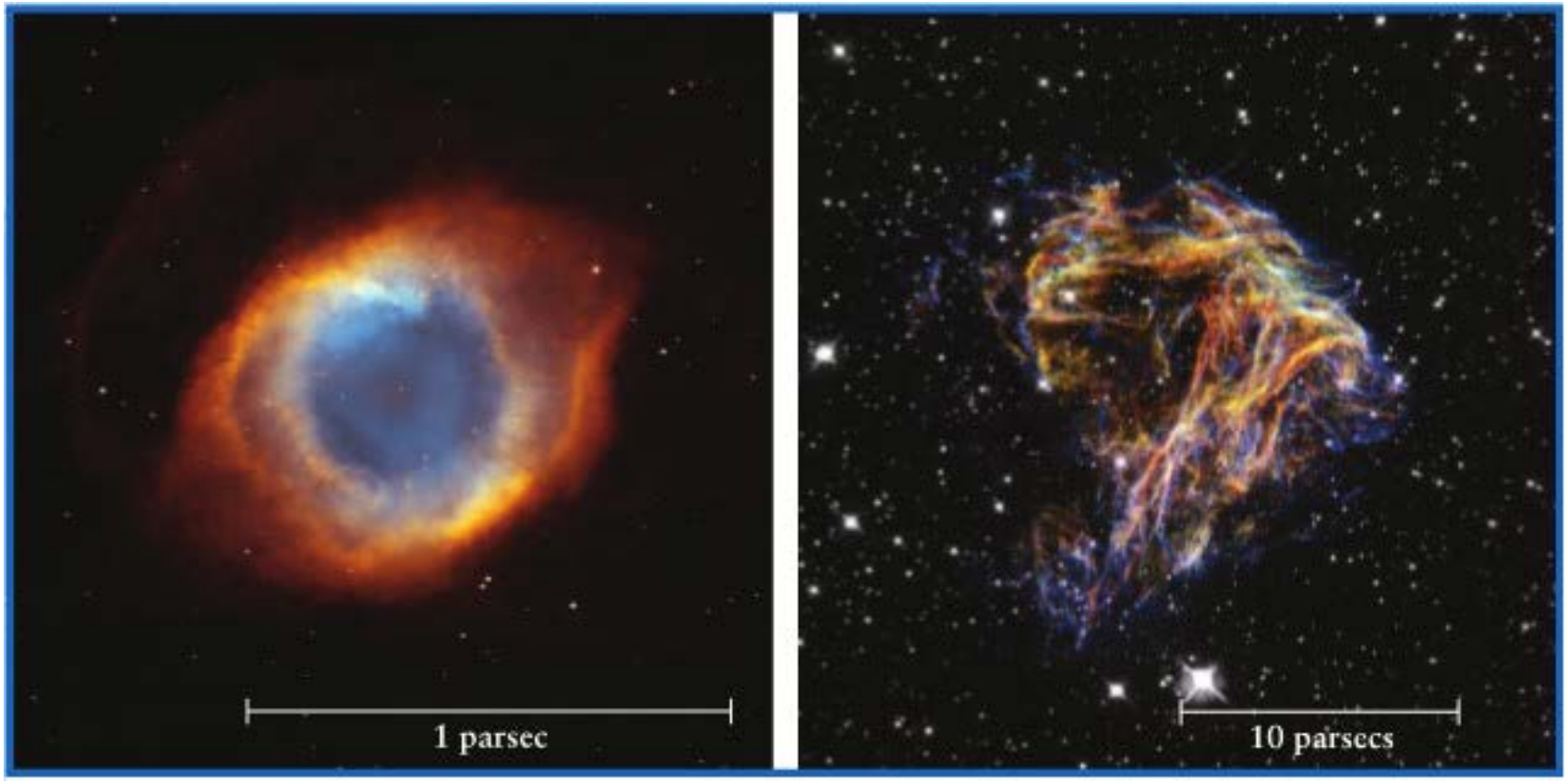
Stellar Evolution: The Death of Stars



(a) A planetary nebula R I V U X G (b) A supernova remnant

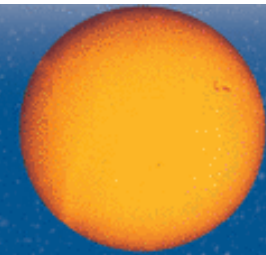
The Source of a Stars Energy

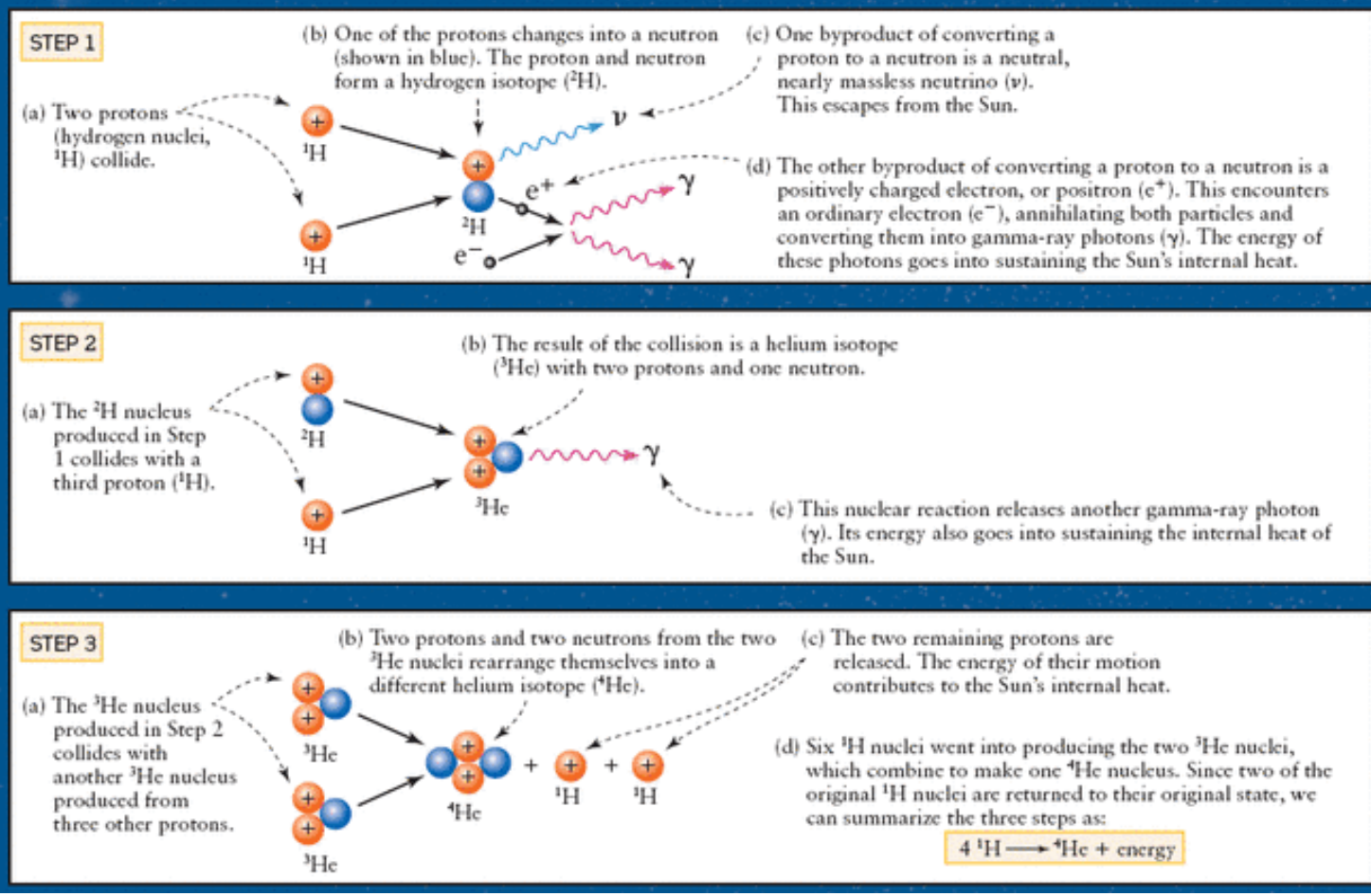
There are two avenues by which fusion of hydrogen proceeds in stars.

$T \approx T_{\odot} \approx 15 \times 10^6$ K **proton – proton chain**
(example: $4\ {}^1H \rightarrow {}^4He$ + neutrinos + gamma-ray photons)

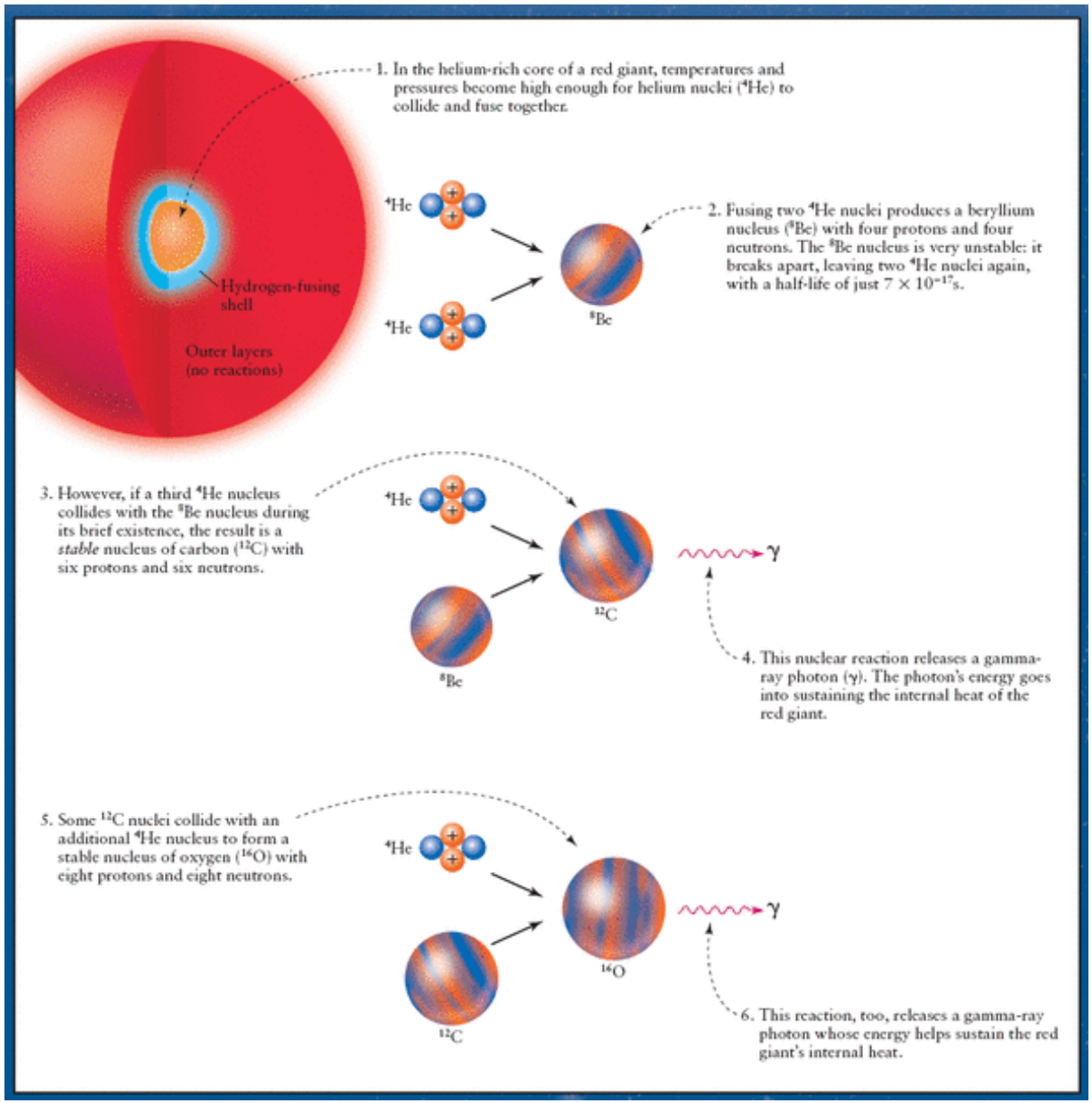
$T >> T_{\odot}$ **CNO cycle** (a carbon nucleus absorbs protons and finally emits a helium nucleus)

Hydrogen fusion in the Sun usually takes place in a sequence of steps called the proton-proton chain. Each of these steps releases energy that heats the Sun and gives it its luminosity.





Core Helium Fusion: The Triple Alpha Process



Stellar Evolution: The Death of Stars

After the H fusion reactions cease the core begins to collapse (why?) and the outer layers expand (why?).

The **star becomes a red giant** in which its radius increases, its luminosity increases and its surface temperature slightly decreases.

The heat produced from the compression of the core raises the temperature to the point where **H fusion begins in a shell around the core**.

The heat generated in the core's collapse also eventually starts (when $T_{core} \sim 100$ million K) fusion of He in the core.

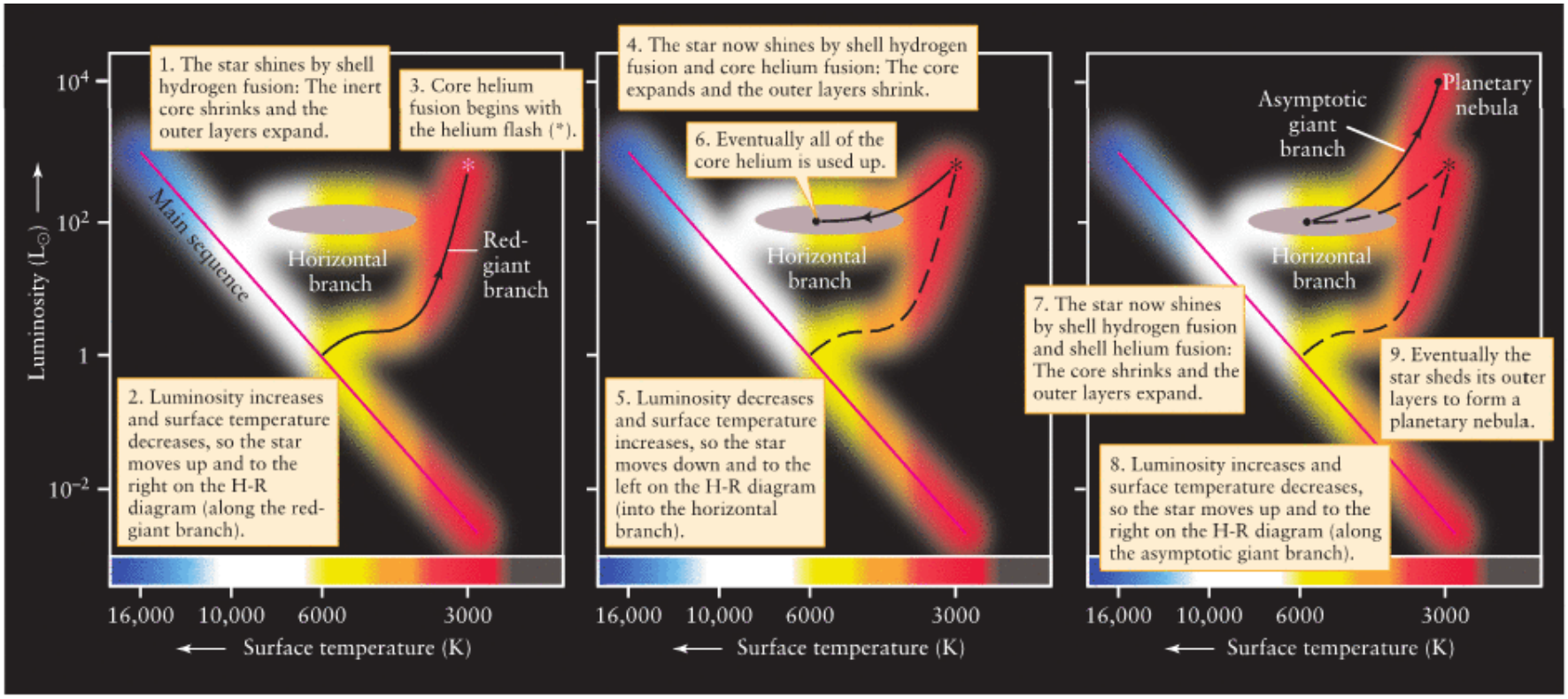
Stellar Evolution: The Death of Stars

He fusion in stars with $M > 2\text{-}3\ M_\odot$ starts in a gradual manner while in less massive stars it starts with a **Helium flash**.

During **core helium fusion**, the surrounding hydrogen-fusing shell still provides most of the red giant's luminosity.

After He fusion begins the core expands a bit and cools down. This cooling down reduces the rate of He fusion in the core and in the shell. During this phase the star moves along the **horizontal branch** in the H-R diagram.

Stellar Evolution: The Death of Stars

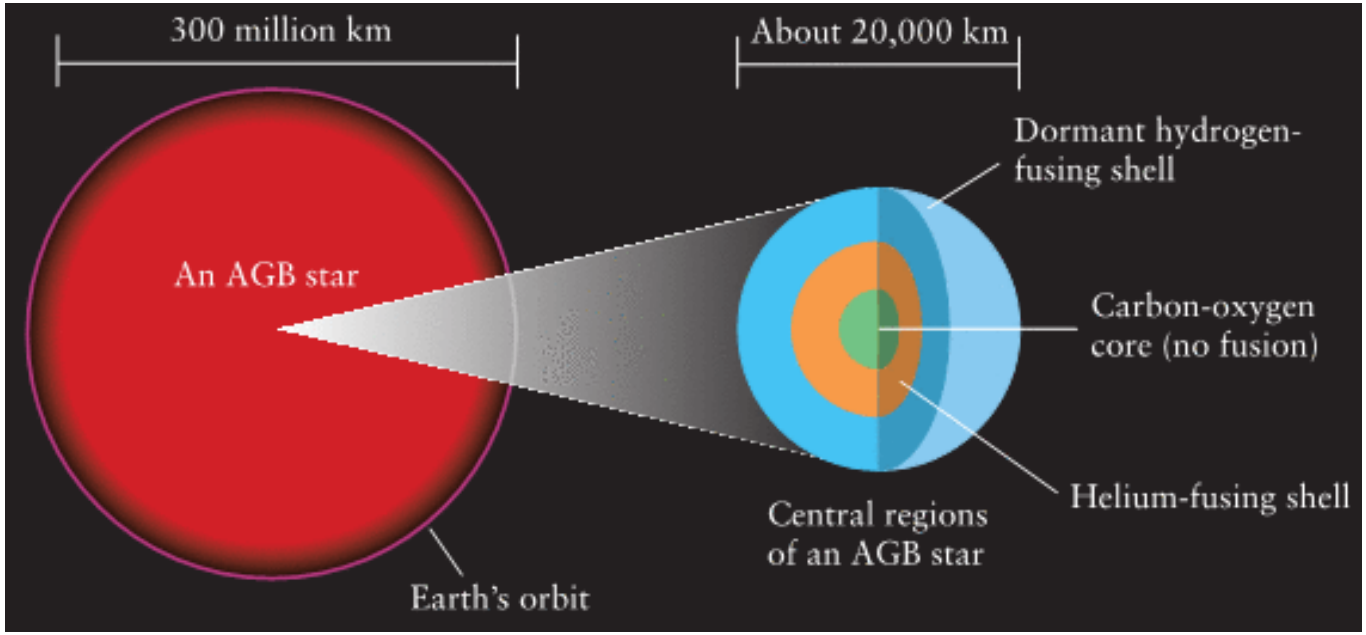


(a) Before the helium flash: A red-giant star

(b) After the helium flash: A horizontal-branch star

(c) After core helium fusion ends: An AGB star

Stellar Evolution: The Death of 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.

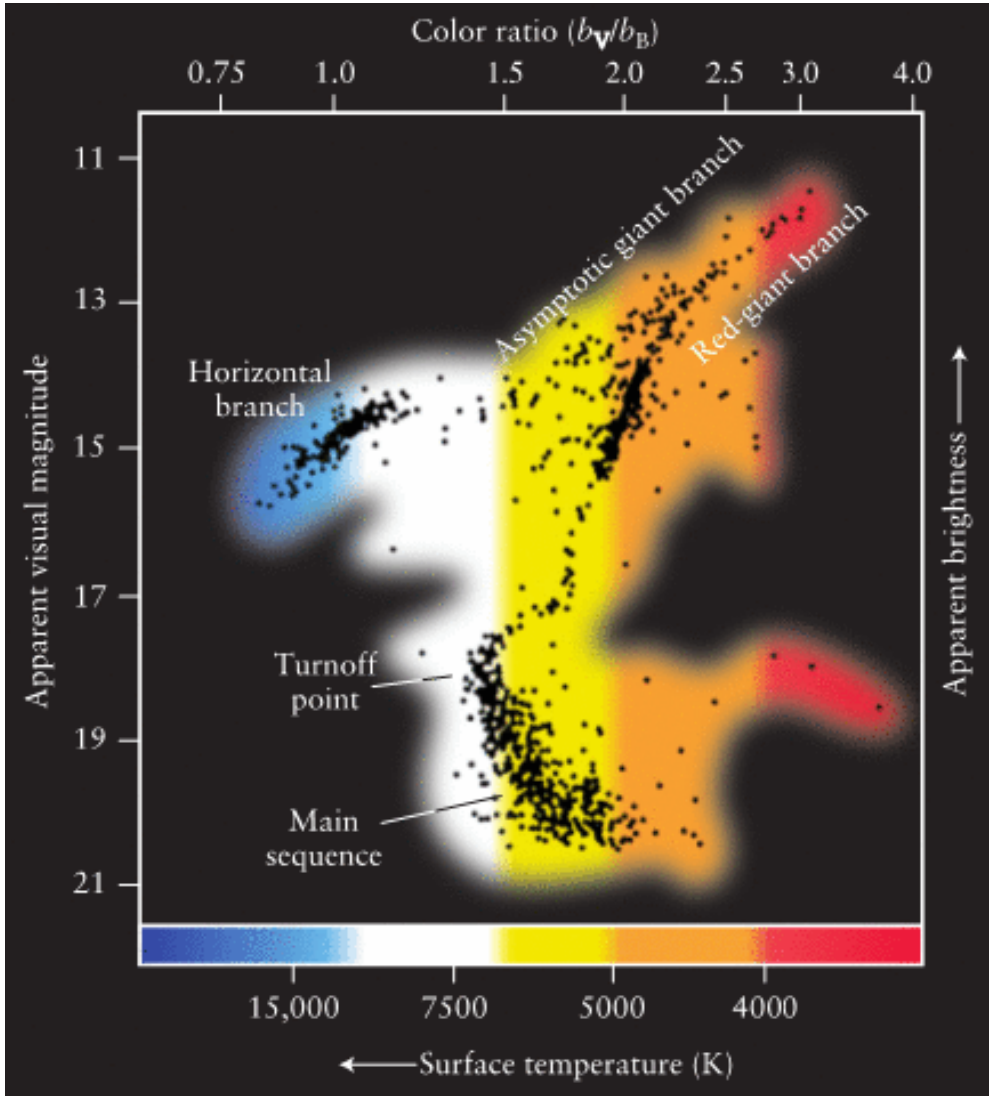
When He runs out, the core will collapse again resulting in an increase in the core temperature (T). This increase in T results in an increase in the reaction rate in the He shell that leads to the expansion of the outer layers for a second time. The resulting star is called an **asymptotic giant branch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

Stellar Evolution: The Death of Stars

In M55 the less massive stars are still on the main sequence.

Progressively, more massive stars have evolved to the **red giant branch, the horizontal branch, and the asymptotic giant branch.**

An AGB star is about 10,000 times more luminous than when it was a main sequence star.



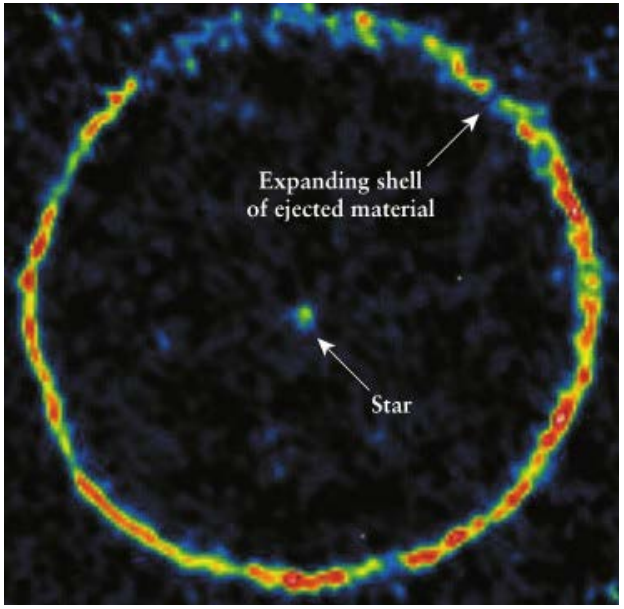
Stellar Evolution in globular cluster M55.

Stellar Evolution: The Death of 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.

There are 2-3 drudge-ups . The third one occurs in the AGB phase of stars with $M > 2M_\odot$. 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 $\sim 10^{-7}\ M_\odot$ per year and the sun's is $\sim 10^{-14}\ M_\odot$ per year.

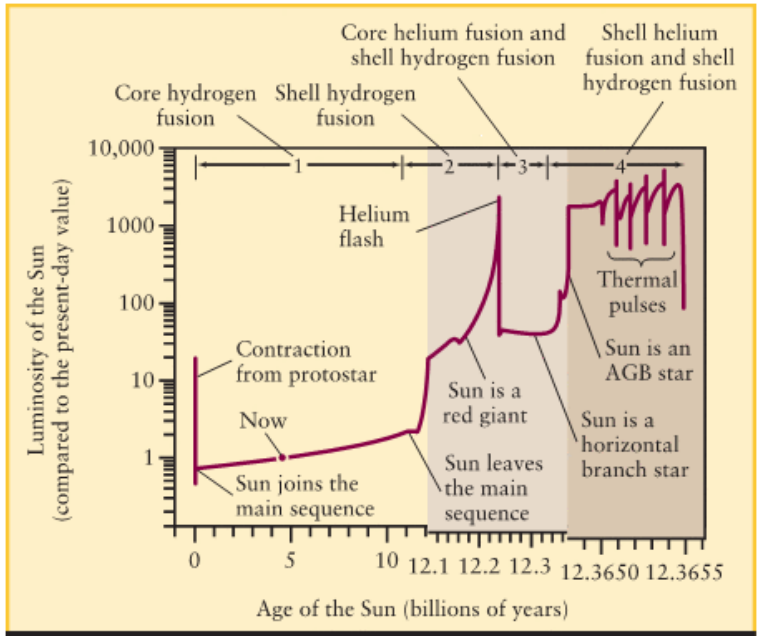
Stellar Evolution: The Death of Stars

How does an AGB star expel its outer layers?

When He shell fusion stops the pressure that holds up the dormant hydrogen-fusing shell decreases. As a result the Hydrogen shell collapses and gets compressed, heats up and **H shell fusion starts up again**.

H fusion produces He that falls below into the He shell region. As the mass of the dormant He shell region increases it shrinks and heats up. When the temperature is high enough He fusion begins again in a **helium shell flash**.

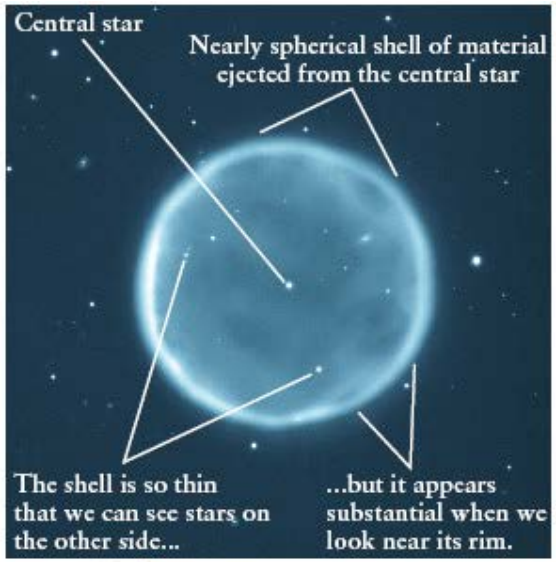
During the onset of He fusion in a degenerate electron plasma the rate of thermonuclear reactions increases very rapidly leading to **thermal pulses**. These pulses eject the outer layers of an AGB star.



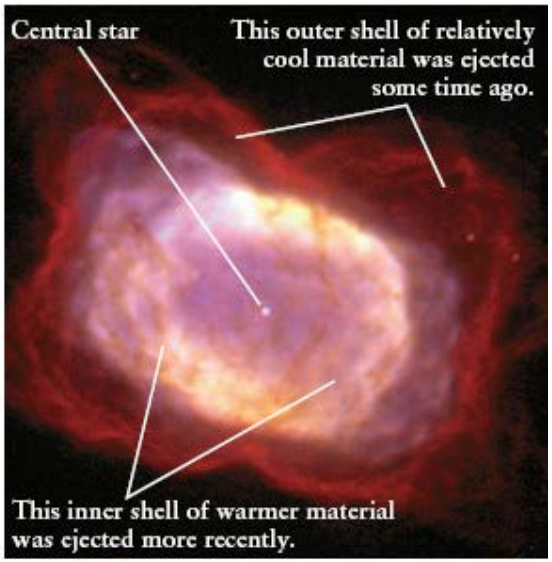
Evolution of the luminosity of the sun.

Stellar Evolution: The Death of Stars

R I V U X G



R I V U X G

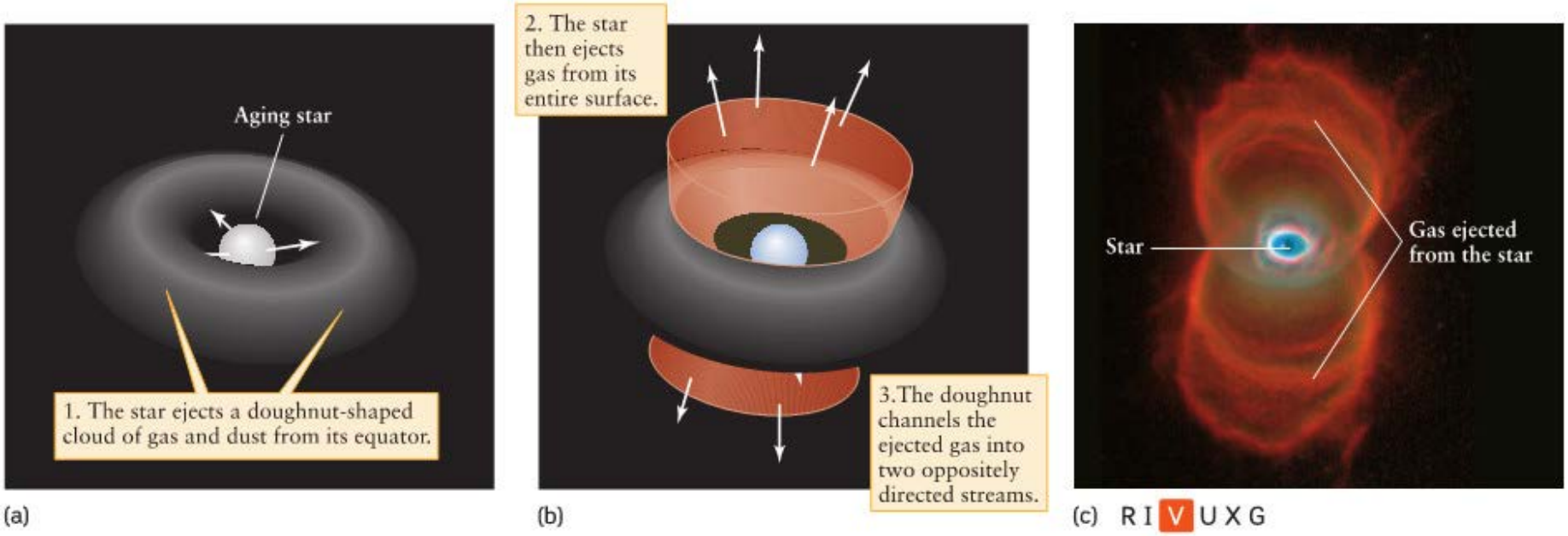


R I V U X G

An AGB star can loose a significant fraction of its mass from thermal pulses. As the outer layers are ejected what remains is the C, O core that is quite hot (T_{core} ~ 100,000 K). This exposed core is called the **white dwarf**. Its strong UV radiation can ionize the surrounding shell and make the planetary nebula glow.

Planetary nebulae **enrich the interstellar medium** (ISM) with heavy elements produced in the AGB stars. About 15% of all matter ejected from stars into the ISM originates from planetary nebulae.

Stellar Evolution: The Death of Stars



There are **about 20,000-50,000 planetary nebulae in our galaxy**. Most have spherical shapes but if the expansion is not the same in all directions then they can have elongated appearances.

Doppler shifts of H, O and N emission lines imply outflow velocities of 10-30 km s^{-1}.

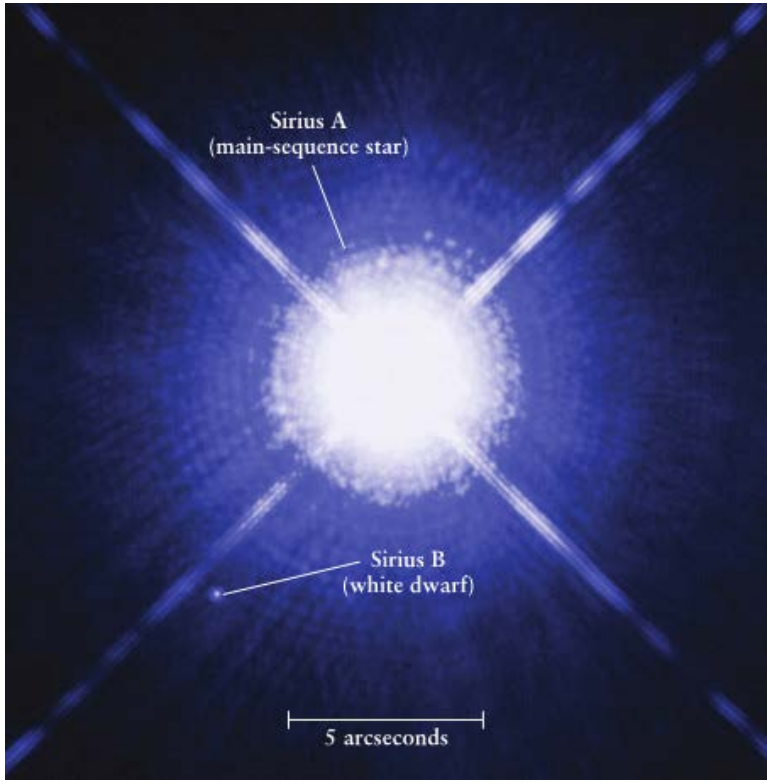
What is the age of a PN that is 1 ly wide and $v_{outflow}$ = 30km/s?

Stellar Evolution: The Death of Stars

When does a star evolve into a **white dwarf**.?

A star with a mass of
$0.4\ M_\odot < M < 4\ M_\odot$ after consuming all the H in its core will begin fusing He into C and O.

Such stars do not have high enough temperatures and densities in their cores to fuse C when He runs out in the core and end their life by ejecting the outer layers and leaving behind a hot core of C and O. This relic gradually cools done and is called a **white dwarf**.



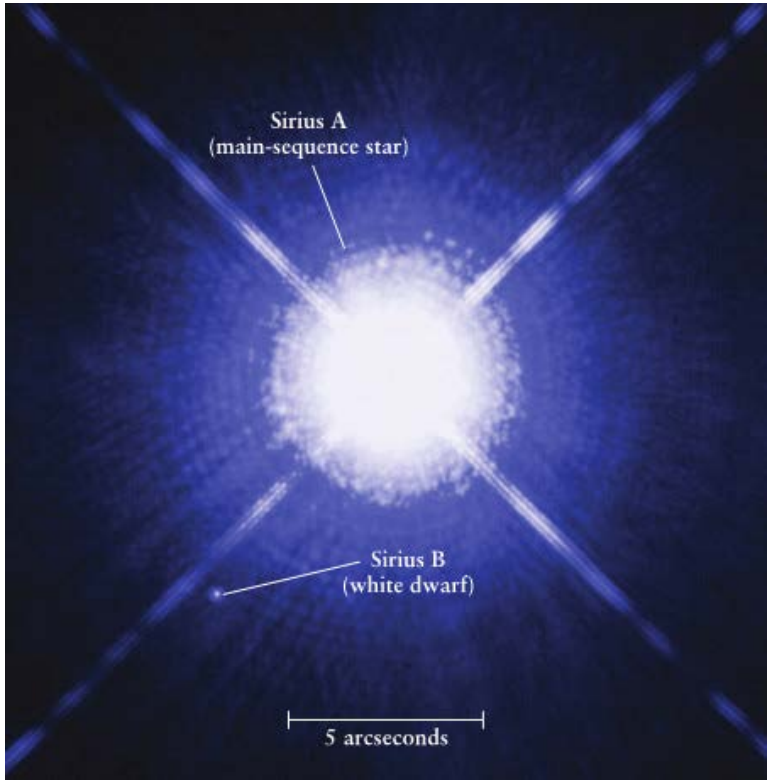
HST image of Sirius and its white dwarf binary companion.

Stellar Evolution: The Death of Stars

A **white dwarf** gradually cools down as it radiates away its energy but **does not shrink**. It is supported by **electron degeneracy pressure** against gravitational collapse.

Electron degeneracy pressure does not depend on temperature.

Observations of white dwarfs in binary systems allow us to determine their mass, radius and density. The degenerate electron gas has a density of about 10^9 kg m^{-3} .
(ρ_{water}~1,000 kg m^{-3})



A teaspoon of degenerate electrons from Sirius B brought back to Earth would weigh as much as en elephant.

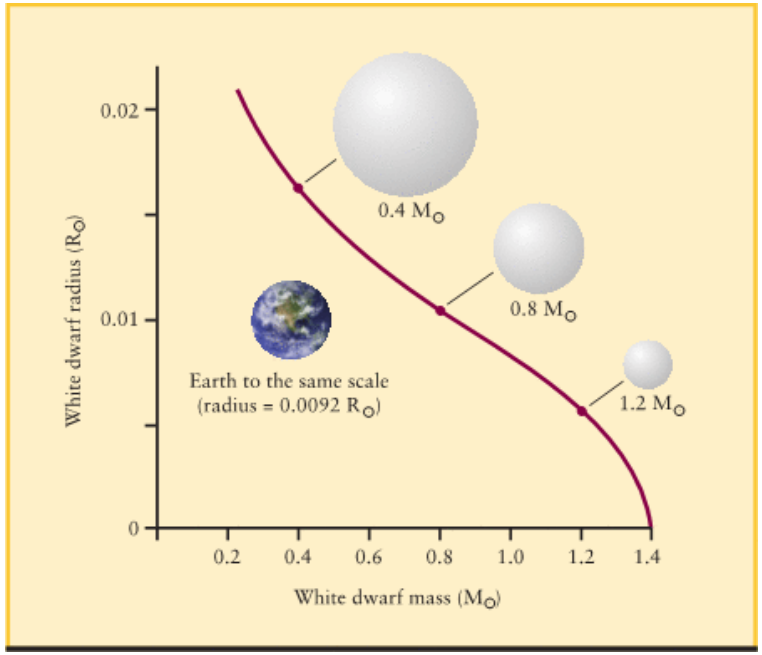
Stellar Evolution: The Death of Stars

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 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.



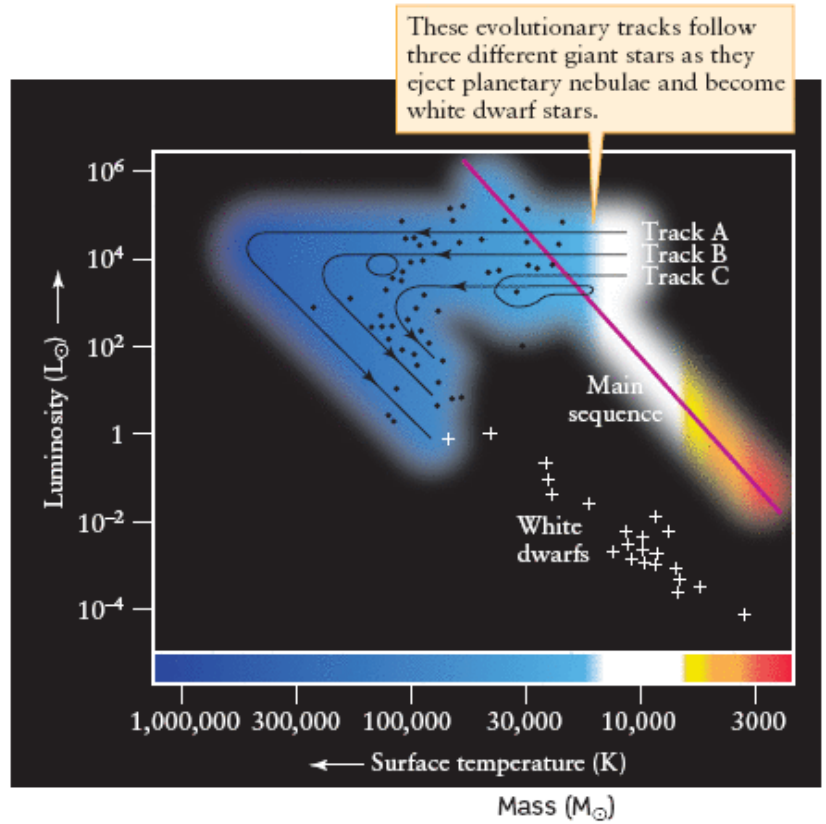
The mass-radius relation for a white dwarf. The maximum mass of a white dwarf, called the *Chandrasekhar limit*, is 1.4 $M_\odot$.

Stellar Evolution: The Death of Stars

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.

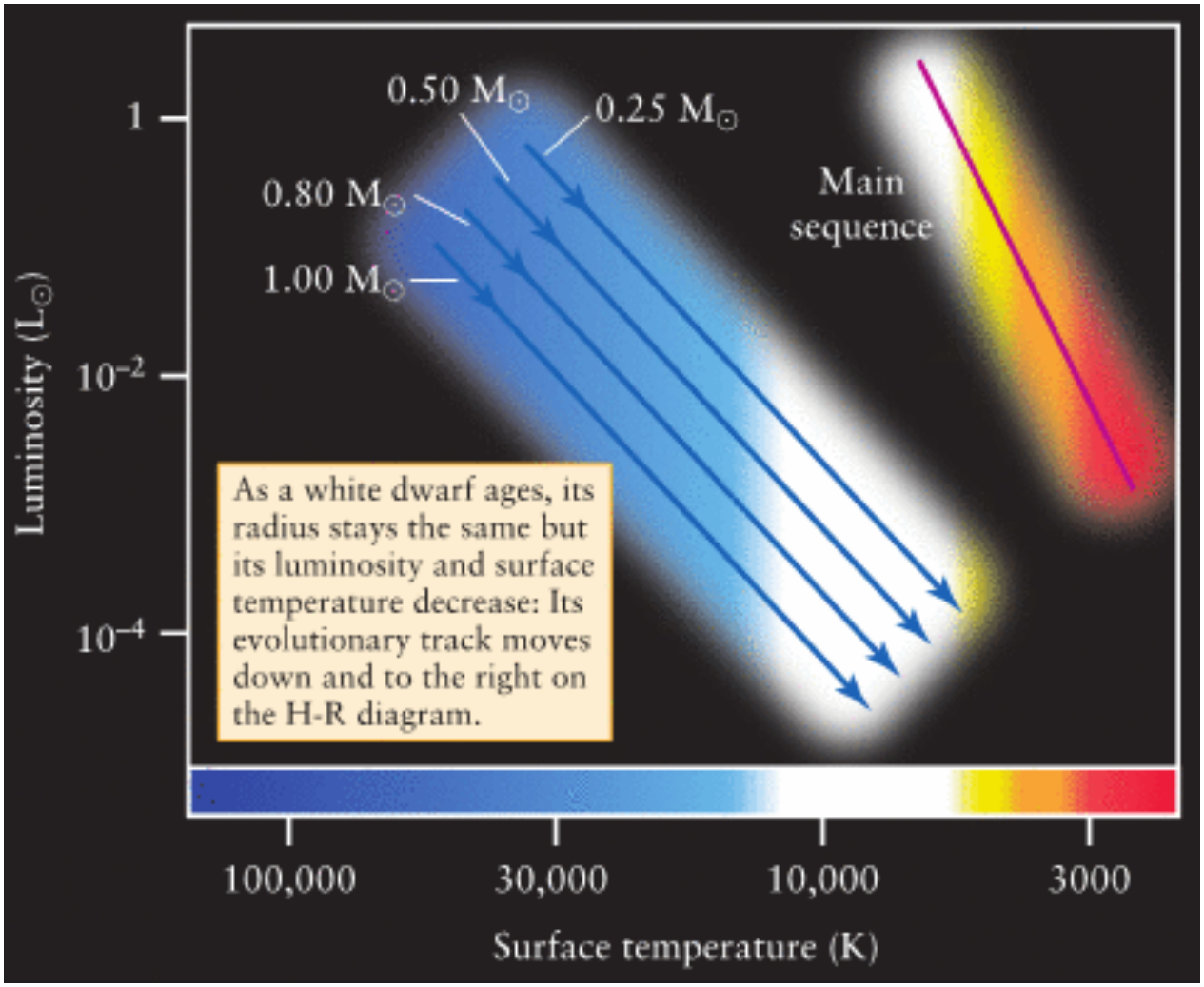
The fraction of material ejected will depend on the mass of the giant star.



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

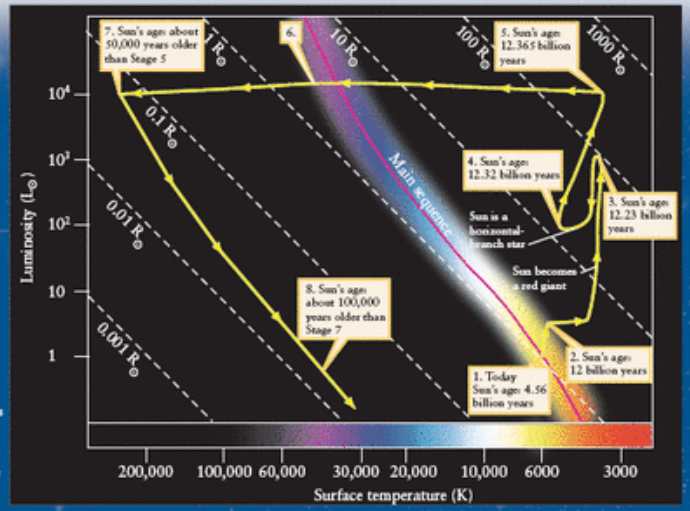
Stellar Evolution: The Death of Stars



COSMIC CONNECTIONS

Our Sun: The Next Eight Billion Years

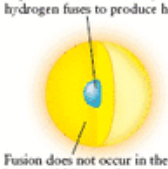
The Sun is presently less than halfway through its lifetime as a main-sequence star. The H-R diagram and cross-sections on this page summarize the dramatic changes that will take place when the Sun's main-sequence lifetime comes to an end.



NOTE: The illustrations below do *not* show the dramatic changes in the Sun's radius as it evolves. The sizes of the various layers are not shown to scale.

1. On the main sequence

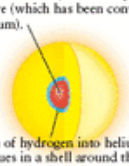
The present-day Sun is a main-sequence star – in its core, hydrogen fuses to produce helium.



Fusion does not occur in the outer layers (which contain predominantly hydrogen and helium).

2. Becoming a red giant

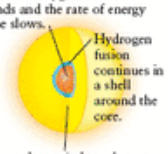
At the end of the Sun's main-sequence lifetime, fusion stops in the core (which has been converted to helium).



Fusion of hydrogen into helium continues in a shell around the core. The core shrinks, accelerating the fusion reactions in the shell and making the outer layers expand and cool.

3. The helium flash

As the core contracts and heats, the core helium begins to fuse to make carbon and oxygen. The core expands and the rate of energy release slows.



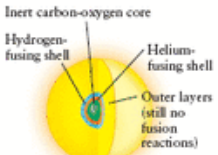
The outer layers (where there are still no fusion reactions) contract and get hotter due to the slower rate of energy release.

4. Beginning the second red giant phase

Once the core helium is consumed, what remains is an inert core of carbon and oxygen. The core again shrinks and gets hotter.

The shrinkage of the core again accelerates fusion reactions in the shells, making the inert outer layers expand and cool.

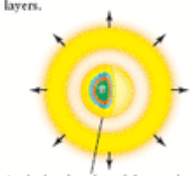
5. The Sun reaches its maximum size



The Sun is more than 100 times larger in radius than when it was a main-sequence star. Part of the outer layers escapes into space in a stellar wind.

6. A planetary nebula

Thermal pulses cause spikes in luminosity that eject the star's outer layers.



As the hot interior of the star is exposed, we observe an increase in the star's surface temperature.

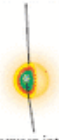
7. The end of nuclear reactions

With the outer layers gone, the pressure on the shells around the core is too little to sustain nuclear reactions.

The star still glows intensely because of its high temperature. As energy is lost in the form of electromagnetic radiation, the star slowly cools.

8. A white dwarf

The core is now a white dwarf star, and the former shells around the core become its thin atmosphere.



The carbon-oxygen interior of the white dwarf is degenerate, so it does not contract as it cools. Hence the white dwarf's radius no longer changes.

Hydrogen and helium, no fusion | Hydrogen fusion producing helium | Helium, no fusion | Helium fusion producing carbon and oxygen | Carbon and oxygen, no fusion

Stellar Evolution: The Death of Stars

Stars with $M < 0.4M_\odot$ have convection all the way through their interior so they end up converting all their H to He and then cool off and leave the main sequence.

Star with $0.4M_\odot < M < 4M_\odot$ fuse H to He and then fuse He to C and O but do not reach large enough densities and temperatures to fuse C.

We now will see what happens to stars with $M > 4M_\odot$.

Stellar Evolution: The Death of 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 $\mathbf{M > 4M_\odot}$ 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 $\mathbf{M > 4M_\odot}$** 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 kelvin carbon fusion begins.

Stellar Evolution: The Death of 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 reaction 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)

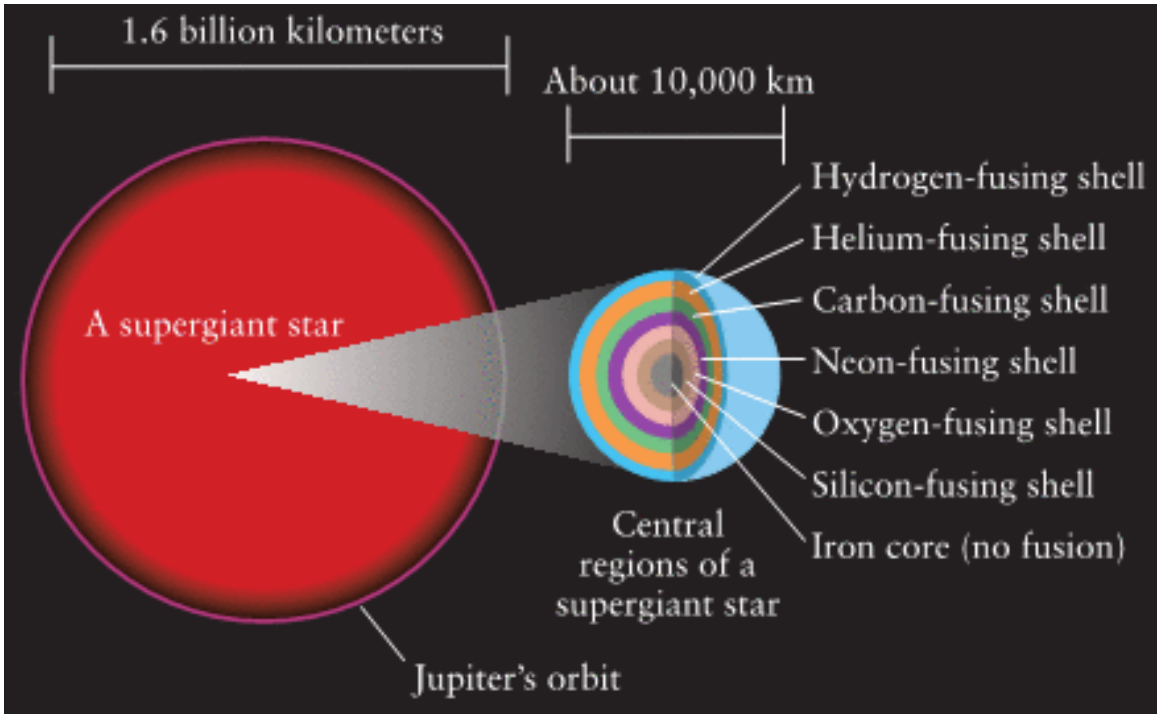
Stellar Evolution: The Death of Stars

Table 20-1 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

Based on calculations by Stanford Woosley (University of California, Santa Cruz) and Thomas Weaver (Lawrence Livermore National Laboratory).

Stellar Evolution: The Death of Stars



The structure of a supergiant star with an initial mass of > 8M$_\odot$. After several stages the core of the supergiant star will have multiple shells of material and its structure resembles that of an onion.

Stellar Evolution: The Death of Stars

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** (endothermic) so the core cannot generate heat from fusion but instead begins to collapse and heat up.

• The **gamma rays** emitted from the hot core have very large energies that break the iron into helium nuclei. This process is called **photodisintegration**.

• Because of the high density electrons combine with protons to form neutrons and neutrinos: $\mathbf{e^- + p^+ \rightarrow n + \nu}$

• 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 $\sim 4\times10^{17}$kg m^{-3}.

Stellar Evolution: The Death of Stars

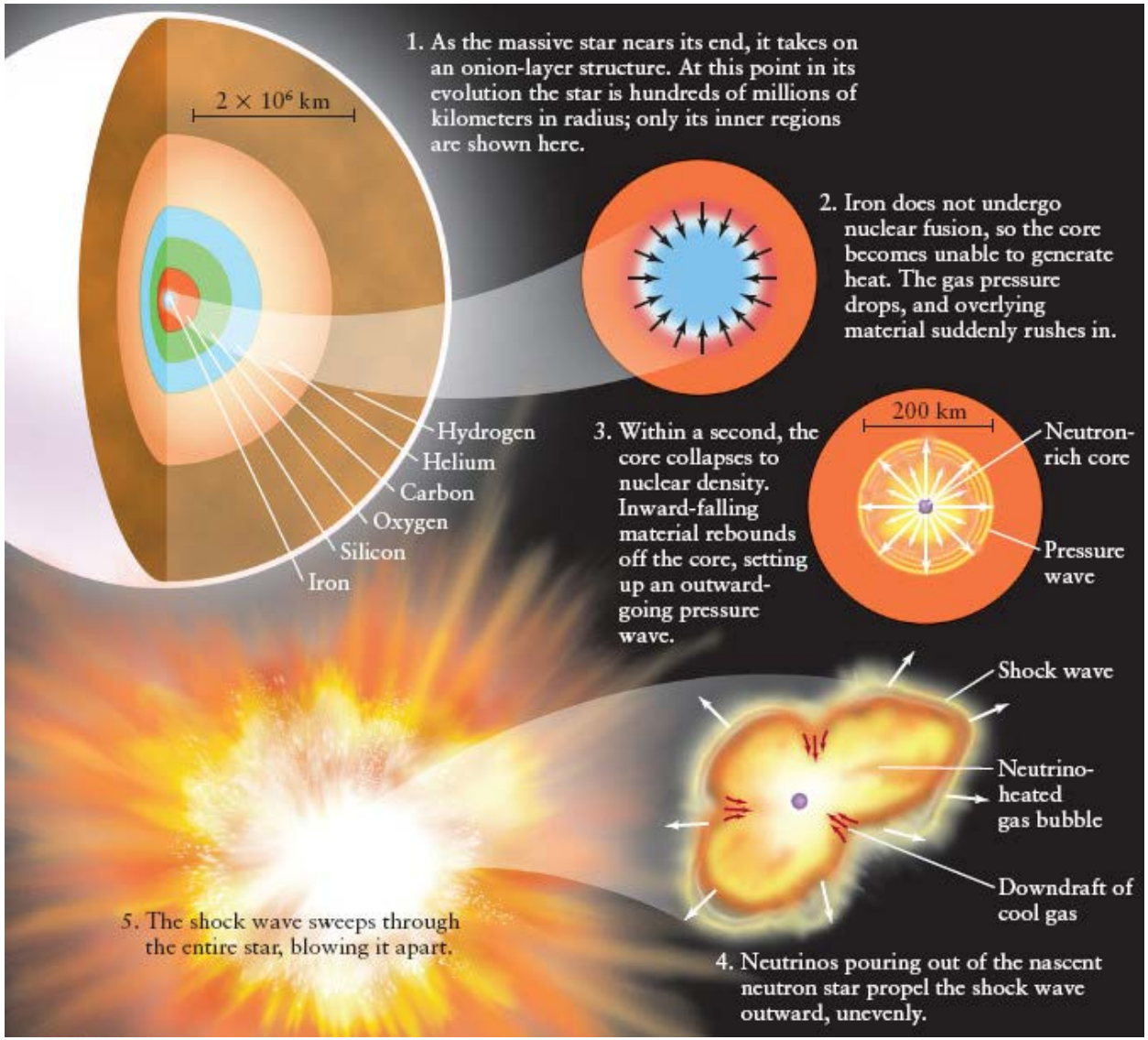
Core Bounce: The core becomes very rigid at nuclear density and further compression results in the innermost part of the core **bouncing back and sending out a pressure wave**.

While the inner core is cooling there isn't enough pressure to hold the outer layers up against gravity, and the **material from the outer layers plunges inward** at speeds of up to 15% of the speed of light.

When the infalling material encounters the outward moving pressure wave it changes direction and starts moving outward reaching supersonic speeds.

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

Stellar Evolution: The Death of Stars



Stellar Evolution: The Death of Stars

ENERGETICS: The energy released in a **core-collapse supernova** explosion is extremely large at ~ 10^{46} Joules!

The **energy released** in a core-collapse supernova explosion **comes from gravitational energy** released by the collapse of the core and the infall of the outer layers of the star.

The gravitational energy released by the collapse of the core is mostly converted into a **burst of neutrinos**.

The gravitational energy released by the infall of the outer layers provides the energy to power the nuclear reactions that generate the supernova's electromagnetic radiation.

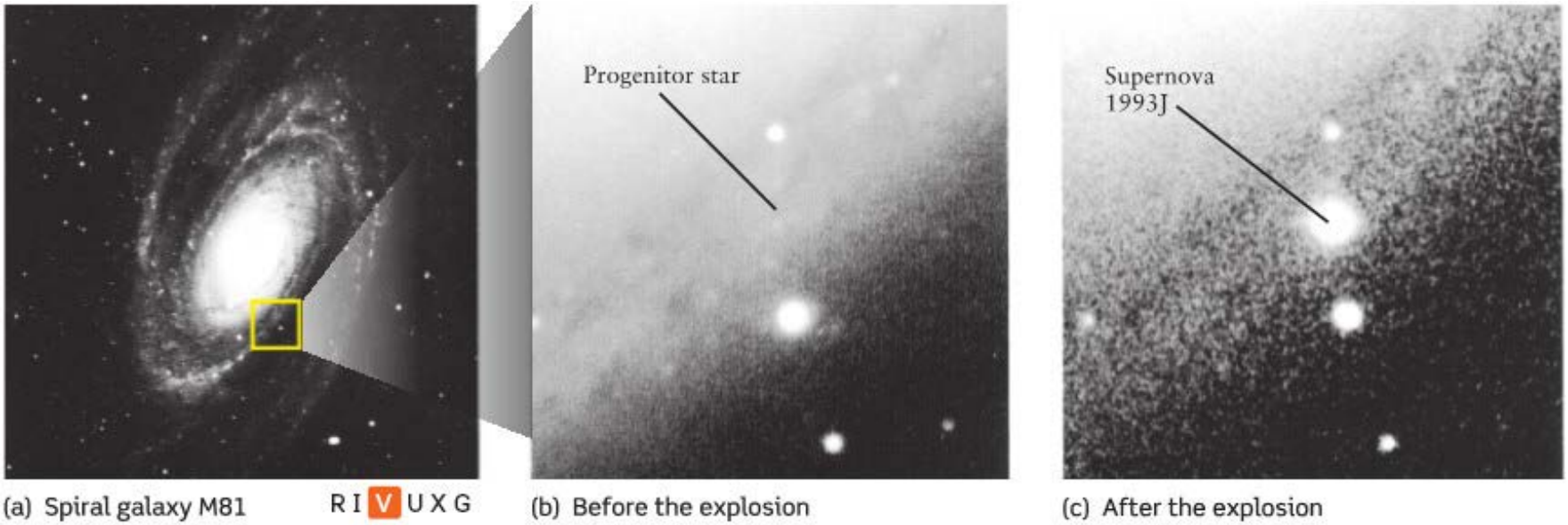
Stellar Evolution: The Death of Stars

Heavy elements are produced during supernova explosions

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 that are even heavier than iron, such as **zinc, silver, tin, gold, mercury, lead, and uranium.**

Since we find these heavy elements on Earth it has been suggested that they were produced long ago by a star that went through a core-collapse supernova.

Stellar Evolution: The Death of Stars



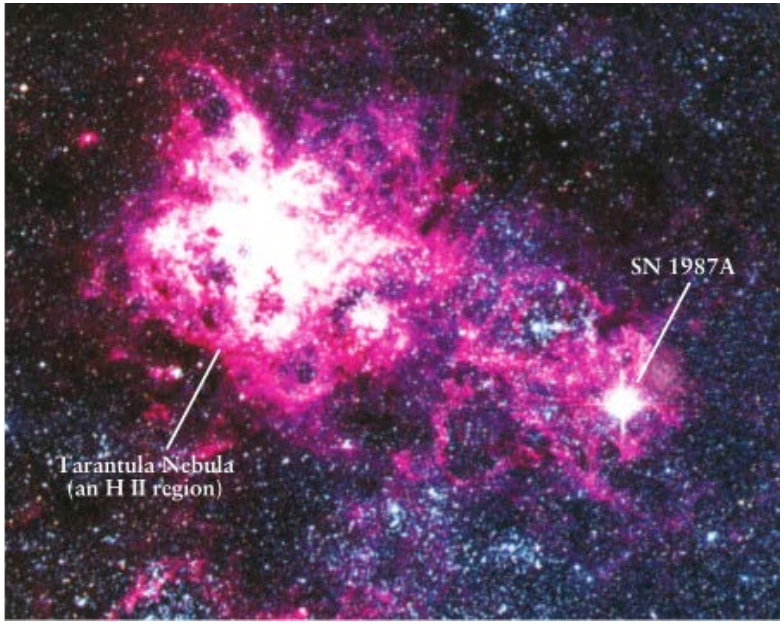
Supernovae are very luminous and can reach peak luminosities of $\sim 10^9\ L_\odot$. Occasionally the **progenitor star is detected** before the explosion. Credit to amateur astronomer Francisco Garcia Diaz for making the discovery of supernova SN 1993J in M81.

Stellar Evolution: The Death of Stars

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

For the first 20 days after the supernova the ejected **outer layers were glowing** from the heat deposited by the shock wave.

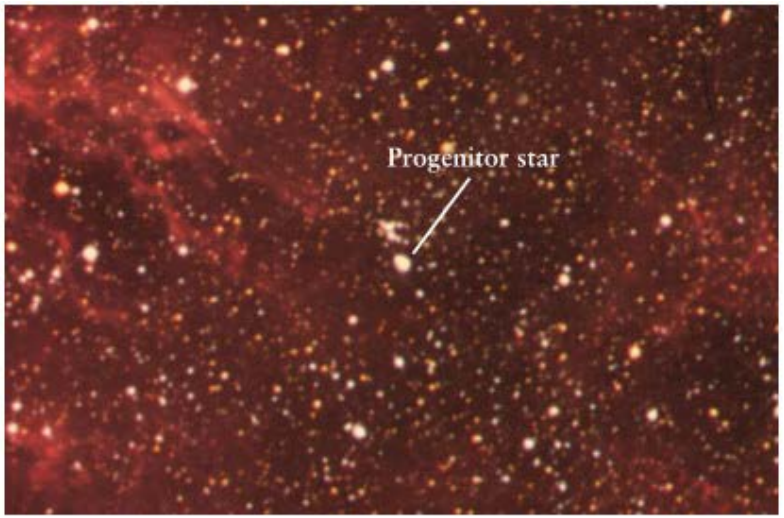
SN 1987 A is also emitting **gamma rays from the decay of radioactive isotopes** created during the supernova explosion.



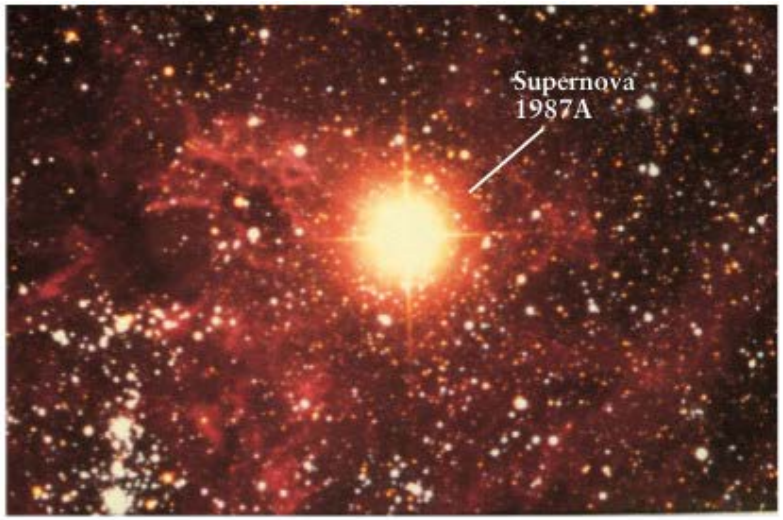
On Feb 1987 a supernova was discovered in the Large Magellanic Cloud (~ 170,000 ly away). It was so bright it could be seen without a telescope in the southern hemisphere.

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

Stellar Evolution: The Death of Stars



(a) Before the star exploded

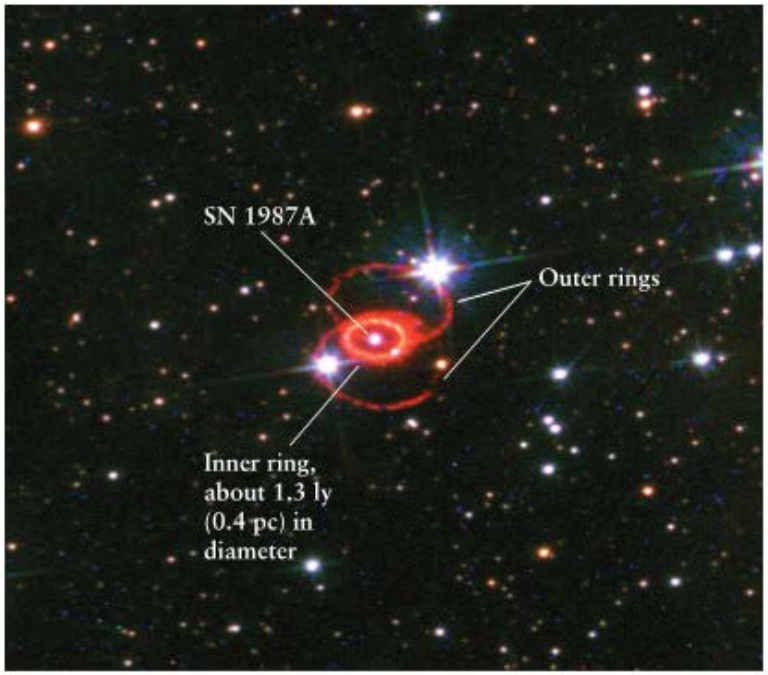


(b) After the star exploded

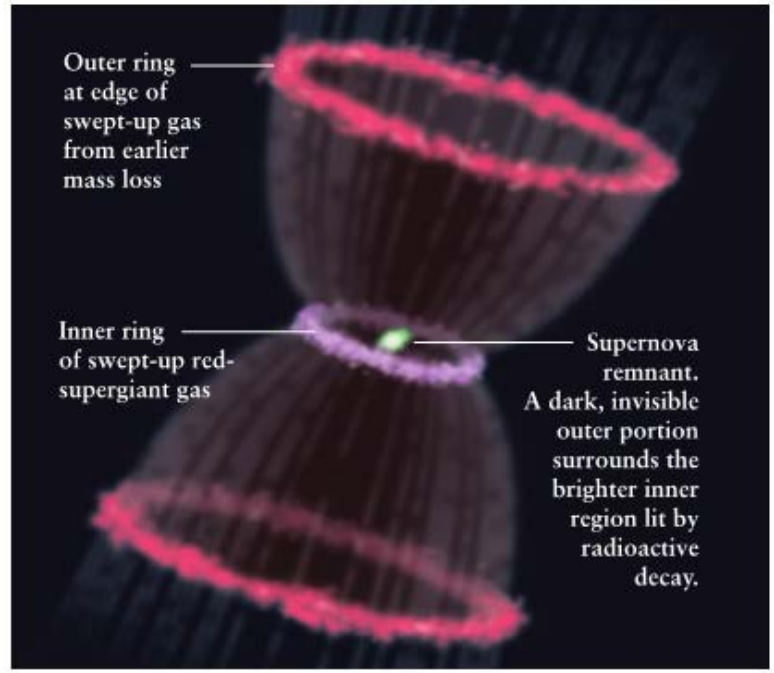
SN 1987A was not typical! Its luminosity peaked at 10^8 $L_\odot$ ~10 times fainter than what was expected. **The progenitor was a B3 I blue supergiant** with a mass of ~20 $M_\odot$. Most stars in the LMC are **population II stars** meaning they have a low abundance of metals compared to population I stars.

Population II stars **alternate from** being cool **red giants to being** hot but smaller in size **blue giants**. During the supernova explosion 1987A was a blue giant. Its smaller size implies that some of the shock wave energy was used to eject the stars outer layers resulting in the low peak luminosity.

Stellar Evolution: The Death of Stars



(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.

Stellar Evolution: The Death of Stars

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 by the following reaction:

$$p^{+} + e^{-} \rightarrow \text{neutron} + \text{neutrino}$$

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 a few hours to reach the surface.

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

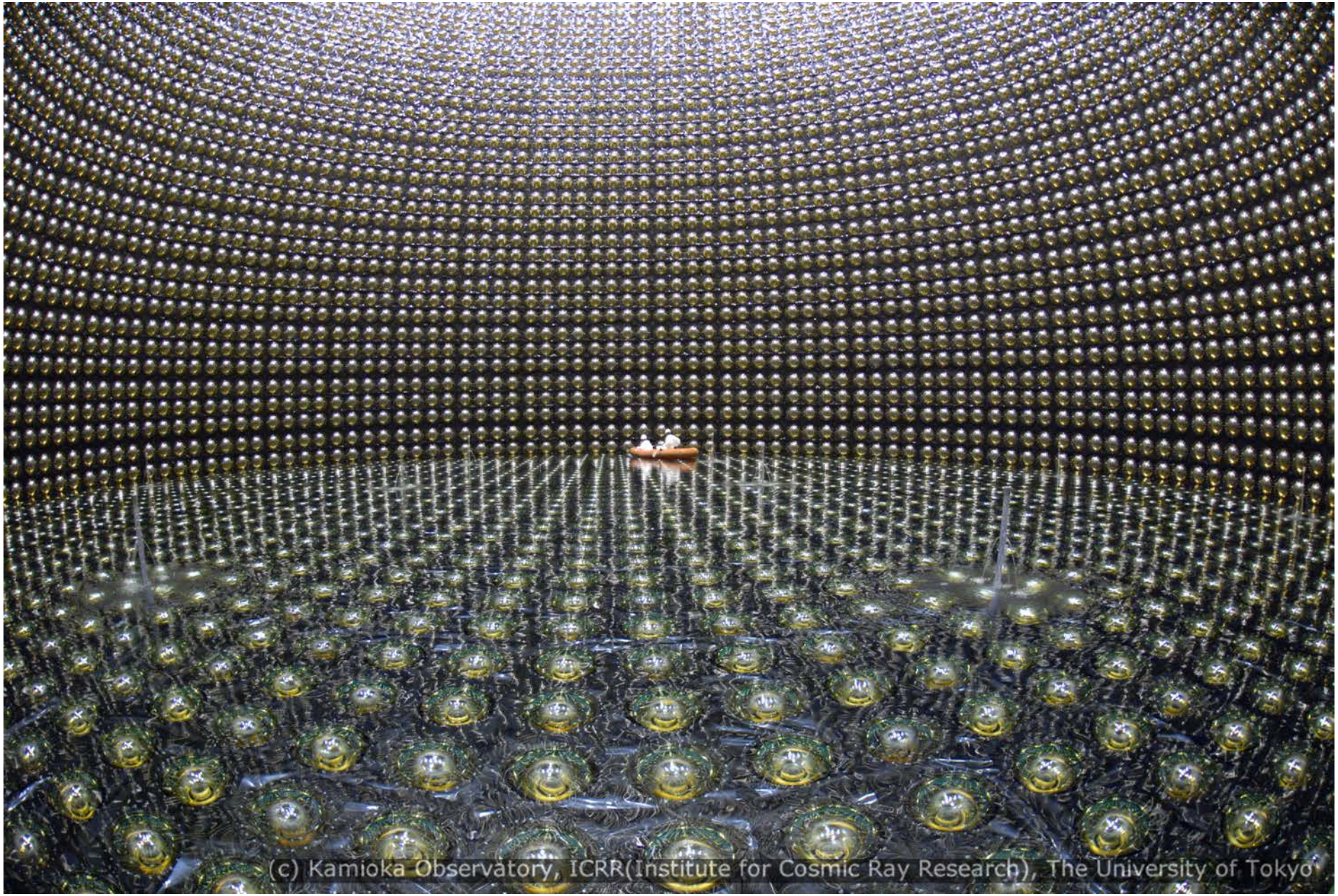
Stellar Evolution: The Death of Stars

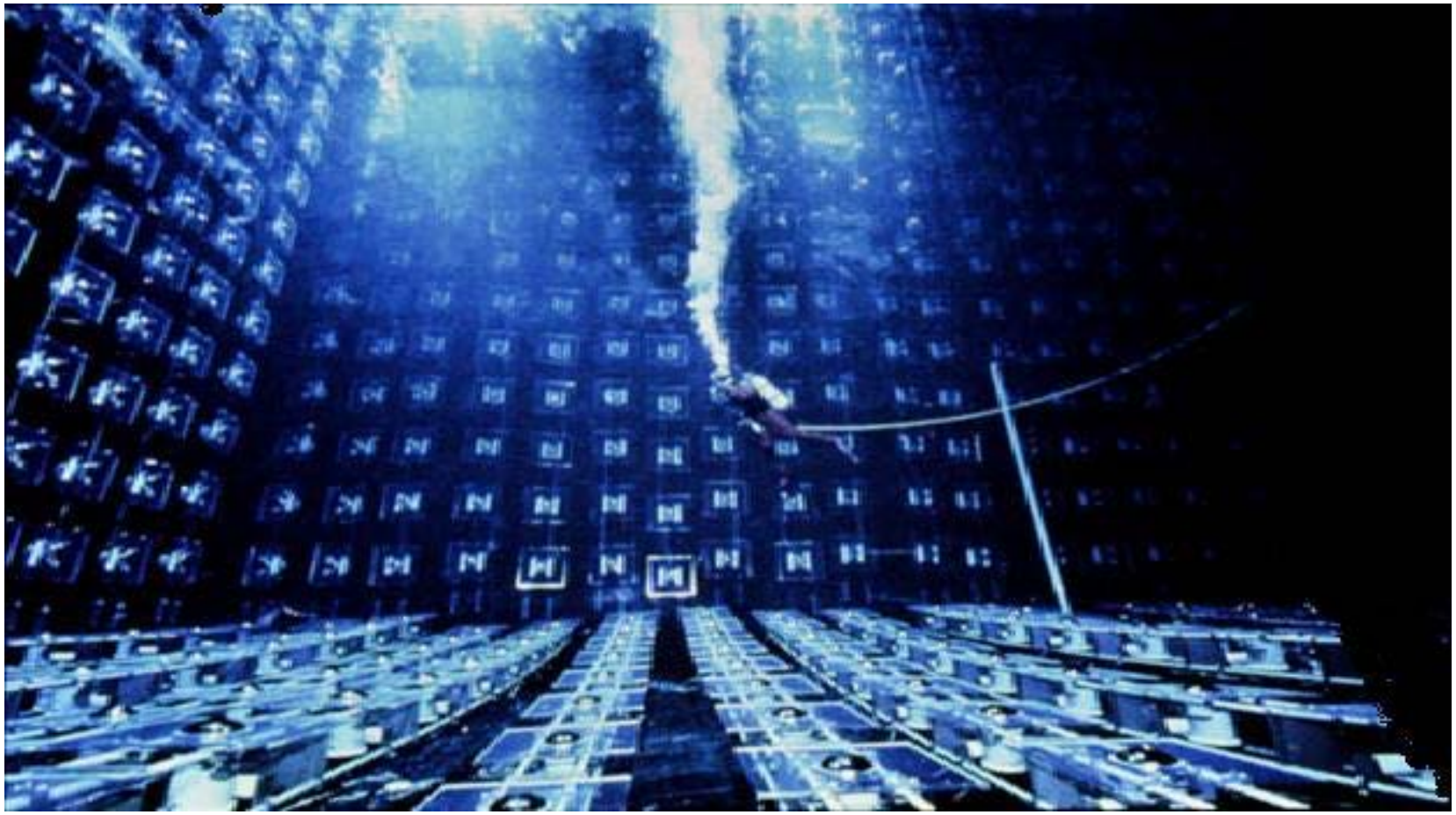
Neutrino telescopes: On a very rare occasion a neutrino collides with the water molecule and creates a neutron and **positron**. The neutron moves undetected but the positron moves at a speed faster than the speed of light in water.

When an **particle moves faster than the speed of light in that medium** it emits a shock wave of radiation (Cerenkov radiation).

Neutrino detectors are placed deep underground to prevent other cosmic particles from creating flashes. Only neutrinos can easily penetrate so deep.

Each neutrino from a collapsed star carries a significant amount of energy ~ 20 MeV.


(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.

Stellar Evolution: The Death of Stars

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

When one factors in the cross section of the detectors to neutrino events the true number of neutrinos that went through these detectors was about 10^{16} !

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!

Stellar Evolution: The Death of Stars

Not all supernovae are the result of the core collapse of a massive star. A different type of supernova occurs when a white dwarf in a binary system explodes.

Different Types of Supernovae:

(1) Supernovae with bright hydrogen emission lines are called **Type II supernovae** and are the result of the core collapse of a highly evolved massive star that still has a lot of hydrogen in its atmosphere when it explodes.

(2) Type I Supernovae have no hydrogen lines in their spectra.

Stellar Evolution: The Death of Stars

Type Ia SN: Accretion onto a white dwarf from a companion star leads to the explosion of the white dwarf. No hydrogen lines are detected in the spectra of type Ia but strong absorption from ionized Si is detected.

Type Ib SN: Core collapse of evolved massive star that has lost most of its hydrogen atmosphere from a stellar wind or by mass transfer to a binary companion.
No H lines but strong He absorption lines are detected.

Type Ic SN: Core collapse of evolved massive star that has lost most of its hydrogen and helium atmosphere from a stellar wind or by mass transfer to a binary companion.
No H lines and no He lines are detected.

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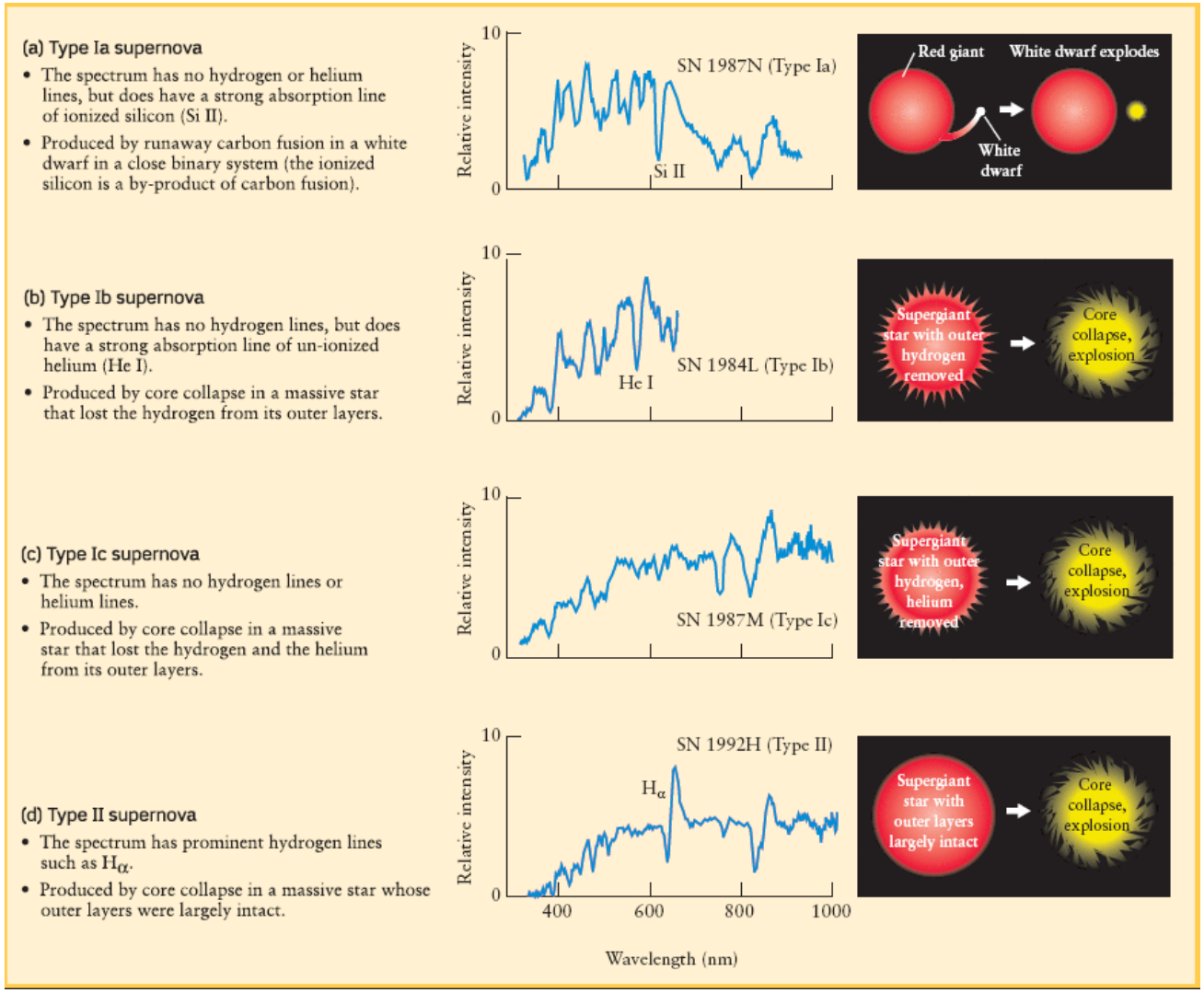


Type II, Type Ib, and Type Ic supernovae all begin as massive stars and all three types are found only near sites of recent star formation! Why?

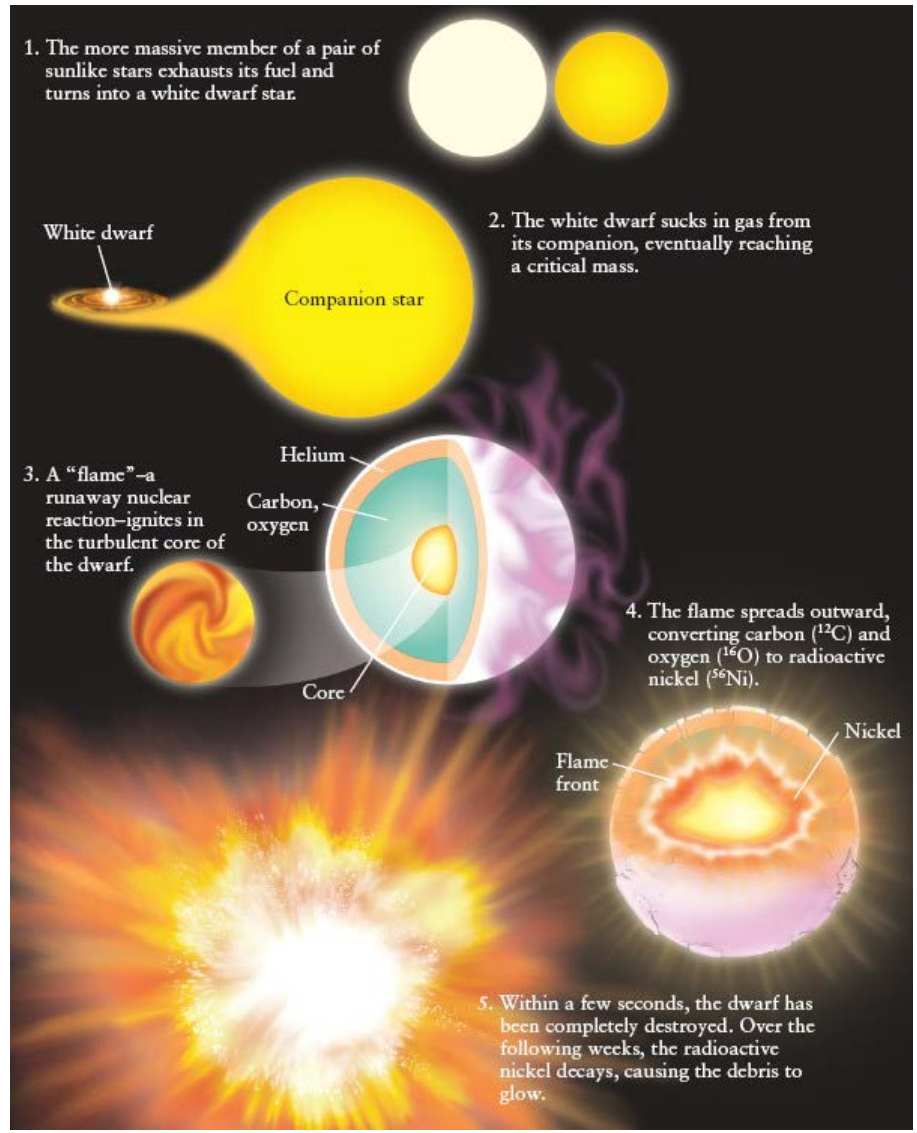
Stellar Evolution: The Death of Stars

Type Ia supernovae are thought to result from the thermonuclear explosion of **a white dwarf star that is in a binary system** with a red giant star.

The **white dwarf sucks in mass from its companion** and eventually the total mass of the white dwarf approaches the *Chandrasekhar limit*.

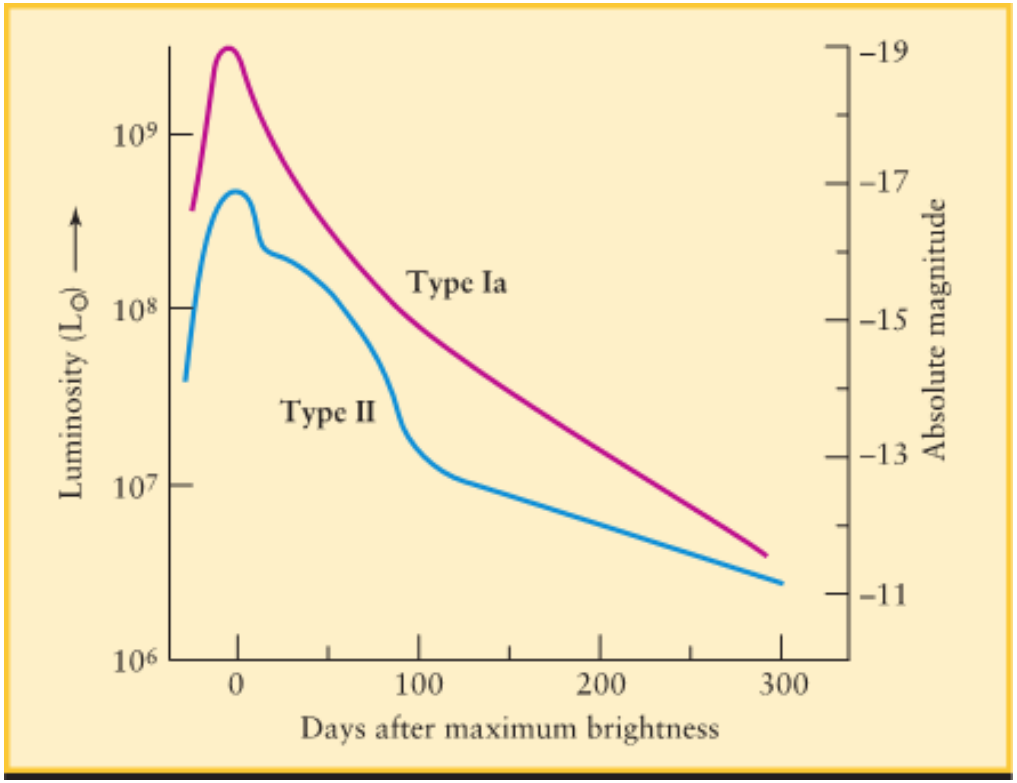
The increased pressure applied to the white dwarf's interior causes **carbon to fuse to silicon in the core** resulting in an increase of the core temperature.

Degenerate matter does not expand with increasing pressure and the nuclear reaction rate increases rapidly.



Stellar Evolution: The Death of Stars

For all supernova types, the energy source during the period of declining brightness is the **decay of radioactive isotopes** produced during the supernova explosion.



Because a different set of thermonuclear reactions occurs for each type of supernova, each type produces a unique set of isotopes that decay at different rates.

The slower a Type Ia supernova fades, the greater its luminosity. Hence, by observing how rapidly a distant Type Ia supernova fades, astronomers can determine its peak luminosity.

Stellar Evolution: The Death of Stars

Supernova Remnant: The gases ejected by a supernova.

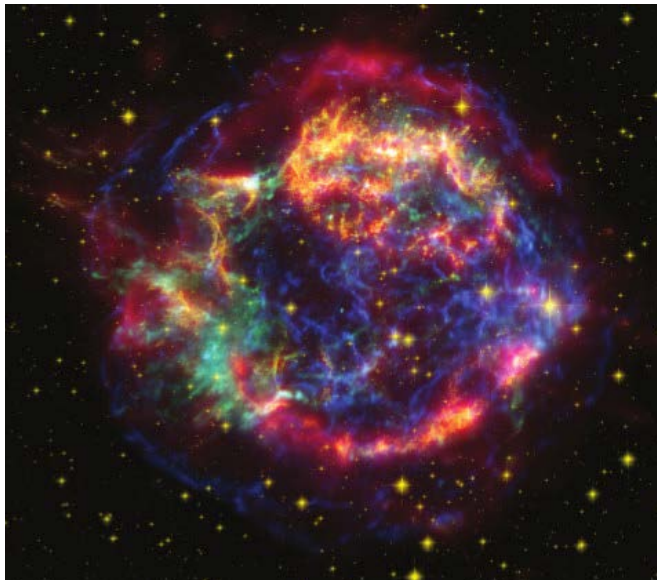
The passage of a supernova remnant through the interstellar medium can trigger the formation of new stars, so the death of a single massive star (in a core-collapse supernova) or white dwarf (in a thermonuclear supernova) can cause a host of new stars to be born.

The Gum Nebula is a Supernova Remnant in our galaxy that occurred about 11,000 years ago.

Stellar Evolution: The Death of Stars

From the frequency with which supernovae occur in distant galaxies, it is reasonable to suppose that a galaxy such as our own should have as many as **five supernovae per century.**

Where have they been?



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.