7.6 The dependence of mass on post main-sequence evolution

Stars can be divided into three main categories by mass – low, intermediate and high mass. The boundaries are determined by the minimum mass needed by a star to form its first degenerate core.

Mass Range ($M_\odot$)	First degenerate core composition	Category
≤ 2	He	Low
2–8	C/O	Intermediate
8–11	O/Ne/Mg	High
≥ 11	None	High

Low mass stars: develop degenerate He core while ascending the RGB. He ignition occurs explosively – the helium flash. The increased core temperature causes the degeneracy to be lifted, the core expands, and He burning becomes stable. Eventually they develop a degenerate C/O core before ending as white dwarfs.

Intermediate mass stars: burn He and then develop degenerate C/O cores. The star will lose sufficient mass (via stellar winds) in its post-main sequence phase to end its evolution as a white dwarf.

High mass stars: Between 8 and 11 $M_\odot$, stars undergo C fusion before developing O/Ne/Mg degenerate cores. Above 11 $M_\odot$, they are able to fuse successive elements to Fe. All stars in this category explode as Type II supernovae.

7.7 Intermediate mass stars: evolution beyond the Red Giant Branch

7.7.1 The first dredge-up

As an intermediate mass star ascends the RGB, it develops a huge convective envelope which grows until it reaches down to the H-burning shell. The star now undergoes *the first dredge-up*. The convective envelope brings material processed by the CNO cycle to the surface. The C-N cycle reaches equilibrium before the O-N cycle and thus CN-processed material (N enriched, C depleted) is first exposed on the surface. The N abundance increases by a factor of 2, C is decreased by 30% and O is unchanged. Red giants are observed to have CN-processed material in their atmospheres. This is the first observational indication of nuclear-processed material – all the previous evolution has been hidden from view.

Red giant stars are observed to lose mass in the form of a slow (5–30 $\mathrm{km\,s^{-1}}$) wind at a rate of $\sim 10^{-8}\,M_\odot/\mathrm{yr}$. The total amount of mass lost can be $\sim 0.2\,M_\odot$, depending on luminosity (see later).

7.7.2 The Helium Burning Phase

Eventually, the inert He core reaches a temperature of 10^8 K and He fusion can start. The star now has two sources of energy generation: core He fusion and shell H fusion. When He fusion starts, the core expands as a result of the extra supply of energy. According to the shell-burning law, the core expansion leads to a contraction of the envelope, reflected in the evolution down the RGB and later towards higher effective temperatures. The H-burning shell contributes more than 70% of the total luminosity.

The core which is convective starts to contract again with the continuing He fusion, the envelope expands, and the star evolves towards lower $T_{\rm eff}$. Finally, He is exhausted in the core which is now composed of C, O and heavier elements. A thick He-burning shell source is now established. The luminosity from this shell will cause the region outside of it to expand. When this happens, the temperature and density of the H-burning shell will decrease, and H-burning will be extinguished. At this point energy is provided only by the He-burning shell. The contraction of the core leads to a strong expansion of the envelope and the star moves back to the Hayashi track on the so-called asymptotic giant branch (AGB).

7.7.3 The Early Asymptotic Giant Branch E-AGB

The star will begin to ascend the Asymptotic Giant Branch. The envelope expansion causes the opacity to increase and the envelope becomes convective. The convective envelope reaches down to the dormant H-burning shell and products of H-burning are then convected to the surface. These are CNO products i.e. all H has been burnt to He and C, O to N so the surface He and N abundances increase but C and O decrease. *This is the second dredge-up phase.* The contracting C-O core becomes degenerate.

During the AGB phase, the mass loss increases dramatically from 10^{-8} to 10^{-6} $\mathrm{M}_\odot$/yr. The wind is driven by absorption by dust. The luminosity of the star is strictly related to the mass of the core by the “Paczynski relation” during the AGB phase:

$$L_*/L_\odot = 5.2 \times 10^4 (\frac{M_{core}}{M_\odot} - 0.456)$$

The core mass increases due to the ash from the He-burning shell and so (from the above relation) does L i.e. as the star evolves it moves up the AGB. The He-burning shell narrows and moves outward. The H-burning shell is heated and eventually re-ignites. The star now undergoes thermal pulsations.

A $3\,\mathrm{M}_\odot$ star spends 7×10^6 yr in the E-AGB phase, compared to 2×10^8 yr on the m-s, and 6×10^7 yr burning He in its core.

7.7.4 The Thermally Pulsating AGB Phase

The structure of the star is now:

a degenerate C-O core;
helium-burning shell;
helium layer;
hydrogen-burning shell; and
an outer H-rich convective envelope.

The evolution is now complex because the huge differences between the two nuclear fusion processes do not allow a steady state to exist.
The two shells supply the luminosity of the AGB star alternately in a cyclical process or a thermal pulsation which has a period of ~ 1000 yrs.

The thermal pulse mechanism
The H-burning shell produces about 99% of the luminosity and the He-burning shell about 1%. But He fusion produces 1/10 of the energy of H fusion per unit mass i.e. $\epsilon_H \approx 10 \times \epsilon_{He}$. This means that the H-shell uses $10\times$ more mass per second than the He-shell. Thus, in terms of mass $m(r)$, the H-shell moves outward faster than the He-shell. This also implies that the He layer separating the two shells increases in mass. The increase in the mass of the He layer increases the pressure and density of the thin He-shell sitting on top of the 'hard' degenerate C-O core. It can be shown that as a result, the temperature decreases in the He-shell, and thus the He-fusion switches off.

The thermal pulse operates as follows:

1. The H-burning shell moves outward, the temperature of the He-fusion shell decreases and He-fusion stops. The He layer becomes more massive as a result of the H-fusion in the H-shell.
2. The He layer becomes degenerate but the pressure keeps increasing and the temperature rises (this is different to the thin He-shell case because here we are dealing with a degenerate gas).
3. When the temperature reaches the critical point for He ignition ($\sim 10^8$ K), the He-flash occurs because of the degenerate conditions and this results in a runaway situation or the 'thermal pulse'.
4. The thermal pulse drives out the H-fusion shell which decreases in density and the H-fusion stops.
5. The convective envelope now extends deep down into the layer where He-fusion has occurred. This brings carbon to the surface and 's-process' elements (see later) made during the He-shell flash. This is the *third dredge up*.

6. The He-fusion shell front advances through the He layer, processing He into C and O, until it meets the extinct H shell which is heated.
7. The H shell then re-ignites, starts to move outward, and the whole process is repeated.

For most of the cycle, the H shell is active and the inner He shell is extinct.

The Third Dredge Up

Since the energy source for the thermal pulse is the triple-α reaction, the most abundant element produced during a pulse is ^{12}C. The actual products brought to the surface depend on the mass and the number of thermal pulses:

(a) The star will become a carbon star with C/O > 1 (solar ~ 0.4) if the products of He-fusion are brought to the surface.

(b) If the star is massive enough ($M > 3\,\mathrm{M}_\odot$), the base of the convective envelope becomes hot enough for the CN cycle to operate, and the transition to a carbon star will not occur because the dredged-up C is converted to N. This is called 'envelope' or 'hot bottom burning'.

When the thermal pulse occurs, the He-shell engulfs the region containing fresh ^{14}N and $^{14}\mathrm{N} \rightarrow {}^{22}\mathrm{Ne}$ via:

$$^{14}N\,(\alpha,\gamma)\,^{18}F\,(\beta^+,\nu)\,^{18}O\,(\alpha,\gamma)\,^{22}Ne$$

For stars with a core mass $> 1\,\mathrm{M}_\odot$, ^{22}Ne is converted into ^{25}Mg and neutrons:

$$^{22}Ne\,(\alpha,n)\,^{25}Mg$$

The neutrons are captured onto Fe-peak elements allowing elements to be formed beyond the Fe-peak – this is called the "s- process" e.g. Ba, Sr.

For stars with a core mass $< 1\,\mathrm{M}_\odot$,

$$^{12}C\,(p,\gamma)\,^{13}N\,(\beta^+,\nu)\,^{13}C\,(\alpha,n)\,^{16}O$$

and ^{13}C is the source of neutrons.

The dust formed in the outer cool atmospheres of AGB stars depends on the C/O ratio. If O>C, then all the C is locked into CO (most stable moelcule) and the remaining O forms O-rich dust, mainly silicates. If C>O, then all O is locked into CO and the remaining C forms C-rich dust e.g. SiC, $\mathrm{C}_n\mathrm{H}_n$ molecules.

7.7.5 The post-AGB and planetary nebula phase

The mass of the convective envelope during the AGB phase decreases steadily through two effects:

(1) Shell burning removes mass from the bottom of the envelope by adding it to the core;

(2) Mass loss removes material from the envelope – this is the most important effect.

Reimer's Relation: empirical expression for mass loss:

$$\dot{M}_{wind} = 10^{-13} \frac{L_*/L_\odot \, R_*/R_\odot}{M_*/M_\odot} \, M_\odot/yr.$$

with typical values of $\sim 10^{-6}$ M$_\odot$/yr.

Paczynski relation: L increases as the core mass increases so mass loss rate must also increase and reaches a maximum at the end of the AGB phase which can be as high as $\sim 10^{-5}$ M$_\odot$/yr.

The mass loss rate increases until the mass of the remaining envelope has reached some minimum value ($\approx 10^{-2}$–10^{-3} M$_\odot$) so that a convective envelope can no longer be sustained and the envelope starts to contract into radiative equilibrium. The star still satisfies the Paczynski relation. The crossing of the HRD is fast ($\sim 10^4$ yr) so M$_{core}$ hardly changes and thus L is constant.

The star is optically invisible during this phase because it is hidden by the dust ejected during the heavy mass loss at the end of the AGB phase.

When the effective temperature reaches 30 000 K, the star develops a radiation-driven wind (same mechanism as high mass stars), and the high UV flux destroys the dust grains, dissociates the molecules, and ionizes the atoms. A young planetary nebula is born.

For a long time it was believed that the PN represented the previous AGB wind. The problem with this is that the observed expansion speed of PN is about 50 km s^{-1} but the AGB winds are ejected with velocities of 10–15 km s^{-1}. How could the AGB material be accelerated?

In 1975 it was realised that the central stars of PN (CSPN) have fast stellar winds ($\sim 10^{-6}$ M$_\odot$/yr, and wind velocities of 2000 km s^{-1}). Sun Kwok proposed a completely different scenario: PN are the result of the interaction between the slow AGB wind and the fast CSPN wind. The fast wind sweeps up and accelerates the AGB wind.

Images taken with the *Hubble Space Telescope* reveal that PN have extremely complex shapes.

The PN phase lasts about 10,000 yrs. The envelope mass is decreased by the mass loss from the CSPN until it reaches a mass of $\sim 10^{-6}$ $M_\odot$. The shell fusion then stops; the luminosity decreases and the radius decreases. The star now moves onto the white dwarf cooling track and it gradually cools down ($\sim 10^9$ yr).

In summary the AGB phase is one of the most fascinating evolutionary phases for the following reasons:

1. The luminosity is uniquely determined by the core mass, independent of the total mass of the star.
2. The two shell sources alternate in producing the luminosity of the star, with a periodicity of about 1000 yrs, with the changes triggered by shell flashes.
3. The very deep convection can bring the products of He-fusion (i.e. carbon) to the surface, creating a sudden change in surface composition from a C/O ratio of < 1 to > 1. Depending on the mass of the star, the thermal pulse can also produce s-process elements which are then dredged to the surface.
4. The evolution on the AGB is completely governed by the mass loss rate which increases dramatically as the star ascends the AGB.

7.8 Late Evolution of Low Mass Stars

The locus of low mass (i.e. those that undergo a helium flash: 0.7–2 $M_\odot$) core He burning stars is called the “horizontal branch” in the HRD, and is roughly a horizontal strip stretching between the main sequence and the RG branch, corresponding to luminosities of 50–100 $L_\odot$. Low mass stars spend $\sim 10^8$ yr here and their exact position depends on the envelope mass which determines $T_{\rm eff}$. Stars near the blue end have the smallest envelopes. These envelopes become radiative and are prone to a dynamical instability, in the region of H and He ionization. An instability strip therefore crosses the horizontal branch. Stars in this strip pulsate with a period of a few hours and are called *RR Lyrae variables.*

(N.B. Cepheid variables correspond to He-burning intermediate mass stars which go through a phase of envelope instability resulting in pulsations with periods of days to months.)

The post-core-He-burning evolution of low mass stars is similar to that of the intermediate mass star. They have a double shell source and evolve through loops in the HRD and finally up the AGB. Such stars will have a degenerate C-O core, and go through the PN phase.