Large mass evolution (continued)

All of the successive fusion cycles (C, Ne, O, Si) leaves behind a very onion like core – most massive stars have iron in the core as the last major fusion product.

What happens next?
Iron photodisintegrates once the core becomes hot, dense enough.
This is about the only time core is degenerate for these big guys.

The mass is to much for the Chandrasekhar limit, so it continues to contract.
Temperature will rise big time!

Iron fusion! Not really but it's break down gives us the following:
$^{56}\text{Fe} \rightarrow 13\ ^{4}\text{He} + 4\text{n} - 100\ \text{MeV}$
So you get a bunch of helium some neutrons and the LOSS of energy.
This is an *endothermic* reaction.
The loss of energy lead to further core collapse (free – fall of the core).
At this point the core is only about 50 km in size.
Density increase by a factor of 1 million in about 1 second.
Velocity of collapse at outer edge close to 70,000 km/sec.

The rest of the star is still not really reacting to all of this.

Collapse (free-fall) continues…
Helium breaks down to protons and neutrons, which absorbs even more energy – more collapse.
Get to the point where the following happens
$p^+ + e^- \rightarrow n + \nu$

End up with a neutron gas
Density is around 10^{18} kg/m^3 = density of a proton or neutron.
Mass of the core < 1 solar mass
Radius ~ 20 km.
That's a **neutron star**
It is a neutron degenerate object.

Since it is degenerate, if you increase the mass, the radius decreases.

We'll get back to the neutron star later, but we have to continue to kill the star.

Once the core forms in the collapse, it is very inert – a brickwall to anything coming at it.
The rest of the star will eventually fall on to the core – a huge amount of energy in the mass of this falling layer of material.

Collapse of the star releases about 3 x 10^{46} joules of energy.

1/10 goes into nuclear fusion (2 x 10^{45} J)
1/100 goes into light (3 x 10^{44} J)
Similar amount goes into blasting off the outer layers (5 x 10^{44} J)
And moving them away – kinetic energy (10^{45} J)

Add of that up and you see have more energy that went into something – where?
Most of the energy from this event goes into producing and charging up neutrinos!
Around 10^{57} neutrinos are produced!

Some of the energy is transmitted into the material around the star – and it heats it up. When the neutrinos are created during the core collapse, the layers are very dense and even the neutrinos have a hard time escaping – but only a little. There are a lot of neutrinos after all – you can't block them all. Some of the energy of the neutrinos goes into heating up these layers.

Rather quickly the neutrinos do get out of the layers since they are able to pass through even very dense layers easily.
After the layers become spread out enough, the light from the explosion can get out – this is usually a few hours after the neutrinos get out.
There is always a lag between the neutrino escape and the light escape – when you actually can "see" what has happened.

And what has happened is a Supernova (SN type II).
Absolute magnitude of this event is around -16
Escape velocity of material is close to 15,000 km/s (5% the speed of light).

High temperatures/densities in the collapse (over 5 billion K) lead to the production of radioactive nickel and other elements.

Radioactive nickel decays into cobalt (with a half life of 6.1 days)
Cobalt decays into iron (with a half life of 77.1 days)

With each major decay event, there is a release of energy – this helps to maintain the brightness of the supernova over time – and can cause the brightness to peak well after the explosion. SN1987A had its peak brightness occur 80 days after the collapse!

As the supernova cools, material will form into molecules and dust. This will block visible light from the supernova remains and make it a very bright IR object.

SN II is what has been described so far. What is a type I supernovae?

That is what comes from a white dwarf that is in a close binary system.

Most white dwarfs are carbon/oxygen – when pushed over the mass limit, the carbon ignites (it's degenerate, so it's a thermonuclear runaway).

Energy pretty much goes all into the explosion (kinetic) – not much is left behind (was small to begin with).
Luminosity dominated by the decay of radioactive nickel – has a quick peak in brightness and then steadily declines – probably doesn't leave much behind, though we're not sure – could leave a neutron star behind.

Spectra of type I SN has no hydrogen in it – full of helium, oxygen, carbon, etc, but no hydrogen.

There are further ways to distinguish type I and type II supernova based upon spectra features, which indicate the likely type of source for the supernova.

SN I – white dwarf
Ia – has Si II in spectra, sort of the standard type
Ib – has He, no Si – outer layers of hydrogen removed
Ic – no Si, no He – out layers of hydrogen, helium not present.

SN II – massive star
IIb – no hydrogen – lost before the SN, helium is dominant
IIL – light curve is linear – lots of hydrogen – sort of standard
IIP – light curve has a plateau – lots of hydrogen – sort of standard

Usually SN Ia has an absolute magnitude of -19.5 or thereabouts
Very well defined light curve
Very good for use as a distance indicator (brighter than Cepheid)
Very popular targets for cosmology studies.

Famous SN in history
1006 – in Lupus – Arabic, Chinese, Japanese observations
    m = -9 or -10, visible for 2 years
    Linked with modern supernova remnant
1054 – in Taurus – Chinese, Japanese observations
    m = -4
    Current object: Crab Nebula (M1)
1572 – in Cassiopeia – Tycho's Supernova
    m = -4
    Well defined light curve
1604 – in Ophiuchus, Kepler's supernova
    m = -3
    Well defined light curve

And then we had….
SN 1987A – early morning of February 24, 1987
Brightened by a factor of 100 in about 3 hours
Early spectra showed broad, shallow absorption features with velocities ~ 10% speed of light. An lots of hydrogen (type II SN).

Temperature also changed very rapidly (from 14,000 K → 5,500 in 20 days)

Star that became SN1987A was
Sanduleak -69 202
B3 I
V = 12.4, B-V=0.04 (very blue, absolute magnitude = -7.9)
2 other stars were also near it.
Spectrum showed unusual variations and high UV flux which dropped quickly.
There was also a rapid drop in velocity.
Helium was relatively high (indicates mass loss before SN).

Early models tried to explain unusual features, including the fact that a merger of two stars created a BLUE star which became a SN. Its mass was around 20 solar masses, core mass near 10 solar masses. The unusual composition + mass loss made it a denser, bluer star than was predicted by models as a SN source. This also produced a much fainter than normal supernova.

The light variation is divided in two parts. Early stages in the light are dominated by shock events, later stage dominated by radioactive decay. Rapid cooling cause the UV the drop – after that visible light dominated.
The luminosity plateaus as the temperature drops but the radius increases.

After 110-300 days following the SN, the light drops off in a way that matches the decay of cobalt.
Observational tidbit – neutrinos were observed before the light of the supernova was observed – confirmation of theory of neutrino production with core collapse.

There is also an extensive set of ring structures around the supernova – while the star was a RED supergiant it had several mass loss episodes – especially around the equator. This probably happened about 20,000 years before the supernovae. This produced relatively slow moving material. Later the star became a BLUE supergiant. The wind from this were faster. This caused the material to funnel up/down from the equator ring and form an hour glass shape around the star (before the SN).

Then the supernova happened – energy from the blast (photons) heated up the slower, closer inner ring about 0.75 years after the supernova went off – time for the light to get to the ring. This tells us the ring is 0.75 lightyears from the supernove. The outer rings (hour glass) heated up much later.

Now the inner ring is being hit again by the blast wave (shock wave) from the explosion and is re-heating again. This heating was predicted based on the velocity of the shockwave (around 5% the speed of light).

After the shockwave finishes going through the ring, it will eventually fade way – but that may take decades for us to lose sight of it completely. During this time, the light from the ring will help to illuminate the structures around the supernova which may have been produced by the star before the supernova event.

We are also now observing material from the area of the supernova being ejected out as well in the hourglass direction – what is it? More outflow from the supernova.

What is left over from a supernova?
Two options – neutron star or black hole.

Neutron star – a neutron degenerate “gas”.
To approximate conditions in a neutron star, you have that it has a minimum stable density (neutrons tend to not be able to exist without protons – they evaporate easily).
Also have to into account the relativistic effects. This limits the lower mass range to 0.18 solar masses (radius of 300 km – remember, small mass=large radius, and large mass = small radius).
Highest mass is around 1.11 or so (not a certain value), radius is around 15 km.
Most neutron star masses are around 1 solar mass.

It does have some structure though –
“Atmosphere”
  Only a few cm thick
  Densities of 1 million kg/m^3
  Electrons, protons, iron nuclei
  Temperature around 10 million K.
Surface layer
  density close to 10^9 kg/m^3
  closely packed solid atomic polymers of iron
Outer crust
  Similar to a white dwarf, with relativistic electrons in neutron lattice
Inner crust
  Density close to 4.3×10^{14} kg/m^3
  Lattice loses structure further in, becomes a neutron gas
Liquid interior/Superfluid neutrons
  Superfluid = ultimate lubricant
  Happens at densities greater than 2×10^{17} kg/m^3
Core?
  Not sure if this exists, or what it is like.
  When densities > 3×10^{18} kg/m^3, things are a bit uncertain.
  Possibly a quark rich region.
  Might not have these density limits.

Neutron stars are most frequently observed as Pulsars.
99% of all pulsars are detected by radio telescopes.
Periods of a few seconds down to 0.0014 seconds (716 rotations/second).

Period of pulsars tend to slow down over time, with a loss of rotation on the order of 10^{-8} second/year.

Fast rotation, and the strong magnetic field (B=100 million tesla, Earth's field = 10^{-5} T) How come it is so fast and so strong?

Conservation of angular momentum produces the fast rotation –

$$\Omega_{final} = \Omega_{initial}\left(\frac{R_{initial}}{R_{final}}\right)^2 \qquad 60$$

And the magnetic field follows a similar relation

$$B_{final} = B_{initial}\left(\frac{R_{initial}}{R_{final}}\right)^2 \qquad 61$$

The strong magnetic field is what will eventually kill the pulsar – it is radiating away energy (energy of rotation, from the magnetic field – synchrotron radiation).
And the magnetic field drags in the interstellar medium.

The slow down rate is directly related to the rate at which it is spinning (pulse frequency)

$$\frac{dP}{dt} = \frac{5}{8\pi^2}\frac{LP^3}{MR^2} \qquad 62$$

As it emits more energy, it slows down faster.
And the period gets longer, its slows down even faster.

Pulsars don't last forever (don't pulse forever). Around 2000 are known to exist.

Other strange variations on a pulsar include the magnetar and the quark star.

Magnetars – neutron stars on steroids.

Ultra high strength magnetic field, up to 100 billion Tesla. The most likely way for this to happen, and not to make a regular neutron star, is to have a previously strong magnetic field (so have a large value for B in equation 61 to begin with).

The surfaces of magnetars are a bit unstable. They are prone to "starquakes", basically an earth quake in the crust layers of the star. This can release large amounts of x-rays or gamma rays. Soft gamma rays (low energy) are often seen to come from these objects in a periodic manner – soft gamma ray repeaters. The star quakes can disrupt the emissions from these objects, in particular any sort of pulses that come from them lose their rhythm.

The star quakes can release not only energy but also matter from the star, and this will slow down the rotation and decrease the magnetic field strength, so the more eruptions the less powerful the magnetic field. The magnetar phase should not last very long (10,000 years?), since their slow down rates are very high. The final result is an x-ray strong object, but that will continue to weaken and after another 10,000 years the star will be too quiet to pick up.

About a dozen magnetars are known.

The magnetic fields of a magnetar are deadly – could be lethal even at a distance of 1000 km, due to the disruption of water molecules in flesh. But also the tidal forces would be pretty severe from this thing and would also rip you apart (more on those later).

Quark stars – also called a strange star. A star composed of quark or strange matter. This would be ultra-ultra-super-degenerate material.

You can get a quark star if you put the neutrons in a neutron star under enough pressure so that they break down into the individual quarks (3 quarks per neutron). So rather than having a couple of quarks bound together to make a neutron or proton, you have them bound together to make an entire star.

To get a star to do this you really need to push it beyond the normal limits – take a rather massive neutron star (1.5 – 1.8 solar masses), spin it really fast and cause the neutrons to break down. The resulting explosion (quark nova) should be much more powerful than a supernova. The steps leading to the quark nova should start relatively soon after the creation of the neutron star itself from a regular supernova, perhaps only a few hours – during this time the neutrons in the center of the neutron star would start to break down into quarks and this would increase over time. It may take 1000 years before the star has enough free quarks to have a quark nova. It is also possible that the quark nova is currently being observed in some strong gamma-ray bursts that are currently detected.

How do you identify a quark star – should be much more dense than a neutron star. A few candidates exist that might be quark stars based upon their mass and radius values.

One example RX J1856.5-3754 – has a radius that is only 3.8-8.2 km, much too small for a neutron star. This is actually an interesting star since it is also a close neutron star (if it is that), only 450 light years away (150 pc). The temperature of this thing is around 700,000 K.

Another is 3C58 – object associated with a supernova from 1181 AD. The surface temperature for this object is too cool for such a young neutron star, which might be possible if it had lost much more energy during formation into a neutron star – perhaps it formed into a quark star?

These results may be interesting, but they are not conclusive - there is still much debate about the quality of this information. New observations are needed to determine if these objects really are quark stars.

Gamma Ray Bursters and Soft gamma-ray repeaters – gamma rays are a mystery.

Hard to target the sources, hard to catch (fade away quickly), hard to link with any single type of phenomena. A typical GRB may release up to 10^{45} Joules of energy though they can go as high as 10^{47} Joules of energy.

Soft gamma-ray repeaters have been linked with magnetars. There are 4 soft gamma-ray repeaters known.
SGR 1806-20 produced the strongest/largest soft gamma-ray burst on December 27, 2004. It is 14.5 kpc away (50,000 light years). It rotates once every 7.5 seconds. During the outburst it had a gamma ray absolute magnitude of -29. The gamma-rays actually impacted on Earth's ionosphere and caused it to expand and blinded some satellites temporarily. More energy came out of this event than is released by our Sun in 100,000 years. This burst is thought to be tied directly to a star quake.

General gamma-ray bursters (GRB) may not be one single source – they could be possibly associated with neutron stars or magnetars, or even black holes, that give off a huge amount of gamma rays. They are amongst the most energetic events in the universe, but we generally can't see anything associated with them with our eyes.

One burst per day is detected. Originally bursts were discovered during the cold war by satellites looking for radiation from nuclear tests.

There are two classes of GRBs – short duration with hard spectrum, and long duration with soft spectrum. These are really clear cut designations, but general.

Short GRB – 2 seconds
    Dominated by high energy photons
Long GRB - > 2 seconds
    Dominated by low energy photons

Theories are still incomplete but we already have a link between the softer gamma-ray sources associated with magnetars. It is possible that neutron stars may be linked to the bursters in general. It is also possible that events such as hypernovae (supernova on steroids) may also be the sources of some GRBs. Some observations show an afterglow of light of other types following a GRB that might be associated with hypernova events in distant galaxies. This might produce the long GRB.

Several GRB have been directly linked to supernova events. Quite a few are observed at great distances (well outside of our galaxy).

The short GRB may be the result of cosmic collisions of such as the collision of two neutron stars, or of a neutron star getting swallowed by a black hole. The merger of two stars is a much shorter event then the supernovae collapse model, which accounts for the difference in how they are categorized.

Gamma-rays are the most deadly form of light. Can these events hurt us?

The biggest GRB recorded was SGR 1806-20. If the explosion had occurred a lot closer (10 light years) it could have destroyed our ozone layer, and would have been like having a nuclear blast in the atmosphere.

Some people studying mass extinction events have looked at GRB as a possible killer of life on the earth. You would get a lot of damage from the radiation, but it would be brief. However, the damage to things like the ozone layer would be longer and more important. Calculations show that this could possibly explain some of the earth's past mass extinction events (Ordovician-Silurian, 450 mya). But it would have to be really close to really hurt us.