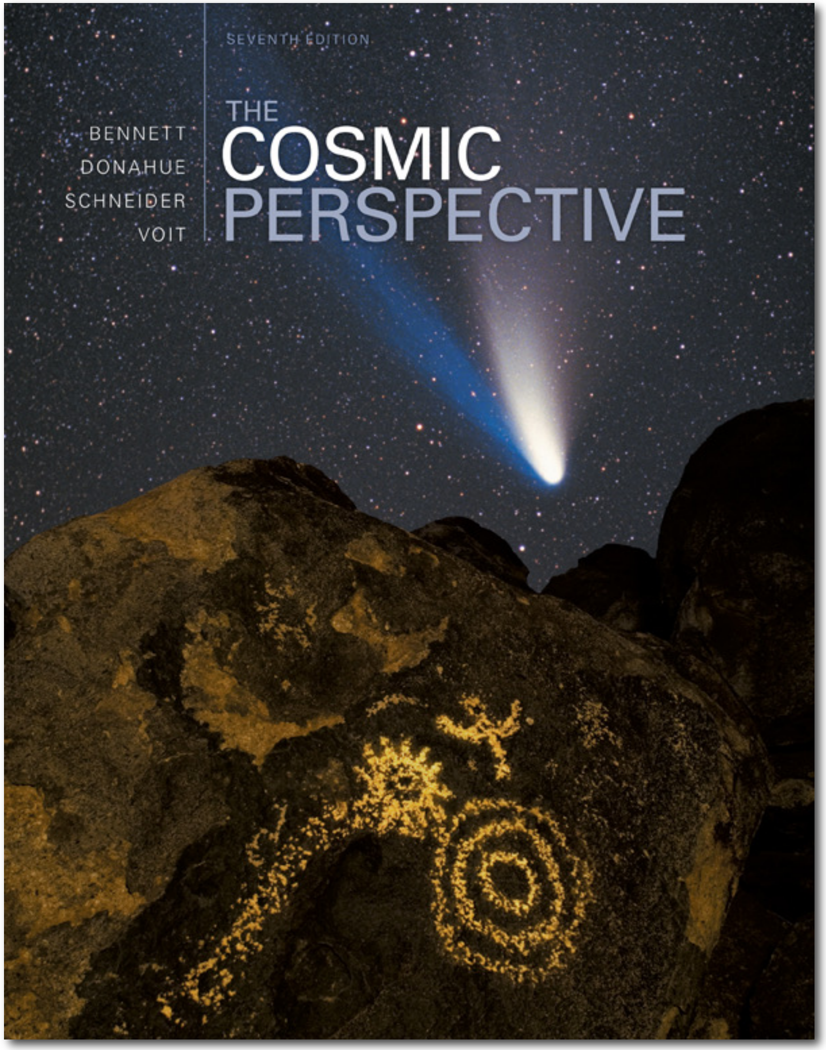
The Cosmic Perspective

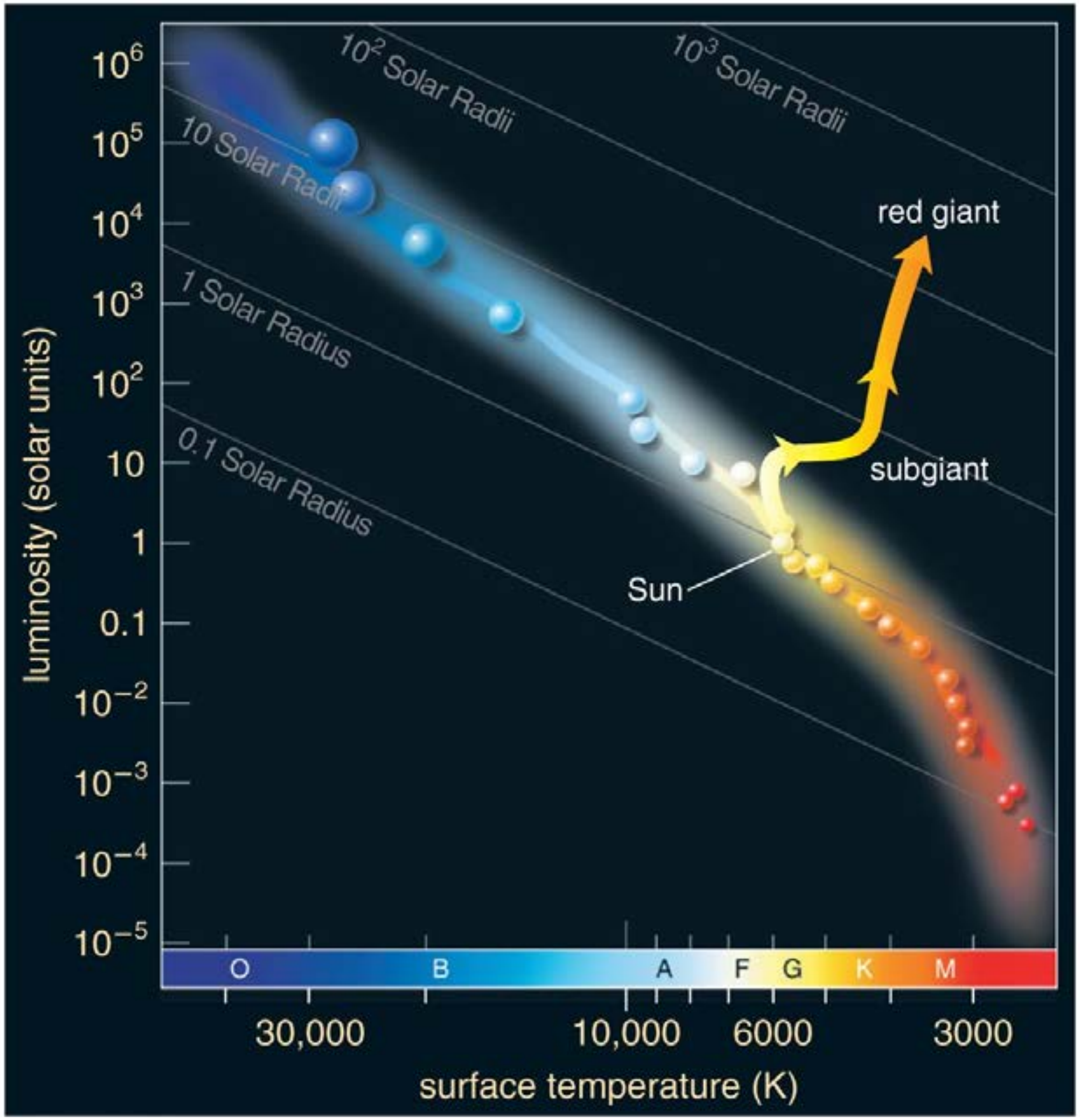


Star Stuff

17.1 Lives in the Balance

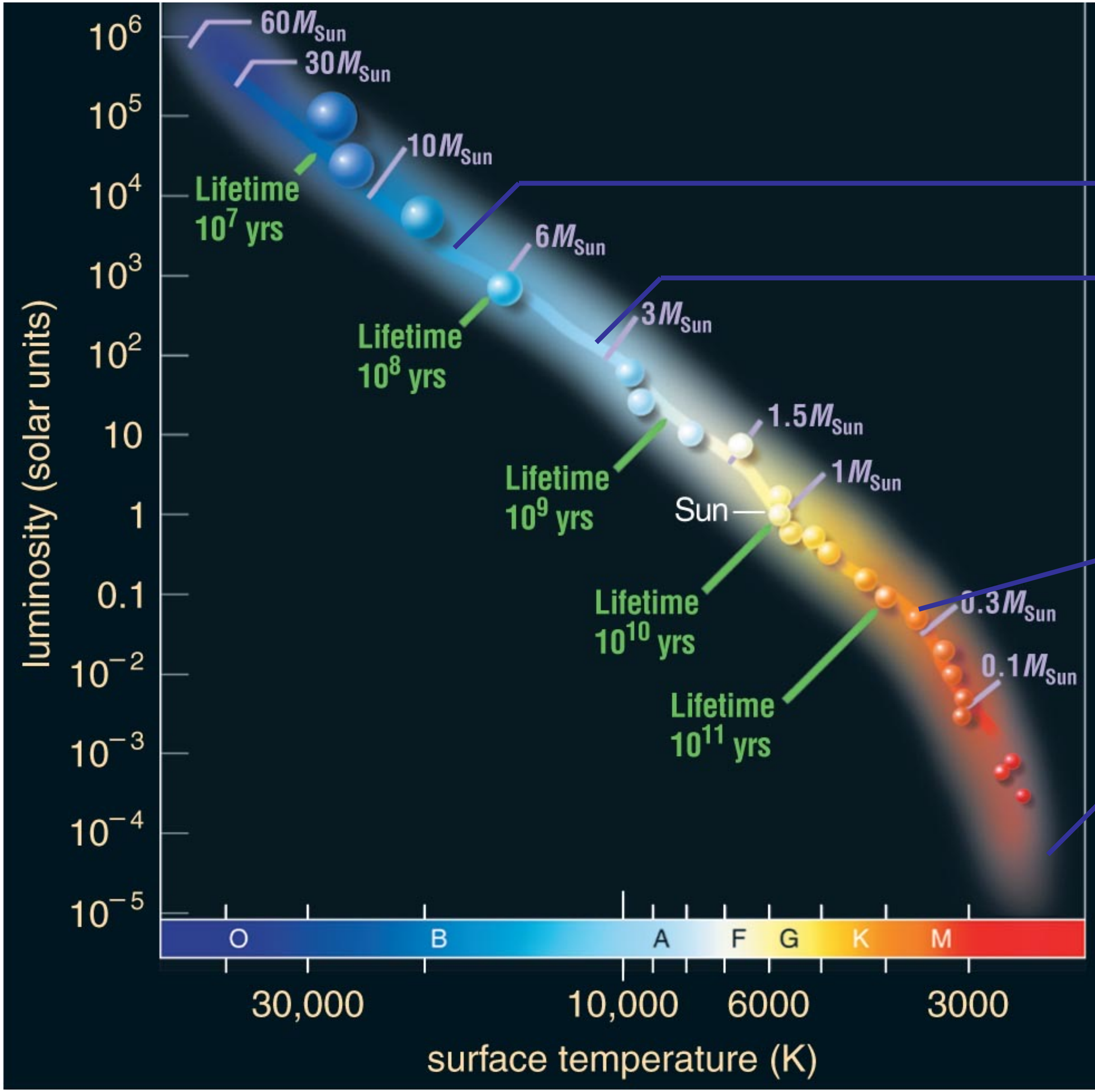
- Our goals for learning:
  - **How does a star's mass affect nuclear fusion?**

How does a star's mass affect nuclear fusion?



Stellar Mass and Fusion

- The **mass** of a main-sequence star **determines its core pressure and temperature**.
- **Stars of higher mass** have higher core temperature and more rapid fusion, making those stars both more luminous and **shorter-lived**.
- **Stars of lower mass** have cooler cores and slower fusion rates, giving them smaller luminosities and **longer lifetimes**.



High-Mass Stars

$> 8 M_{Sun}$

Intermediate-Mass Stars

Low-Mass Stars

$< 4 M_{Sun}$

Red Dwarfs

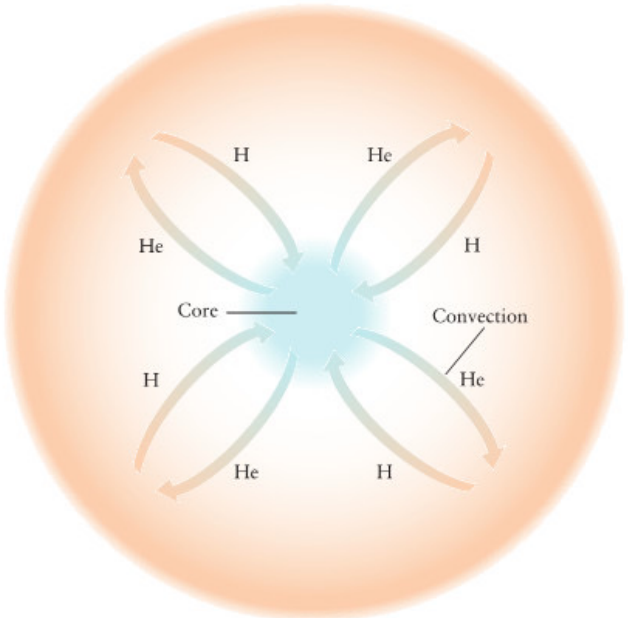
$0.08\ M_{Sun} < M < 0.4\ M_{Sun}$

Brown Dwarfs

Stellar Evolution: On and Off the Main Sequence

Case of $0.08\ M_{\odot} < M_{star} < 0.4\ M_{\odot}$

These stars are called **red dwarfs** because they are less massive than the sun and they are red in color due to their low temperature.



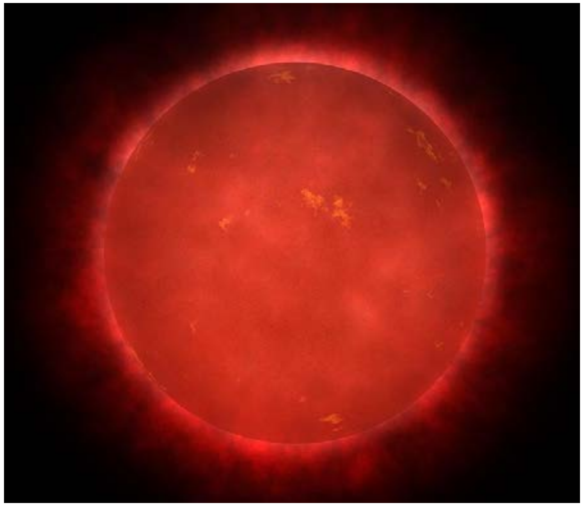
85% of the stars in the Milky Way are M class red dwarfs. **Energy in red dwarfs is transported by convection** from the core to the outer layers and therefore they do not build up He only in the core as do stars with > $0.4\ M_{\odot}$.

Stellar Evolution: On and Off the Main Sequence

Case: $0.08\ M_{\odot} < M_{star} < 0.4\ M_{\odot}$

Question: What happens when the H runs out?

Answer: In a red dwarf when the H runs out the temperature and density are not high enough to initiate fusion of He.



Artistic presentation of a red dwarf star.

After H fusion ends in a red dwarf it radiates its energy away, slowly cools and shrinks in size.

Calculations indicate that it takes ~ 100 billion years for a red dwarf to convert all of its H to He.

Stellar Evolution: On and Off the Main Sequence

Low Mass Stars: 4 $M_\odot$ > M_{star} > 0.4 $M_\odot$

Question: What happens when the H runs out?

Answer: When H runs out in the core **H fusion continues in a shell around the core.**

The **core** cannot support the material above it so it **begins to shrink** and is compressed from the weight of the outer layers. When the gas in the core becomes compressed, its temperature again begins to rise.

Stellar Evolution: On and Off the Main Sequence

Low Mass Stars: 4 $M_{\odot}$ > M_{star} > 0.4 $M_{\odot}$

Answer continued: The increase in core temperature increases the rate of H fusion reactions in the thin H shell that surrounds the core while there is no core H fusion.

Star Expands

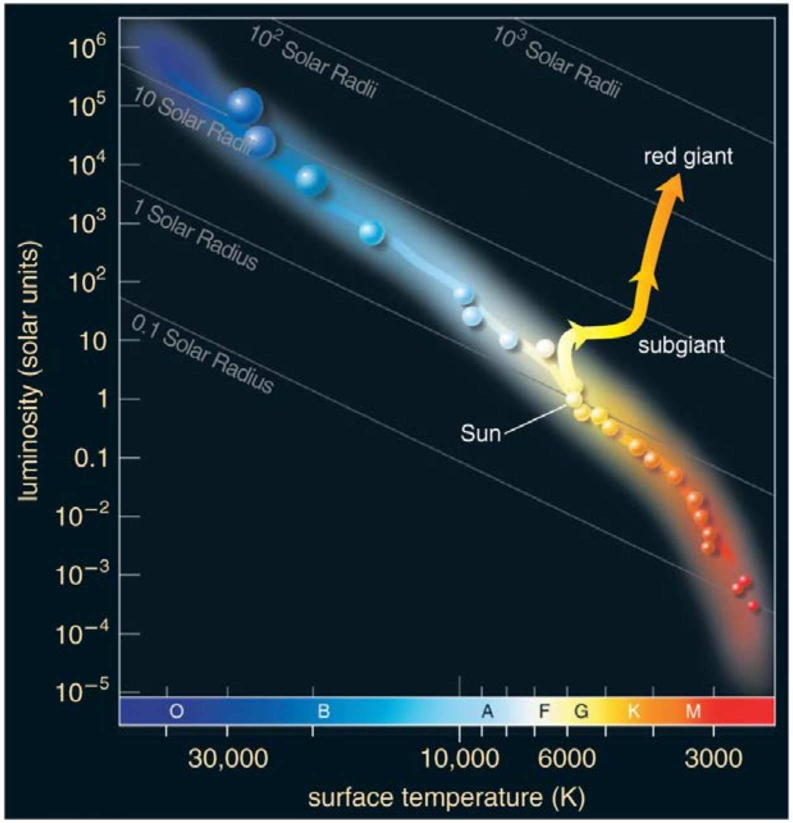
The outer layers expand by the increased luminosity of the H burning shell. As the external layers of gas expand the surface temperature of the star decreases.

When the temperature of the external layers drops to ~ 3,500 K the star appears reddish at which point is has become a **red giant**.

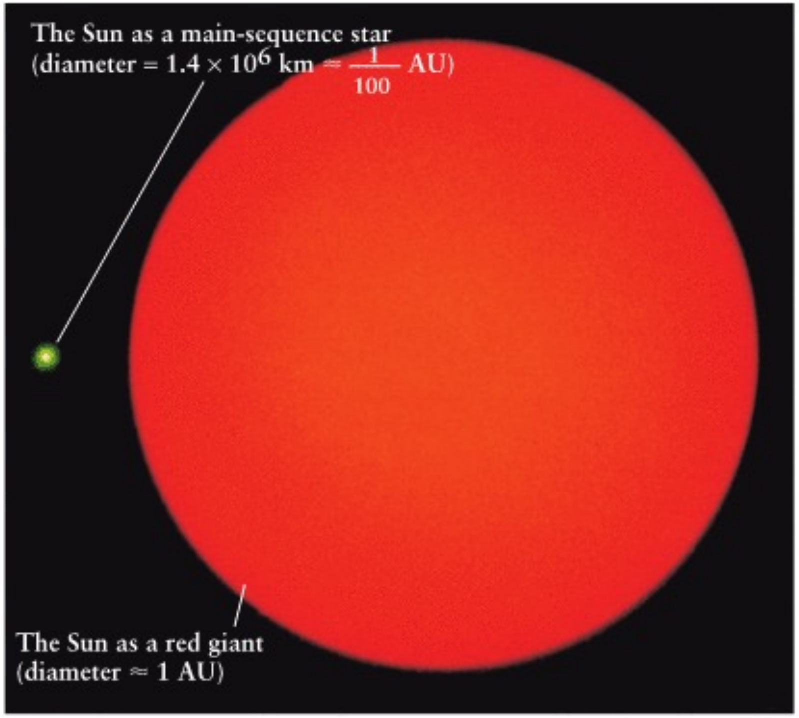
Stellar Evolution: On and Off the Main Sequence

Low Mass Stars: $4\ M_\odot > M_{star} > 0.4\ M_\odot$

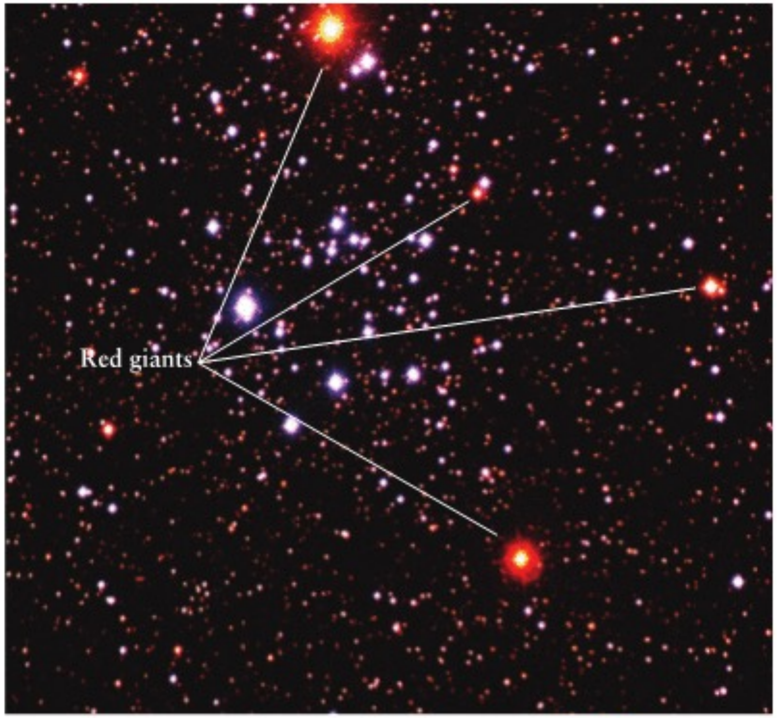
A star leaves the main sequence when hydrogen fusion ends in the core. The star becomes a red giant.



Stellar Evolution: On and Off the Main Sequence



(a) The Sun today and as a red giant



(b) Red giant stars in the star cluster M50 R I V U X G

When the sun becomes a red giant its diameter will increase from ~ 0.01 AU to ~1-2 AU.

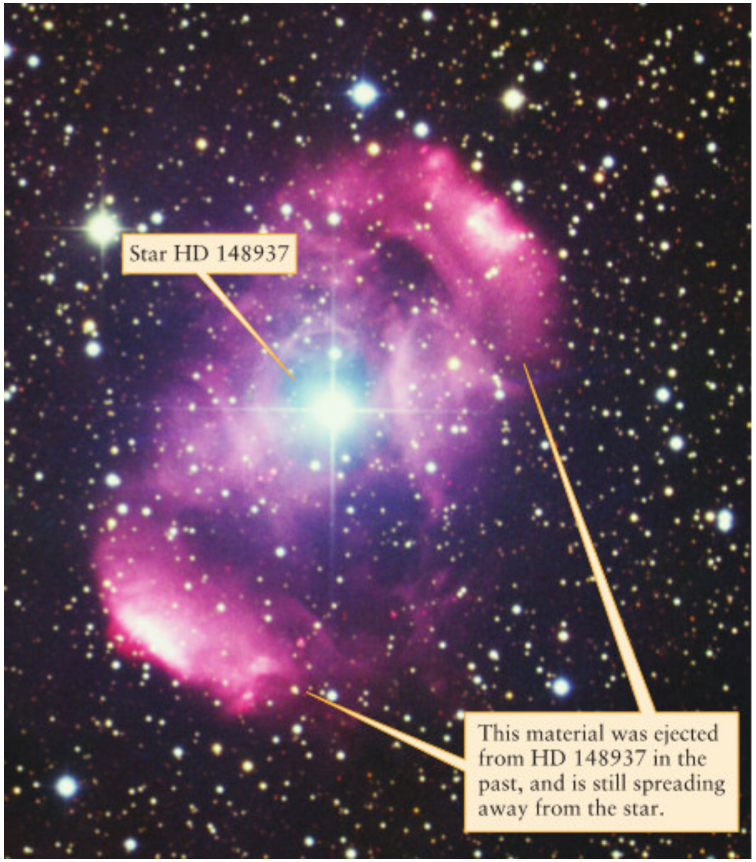
Stellar Evolution: On and Off the Main Sequence

Red giants lose a substantial amount of gas from the outer layers.

The reason for this is that the outer layers have expanded far from the center and since *force* is proportional to $1/R^2$ the force keeping the gas bound is substantially weaker.

Mass loss from red giants is detected from blue-shifted emission lines that imply wind velocities of 10 km/s.

A red giant may lose ~ $10^{-7}\ M_{\odot}$ per year (the sun loses $\sim 10^{-14}\ M_{\odot}$ per year).



Winds from red giant HD 148937

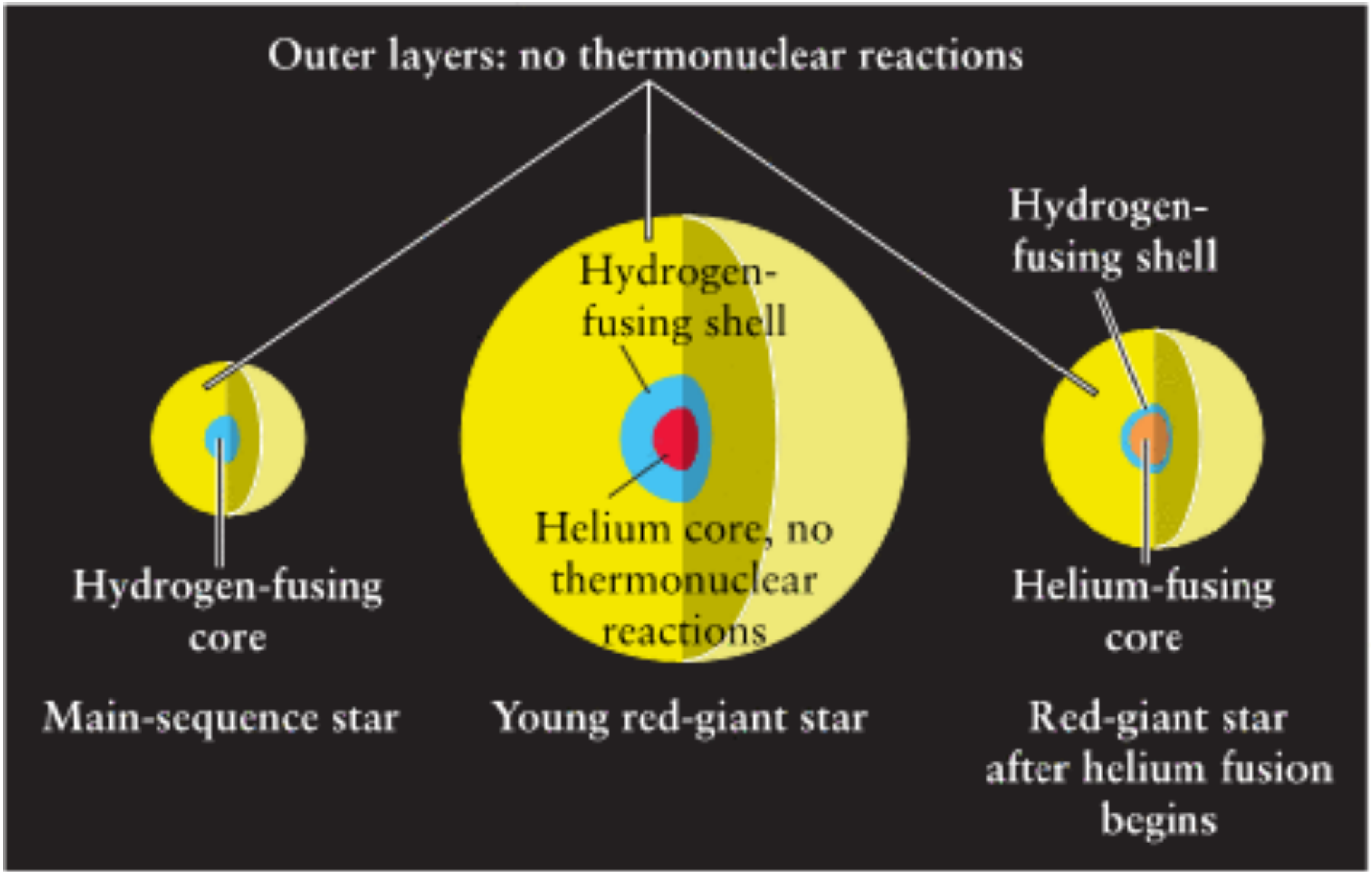
The Sun's Fate

While still on the main sequence the Sun's luminosity will continue to increase. In about 3.5 billion years the average temperature on Earth will be > 100 °C and the water on the surface will boil away.

H fusion reactions in the core are expected to cease in about 7.5 billion years from now!

At about ~7.7 billion years from now the Sun will have expanded to a diameter of about 2 AU.

Stellar Evolution: On and Off the Main Sequence



Thought Question

What happens when a star can no longer fuse hydrogen to helium in its core?

A. The core cools off.
B. The core shrinks and heats up.
C. The core expands and heats up.
D. Helium fusion immediately begins.

Thought Question

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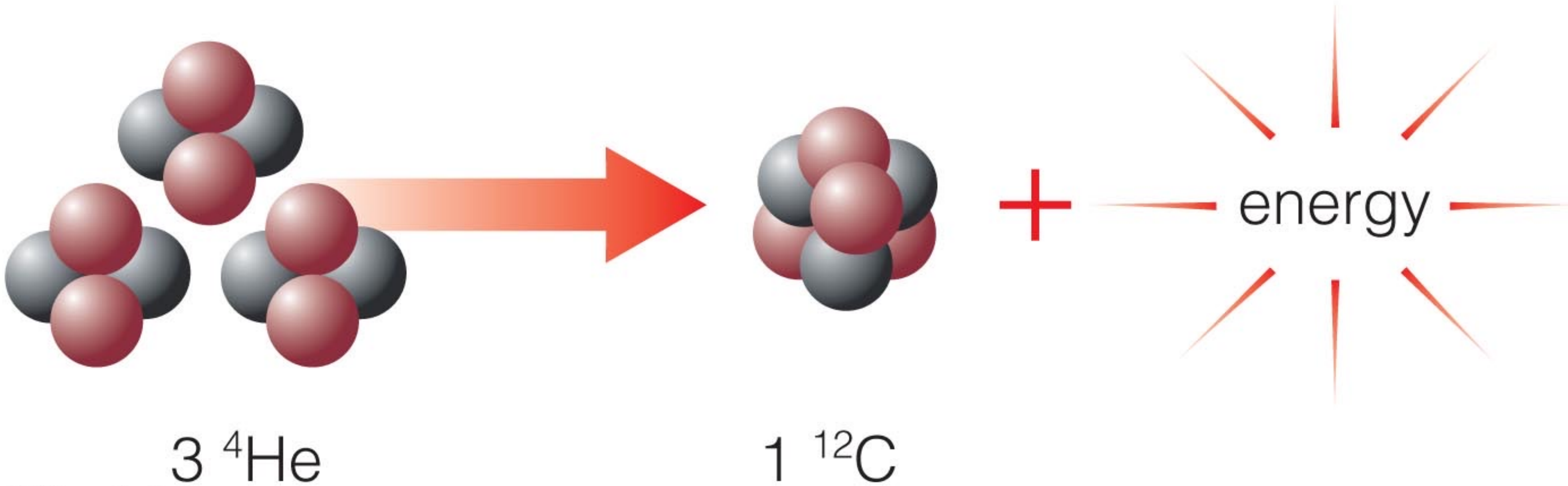
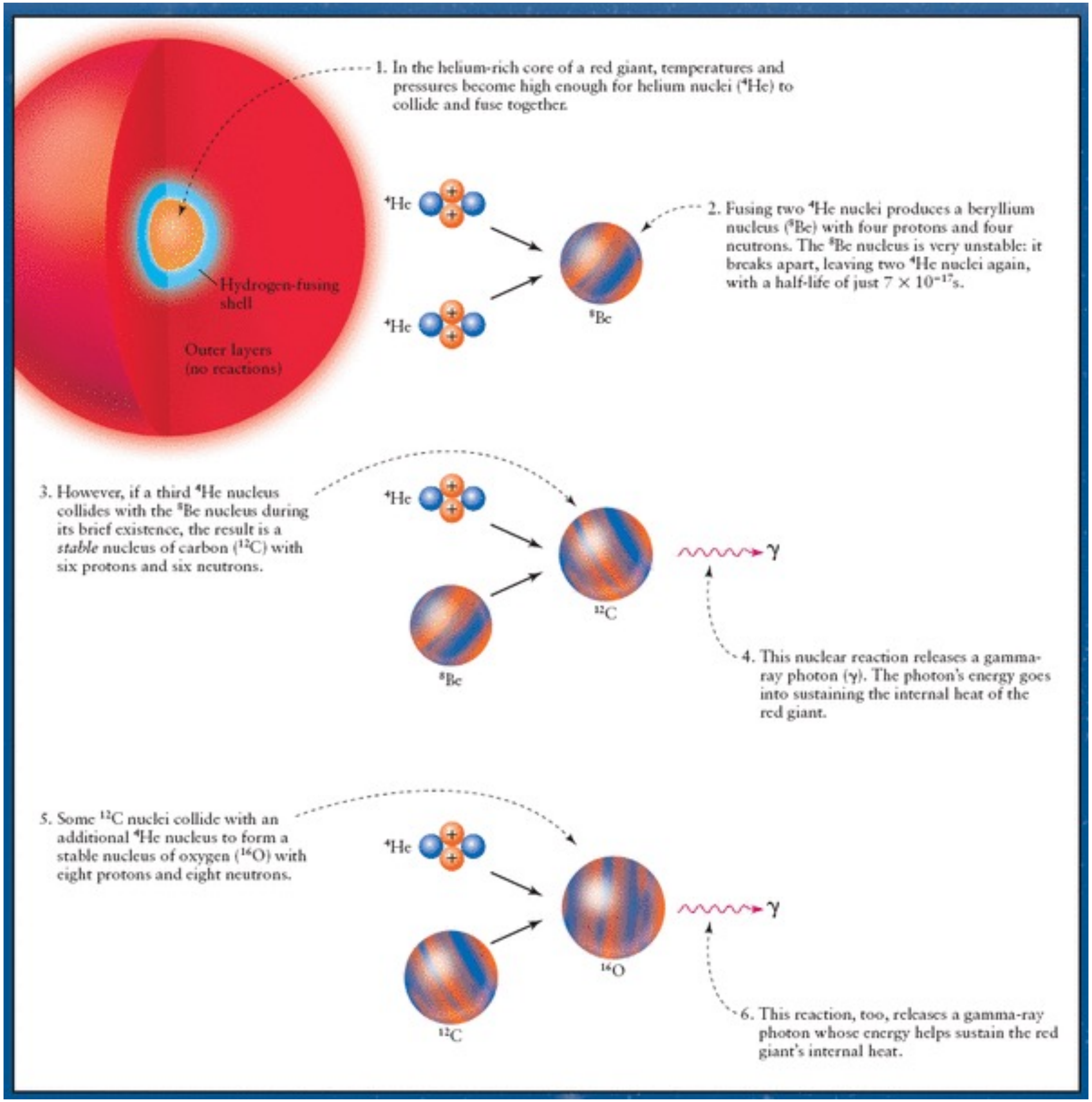


- Helium fusion does not begin right away because it requires higher temperatures (~ 100 million K) than hydrogen fusion (~10 million K)—**larger charge leads to greater repulsion.**

- Fusion of two helium nuclei doesn't work, so helium fusion must combine three helium nuclei to make carbon.

Core Helium Fusion: The Triple Alpha Process



Core He Fusion

The way He fusion begins in the core of a star depends on its mass.

for $0.4\ M_{\odot} < M_{star} < 2\text{-}3\ M_{\odot}$ Helium flash

$M_{star} > 2\text{-}3\ M_{\odot}$ we have gradual ignition of He

Safety Valve in Stars

In most cases the gases of a star obey the following law: **When the gas expands the temperature goes down.**

When the rate of fusion reactions increases, the outward radiation pressure also increases and expands the core. This expansion results in a decrease in temperature and the reaction rate goes down. This provides a **safety valve** for the star that keeps the reaction rate roughly constant.

Conversely, a decrease in the reaction rate causes a compression of the gas resulting in an increase of the core temperature and the reaction rate goes up.

DEGENERACY PRESSURE

Closely packed electrons resist compression.

The pressure of the electrons resisting compression is called degeneracy pressure.

In a red giant with $0.4\ M_{\odot} < M_{star} < 2\text{-}3M_{\odot}$ the core must be compressed tremendously in order to become hot enough for helium fusion to begin.

Electron degeneracy pressure prevents a low mass red giant from compressing any further.

Wolfgang Pauli

Helium Flash

Helium flash is the sudden beginning of helium fusion in the core of stars of less than about 2.25 solar masses. The core is held up mostly by degeneracy pressure.

The cores of 0.4 M_{solar} < M_{star} < 2-3 M_{solar} red giant stars are degenerate. A helium flash occurs when fusion begins in a degenerate gas.

The cores of M_{star} > 2-3 M_{solar} red giant stars are not degenerate. In these stars He fusion begins gradually with no flash.

Thought Question

What happens in a low-mass star ($\mathbf{0.4\ M_{solar} < M_{star} < 2\text{-}3\ M_{solar}}$) when the core temperature rises enough for helium fusion to begin?

A. Helium fusion slowly starts.

B. Hydrogen fusion stops.

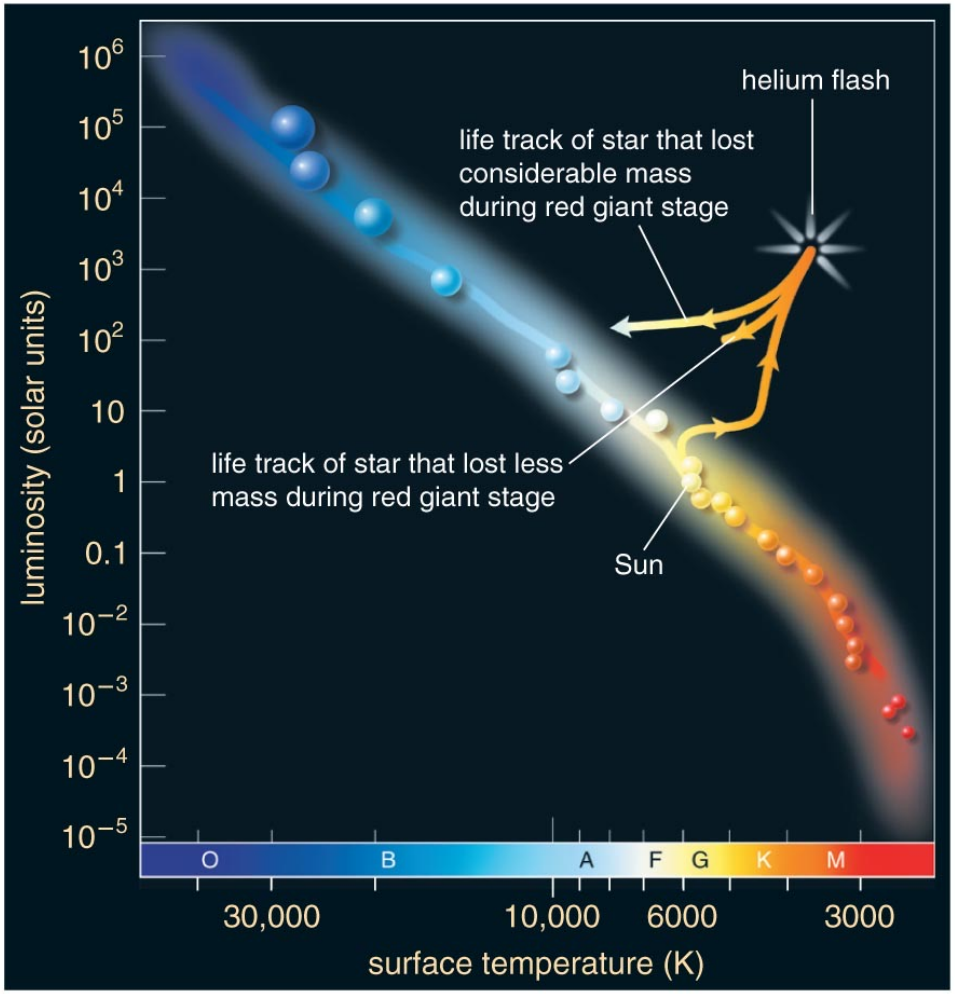
C. Helium fusion rises very sharply producing a flash.

Thought Question

What happens in a low-mass star (**0.4 M_{solar} < M_{star} < 2-3 M_{solar}**) when the core temperature rises enough for helium fusion to begin?

A. Helium fusion slowly starts.
B. Hydrogen fusion stops.
C. Helium fusion rises very sharply producing a flash.

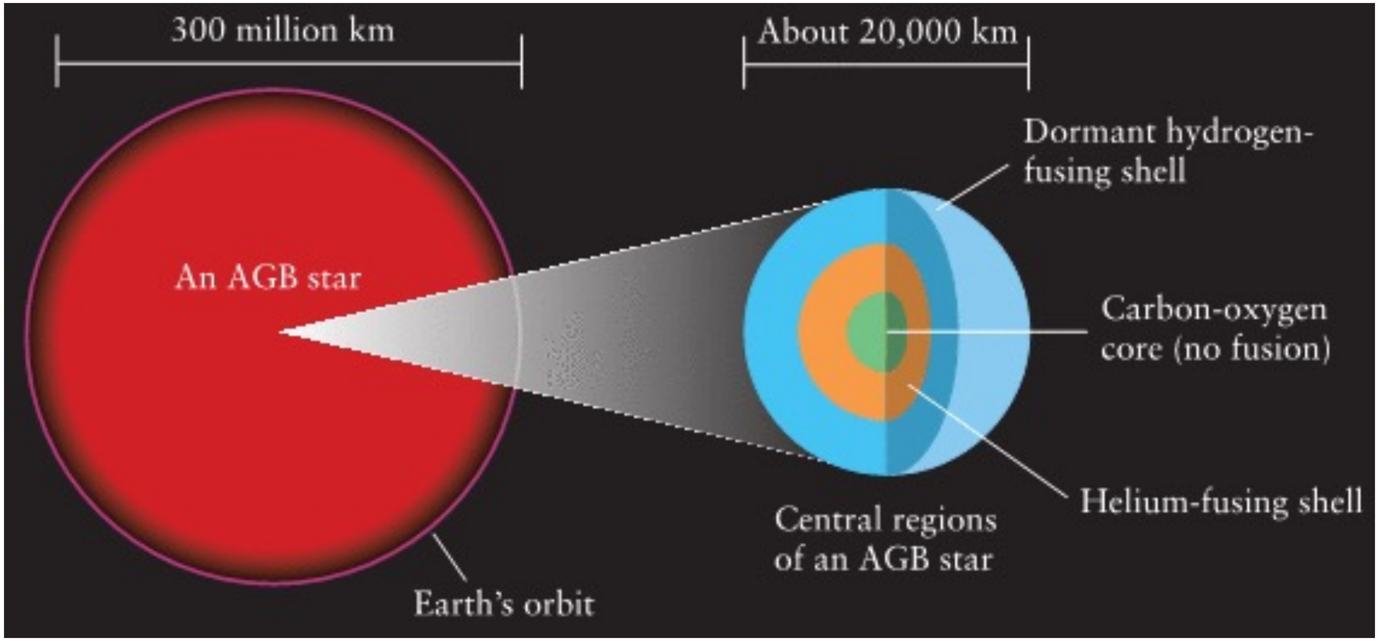
Life Track after Helium Flash



a Helium fusion begins with the helium flash, after which the star's surface shrinks and heats, making the star's life track move downward and to the left on the H-R diagram.

- Models show that a red giant should shrink and become less luminous after helium fusion begins in the core.
- During helium fusion in the core the star lies on the horizontal branch

The Death of Low Mass Stars



He fusion produces O and C in the core. In a 1 $M_\odot$ star He fusion will last for about 10^8 years.

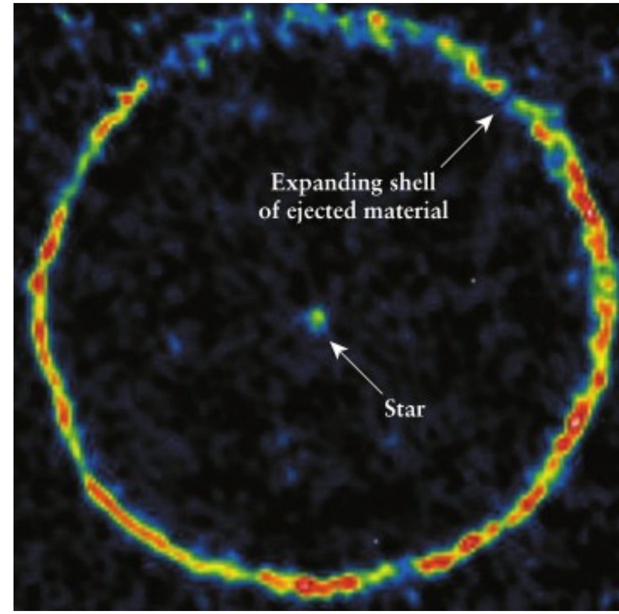
When He runs out, the core will collapse again resulting in an increase in the core temperature (T). This increase in T results in an increase in the reaction rate in the He shell that leads to the expansion of the outer layers for a second time. The resulting star is called an **asymptotic giant branch (AGB) star.**

The Death of Low Mass Stars

The convection zone can grow significantly during the AGB phase of a $M < 4M_\odot$ star.

This broadening of the convection zone **drudges-up heavier elements** (ie. C, N and O) from the core to the surface.

The **drudged-up carbon** produces strong absorption lines in the spectra of some AGB stars. These are called **carbon stars**.



Carbon AGB star TT Cygni showing radio emission from CO in the ejected shell. AGB stars have very powerful winds with outflow rates of 10^{-4} $M_\odot$ per year. A red giant's outflow is ~10^{-7} $M_\odot$ per year and the sun's is ~ 10^{-14} $M_\odot$ per year.

Thought Question

What happens when the star's core runs out of helium?

A. The star explodes.
B. Carbon fusion begins.
C. The core cools off.
D. Helium fuses in a shell around the core.

Thought Question

What happens when the star's core runs out of helium?

A. The star explodes.
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D. Helium fuses in a shell around the core.

Planetary Nebulae

a Helix Nebula. The central white dot is the hot white dwarf.

b The Butterfly Nebula. The hot white dwarf is hidden in the dark ring of dust at the center.

- Double shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*.
- The core left behind becomes a white dwarf.

How does a low-mass star die?

The Helix Nebula, is a large planetary nebula. The estimated distance is about 700 light-years. Its age is estimated to be about 10,000 years.

This observation of the Helix Nebula was made with the College of Charleston 24 inch CDK PlaneWave telescope

Observers: CofC Students: Lucy Williamson and Dereck Morgado, CofC Faculty: Dr. Ashley Pagnotta and Dr. George Chartas.

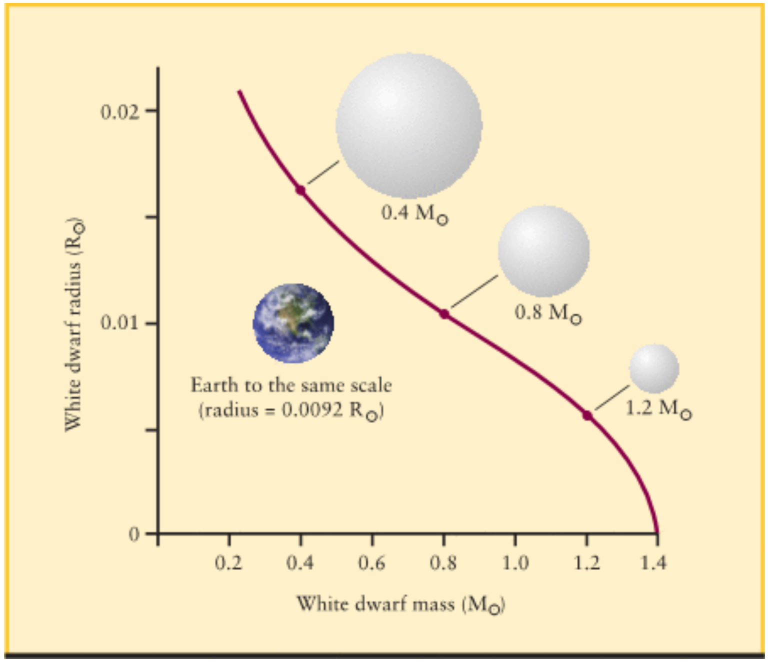
White Dwarfs

One unusual property of white dwarfs is **the larger the mass the smaller the radius**.

There is a limit however as to how much mass a white dwarf can have. Above this limit degeneracy pressure cannot overcome gravity. **The upper limit is 1.4 $M_\odot$** and was first derived by Indian astronomer *Chandrasekhar*.

When a white dwarf is initially formed it consists of ionized carbon and oxygen atoms floating in a sea of degenerate electrons.
As the white dwarf cools the motion of the C and O reduces to the point where the atoms form a **crystal lattice.**

A cool carbon-oxygen white dwarf resembles a huge diamond.



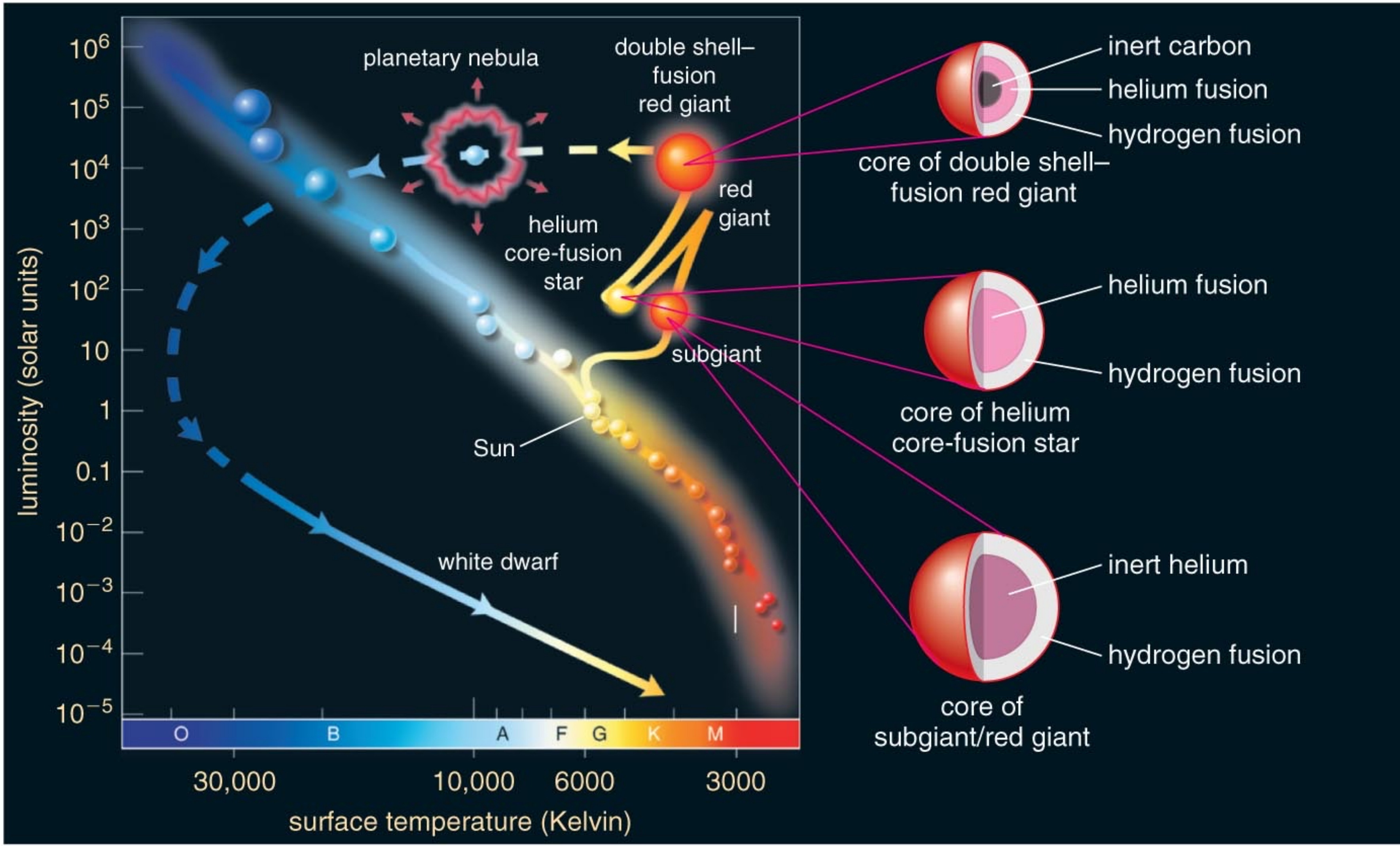
The mass-radius relation for a white dwarf. The maximum mass of a white dwarf, called the *Chandrasekhar limit*, is 1.4 $M_\odot$.

End of Fusion

- Fusion progresses no further in a low-mass star because the core temperature never grows hot enough for fusion of heavier elements.

- **Degeneracy pressure supports the white dwarf against gravity.**

Life Track of a Sun-like Star



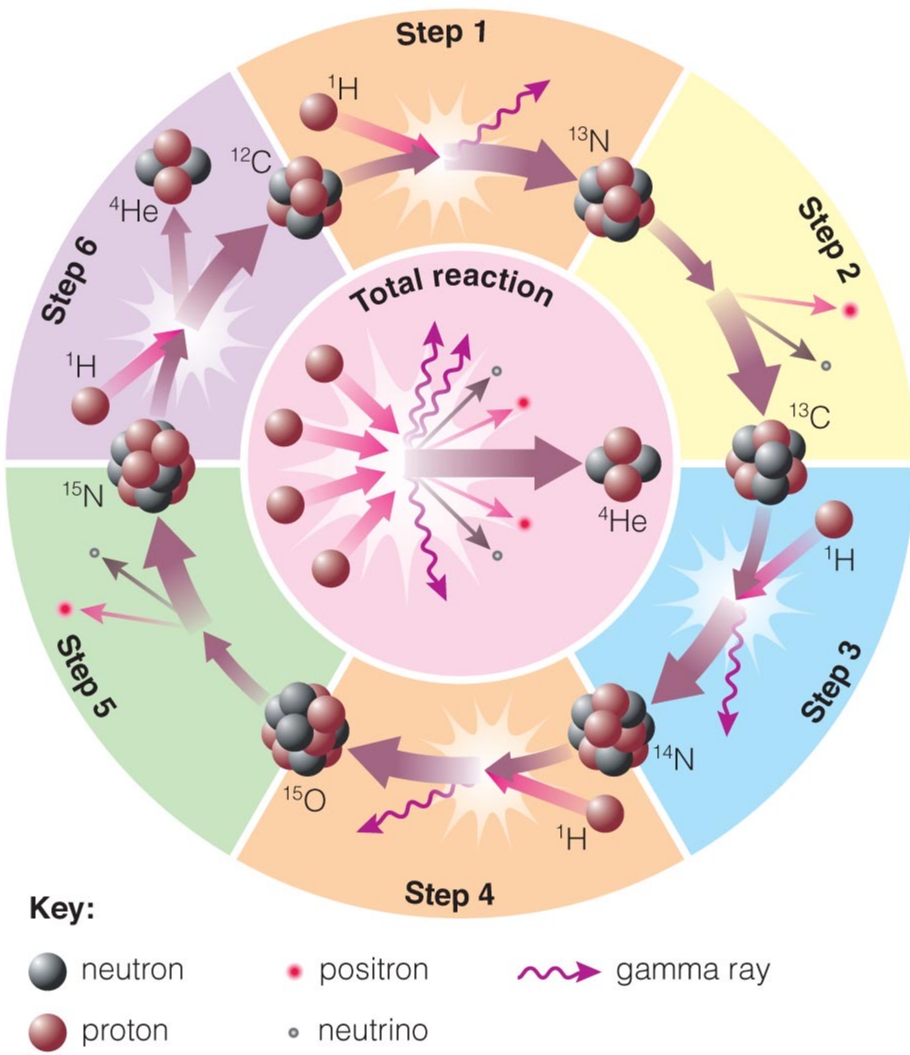
What have we learned?

- **What are the life stages of a low-mass star?**
  - Hydrogen fusion in core (main sequence)
  - Hydrogen fusion in shell around contracting core (red giant)
  - Helium fusion in core (horizontal branch)
  - Double shell burning (AGB red giant)
- **How does a low-mass star die?**
  - Ejection of hydrogen and helium in a planetary nebula leaves behind an inert white dwarf.

17.3 Life as a High-Mass Star

- Our goals for learning:
  - **What are the life stages of a high-mass star?**
  - **How do high-mass stars make the elements necessary for life?**
  - **How does a high-mass star die?**

CNO Cycle



- High-mass main-sequence stars (M > 8M$_\odot$) fuse H to He at a higher rate using carbon, nitrogen, and oxygen as **catalysts**.
- Greater core temperature enables hydrogen nuclei to overcome greater repulsion.

Life Stages of High-Mass Stars

- Life stages of high-mass stars are similar to those of low-mass stars:
  - Hydrogen core fusion (main sequence)
  - Hydrogen shell burning (supergiant)
  - Helium core fusion (horizontal branch)

Life Stages of High-Mass Stars

The reason why high densities and temperatures are required to fuse elements heavier than He is that **heavy nuclei have large charges and therefore large electric forces** that tend to keep the nuclei apart.

When a star with initial mass **$M > 8M_\odot$ runs out of He** in its core, the core begins to contract, and the outer layers of the star expand.

Because the mass of the core of **a star with $M > 8M_\odot$** is more than the *Chandrasekhar limit* of 1.4 $M_\odot$, **degeneracy pressure cannot prevent the collapse of the star**. The temperature continues to rise and when it reaches 600 million K carbon fusion begins.

Stellar Evolution of Massive Stars

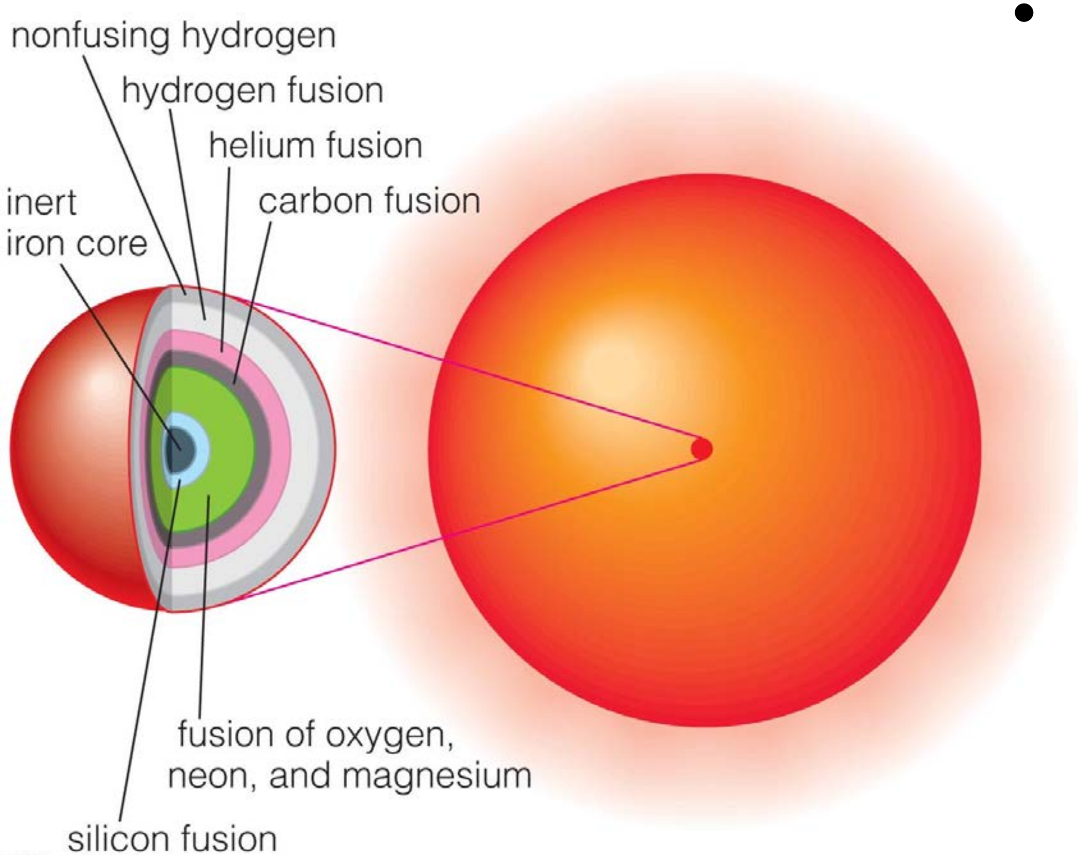
Carbon fusion: $T_{Fusion} = 600 \times 10^6$ K
Products = oxygen (O), neon (Ne), sodium (Na), magnesium (Mg)

If the star has $M > 8M_\odot$ additional reactions can occur:
Neon fusion: $T_{Fusion} = 10^9$ K
Products = oxygen (O), magnesium (Mg)

Oxygen fusion: $T_{Fusion} = 1.5 \times 10^9$ K
Product = silicon (Si), magnesium (Mg), phosphorus (P), sulfur(S)

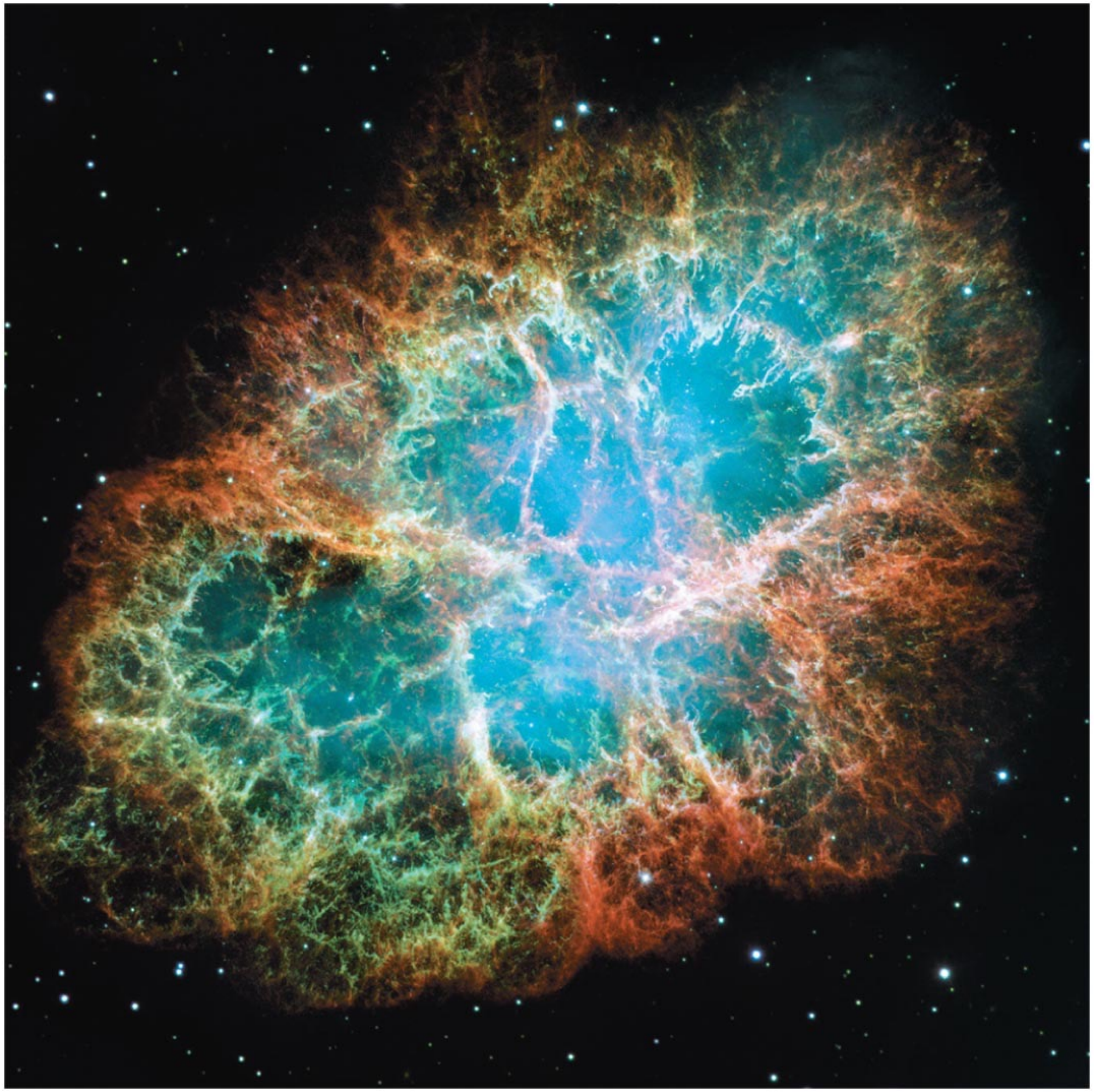
Silicon fusion: $T_{Fusion} = 2.7 \times 10^9$ K
Products = Sulfur (S), Iron (Fe), Nickel (Ni)

Multiple Shell Burning



- Advanced nuclear burning proceeds in a series of nested shells.

How does a high-mass star die?

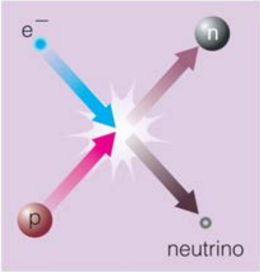


Core Collapse

Core Collapse: A massive star with $M > 8M_\odot$ will eventually reach the point of fusing Si into Fe. **Fusion of Fe does not produce energy** so the core cannot generate heat from fusion but instead begins to collapse and heat up.

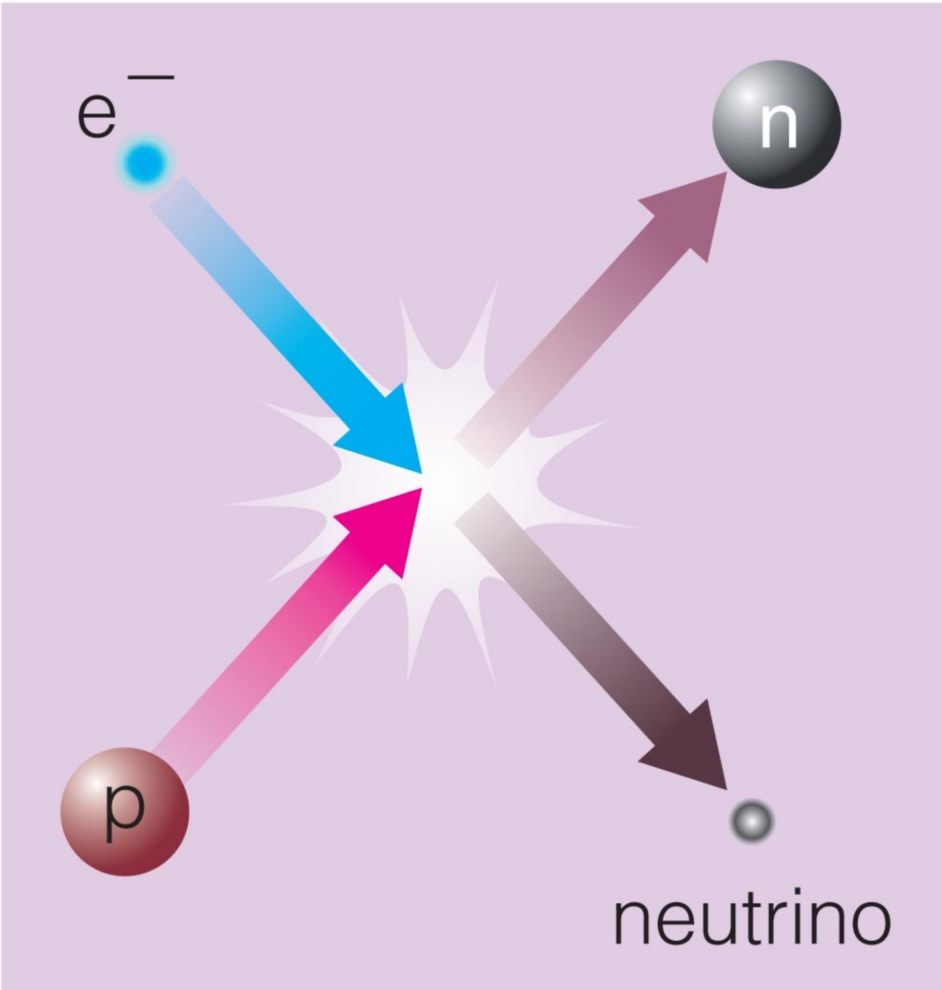
• Because of the high density, electrons combine with protons to form neutrons (**n**) and neutrinos (***ν***):

$$\mathbf{e^- + p^+ \rightarrow n + \nu}$$



• The **escape of the neutrinos cools down the core** and leads to more compression. Seconds after the contraction began the density reaches the nuclear density value of $\sim 4 \times 10^{17}$kg m^{-3}.

Core Collapse



- **Electron degeneracy** pressure goes away because electrons combine with protons, making neutrons and neutrinos.
- Neutrons collapse to the center, forming a **neutron star.**

Core Bounce

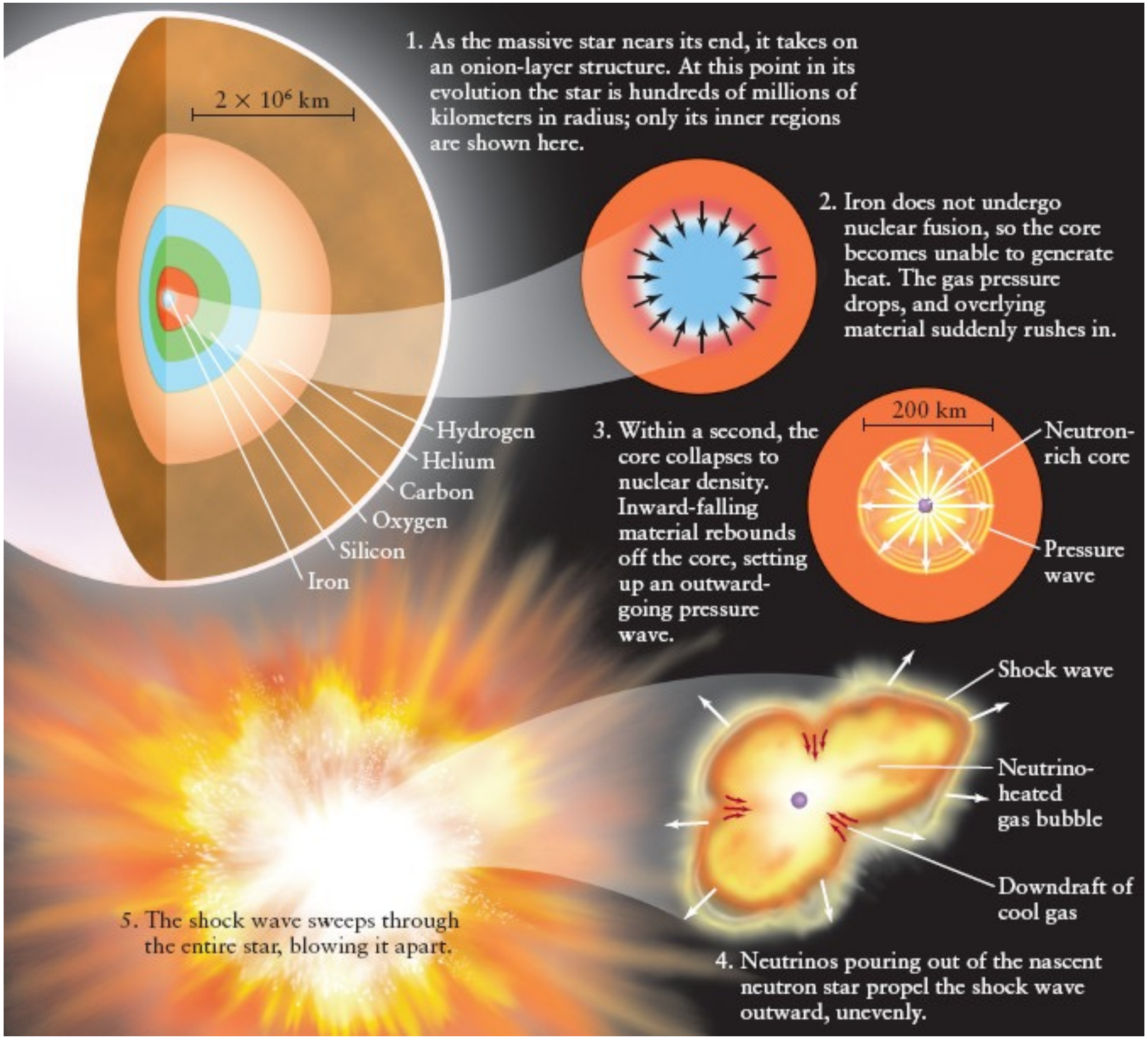
Core Bounce:

The **strong nuclear force and neutron degeneracy pressure** prevent the core from collapsing any more.

Further compression results in the innermost part of the **core bouncing back and sending out a pressure wave**.

It takes a few hours for the **shock wave** to reach the surface and **lift away the outer layers of the star**.

Supernova Explosions



Energetics

The **energy released as radiation in a core-collapse supernova explosion is ~ 10^{44} Joules** and comes from gravitational energy released by the collapse of the core and the infall of the outer layers of the star.

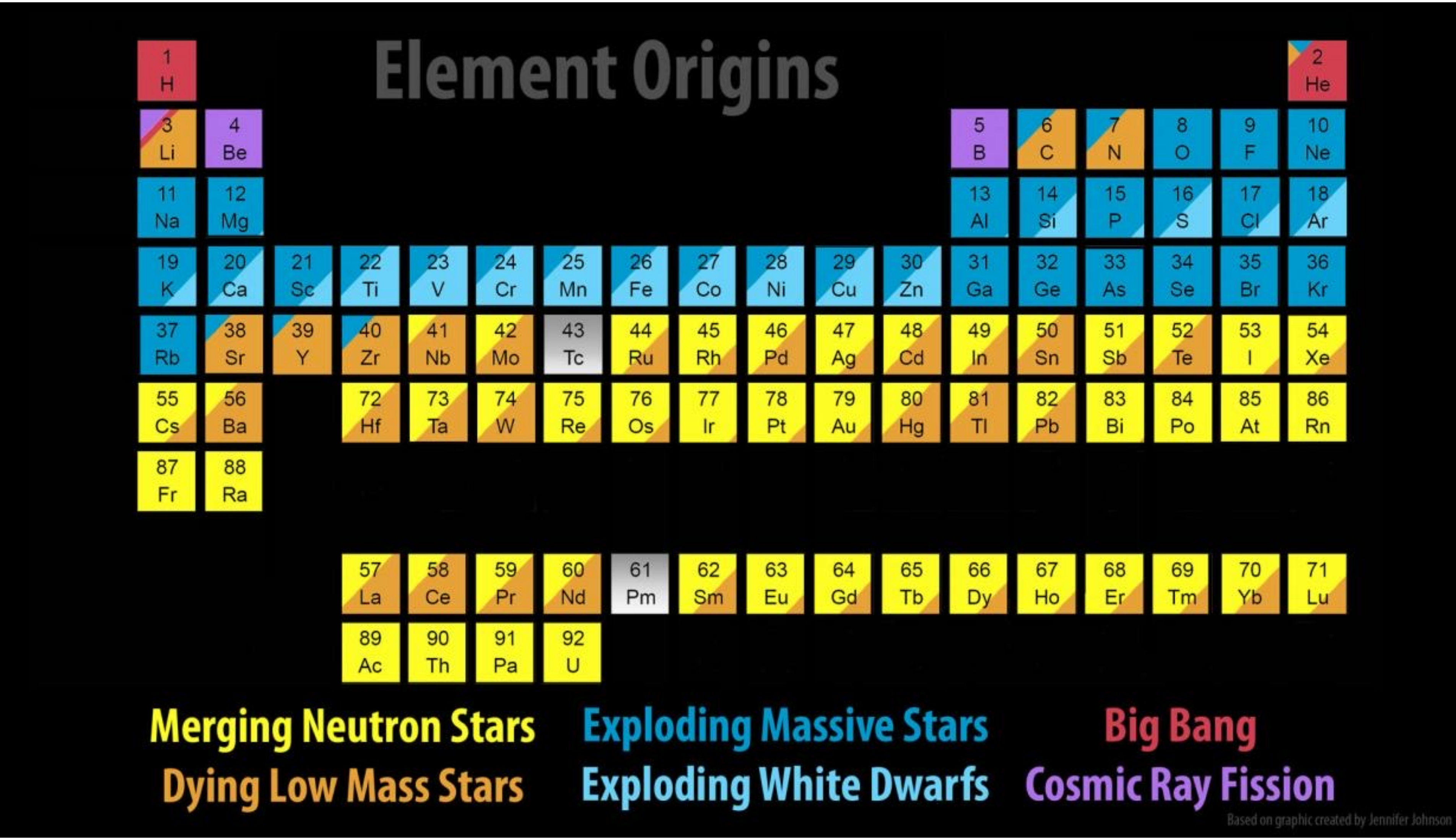
Our sun's power output is 3.8×10^{26} Joules per sec.
The sun will release about **10^{44} Joules** over its lifetime, which is close to the energy released in a single supernova explosion in the form of radiation.

The energy released in the form of neutrinos is about 100 times larger than the energy released in radiation.

Heavy Elements Produced During Supernova Exposions

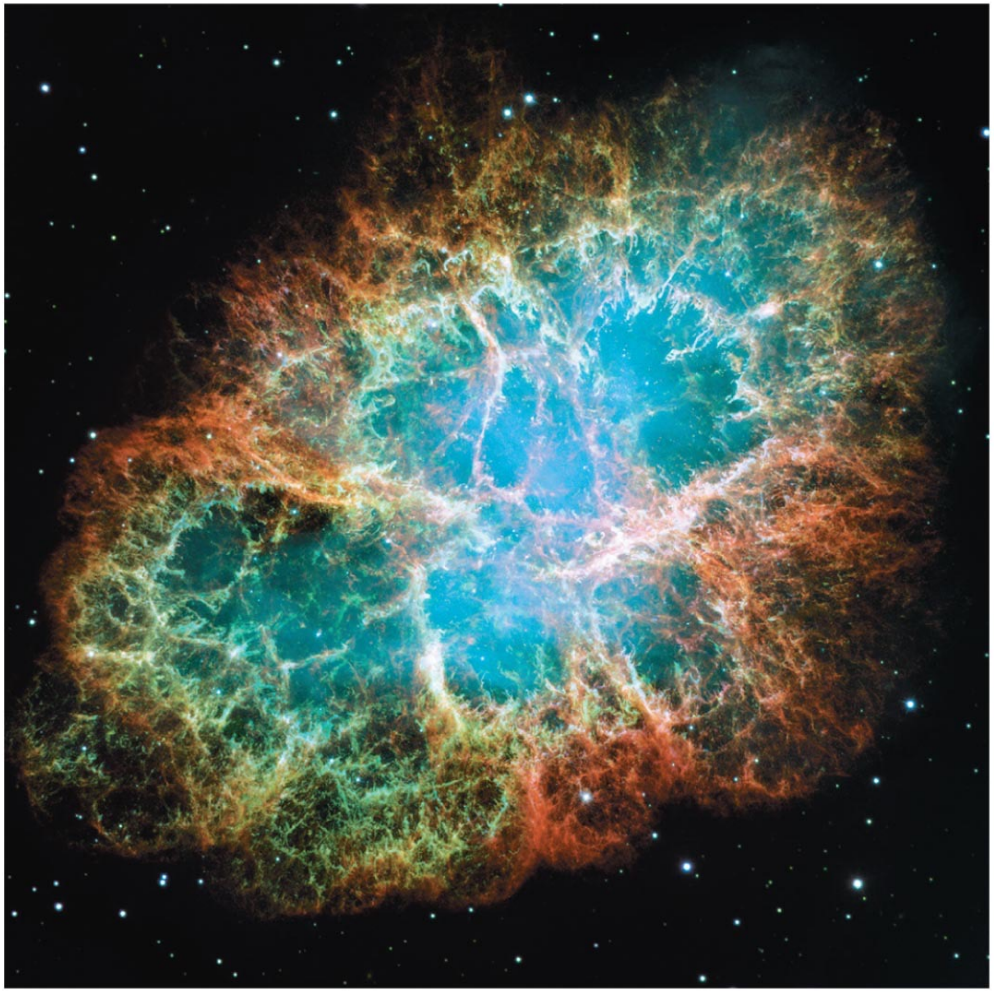
Material ejected from a massive star during a core-collapse supernova **is compressed by the outward shock wave** and thermonuclear reactions occur in the gas **that produce elements**, such as oxygen (O), Magnesium (Mg), Sodium (Na), and iron (Fe)

The following heavy elements can also be produced by merging neutron stars: silver(Ag), tin(Sn), gold(Au), mercury(Hg), lead(Pb), and uranium(U). Gallium (Ga), Germanium (Ge), Arsenic (As), Krypton (Kr)

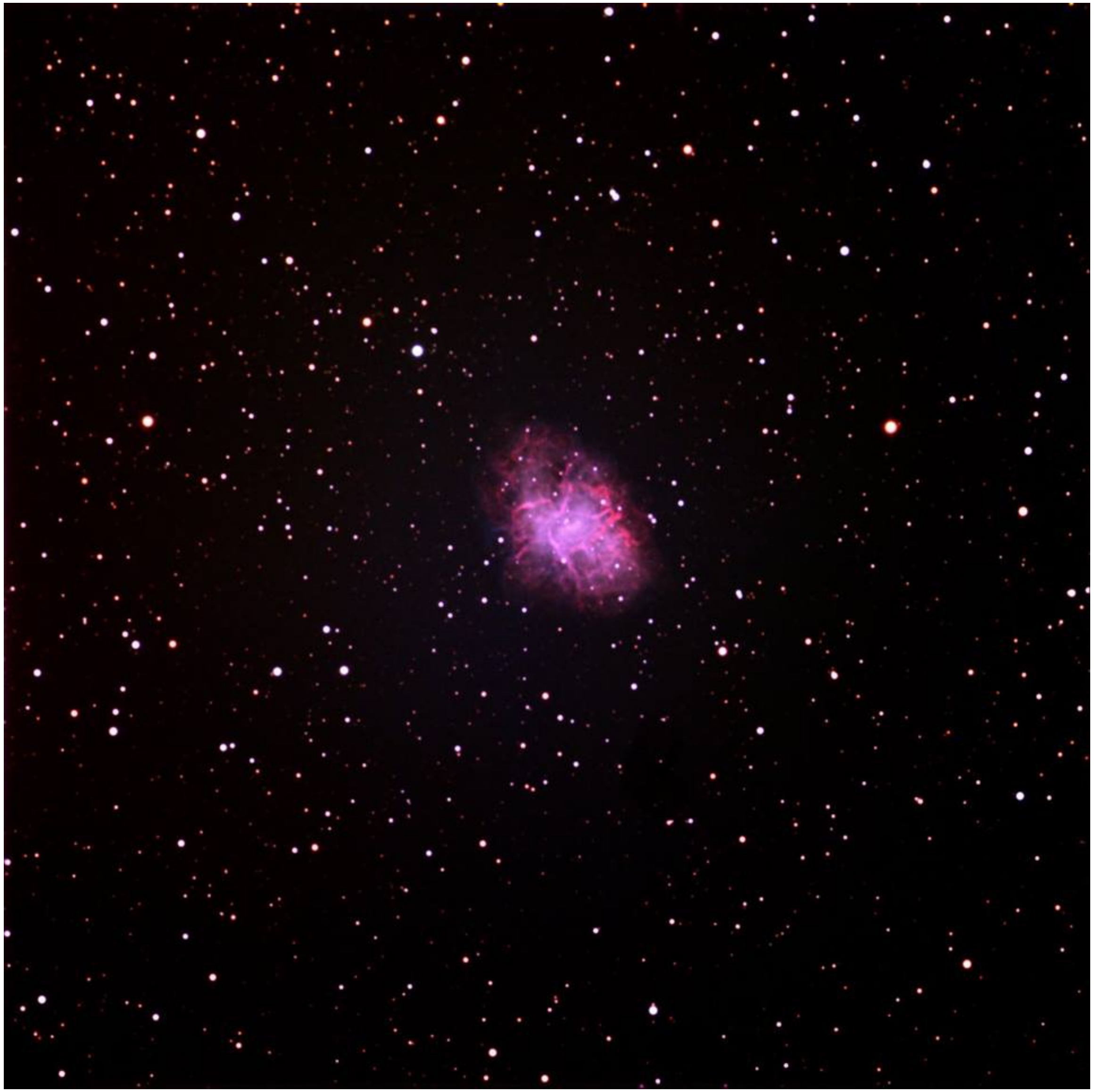


Element Origins
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
Merging Neutron Stars
Dying Low Mass Stars
Exploding Massive Stars
Exploding White Dwarfs
Big Bang
Cosmic Ray Fission
Based on graphic created by Jennifer Johnson

Supernova Remnant



- Energy released by the collapse of the core drives the star's outer layers into space.
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054 (6500ly away).

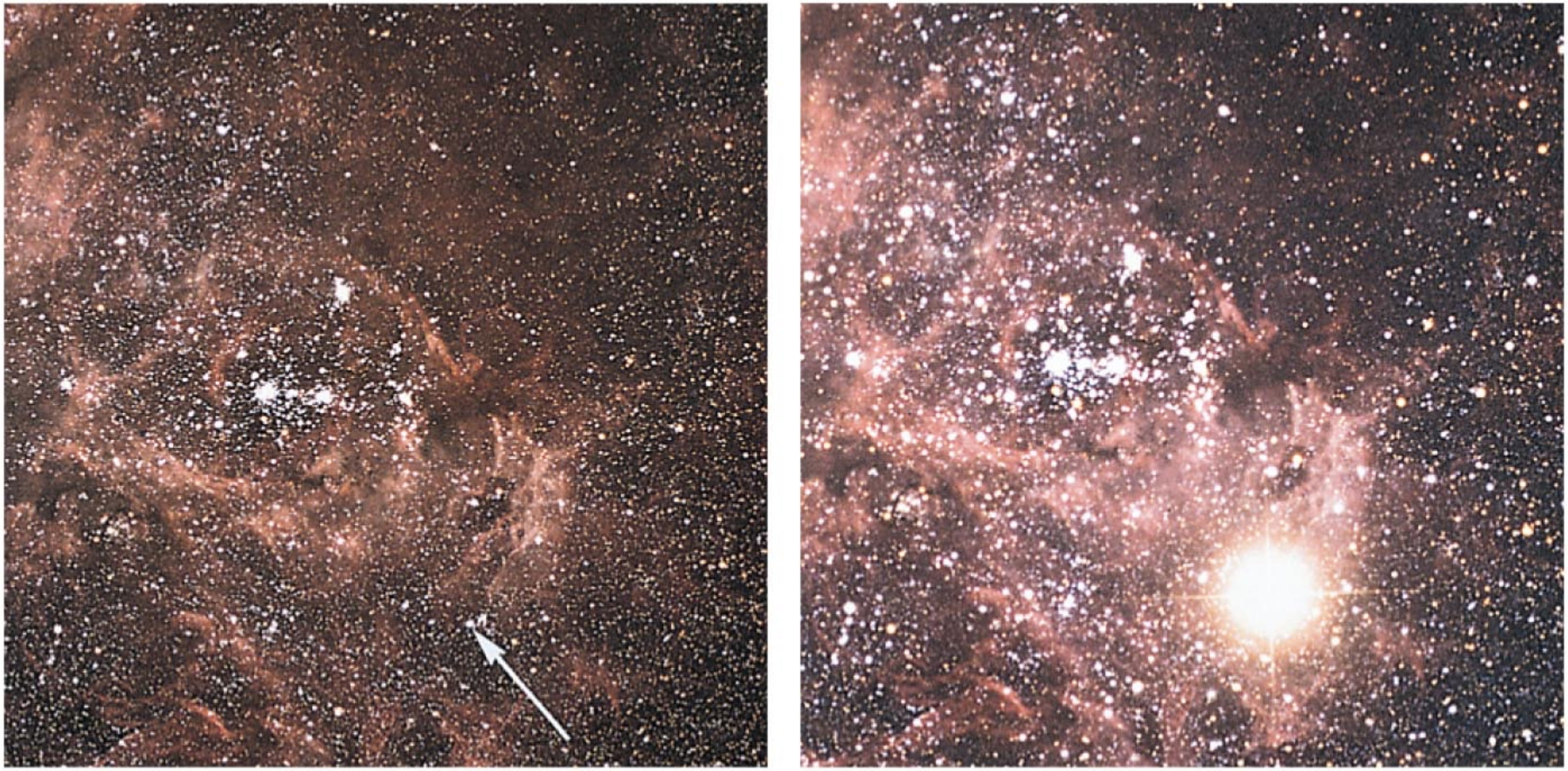


The Crab nebula is the remnant of a bright supernova. Light from this supernova first reached Earth in 1054.

The Crab nebula lies at a distance of about 6,500 light-years from Earth.

The observation was made with the College of Charleston 24 inch CDK PlaneWave telescope.

Supernova 1987A



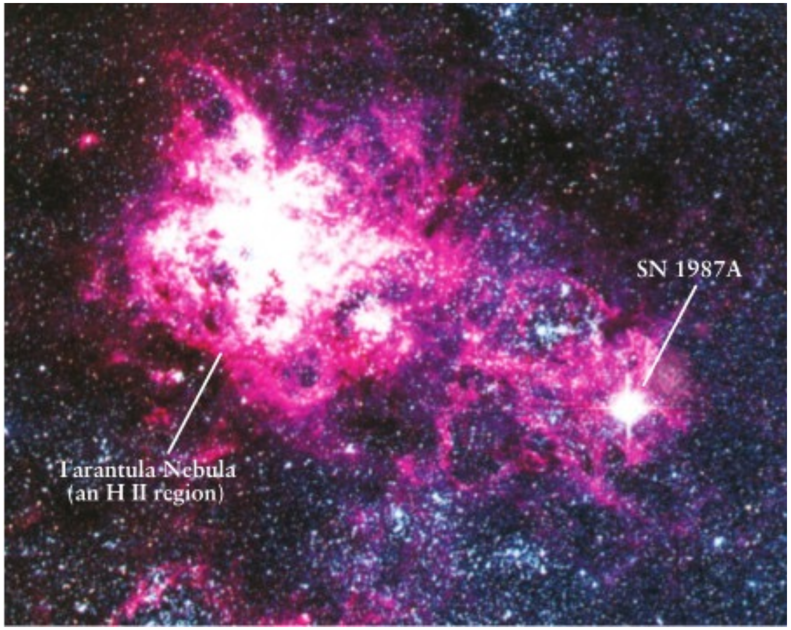
- The closest supernova in the last four centuries was seen in 1987 (~ 170,000 ly away).

Supernova 1987A

Light from SN 1987 A continues to arrive. It doesn't all come out at one short period.

SN 1987 A is also emitting **gamma rays from the decay of radioactive isotopes** created during the supernova explosion.

Five *very* ***bright supernovae within our Galaxy*** *have been observable without a telescope* ***in the last 1000 years****.*

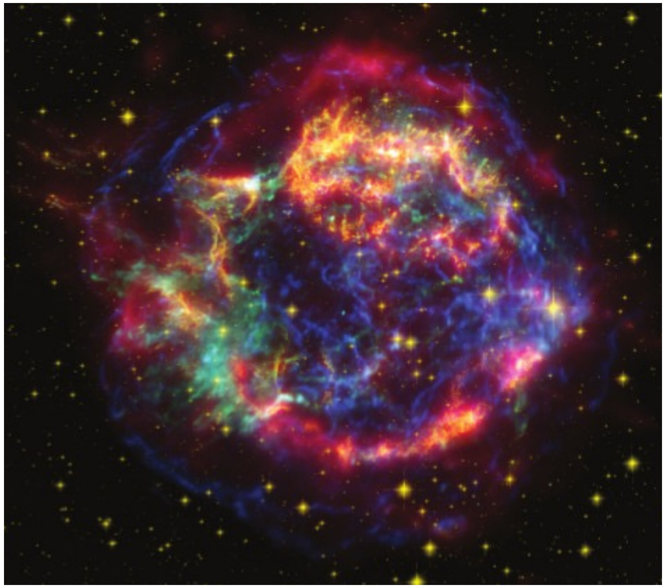


On Feb 1987 a supernova was discovered in the **Large Magellanic Cloud**. It was so bright it could be seen without a telescope in the southern hemisphere.

Rate of Supernovae in the Milky Way

From observations of other galaxies, we know that about **20 bright supernovae** occur **in nearby galaxies** similar to ours **every 1000 years**.

Why is the observed supernova rate in our galaxy so much lower?



A composite of observations of SNR Cassiopeia A at X-ray, visible, and infrared wavelengths.

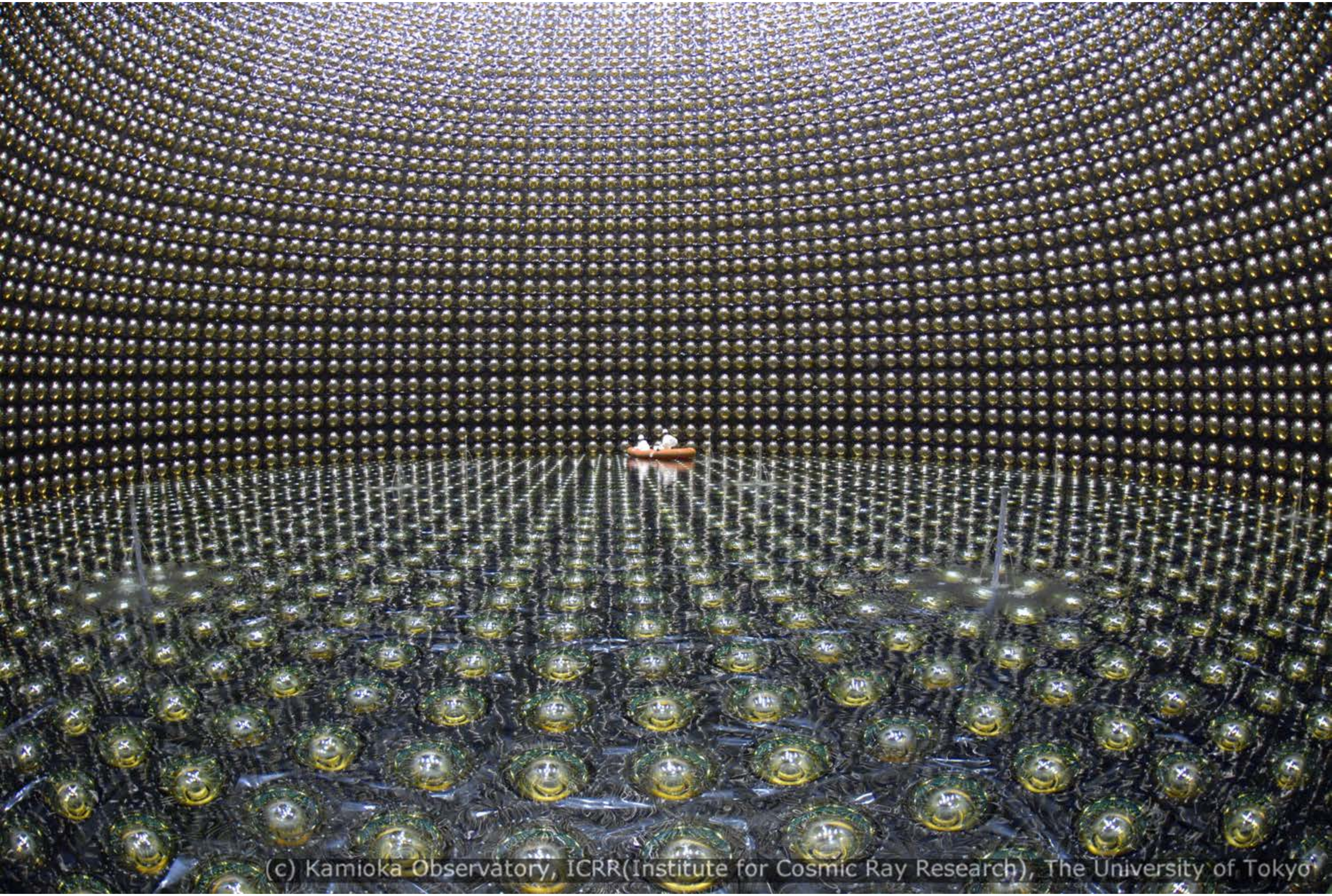
Cas-A is about 11,000 ly away and the photons from the supernova explosion arrived ~300 years ago.

Confirmation of Supernova Model

During the core collapse of a star $M > 8M_\odot$ the density and temperature in the core are so high that a flood of neutrinos are produced. **A detection of these neutrinos would provide support to the core collapse model.**

The core collapse and bounce model predict that the neutrino outburst lasts for a few seconds and that the shock wave takes about 3 hours to reach the surface.

At the time of SN 1987 A two major neutrino detectors were operating: **Kamiokande II and IMB**


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

The Irvine-Michigan-Brookhaven (IMB) detector was a 60-foot cube of ultra-pure water constructed in a salt mine underneath Lake Erie. The water was surrounded by 2000 light-sensitive phototubes, designed to detect proton decay. The experiment became famous for the observation of the neutrino burst emitted by Supernova 1987 A.

Confirmation of Supernova Model

12 neutrinos were detected by Kamiokande and 8 neutrinos by IMB from SN 1987 A on Feb 23, 1987 !

The neutrino events were detected 3 hours before the UV flash from SN 1987 was detected.

Astronomers found that over a 10-second period, SN 1987A emitted 10^{58} neutrinos with a total energy of 10^{46} Joules! This is more than 100 times the amount of electromagnetic radiation emitted by the supernova and 100 times more than what the sun has emitted over its 4.56 billion years!

What have we learned?

- **What are the life stages of a high-mass star?**
  - They are similar to the life stages of a low-mass star.
- **How do high-mass stars make the elements necessary for life?**
  - Higher masses produce higher core temperatures that enable fusion of heavier elements.
- **How does a high-mass star die?**
  - Its iron core collapses, leading to a supernova.

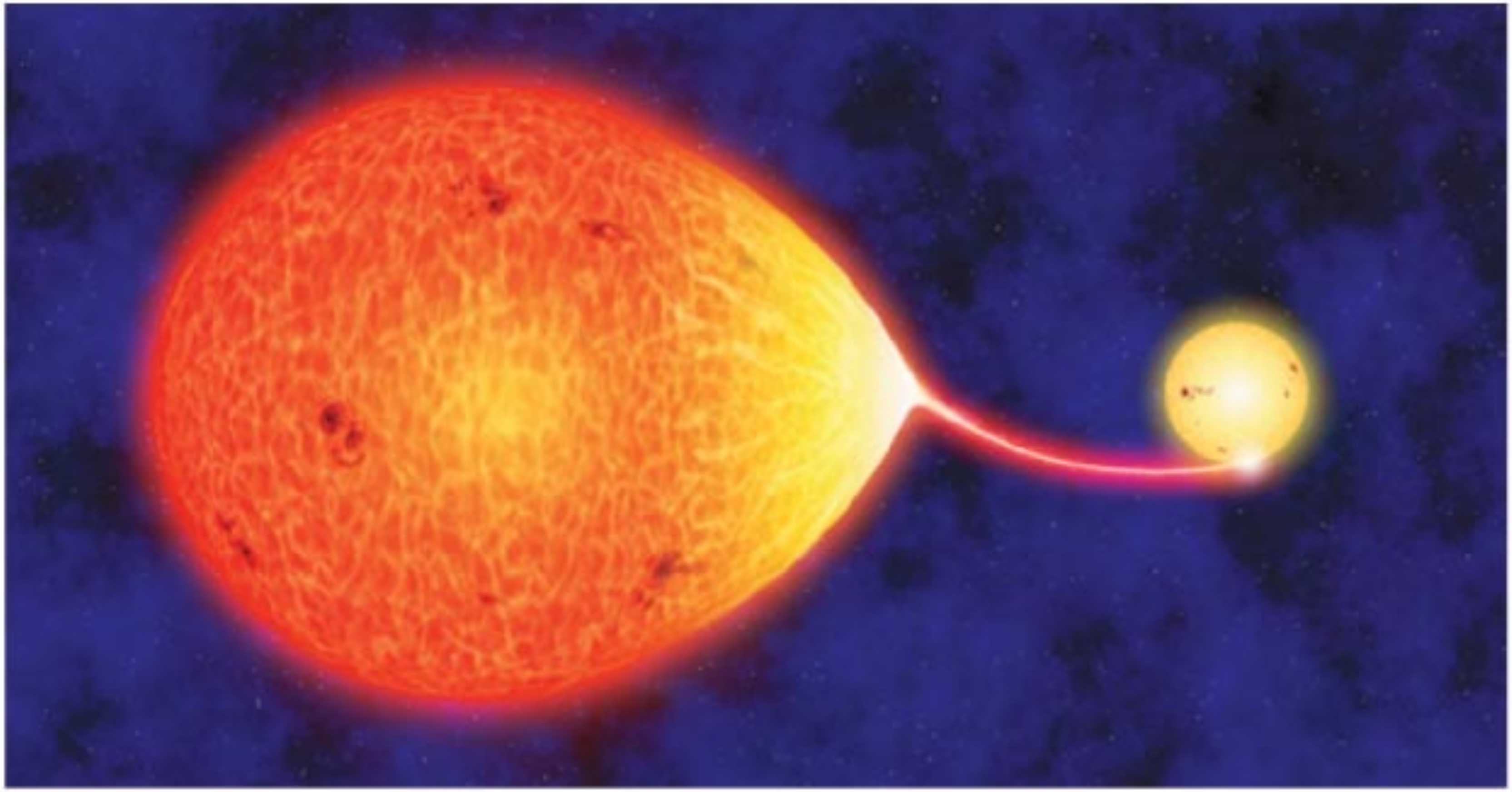
17.4 The Roles of Mass and Mass Exchange

- Our goals for learning:
  - **How does a star's mass determine its life story?**
  - **How are the lives of stars with close companions different?**

Role of Mass

- **High-mass stars with > 8M_{Sun}** have short lives, eventually becoming hot enough to make iron, and **end in supernova explosions**.
- **Low-mass stars with < 4M_{Sun}** have long lives, never become hot enough to fuse carbon nuclei, and **end as white dwarfs.**
- **Intermediate-mass stars** can make elements heavier than carbon but **end as white dwarfs**.

How are the lives of stars with close companions different?



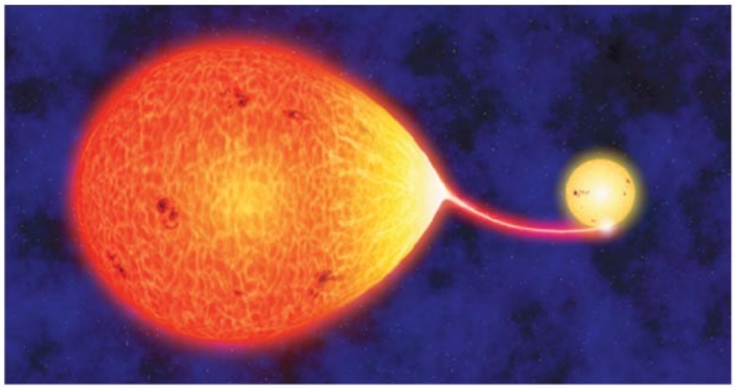
Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.

Thought Question

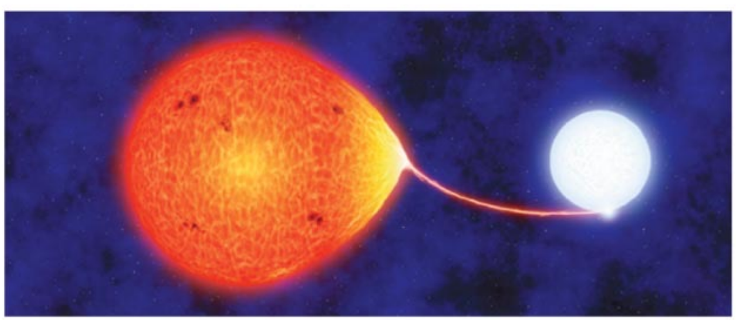
- The binary star Algol consists of a $3.7 M_{Sun}$ main-sequence star and a $0.8 M_{Sun}$ subgiant star.
- What's strange about this pairing assuming both stars were formed at the same time?
- How did it come about?

Thought Question Answers

Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



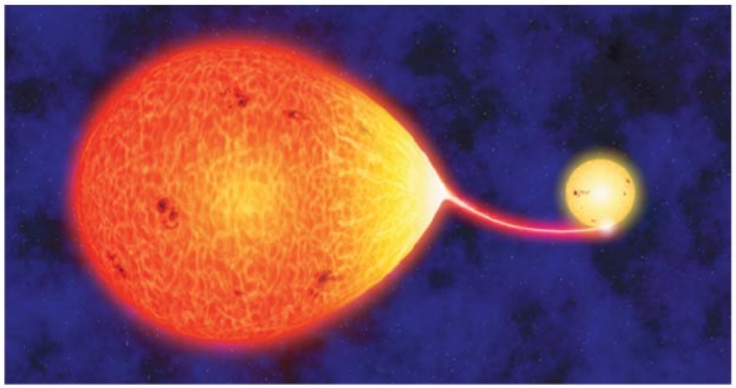
Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.



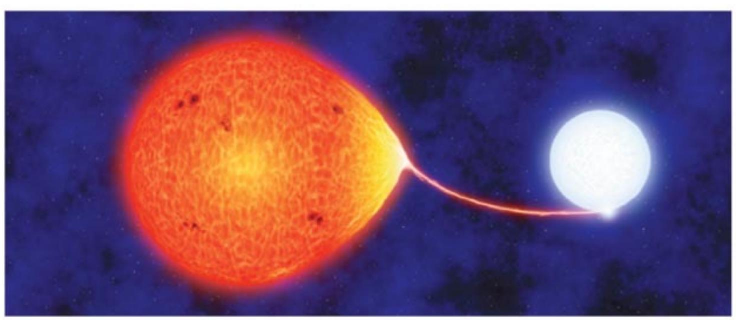
Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

- The stars in Algol are close enough that matter can flow from the subgiant onto the main-sequence star.

Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.

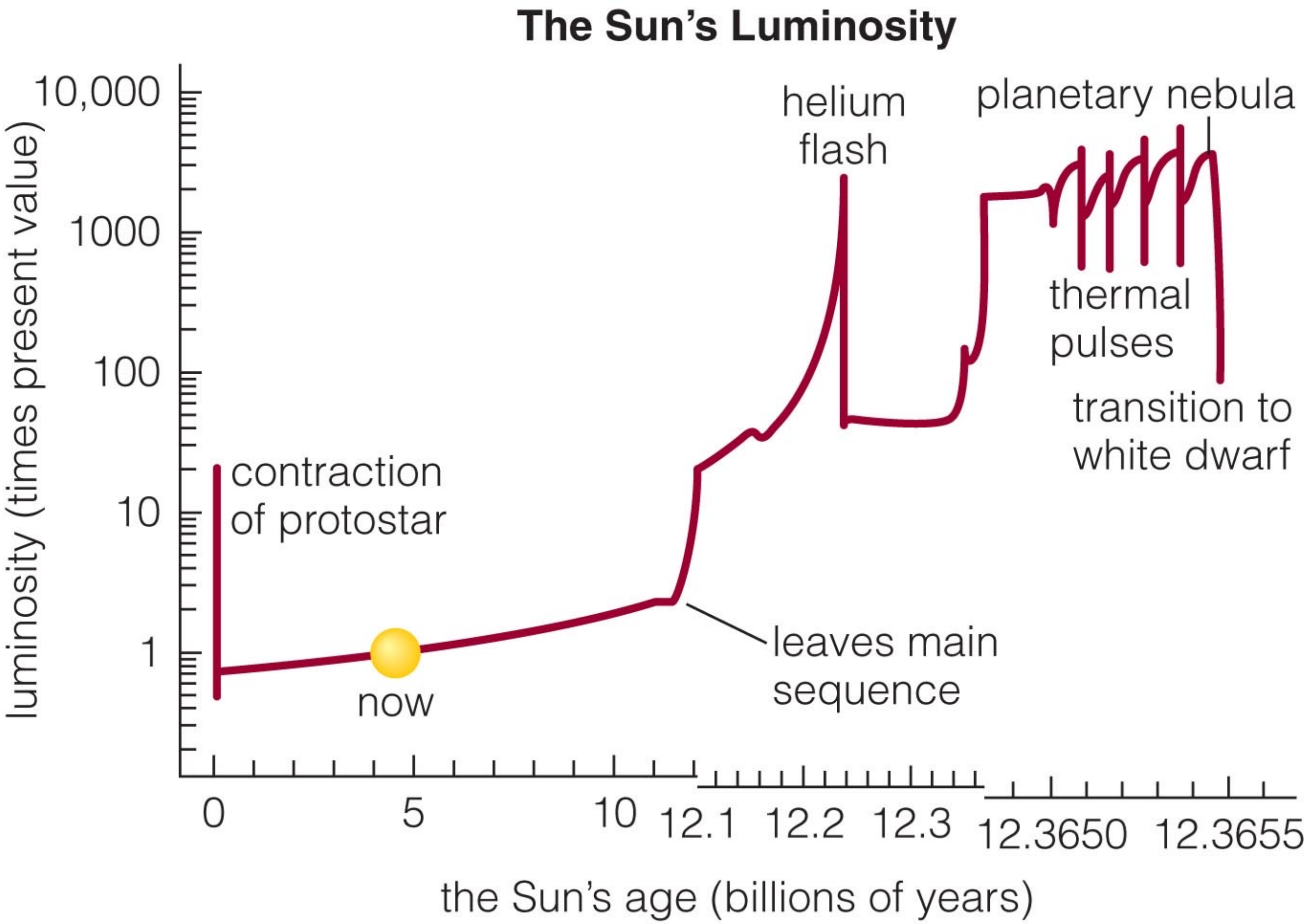


Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

- The star that is now a subgiant was originally more massive.
- As it reached the end of its life and started to grow, it began to transfer mass to its companion (*mass exchange*).
- Now the companion star is more massive.

EXTRA SLIDES

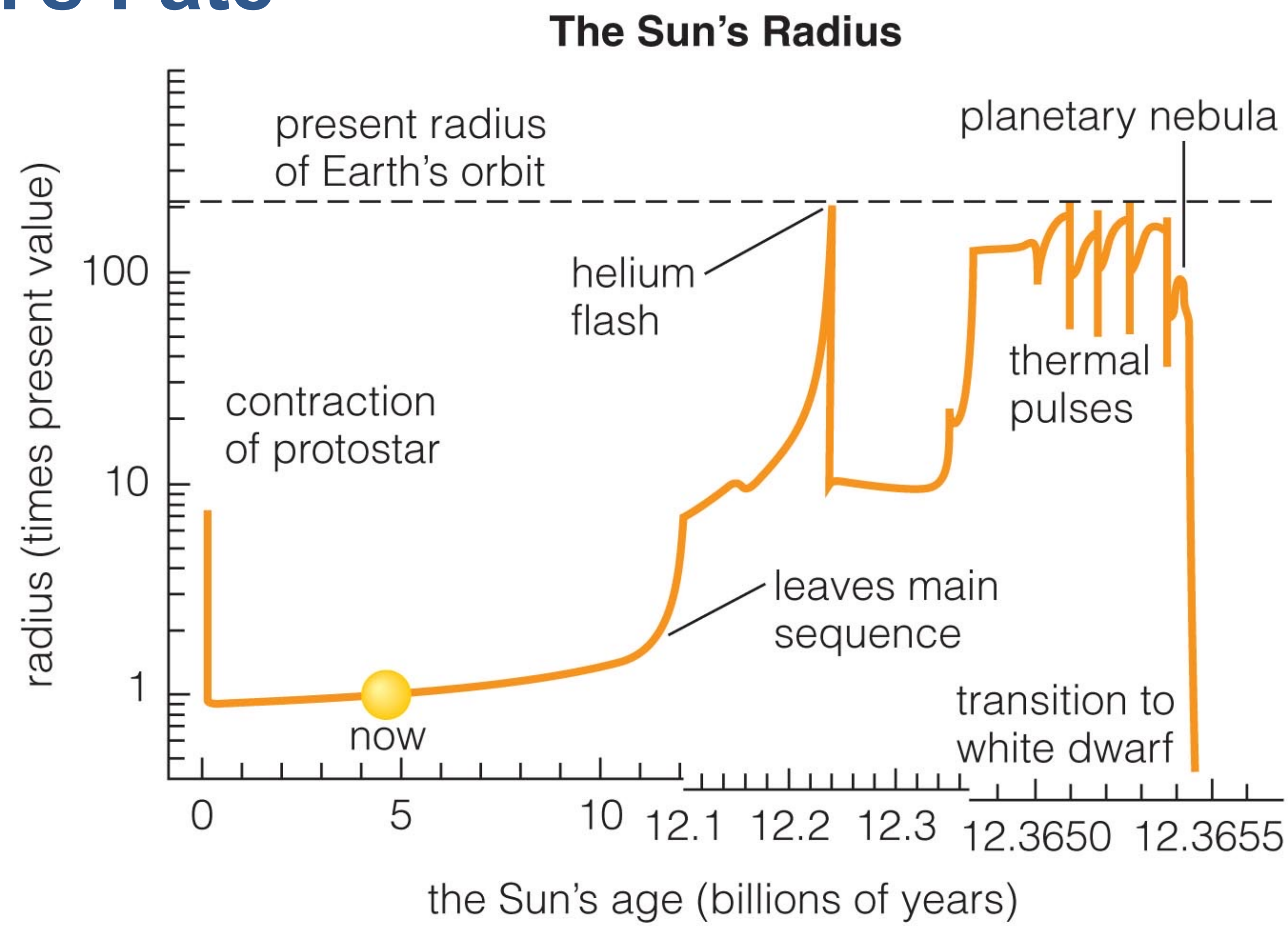
Earth's Fate



a Changes in the Sun's luminosity over time.

- The Sun's luminosity will rise to 1000 times its current level—too hot for life on Earth.

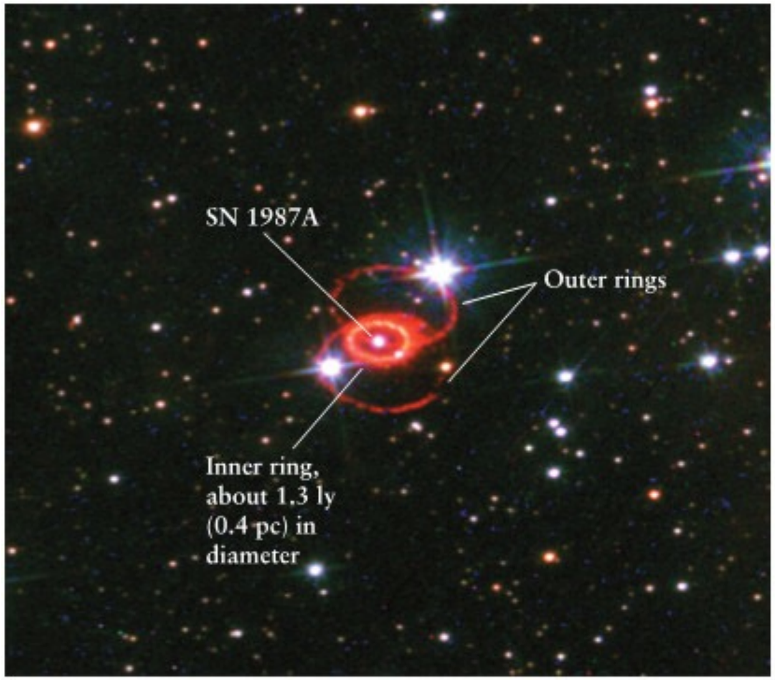
Earth's Fate



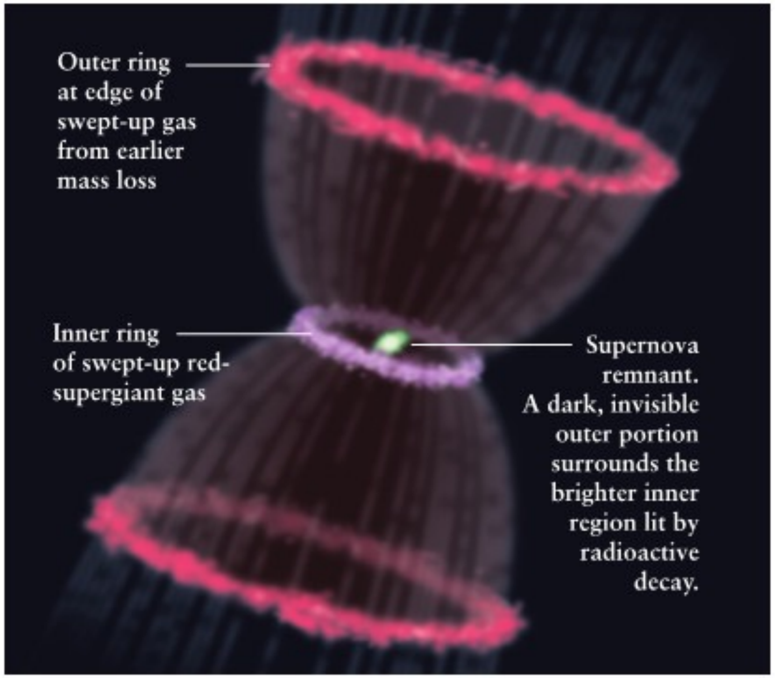
b Changes in the Sun's radius over time.

- The Sun's radius will grow to near current radius of Earth's orbit.

Rings around Supernova 1987A



(a) Supernova 1987A seen in 1996 R I V U X G



(b) An explanation of the rings

Rings of SN 1987 A About 20,000 years before the explosion a shell of gas was ejected from the red giant and about 10,000 years before the explosion another shell of gas was ejected.

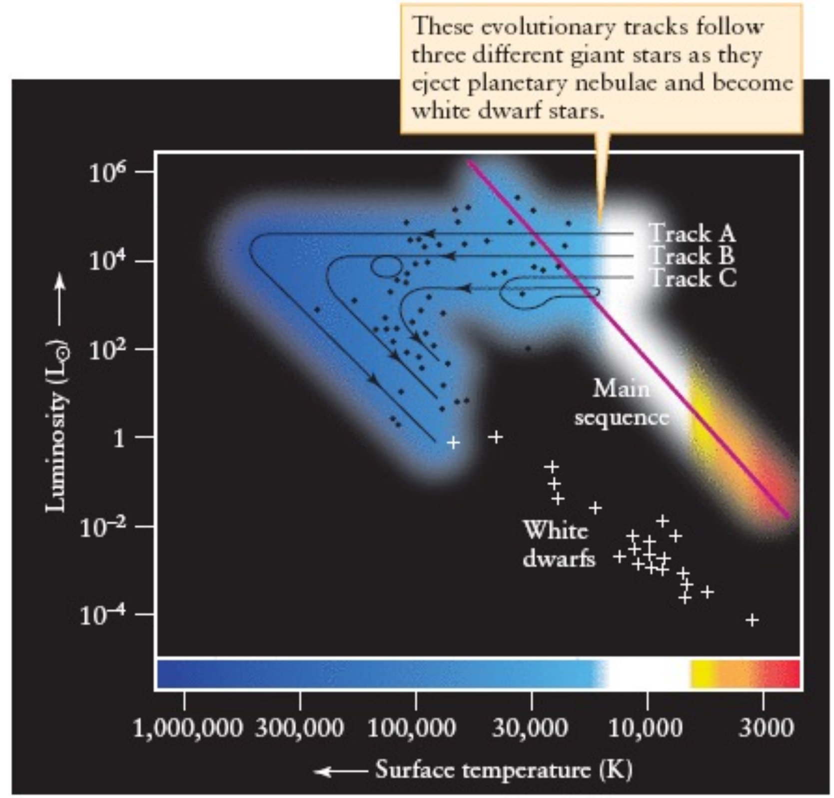
The UV flash of the supernova explosion ionized the ejected stellar material and caused it to glow.

White Dwarfs

During the asymptotic giant branch a star ejects its outer layers exposing the burned-out core.

Once all the outer layers are ejected and the planetary nebula fades away the core continues to cool down and its luminosity decreases. **A white dwarf's size does not change because it is supported by degeneracy pressure.**

The fraction of material ejected will depend on the mass of the giant star.



Evolutionary track	Mass ($M_{\odot}$) Giant star	Ejected nebula	White dwarf
A	3.0	1.8	1.2
B	1.5	0.7	0.8
C	0.8	0.2	0.6

Evolution from Giants to White dwarf

Stellar Evolution: On and Off the Main Sequence

Table 19-1 Approximate Main-Sequence Lifetimes

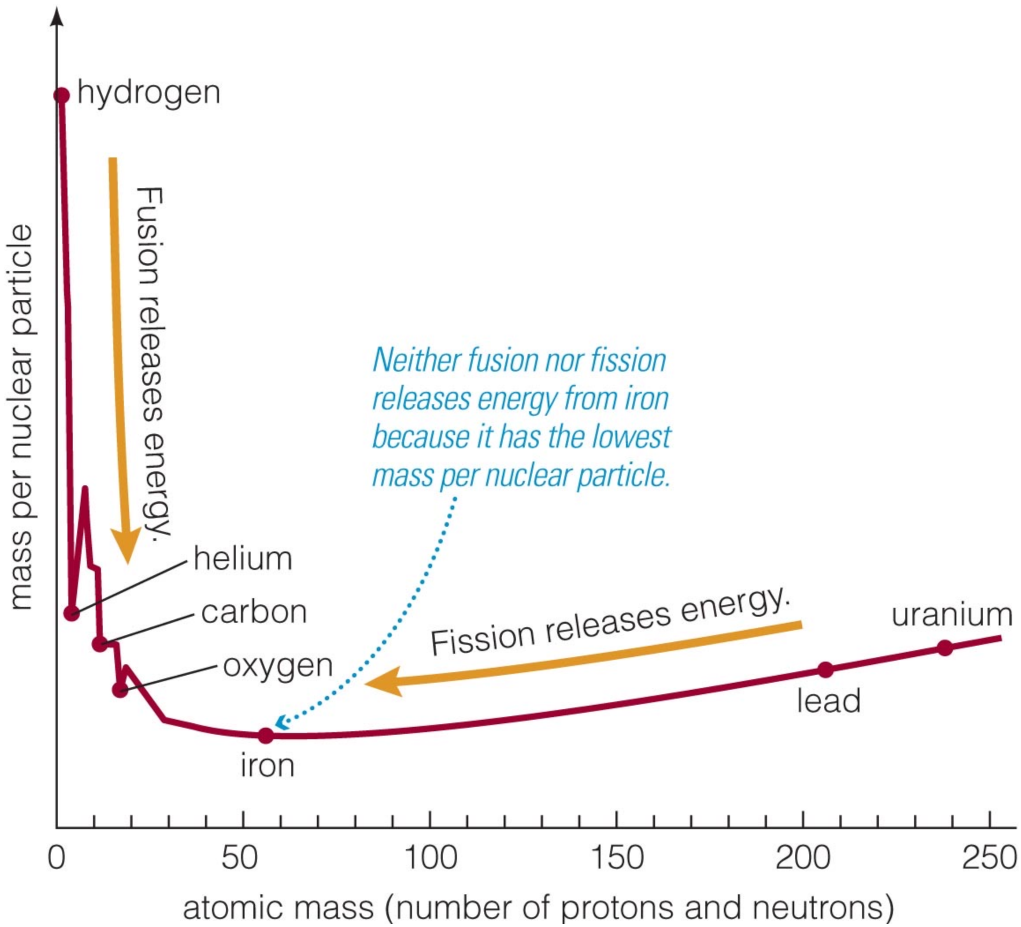
Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetime (10^6 years)
25	35,000	O	80,000	4
15	30,000	B	10,000	15
3	11,000	A	60	800
1.5	7000	F	5	4500
1.0	6000	G	1	12,000
0.75	5000	K	0.5	25,000

How long will a star remain on the main sequence? The energy E released over the lifetime t of a star is:

$E = fMc^2$, where f is the fraction of the star's mass that's converted into energy

$$L = \frac{E}{t} \Rightarrow t = \frac{E}{L} = \frac{fMc^2}{L} \propto \frac{M}{M^{3.5}} = \frac{1}{M^{2.5}}$$

$$t_{star} = t_{solar}\left(\frac{M_{solar}}{M_{star}}\right)^{2.5}, \quad t_{solar} = 1.2\times10^{10}\,\text{years}$$



- Iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

- (This is because iron has lowest mass per nuclear particle.)