$\geq$60M$_\odot$ stars...

This is the final frontier for stellar evolution. Firstly we don't even know how big stars can get, although stars of up to 100M$_\odot$ have been proposed (and people claim observed...).

The problem is that very massive stars produce so much energy that gravity shouldn't be able to hold them together - the **Eddington limit** for the mass and luminosity of a star.

Nevertheless, for stars above $\geq$60M$_\odot$ it's thought that the mass lost on the MS and also in the LBV phase dominates their post-MS evolution.

In the LBV phase, mass loss rates can exceed 1/100th of a solar mass per year - the most famous LBV η Carinae ejecting $\sim$15M$_\odot$ in only 20 years!

In this case the H rich mantle of the star is completely ejected before the star can become a RSG and so it always remains on the hot side of the HR diagram, evolving from the Main Sequence to form a Blue Supergiant and then directly becoming a WR without the intervening RSG phase seen for lower mass stars.

So what happens to RSGs or WRs to cause them to die?

One step beyond...

Silicon burning is the last fusion reaction that can *yield* energy. This reaction results in Fe production, which is the most stable nucleus known. The development of an Fe/Ni core signals the final death throes for a massive star.

Without another nuclear energy source to save it the Fe core collapses very quickly, reaching T$\sim 5 \times 10^9$K within 0.1sec. The γ rays so produced interact with the Fe-nuclei and break them down to form He nuclei in a process called photo disintegration.

Within a further 0.1 sec the He nuclei also break down into Protons and neutrons. The protons and electrons then combine:

$p^+ + e^- \rightarrow$ neutrons + neutrinos

Densities are now so high that the neutrinos can interact with the core, but enough escape to allow the core to collapse still further...

The final countdown

After 0.25 s the core is now only 20 km across and its density is $\geq 10^{17}$ kg/m^3. This is the nuclear density - the density of the nucelus of an atom.

It is now difficult to compress the core any further - indeed the inner regions of the core actual expand slightly - the *core bounce*, sending a huge amount of energy outwards.

With nothing to support them, the overlying regions of the star collapse inwards at 0.15 times the speed of light!

This material impacts on the core, where it interacts with the outwards moving shockwave and is ejected, helped on its way by the neutrino flux.

After a few hours the shock wave reaches the 'surface' of the star and the outer layers are ejected in a **Supernova**. During this event 10^{46}J are emitted, or more than 100 times the energy radiated so far by the Sun.

SN are of intense interest since they eject significant quantities of chemically enriched material into the ISM.

Supernovae are dealt with the in the High Energy course next year, but one of the most famous recent SN occured in the LMC on Feb 23 1987, and involved a B3I progenitor.

The ultimate fate of the core depends on its final post-SN mass...

Post-SN: Neutron Stars

This possibility was once ignored by the astronomical community, since many people didn't believe such objects could exist...

- A thimbleful would weigh 100 million tons
- Such an object would be small - only 30km in diameter
- Its surface gravity would be so strong the escape velocity would be one half the speed of light

Nevertheless, in 1967 Jocelyn Bell detected a radio source which pulsed with a period of 1.3 secs.

Several more '**pulsars**' were subsequently discovered with periods ranging from 0.25 s – 1.5 s.

So what are pulsars?
Not ordinary stars or nebulae (both of which were known to emit in the radio).

A binary? To have a period of 1s would suggest an orbital separation of only 1000
,km. This is less than even a WD can manage so the stars would have to overlap! Not physical...

A pulsating star. Again the period is simply too rapid for this to occur.

A hotspot on the surface of a WD? A WD rotating with a period of 1 s would be on the verge of breaking up. The discovery of the Crab pulsar with a period of only 0.033 s ruled this out.

The only possibility left was a neutron star, since only that would be compact enough to rotate so rapidly.

NS - a brief overview

(For more details see Chapter 23). The radio emission observed in Pulsars results from the intense magnetic fields of Pulsars.

As the NS forms, the collapsing core drags the stars magentic field inwards with it, causing it to become more 'concentrated'. In a MS star the magnetic field is spread over the billions of square kilometers of the star's surface but the surface area of a NS is some 10^{10} smaller, so the magnetic field becomes some 10^{10} times stronger at the *surface*.

For example the magnetic field of the sun is 1 Gauss (G), while the strongest field ever produced on the Earth is 10^6 G, while typically for NSs it's 10^{12} G!

The mag. field of a NS is likely to resemble a giant bar magnet and there is no reason for it to be aligned with the rotational axis of the NS.

The combination of strong magnetic field and rapid rotation would act like a bike dynamo - generating powerful electric currents.

Some of the energy in the electric fields would produce electrons (and positrons to keep the overall electric charge constant) via $E=mc^2$.

These would then be accelerated along the axis of the magnetic field, generating powerful radio emission as they interact with the mag. field.

Hence, they generate two strong beams of radio emission aligned with the mag. field of the NS.

We see a pulse of radio emission whenever the rotation of the NS causes the radio beams to sweep past the Earth.

Neutron Stars are of interest to particle physicists as well since they exist at densities which we cannot probe on the Earth.

Many exotic forms of matter have been proposed to exist in NS cores, but whichever proposal and whatever physics is invoked there comes a limit - probably between 1.8 and $3M_\odot$ where nothing can stop the collapse of the core under gravity to a **Black Hole**.

Black Holes

Black Holes will be covered next term in your high energy course so we will only give a brief overview here, although if you can't wait then see Chapter 24.

Black Holes represent the ultimate fate for stars with post-SN cores with masses in excess of $\sim 3M_\odot$.

Above this mass and not even neutron degeneracy can win the fight against gravity - indeed there is no known physical phenomenon that can support the collapsing core aainst gravity.

The core continues to collapse and as it does so it becomes more and more dense and with it the escape velocity increases until it finally exceeds the speed of light - a BH has formed.

At this stage we can define a surface around the collapsing core within which the escape velocity exceeds the speed of light - this is known as the Schwarzchild radius.

Note this is not a solid surface - an object can pass through it but once it has done so it may never escape. Not even light can avoid this fate -hence the name!

This means we can't see inside the BH at the collapsed core of the star - which is a shame since our current theories of gravity - Einstein's theory of General Relativity - break down at this point.

Indeed, despite more than 70 years of effort, we still can't understand the physics of black holes.

Finally, how massive does a star have to be to form a black hole? This is a *very* difficult question.

It appears likely that single stars heavier than $25\mathrm{M}_\odot$ form BHs.

We would like to use binary stars containing black holes to calculate the masses of BH progenitors but recent work suggests that results from binary systems may not be directly applied to single stars.

Nevertheless, it appears likely that single stars heavier than $25\mathrm{M}_\odot$ form BHs, so anything lighter than this should from a NS, while WDs form from $\sim$solar ($\leq 4\mathrm{M}_\odot$) mass stars.