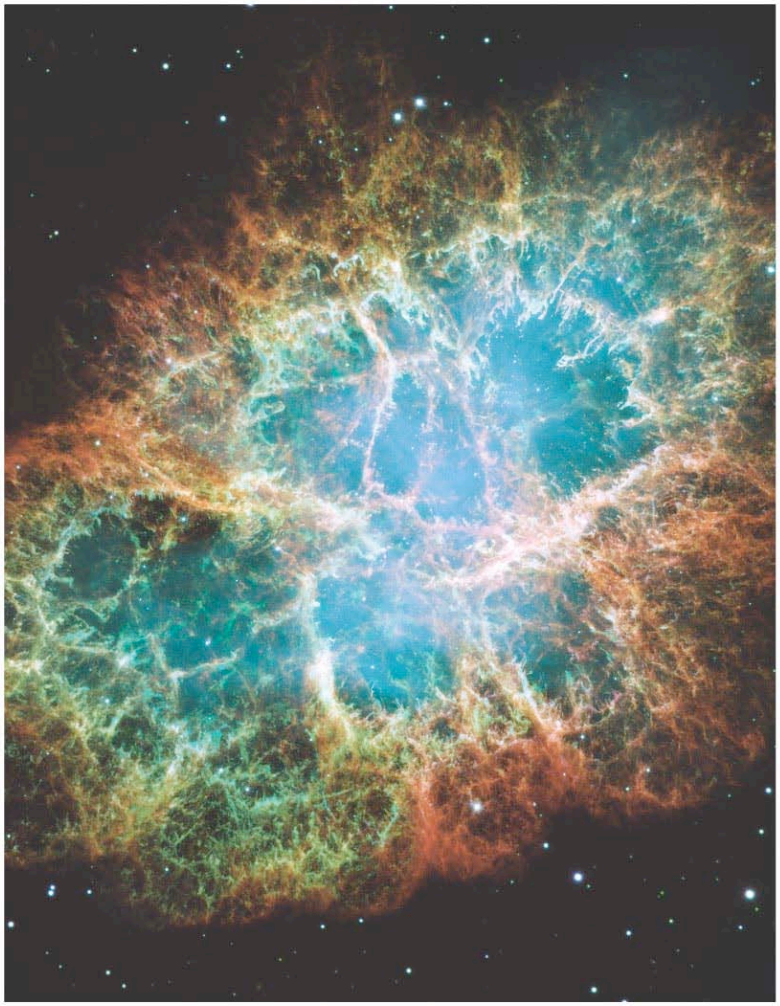
Chapter 21
Stellar Explosions



Units of Chapter 21

21.1 XXLife after Death for White Dwarfs

21.2 The End of a High-Mass Star

21.3 Supernovae

    Supernova 1987A

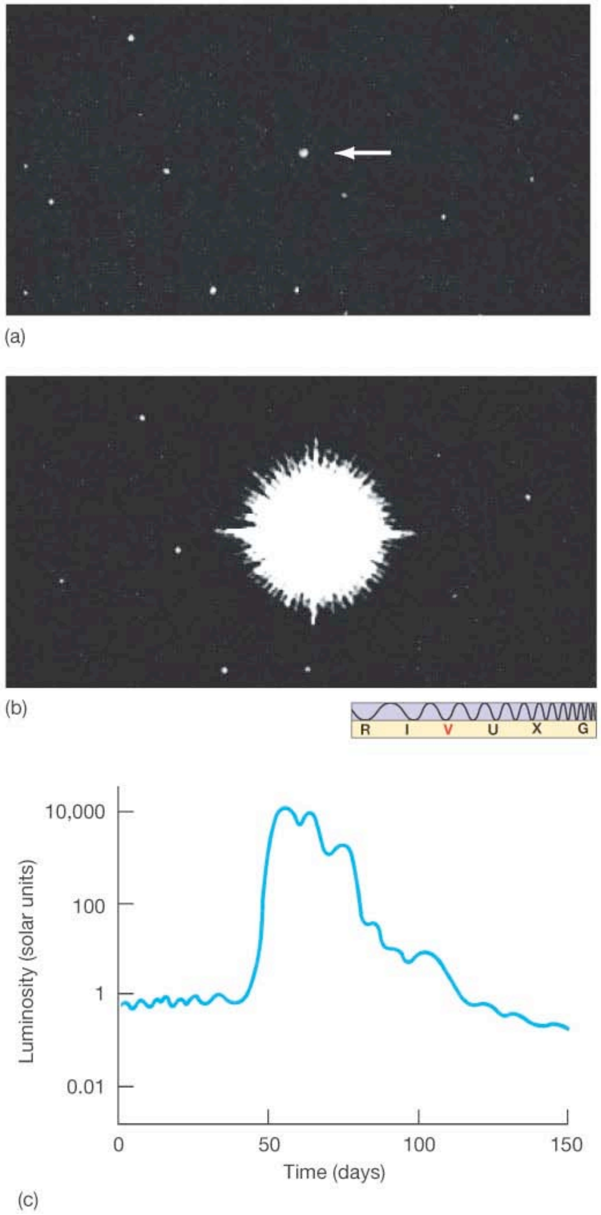
    The Crab Nebula in Motion

21.4 The Formation of the Elements

21.5 The Cycle of Stellar Evolution

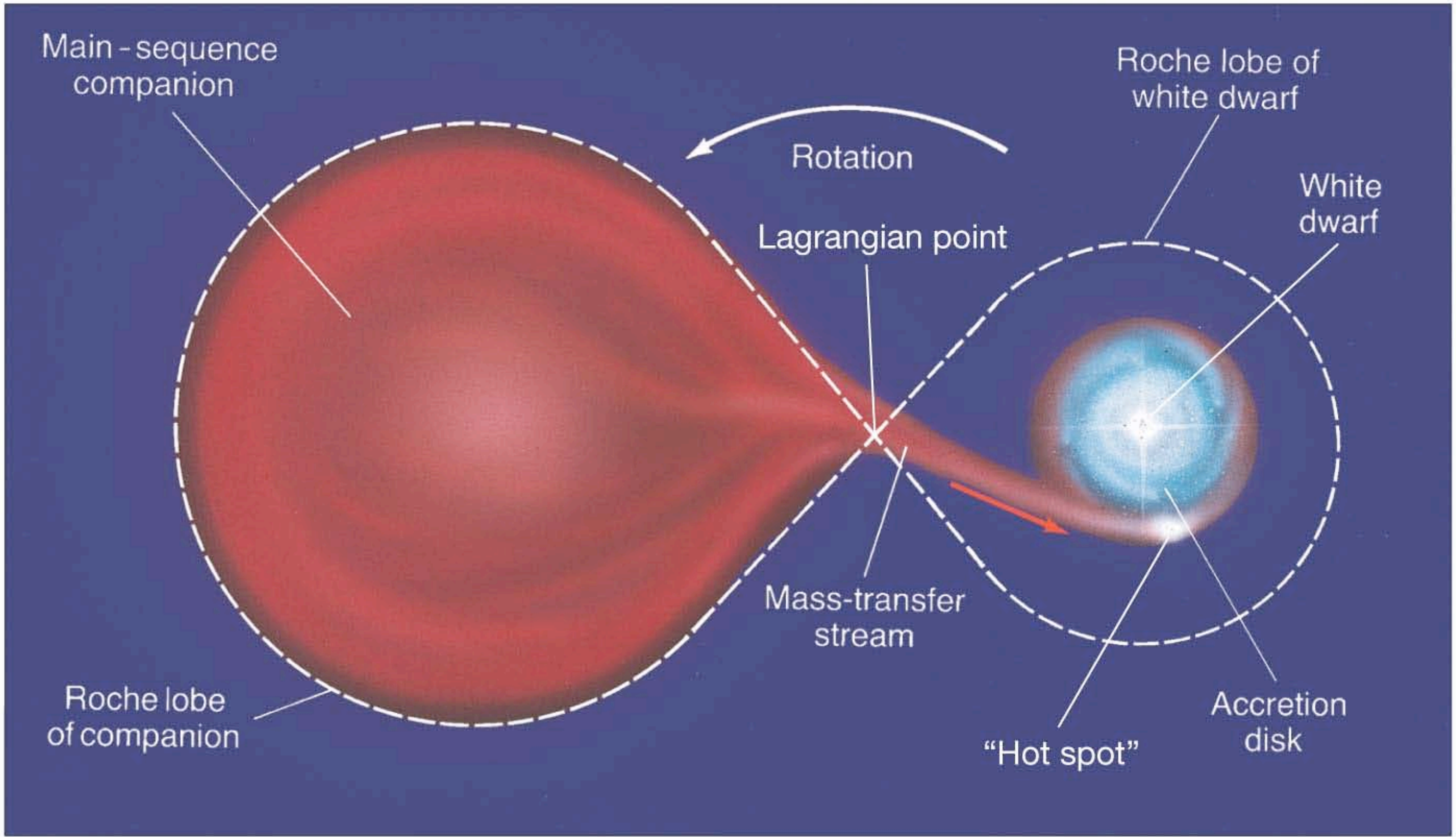
21.1 Life after Death for White Dwarfs

A nova is a star that flares up very suddenly and then returns slowly to its former luminosity:



21.1 Life after Death for White Dwarfs

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

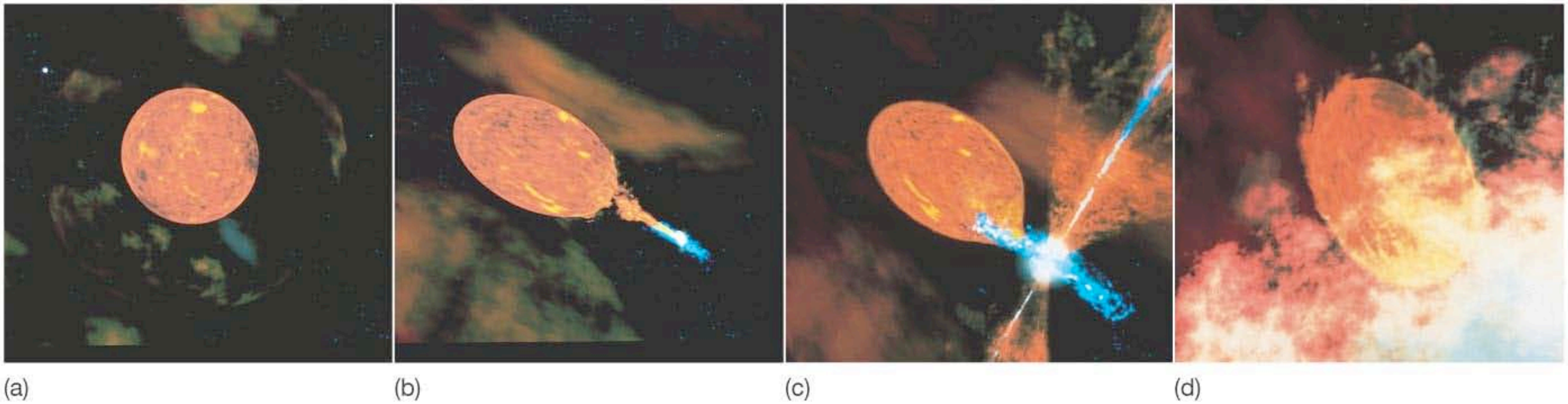


21.1 Life after Death for White Dwarfs

Material falls onto the white dwarf from its main-sequence companion.

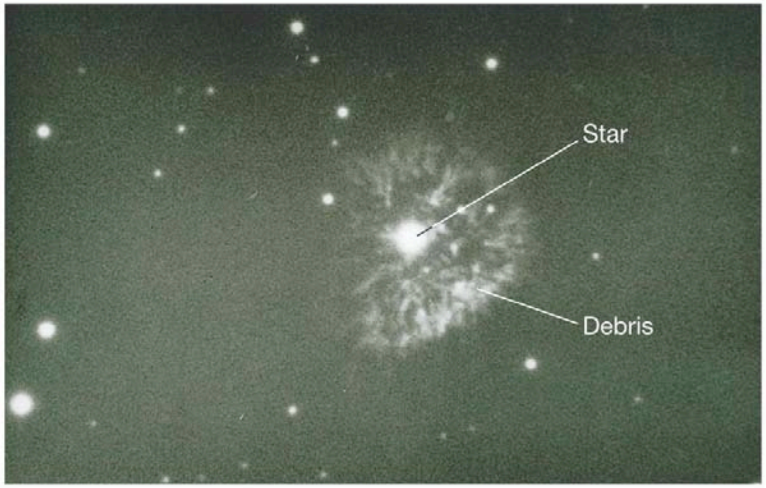
When enough material has accreted, fusion can reignite very suddenly, burning off the new material.

Material keeps being transferred to the white dwarf, and the process repeats, as illustrated here:

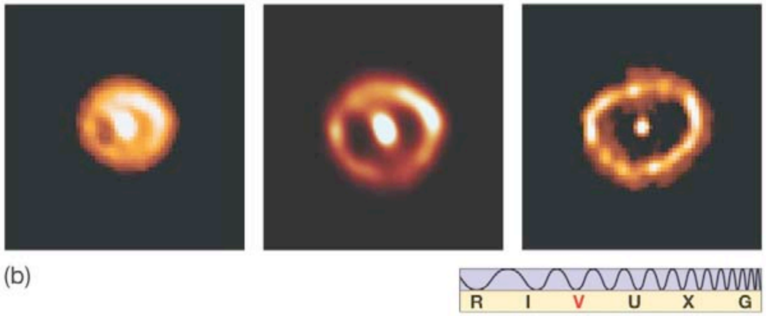


21.1 Life after Death for White Dwarfs

This series of images shows ejected material expanding away from a star after a nova explosion:



(a)

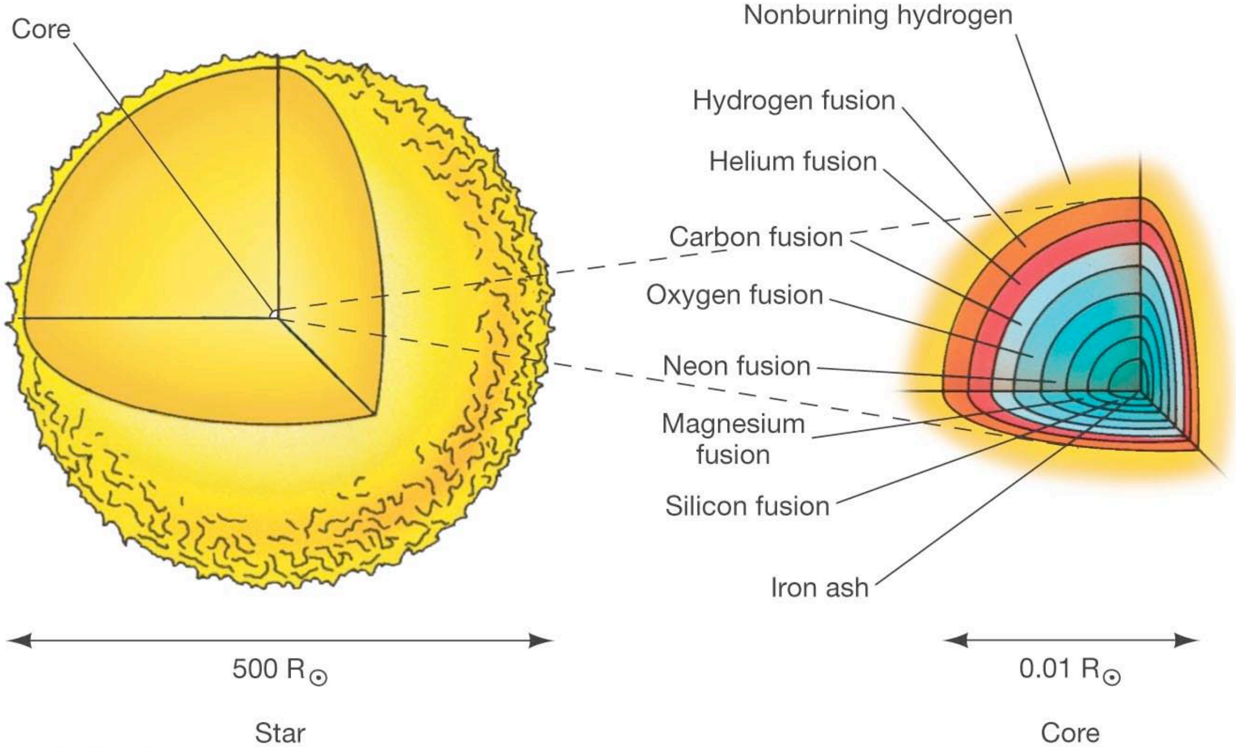


(b)

21.2 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 is energetically unfavored).

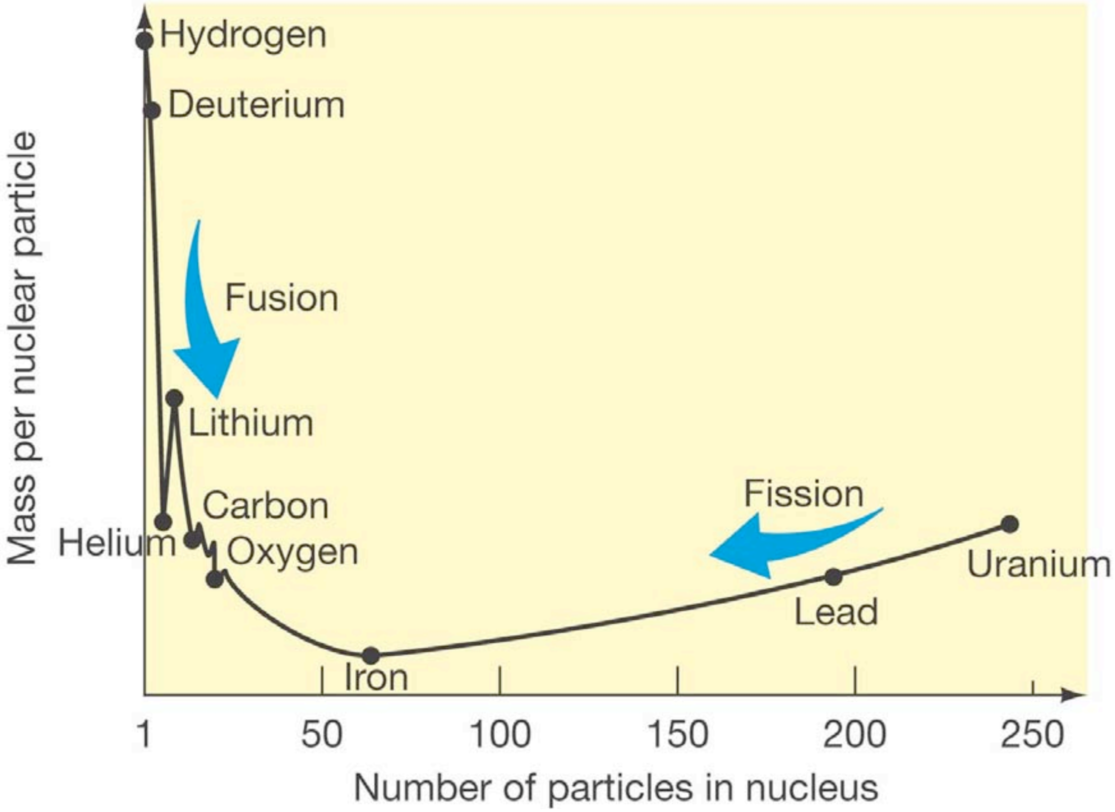
As heavier elements are fused, the reactions go faster and the stage is over more quickly. A 20-solar-mass star will burn carbon for about 10,000 years, but its iron core lasts less than a day.



21.2 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



21.2 The End of a High-Mass Star

The inward pressure is enormous, due to 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:

$$p + e \rightarrow n + \text{neutrino}$$

21.2 The End of a High-Mass Star

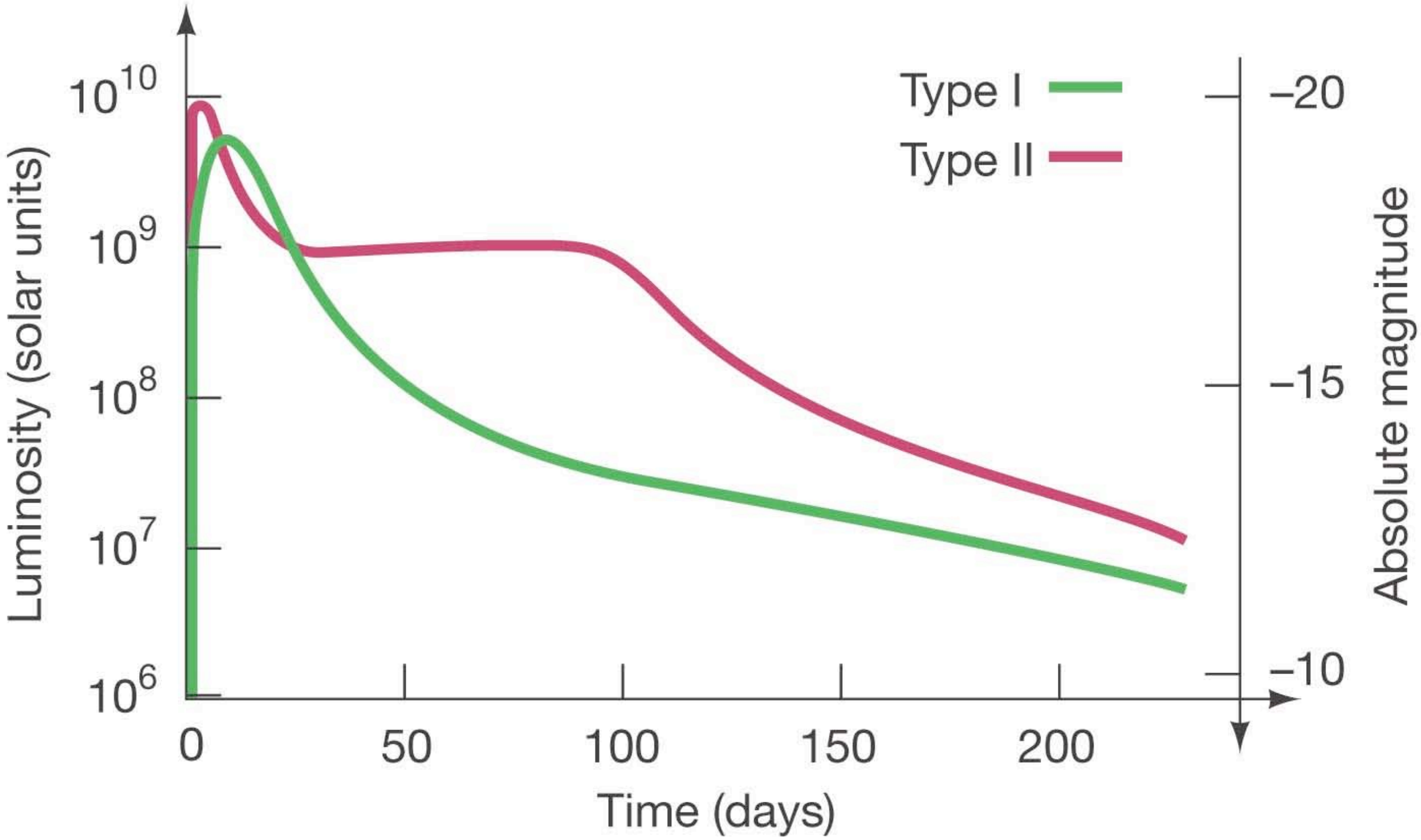
The neutrinos escape; the neutrons are compressed together until the whole star has the density of an atomic nucleus, about 10^{15} kg/m^3.

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

21.3 Supernovae

A supernova is incredibly luminous—as can be seen from these curves— at the peak of their *light curve* they are several *billion* times as bright as the Sun.

[Question: If all supernovae had the same luminosity at their peak, what practical purpose could we use them for?



21.3 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, due to distinctly different causes:

- Type I, which is a carbon-detonation supernova, and
- Type II, which is the death of a high-mass star just described

The next few slides explains the current theoretical understanding of how these two types of supernovae explode.

21.3 Supernovae

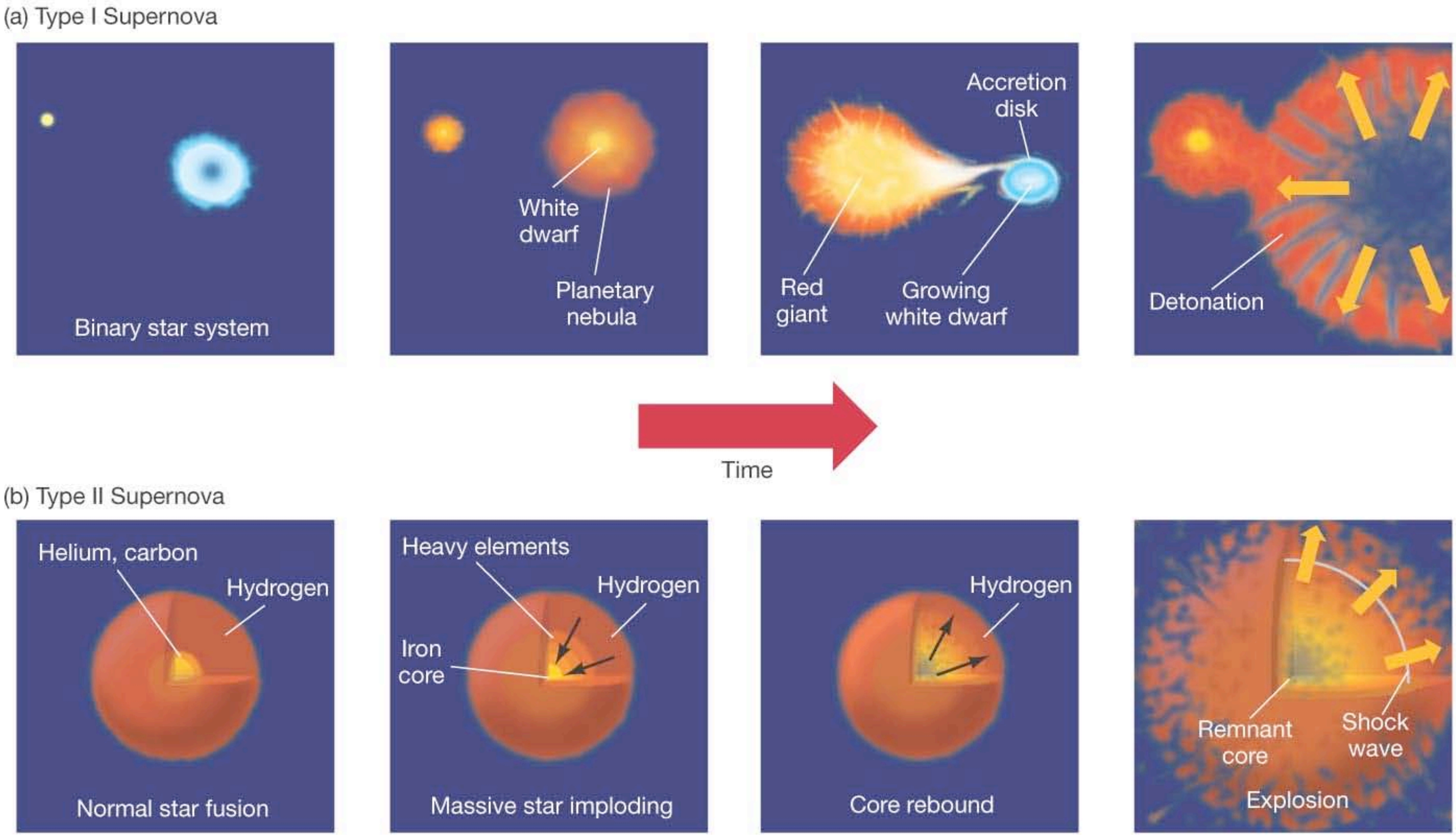
Carbon-detonation supernova: white dwarf that has accumulated too much mass from binary companion

If the white dwarf’s mass exceeds 1.4 solar masses, electron degeneracy can no longer keep the core from collapsing.

Carbon fusion begins throughout the star almost simultaneously, resulting in a carbon explosion.

21.3 Supernovae

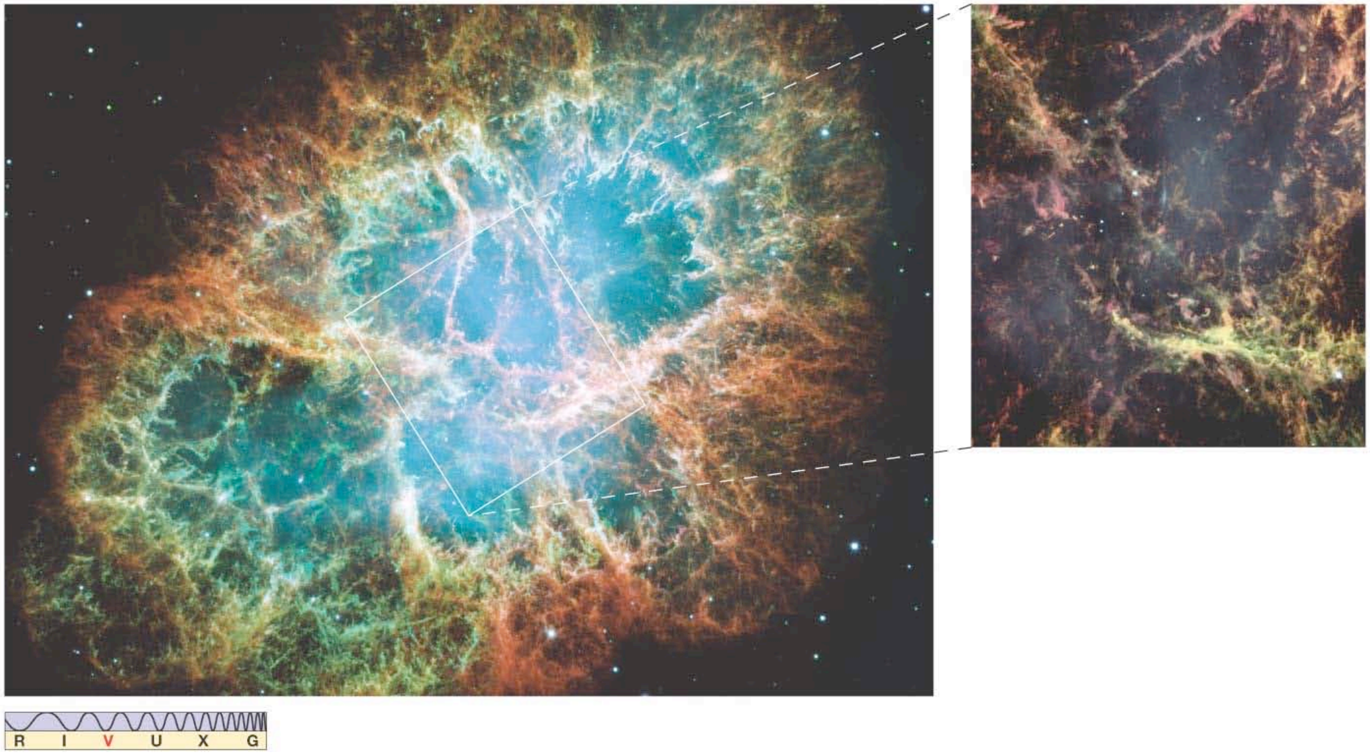
This graphic illustrates the two different types of **supernovae**:



21.3 Supernovae

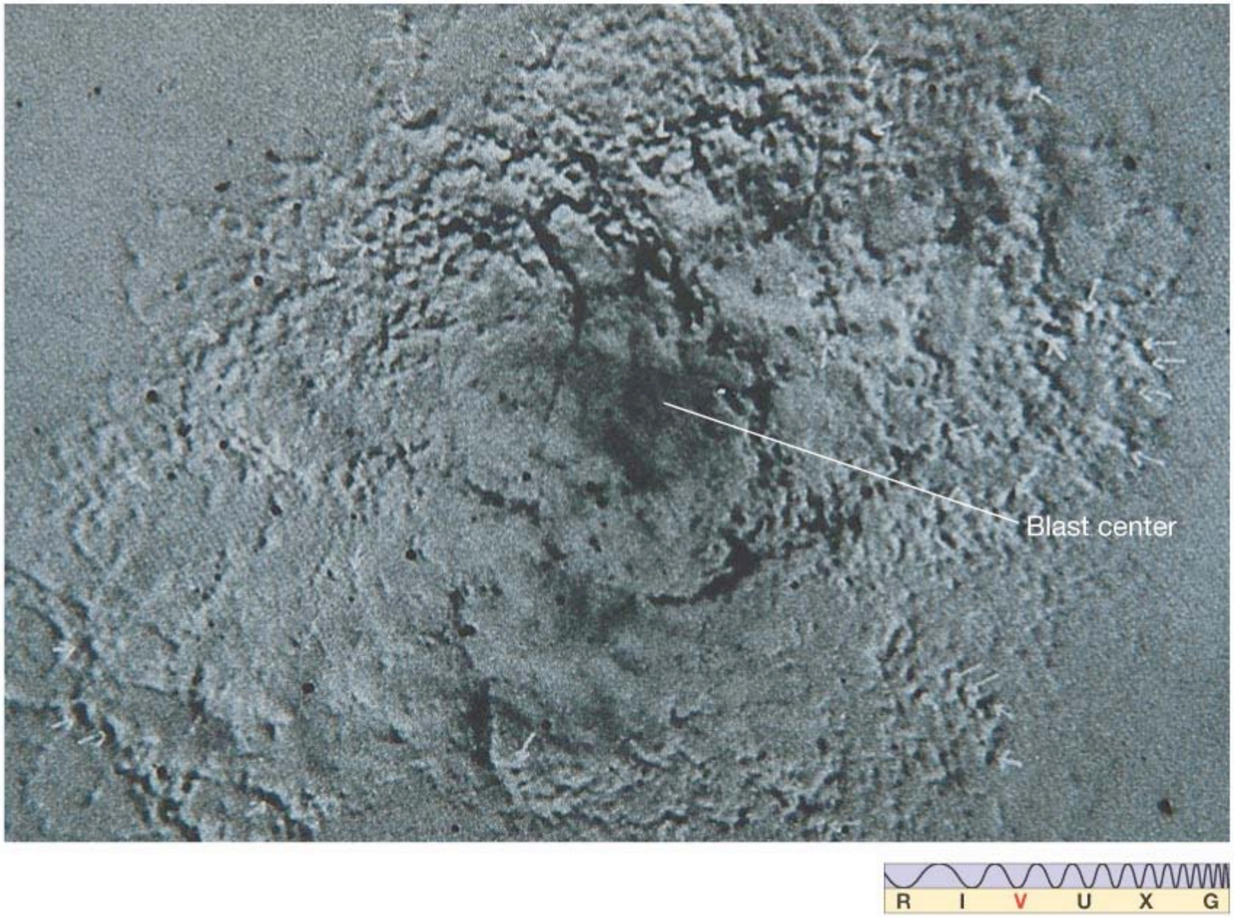
Supernovae leave **remnants**—the expanding clouds of material from the explosion.

The **Crab nebula** is a remnant from a supernova explosion that occurred in the year 1054.



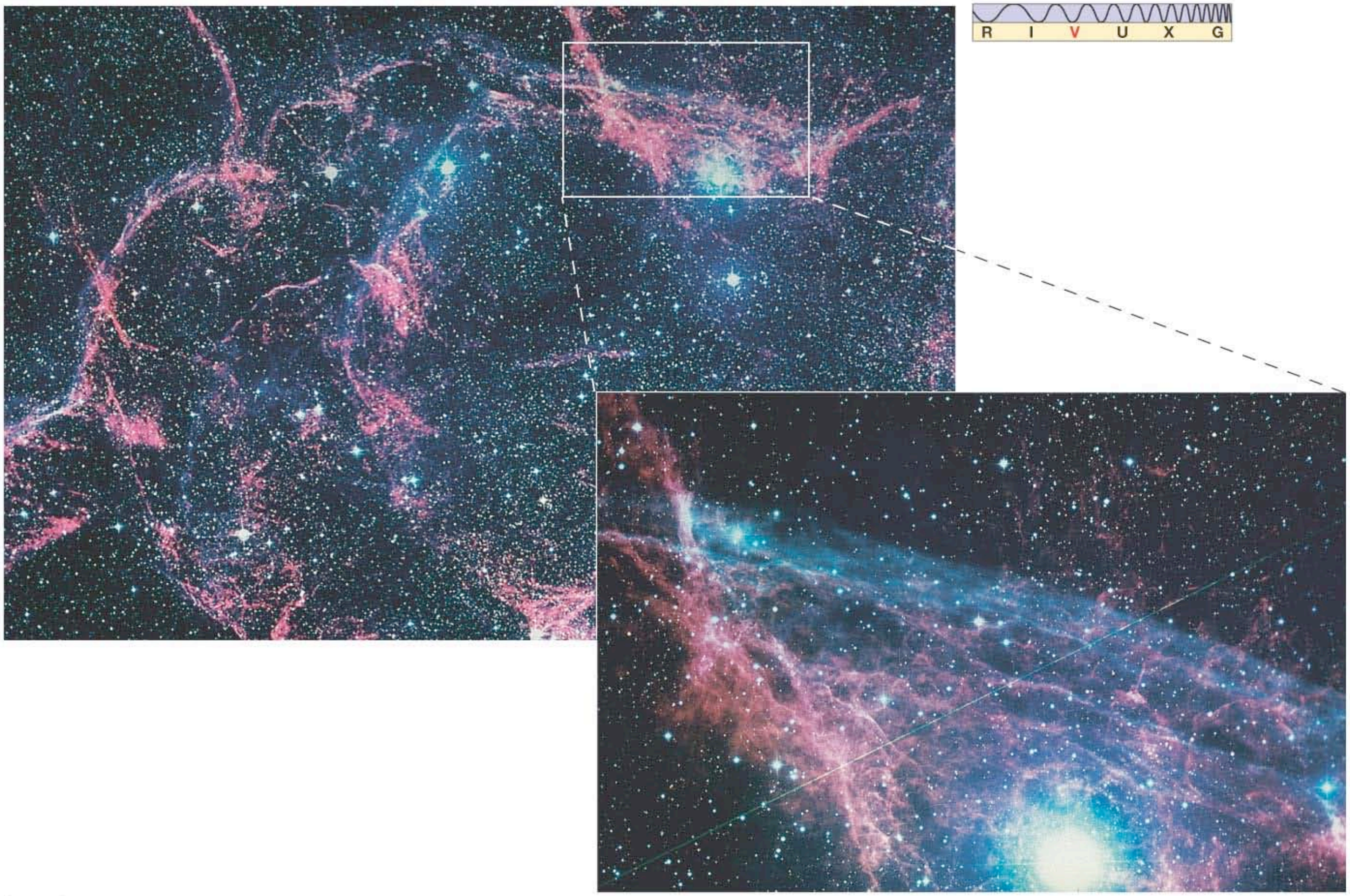
21.3 Supernovae

The velocities of the material in the Crab nebula can be extrapolated back, using Doppler shifts, to the original explosion.



21.3 Supernovae

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

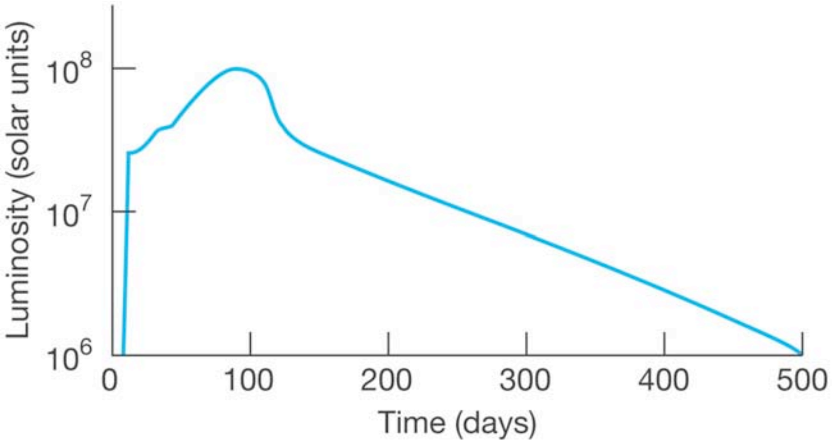


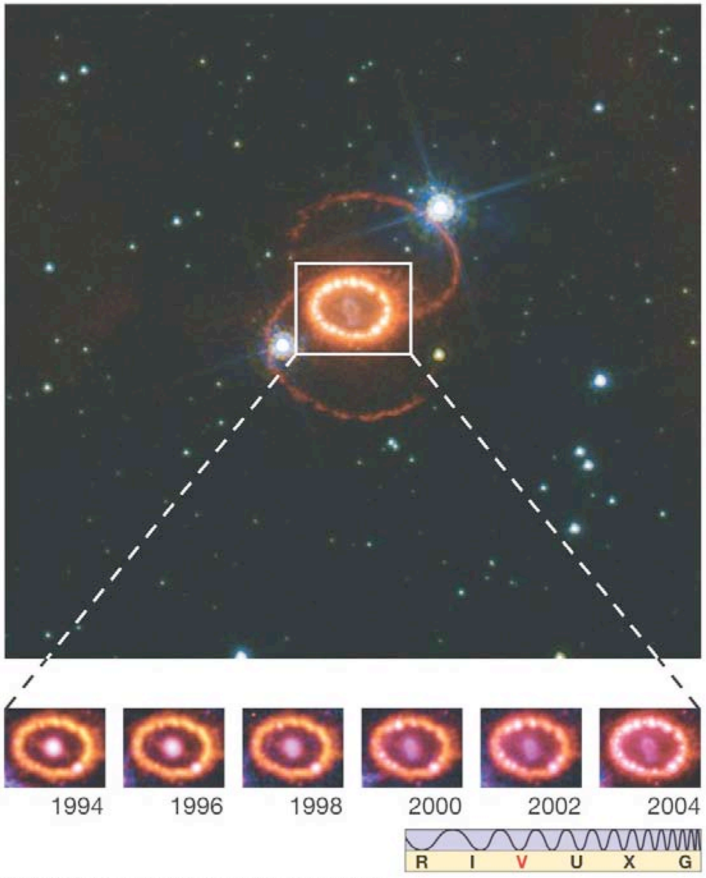
Discovery 21-1: Supernova 1987A

This is the most important supernovae of all time, because astronomers watched it as it exploded.

Supernovae are rare; there has not been one in our galaxy for about 400 years.

A supernova, called SN1987A, did occur in the Large Magellanic Cloud, a neighboring galaxy, in 1987. Its light curve is somewhat peculiar:

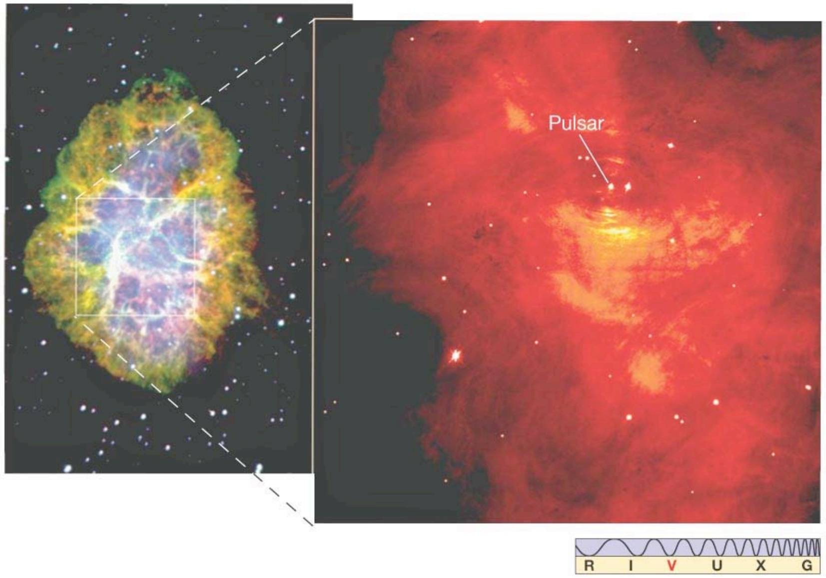




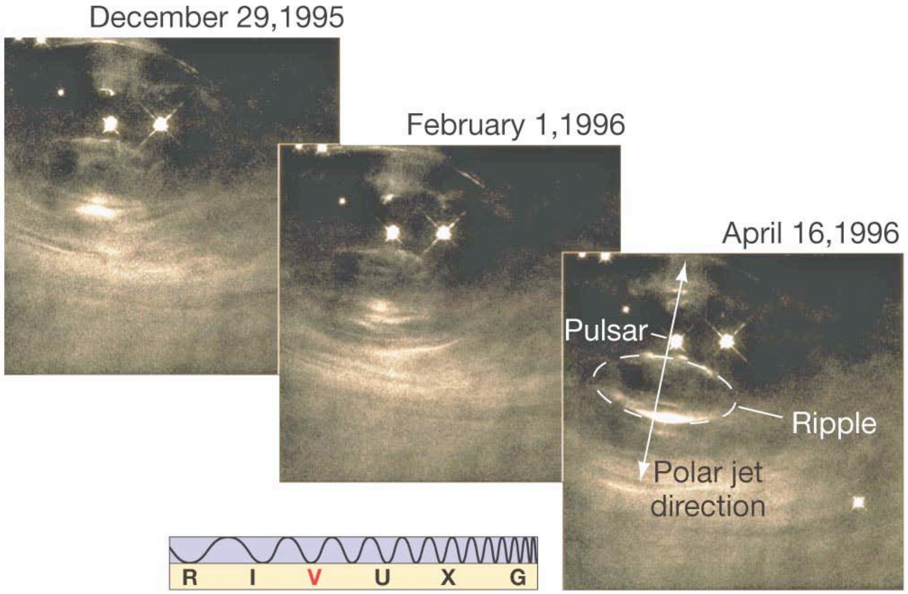
A cloud of glowing gas is now visible around SN1987A, and a small central object is becoming discernible:

Discovery: 21-2
The Crab Nebula in Motion

The Crab Nebula is complex; its expansion is detectable and there is a pulsar at its center.



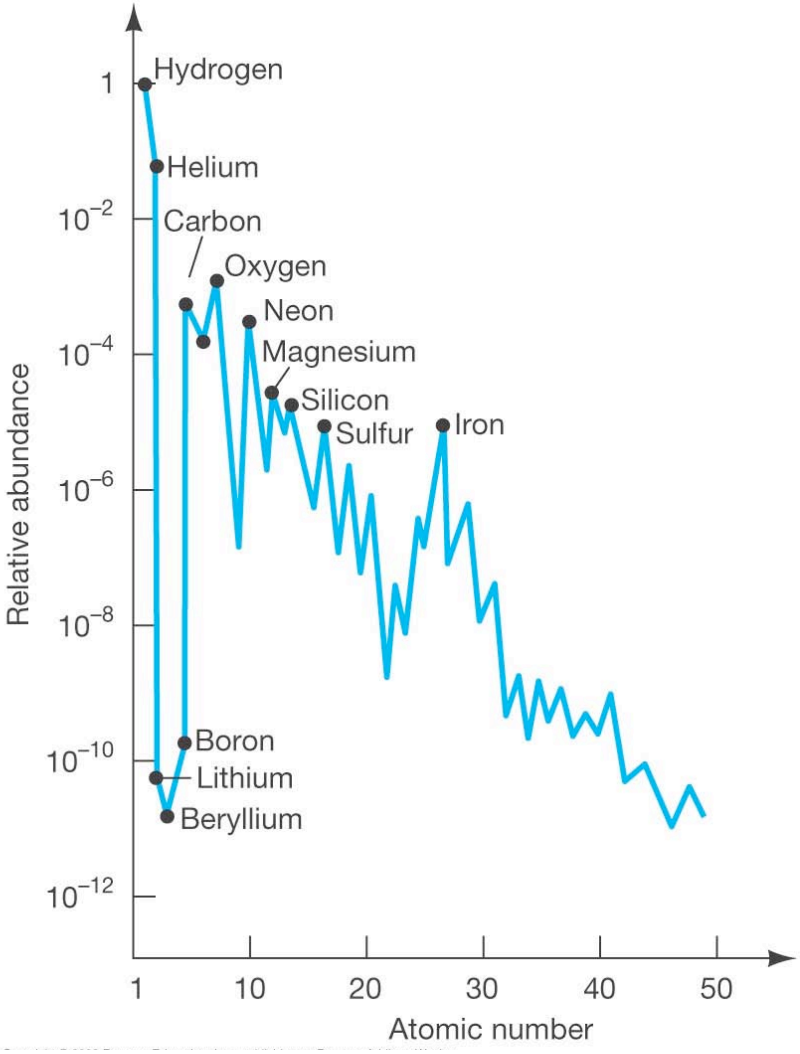
This second set of images, focused in on the central pulsar, shows ripples expanding outward at half the speed of light:



21.4 The Formation of the Elements

There are 81 stable and 10 radioactive elements that exist on our planet. Where did they come from?

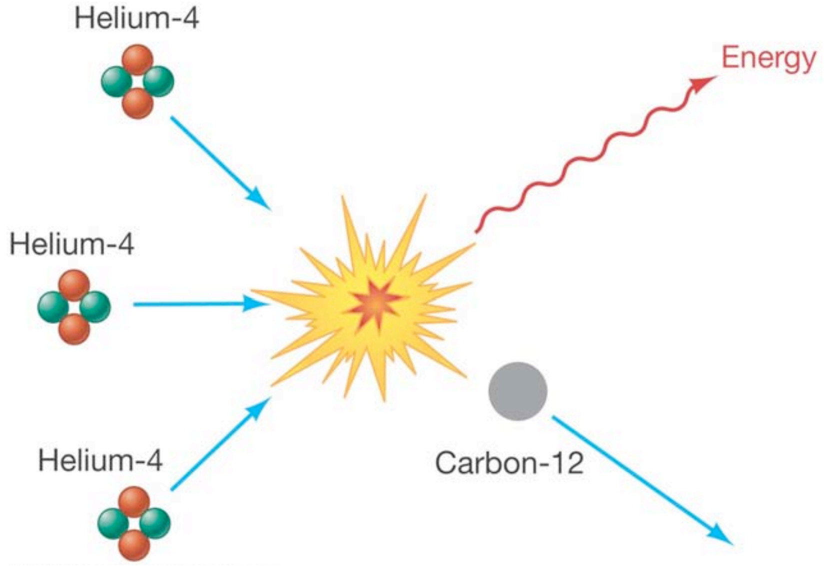
This graph shows the relative abundances of different elements the universe. Observe how the heavier elements are less and less abundant, except for a peak at iro

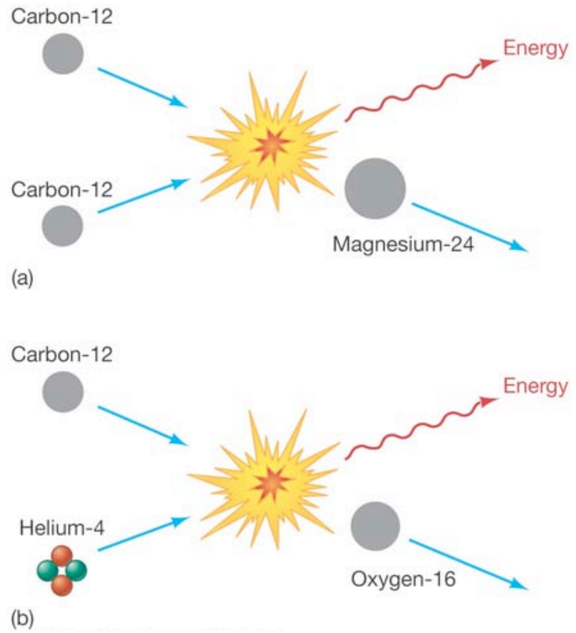


Calculations of *nucleosyntheis* that occurs during the explosions of supernovae account for this pattern of element abundances in detail, every up and down of the graph shown here. It is one of the main successes of stellar evolution models.

21.4 The Formation of the Elements

Some of these elements are formed during normal stellar fusion. Here, three helium nuclei fuse to form carbon. This is the famous *"triple alpha" reaction*, which produces all the carbon in the universe because of a "lucky" energy level, as discussed previously.

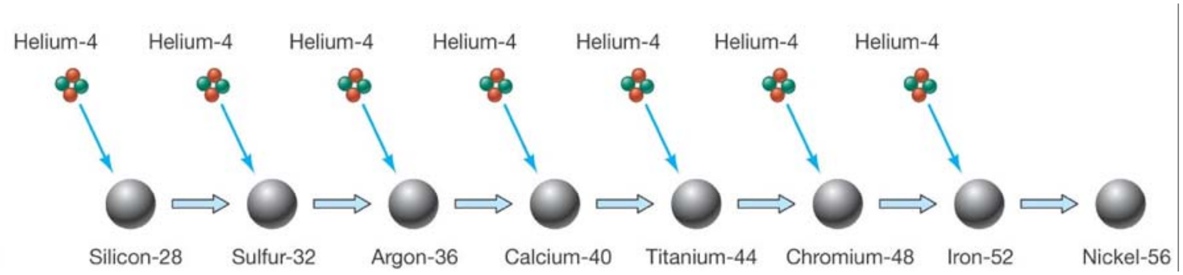




Carbon can then fuse, either with itself or with alpha particles, to form more nuclei (left). Then the products, oxygen and magnesium, can fuse with alpha particles or other nuclei to give even heavier elements, all the way to iron. But that is as far as fusion can take a star.

21.4 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 last nucleus in the alpha-particle chain is nickel-56, which is unstable and quickly decays to cobalt-56 and then to iron-56.

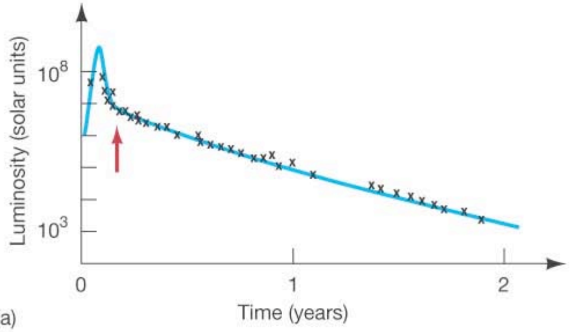
Iron-56 is the most stable nucleus, so it neither fuses nor decays.

However, within the cores of the most massive stars, neutron capture can create heavier elements, all the way up to bismuth-209. Some of this neutron capture occurs in the cores of red giants, but also during the explosions of massive stars.

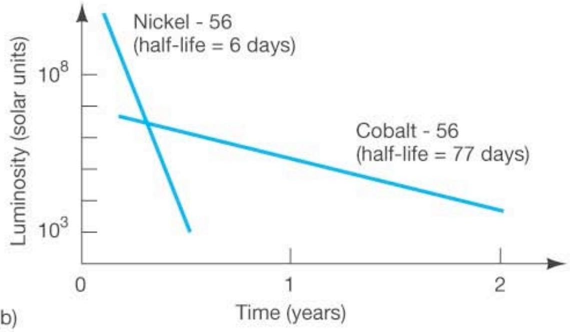
21.4 The Formation of the Elements

This theory of formation of new **elements** in supernova explosions produces a **light curve** that agrees quite well with observed curves (right).

The key is that the model ends up with a collapsing core of almost pure nickel-56, which is radioactive, with a half-life of 6 days. The high-energy radiation from the radioactive decay of nickel is what powers the first part of the supernova light curve.



(a)



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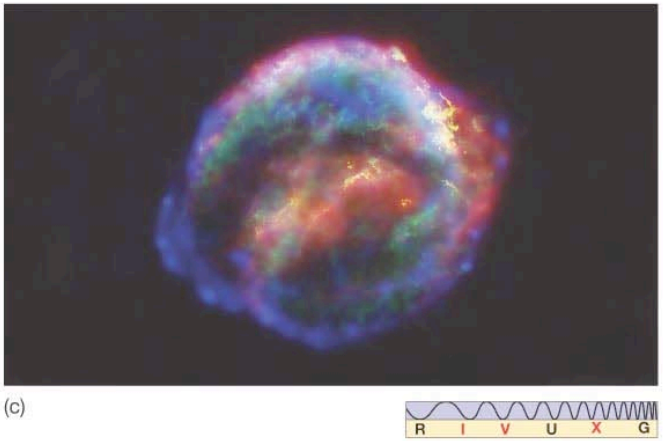

(c)

21.5 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 parts of new stars.

Summary of Chapter 21

- A nova is a star that suddenly brightens and gradually fades; it is a white dwarf whose larger partner continually transfers material to it.
- Stars greater than eight solar masses can have fusion in their cores going all the way up to iron, which is stable against further fusion.
- The star continues to collapse after the iron core is found, implodes, and then explodes as a supernova.
- **Two types of supernovae:**
- Type I, a carbon-detonation supernova
- Type II, a core-collapse supernova
- ***All elements heavier than helium are formed in stars:***