Chapter 20 Stellar Evolution

Stars and the Scientific Method

Before we talk about what is happening in the stars, let's look at how we developed this model. No one has ever witnessed the complete lifetime of a star. All of the low mass stars that ever formed are still around because they use their fuel so slowly. In contrast the O and B class stars use up and leave the main sequence in a few million years. The theory that has been developed over the last century is one of the best tested theories in all of astronomy.

What has been done is that we have looked at billions of stars at every stage of their lives. This allows us to test and refine our models. This model is one more example of the scientific method in use. By taking all of the data that we had astronomers pieced it together over the 19th and 20th centuries to form what we have now.

Structural Change

While on the main sequence a star fuses hydrogen into helium which is called *core hydrogen burning*. When you talk about burning with an astronomer, they are referring to nuclear fusion. A main sequence star is in *hydrostatic equilibrium* which means that the inward pull of gravity and the outward push of the internal pressure are balanced. As the main sequence star ages, it gets brighter and the core temperature increases. The change is very slow, only a factor of 3 or 4 in its entire lifetime of maybe 10 billion years. As the star uses up the hydrogen fuel in its core, its days on the main sequence are numbered.

As the star starts to move away from the main sequence, its days are numbered. Now what happens during the rest of the stars life is guided by the stars mass. The low mass stars die a gentle death while the more massive stars ($> 8\ M_{sun}$) die a violent death.

Evolution of a Sun-Like Star

Our Sun has not changed significantly over the past 5 billion years. It is estimated that it is 30% brighter now than when it first became a star. After another 5 – 7 billion years our Sun will exhaust its hydrogen fuel.

Stage 8: The Subgiant Branch

As time goes on the helium content in the core increases. After about 10 billion years the hydrogen is depleted and the nuclear fires subside. The inner core fills with nonburning helium while a shell of hydrogen continues to burn outside of the core. When the hydrogen stops burning, the outward push increases a little, which opens the door for gravity. The core contracts, but it is not even close to the temperature for helium to start fusing. This is due to the fact that helium is a much heavier atom than hydrogen and has a greater force of repulsion. Because of this the core temperature must reach 100 million K or so. As the core shrinks, the temperature gets higher, causing the outer layer of hydrogen to burn faster than before. This nonburning ash of helium falls onto the core. This is known as the *hydrogen shell burning*. This causes the star to actually get brighter. The star moves horizontally from the main sequence on the H-R diagram. It is following its evolutionary track. It is now in the *sungiant stage*.

Stage 9: The Red Giant Branch

The core is shrinking and heating up which causes the hydrogen layer just above it to fuse hydrogen at a furious rate. The outer layers expand outwards, becoming more luminous and cooler in the process. It is becoming a *red giant star*. On the H-R diagram the star enters a vertical branch to the *red giant branch*. The red giant is huge, about the size of Mercury's orbit. The core continues to shrink to a point where about 25% of the stars mass is in an area the size of a planet.

Stage 10: Helium Fusion

A few hundred million years after leaving the main sequence the helium fuel ignites. Going from helium to carbon (the next product) is a 2 step process: 2 helium atoms join to become Beryllium 8 which is an unstable element. Then another helium atom joins the beryllium atom to produce carbon12. Helium 4 atoms are called alpha particles, so this process is called the *triple alpha process*.

The Helium Flash

At the really high temperatures, electrons have been stripped off the atoms in the core. At this point there is something called *electron degeneracy*. This is where the core can collapse until the electrons touch each other. At this point there is no more compressibility in the core. In a degenerate core the pressure is independent of the temperature. When the burning starts, there is no increase in the pressure and no expansion of the gas. This means that there I s no decrease in the core temperature and no stabilization of the core. The nuclear reaction rate increases and the temperature jumps without any change in size. This leads to the *helium flash*. The helium burning goes on for while; until it heats the core and thermal pressure again dominates in the star. This leads to the star reaching hydrostatic equilibrium. This all takes about 100,000 years. At this point the star resides on the horizontal branch where stars reside before continuing their journey on the H-R diagram.

Stage 11: Back to the Giant Branch

As the temperature in the core increases, the helium fuel gets used up at an increasing rate. This fuel will last only a few 10's of millions of years. As the helium becomes carbon, the core becomes depleted of the helium. Fusion ceases in the core and the carbon core starts to shrink. As it does, the temperature increases and the outer layer of helium starts to burn and the hydrogen shell above that is still burning. The outer layer of the star expands and the star becomes a red giant for the second time. The stars second ascent of the giant phase is often called the *asymptotic giant branch*. The carbon in the shell increases due the helium burning shell, but the core gets smaller. The temperature increases and so does the luminosity.

The Death of a Low Mass Star

When our Sun reaches stage 11 the outer envelope will have swollen greatly. The carbon core continues to contract. If the temperatures could get high enough, the carbon would fuse and life would go on. But for a star like our Sun this will never happen; the temperature will never reach 600 million K in the core. So what does happen?

The Fires Go Out

Before the core reaches a temperature where carbon can fuse, the density reaches a point where it can no longer contract. It becomes degenerate. This would be stage 12. Density is high; a cubic centimeter would weigh 1000 kg on Earth. The core temperature is only about 300 million K.

Stage 12: A Planetary Nebula

Our star is now in trouble. As the core contracts, the temperature goes up causing the 2 above layers the core to increase their rate of burning. This pushes the outer layer of the star out to about where Mars would be. The burning becomes unstable, with several explosive *helium-shell flashes* occurring. This is caused by enormous pressure in the helium shell. This causes the outer layers to pulse violently. The outer layer will heat, expand, cool and contract. At the peak of each pulse, the electrons can recombine to form an atom which gives off a photon. The release of this energy gives the outer layers a little extra push. This causes the outer layers to be expelled into space in a few million years. At this point a rather unusual looking object appears. At the center you have a small, hot exposed core of the star. Only the outer layer still fuses helium into carbon. Surrounding this is an expanding cloud of dust and cool gas. It heats up and moves left on the H-R diagram. This heat causes the cloud to glow. What you now have I s called a *planetary nebula*. They have nothing to do with planets, but when first observed in the 18th century, they looked like planetary disks. It shines in the same basic manner as the emission nebulae, by ionization. We used to think the clouds were spherical in shape, but we now know that they have a variety of shapes. Figure 20.10 We are not sure why this is true. We don't understand the mechanism that causes these shapes. After a few ten's of thousands of years the cloud will have expanded into oblivion, becoming part of the interstellar medium. The core will eventually fade from view. The evolution of low mass stars is the source of almost all of the carbon-rich dust throughout the galaxies.

Stages 13 and 14: White and Black Dwarfs

The core takes thousands of years to appear from behind the atmosphere of the star. By the time it appears, it has shrunk down to the size of the Earth. It has the mass of about half of our Sun. It shines white hot and is now called a *white dwarf*. This is stage 13. Not all white dwarfs have the planetary nebula around them. Several hundred naked white dwarfs have been discovered. Why? An example of this is a white dwarf around the star Sirius. It is called Sirius B. It has a mass more than our Sun packed into a volume smaller than the Earth. Theory predicted white dwarfs in globular cluster, but it wasn't until the Hubble Space Telescope that we actually saw them. Figure 20.14

Not all white dwarfs are composed of carbon and oxygen. The low mass stars will never reach helium fusion. They are supported by electron degeneracy. The outer layers will be ejected and you will have a *helium white dwarf*. This would take hundreds of billions of years, so it has not happened yet. For the heavier stars in the low mass stars (near the 8 M_{sun} cut off) the core will go on to produce other things. $^{16}O + ^{4}He$ -◊ ^{20}Ne + energy This is a *neon-oxygen white dwarf*. Once an isolated star becomes a white dwarf, it life is over. It will keep cooling, but it won't shrink any more. Eventually it will become a *black dwarf*, a burned out ember in space.

Evolution of Stars More Massive than the Sun

High mass stars evolve much faster than lower mass stars. Our Sun will live on the main sequence for about 10 billion years while a $5M_{sun}$ star will exist there for only 100 million years and a 10 M_{sun} star will only be on the main sequence for about 20 million years. Even after they leave the main sequence the mass will drive what happens to them.

Red Supergiants

A high mass star in the beginning follows the path of their low mass cousins. They use up the hydrogen fuel and go on to burn helium. After that though, the high mass stars follow their own path. Figure 20.16 As a low mass star leaves the main sequence it ascends almost vertically while a high mass star evolves horizontally. Their luminosity remains almost the same as this happens. In stars more than 2.5 M_{sun} there is no helium flash. Calculations show that the more massive the star, the lower the core density and you don't get an unstable condition. Beyond 8 M_{sun}, things progress quite rapidly. A star that is 15 M_{sun} will start its helium fusion before it reaches the red giant phase. As each fuel is burned to completion, it contracts and fusion begins again. It occurs so rapidly that the star progresses horizontally across the H-R diagram. It continues to produce heavier and heavier elements until it reaches its ultimate fate: a supernova.

The End of the Road

The magic number of 8 M_{sun} was chosen because this is where carbon can start to burn. The truth is that these stars have a large solar wind where they lose mass. We really don't understand, but some stars that are between 10 – 12 M_{sun} may not go supernova. If they don't they will become a neon – oxygen white dwarf. Above 12 M_{sun} the end will be a supernova.

Observing Stellar Evolution in Star Clusters

Star clusters are excellent objects to look at when studying the evolution of stars. They are a concentrated grouping of stars that were all born at about the same time. This means that any differences that we can see must only be due to the difference in masses. We will begin our look at the cluster with the upper mass stars already on the main sequence while the low mass stars are just beginning to arrive there. Figure 20.17 We then see the H-R diagram as it would be after 10 million years. The o class stars have left the main sequence. Most would have already gone supernova, but there may be some red supergiants left. The main sequence seems a little cut off. The 3rd picture shows the diagram after 100 million years. Stars brighter than B5 have left the main sequence. The low mass stars are finally all on board. As time goes on, we can imagine the upper main sequence being peeled off. This area is called the *main sequence turnoff*. At 1 billion years the turnoff is at around 2 M_{sun}. The subgiant and giant branches are just becoming visible. Also we just now see the first white dwarfs. At 10 billion years the turnoff has reached stars the size of the Sun. The subgiant and giant branches are now very distinct. The horizontal and asymptotic-giant branches are now distinct. These branches are more distinct because the high mass stars evolve so quickly that they don't stay in a phase very long. Figure 20.18 shows the Double Cluster. The H-R diagram shows an age of about 10 million years. Figure 20.19 shows the Hyades cluster. Its H-R diagram shows an age of about 600 million years. Figure 20.20 shows the cluster 47 Tucanae. From its H-R diagram it has been estimated that its age is between 12 – 14 billion years old.

The Evolution of Binary Systems

Binary systems are a little different in their evolution. If the stars are widely separated, more than a thousand stellar radii, they will evolve like 2 individual stars. If they are closer, their gravitational pull may affect the evolution. Let's look at Algol. It is a 3.7 M_{sun} main sequence star with a .8 M_{sun} red subgiant companion. But if they were born at about the same time, how could the smaller star have evolved faster than the big star? Around each of these stars is a tear drop shaped zone called the *Roche lobe*. The 2 lobes meet on a line joining them called the Lagrangian point (L1). This is where the gravitational attraction of the 2 stars exactly balances the rotation of the system. The greater the mass of one star, the greater the Roche lobe is and the farther from its center of the star. If one of the stars heads towards the red giant phase, it could overflow its Roche lobe. When this happens, the other star will start to pull mass off of the red giant star. This is called *mass transfer binaries*. It is also known as *semidetached*. If some reason both stars overflow their Roche lobes, then you have what is known as *contact binaries*. Figure 20.22 Many astronomers feel that Algol originally was a 2 M_{sun} star that pulled mass off its companion.