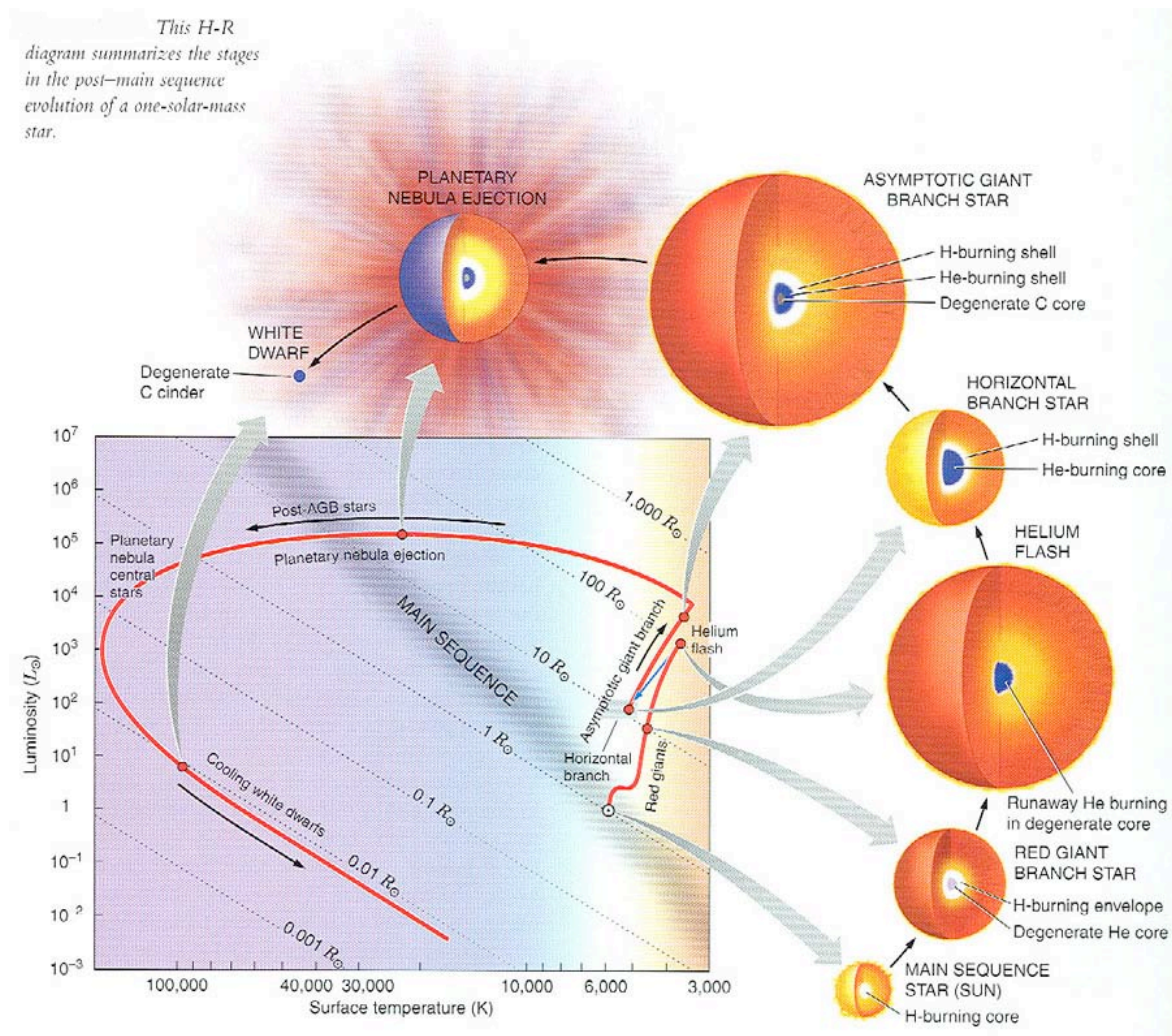# Stellar Explosions (ch. 21)

First, a review of low-mass stellar evolution by means of an illustration shown below. You should be able to talk your way through this diagram and it should take at least half an hour.

Remember that all stars less massive than about 8 Mo go through these phases (except not the helium flash above about 2 Mo). What is the major reason why the advanced evolution of higher-mass stars is so different?

This H-R diagram summarizes the stages in the post–main sequence evolution of a one-solar-mass star.

➡ Before discussing high-mass stellar deaths, don't forget the material in **Sec. 21.1**: "nova explosions" by mass transfer from a RG to a WD companion. This is really a continuation of sec. 20.6 on binary star evolution. *Read this for your interest, but it will not be on the exam.*

However, you will find it extremely useful throughout the rest of the course to understand the idea of an <u>accretion disk</u> that is introduced in this section. They will come up again and again.

Death of a High-Mass Star

In short:

Envelope explodes as a <u>core collapse supernova</u>.
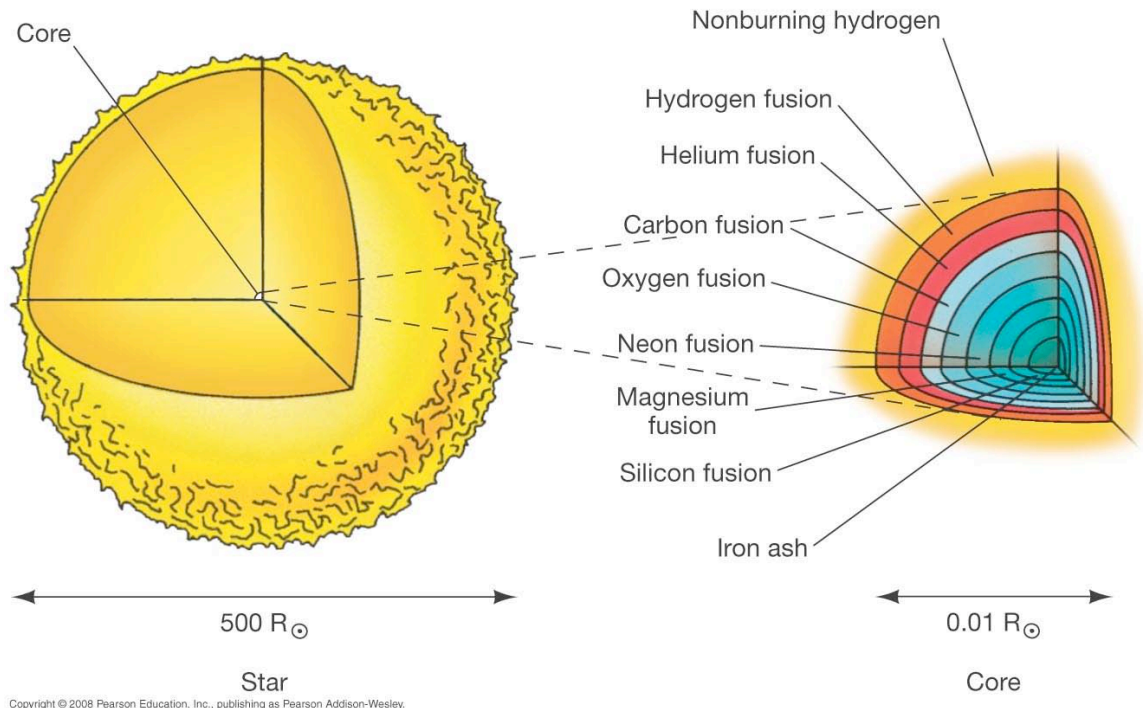
The *core* implodes and ends up as a <u>neutron star</u> or (more massive) a <u>black hole</u>.

Let's see how this occurs. (Remember, this is all theoretical calculations, but later you'll see that there is surprising observational confirmation for these calculations.)

Core is layered like an onion, with heavier elements closer to center (since they are the ashes of a previous fuel):
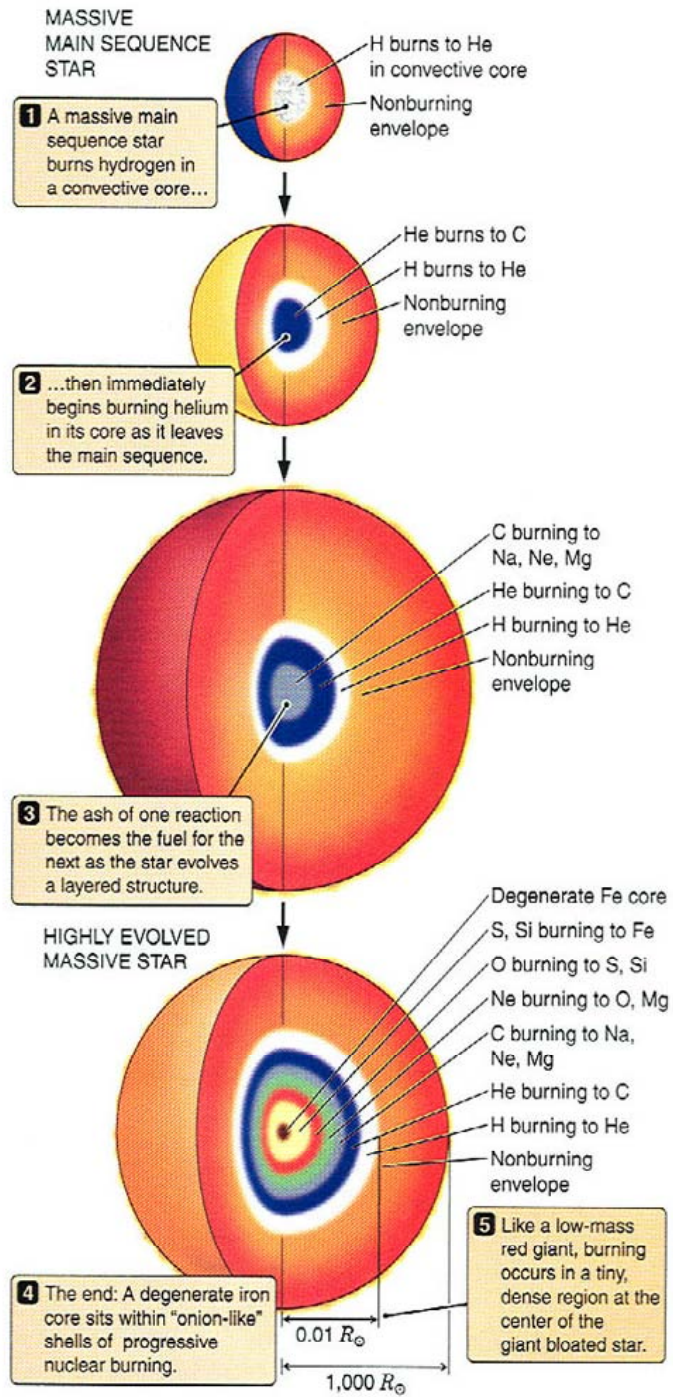
He, C, O, Ne, Mg, Si, **Fe**

These are the main elements produced up to this phase because they are produced by adding helium (He, "alpha particles") to heavier and heavier nuclei. (Iron Fe is in bold in this list because it is the "end of the line" for stellar nuclear fusion—see below.)

Core

Nonburning hydrogen

Hydrogen fusion

Helium fusion

Carbon fusion

Oxygen fusion

Neon fusion

Magnesium fusion

Silicon fusion

Iron ash

500 $R_\odot$

0.01 $R_\odot$

Star

Core

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(Question to see if you understand nuclear fusion: **Why is so much easier to burn He with, say, O, rather than C+O or O+O ?** Hint: why do main sequence stars burn hydrogen rather than something heavier?)

On the next page is a cutaway drawing of what the inside of a massive star might look like as it completes more and more burning stages. A good "cutaway" sketch of this structure is also given in your text, Fig. 21.5, p. 558.

MASSIVE
MAIN SEQUENCE
STAR

H burns to He
in convective core

Nonburning
envelope

1 A massive main
sequence star
burns hydrogen in
a convective core...

He burns to C
H burns to He
Nonburning
envelope

2 ...then immediately
begins burning helium
in its core as it leaves
the main sequence.

C burning to
Na, Ne, Mg
He burning to C
H burning to He
Nonburning
envelope

3 The ash of one reaction
becomes the fuel for the
next as the star evolves
a layered structure.

HIGHLY EVOLVED
MASSIVE STAR

Degenerate Fe core
S, Si burning to Fe
O burning to S, Si
Ne burning to O, Mg
C burning to Na,
Ne, Mg
He burning to C
H burning to He
Nonburning
envelope

5 Like a low-mass
red giant, burning
occurs in a tiny,
dense region at the
center of the
giant bloated star.

4 The end: A degenerate iron
core sits within "onion-like"
shells of progressive
nuclear burning.

$0.01\ R_\odot$

$1,000\ R_\odot$

*As a high-mass star evolves, it builds up a layered
structure like an onion, with progressively more advanced stages of
nuclear burning found deeper and deeper within the star.*

First way to get a supernova: *core collapse.*

Massive stars burn nuclear fuels up to iron (Fe). **But nuclear fusion of iron does not produce energy, it *uses* energy.** (Fig. 21.6, p. 559) **This leads to loss of pressure support** $\Rightarrow$ core collapse

Temp. is so large (~10 billion K) that the gamma ray photons (Wien's law) have huge energies and photodisintegrate the iron into protons and neutrons. This *absorbs* even more thermal (heat) energy, so the core collapses even faster! Gravity is having its way…

The protons combine with electrons to give neutrons and neutrinos (which escape immediately—later we'll see that they have been accidentally observed in one case). The core has been converted into one massive collection of neutrons ("neutronization"; see p. 559 of textbook), all collapsing under gravity.

Now nothing can stop the core collapse *except* neutron degeneracy pressure, which sets in at a density of about 10^{12} grams per cc (!). Analogous to electron degeneracy pressure (which saved lower mass star cores as white dwarfs), but at *much* higher densities.

But the collapse is so violent that the core overshoots this density and then "bounces" $\Rightarrow$ violent shock wave propagating outward.

All this takes ~ 1 second. (Remember, star took at least millions of years to get to this phase in its evolution.)
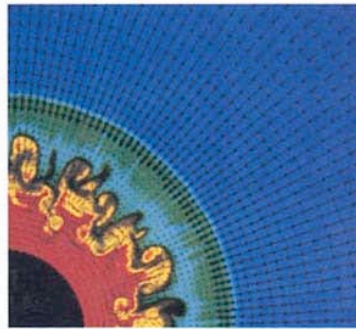
The shock wave blasts through all the overlying layers $\Rightarrow$ star explodes as core collapse supernova.

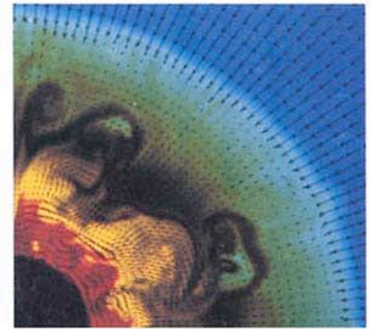(We'll see another way to make a supernova below.)

The next two pages show a simulation of the explosion deep in the core, and an illustration showing the chain of events that leads to this spectacular death for massive stars.
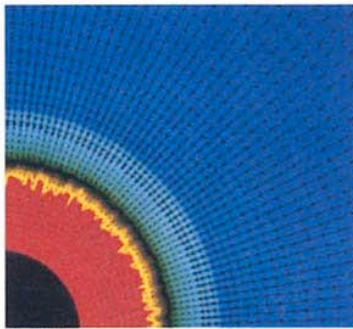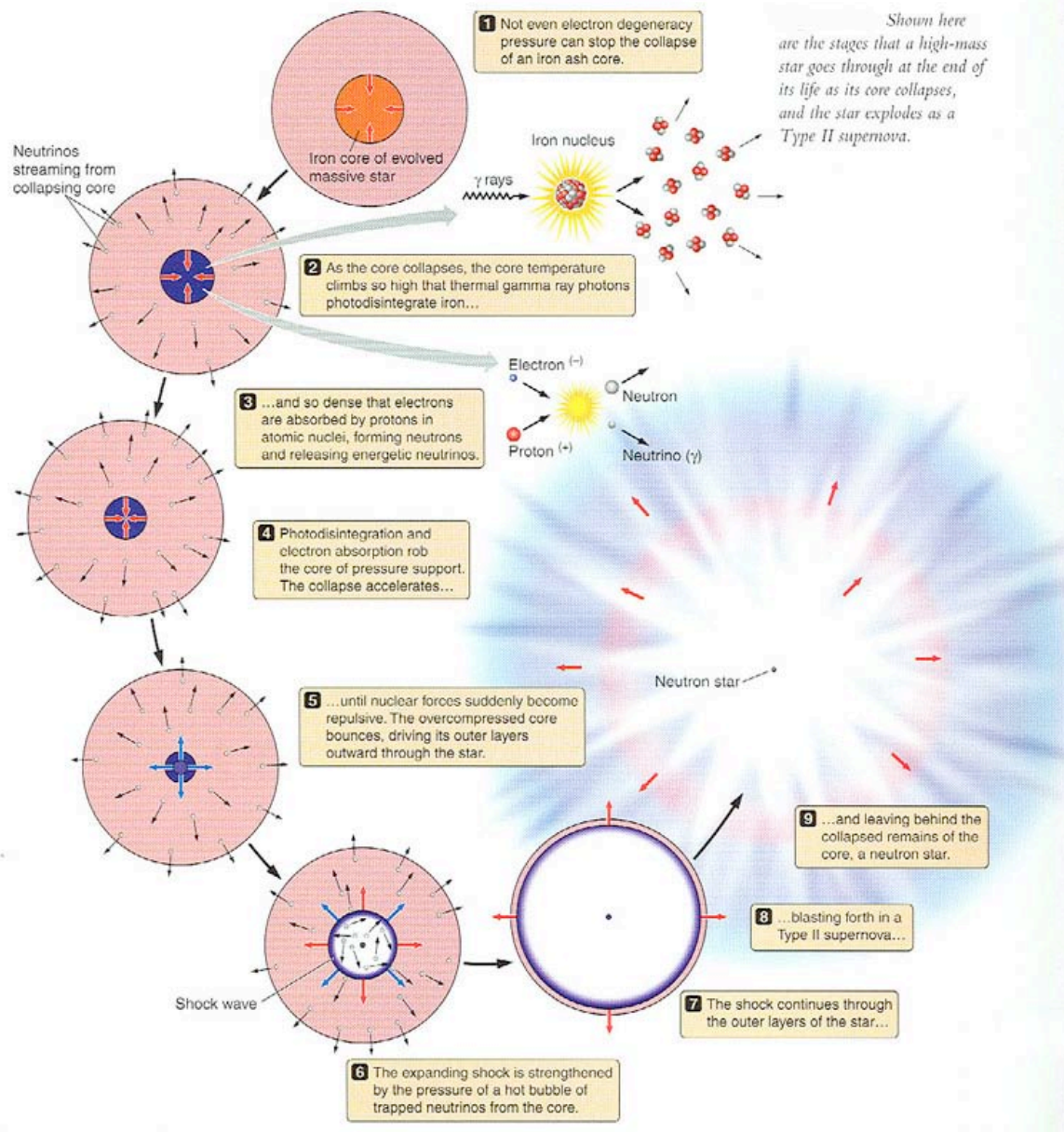
5 milliseconds   10 milliseconds   20 milliseconds

The Core of a Supernova These images from a supercomputer simulation show the core of a massive star during the first 20 milliseconds of a supernova explosion. The colors indicate temperatures that range from 2×10^{10} K (red) to 6×10^8 K (blue). Matter that bounces off the stiffened core of the star (colored black) produces a shock wave. Instabilities generate turbulent eddies that grow as the shock wave moves outward. (Courtesy of Adam Burrows, University of Arizona; and Bruce Fryxell, NASA/GSFC)
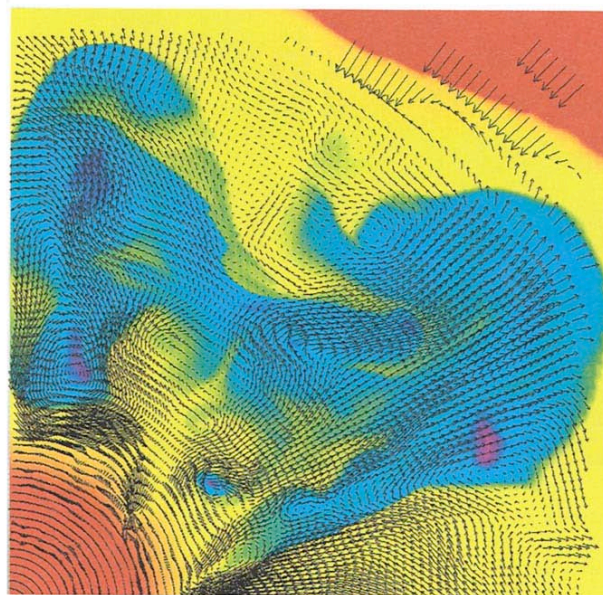
The inside of an exploding star is shown in this mathematical model of a supernova explosion. The image here represents a region 150 km on a side near the center of the star (lower left). Black arrows indicate the motion of the gas. Turbulent material (blue) has bounced off the core and is rushing outward to meet the rest of the star, which is falling inward (red at upper right). The innermost part of the star is forming a neutron star (red at lower left). To show the entire star at this scale, this figure would have to be 140 km in diameter. *(Courtesy Adam Burrows, John Hayes, and Bruce Fryxell)*

1 Not even electron degeneracy pressure can stop the collapse of an iron ash core.

Shown here are the stages that a high-mass star goes through at the end of its life as its core collapses, and the star explodes as a Type II supernova.

Iron core of evolved massive star

Iron nucleus

γ rays

Neutrinos streaming from collapsing core

2 As the core collapses, the core temperature climbs so high that thermal gamma ray photons photodisintegrate iron...

Electron (−)

Neutron

Proton (+)

Neutrino (γ)

3 ...and so dense that electrons are absorbed by protons in atomic nuclei, forming neutrons and releasing energetic neutrinos.

4 Photodisintegration and electron absorption rob the core of pressure support. The collapse accelerates...

5 ...until nuclear forces suddenly become repulsive. The overcompressed core bounces, driving its outer layers outward through the star.

Neutron star

9 ...and leaving behind the collapsed remains of the core, a neutron star.

8 ...blasting forth in a Type II supernova...

7 The shock continues through the outer layers of the star...

Shock wave

6 The expanding shock is strengthened by the pressure of a hot bubble of trapped neutrinos from the core.

Many supernovae (SN) have been observed in historical times in our own Galaxy, visible to the naked eye (sometimes in daylight!). Best example is SN 1054 A.D., the Crab Nebula. Here is an image of what the remains of the explosion look like today, nearly 1000 years later. A "zoom-in" on this image is on p.564 of the text.
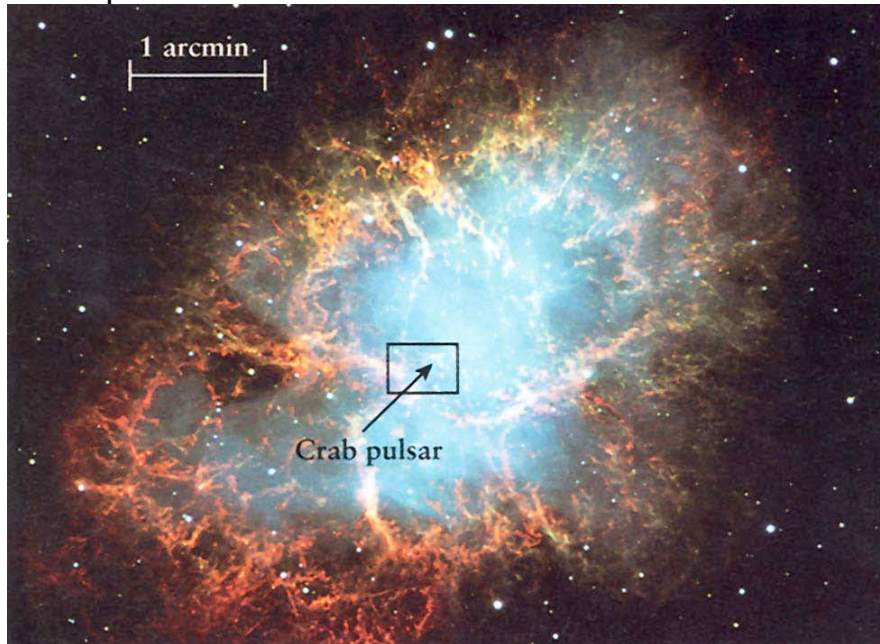
A SN produces a billion solar luminosities in just a few hours or less. Until discovery of gamma ray bursts (ch.22), these were, gram for gram, the most luminous objects in the universe. That is why they can be observed even in very distant galaxies (e.g. 100s of Mpc away), or even at the edge of the observable universe (later we'll see that they play a crucial role as the standard candles that have led to the belief that there is a "dark energy" that pervades the universe).

A second way to get a supernova :
A white dwarf accreting matter from a binary companion.
This increases the mass of the white dwarf. If white dwarf mass gets larger than 1.4 Mo (the "Chandrasekhar limit"), electron degeneracy pressure can't support the white dwarf against gravity and the white dwarf collapses. As it collapses, it heats up, carbon fusion occurs explosively $\Rightarrow$ carbon detonation supernova. See Fig. 21.9, p. 564 of text for pictorial.

Observationally, there *are* two classes of supernovae, which differ in their composition and their <u>light curves</u> (brightness vs. time—see Fig. 21.8, p. 561 in text).

Type I: H-poor $\Rightarrow$ carbon detonation SN (former white dwarfs)

Type II: H-rich $\Rightarrow$ core collapse SN (massive stars that burn up to iron)

(You don't have to memorize the types, just that there are two of them and how they differ.)
See Fig. 21.9, p. 564 for good illustration of the two mechanisms.
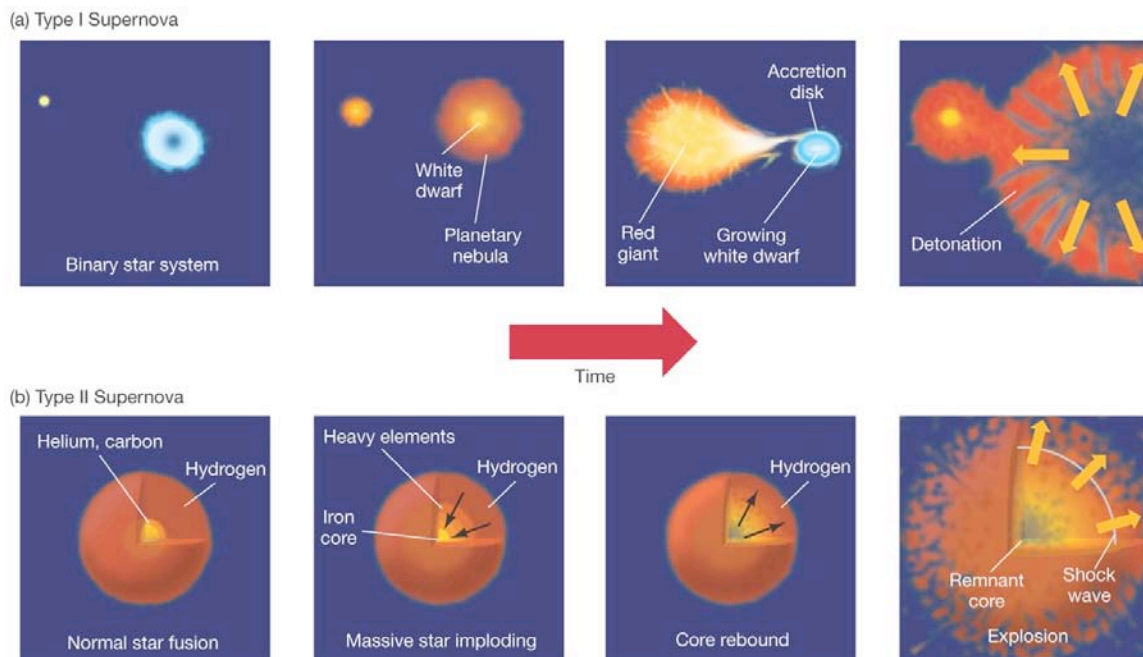
The SN explosion produces a fast-moving expanding shell of gas, observed as **supernova remnants** (SNRs). E.g. Crab Nebula (explosion in 1054 A.D. recorded by Chinese and Native Americans).   Hundreds of these are known (see illustrations in book for the interesting forms that are produced).

How can you prove that the SNR is from the 1054 A.D. SN? Observed radial velocities of a few thousand km/sec gives age, which comes out to be about 950 years as it should. See Discovery 21-2 on p. 566.

From the observed number of SNe (supernovae) in our own and other galaxies, we expect about 1 SN per 100 years in our Galaxy. But the last one was seen 400 years ago (Tycho's SN). So we are overdue!

Here is an image of the Cas A SNR in X-rays (left) and at radio wavelengths (right). The X-rays are emitted because the gas is so hot (~ million degrees K), while the radio emission is from electrons that are gyrating at nearly the speed of light around the strong magnetic field in the remnant—this is where it is believed that **cosmic rays** are accelerated.
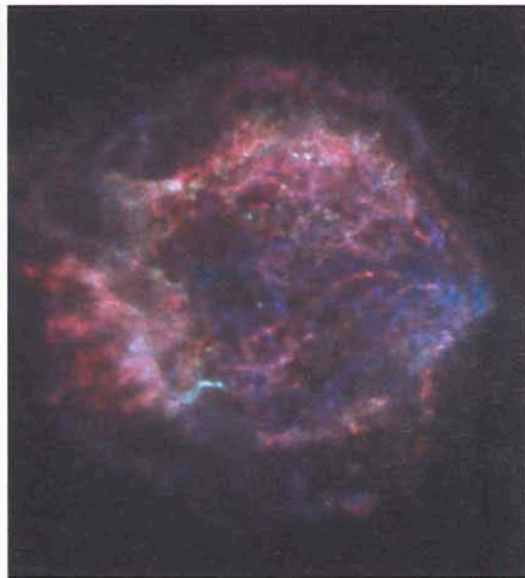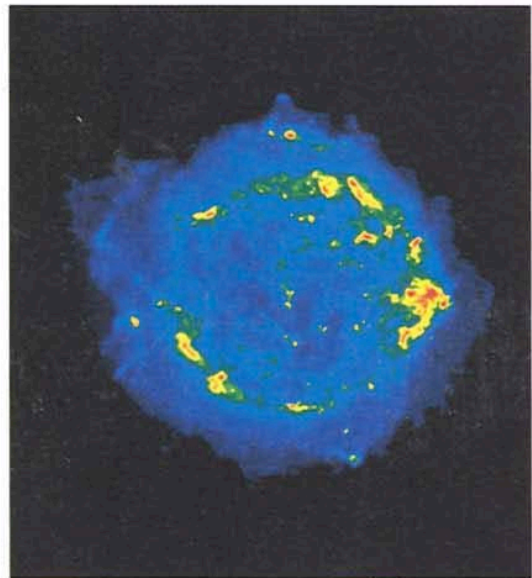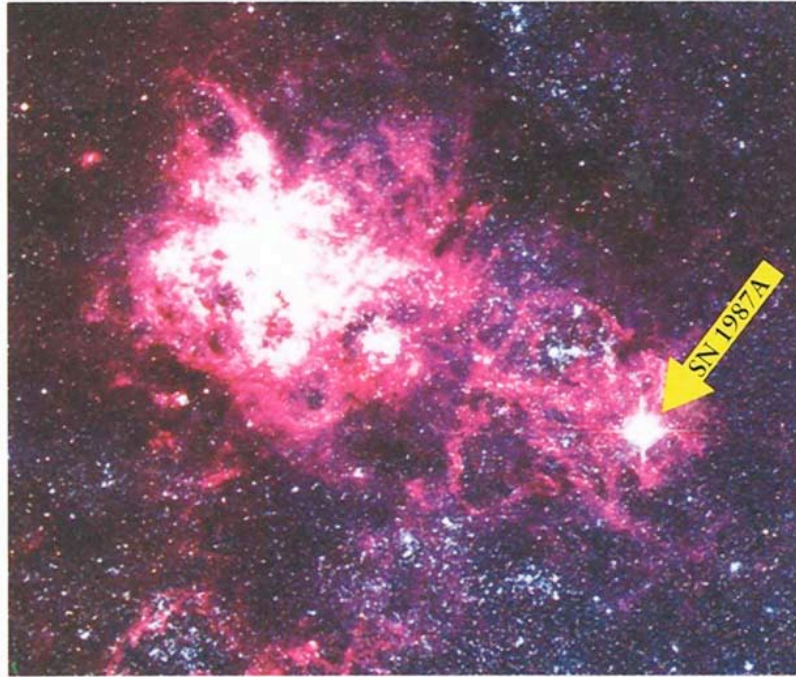

a   R I V U **X** G   b   **R** I V U X G

SN 1987A in the Large Magellanic Cloud (LMC)
(Fig. 21.7, reproduced below, and Discovery 21-1 on p. 562)
This was a major event for astronomers, since by far it's the nearest SN since we've been observing them. It outshined the entire LMC galaxy at its peak!
(See illustration below)

R I **V** U X G

Supernova 1987A A supernova appeared in a nearby galaxy called the Large Magellanic Cloud (LMC) in 1987. This photograph, taken soon after the discovery, shows a portion of the LMC that includes the supernova (SN 1987A) and a huge H II region called the Tarantula Nebula. SN 1987A was the first supernova in almost 400 years that was bright enough to be seen without a telescope. (European Southern Observatory)

SN 1987a gives fairly good confirmation of the core collapse model for Type II SN.
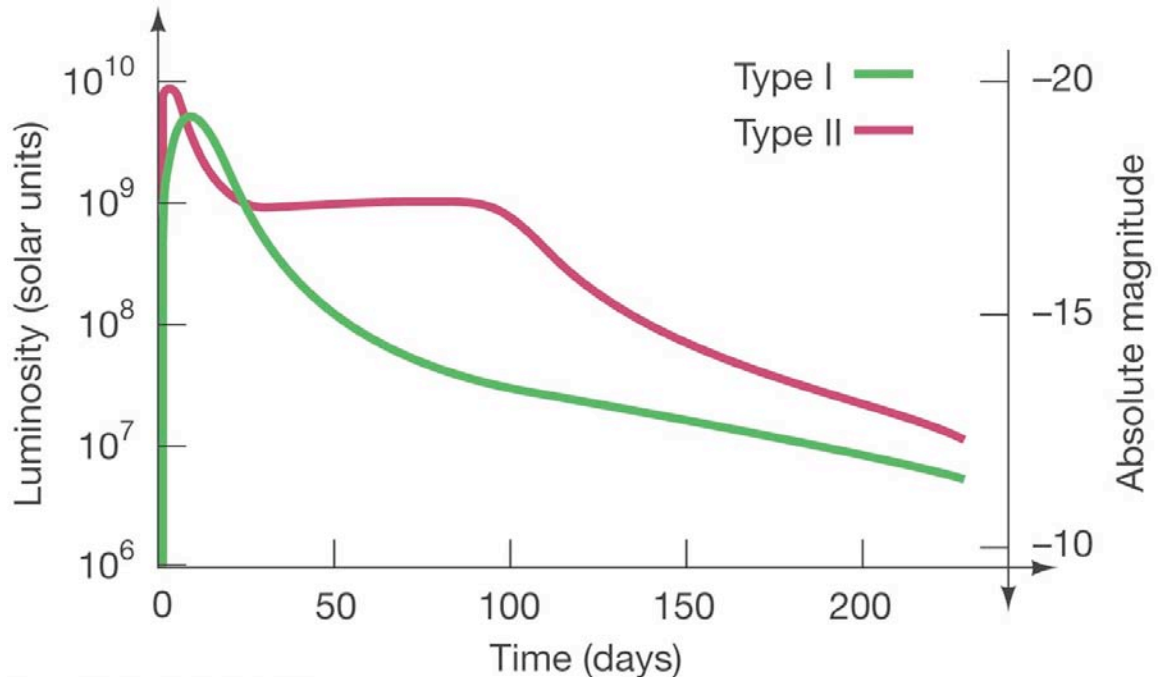In particular, an unexpected neutrino burst was observed about 20 hours *before* the explosion was observed (visually) by underground neutrino detectors in Japan and U.S. (The delay is because most of the light from the

SN has to diffuse through the thick exploding envelope, while the neutrinos pass right through.)

But the progenitor object (pre-SN) was a *blue* supergiant, not red as expected, and the light curve was strange, so it is something of an anomaly.

SN as distance indicators. *If* all SN reached the same *peak* luminosity in their light curve, then we could use them as <u>standard candles</u> to get the distances by observing supernova light curves, since we know the luminosities of nearby supernovae in galaxies whose distances we know by other means.

Your textbook shows the two characteristic light curves of the two types of supernovae (don't worry about remembering the "types", but know that there are two of them and why):

Actually one subclass of supernovae *are* found to have remarkably similar peak luminosities. Later we'll see how these have been used to map the expansion of the most distant parts of the universe, and to discover that most of the universe is apparently filled mostly with the most mysterious thing in astronomy: "dark energy."

Formation of the elements (21.4 in textbook)

This is an especially important subject. Where do all the (110 or so known) different elements, from H, He,…to uranium, lead,… come from?

Except for H and He, they come from stellar nucleosynthesis: nuclear fusion in stars.

Look at the <u>pattern of abundances of elements</u> as a function of their atomic weight in **Fig. 21.13** (p. 568). You can see that the heavier elements are less abundant than the light elements, and that there are peaks at (C, N, O) and at Fe.
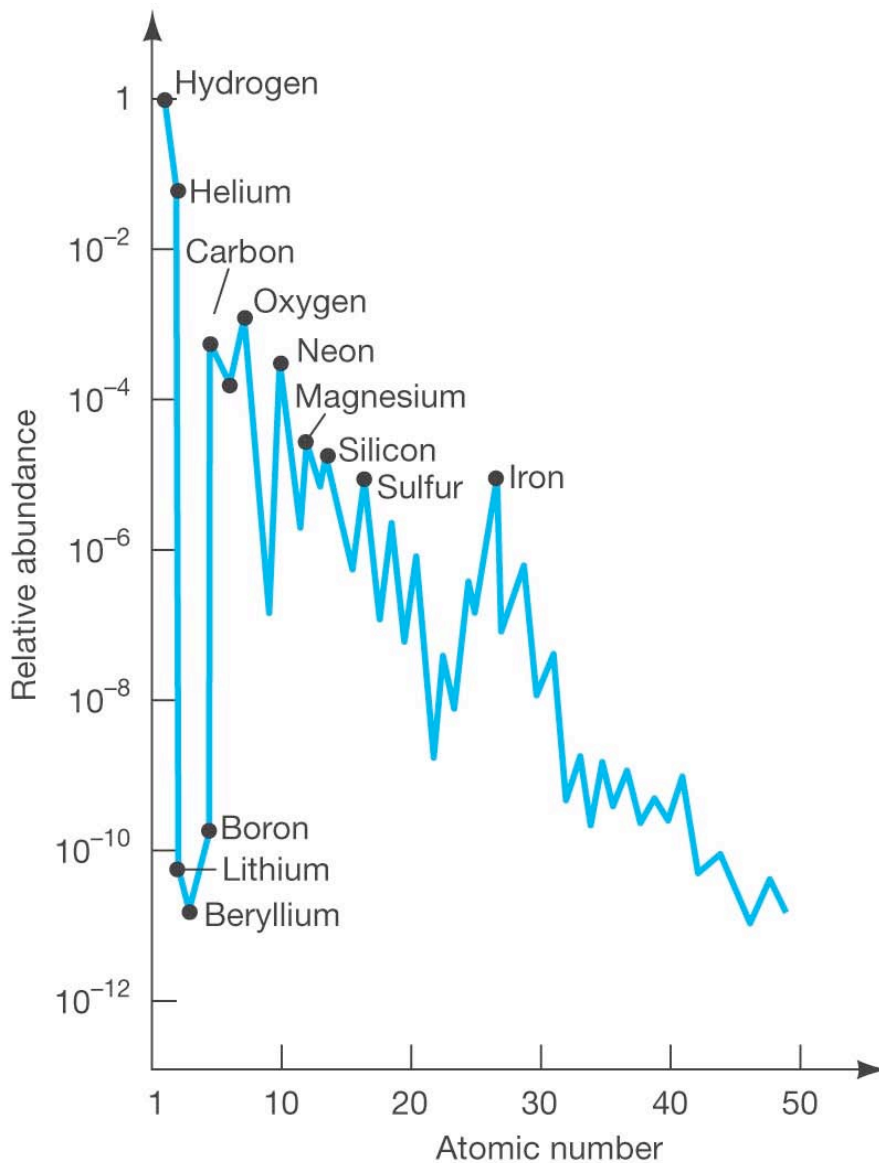
Most heavier elements up to iron are made by **helium capture**, which we discussed earlier. Get C → O → Ne → Mg → … → Fe. Their masses are divisible by four (do you understand why?)

Proton capture—makes the (lower abundance) elements whose mass is not divisible by four. These are the "dips" between the minor "peaks" in the figure.

Neutron capture (mainly on iron). Two types:

1. s (slow) process—takes place in red giant interiors, stops at bismuth 209.

2. r (rapid) process—probably takes place in supernova explosions, goes out to thorium 232, uranium 238, plutonium 242.

This is all discussed in much more detail in sec. 21.4 which you should read.

Observational evidence for stellar <u>nucleosynthesis</u>:

1. The theoretically-predicted abundances agree with observations (Fig. 21.13, included above), e.g. the peaks at C, O and Fe, and even the patterns in between and the s-process patterns. This is amazing agreement considering that we are not even sure about the details of stellar explosions.

2. Technetium—this element is predicted to be produced in the s-process, but it is radioactive, and decays in 200,000 years. Yet it is observed *in the atmospheres* of some red giant stars ⟹ must have been produced in the interior and mixed to the surface, where the red giant wind will spew it back into the interstellar medium. **This is direct evidence that s-process nucleosynthesis occurs in the cores of stars!**

3. Supernova light curves (see **Fig. 21.8, and below**): For Type I supernovae, the light curves can be fit by the radioactive decay of nickel 56 (55 days) and cobalt 56 (78 days); **these are predicted to be some of the main nuclear products of nucleosynthesis in carbon detonation supernovae.** We don't actually see the nickel and cobalt, but the timescales for decline match very well. And the gamma ray line emitted by cobalt 56 *has* been observed from a supernova in another galaxy.

(a)

(b)
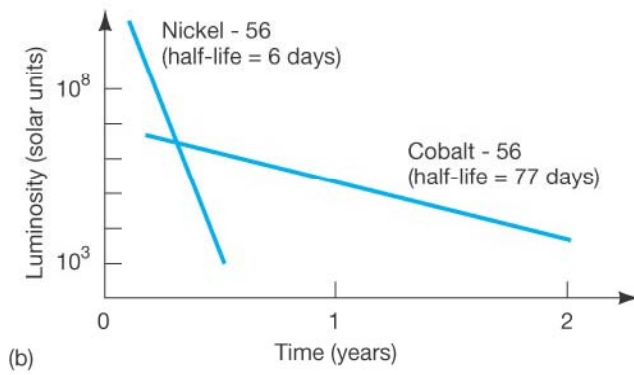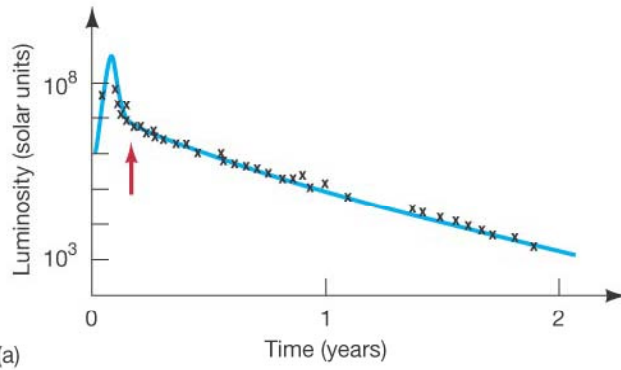
Taken together, this is strong evidence that the theory of stellar nucleosynthesis in stars is correct, and also supports the explosion models for supernova explosions.

Here is a pictorial review of the difference in evolution between low-mass and high-mass stars. Do you remember the physical condition that distinguishes between them? For the high-mass stars, the envelope may explode as a supernova, but the core probably ends up as a neutron star or a black hole, the subjects of Ch. 22, which we cover after this exam.

Main-sequence mass ($M_\odot$) ⟶

0.1   1   10   100

Main-sequence stars

Red giants

Helium flash

Supergiants

AGB stars

Planetary nebulae   Supernovae

White dwarfs   Neutron stars   Black holes

0.5   1   3   10

Stellar corpse mass ($M_\odot$) ⟶