Globular clusters

In contrast to the clusters we have already observed, globular clusters are much more massive and older - hence they form an important laboratory for studying post-MS evolution of objects like the Sun.

They typically have no upper MS stars, and have ages that are comparable to the age of the Unverse!

In particular, they show the presence of the next stage of post-MS evolution for low mass stars - the *Horizontal Branch* stars.

Remember that during He core burning, somewhat counter-intuitively the star both fades (contracts) and becomes bluer (heats up), moving to a new position on the HR diagram.

These objects are known as *horizontal branch stars* and occupy a distinct region of the HR diagram.

This phase ends when the star has burnt all its supply of helium in its core. As the core contracts the temperature in a shell around it becomes high enough to start shell He burning and a second Red Giant phase occurs, this time powered by He rather than H shell burning (Fig 22-2). Note that while the core contracts it never becomes hot enough for any further nuclear reactions to occur there. Stars in this phase of life are called **Asymptotic Giant Branch** stars.

An aside: Globular clusters and Population I & II stars

Over the history of the galaxy stellar evolution has produced two distinct **Populations** of stars.

Population II : Globular clusters are known to contain very old stars, which are metal poor e.g. elements such as C, O & N are less than 3% of solar abundance.

Population I : These are seen in, for example, young clusters and have the same abundances as the Sun.

This is because when population II stars formed the chemistry of the gas they formed from had changed little since the Big Bang, and so was lacking in heavy elements.

The more massive population II stars have already died and have ejected significant quantities of heavy elements into the ISM from which the current generation of population I stars subsequently formed.

So how are these elements released into the interstellar medium?

Convective Dredge Up

When stars become RGs they develop deep convective zones, extending through the deep H rich mantle into the inner regions of the star. The bulk motion of the convection cells means that nucelar processed material can be 'dredged' up to the outer layers, altering the chemistry.

The first dredge up occurs after MS H burning stops, changing the surface abundances of He, C, N and O.

A second phase occurs after core He burning stops, further changing the surface abundances.

The third dredge up occurs in the AGB phase further enhancing the C abundances and producing a Carbon star with a spectrum containing prominent bands from molecules such as C_2, CH and CN.

Note that AGB stars with M$> 2M_\odot$ have strong stellar winds (due to their low surface gravity) with M(wind)=10^{-4}M$_\odot$/yr, sometimes ejecting shells of material (Fig. 22-4); they are a source of injection of light elements into the ISM.

Planetary Nebulae

The upper reaches of the HR diagram are criss-crossed with so called instability strips, and during the AGB phase the star becomes unstable and undergoes bursts of increased luminosity and ejection events.

Gradually the outer layers are ejected and all thats's left is the hot exposed core surrounded by glowing ejects - a **Planetary Nebula**.

Typically a one solar mass star can eject 0.4 solar masses.

The surface temperature of the exposed core is ∼100,000 K, which is sufficient to keep the nebular gas ionised, even though it is physically small - a **White Dwarf**.

White Dwarfs

Stars less massive than ∼4M$_\odot$ never develop core densities and temperatures high enough to allow nuclear burning of elements heavier than He.

At the end point of core He burning the outer layers are ejected as a PN, and the core - with no energy sources left, shrinks under gravity.

So what stops it collapsing to an infinitely small point?

The answer is Quantum Mechanics and an effect called the **Pauli Exclusion Principle**.

Pauli Exclusion Principle

Simply stated, the P.E.P. states that there is a limit as to how close you can pack together matter composed of the same type of particle, i.e. electrons, neutrons etc.

In particular, no two particles can occupy the same quantum mechanical *state*. A quantum state is a particular way of representing the physical property of a particle such as its location and velocity.

In practice all this means is that you can't have two things occupying the same place at the same time.

For matter in White Dwarfs, the electrons are packed so closely together that they cannot be squeezed together more tightly. Because of this, they exert a pressure that supports the WD against gravity.

In this situation the matter is said to be Electron Degenerate, and the resulting pressure is the Electron Degeneracy Pressure.

Studies of nearby WDs indicate that they may have densities of of $\sim 10^9$kg/m^3 - a teaspoon of such matter would weigh 5.5 tons, or the weight of a fully grown elephant!

One result of the P.E.P. is that the larger the mass of the WD, the smaller its radius becomes. (Fig. 22-9).

The final evolution paths of post-AGB stars are shown in Fig. 22-10. This shows that after the outer atmosphere is ejected to leave the degenerate core, 3, 1.5 & $0.8M_\odot$ stars yield 1.2, 0.8 & 0.6$\mathrm{M}_\odot$ WDs respectively.

Note that WDs don't produce energy so as they radiate energy they cool down, which is accompanied by a decrease in luminosity (Fig. 22-11).

Eventually they cool so much they become too faint to be observed in the optical.

There is a maximum mass that the electron degeneracy can support, which is called the **Chandrasekhar Limit**, of $\sim$1.4$\mathrm{M}_\odot$. Above this the gravity wins out and the core contracts further, until neutron degeneracy halts the collapse.

This yields a **Neutron Star**...which we will return to later.

The lowest high mass stars...

So far we have looked at the evolution of comparatively low mass stars. Now we're going to look at their big brothers. Here evolution is significantly altered due to two additional processes not open to lower mass stars: (i) New sources of nuclear fuel and (ii) the effects of mass loss via their stellar winds.

For stars in the $\leq$40$\mathrm{M}_\odot$ range we see a modification of the evolution of low mass stars.

Other nuclear reactions that may occur include:

Carbon Burning ($\sim 6 \times 10^8$K) $\rightarrow$ O, Ne, Na, Mg

Neon Burning ($\sim 10^9$K) $\rightarrow$ O, Mg

Oxygen Burning ($\sim 6 \times 10^8$K) $\rightarrow$ S

Silicon Burning ($\sim 6 \times 10^8$K) $\rightarrow$ Fe, Ni

Between each stage we have core contraction to raise the temperatures sufficiently to enable the next reaction to occur. This is accompanied by the expansion and cooling of a star (Red Supergiant), and eventually a nested structure for the star develops (Fig. 22-13), with nuclear burning occurring in a series of concentric shells.

$25M_\odot$ star

We have relatively good models for how stars of about 25 solar masses die, and can even predict how long each new product of nuclear burning can last as a fuel source.

Each new stage of nucelar burning requires higher temperatures and last for less time than the preceding one(s). For a $25M_\odot$ mass star this corresponds to (Tab 22-1):

Stage	Core Temp (K)	Duration
H burning	4×10^7	7×10^6yrs
He burning	2×10^8	7×10^5yrs
C burning	6×10^8	600yrs
Ne burning	1.2×10^9	1yr
O burning	1.5×10^9	0.5yr
Si burning	2.7×10^9	1 day

$\geq40M_\odot$ stars...

For stars in the $\geq40M_\odot$ range we are much more uncertain about how evolution proceeds.

In this range the same nuclear reactions occur, but the mass loss rates via stellar winds are so high that the post-MS evolution is significantly affected.

For $\sim$40-60$M_\odot$ stars its thought that they *may* still evolve into Red Supergiants, but such a phase is likely to be *very* short lived.

This is because the outer, H-rich mantle is quickly stripped away as a result of very high mass loss rates ($\sim\geq 10^{-5}M_\odot$/yr and instabilities of unknown origin e.g. the Luminous Blue Variable phase.

Because of this the star quickly returns from the red side of the HR diagram and becomes a **Wolf Rayet** star.

Such objects are essentially the naked cores of the stars, and as such are chemically evolved (i.e. no H in their spectra), hot (up to 100 kK) and have prodigious stellar winds (i.e $10^{-4\rightarrow-5}M_\odot$/yr and velocities of 1000's km/s).