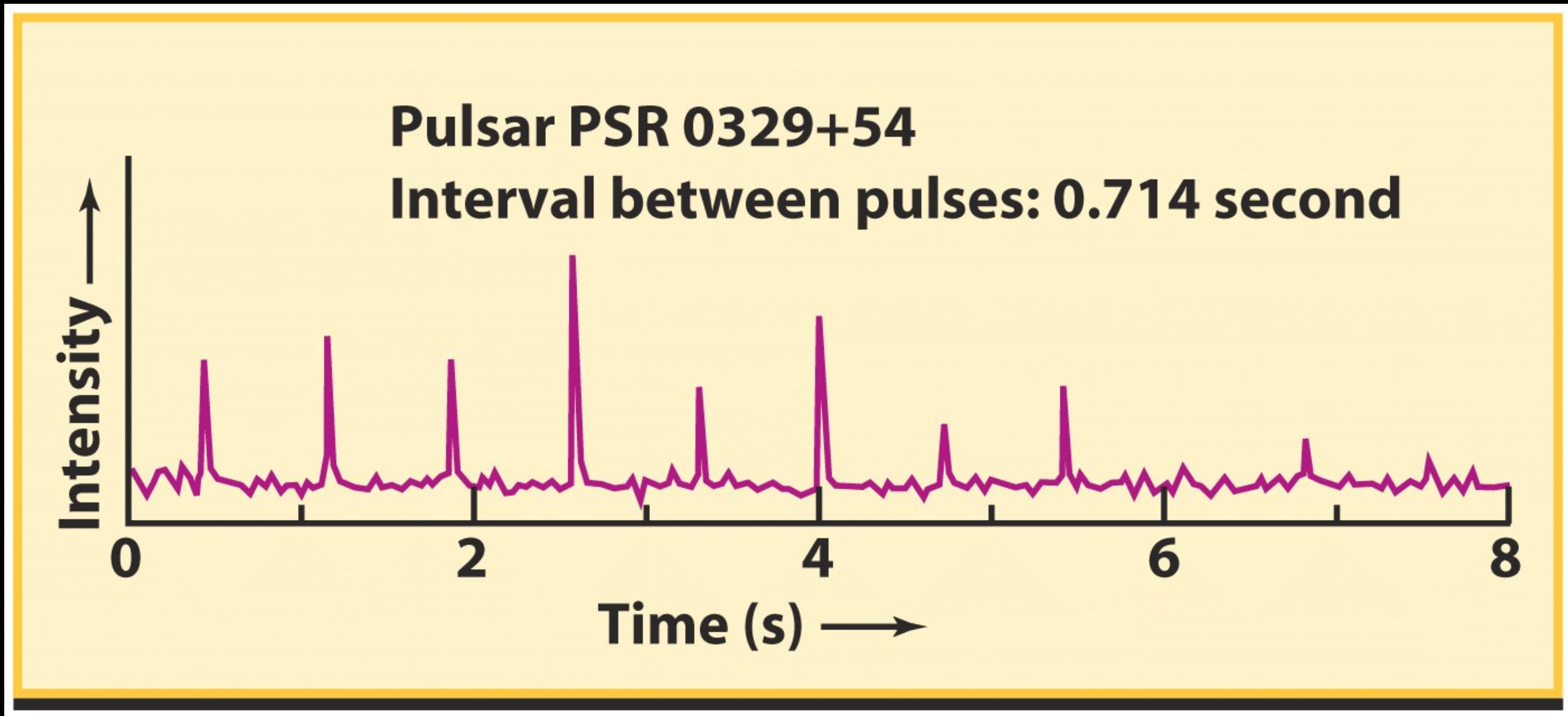
Neutron Stars

- A neutron star forms during the supernova explosion if the mass of the collapsing core exceeds the Chandrasekhar limit of 1.4 Msun
- Degenerate neutron pressure count-balances the gravitation
- A neutron star is a dense stellar corpse consisting primarily of closely packed degenerate neutrons
- Proposed in 1930's, Not verified until 1960's

Properties of Neutron Stars

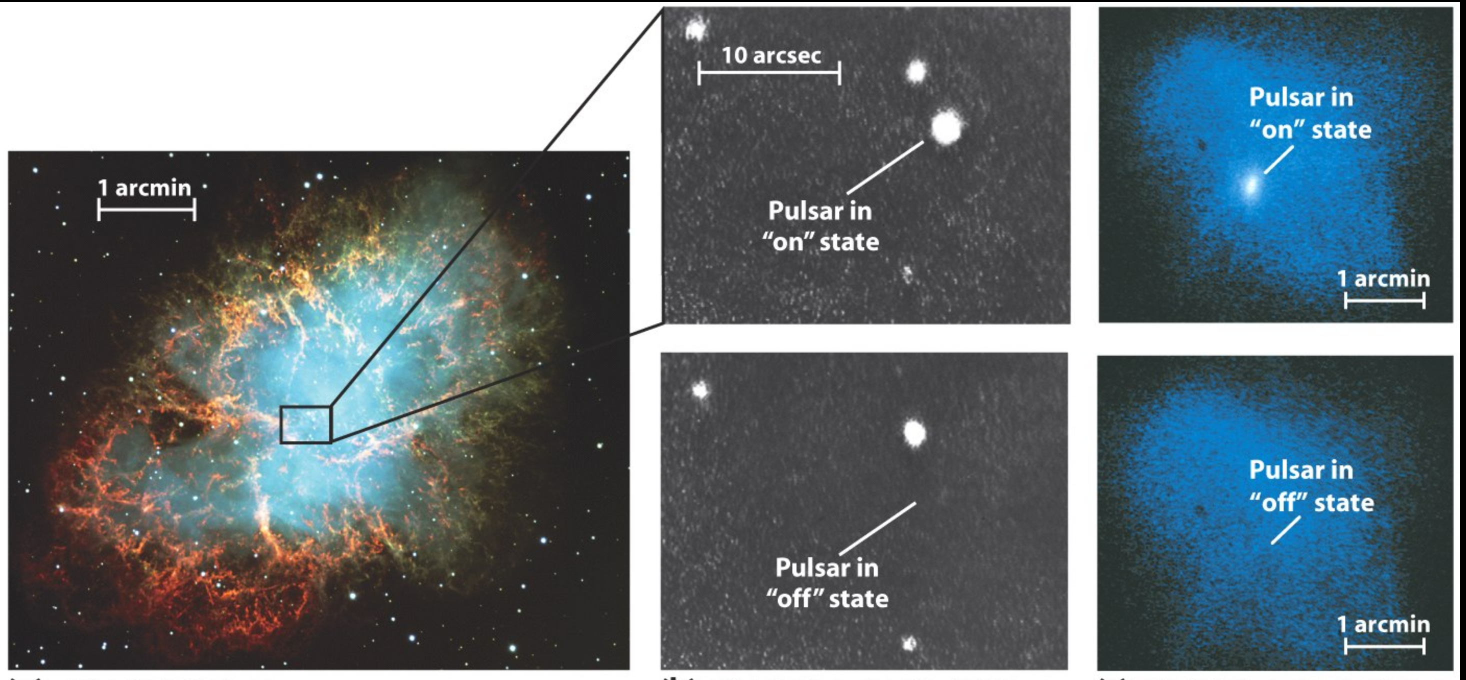
- Diameter of about 20 km
- Mass less than 3 Msun
- Magnetic field 10^{12} times stronger than that of the Sun
- Rotation period of roughly 1 second

The discovery of pulsars in the 1960s



Pulsar Found in the Crab Nebula

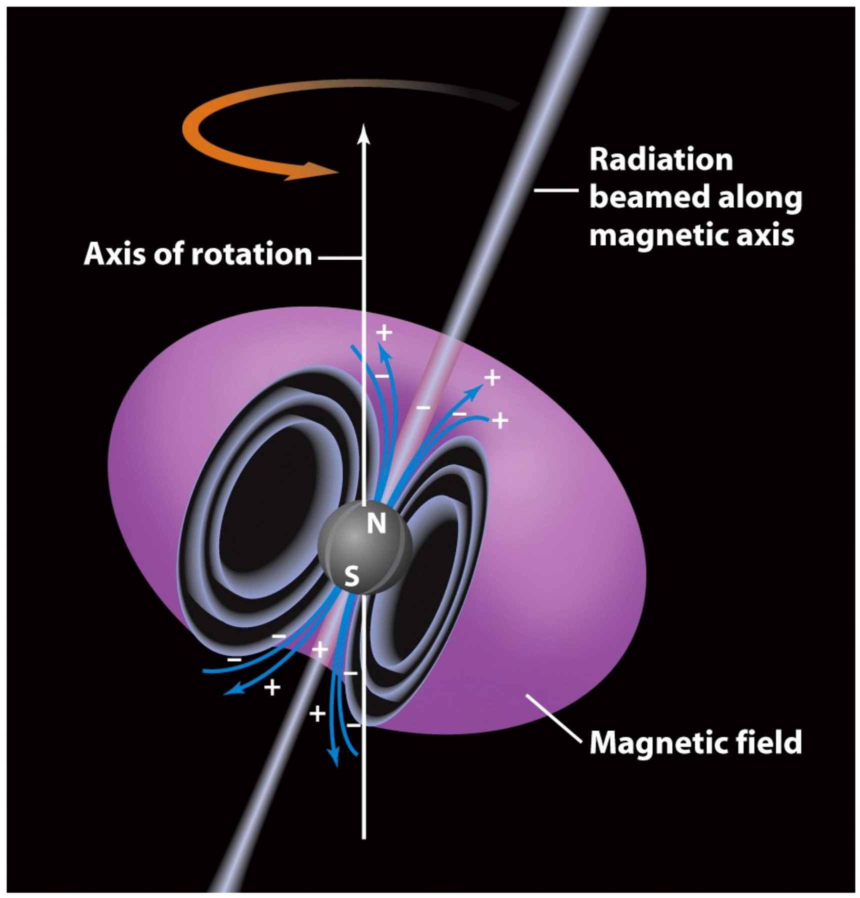
- Crab nebula was created by the supernova explosion occurred on July 4, 1054, recorded by Chinese astronomer
- A fast rotating pulsar, with period of 0.033 second, or 30 times per second, is discovered at the center of the Crab nebula
- Such fast spin can not be from a white dwarf



(a) The Crab Nebula (b) The Crab pulsar in visible light (c) The Crab pulsar in X rays

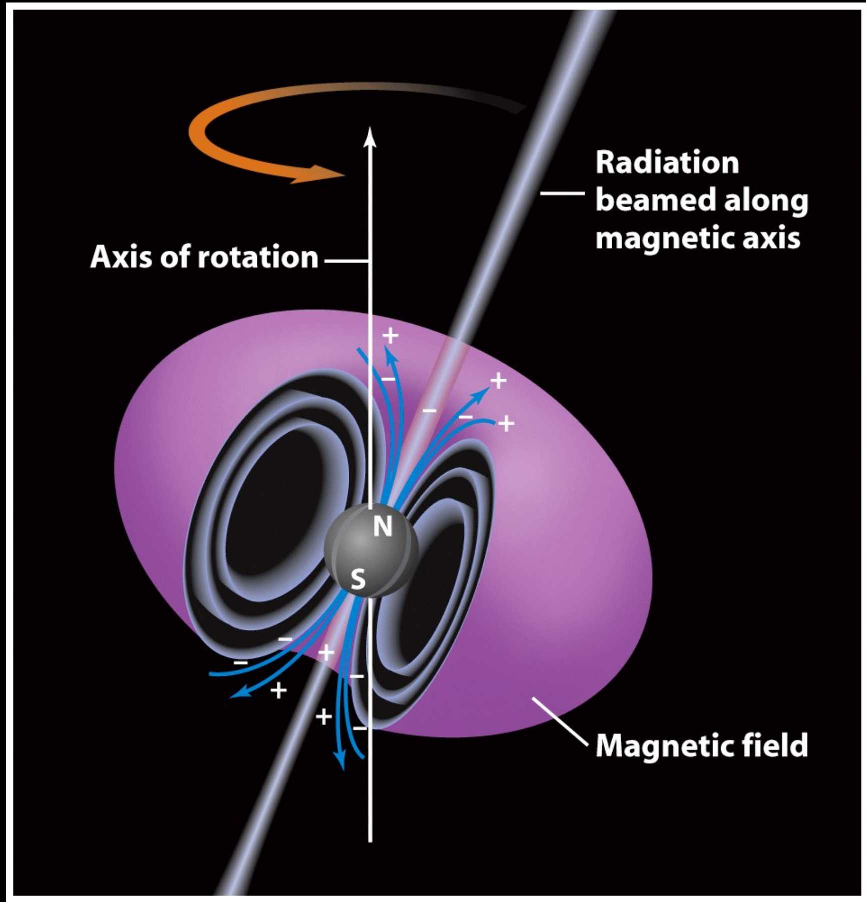
Pulsars are rapidly rotating neutron stars

- A neutron star can spin very fast because of its small size
- Magnetic field is strong because all magnetic field in the progenitor star is squeezed and concentrated into the neutron star size.
- Magnetic axis is inclined to the rotation axis
- Charged particles from the surface are accelerated along the intense magnetic field, and radiate electromagnetic radiation



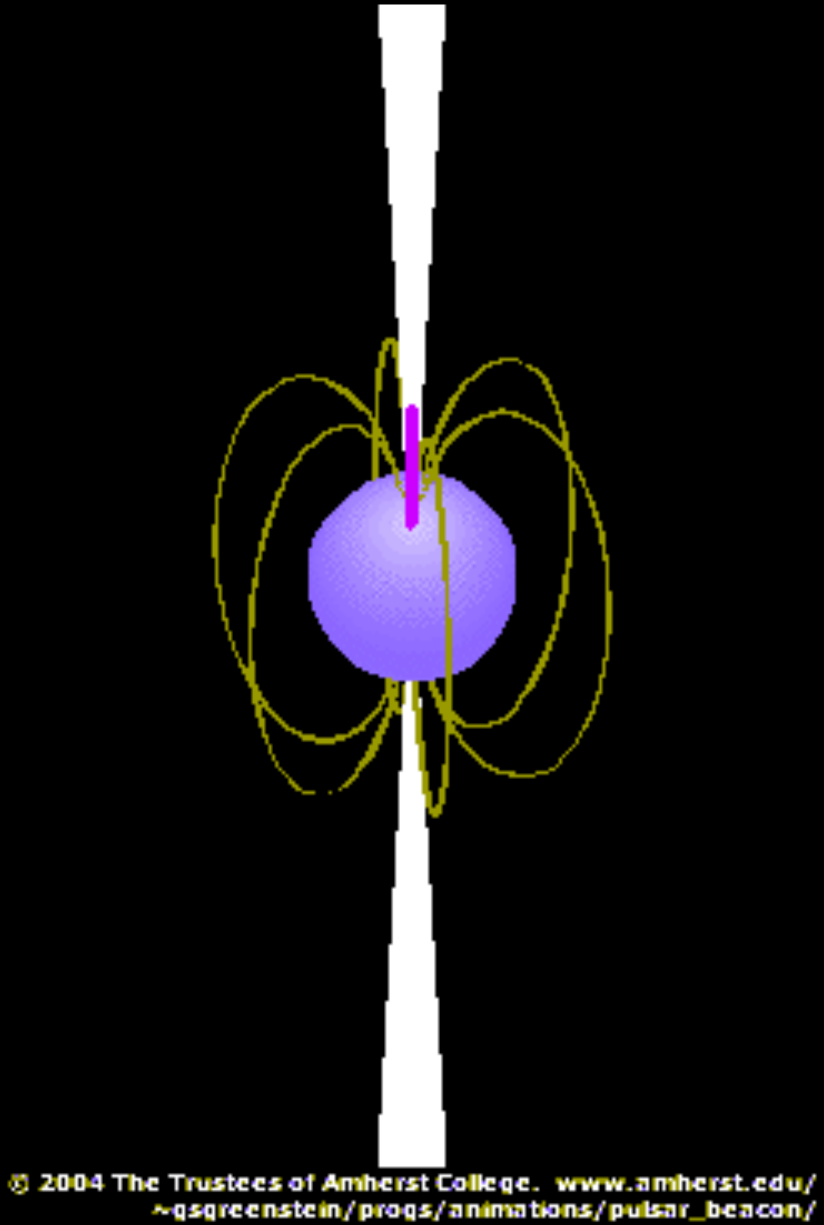
Pulsars are beamed radiation sweep the Earth

- Because charged particles move along the magnetic field lines
- The radiation is also along the magnetic field lines, forming a radiation beam in parallel with the magnetic axis
- The beam sweeps around the sky as the star rotates
- If the Earth happens to lie in the path of the beam, the pulsar can be detected



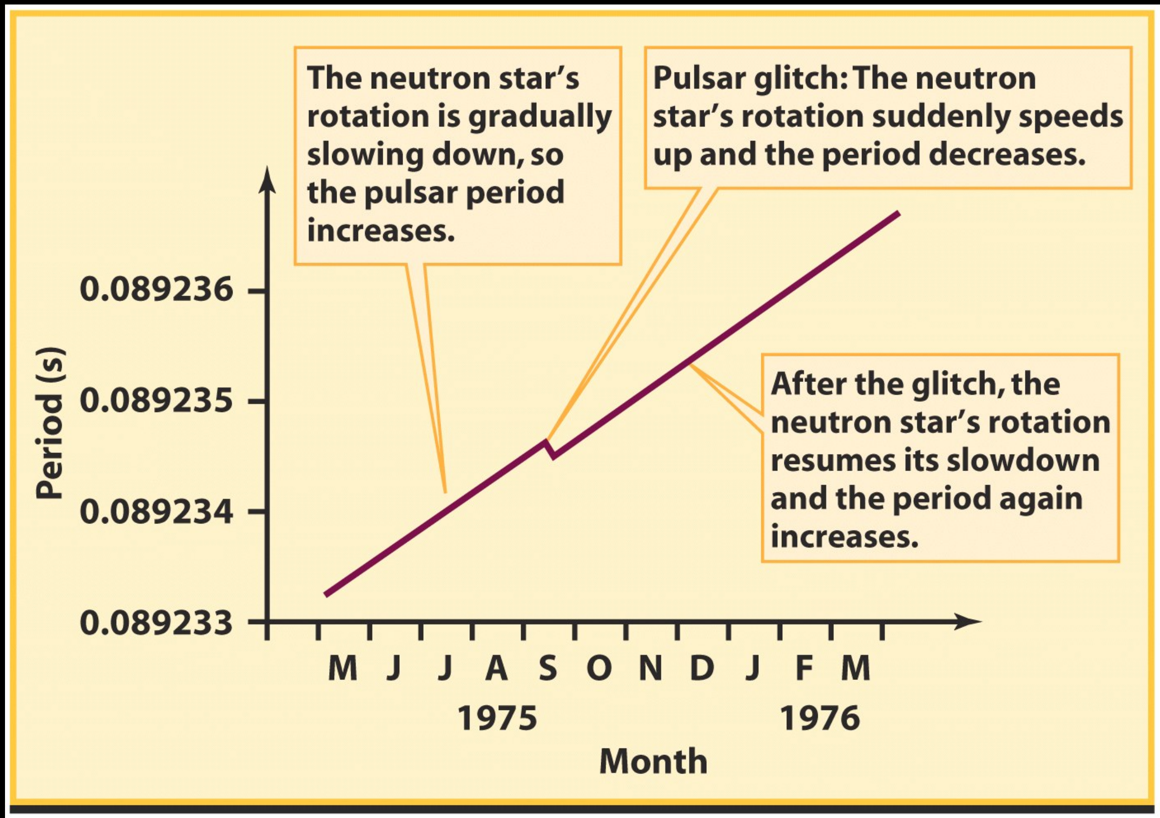
Pulsars is like a lighthouse beacon

- Pulsar is a rotating neutron star whose radiation beam happens to sweep the Earth



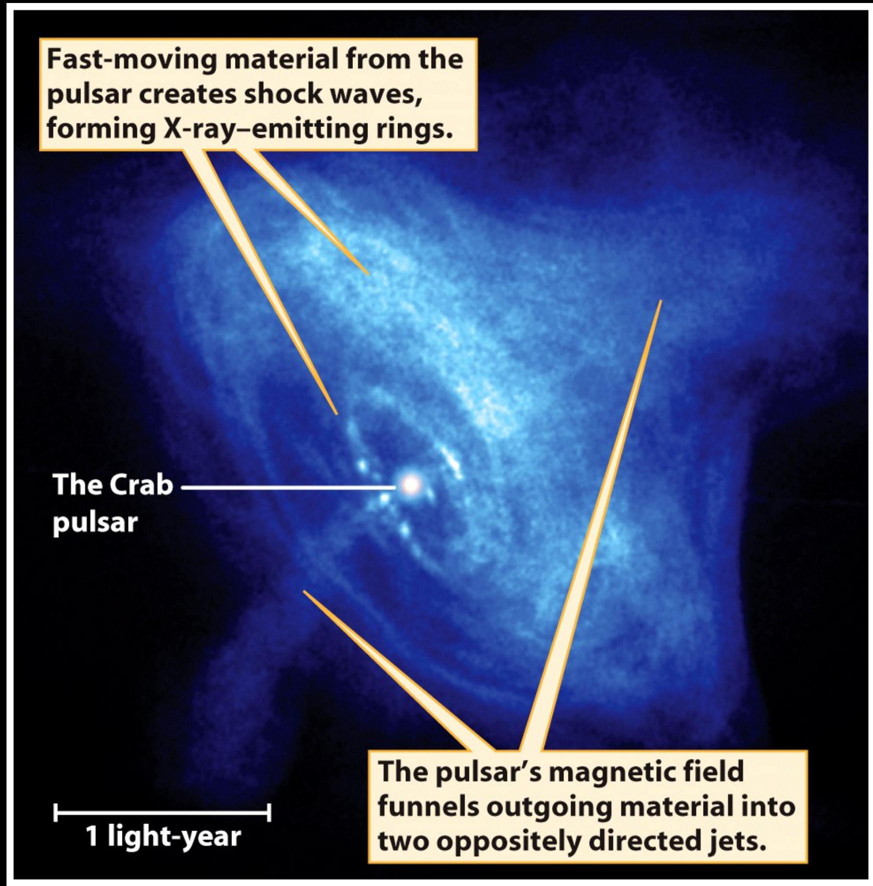
Periods of Pulsars

- Radio telescopes have found more than 1000 pulsars
- Their rotation period is in a wide range from 1 ms (mili-second or 0.001 sec) to 10 second
- **An isolated pulsar slows down as it ages, so its period increases**

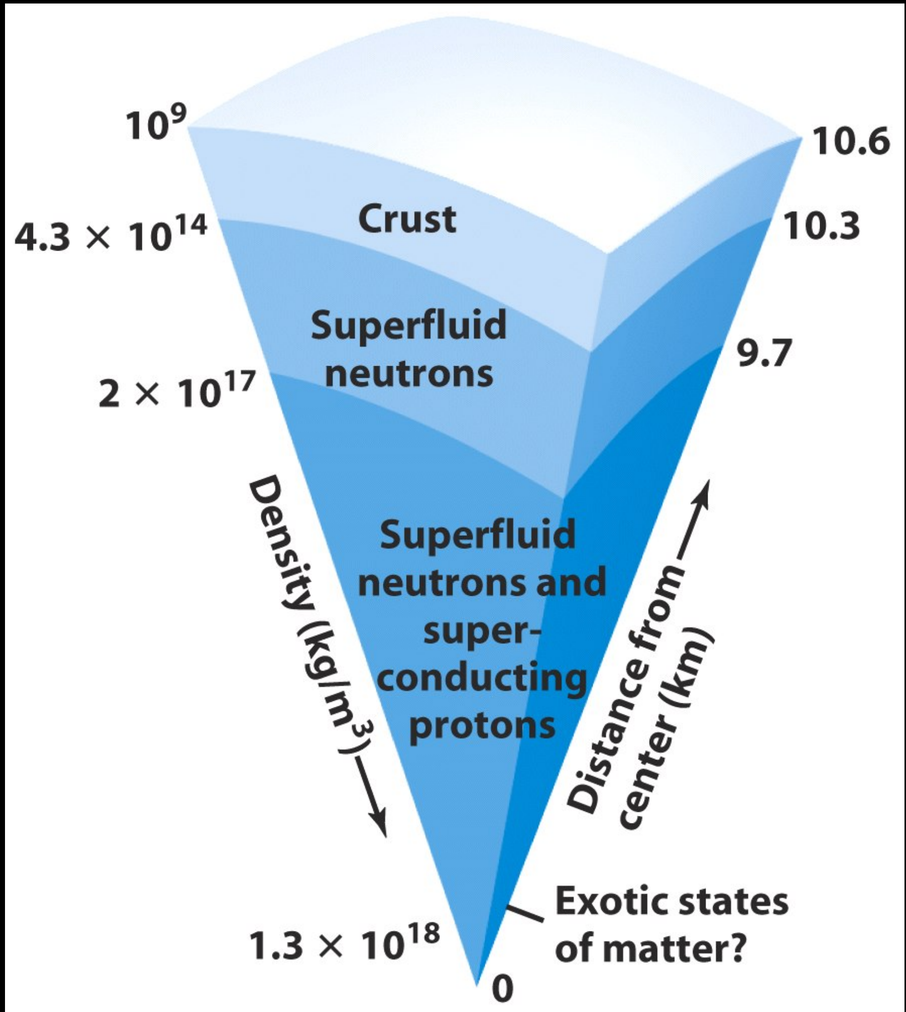


What powers the Crab Nebula?

- The ultimate energy source for the luminous nebula is the spinning of the neutron star
- **The spinning or rotation energy is transferred into the surrounding nebula, which results in the gradual slow down of the star**
- The nebula shines due to the radiation from the energetic electrons accelerated along the magnetic fields



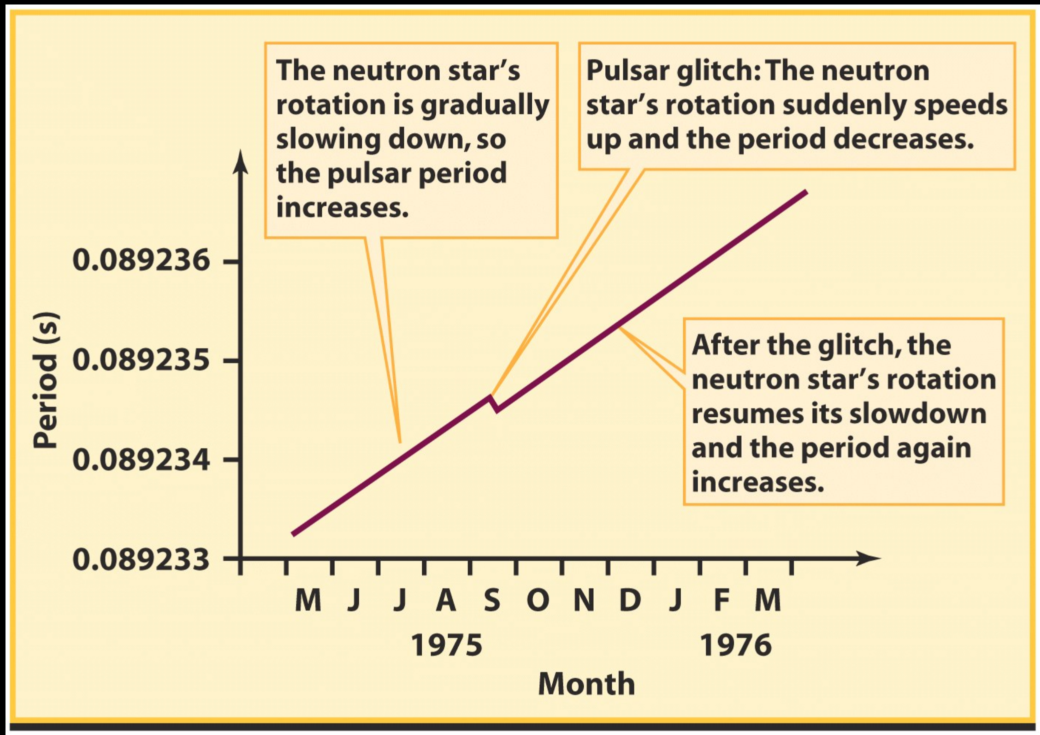
A Model of Neutron Star Structure



- A neutron star consists of a superfluid, superconducting core surrounded by a superfluid mantle and a thin, brittle crust
- There is evidence for an atmosphere

Pulsars gradually slow down, but have glitches

- The pulse rate of many pulsars is slowing steadily
- Sudden speedups of the pulse rate, called glitches, may be caused by interactions between the neutron star's crust and its superfluid interior

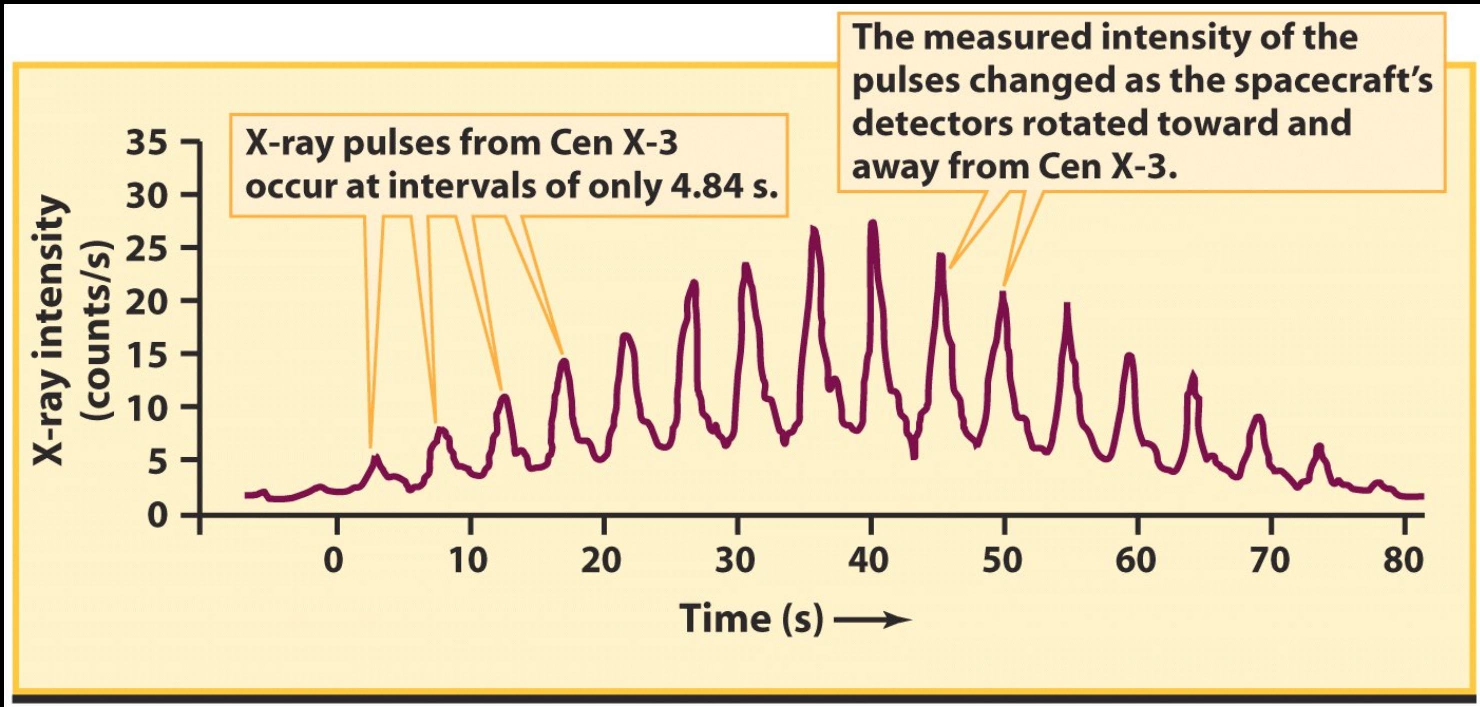


Pulsars in close binary systems

- **The fastest neutron stars (millisecond pulsars**), with period of ms (rotate a thousand times a second), are found in close binary systems
- In contrast to most pulsars, they spin faster with time
- When the companion star develops into a giant star as it ages, the mass transfers toward the neutron star
- The infalling gas strikes the neutron star's surface at a high speed and at an angle that **cause the star to spin faster**

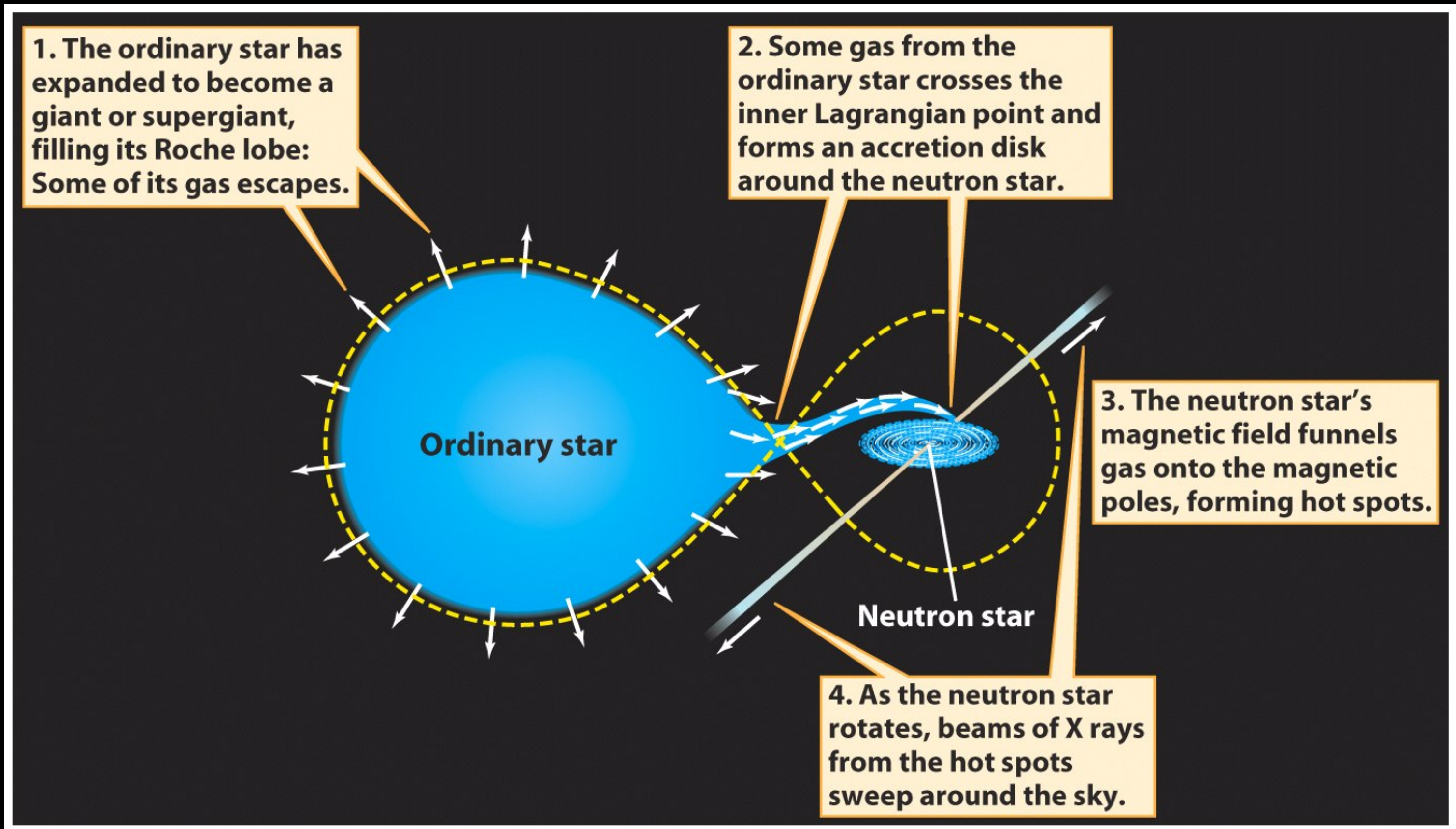
Pulsating X-ray sources

- Pulsars are originally found in radio wavelength
- But they are also found in X-ray wavelength
- X-ray pulsars are found in close binary systems



Pulsating X-ray sources

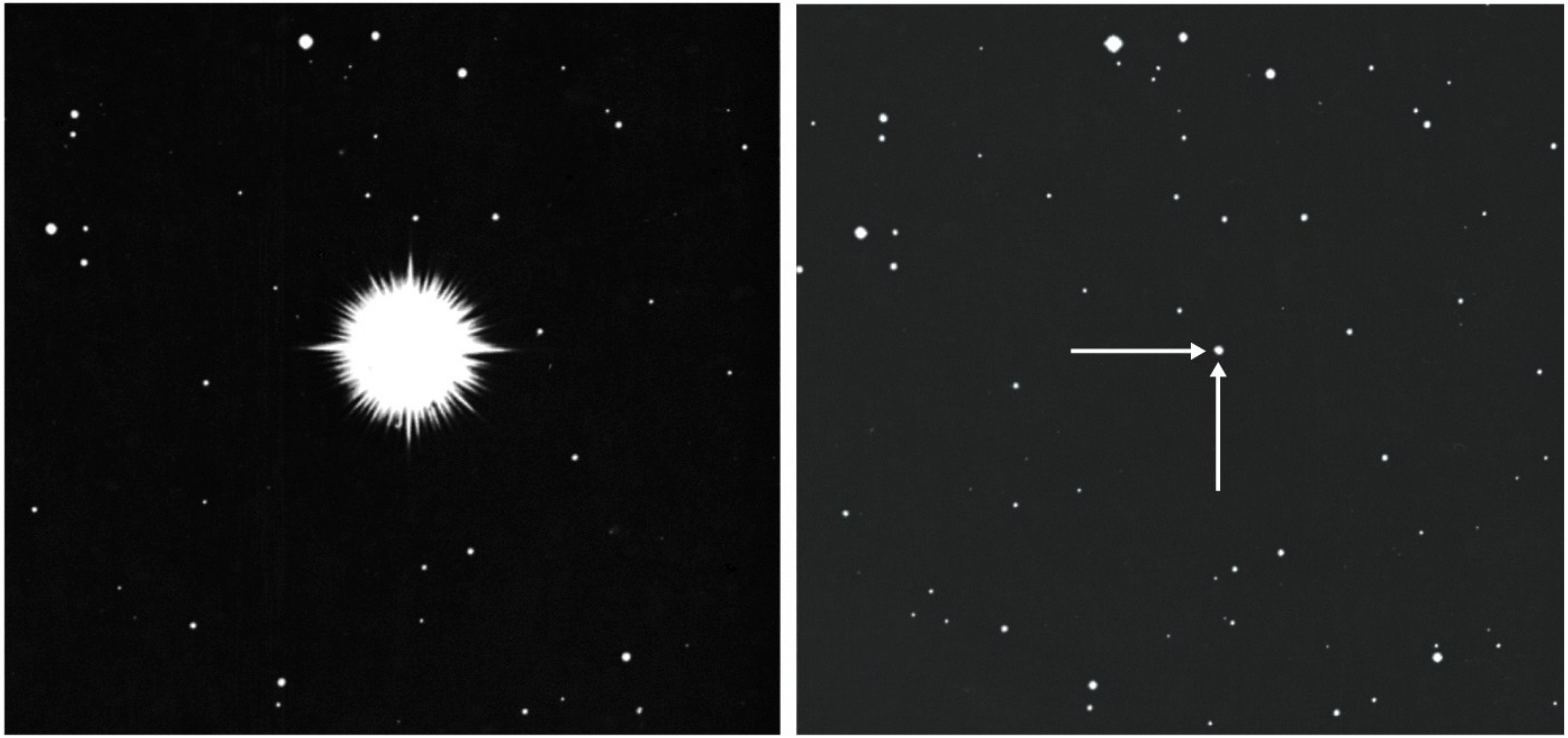
- Mass is transferred from companion star to neutron star
- Magnetic forces can funnel the gas onto the neutron star's magnetic poles, producing hot spots (~ 10^8 K)
- These hot spots then radiate intense beams of X rays



Novae: white dwarf re-ignition in binary system

- Nova is a faint star suddenly brightens by a factor of 10^4 to 10^8 over a few days or hours
- It reaches a peak luminosity of about 10^5 Lsun
- A nova is different from supernova (luminosity of 10^9 Lsun)
- Material from an ordinary star in a close binary can fall onto the surface of the companion white dwarf
- Because of strong gravity, the transferred hydrogen mass is compressed into a dense layer covering the while surface
- When the temperature reaches about 10^7 K, hydrogen fusion ignites through the surface layer, producing the sudden increase in luminosity

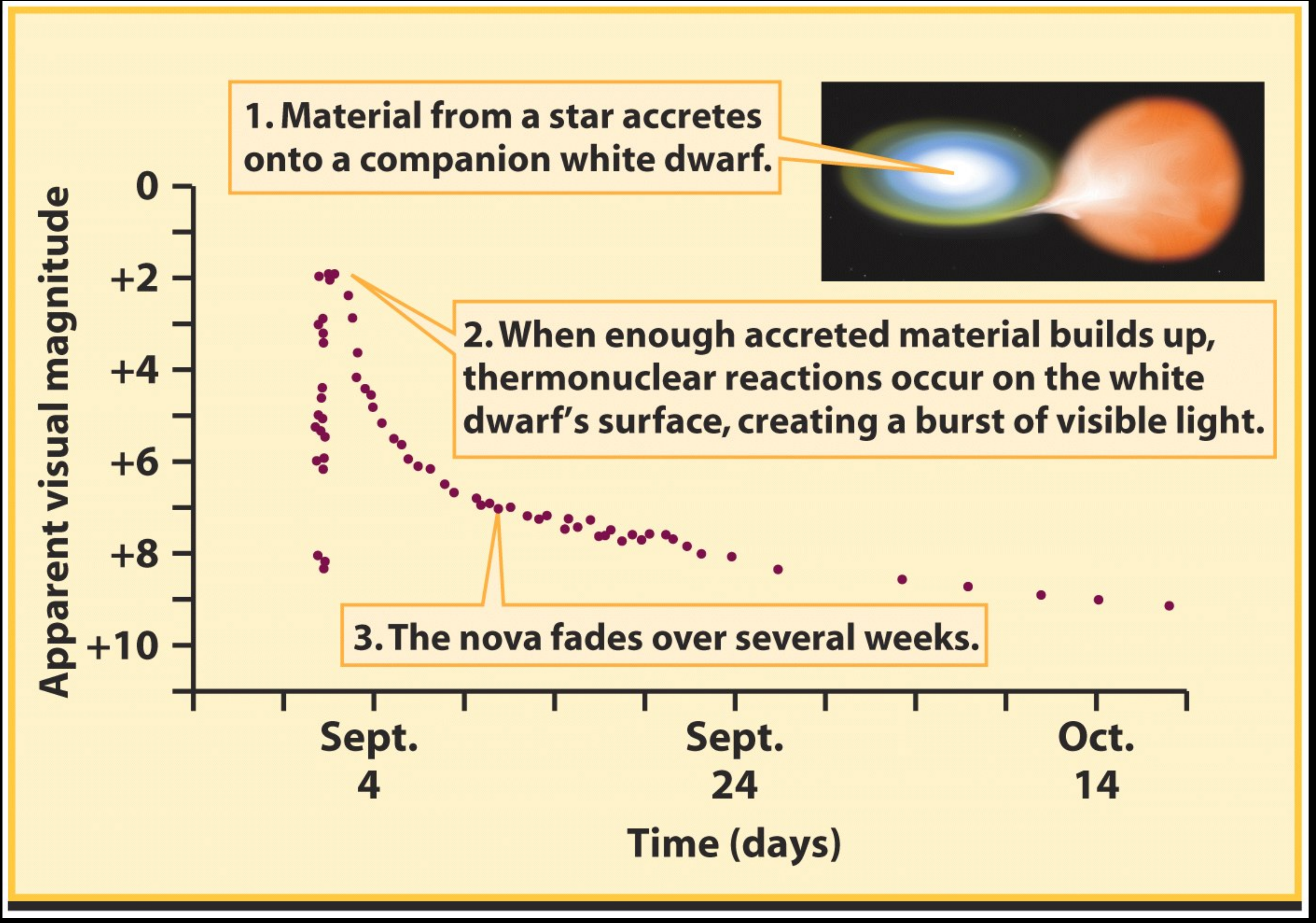
Novae



(a) **Nova Herculis 1934 shortly after peak brightness** **(b)** **Two months later**

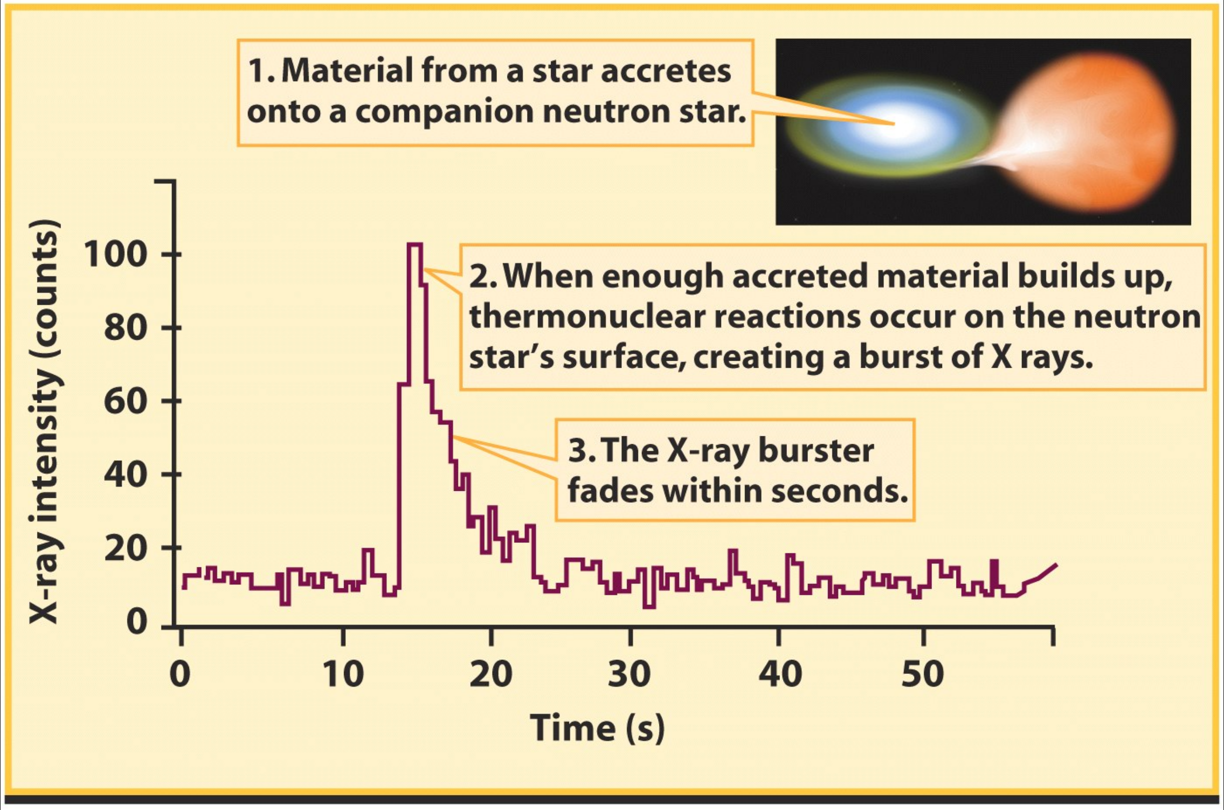
Novae

- The nova fades over several weeks, and can happen again



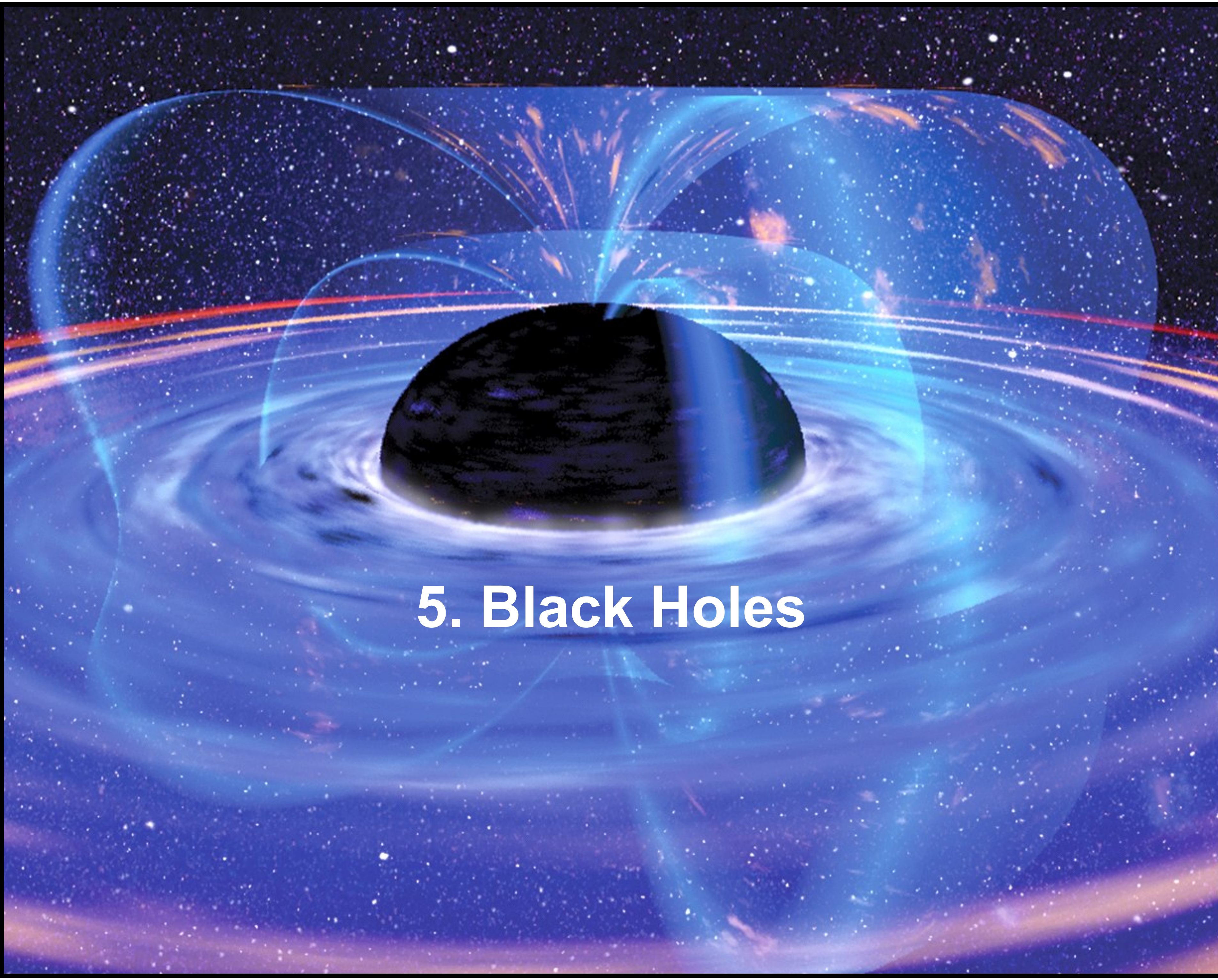
X-ray Burster: neutron star re-ignition in binary system

- Similar mass accretion process as in white dwarf case
- Helium flash (or helium fusion) occurs at the surface, and heats the surface to about 3 X 10^7 K
- At this temperature, the surface predominantly emits X-ray



A neutron star has an upper limit on its mass (3 Msun)

- The pressure within a neutron star comes from *two* sources
- One is the degenerate nature of the neutrons, and the other is the strong nuclear force that acts between the neutrons themselves
- **If mass exceeds 3 Msun, the degenerate neutron pressure can not resist the gravitational compression**
- The discovery of neutron stars inspired astrophysicists to examine seriously one of the most bizarre and fantastic objects ever predicted by modern science, the **black hole**


5. Black Holes

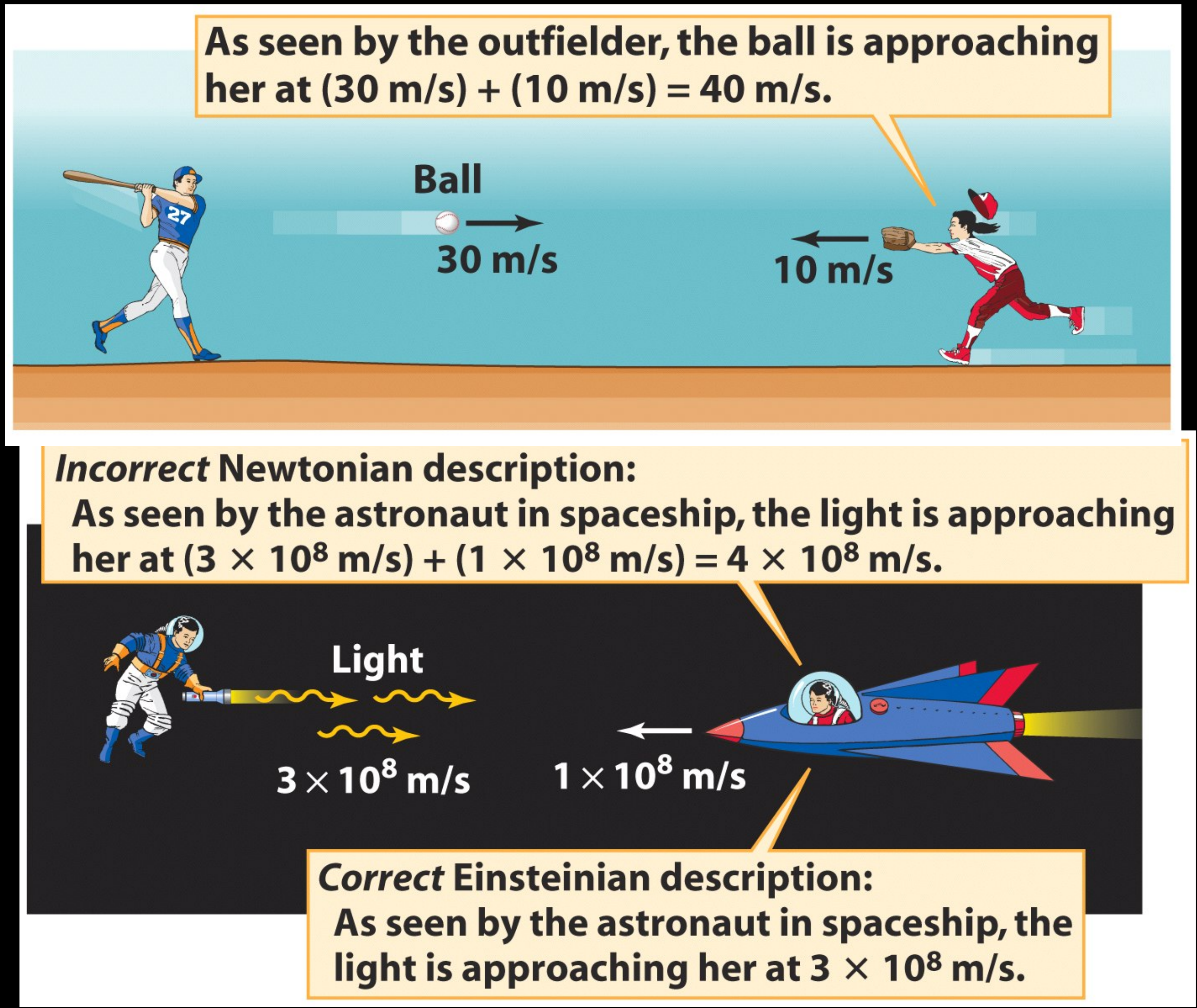
Guiding Questions

1. What are the two central ideas behind Einstein's special theory of relativity?
2. How do astronomers search for black holes?
3. What are super massive black holes, and where are they found?
4. In what sense is a black hole "black"?
5. In what way are black holes actually simpler than any other objects in astronomy?
6. What happens to an object that falls into a black hole?
7. Do black holes last forever?

- This theory, published by Einstein in 1905, is based on the notion that there is no such thing as absolute space or time
- Space and time are relative value, depending on the speed of the measuring object

1. The laws of physics are the same regardless of the constant velocity at which you move

2. You always measure the speed of light to be the same, regardless of your speed or direction of motion

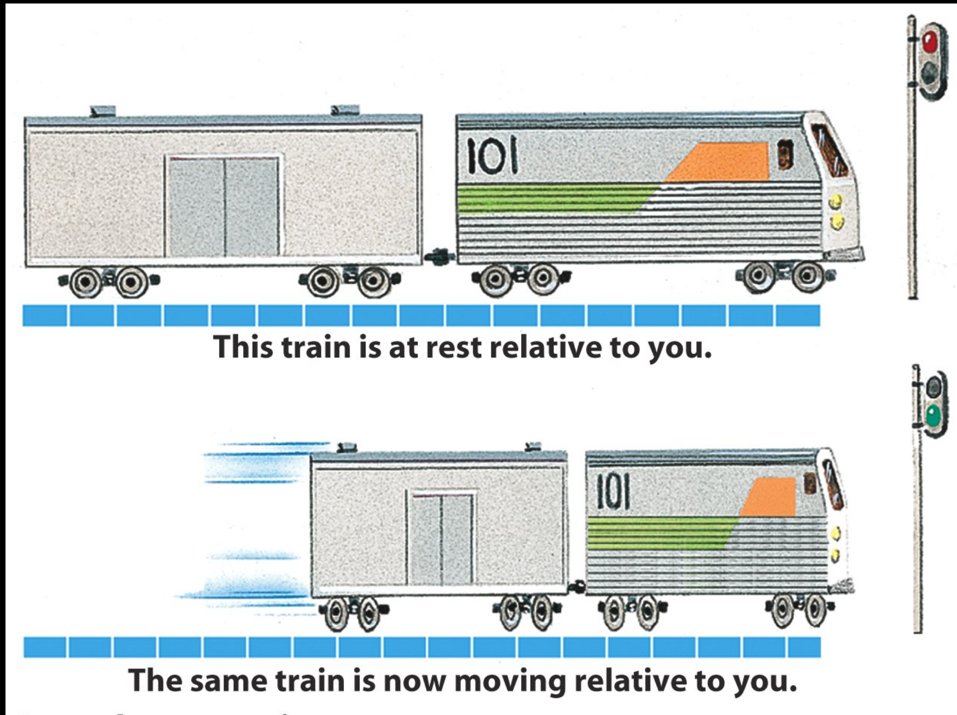


As seen by the outfielder, the ball is approaching her at (30 m/s) + (10 m/s) = 40 m/s.
Ball
30 m/s
10 m/s
27
Incorrect Newtonian description:
As seen by the astronaut in spaceship, the light is approaching her at $(3 \times 10^8$ m/s$) + (1 \times 10^8$ m/s$) = 4 \times 10^8$ m/s.
Light
3×10^8 m/s
1×10^8 m/s
Correct Einsteinian description:
As seen by the astronaut in spaceship, the light is approaching her at 3×10^8 m/s.

•The length of a moving object is shorter; the faster it moves, the shorter it is

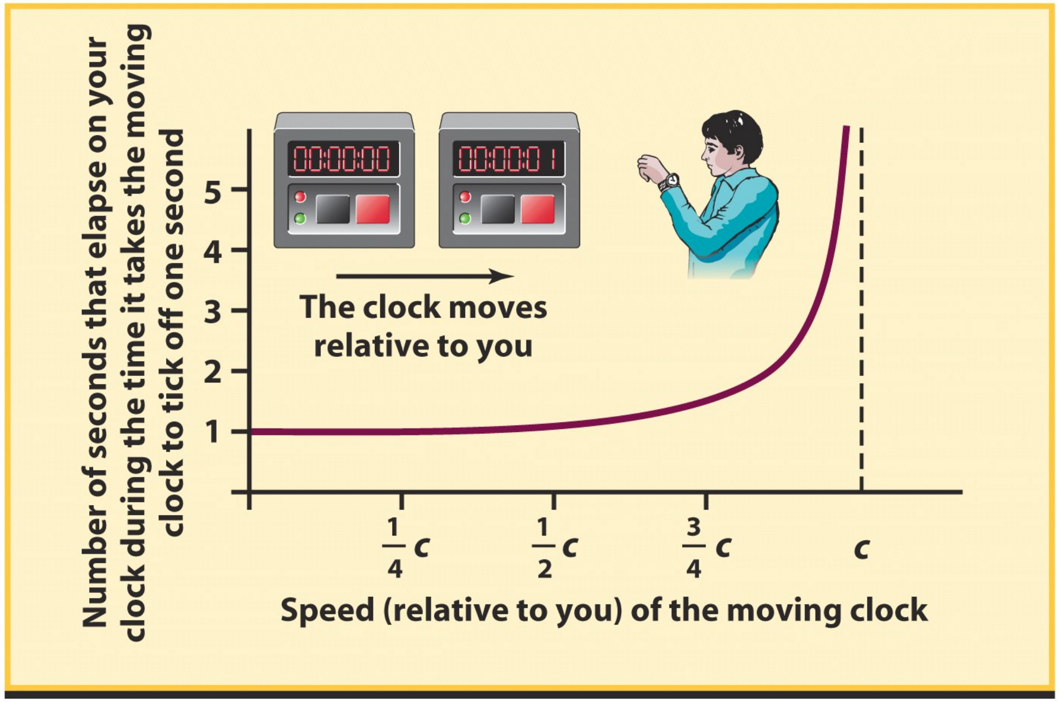
•Spaceship, 10 km/s, contraction 10^{-9}

•Moving at 98% of C, contraction by a factor of 5



Length contraction

- Time goes by slower in a moving object
- Moving at 98% of C, one second becomes five seconds
  - Clock at rest ticks every second
  - Same clock, when moving at 98% of speed of light, ticks every 5 seconds as observed by an observer at rest



Time dilation

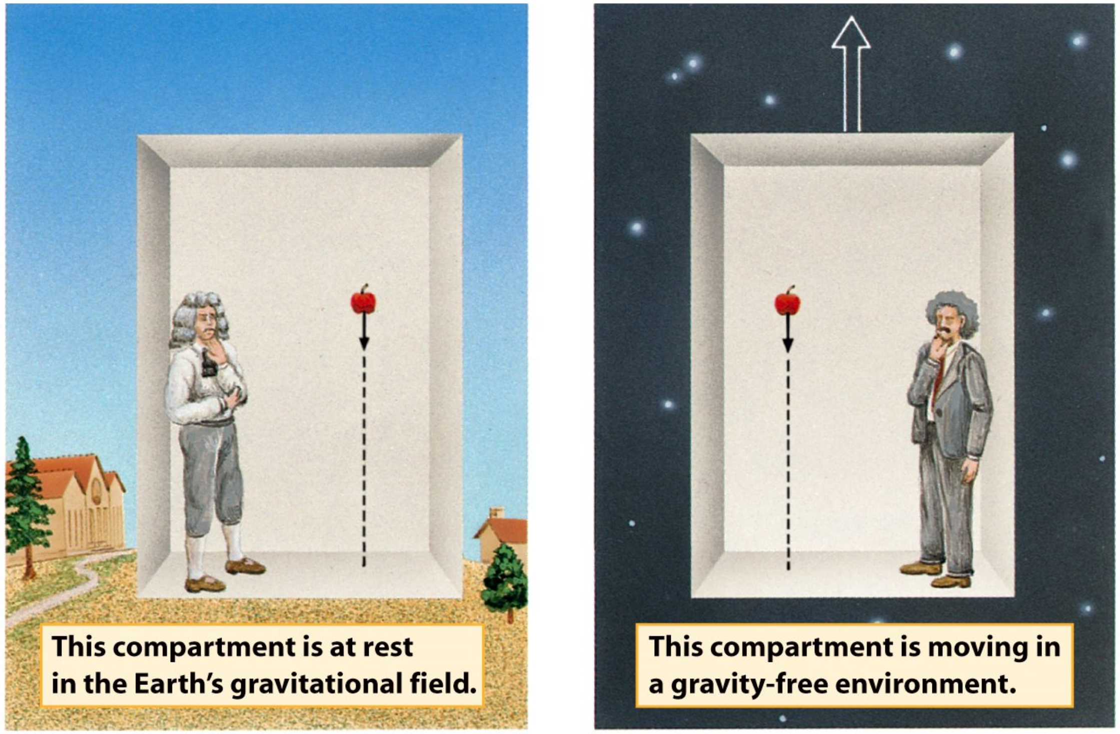
- For a moving object, space becomes shorter, time becomes longer
- However, the entity “spacetime”, which couples space and time, remains the same in both the rest frame and the moving frame
- The spacetime is a four-dimensional entity, combining 3-dimensional space and one dimensional time
- In the spacetime description, space and time becomes inter-changable

General Theory of Relativity

- Published by Einstein in 1915, this is a theory for a more complete description of gravity
- A massive object causes space to curve and time to slow down
- The distortions of space and time are most noticeable in the vicinity of large masses or compact objects, e.g, the surface of a neutron star and a black hole

Equivalence Principle

- The downward pull of gravity can be completely duplicated by an upward acceleration of the observer
- Gravity is equivalent to the bend or curvature of space

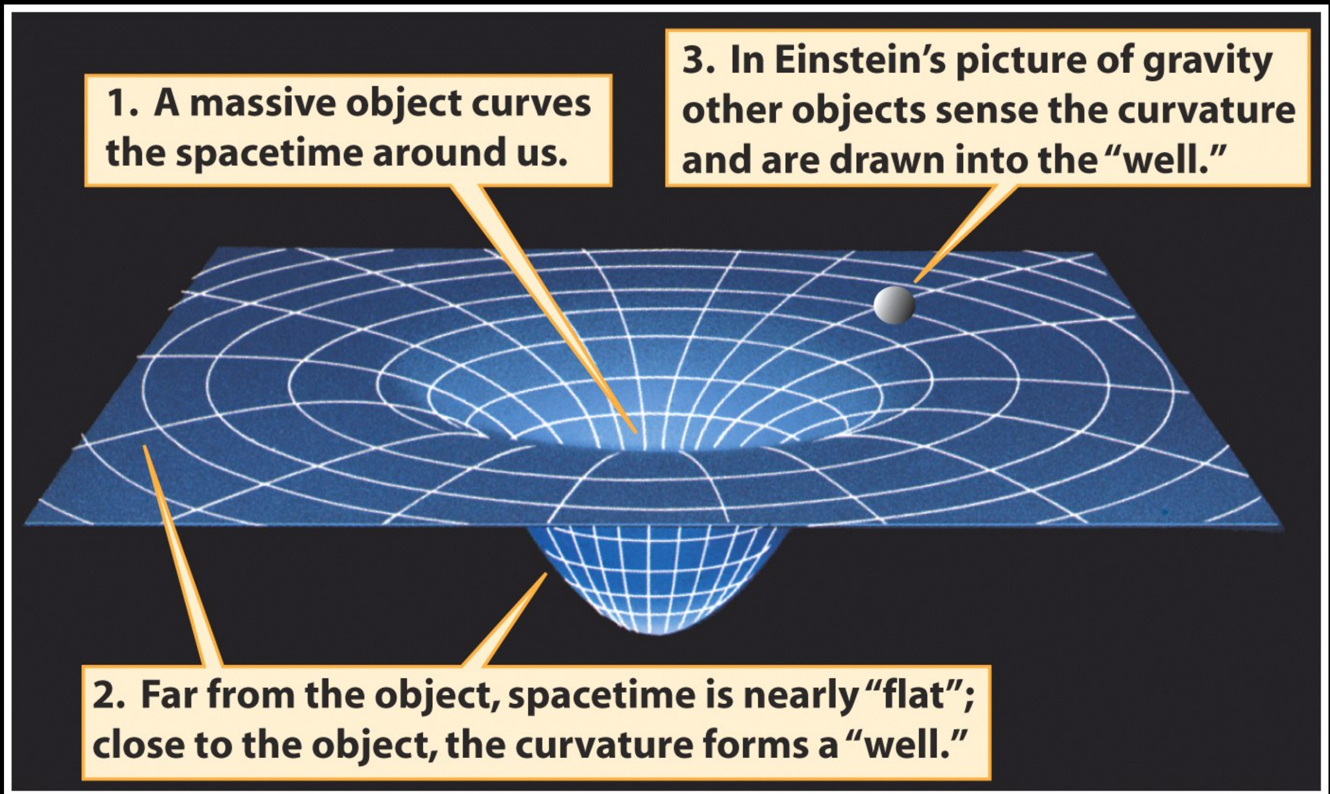


(a) The apple hits the floor of the compartment because the Earth's gravity accelerates the apple downward.

(b) The apple hits the floor of the compartment because the compartment accelerates upward.

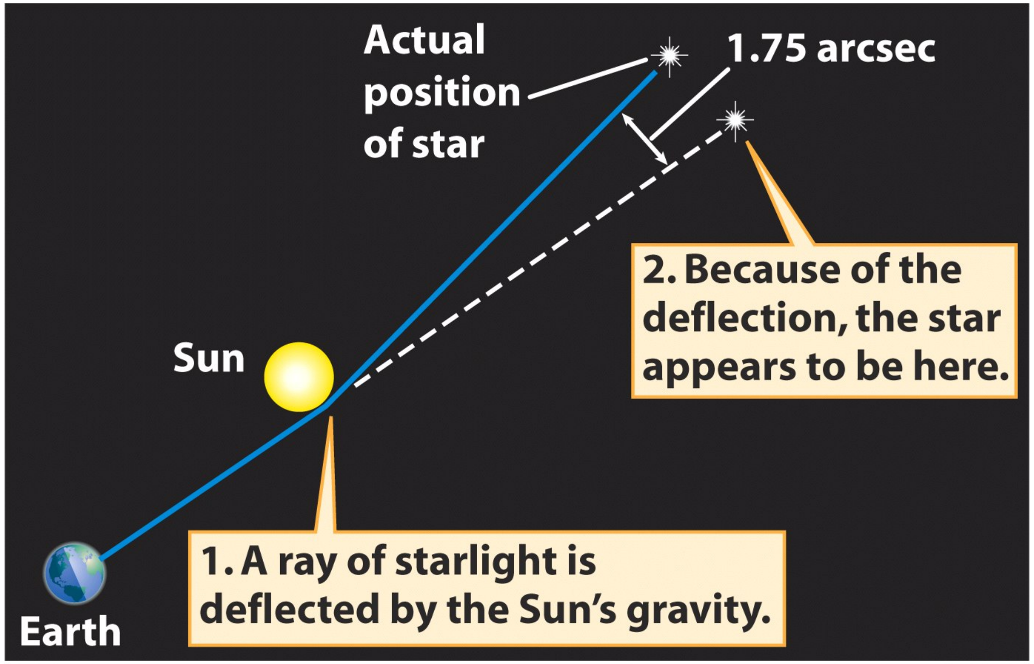
Gravity Equivalent of Curvature of Space

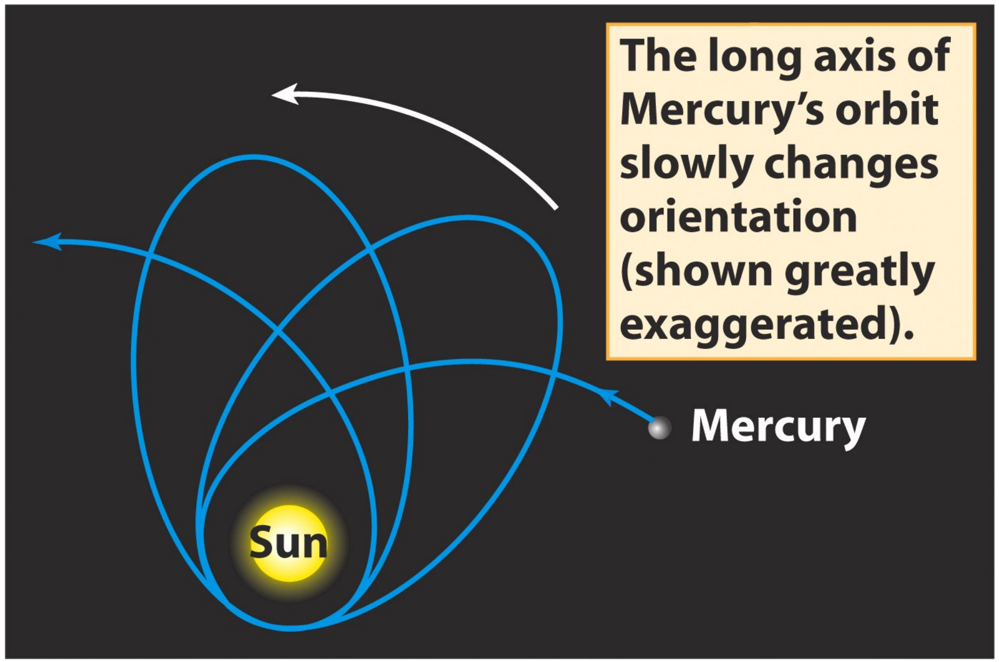
- The curved space not only acts on the object with mass
- The curved space also acts on the light, even though light does not have mass
- The light seeks to move across the shortest distance between tow points; in a curved space, the light bends instead of moving in a straight line



Proof of Theory of Relativity

1. During the solar eclipse, the starlight is deflected by the Sun's gravity by an amount of 1.75 arcsec (1919)
2. Mercury, the closest planet to the Sun, shows an excessive precession that perfectly fits the slightly curved space near the Sun.

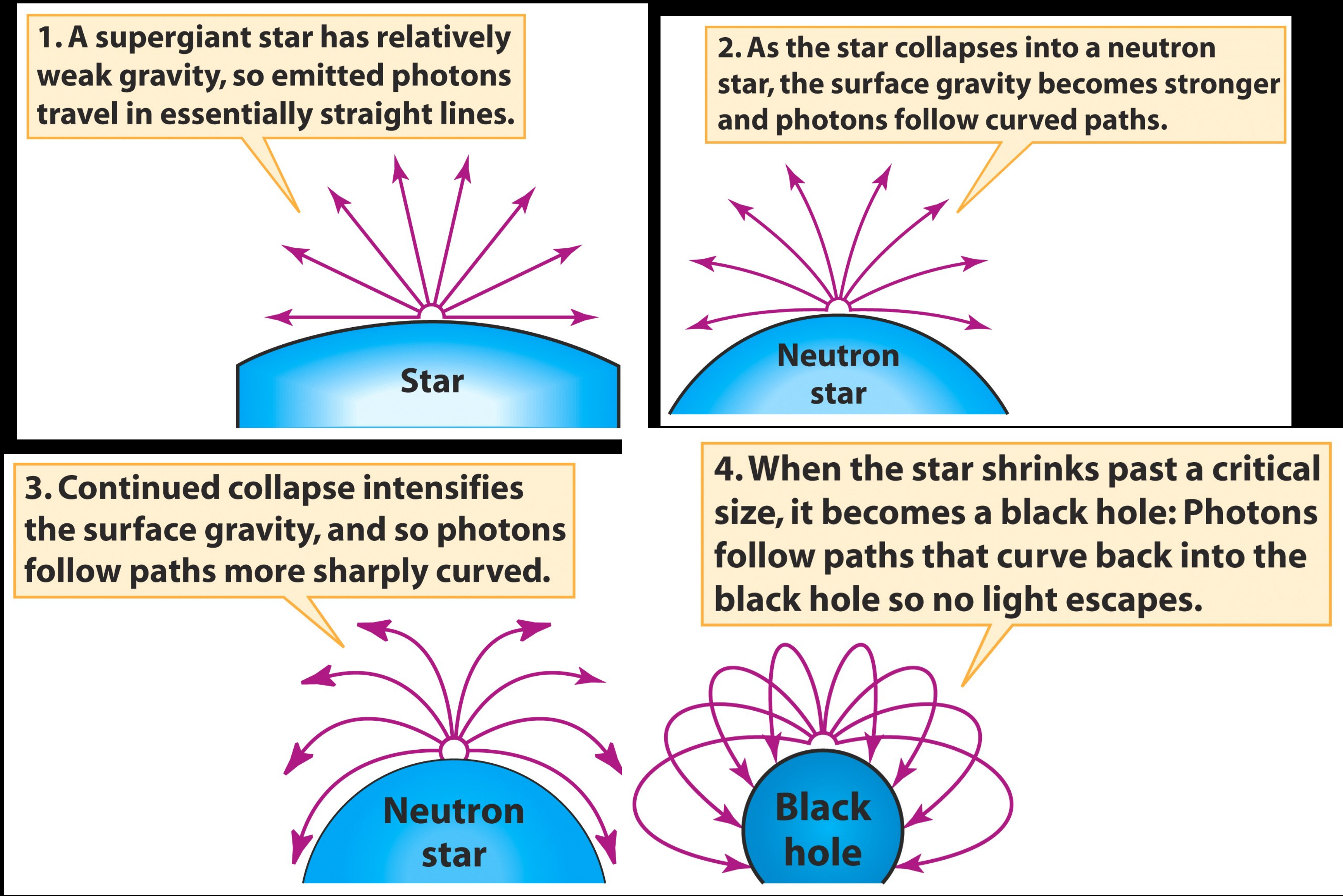




Gravitational Red Shift

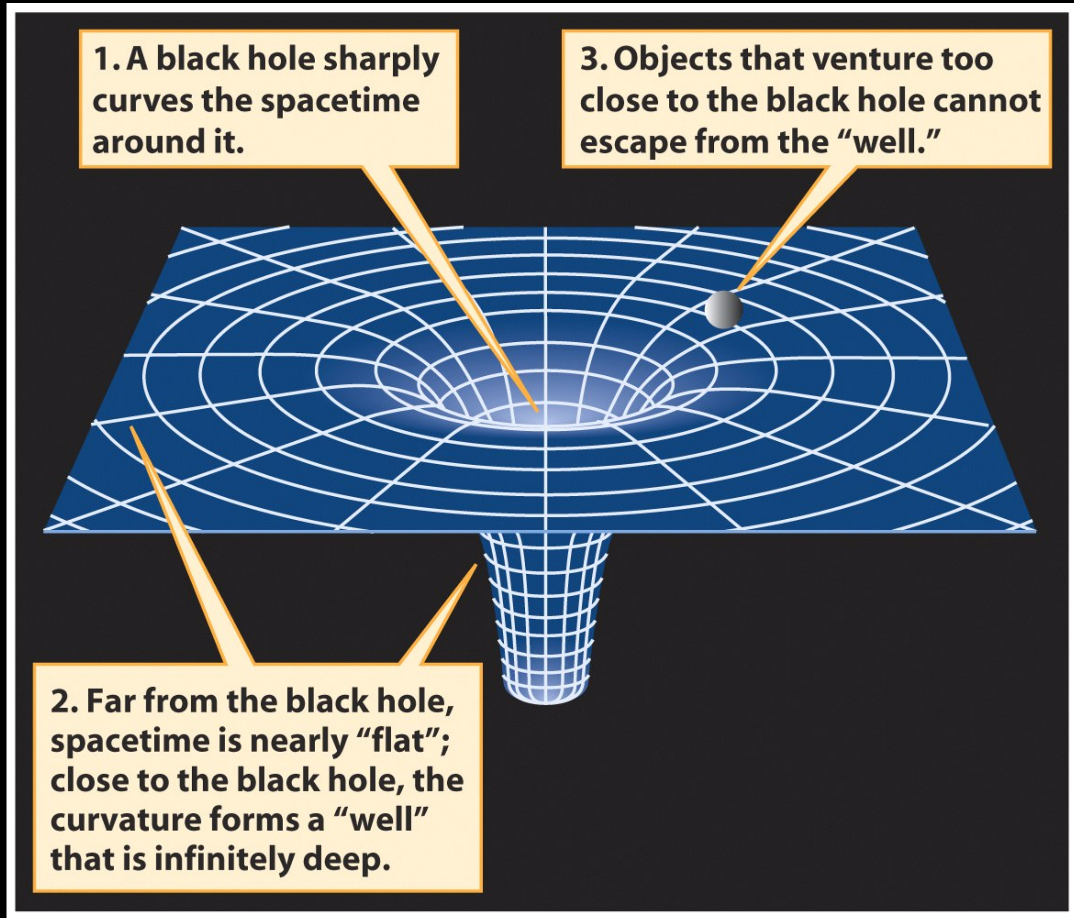
- Because of the time dilation, the period of light wave from the surface of a strong gravity becomes longer, and thus the frequency becomes smaller
- Or equivalently, wavelength becomes longer; this is so called gravitational red shift
- On the surface of a white dwarf, red shift ($\Delta\lambda/\lambda$) is a factor of 10^{-4}
- On the Sun, the gravitational red shift is negligible

Theory of Relativity Predicts Black Holes

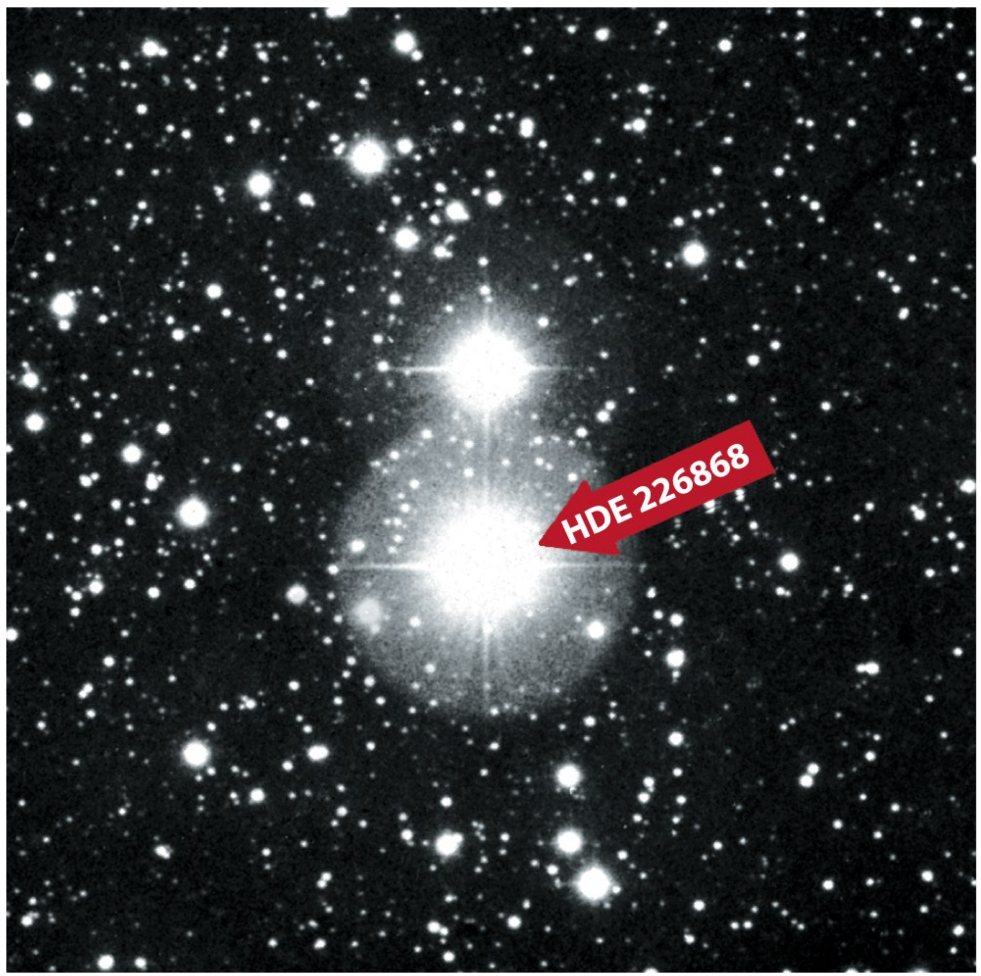


Stellar Black Hole

- If a stellar corpse has a mass greater than about 2 to 3 $M_{\odot}$, gravitational compression will overwhelm any and all forms of internal pressure, including degenerate neutrons and nuclear forces
- The stellar corpse will collapse to a singularity, immediately around which the escape speed exceeds the speed of light

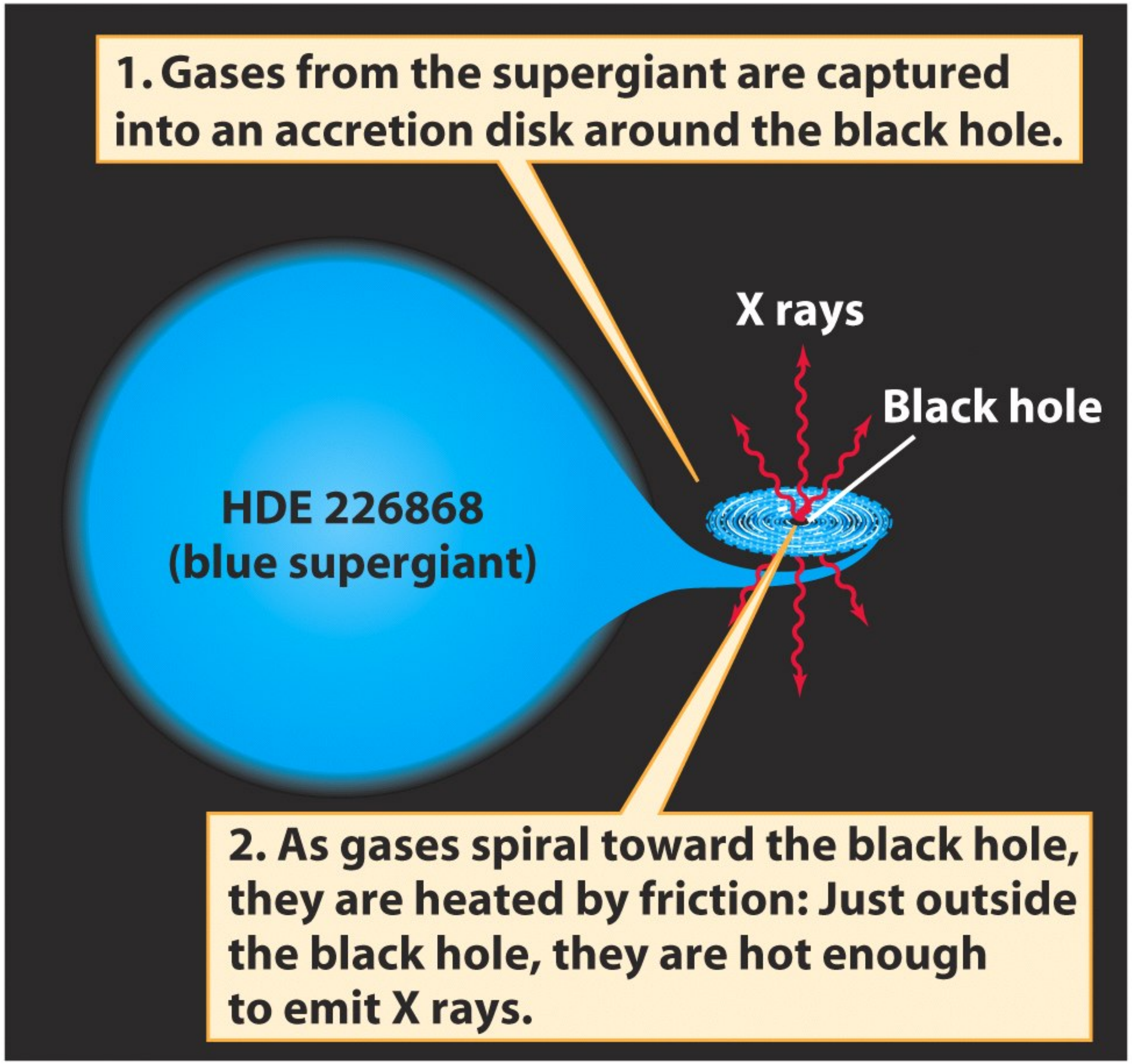


Certain binary star systems probably contain black holes



- Black holes have been detected using indirect methods
- Some binary star systems contain a black hole
- In such a system (e.g., Cygnus X-1), gases captured from the companion star by the black hole emit detectable X rays

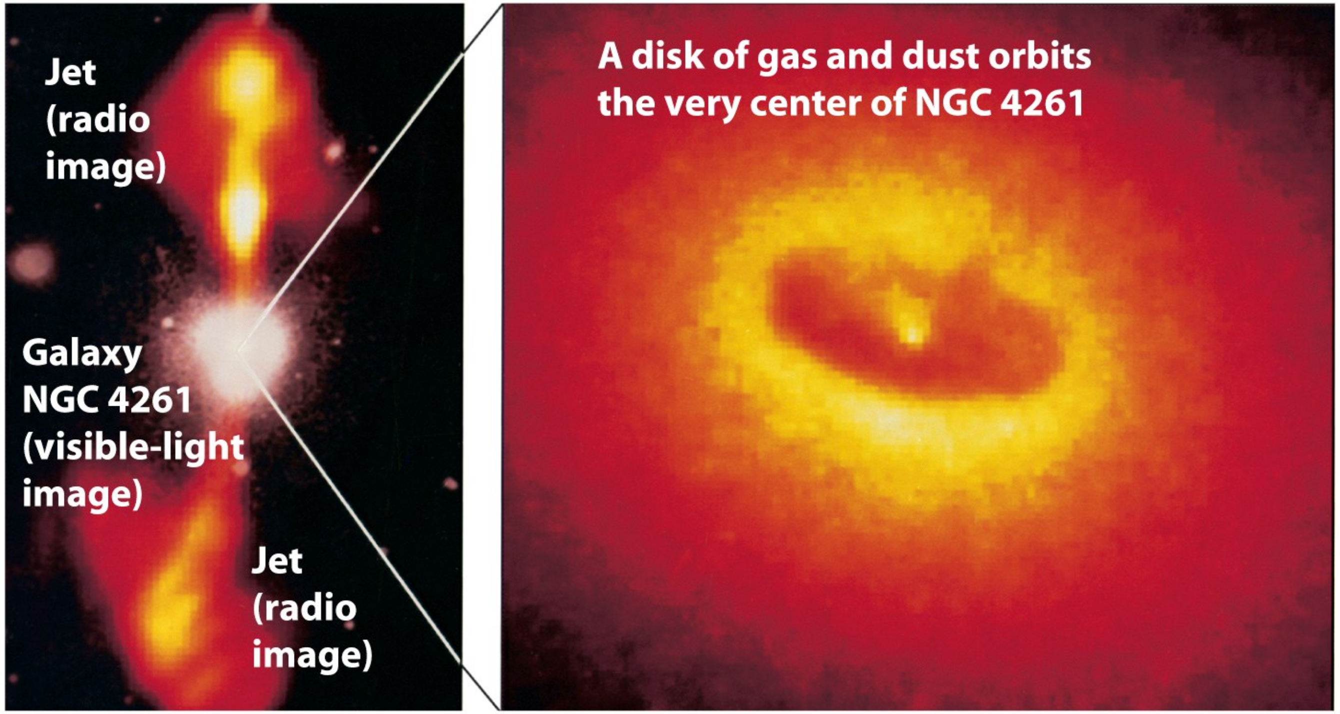
Stellar Black Hole



A schematic diagram of Cygnus X-1

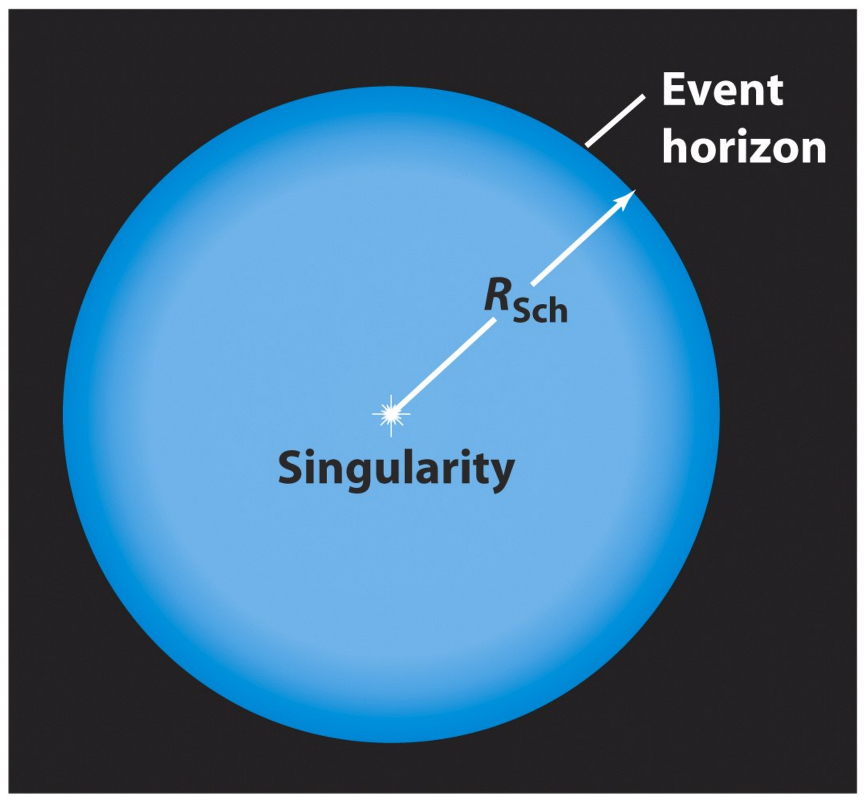
Supermassive Black Holes at the Centers of Galaxies

- Supermassive black holes, one million to one billion solar masses, exist at center of almost every galaxy
- These are detected by observing the motions of material around the black hole



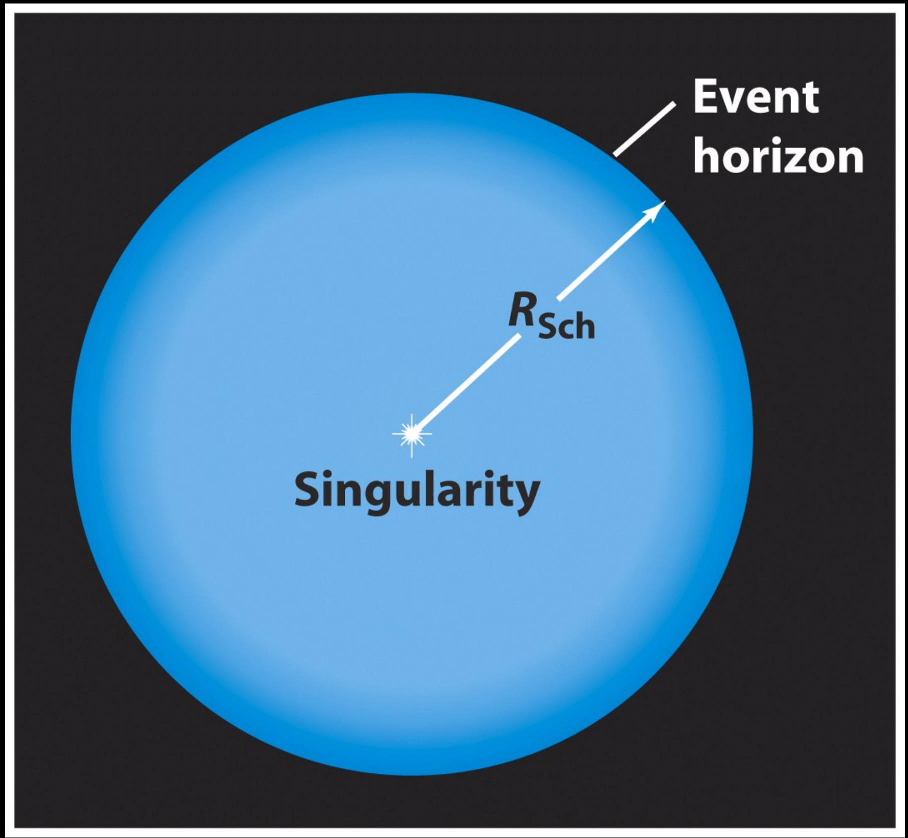
(a) Galaxy NGC 4261 **(b)** Evidence for a supermassive black hole in NGC 4261

Schwarzschild Radius



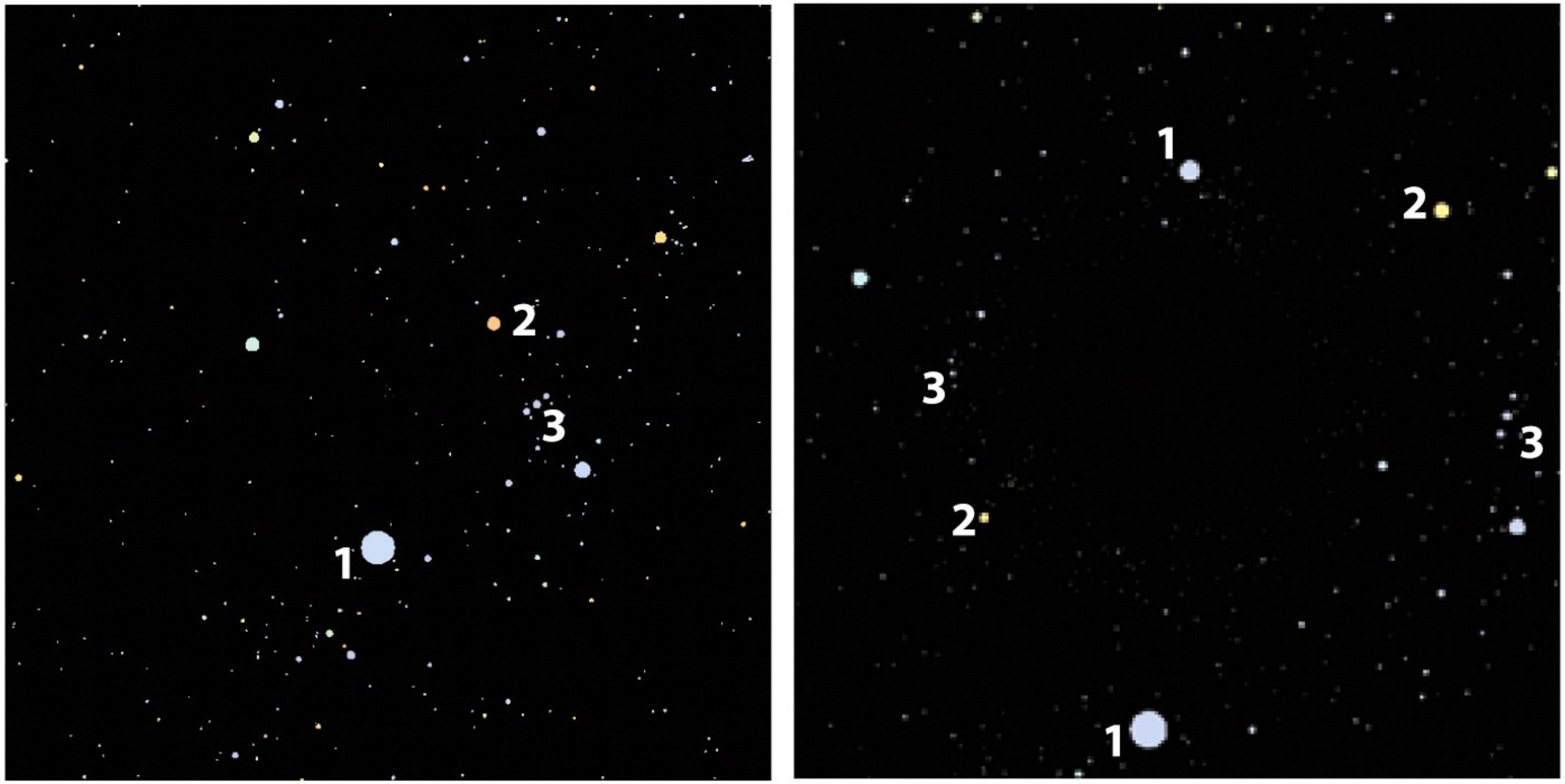
- Schwarzschild radius is the distance from the center to its event horizon
- It can be regarded as the "size" of a black hole
- For a black hole with 5 solar mass, the radius is 15 km

Singularity and Event Horizon



- The entire mass of a black hole is concentrated in an infinitely dense **singularity**
- The singularity is surrounded by a surface called the **event horizon**, where the escape speed just equals the speed of light
- Nothing—not even light—can escape from inside the event horizon

Black Hole Bends Light Causing Multiple Images

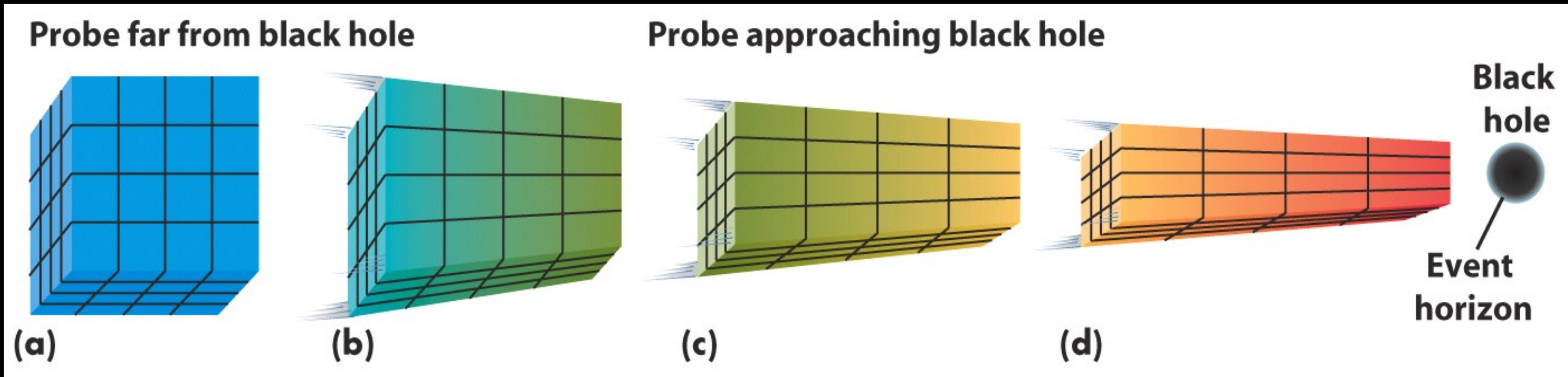


(a) Looking directly toward the black hole from a distance of 1000 Schwarzschild radii: Note positions of stars 1, 2, and 3.

(b) Looking directly toward the black hole from a distance of 10 Schwarzschild radii: Light bending causes multiple images.

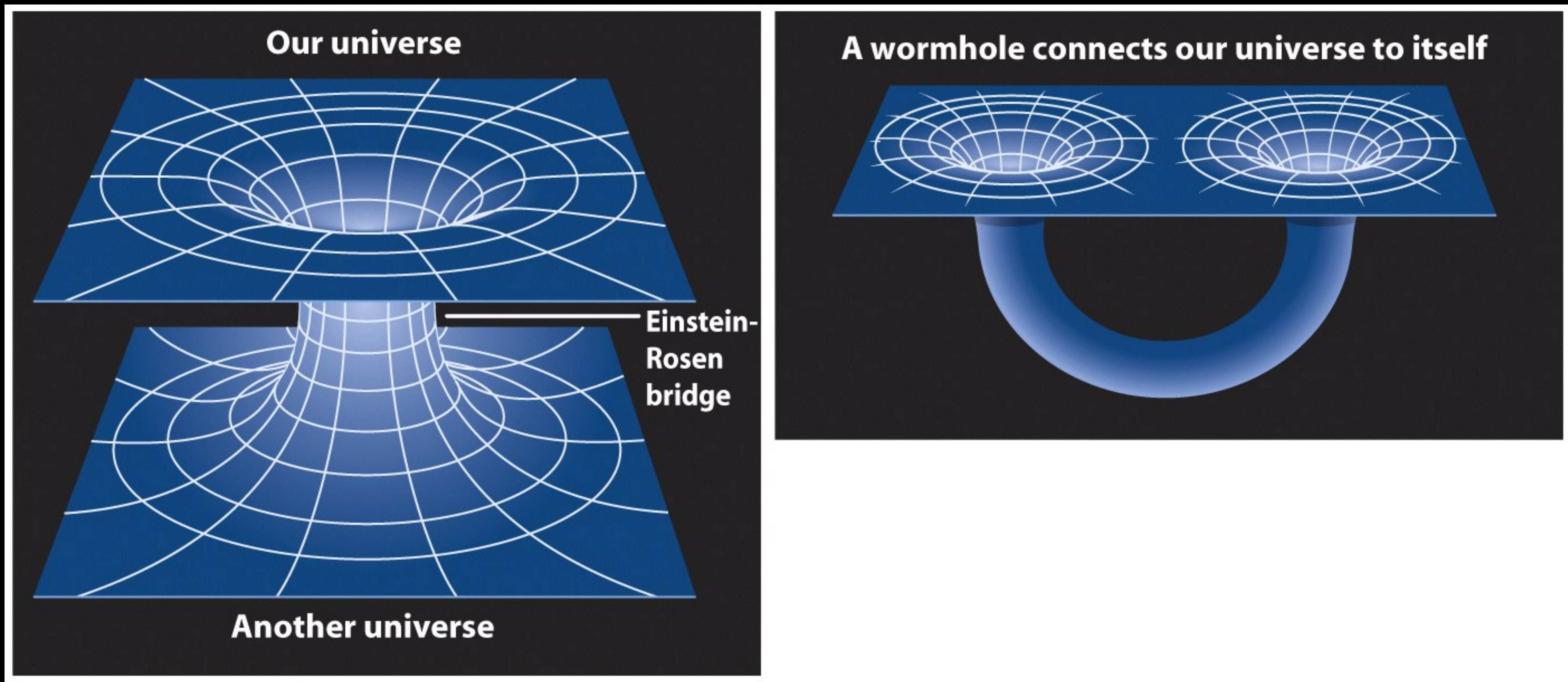
Falling into a black hole: an infinite voyage

- Stretched along the line pointing toward the hole due to the strong tidal force
- Gravitational red shift: blue color turns to red
- The probe appears to slow down, and takes an infinite time to reach the horizon because of the gravitational time dilation
- The probe will appear to remain suspended for eternity at the event horizon
- However, if you ride with the probe, it plunges right through the event horizon, and into the singularity



WormHole

- Could a black hole somehow be connected to another part of spacetime, or even some other universe?
- General relativity predicts that such connections, called wormholes, can exist for rotating black holes



Black holes evaporate