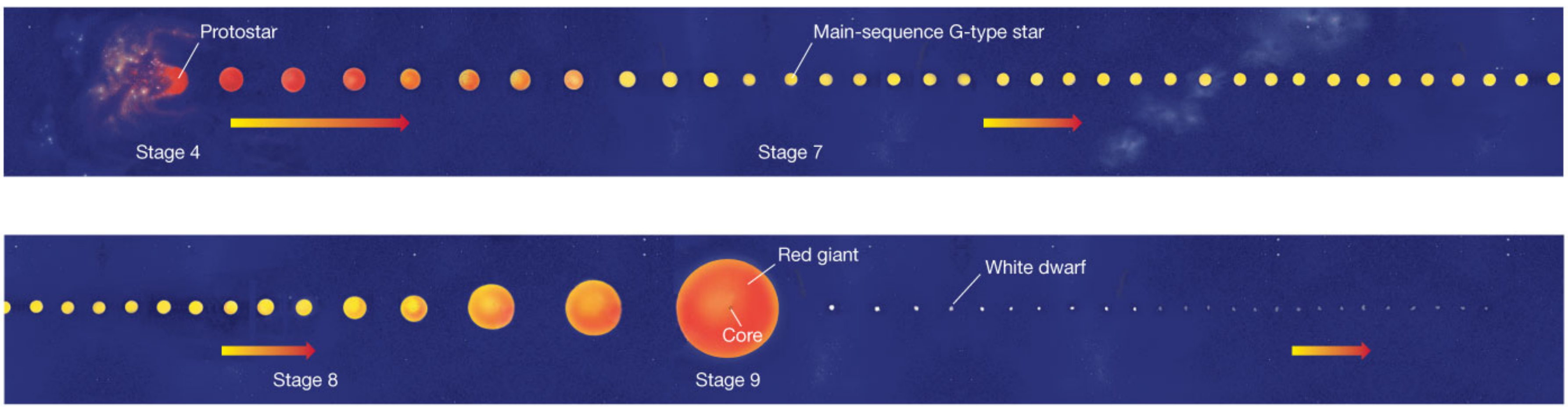
The Deaths of Stars

Death of Low-Mass Stars
Planetary Nebulae
White Dwarfs
Novae
Death of High-Mass Stars
Supernovae
Nucleosynthesis

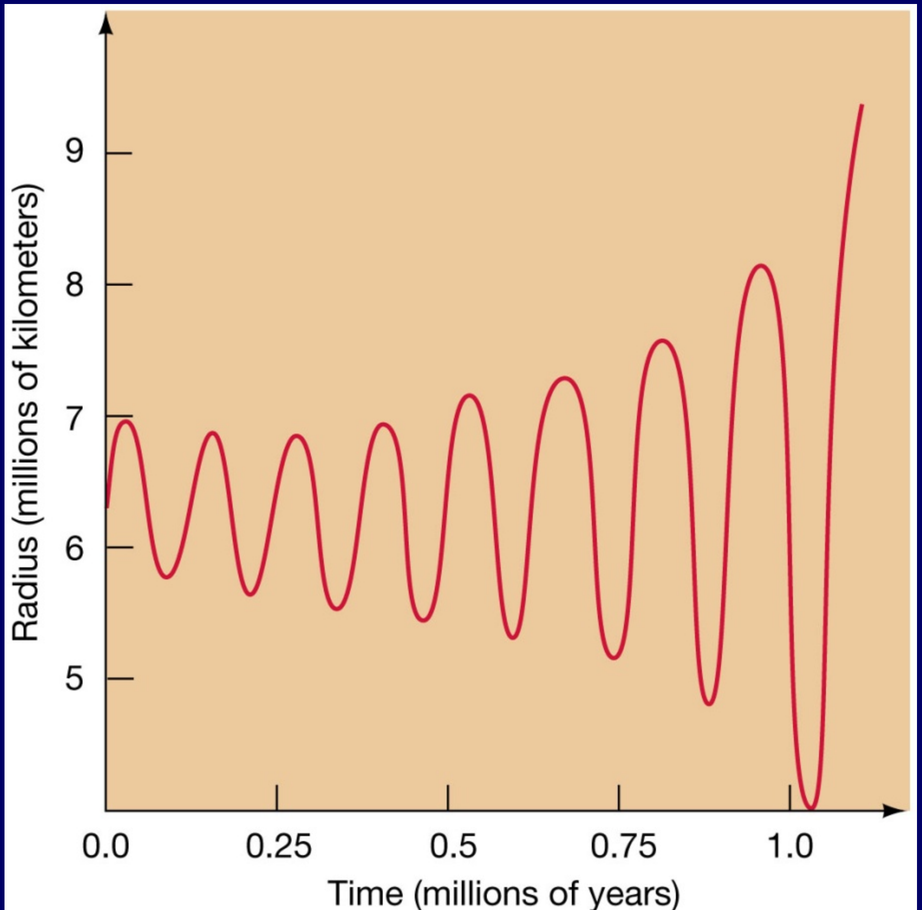
The Death of a Low-Mass Star

- This cartoon shows the entire evolution of a Sun-like star.
- Low-mass stars never become hot enough for fusion past carbon to take place.



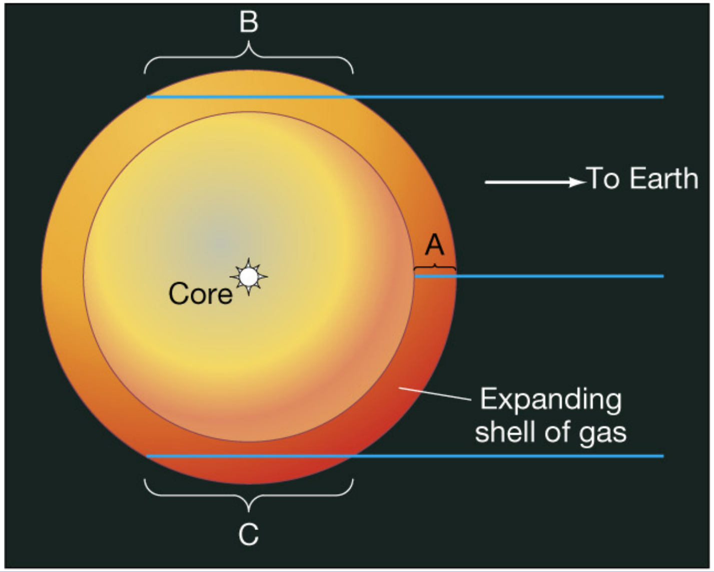
The Death of a Low-Mass Star

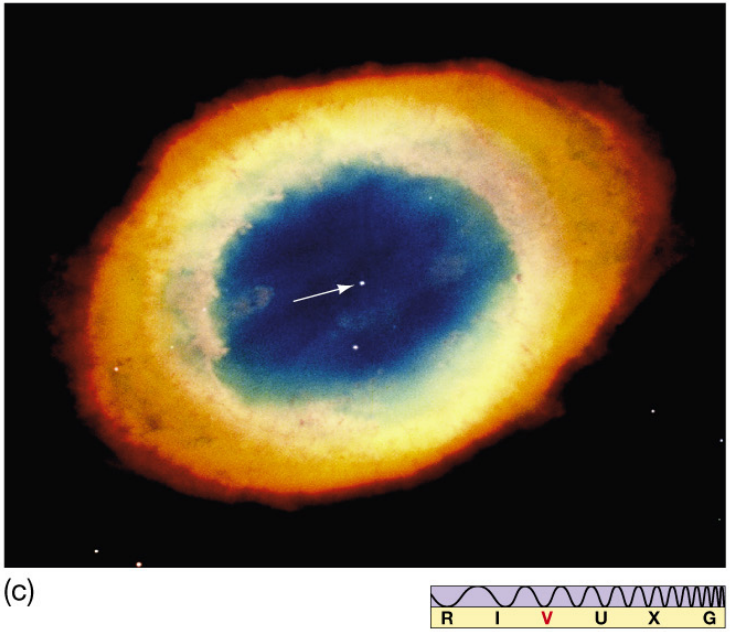
- **There is no more outward thermal pressure being generated in the core, which continues to contract.**
- **Meanwhile, the outer layers begin to pulsate slowly and eventually the gases of the star expand faster than the escape velocity.**



The Death of a Low-Mass Star

(a)





(c)

- **Stages 11-12: When the outer layers reach escape velocity they drift from the star's core and become detached from the star and forming a planetary nebula (above and left).**

The Death of a Low-Mass Star

The star now has two parts:

1. A small star that is the extremely dense core of the original star made of helium, carbon, oxygen, or neon depending on the original size of the star. Gravitational contraction quickly forces the material into electron degeneracy. It is called a white dwarf.

2. An envelope expanding away from the white dwarf. Ones we can see are about the size of our solar system. The envelope is called a planetary nebula, even though it has nothing to do with planets – early astronomers viewing the fuzzy envelope thought it resembled a planetary system and had the apparent color of Uranus and Neptune. The planetary nebula continues to expand. Eventually, its density becomes very low and it is no longer observable.

Planetary Nebulae

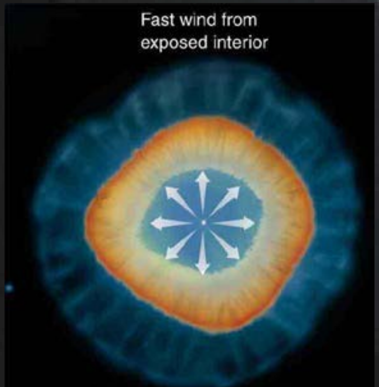
NGC 7293 in Aquarius

The Helix Nebula

The Formation of Planetary Nebulae

Two-stage process:

Slow wind from a red giant blows away cool, outer layers of the star



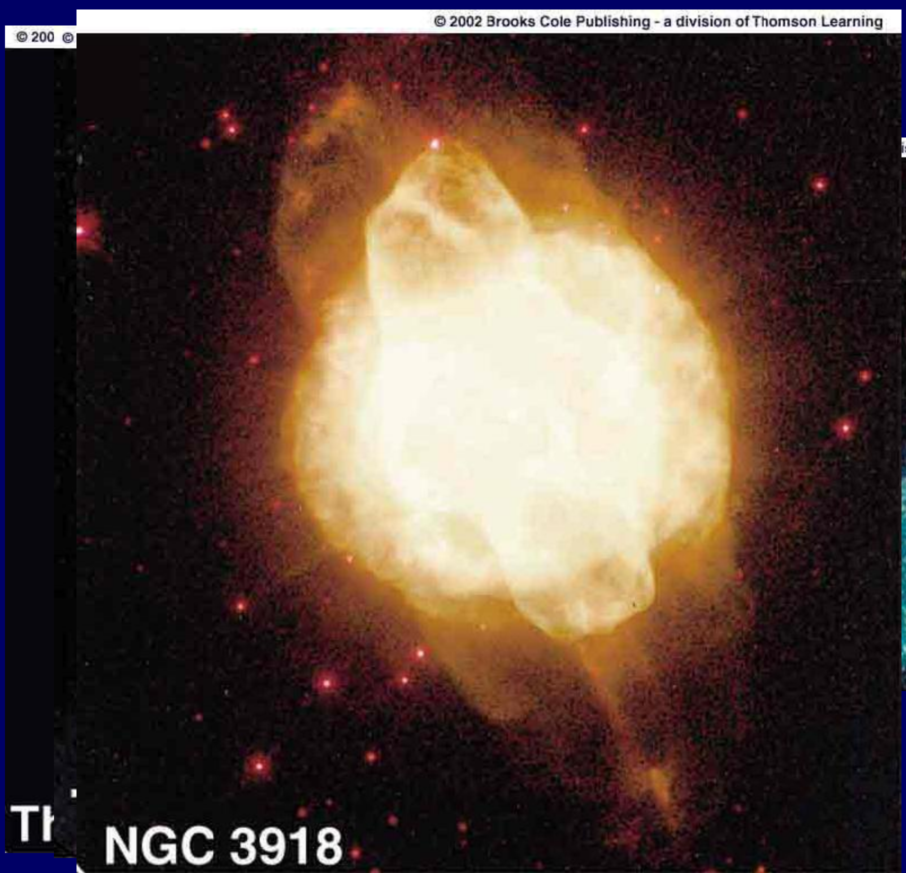
Fast wind from hot, inner layers of the star overtakes the slow wind and excites it
⇒ planetary nebula

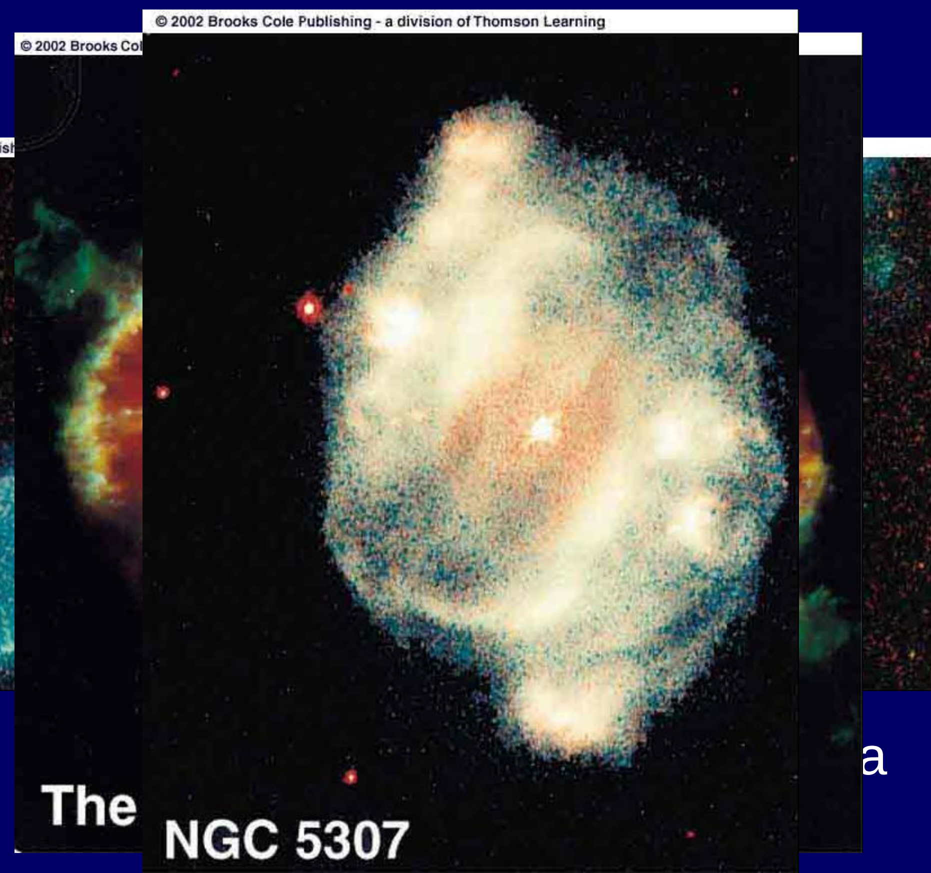
NGC 6720 (M57)
The Ring Nebula in Ly

Planetary Nebulae

Often asymmetric, possibly due to

- **Stellar rotation**
- **Magnetic fields**
- **Dust disks around the stars**

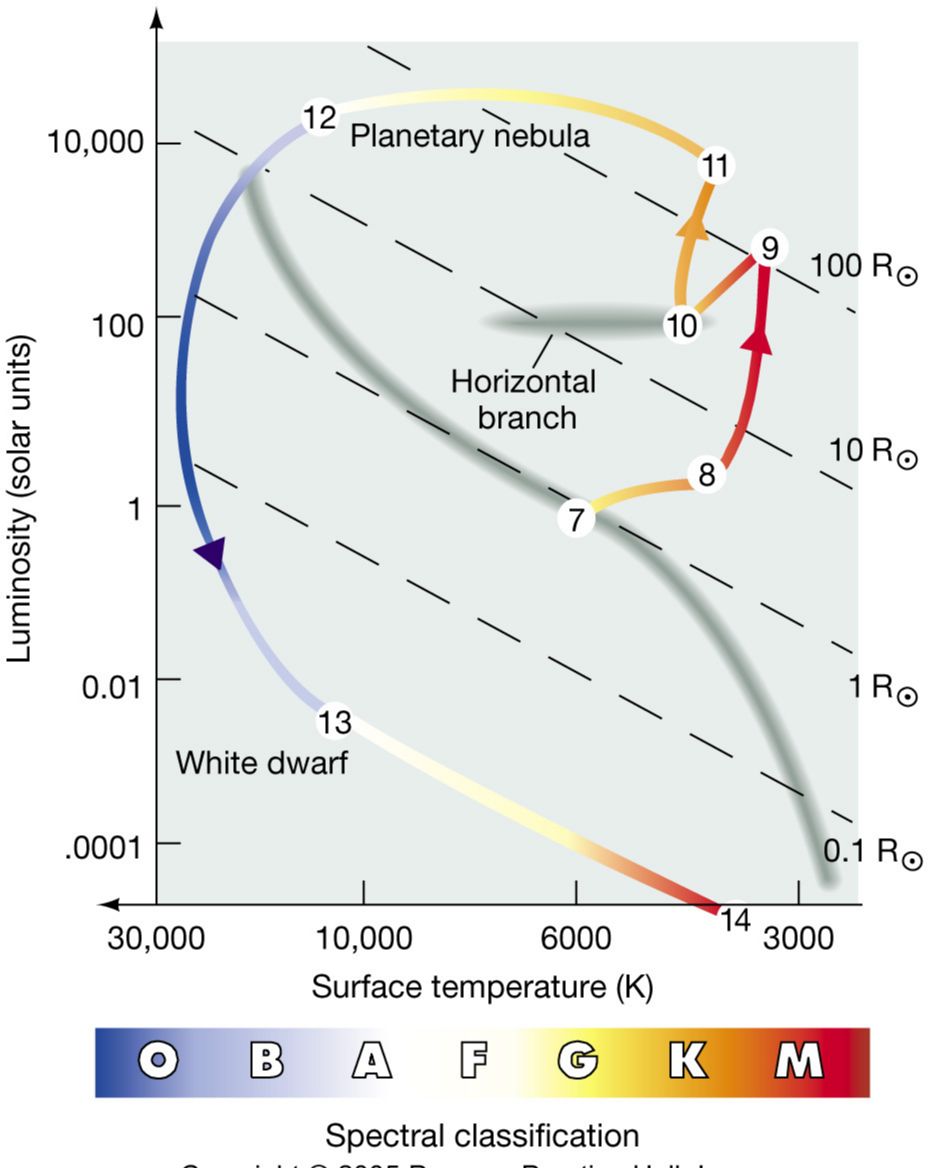




The Death of a Low-Mass Star

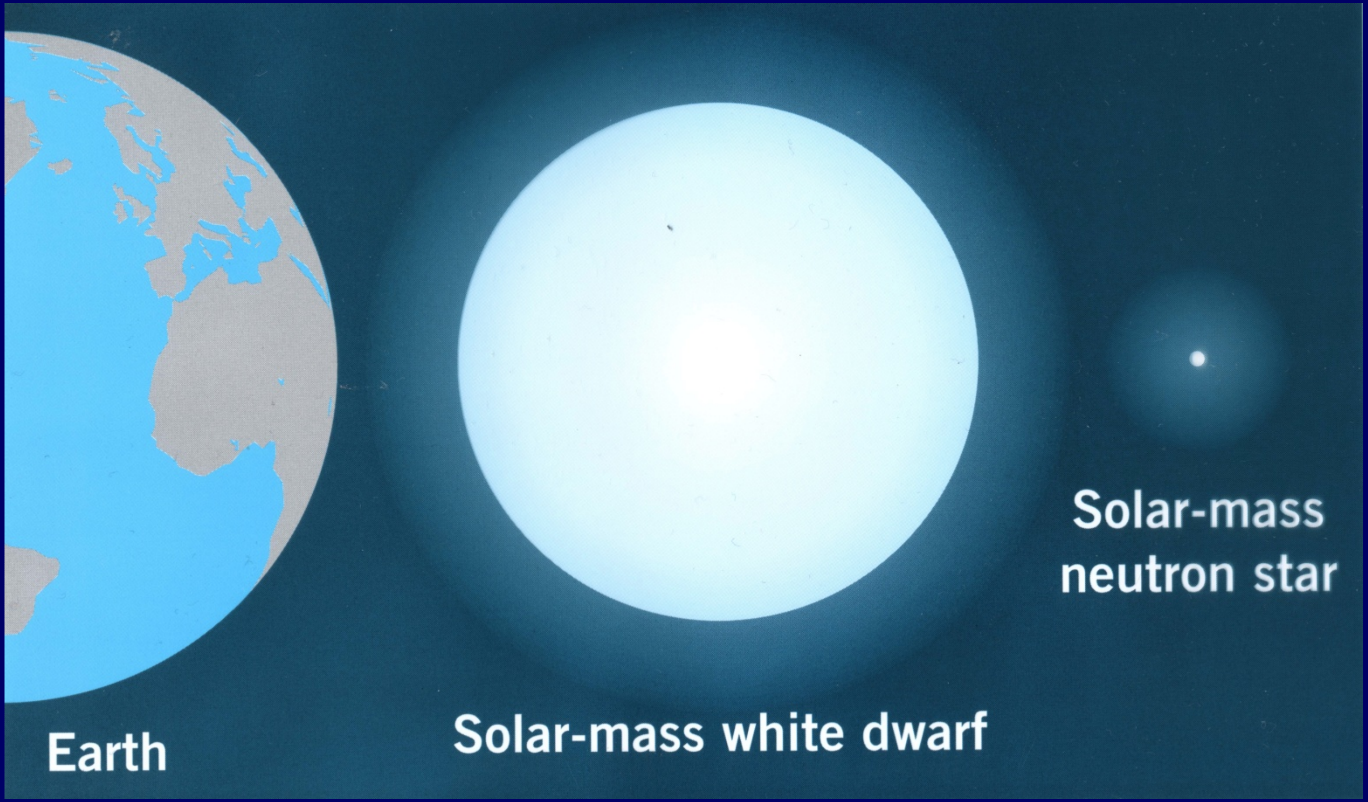
Stages 13-14: White and black dwarfs

- Centered in the planetary nebula is the remaining core which is extremely dense and extremely hot, but quite small. It is called a **white dwarf**.
- It is luminous only because of its high temperature. The luminosity decreases as it cools by radiation.
- When its luminosity decreases to the point where it is unobservable, it is called a **black dwarf**.



Properties of White Dwarfs

- An electron degenerate stellar remnant (He, C,O or Ne core)
- Extremely dense: 1 teaspoon of white dwarf material has a mass ≈ 16 tons!!! A chunk of white dwarf material the size of a beach ball would outweigh an ocean liner!

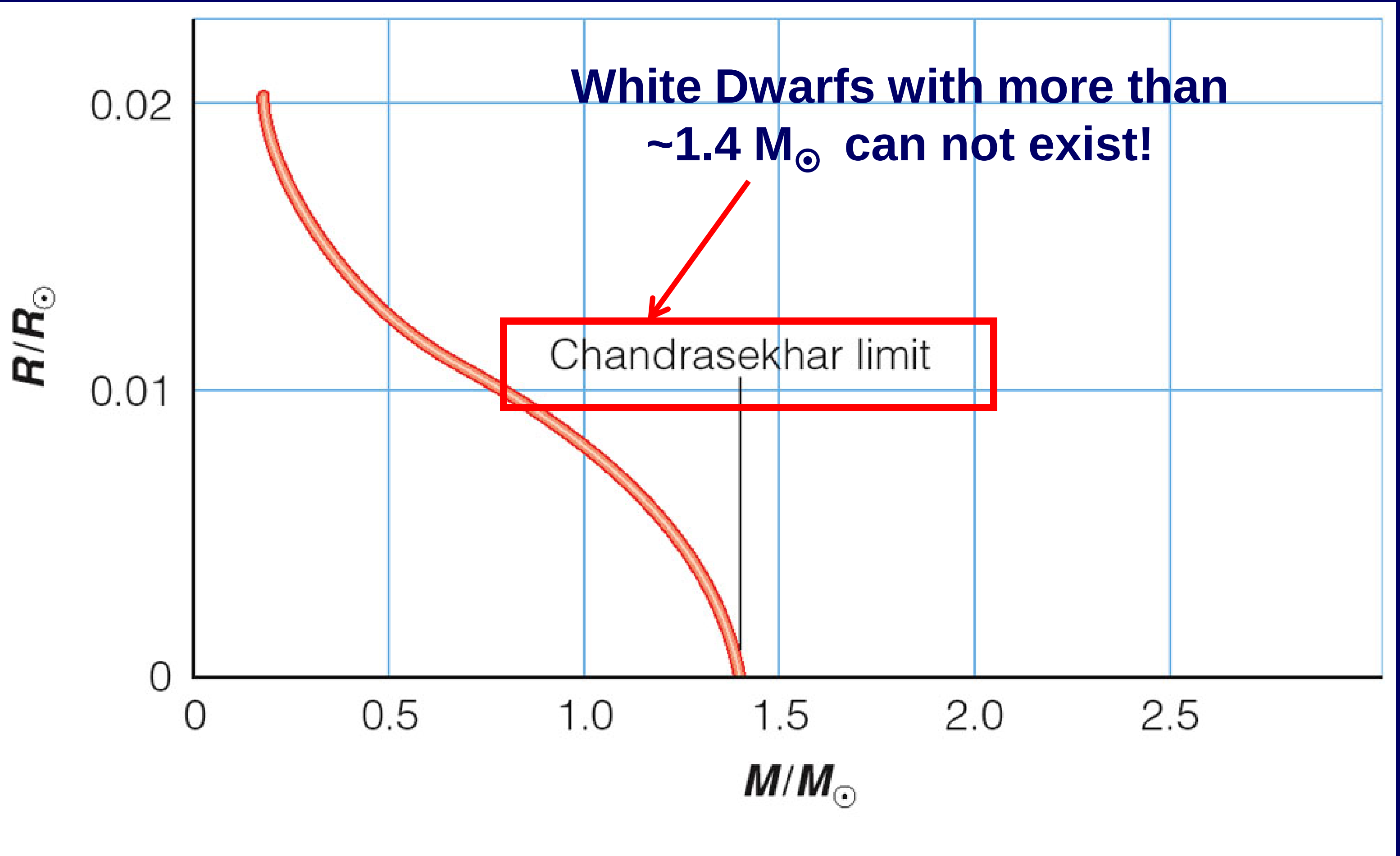


White Dwarfs:

- Mass: ~1 $M_{\odot}$
- Temp.: ~25,000 K
- Luminosity: ~0.01 $L_{\odot}$
- Radius: ~1 $R_{\oplus}$
- Remnants of stars with ~1 – a few $M_{\odot}$
- Expanding at ~10 – 20 km/s (from Doppler shifts)
- Less than 10,000 years old

The Chandrasekhar Limit

The more massive a white dwarf, the smaller it is. Pressure becomes larger, until electron degeneracy pressure can no longer hold up against gravity. The maximum mass of a star that can be supported by electron degeneracy is ~1.4 $M_{\odot}$, the Chandrasekhar limit.



The Death of a Low-Mass Star

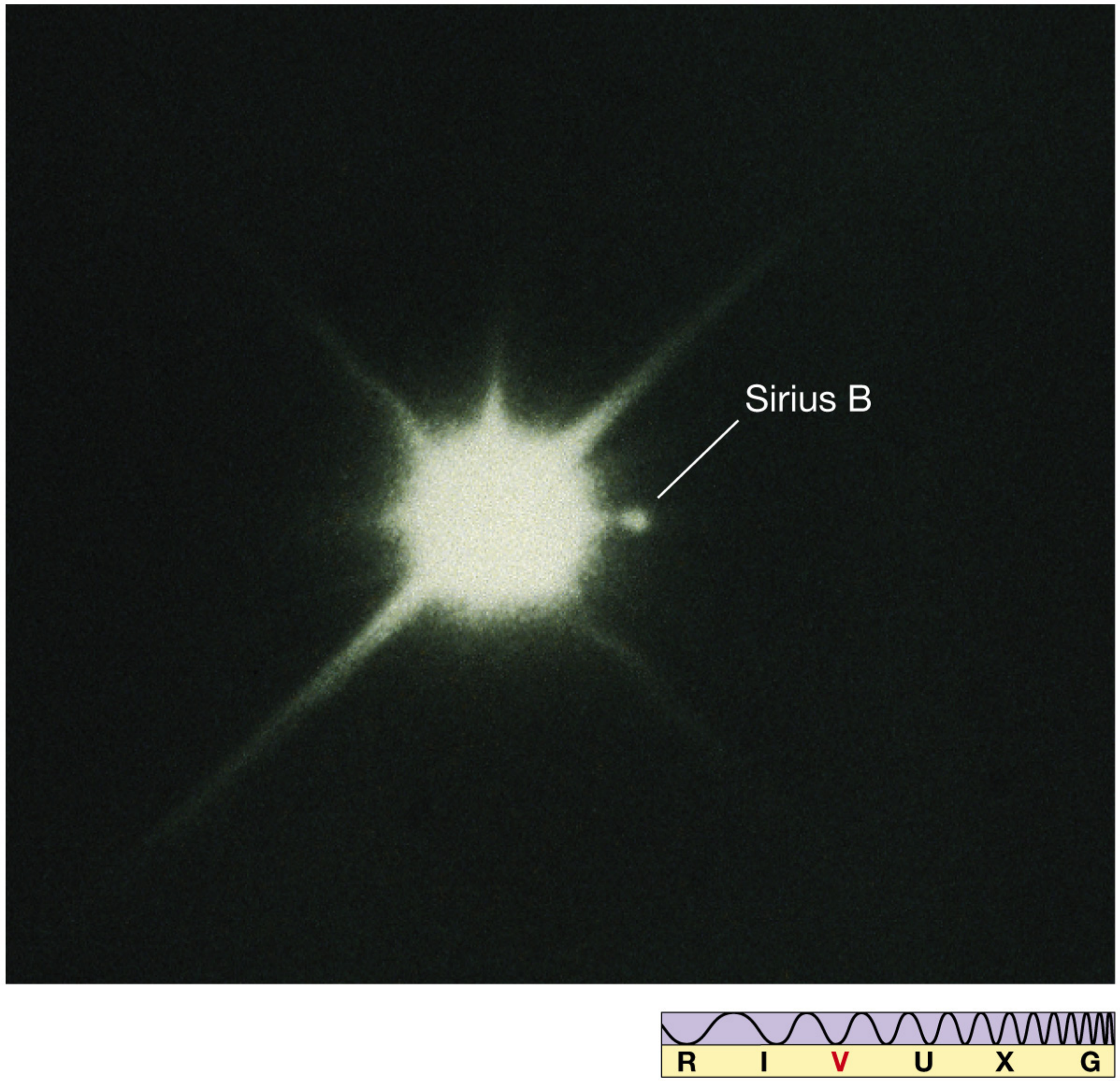
The small star Sirius B is a white-dwarf companion of the much larger and brighter Sirius A

Sirius is the brightest star in the northern sky and has been recorded throughout history. But there is a mystery!

All sightings recorded between about 100 BCE and 200 CE describe it as being red—it is now blue-white. Why?

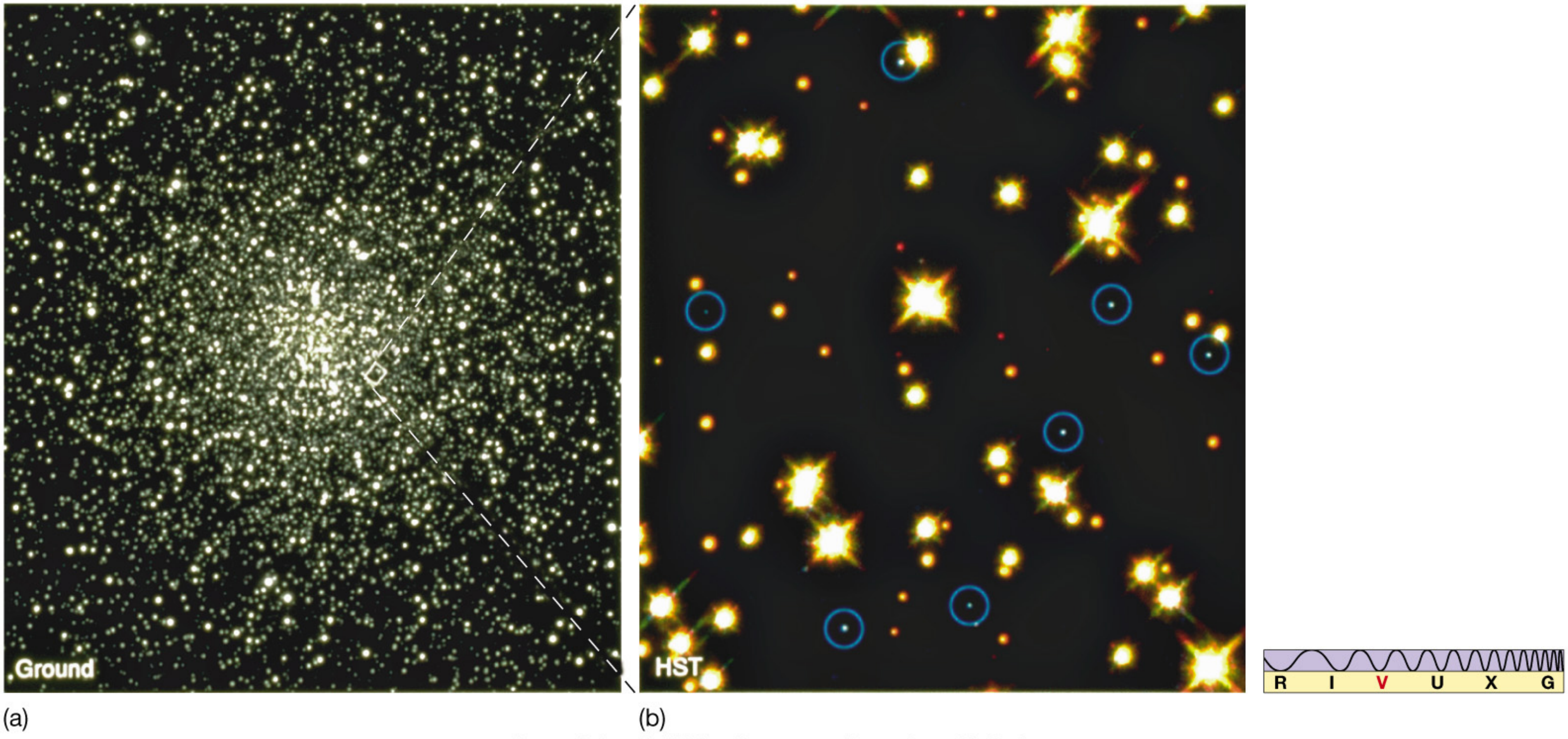
Could there have been an intervening dust cloud? (Then where is it?)

Could its companion have been a red giant? (It became a white dwarf very quickly, then!)



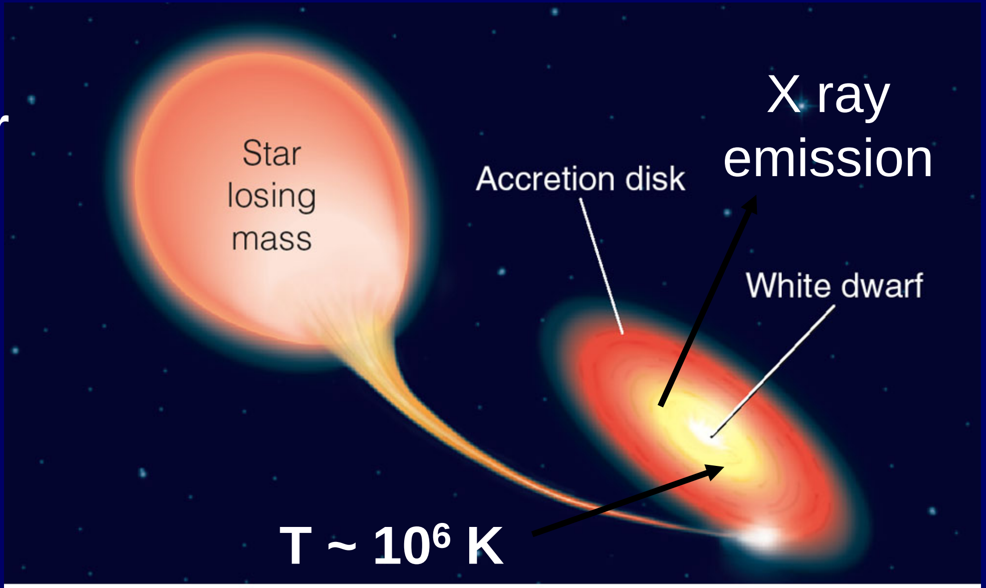
The Death of a Low-Mass Star

The *Hubble Space Telescope* has detected white dwarf stars (circled) in globular clusters



White Dwarfs in Binary Systems

- A close binary system consisting of a white dwarf + a main-sequence or red giant star $\Rightarrow$ white dwarf can accrete matter from the companion
- Conservation of angular momentum $\Rightarrow$ accreted matter forms a disk, called an **accretion disk**.



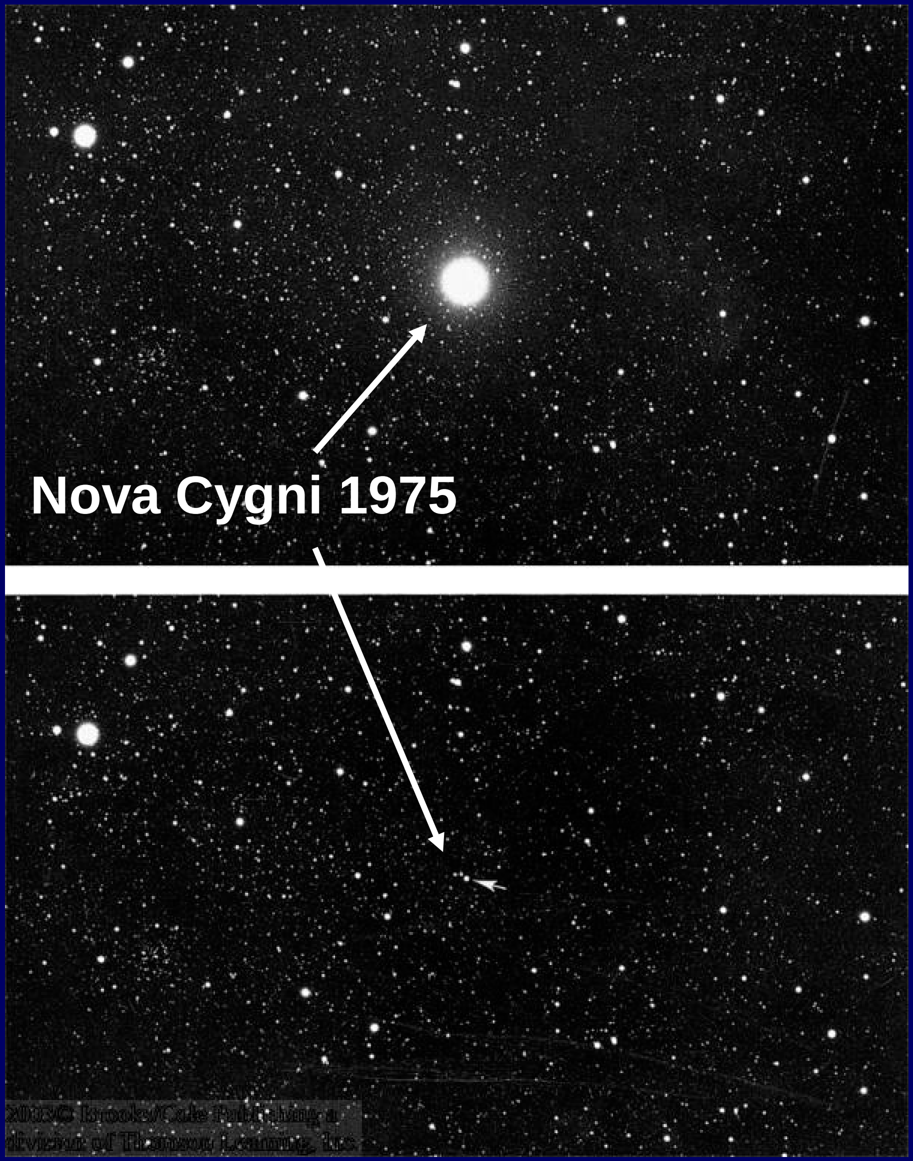
Matter in the accretion disk heats up to ~1 x 10^6 K

$\Rightarrow$ X ray emission

$\Rightarrow$ "X ray binary".

Nova Explosions

During the Nova



Before and after the Nova

Hydrogen accreted through the accretion disk accumulates on the surface of the white dwarf

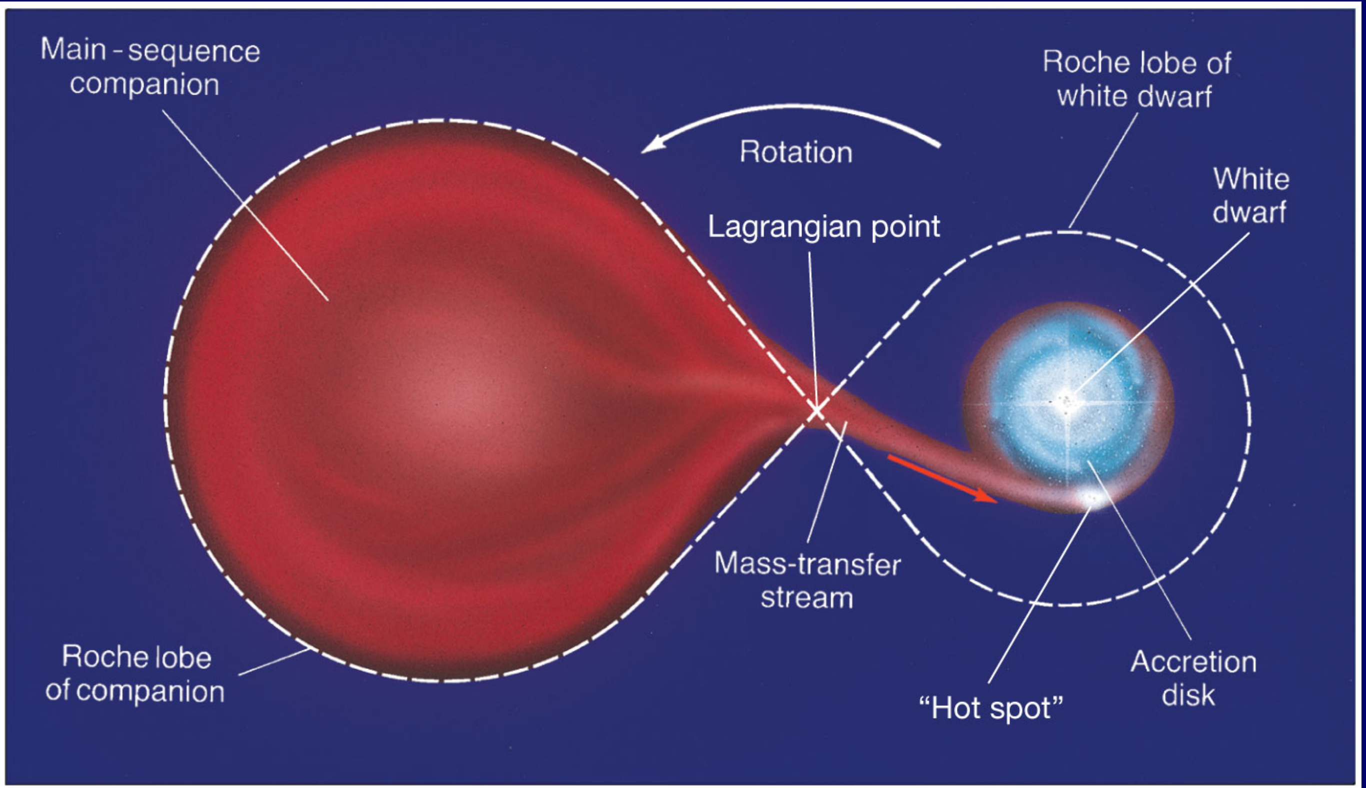
⇒ **Very hot, dense layer of non-fusing hydrogen on the white dwarf surface**

⇒ **Explosive onset of H fusion**

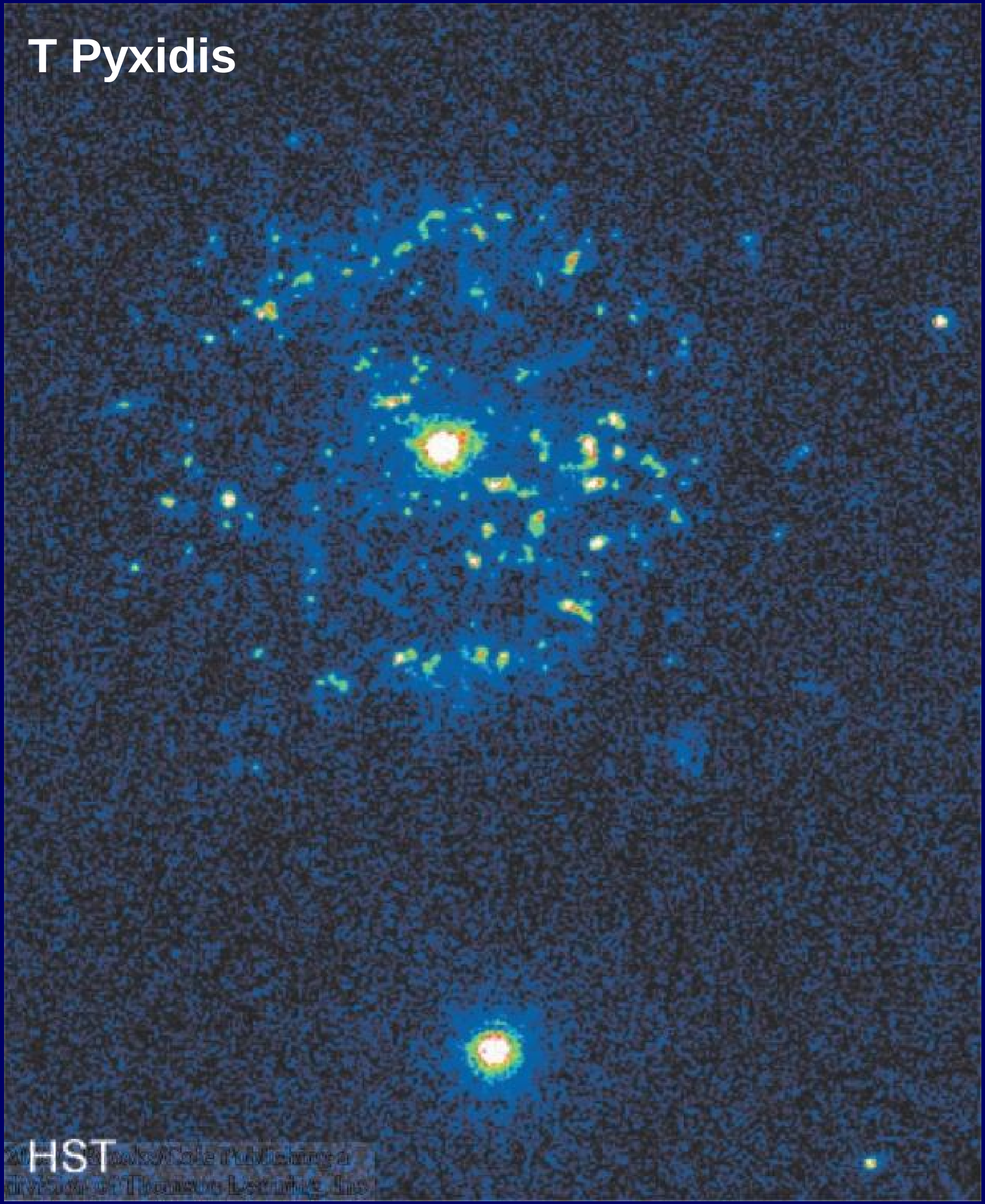
⇒ **Nova explosion**

Recurrent Novae

A white dwarf that is part of a semidetached binary system can undergo repeated novae.



Material falls onto the white dwarf from its main-sequence companion. When enough material has accreted, fusion can reignite very suddenly, burning off the new material. Material keeps being transferred to the white dwarf, and the process repeats.



Recurrent Novae

In many cases, the mass transfer cycle resumes after a nova explosion.

$\Rightarrow$ Cycle of repeating explosions every few years – decades.

The Fate of our Sun and the End of Earth

- Sun will expand to a red giant in ~5 billion years
- Expands to ~Earth's orbit
- Earth will then be incinerated!
- Sun may form a planetary nebula (but uncertain)
- Sun's C,O core will become a white dwarf

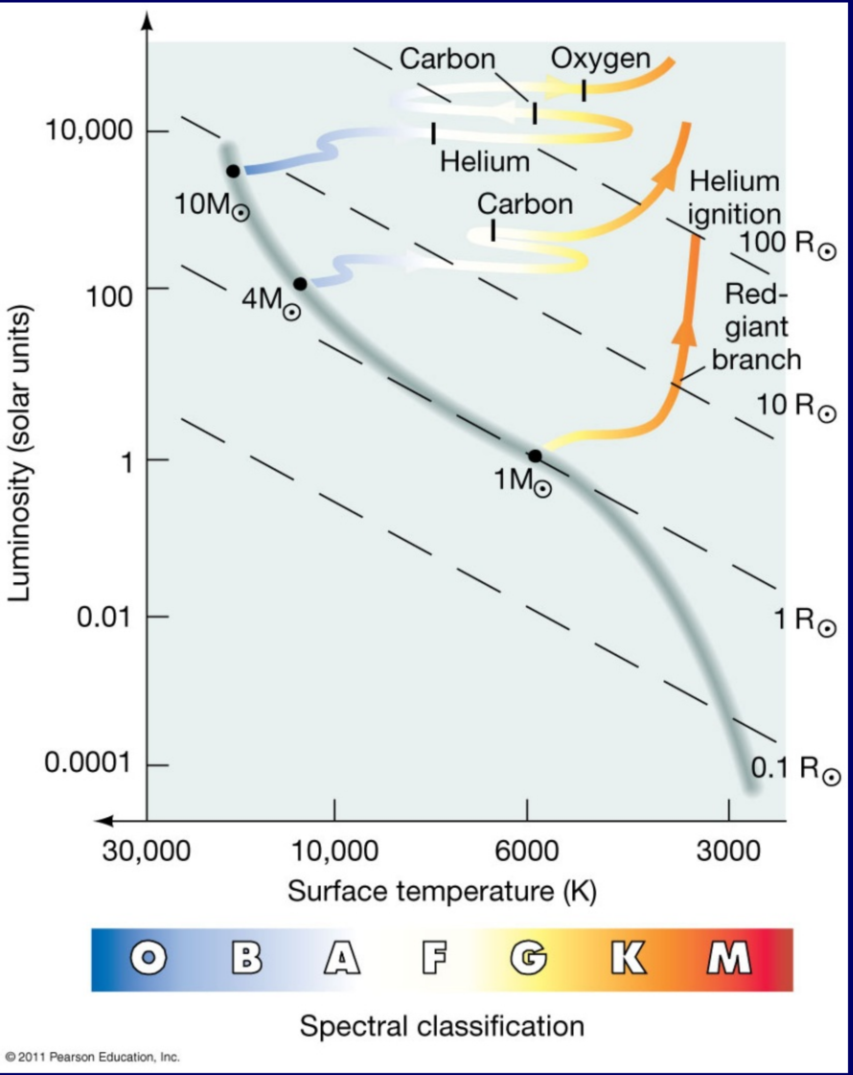
Evolution of Stars More Massive than the Sun

Stars more massive than the Sun follow different paths when leaving the Main Sequence

- High-mass stars, like all stars, leave the Main Sequence when there is no more hydrogen fuel in their cores.
- The first few events are similar to those in lower-mass stars—first a hydrogen shell, then a core burning helium to carbon, surrounded by helium- and hydrogen-burning shells.
- Stars with masses more than 2.5 solar masses DO NOT experience a helium flash—helium burning starts gradually.

Evolution of Stars More Massive than the Sun

- A 4 $M_\odot$ star makes no sharp moves on the H-R diagram—it moves smoothly back and forth.
- A star of more than 8 $M_\odot$ can fuse elements far beyond carbon in its core, leading to a very different fate.
- Its path across the H-R diagram is essentially a straight line—it stays at just about the same luminosity as it cools off.
- Eventually the star dies in a violent explosion called a supernova.



The End of a High-Mass Star

- **A high-mass star can continue to fuse elements in its core right up to iron (after which the fusion reaction absorbs energy instead of producing it).**
- **As heavier elements are fused, the reactions go faster and the stage is over more quickly.**
- **A 20 $M_\odot$ star will burn carbon for about 10,000 years, but its iron core lasts less than a day.**

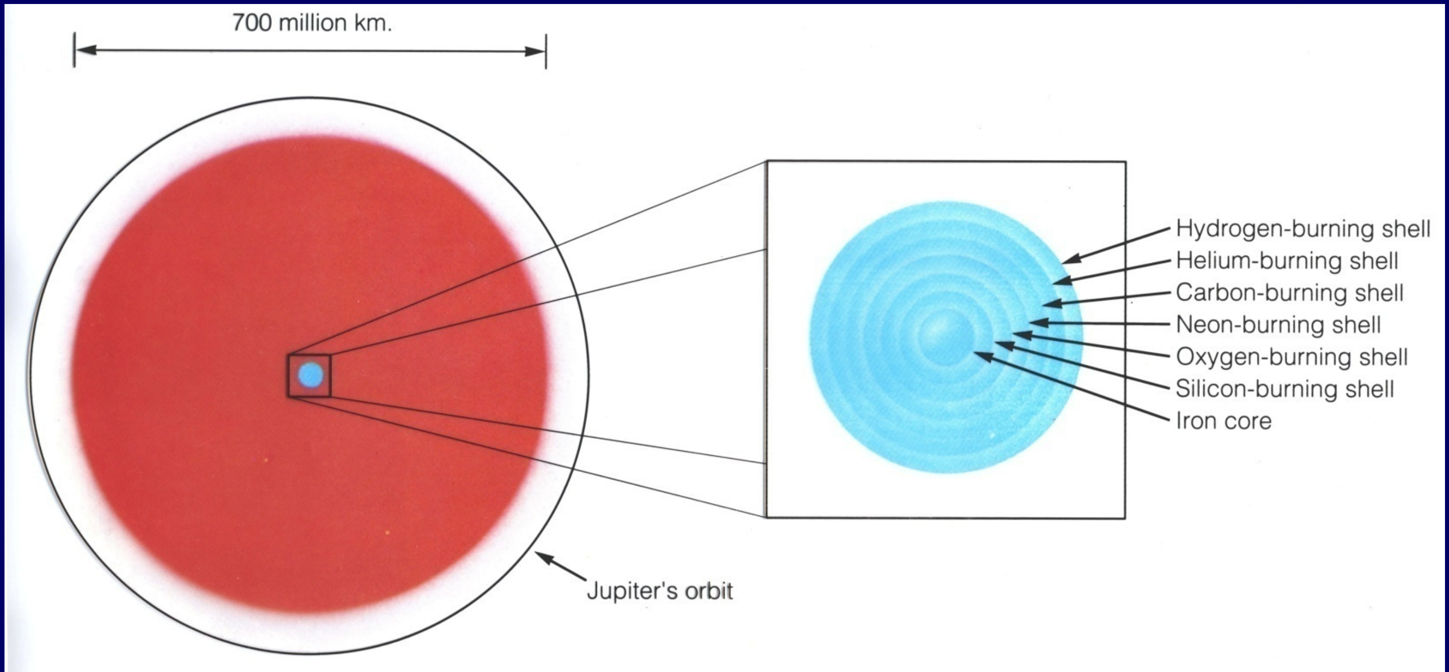


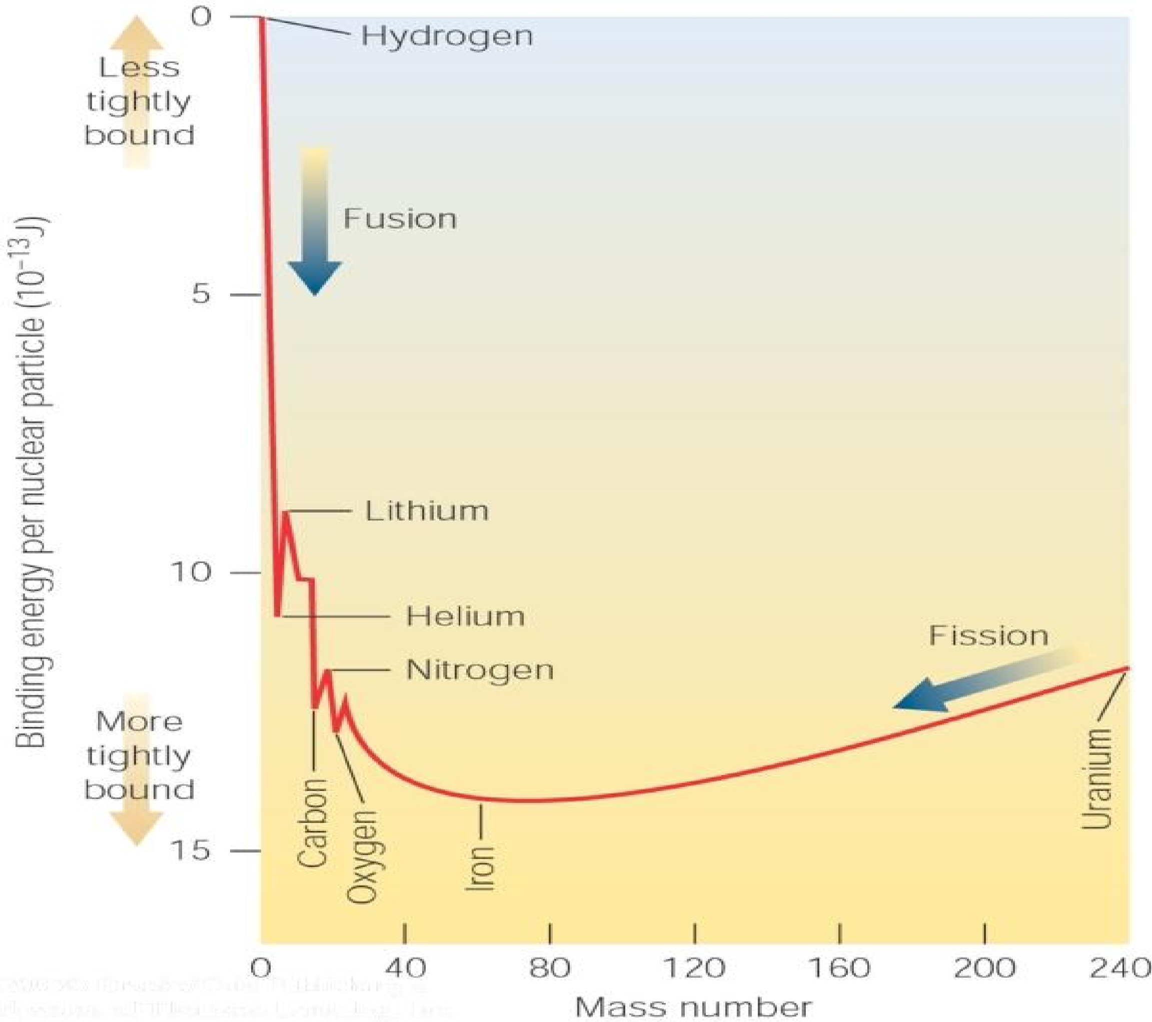
Table 10-1 | Heavy-Element Fusion in a 25-$M_\odot$ Star

Fuel	Time	Percentage of Lifetime
H	7,000,000 years	93.3
He	500,000 years	6.7
C	600 years	0.008
O	0.5 years	0.000007
Si	1 day	0.00000004

The End of a High-Mass Star

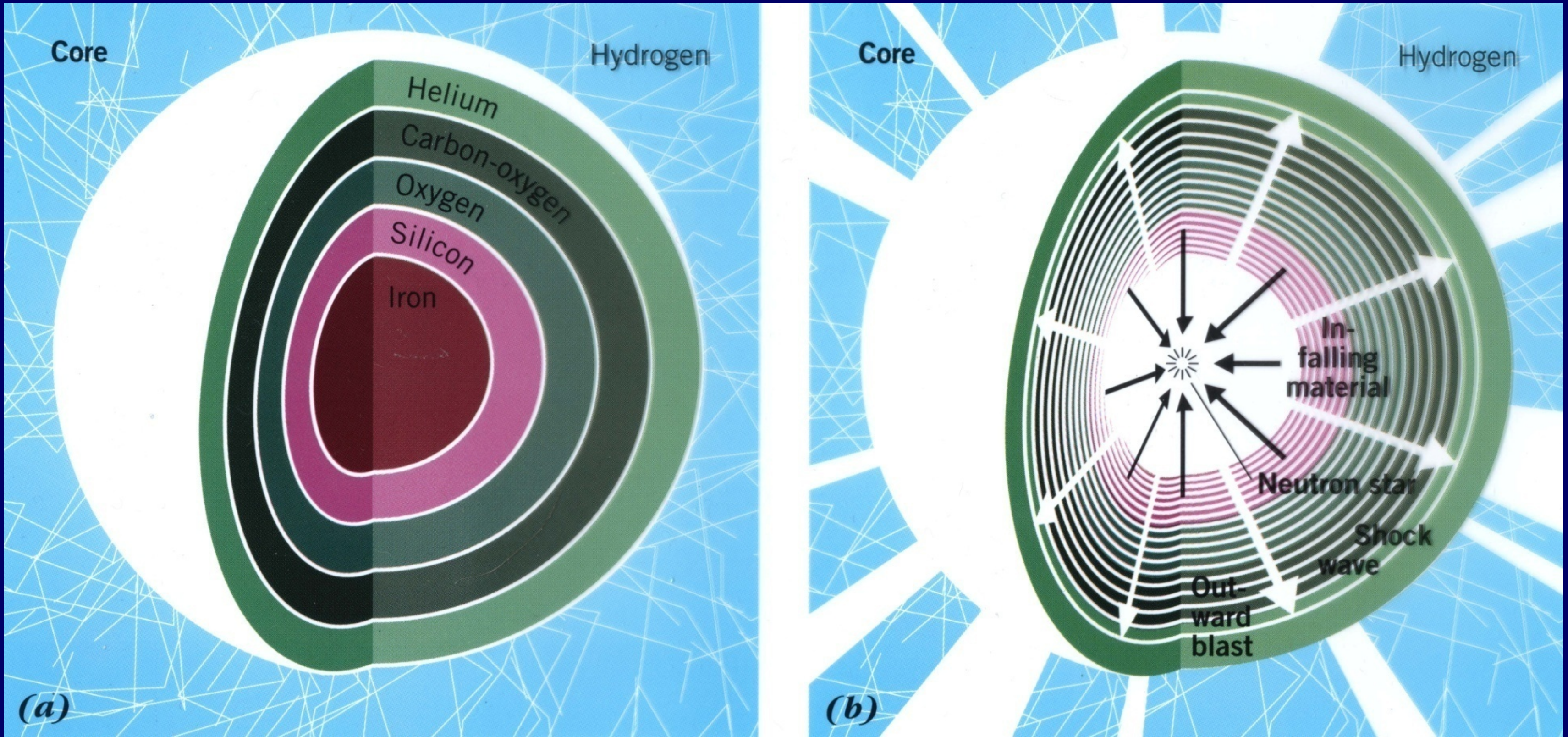
This graph shows the relative stability of nuclei. On the left, nuclei gain energy through fusion; on the right they gain it through fission.

Iron is the crossing point; when the core has fused to iron, no more fusion can take place.



The End of a High-Mass Star

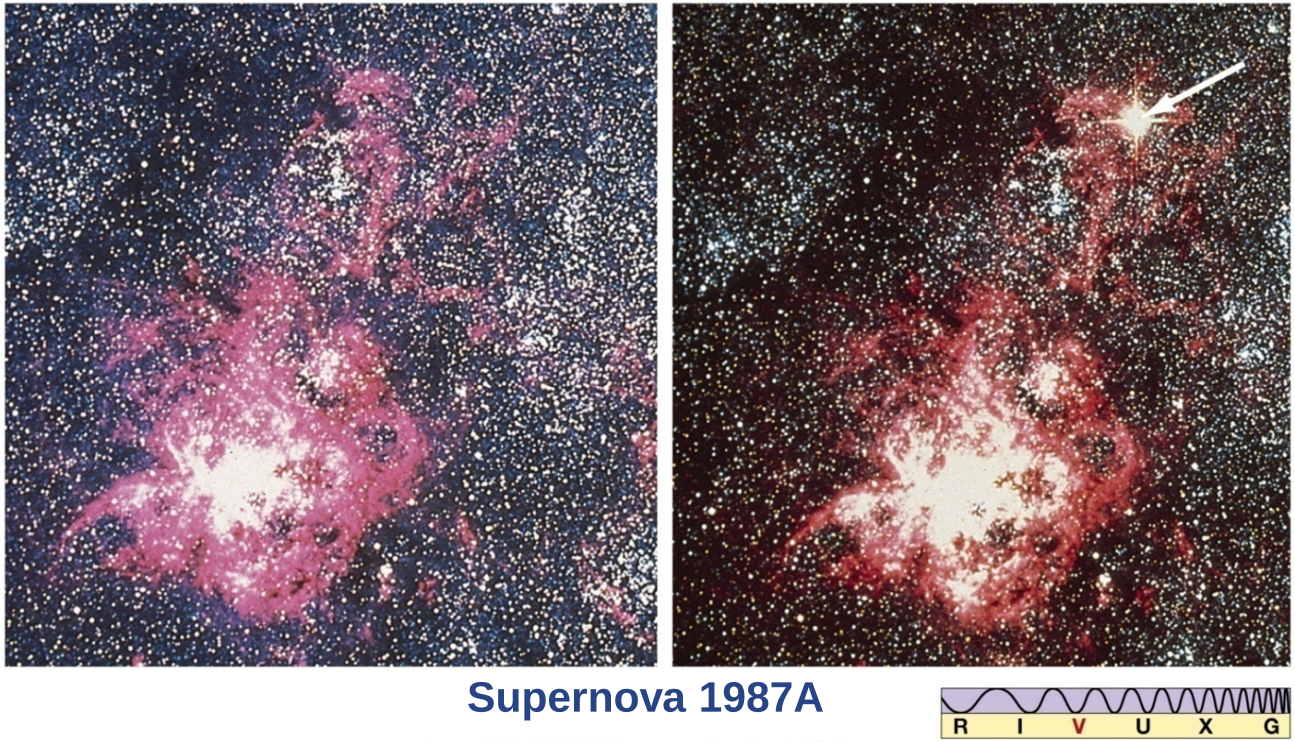
- The inward pressure is enormous, because of the high mass of the star.
- There is nothing stopping the star from collapsing further; it does so very rapidly, in a giant implosion.
- As it continues to become more and more dense, the protons and electrons react with one another to become neutrons, $p + e \rightarrow n + \nu$.



The End of a High-Mass Star

The neutrinos escape and the neutrons are compressed together. The neutrons are forced into a state known as neutron degeneracy. The whole star has the density of an atomic nucleus, about 10^{15} kg/m^3.

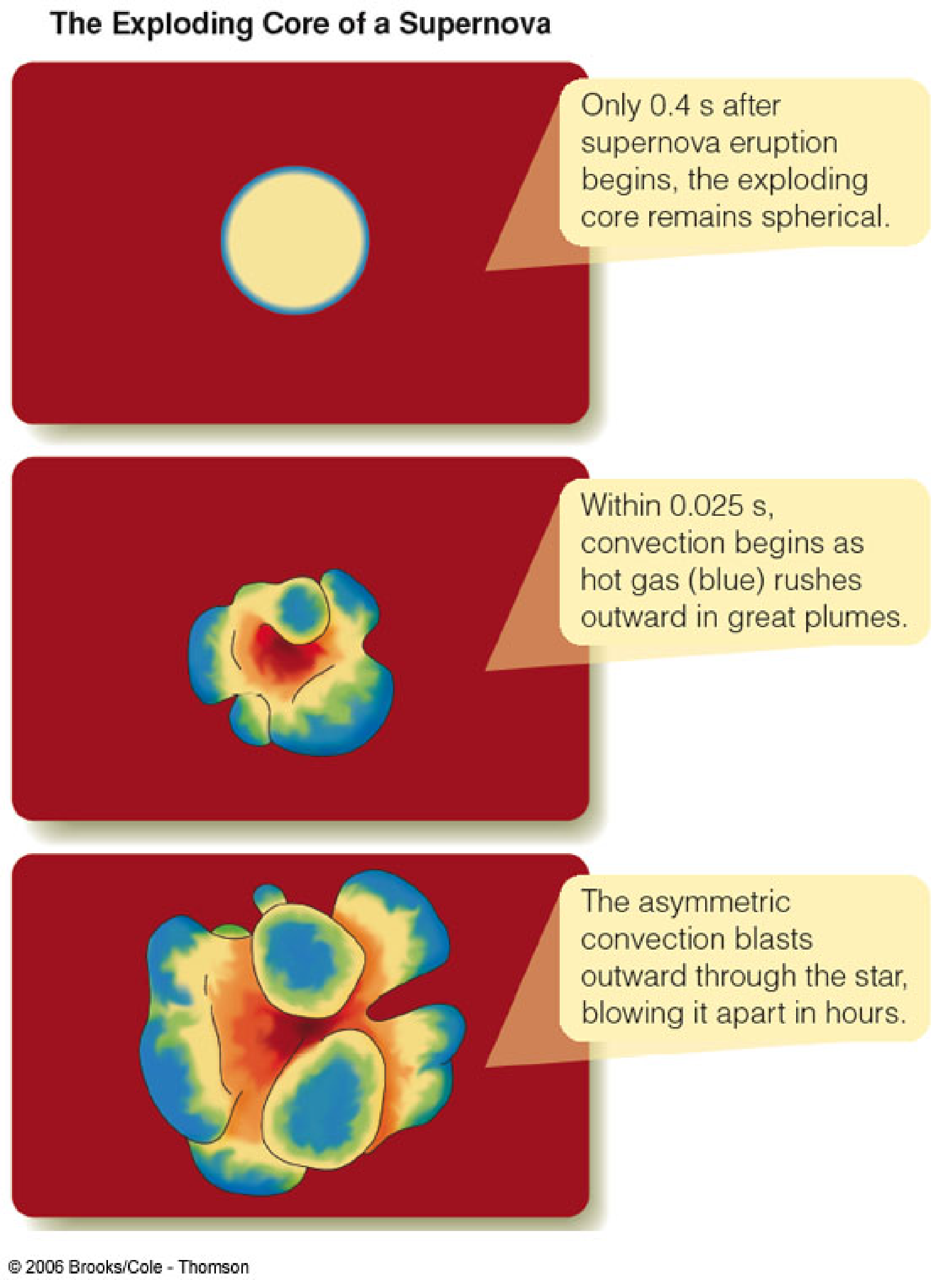
The collapse is still going on; it compresses the neutrons further until they recoil in an enormous explosion called a Type II supernova.



Supernova 1987A

Numerical Simulations of Type II Supernova Explosions

The details of supernova explosions are highly complex and not quite understood.



Stellar Remnants

Low-mass stars die without an explosion leaving stars of reduced mass called white dwarfs and remnants of expanding gases called planetary nebulae.

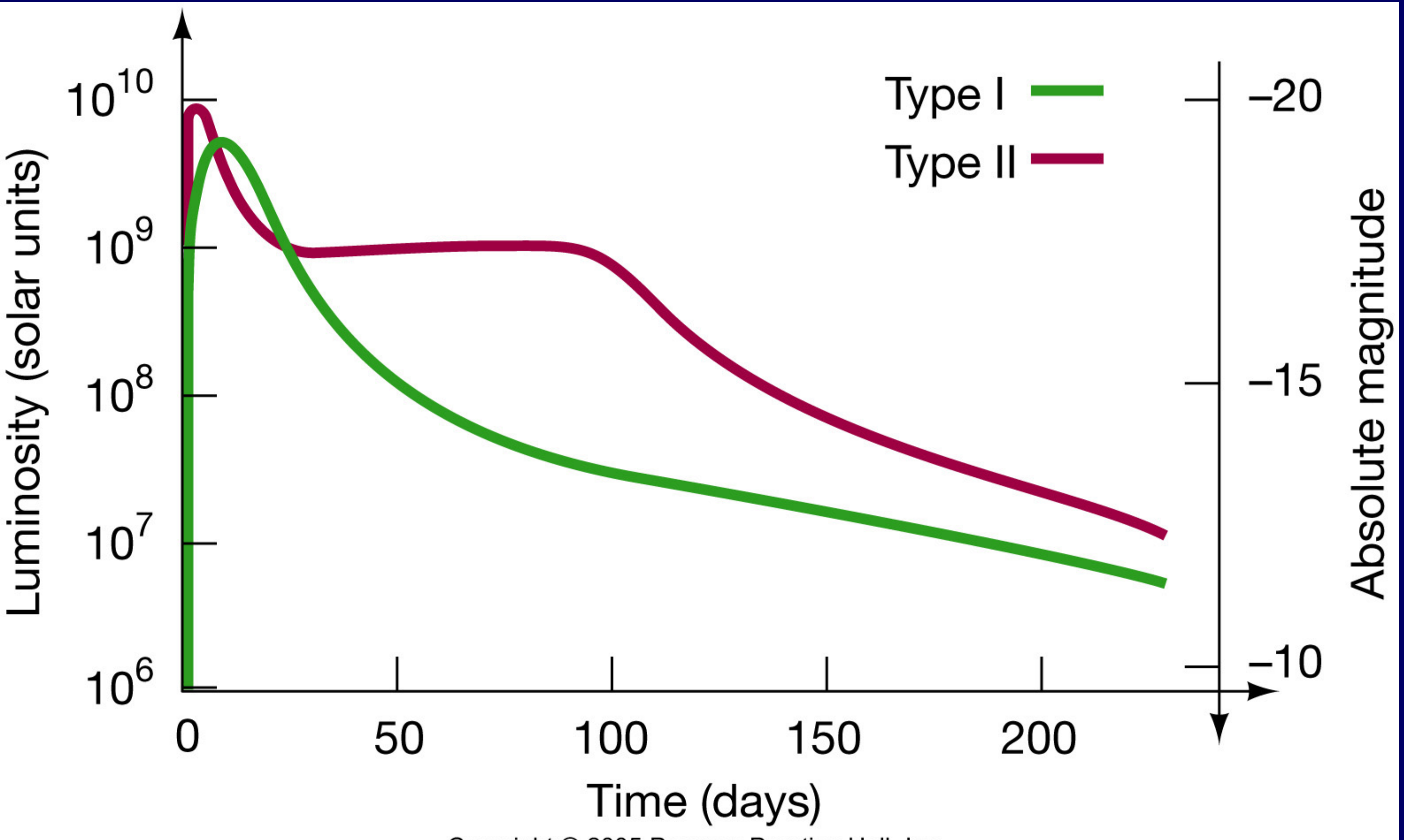
High-mass stars die explosively as type II supernovae leaving cores of reduced mass, neutron stars or stellar black holes, and remnants of expanding gas and dust called a supernova remnants.

Supernovae

- A supernova is a one-time event – once it happens, there is little or nothing left of the progenitor star.
- There are two different types of supernovae, both equally common
  - **Type I**, which is a **carbon-detonation** supernova
  - **Type II**, which is the death of a high-mass star just described

Supernovae

A supernova is incredibly luminous – more than a million times as bright as a nova.



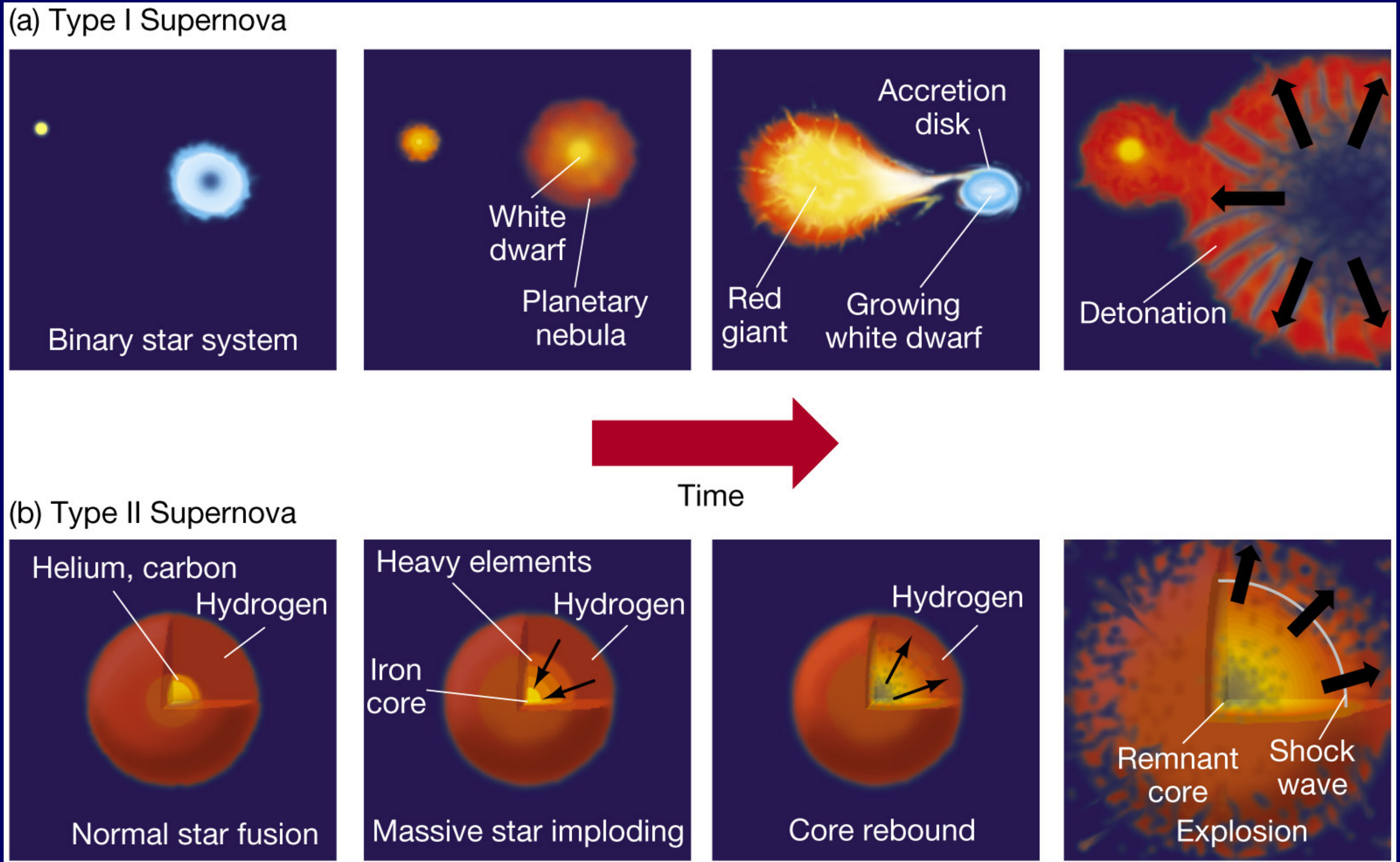
Type I Supernovae

Carbon-detonation supernovae

- Begins with a white dwarf in a contact binary system which is accumulating mass from its companion.
- If the white dwarf's mass exceeds 1.4 $M_{\odot}$ (the Chandrasekhar limit), electron degeneracy can no longer keep the core from collapsing.
- Carbon fusion begins throughout the star almost simultaneously, resulting in an explosion.

Supernovae

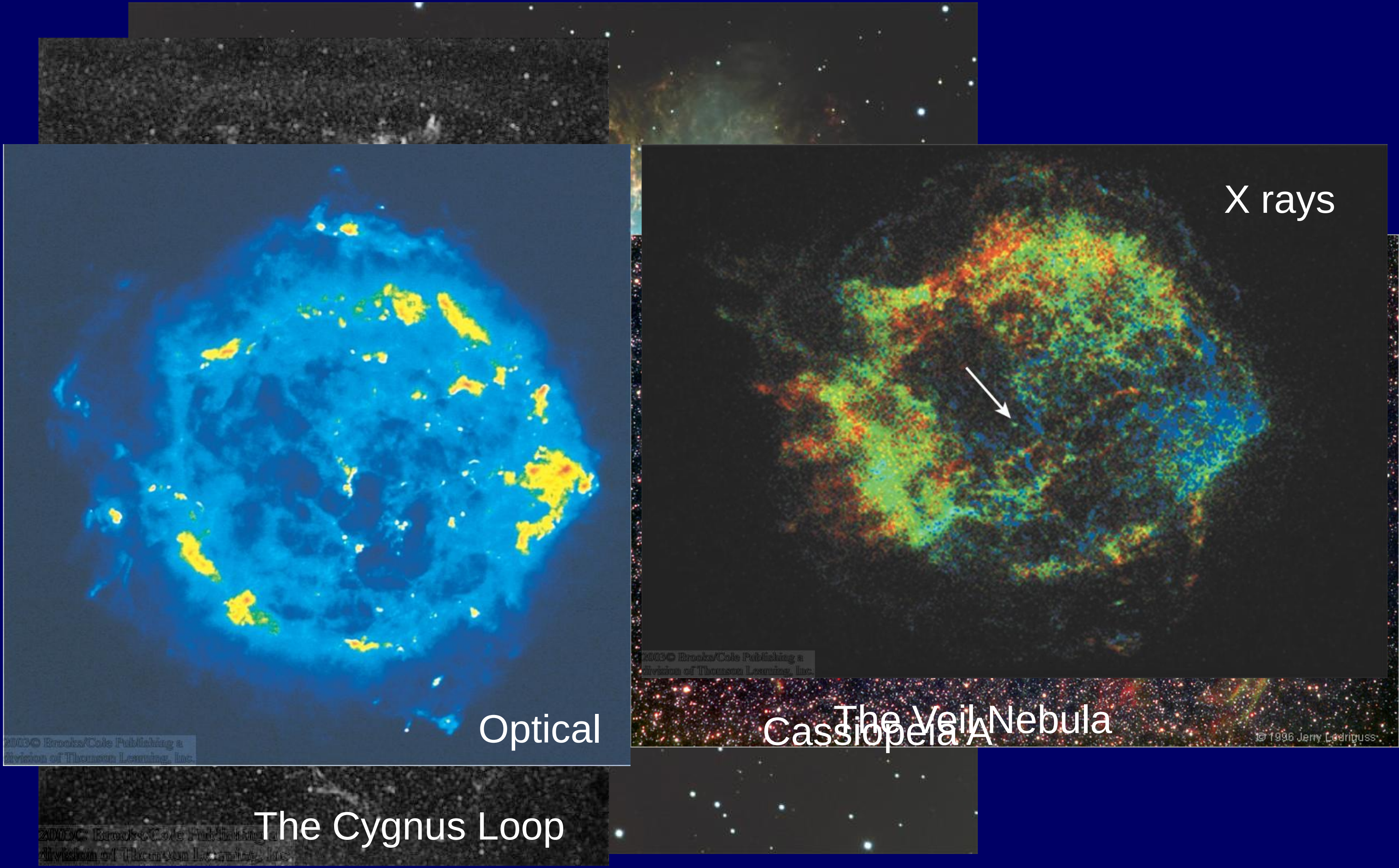
This graphic illustrates the two different types of supernovae:



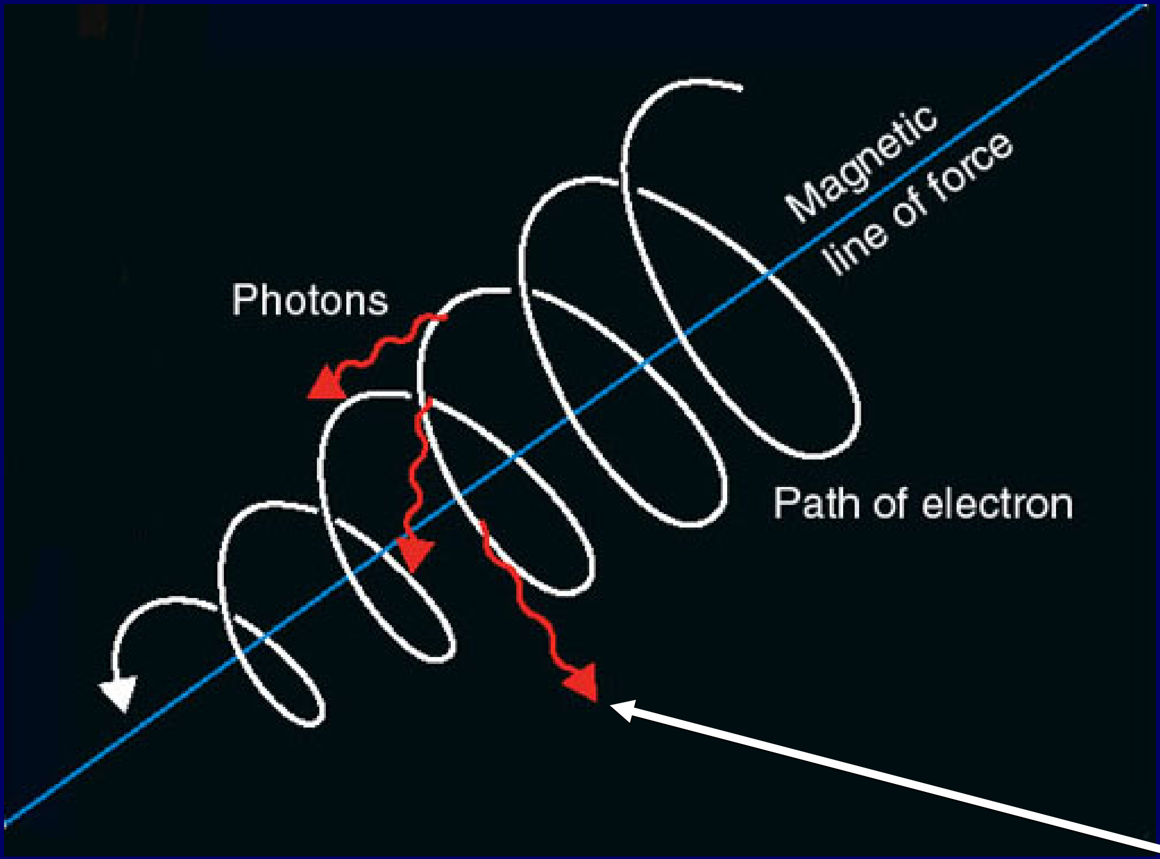
Supernovae

- Type I supernovae do not leave a remnant core
- Type II supernovae leave a remnant core, either a neutron star or a stellar black hole to be discussed in the next chapter
- Both types of supernovae leave an expanding plasma (ionized gas) called a supernova remnant

Supernova Remnants



Synchrotron Emission and Cosmic-Ray Acceleration



The shocks of supernova remnants accelerate protons and electrons to extremely high, relativistic energies.

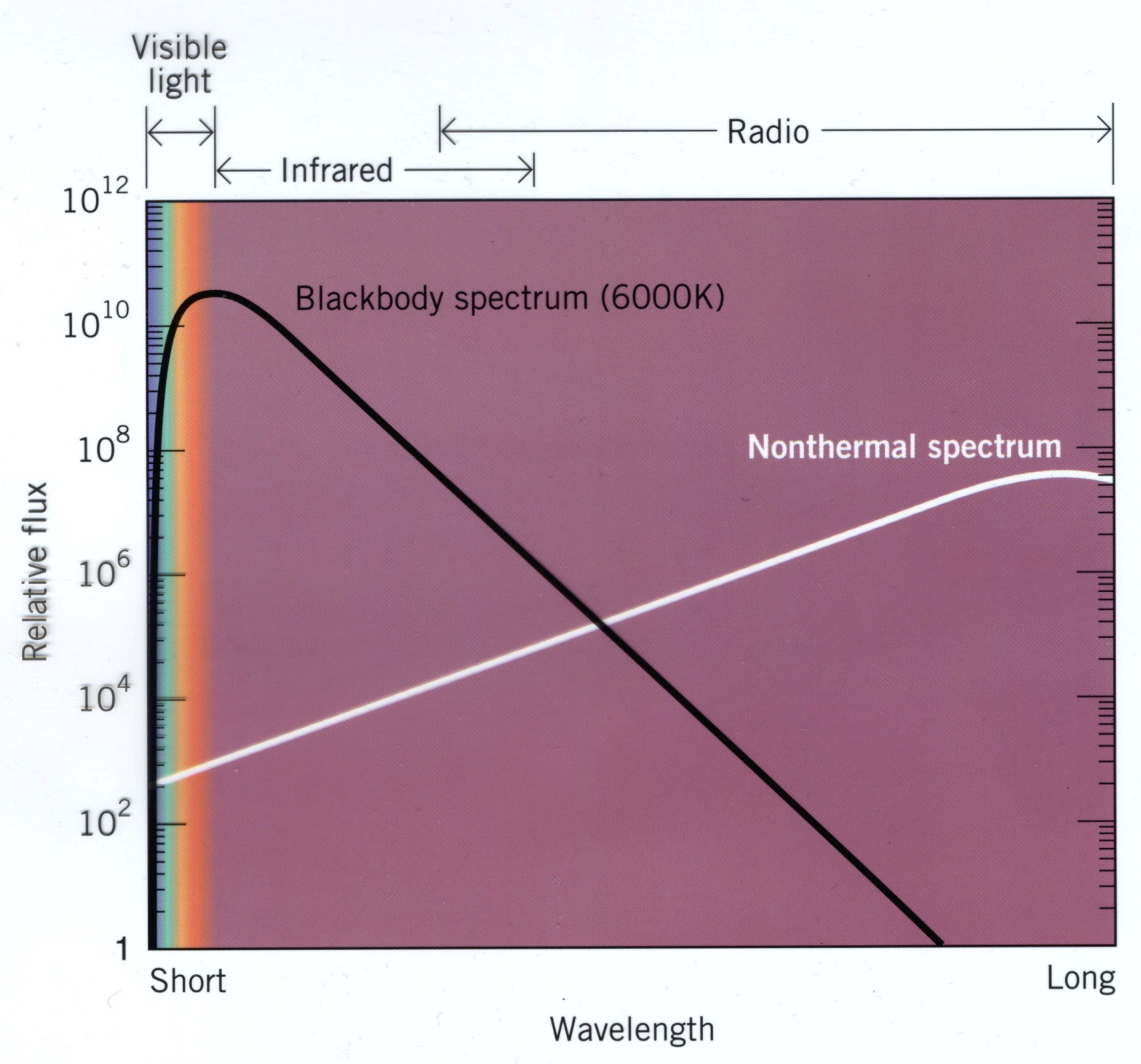
$\Rightarrow$ "cosmic rays"

In magnetic fields, relativistic electrons emit

synchrotron radiation

Synchrotron Emission

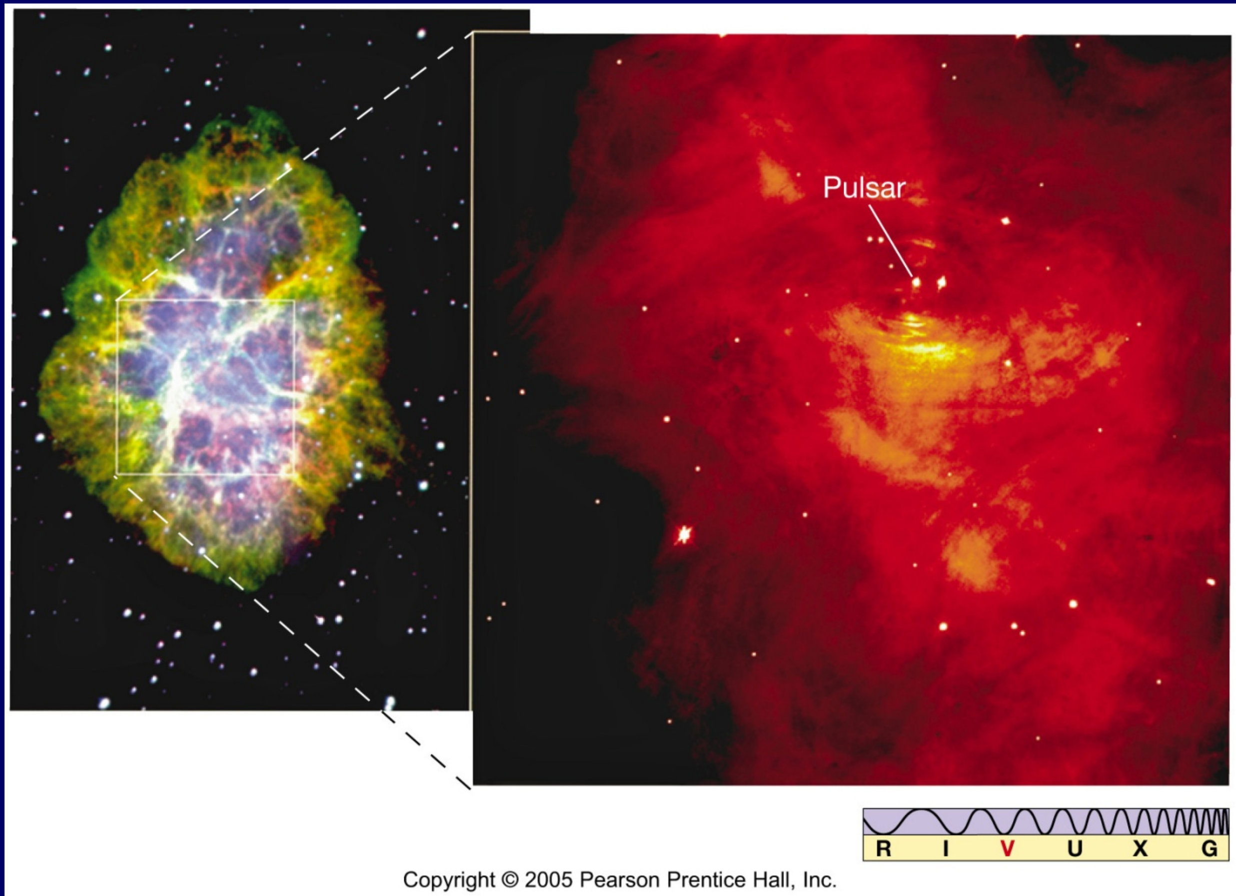
Synchrotron (nonthermal) radiation has a much different spectrum than Planck radiation



Supernovae

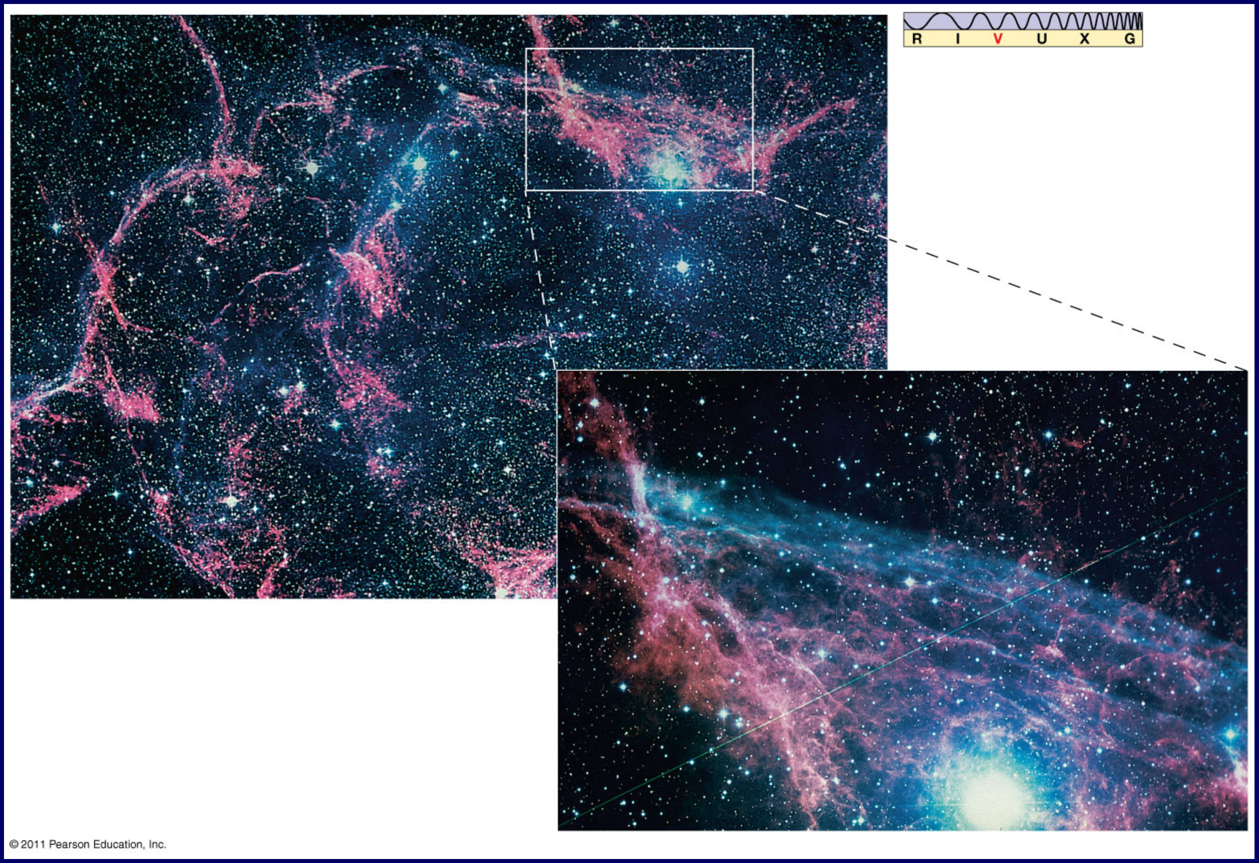
The expansion velocities of the material in the Crab Nebula, measured using Doppler shifts, and its size can be used to calculate the time of the original explosion which agrees within experimental error to the observed explosion in 1054 CE.

There is a neutron star (pulsar) at the center of the Crab Nebula



Supernovae

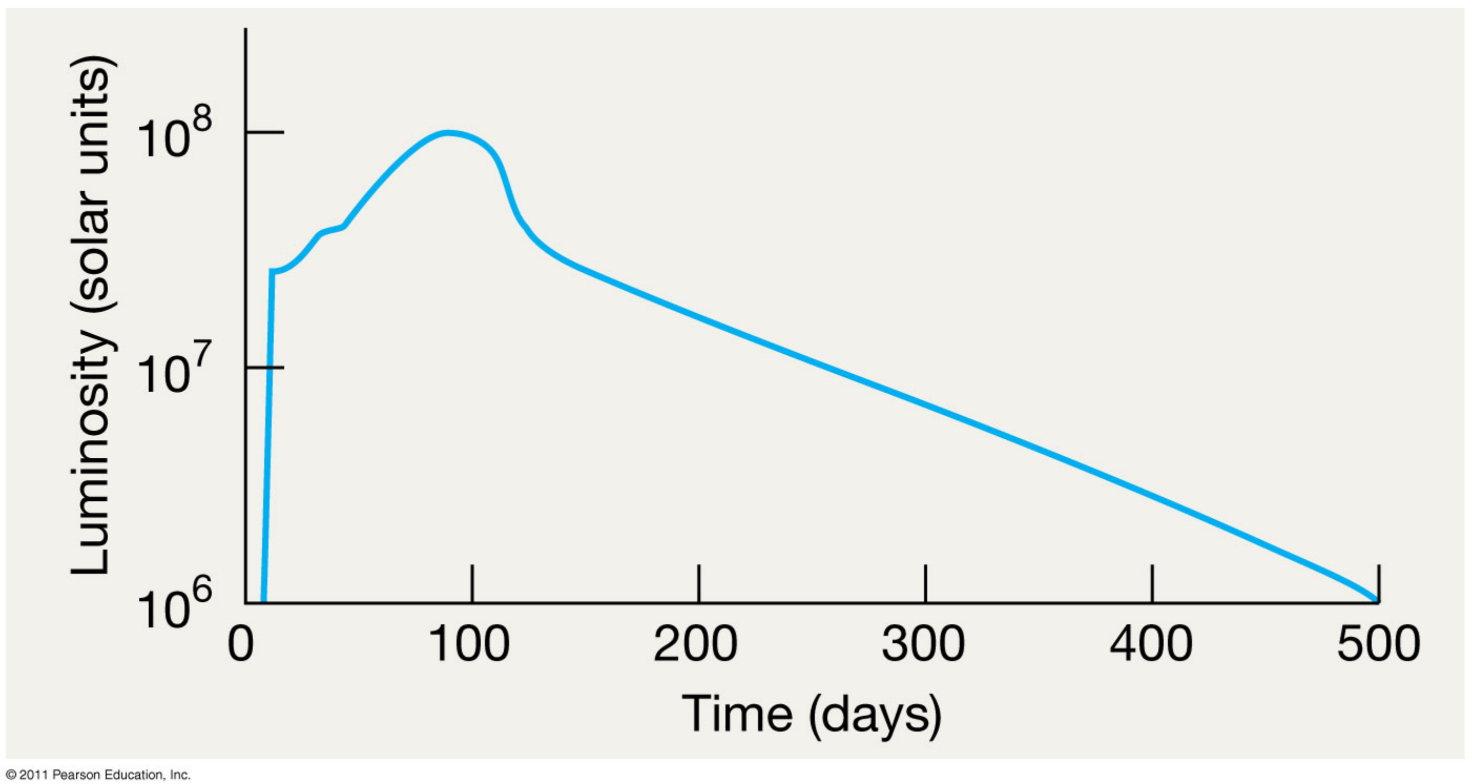
This is the Vela supernova remnant: Extrapolation shows it exploded about 9000 BCE



Supernova 1987A

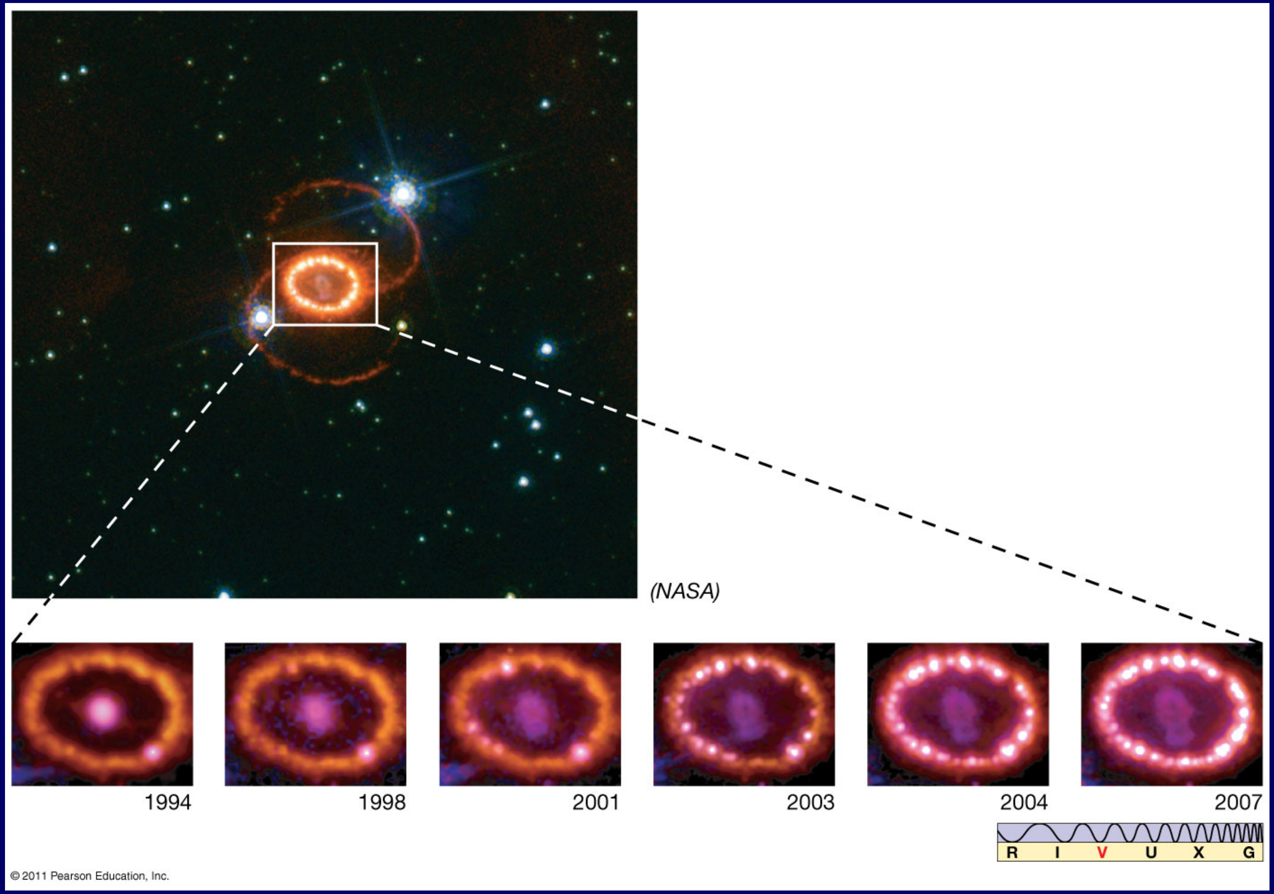
Supernova 1987A

- Supernovae are rare; there has not been one in our Galaxy for about 400 years.
- In February 1987, SN1987A occurred in the Large Magellanic Cloud, a neighboring galaxy. Its light curve indicates a somewhat atypical type II supernova.



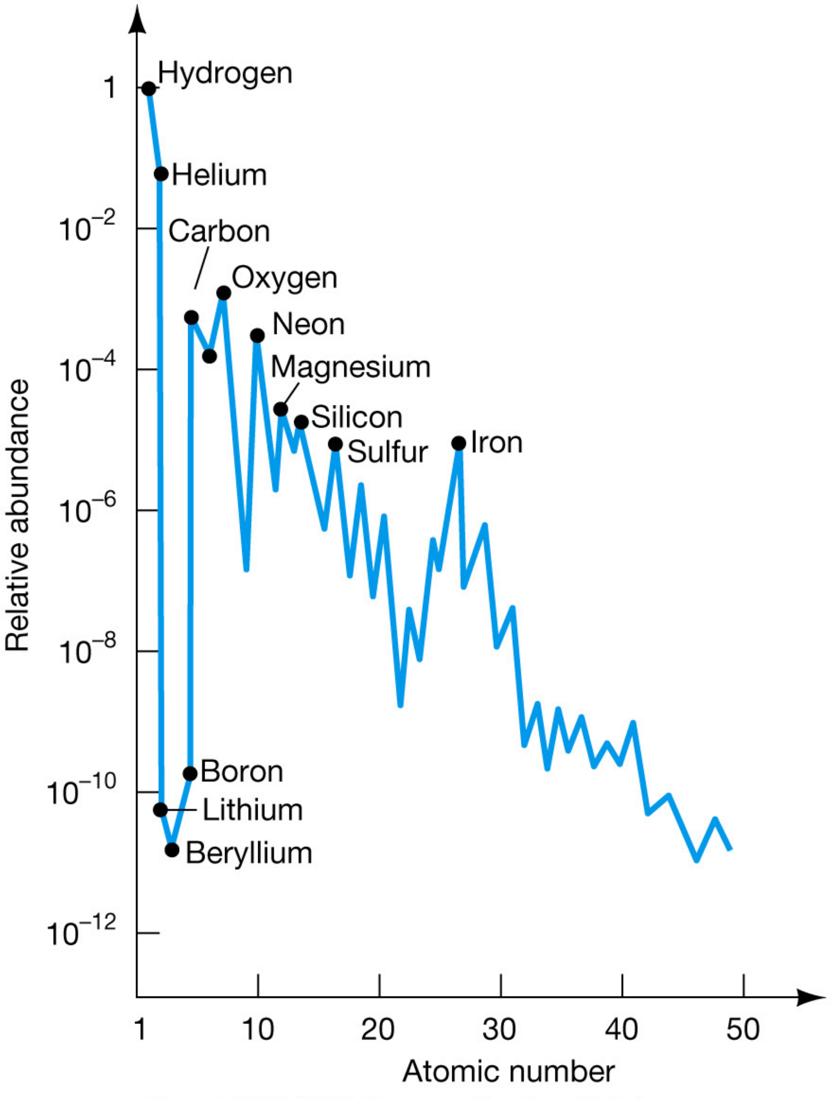
Supernova 1987A

A cloud of glowing gas is now visible around SN1987A, and a small central object is becoming discernible



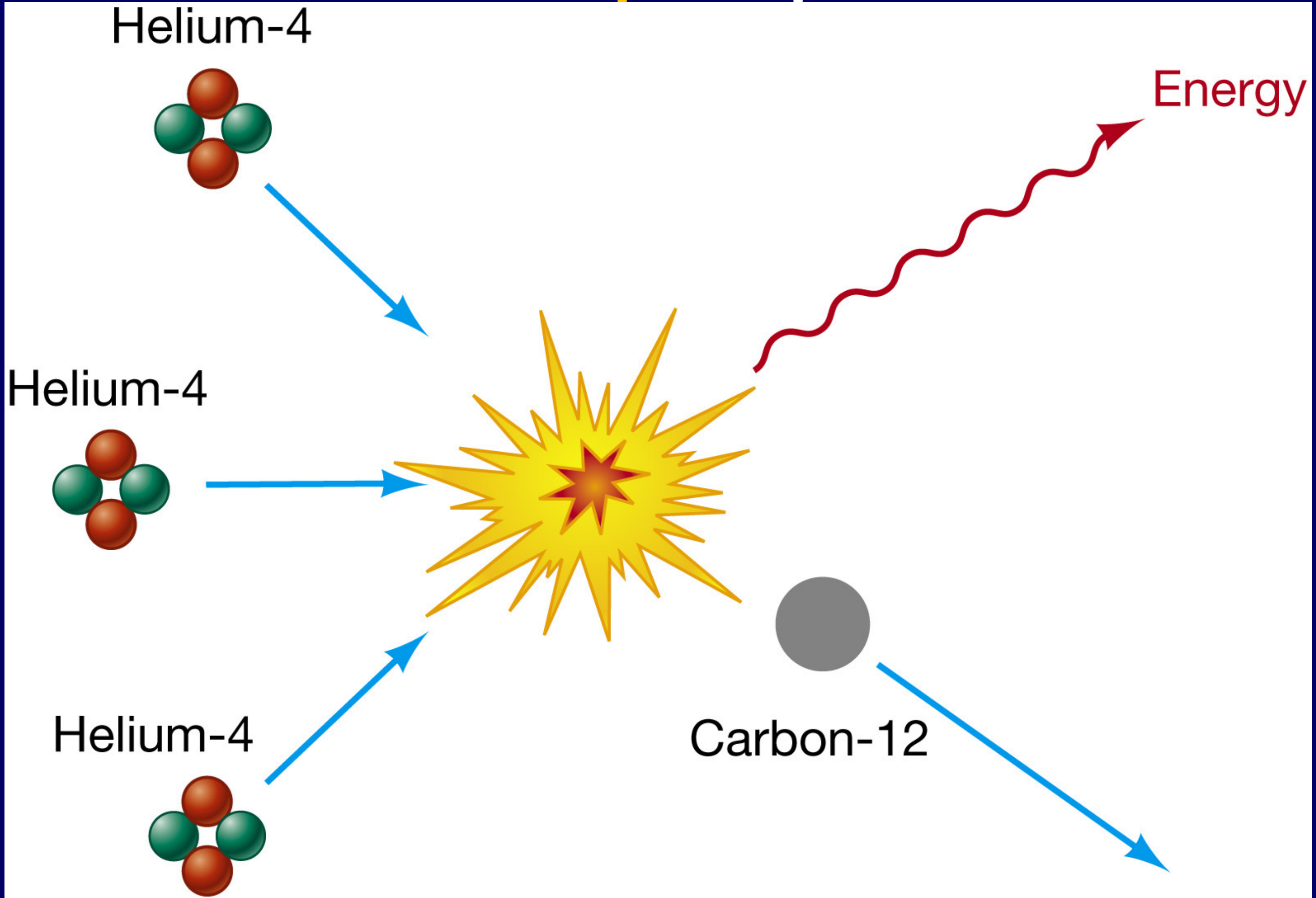
The Formation of the Elements: Nucleosynthesis

- There are 81 stable and 10 radioactive elements that exist on our planet. They are not primordial.
- This graph shows the relative abundance of different elements in the solar system (but they are called cosmic abundances).



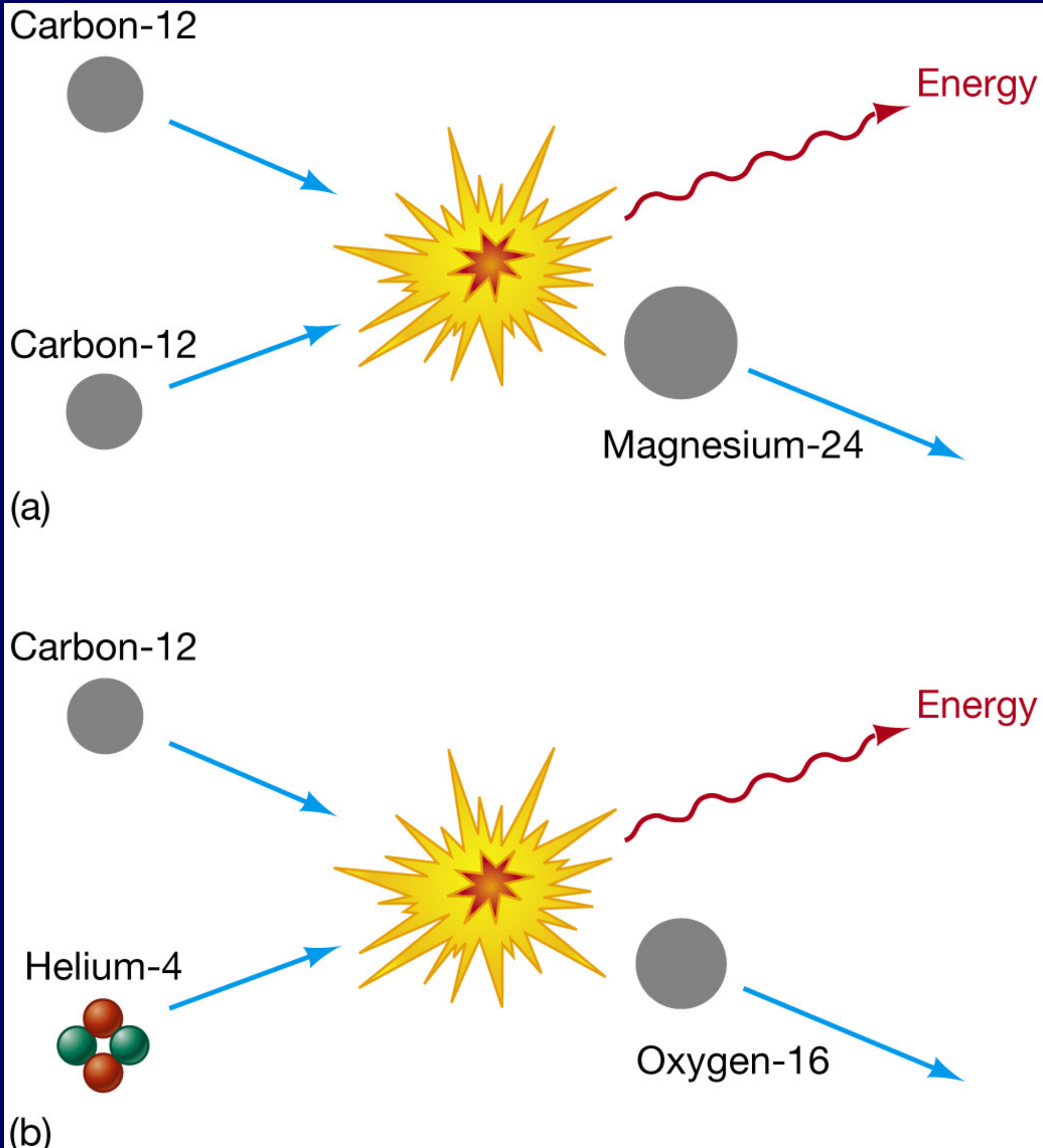
The Formation of the Elements

Some of these elements are formed during normal stellar fusion. For example, 3 helium nuclei fuse to form carbon in the triple α process.



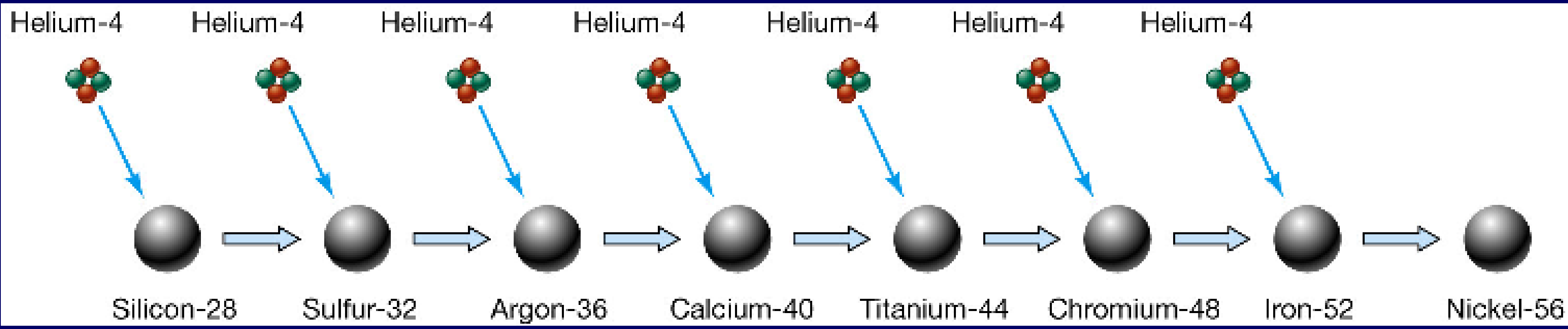
The Formation of the Elements

- Carbon can fuse, either with itself or with He nuclei, which are also called alpha particles, to form more nuclei
- These cartoons show fusion of (a) ^{24}Mg and (b) ^{16}O



The Formation of the Elements

The elements that can be formed through successive alpha-particle fusion are more abundant than those created by other fusion reactions

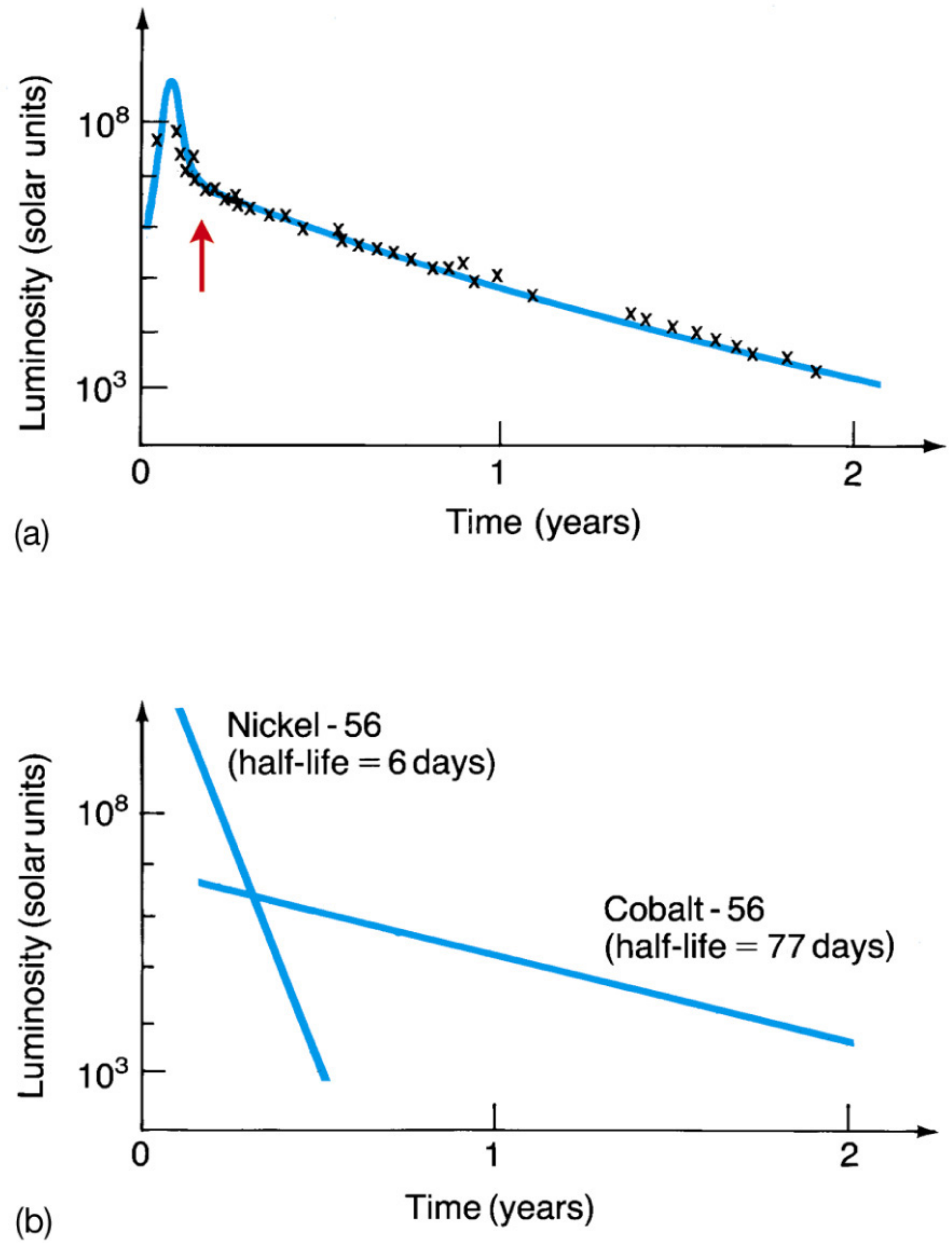


The Formation of the Elements

- The last nucleus in the alpha-particle chain is ^{56}Ni, which is unstable and quickly decays to ^{56}Co and then to ^{56}Fe.
- ^{56}Fe is the most stable nucleus.
- Within the cores of the most massive stars, slow neutron capture can create heavier elements up to ^{209}Bi.
- The heaviest elements are made during the first few seconds of a supernova explosion by rapid neutron capture.

The Formation of the Elements

The formation of ^{56}Ni and its decay to ^{56}Co at the beginning of a type II supernova explosion is verified in the supernova light curve which depends on the radioactive decay of the ^{56}Ni and ^{56}Co



The Cycle of Stellar Evolution

- Star formation is cyclical: stars form, evolve, and die.
- In dying, they send heavy elements into the interstellar medium.
- These elements then become incorporated in new stars.
- Gradually, heavy elements become more abundant.
- Stars formed with a minimum of heavy elements are Population II stars. Stars formed with more heavy elements are Population I stars.