Neutron Stars, Gamma Ray Bursts
(postponing material on black holes until the next exam)

For carbon detonation SN ⇒ probably no remnant
For core-collapse SN ⇒ remnant is a neutron-degenerate core
⇒ neutron star
Densities ~ 10^{14} to 10^{15} g/cm^3 ~ billion times denser than water

Cubic centimeter contains ~ 100 million tons! Like a single enormous nucleus, all neutrons nearly touching.

Gravity at surface is huge. e.g. a human would weigh ~ million tons

Rotation period ~ fraction of a second when first formed (conservation of angular momentum)

Magnetic field is huge, amplified by the collapse (~10^{12} x Earth's field strength). Most extreme of these are called "magnetars"—100s now known.

Observed as pulsars (discovered 1967). Each pulsar has different pulse period (0.03 to 0.3 sec for most) but most are *very* stable. (Fig. 22.2)

A few pulsars are seen within supernova remnants (e.g. Crab Nebula, Fig. 22.4, 22.5), but not all remnants have a detectable pulsar.

Interpretation: rotating "lighthouse model." (Fig. 22.3) Rotation slows down with time, on a timescale of about a million years.

Understand why, in this model, not all neutron stars can be observed as pulsars.

"Glitches" (not in text) –sudden change in period probably due to "starquakes".

Neutron stars in binaries

1. x-ray bursters—neutron star accretes matter from main sequence or giant companion. Get accretion disk, heating at surface ⇒ fusion of H ⇒ outburst of x-rays lasting only a few seconds (analogous to novae, but much more violent).

Where did the binary companion go? See Fig.22.10 on p.575 for strange process that could explain it.

SS443—Some material being shot out in jets at 25% the speed of light! See Fig. 22.9.

2. Millisecond pulsars—Periods ~ few x 0.001 sec. Spinning 100s of times per second! Found in globular clusters! (Fig. 22.11. Unexpected because pulsars should slow down and fade in millions of years, while all globular clusters are more than 10 billion years old!) So very old. Interpretation: Neutron star spun up by accretion from binary companion (closely related to x-ray bursters, which may be on their way to becoming millisecond pulsars). See Fig. 22.10.

Pulsar planets—1992: Pulse period of a millisecond pulsar found to vary periodically ⇒ planet in orbit around pulsar. Pulses arise earlier and later, depending on what part of the orbit the pulsar is in. Now evidence for *three* planets orbiting this pulsar, with masses like that of the Earth! But almost certainly not primordial (because planet would be destroyed by the supernova explosion that gave rise to the neutron star).

Gamma Ray Bursts

Known since 1970s—brief (~10 sec) highly irregular (see Fig.22.13) flashes of gamma ray light. Until about 1995, no one knew what they could be or where located—solar system? Nearby stellar event flare? Need distance to get brightness (luminosity).

First indication: they are distributed *isotropically* in the sky (no preferred direction, like the plane of the Milky Way if they were in our Galactic disk). But they could be in the Oort comet cloud surrounding our solar system, or in the halo of our Galaxy, or…

Then in 1997 it was possible (from the Italian-Dutch BeppoSAX satellite) to see the x-ray "afterglow" from a gamma ray burst to locate its position in the sky more accurately, and then see spectral lines in its optical "afterglow." The resulting Doppler shift was a redshift and it was enormous. As we'll see later, because the universe is expanding, redshift can be used to get distance. Resulting distance for this gamma ray burst was 2 billion parsecs!

By now we have seen ~10 afterglows from gamma ray bursts (and their parent galaxies) and they are all extremely distant ⇒ *extremely* luminous. In fact more energy produced than a supernova, and all in a matter of seconds! Probably most powerful objects in the universe.

What are they?? A hint is that they flicker on timescales of a hundredth or thousandth of a second, which means they can't be larger than a few hundred kilometers across. (See p. 578 for the explanation.)

Much evidence that these are relativistic (i.e. moving near the speed of light) expending fireball jets. But what causes them? Leading theories:

1. Coalescing neutron star binary.
2. Hypernova—some evidence for this because of probable association of 1998 supernova with a gamma ray burst. Actually these may just be supernovae in a particular mass range, since the rate of supernova explosions far exceeds that of gamma-ray bursts.

See discussion and sketches of these models on pp. 578-579. We will discuss briefly in class.

But really, no one knows, and it is one of the biggest challenges for theoretical modelers. Recent evidence supports the idea that the *short*-duration bursts (~ few seconds) are best explained as coalescing neutron stars, while the *longer*-duration bursts are probably exploding stars.