Lecture 10 : Stellar Evolution

10.1 INTRODUCTION

Stars on the main sequence burn Hydrogen in their cores into Helium. This week we will look at what happens to stars after the Hydrogen runs out.

The process of change in stars from birth to death is called stellar "evolution". This may be an unfortunate name, since evolution in biology is concerned with changes that take place over many generations in a species, rather than in individual members of the species during their lifetime. The latter is what is meant by stellar evolution!

The key observations which lead to the discovery of the processes which take place within the stars during their lives, were of the open and globular clusters. We saw the colour magnitude of examples of these in lecture 2, and it would be worth reviewing that material.

There are quite a number of phases which a star can pass through after it has used up its core Hydrogen. These phases are termed **post main sequence** evolution. The time spent in this phase and the changes that take place are very dependent on the mass of the star and properties of the core.

10.2 WHAT HAPPENS WHEN HYDROGEN RUNS OUT?

Consider the core of a star which is burning Hydrogen into Helium. Because of the temperature and density gradient in the core, Hydrogen will be converted more rapidly in the center of the core than at its edge. Eventually the Hydrogen at the center will run out. Further out, there may still be burning of Hydrogen in a **shell** around the core (see figure 10.1).

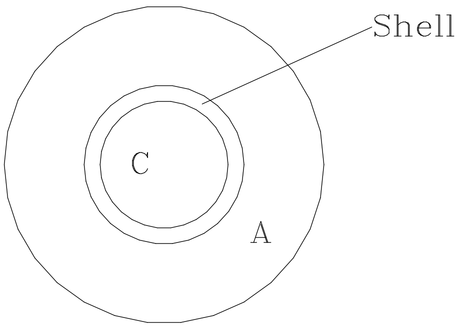

Figure 10.1. Core of a star towards the end of main sequence burning. In the center of the core (marked "C"), H burning has ceased, although it continues on a shell around the core. No burning takes place at all in the outer parts of the star, marked "A".

10.2.1 Inert core

The luminosity of the core has dropped because it is no longer burning, but it can still release energy through **gravitational collapse**. Since the temperature gradient in a star is proportional to the luminosity

$$\frac{dT}{dR} = -\frac{3\kappa L\rho}{16\pi acr^2T^3} \tag{10.1}$$

this means that the core temperature becomes almost **isothermal**, i.e. close to constant.

10.2.2 Core collapse

The evolution of the star can be followed as the core releases energy gravitationally and Hydrogen is burnt in the shell. It turns out that when the isothermal, non-burning core mass is 10 to 15% of the total mass of the star, the first big changes take place. At this point the internal pressure in the core is no longer able to support the outer layers, and the **core collapses** rapidly. This point is called the **Schönberg-Chandrasekhar limit**. This releases gravitational energy, and the **core heats up**. Surprisingly, the outer layers of the star **expand** at this stage, although this seems counter-intuitive. One explanation of this is that the Hydrogen burning shell luminosity increases and that in order for the energy to escape the outer layers of the star must have lower opacity, which it achieves by expanding and becoming less dense.

10.2.3 Core stabilisation

What stops the core continuing to collapse? Eventually the density in the core can reach a high enough temperature that Helium burning begins. Furthermore the core may reach sufficient densities that the effect of **degeneracy pressure** comes into play. Up to now we have considered the gas in the stars to be ideal, so that its pressure and density obey the perfect gas law. However, at high enough density **Pauli's exclusion principle** provides a new source of pressure support in the star. This states that no more than one electron can occupy a bound energy level state in an atom (in fact, two electrons can occupy the state but must have opposite spin). Free electrons which are tightly packed together must satisfy the **Heisenberg uncertainty principle**

$$\delta x\delta p > \frac{h}{4\pi} \tag{10.2}$$

where x is the position and p the momentum. In order to satisfy this relation, at very high density, the electrons must have a greater momentum (and hence pressure) than would be predicted by the perfect gas law. The free electrons in the plasma at the stellar core eventually reach densities that allow the core to be supported by this degenerate pressure.

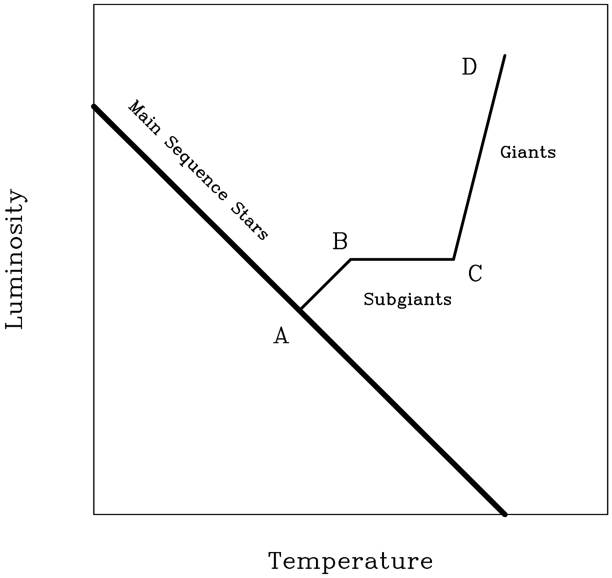

Figure 10.2. Schematic illustration of post-main sequence evolution for a circa 5 $M_\odot$ star. The heavy line shows the main sequence. Note that temperature is from hot on the left to cool on the right. At **A**, the star is on the main sequence and as Hydrogen burning proceeds its luminosity increases somewhat until it arrives at **B**. At this point the core Hydrogen is used up; the core collapses and the outer layers expand, and the star evolves toward **C**. The core collapse is halted at C and burning of Helium begins, which leads to a great increase in the luminosity, **D**. Stars are termed to be on the **main sequence**, on the **sub-giant branch** and the **giant branch**, as marked.

10.2.4 Radiative versus convective cores

One further factor plays an important role in the development of the core. If the core is radiative (i.e. energy is transported out of the core by radiation), then as the core Hydrogen is burnt, the chemical composition of the core will change, with more Helium in the core center than at the surface. On the other hand, if the core is convective (i.e. energy transport by bulk motion), the rate at which Hydrogen can be moved from the surface of the core to the center, where it can be burnt, will control the core evolution.

10.3 EVOLUTION FOR STARS OF DIFFERENT MASS

10.3.1 High mass stars

Stars more massive than the sun can have convective cores, and this allows a lot of Hydrogen to be transported to the central regions where it can be burnt into Helium. A considerable fraction of the Hydrogen can be processed before the core reaches the Schönberg-Chandrasekhar limit, and the gravitational collapse phase which follows may be relatively short, before the star begins Helium burning. High mass stars spend only a short time between the points marked B and C in figure 10.2. In an open cluster for example, where there are a range of stars with different masses but the same age and composition, only a few of the stars will be in this region. The region is called the **Hertzsprung gap** and it lies between the main sequence and the giant branch.

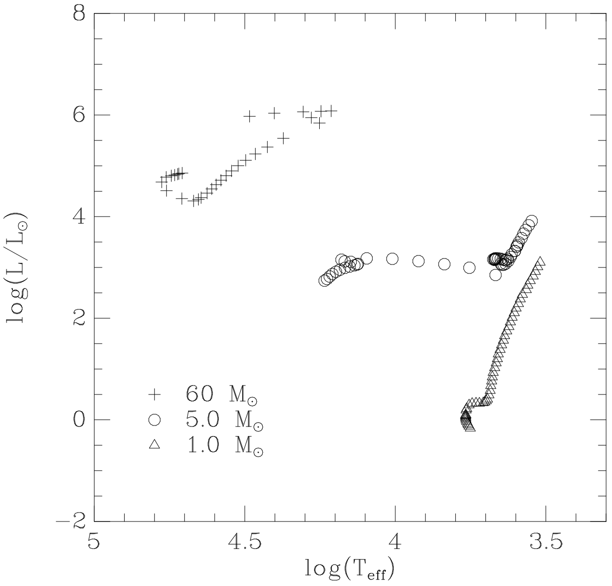

Figure 10.3. Evolutionary tracks for 60, 5.0 and 1.0 $M_\odot$ stars of solar metallicity ($Z = 0.02$).

The evolution of three stars, with masses of 60, 5 and 1 $M_\odot$ is shown in figure 10.3. The track of the 5 $M_\odot$ star well illustrates the Hertzsprung gap. The points along the track in the gap are at approximately equal time intervals of 100,000 years, in order to see the track more clearly, whereas points in the slower evolution regions are at intervals of order 10^6 years.

We will now consider in detail the evolution of a 5 $M_\odot$ star of solar metallicity ($Z = 0.02$). The evolutionary track is shown in figure 10.4, with the following points marked.

- A: The star is 1 million years old and is on the main sequence. The mass fraction of Hydrogen in the core is circa 67% and in Helium 30%, the central temperature is circa 25 million degrees, and the core s about 31% of the total mass of the star.
- B: Evolution is well developed (age is 9.3×10^7 years), but the star is still on the main sequence. The mass contained in the core has dropped to about 13% of the total mass. The Hydrogen mass fraction in the core has dropped to 3% and Helium has risen to 95%. The star is about to run out of fuel!
- C: The star has used up all the Hydrogen in the core. Age is 9.45×10^7 years. The core now becomes close to isothermal, and begins to collapse, releasing gravitational energy. The star is close to the Schönberg-Chandrasekhar limit, and soon the core begins to collapse rapidly due to the weight of the outer layers. Hydrogen burning can continue in a shell outside the core.
- D: The track moves rapidly from C to D, to lower surface temperature, while mainitaining about the same luminosity (it gets a little fainter). The outer regions of the star expand while the core shrinks. The outer part of the star become convective in a very deep region. The core is still not hot enough to ignite Helium burning.
- E: Helium burning has begun in the core. Age is 9.52×10^7 years. The Helium mass fraction in the core is circa 98%, while the initial amount of Carbon is 0.03%. Carbon

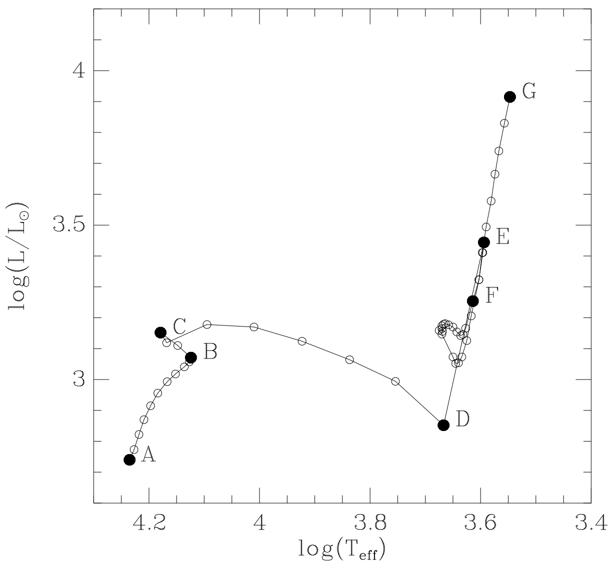

Figure 10.4. Evolution of a 5.0 $M_\odot$ star of solar metallicity ($Z = 0.02$). See text for description of marked points (A-G).

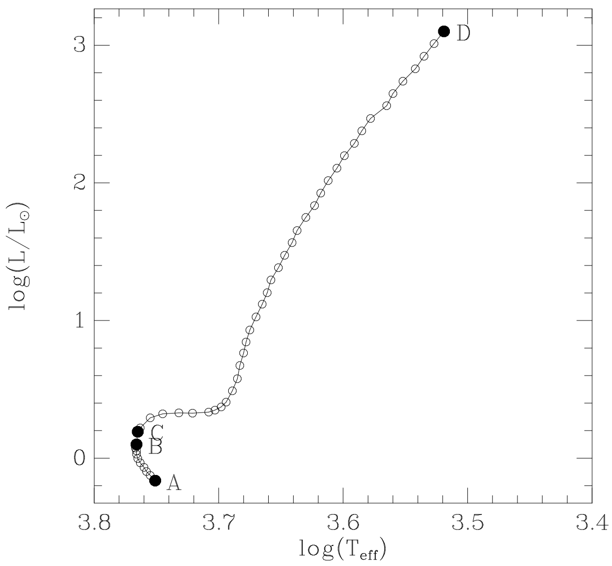

Figure 10.5. Evolution of a 1.0 $M_\odot$ star of solar metallicity ($Z = 0.02$). See text for description of marked points (A-D).

is rapidly built up in the core via the triple-α process. A new convective core is set up, initially containing about 5% of the total stellar mass.

- F: The Helium in the core has been fully burnt to Carbon. Age is 10.8×10^7 years. The mass fraction of the Carbon in the core is about 30%. Helium burning to Carbon can continue in a shell outside the core, while further still out the Hydrogen burning shell (which started at C) is still making Helium. A similiar process takes place in the core as at C. The core contracts, the outer layers expand and become convective (which allows the shell layers to mix into the outer parts of the star), and the star increases in luminosity.
- G: Ignition of Carbon in the core. The track is not computed beyond this point. Products such as Mg, Ne and Na can be built up from 2 C^{12}.

After Carbon burning, and depending on the mass of the star, further elements can be burnt. For a massive enough star, elements can be burnt all the way to Fe, beyond which no further energy can be extracted by fusion. Massive stars can reach a stage where they consist of shells of nuclear burning, with Fe production in the core, surrounded by shells of Si, C and O, He and H. Because the energies of the particles are so high, a small amount of production of elements beyond Fe can take place. Eventualy the fuel sources will end and the star (if the mass is high enough) will undergo a catastophic core collapse and result in a **supernova**. The result of this can be a **neutron star**, in which much of the elements built up over a long time in the core of the star have been converted back into protons, electrons and then to neutrons. For very high mass stars a **black hole** is the possible result. In recent years very strong evidence has been found that black holes of this type actually exist.

10.3.2 Low mass stars

Stars with low masses have radiative cores, so that the surrounding Hydrogen cannot be transported into the core where it can be burnt. Instead, the Hydrogen initially in the inner core, where the temperature is high enough to burn it, is the only Hydrogen which is converted to Helium. Another factor is that burning takes place by the p-p chain rather than by the CNO cycle. This is less sensitive to temperature, and burning can take place in a wider region than would be the case for a high mass star. In any case, when the Hydrogen is used up, the core mass is well below the Schönberg-Chandrasekhar limit, and the gravitational contraction phase is much longer than for a high mass star. In fact, this phase is so long that many stars in a cluster can find themselves in the subgiant phase and the Hertzsprung gap effectively dissapears. This is what we see in older clusters, in which the stars leaving the main sequence have lower masses than for young clusters. Core contraction is halted by the onset of degeneracy. Eventually, the core will heat up until Helium can be ignited and while this occurs the star is in a giant phase. Helium ignition takes place under special circumstances; because the core is degenerate, Helium burning begins but takes place explosively. Helium burning in a non-degenerate core is like a controlled nuclear reaction, where as in a degenerate core it is like a nuclear explosion. This is called the **Helium Flash**. Changes take place very rapidly in the core (few 100 seconds!) and the physics becomes very difficult to compute and the results of such computations are still uncertain.

Let's look at the evolution of a 1 $M_\odot$ star of solar metallicity (i.e. the Sun). The evolutionary track is shown in figure 10.5, with the following points marked.

- A: The star is 20 million years old and is on the main sequence. The mass fraction of Hydrogen in the core is circa 68% and in Helium 30%, the central temperature is circa 13 million degrees, and the core contains about 4% of the total mass of the star.
- B: The star is 7.7 billion years old. The Hydrogen mass fraction in the core has dropped to 3% and Helium has risen to 95%.
- C: The star has used up all the Hydrogen in the core.

Age is 9.4 billion years. The core begins to collapse, releasing gravitational energy. The star is a long way from the Schönberg-Chandrasekhar limit. Collapse to a degenerate core takes a few million years. The central temperature does not yet allow Helium burning. The outer layers expand and the luminosity increases as the star moves up the giant branch towads D.

- D: Ignition of Helium in the core, in the Helium flash. Age is about 12 billion years. The evolution is difficult to follow numerically beyond this point.

Although calculation of the Helium flash is difficult, the star certainly ends up in a stable phase where it burns Helium in the core; this phase is called the **horizontal branch**. After the Helium is used up in the core, shell burning of Helium takes place and the star ascends the giant branch again. Eventually it will be unable to burn any further fuel because it cannot get hot enough in the core, and it will become a dying star, moving to the **white dwarf** region.

10.3.3 Very low mass stars

Below about 0.4 $M_{\odot}$, stellar evolution is much less complicated. We can start by considering stars below about 0.08 $M_{\odot}$. These objects, which have only been found directly in the last few years (although their existance has been suspected for any decades) are called **brown dwarfs**. They are not true stars because they never develop a central temperature which is high enough to ignite Hydrogen burning. Instead, they release energy by gravitational contraction. They radiate this energy away and get slowly fainter and more difficult to find, and do not stop for a long time on the main sequence as stars do. Above the limit for brown dwarfs, between about 0.4 and 0.1 $M_{\odot}$, we find **red dwarfs** or **M dwarfs**. These are real stars and burn Hydrogen so slowly in their cores that they will stay on the main sequence for a very long time, much longer than the Sun. Once the Hydrogen is burnt, the core collapses but never reaches high enough temperatures for Helium burning to commence. Such stars may not become bright giants but instead evolve directly to **white dwarfs** without the complications that arise for stars near 1 $M_{\odot}$. However, the Universe is still so young that no very low mass stars have had time to evolve off the main sequence, so this prediction is not really testable!

Problem 10.1 Mark on figures 10.5 and 10.6 where the following events occur:

- when the star is on the main sequence, is a subgiant, or a giant
- when the core is contracting and there is expansion of the outer layers
- when Hydrogen is being burnt. How hot is the core in the two models during H burning? From the temperature, would you expect the p-p chain or the CNO cycle to be the dominant process?
- when Helium is being burnt. How hot is the core when He burning takes place?
- when the surface temperature decreasing but the luminosity is increasing. How can the surface get cooler and yet the star get brighter? What physical change in the star is making this happen?

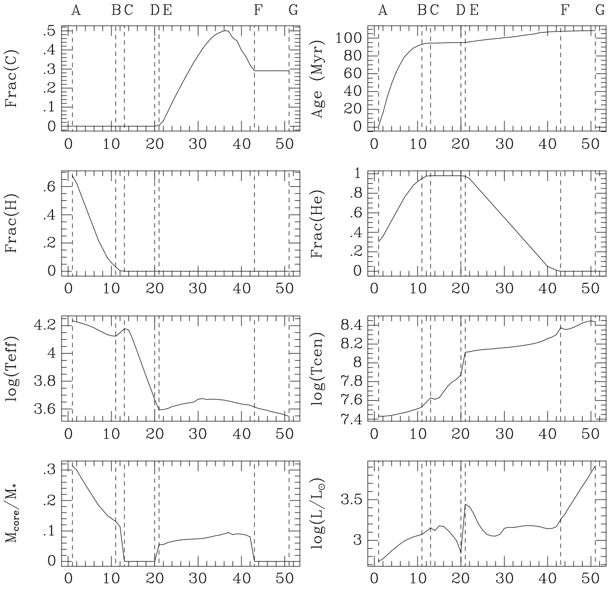

Figure 10.6. Evolution of physical properties of the 5.0 $M_{\odot}$ star in figure 10.4, showing the same points (A-G). The models are computed by Schaller et al (1992). The physical quantities (from bottom left to top right are: fractional mass of the core, relative to the mass of the star, M_{core}/M_*; luminosity relative to the sun, $log(L/L_{\odot})$; effective temperature at the surface (T_{eff} in K; central temperature, T_{cen} in K; fraction of Hydrogen, Helium and Carbon by mass in the core, Frac(H), Frac(he) and Frac(C); and the age (in Myr).

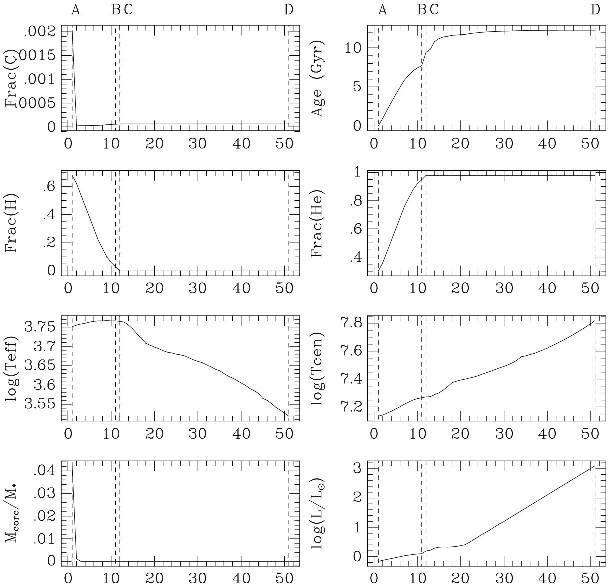

Figure 10.7. Evolution of physical properties of the 1.0 $M_{\odot}$ star in figure 10.5, showing the same points (A-D). The physical quantities are as for figure 10.6. Note that the age is in Gyr.