Stellar Maturity and Old Age

The Main Sequence Phase

Stars spend approximately 90% of their life at this stage. In the core, Hydrogen is being converted to Helium.

Low mass stars similar to the Sun have a radiative core, and an outer region where convection occurs. Energy generation is by the proton-proton cycle.

High mass stars have a hotter core than lower mass stars. This hotter core is required to generate the higher pressures needed to overcome the increased gravitational attraction of the more massive star. Since massive stars are hotter they burn their fuel faster. They are thus more luminous. Energy transport in the core of massive stars is by convection.

In high mass stars the central temperatures are much higher, allowing them to fuse hydrogen into helium by the **CNO cycle** rather than the proton-proton cycle. The **CNO present** in the core of a massive star **acts as a catalyst.**

Eventually the hydrogen in the cores of all main sequence stars is converted into helium. Nuclear energy generation in the core cannot then proceed at a rate necessary to sustain a stable main sequence star.

When the hydrogen in the core becomes depleted, the star enters its post main sequence phases of evolution.

The post main sequence evolution of the star is determined by the stars mass. Stars with a mass less than approximately $5M_{sun}$ all show similar post-main sequence evolution to the Sun.

(Note: The post main sequence evolution of main sequence stars between 5 and 8 Solar masses is unclear, because the amount of mass they lose during their post main sequence phase is hard to calculate.)

Stellar Lifetime

The lifetime of a star is determined by the amount of fuel available, and its rate of use. Thus the lifetime of a star is related to the star's mass and luminosity.

An approximate formula for the stellar lifetime is

$$t = 10^{10} \ M/L \text{ years}$$

where M is in solar masses and L in solar luminosities.

Very massive stars use up their hydrogen quickly. The lower mass stars use up their hydrogen slowly.

The more massive a star, the shorter its lifetime.

Red Giant Phase

Evolution of Stars with mass less than $5M_{sun}$

About 10 billion (10^{10}) years after a $1M_{sun}$ star reaches the main sequence, no hydrogen is left in its core. The core is composed of helium. *The exact time scale depends on the stars mass, with the more massive stars evolving fastest.*

Since there is no fuel (i.e. hydrogen) nuclear reactions in the core stop (the temperatures are **too low** to burn helium into carbon). Nuclear fusion of hydrogen into helium is still occurring in a shell around the core.

Since the core is no longer being heated by nuclear reactions, ***the gas pressure in the core drops (slightly)and gravity makes the core start to contract.*** **The gravitational contraction releases energy which makes the core and the surrounding shell (undergoing hydrogen fusion) much hotter than it was before.**

This has 2 effects:

(a) **the rate of energy generation is increased, causing the luminosity to increase**

(b) **the increase in energy production makes the outer layers of the star expand and the surface temperature of the star decreases**

Net Result.

Star becomes a **red giant.**

Its diameter can be 100 times its main sequence diameter.

Its luminosity can be 100 times larger than its main sequence luminosity.

Because of its lower surface temperature, less energy is coming out of a square cm of the star's surface (Stefan-Boltzmann Law), but the star is much more luminous due to its larger diameter.

During this stage of the evolution, the star resides in the upper part of the HR diagram --- on the **giant branch**. Eventually the core of the red giant star ***becomes so hot that helium can fuse into carbon*** (via the triple alpha process)

This happens suddenly and is called the **Helium Flash.** Carbon starts to form in the star's core. The Helium flash does not increase the luminosity --- it causes a rearrangement of the core and ultimately a reduction in the luminosity. During its evolution the red giant star changes its position in the HR diagram.

The triple alpha process:

In this process **3 alpha particles are converted into a carbon nucleus and gamma rays**. This is the most elementary process for generating elements heavier than helium in stars. Other nuclear reactions in stars are responsible for creating even heavier elements.

The helium flash occurs because the core in low mass stars is **degenerate**. The pressure arises because the electrons resist being squeezed closer together (***electron degeneracy***). **In a degenerate gas, a higher temperature does not mean a higher pressure**. Thus ignition of helium does not make the core expand --- but causes more helium to be burnt explosively. Eventually enough energy is released to lift the degeneracy, and to expand the core.

After helium is depleted in the core, a new inner core of carbon forms, and fusion ceases. Fusion is now occurring in 2 shells.

Helium is fused into carbon in the inner shell

Hydrogen into helium in the outer shell.

The carbon core now begins to shrink, which in turn increases the stars luminosity, causes it to expand, and to decrease its surface temperature. It is now a **red supergiant.** Also called **asymptotic giant branch** stars.

Note the similarity to the red giant phase.

The carbon core continues to shrink, but the core never reaches a temperature high enough to "burn" carbon. The collapse is halted by "**electron degeneracy**"

Planetary Nebula Phase

The rapid evolution of a star in the final red giant phase causes the outer layers of the star to become unstable and pulsate.

Because of these pulsations a star which was originally $1M_{sun}$ will eject about 0.4 $M_{sun.}$ This occurs rapidly --- estimated to be approximately 1000 years. This ejected mass expands to form a `**planetary nebula**' around the remaining $0.6M_{sun}$ star.

The ejected material (which may contain matter that has undergone nuclear processing) eventually mixes with the interstellar medium.

A planetary nebula has nothing to do with planets. It is simply a cloud of gas that is so large that we can resolve it on images taken with telescopes on Earth.

The gas in a planetary nebula emits strong emission lines of hydrogen, oxygen, and nitrogen.

The 0.6 Solar mass star in the center of a planetary nebula looks blue because its surface temperature is so hot (up to 100,000 degrees Kelvin).

Eventually the nebulae disperses, and the core cools to become a **White Dwarf** --- a stellar remnant.

Sun's Life Story

Begins as an interstellar dust cloud. Cloud begins to collapse due to gravity, and grows smaller and hotter.

After a few million years, fusion occurs in the central region, increasing the pressure, and halting the contraction.

Sun moves to the main sequence, where it spends 90% of its life. Energy is generated by the fusion of hydrogen into helium.

After about 10 billion years most of the hydrogen has been consumed in the core. The Sun's core shrinks, causing a rise in temperature that causes the remaining hydrogen to burn more rapidly.

The increase in energy flow forces the Sun's outer layers to expand so that Sun's outer layers **COOL**. The Sun becomes a red giant .

When the Sun's core become hot enough it starts to fuse helium into carbon. It then becomes a yellow giant. For a brief period, it may pulsate as an R-R Lyrae star.

When the helium in the Sun's core is consumed, it becomes a high luminous red giant. The high luminosity drives off the outer atmosphere to form a bare core.

The ejected atmosphere forms a "Planetary nebula"

Eventually, the hot core, which has no further energy supply cools to become a white dwarf. During this evolutionary phase the entire luminosity is derived from **"stored energy".**

Massive Star Evolution.

Massive stars evolve off the main sequence forming first a yellow giant, and then a red giant. At this stage their evolution is governed by much the same process as governs low mass stars --- the exhaustion of the hydrogen fuel supply in its core.

After H exhaustion, the core shrinks and the temperature rises until helium is fused into carbon via the triple-alpha process. This gives the star a "second lease of life". This stage lasts about 10% of its main sequence lifetime.

Ultimately Helium is exhausted, so the core once again begins to shrink. Because of the star's mass, **sufficiently high central temperatures are reached that allow the fusion of carbon into oxygen, and silicon, and eventually the fusion of silicon into iron.** At this stage, the diameter of the core is less than the Earth.

The contraction-fusion cycle tends to build up an onion-like structure, with the heaviest element forming in the center. **Each burning stage proceeds more rapidly than the last.**

The contraction-fusion cycle ends with the creation of Iron. Iron has the most stable nucleus. To create elements of higher mass requires the **addition** of energy.

The process of creating the heavy elements is called **nucleosynthesis**.

After the creation of the Iron core, the large gravitational pull of the core causes the core to rapidly collapse. The rapid core collapse is facilitated by several effects:

(a) At the high temperatures the radiation is so energetic that it can **split Iron into its component neutrons and protons.** This removes energy, and hence decreases the pressure in the core.

(b) The gravitational force is so large that **protons and electrons merge** forming neutrons. This removes the pressure supplied by the electrons.

(c) **The neutrinos,** generated by the forcing of protons and electrons into neutrons, **carry away energy**.

In less than a second the core shrinks from an Earth size object to a ball of "neutrons" less than about 10km in diameter.

The stars outer layers plummet inwards crashing in on the Neutron core, becoming heated to billions of degrees. The sudden pressure increase causes the outer layers to be ejected in a titanic explosion --- **a Type II supernovae.**

A supernova corresponds to an abrupt (few days) increase in luminosity by a factor of 100 million (10^8).

For a few days, a supernova may outshine an entire galaxy composed of 10^{12} stars.

When a supernova occurs, most of the stellar mass is ejected back into the gas and dust in its galaxy. This is the gas, now enriched with heavy elements, from which future generations of stars will form.

Some of the heavy elements come from the "shells" surrounding the core. Trace amounts of very heavy elements (those heavier than Iron) are generated in the supernova explosion.

It is in Supernovae that the atoms that make up our bodies originated.

The matter ejected from recent supernovae can often be observed. These structures are called supernovae remnants. The Crab Nebula, which resulted from a Type II supernova in 1054 AD, is the most famous supernova remnant. A neutron star in the form of a pulsar can be seen at its center.

Evolution in Binary Systems.

Binary evolution is much more complicated than single star evolution. Complications arise because **mass can be transferred from one star to the other.**

Mass transfer can significantly alter the relative masses of the component stars. e.g.

Algol (Binary)

3.7 M_{sun} main sequence star and

0.8 M_{sun} subgiant

NB

In this system the star that initially was the more massive evolved the fastest (as expected on the basis of single star evolution). However, in its evolution it transferred mass to its companion. It now appears as the smaller mass component of the binary system.

When a star loses mass, it generally evolves slower.

When a star gains mass, it generally evolves faster.

Mass transfer most often occurs when one star is evolved. An evolved star generally has a large radius, and the companion star can easily pull material from it.

Binary evolution is **very important**, since 70% of stars are in binaries.

Testing Stellar Evolution

Unfortunately, we cannot witness the birth, life, and death of a single star. Instead we observe stars in various stages of their evolution. Evolutionary scenarios are, by necessity, a combination of theory and observation.

Theoretical H-R diagrams are generated and compared with observation.

e.g. Evolutionary models can predict how many red supergiants we should see compared with solar type stars.

Observations point the way to improvements in theory.

e.g. the absence of very luminous red supergiants indicates that mass loss processes must play an important role in the evolution of very massive stars.

Observations of stars in binaries provide stellar masses and hence help confirm evolutionary scenarios.

e.g. the measurement of the mass (and size) of the White Dwarf companion to Sirius.

Chance events allow us to witness stellar evolution as it happens. e.g.

SN1987a --- A Type II supernova in the Large Magellanic Cloud. Detection of neutrinos (about 10!) provided confirmation of the Supernovae-collapse scenario leading to the formation of a neutron star.