Stellar Evolution

In the remaining 5 lectures of the course we are going to examine how individual stars of different masses evolve over time.

We'll briefly look at star formation (covered in more depth next year), then concentrate on the Main Sequence, post-MS and finally the ultimate fate of stars.

A brief look at stellar evolution

We'll firstly have a brief look at how stars form - note that this will be covered in depth next year.

Stars form from the (gravitational) collapse of massive clouds of dust and gas in the the ISM, which typically have masses of $10^5 - 10^6 M_\odot$.

As the cloud collapses under its own gravity it fragments into smaller condensations which continue to collapse individually until *protostars are formed.*

If the protostar is massive enough the core can become dense and hot enough for nuclear fusion to occur.

This creates an outwards pressure that halts the collapse and the star stabilises on the Main Sequence.

As low mass stars ($< 8M_\odot$) form, the material falls ("accretes") onto their surface via an accretion disc.

As material settles onto the surface it causes the star to rotate more rapidly until the star becomes unstable and it needs to lose mass and rotational energy to slow down and stabilise.

Currently, we think that some of this energy is lost via jets which escape along the poles - this would explain why for a given mass a protostar spins more rapidly than a normal MS star.

Finally a dusty debris disc is left around the MS star - the site of possible planet formation.

The formation of low mass stars is reasonably well understood but high mass star formation is another matter...

Once again the rarity and distance to OB stars doesn't help - but the examples we do know of are heavily obscured.

Moreover we cannot simply scale up low mass star formation since the star would begin to burn H before it was fully formed, dispersing its natal envelope.

Maybe disc-like geometries which funnel material onto the star's equator while channeling radiation along the poles help.

An alternative possibility is that massive star from via collisions of lower mass stars in dense clusters.

Star clusters

Most stars form in clusters. However, in most cases the motion of stars will cause the dissipation of the cluster to form a stellar association and then distribute the stars amongst the field stars of the galaxy.

Nevertheless, we can use HR diagrams for individual clusters to estimate their ages.

Examples include the (relatively) young clusters HD 2264 and the Pleiades. (Figs 22-17 & 22-18)

In the HR diagram for NGC 2264 we find that all the brightest stars lie on the MS while the faintest lie *above* the MS (i.e. they are too red for their luminosities).

As these evolve they will move downwards and to the left of the plot until they lie on the MS. Nevertheless, their presence implies an age for the cluster of only 2 Myrs.

For the Pleiades the situation is slightly different, as all the low mass stars are found on the MS but the *higher* mass stars are found to be too red for their luminosities.

This isn't due to them still being in the process of formation however, rather these have begun to run out of their nuclear fuel.

Hence we may determine that this cluster is rather older, probably of the order of 20 million years or so.

Main Sequence Evolution

As we have seen, the hydrogen burning phase of a star's life is called the Main Sequence (MS).

During the MS a star undergoes significant alterations to its luminosity, temperature and radius, which result from changes in the internal chemical composition as H→He.

Initially a star is 75% by mass of H, 25% He and fewer than 1% of heavier elements or 'metals'.

The fraction of H and He changes over time, as indicated in Fig. 21-1 for the Sun.

As the MS star evolves, the increased energy production in the core heats the surrounding inner layers to temperatures that are sufficient for H-burning to occur in a shell around the core.

This can extend the apparent MS lifetime of a solar mass star by a few million years.

The overall lifetime of a star depends crucially on its initial mass, as shown in Table 21-1.

Mass	Spec type	$L(L_\odot)$	MS life (Myrs)
25	O	80000	3
15	B	10000	15
3	A	60	500
1.5	F	5	3,000
1	G	1	10,000
0.75	K	0.5	15,000
0.50	M	0.03	200,000

We find that the MS lifetime of a star is given by
$t_{MS} \propto 1/M^{2.5}$ (box 21-2)
Thus the more massive the star the shorter the lifetime and vice versa.

Very massive stars ($\geq 25M_\odot$) have core temperatures and densities that are so high that the rate they burn their fuel means that they run out of core H in only a few million years, even though they have plenty to begin with.

Conversely, low mass stars burn their fuel at such a slow rate that they can have lifetimes of hundreds of billions of years - significantly greater than the current age of the universe!

Thus the mass of a star not only determines its temperature and size, but also its lifetime.

Post Main Sequence Evolution

At the end of a star's lifetime all the H in its core has been used up leaving a He core. Nuclear burning in the core stops.

In this new stage H-burning continues in a shell around the inert core: **Hydrogen Shell Burning**.

In the core, the cessation of fusion leads to a decrease in the pressure which supports it against gravity and hence the core contracts. (e.g. Sect. 7.7 & 18.1)

As this occurs heat is released due to the contraction and flows from the core into the overlying shell (e.g. Sect. 7.7 & 18.1).

This causes the temperature of the H burning shell to rise which increases the shell burning rate and causes the shell to expand outwards through the star.

As He from the shell falls into the core it continues to contract and over the course of 100 million years the core of a solar mass star is compressed to a third of the original radius and T_{core} increases from $1.5\times10^7 \rightarrow 10^8$K.

As the H burning shell expands outwards the luminosity of the star increases dramatically, increasing the internal pressure and causing the outer layers to balloon outwards.

This causes the outer layers to cool down to about 3500K - the star has now become a *Red Giant*.

This is the ultimate fate of the Sun (Fig. 21.3), swelling to R$\sim$1AU (currently R$\sim$0.01AU) and swallowing the Earth.

This is expected to occur in about another 5 billion years, so no need to worry...!

Red Giant Evolution

Eventually the temperature and densities in the inert He core become so high ($\geq 10^8$K) that He burning can occur as a source of energy.

This requires a higher temperature and pressure since the nuclear charges on a He nucleus are larger than for a H nucleus, and hence a greater repulsive force has to be overcome.

Helium burning occurs in 2 steps, firstly
$^4\text{He}+^4\text{He} \rightarrow {}^8\text{Be}$
and then
$^8\text{Be}+^4\text{He} \rightarrow {}^{12}\text{C} + \gamma$ ray.
and is termed the *Triple Alpha Process* as three He nuclei (or alpha particles) yield a Carbon nucleus plus (energy) gamma radiation.

Some of the ^{12}C nuclei react with an additional ^{4}He to produce ^{16}O
$^{12}\text{C}+^4\text{He} \rightarrow {}^{16}\text{O} + \gamma$ ray.
Thus both C and O make up the ash of He burning.

Core He burning typically lasts for about 10% of the time a star stayed on the MS (e.g. the Sun will burn He for about 1 billion years).

The onset of core He burning occurs gradually for higher ($\geq$2-3M$_\odot$) stars, but extremely rapidly for stars below this mass (the so called **Helium Flash**: see Sect 21-2 if interested in the underlying, non examinable physics).

Upon the onset of the He buring the core expands - as expected for a heated gas - and hence the surrounding material also is forced to expand and *cools.* This reduces the energy production in the H burning shell that surrounds the core, and hence the *overall* effect is that the total luminosity of the star *decreases.*

This leads to the star's outermost layers contracting, and hence they heat up!

So a core He burning star is at once less luminous but hotter than its RSG progenitor!

Evolution and HR diagrams revisited

We can use the changes in the temperature and size (and hence luminosity) of a star to follow its evolution (and hence determine its age) on the HR diagram.

Our theories of stellar evolution allow us to calculate - for a given intial mass - the temperature and luminosity of a star over its lifetime.

We can plot these *evolutionary tracks* on an HR diagram, and comparing them to real data from a star cluster, we can determine the age of the cluster in question.

We can do this by assuming that the stars in the cluster were all born together - i.e. they are *co-eval.*

The more massive stars evolve more rapidly and are first to leave the MS to become red giants or supergiants.

The point at which this occurs - the *turnoff point* - can trace the age of the cluster.

An example of this is seen for the Pleiades cluster.

We have already observed the turnoff point for the Pleiades cluster (20-17), which indicates that all stars more massive than $\sim 5 M_\odot$ have evolved from the MS, while those less massive are still on the MS.

This implies an age of approximately 50 Mys.

By contrast the HR diagram for NGC 2264 shows no turnoff - this is because the cluster is so young no stars have exhausted their H fuel yet (20-17).

(Fig 21-10 presents further examples of HR diagrams for clusters of different ages).

Fig. 21-7 show the theoretical evolution of a cluster - note how the more massive stars are both the first to reach the MS (at around 100,000 yrs) and also the first to leave (between 3-20 Myrs, depending on initial mass).