PHY20003 ASTROPHYSICS

Lecture 19 Evolution off the main-sequence

19.1 The evolution of low-mass stars $(\boldsymbol{M < 3M_{\odot}})$

From theoretical modelling, the main sequence lifetime of a star with $M = 1\ M_{\odot}$ is $\sim 8 \cdot 10^9$ years.

At the end of its main sequence life, the hydrogen in the core has been used up, and the star starts to gravitationally collapse, heating up the core and surrounding layers.

This heating allows the fusion of hydrogen into helium to continue in a shell surrounding the core (hydrogen shell burning).

The additional heating makes the star's atmosphere expand and cool.

The star moves across and up the H-R diagram over $\sim 10^9$ years to become a red giant.

During this, the region of hydrogen shell burning gradually moves outwards through the star.

The core contraction is slowed down due to the onset of electron degeneracy pressure, which is independent of temperature.

Eventually, the core reaches a temperature of $\sim 10^8$ K, and He-burning begins. This happens very suddenly, and as the electron degeneracy pressure is not dependent on temperature, the core heats up rapidly, increasing the fusion rate even more. This is known as the helium flash. When the electron degeneracy pressure is removed, the helium fusion stabilises, and stable helium burning continues, and equilibrium is maintained as on the main sequence, if the fusion rate is too low, the core shrinks, increasing the pressure, temperature and fusion rate until it is stable. If the rate is too high, the core expands and the temperature, pressure and nuclear fusion rate decreases until the star is in equilibrium again.

Helium fusion occurs through the triple-alpha process:

$$^4_2He + ^4_2He \rightarrow ^8_4Be + \gamma$$
$$^4_2He + ^8_4Be \rightarrow ^{12}_6C + \gamma$$

During stable helium burning the gravitational collapse of the core is haled, and the stellar surface temperature rises again. The star loses some of its luminosity and becomes a horizontal branch star.

After $\sim 10^8$ years the helium in the core is used up. The carbon core will start to contract again, and there will be two shells where fusion continues, the inner shell will have He-burning, while the outer will have H-burning.

During this stage, the star moves back up the H-R diagram along the asymptotic giant branch (AGB).

During this stage He-shell burning can suddenly jump, producing thermal pulses.

The star now has large stellar winds from its surfaces due to the high luminosity. This results in a significant mass loss

$$\frac{dM}{dt} \simeq 10^{-7} M_{\odot}\ \mathrm{yr}^{-1} \tag{19.1}$$

Near the end of the AGB phase, the remaining outer layers of the star are ejected. These expand into space and are then observed as a planetary nebula.

The remaining core of the star does not have any energy source and is supported by electron degeneracy pressure. The star is now a cooling white dwarf.

We can calculate the cooling time

$$t_{cool} \simeq \frac{E}{L} \tag{19.2}$$

$$E = N\left(\frac{3}{2}kT\right) \tag{19.3}$$

Therefore

$$t_{cool} = \frac{3NkT}{2L} \simeq 10^9\ \mathrm{yr} \tag{19.4}$$

The final state will be a black dwarf.

19.2 High-mass stars and Supernovae $(M > 10M_{\odot})$

For high-mass stars, the initial stages are very similar to that of lower mass stars, but in this case fusion of heavier elements (beyond carbon) is also possible, and the stars will get progressively more nuclear burning shells, with each deeper shell fusing heavier elements.

$$H \rightarrow He$$
$$He \rightarrow C, O$$
$$C \rightarrow O, Ne, Na, Mg$$
$$Ne \rightarrow O, Mg$$
$$O \rightarrow Si$$
$$Si \rightarrow Fe$$

During the final stages of their evolution, these stars become progressively more unstable, with large stellar winds resulting in significant mass loss (around $10^{-6}\ M_{\odot}$ per year).

The fusion process reaches a natural limit when an iron core is formed, as the fusion to elements beyond iron is an endothermic process, i.e. it absorbs energy rather than releasing it.

When fusion in the core can no longer continue, core collapse occurs rapidly.

The resulting shock wave throws the remaining atmosphere into space at $v \sim 0.1c$

This catastrophic disruption of the massive stars is known as a supernova.

A typical supernova releases $\sim 10^{45}$ Joules of energy.

Electron degeneracy can only support a white dwarf against further collapse if its mass is $< 1.44\ M_{\odot}$. This limit is known as the Chandrasekar limit.

The typical mass of the core of a high-mass star is $> 2\ M_{\odot}$, so the collapse continues. During this phase, the electrons combine with the protons in atomic nuclei to produce neutrons:

$$P^{+} + e^{-} \rightarrow n + \nu_e$$

The star is now held up against further collapse by the mutual repulsion of neutrons; it has become a neutron star.

The radius of a neutron star is ~ 10 km.

If the core-mass is large enough $(\gtrsim 3\ M_{\odot})$, then not even the nucleon repulsion is sufficient to resist collapse. Before it collapses to a point singularity, it will become a black hole.