

After the Main Sequence

- **Goals:**
 - How long can stars remain on the Main Sequence?
 - What happens as Hydrogen depletes?
 - How are Giants formed?
- **Zero Age Main Sequence (ZAMS)**
 - **Protostars become MS stars.**
 - When the star starts core hydrogen burning and reaches hydrostatic equilibrium it is called a zero age main sequence star.
 - During its life on the MS H is converted to He and there are small changes in the luminosity, radius and temperature.
 - Hydrogen is used up and the core shrinks (fewer particles) \Rightarrow temperature, pressure and density rise.
 - Increased pressure \Rightarrow increase nuclear reaction (more energy). Pressure from photons pushes outer layers \Rightarrow expands.
 - For the Sun: Radius increased 6%, Luminosity 40%, Temperature 300K.

– Hydrogen burning and depletion

- The increased temperature heats material surrounding the core and starts hydrogen burning in outer layers.
- More massive stars (O, B) burn H rapidly ($\sim 3 \times 10^6$ years).
- Low mass stars (M) burn slowly ($\sim 2 \times 10^{11}$ yrs).
- Mass determines formation time, luminosity, temperature and lifetime.
- MS time is longest period of a stars life.
- When the Hydrogen is depleted (converted to ^4He) the core stops producing nuclear energy (shells around the core have not depleted and continue burning - shell hydrogen burning).
- Core does not generate enough pressure, temperature to counter gravity and shrinks.
- Shrinking core releases gravitational energy (Kelvin-Helmholtz) \Rightarrow reheats the core.
- This increases the shell hydrogen burning (energy released heats the outer shells).
- Core of $1M_{\odot}$ star compresses by one-third, T increases to 10^8K over 10^8 years.

- **Main Sequence Lifetimes**

- **Energy output (Einstein)**

$$E = f M c^2$$

- **E**: Total energy released by star
- **f**: Fraction of mass converted to energy
- **M**: Mass of star
- **c**: Speed of light

- **Luminosity vs lifetime**

- Luminosity of a star over its MS life

$$L = \frac{E}{t}$$


- **L**: Luminosity
- **t**: lifetime
- Substituting Mass for Energy

$$t = \frac{f M c^2}{L}$$

- **Luminosity vs mass**

- MS mass related to luminosity $L \propto M^{3.5}$
- Substituting for mass

$$t \propto \frac{1}{M^{2.5}}$$

- Larger mass  shorter lifetime
- $1M_{\odot} \Rightarrow 10^{10}$ years
- $25M_{\odot} \Rightarrow 3 \times 10^6$ years

- **Forming a Red Giant**

Figure 21-4

- **H depletion and core contraction**

- Shell burning spreads outwards through the layers of the star.
- Heat from the contracting core and shell burning increase the internal pressure of the star causing it to expand (x100).
- As the star expands it cools (as the air let out of a tire is cool to the touch). When it cools to 3500 K it emits in the red spectral range (828 nm).
- It is then known as a red giant.
- The larger the size of the giant the less gravitational pull on the outer material. Mass loss increases substantially ($10^{-7} M_{\odot} \text{ yr}^{-1}$ compared to $10^{-14} M_{\odot} \text{ yr}^{-1}$ for Sun).
- For the Sun:
 - Hydrogen depletion: 5×10^9 yrs
 - Red giant Radius: 1 AU
 - Temperature: 3500 K
 - Luminosity: $1300 L_{\odot}$
- Red giants are cool but very luminous (large radii).

- **Helium Burning**

- **Increased core temperature ignites He**

- As a red giant the core is small (30,000 km), compact and almost pure He.
 - For He to ignite requires high T (2 protons per He increases repulsive forces).
 - Hydrogen burning shell increases the mass of He at the core.
 - He ignites at 10^8 K.

- **Triple alpha process**

- Helium “burns” releasing energy (in the same way that Hydrogen reactions work).



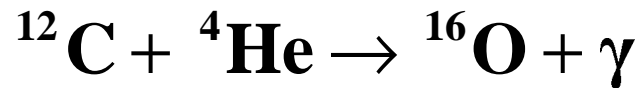
- ${}^8\text{Be}$ is very unstable (breaks down to ${}^4\text{He}$)
A 3rd ${}^4\text{He}$ can collide before breakdown.



- Three ${}^4\text{He}$ have formed to produce ${}^{12}\text{C}$ and a photon (Gamma ray).

– Triple alpha process

- An additional reaction can occur and ^{12}C can be converted to ^{16}O releasing energy.



- Helium burning produces more energy and creates heavier elements (metals).
- Known as core helium burning and lasts about 20% as long as the MS lifetime.
- These elements are essential for the production of life.

– Helium Flash

- How the helium burning starts depends on the mass of the star.
- In high mass stars ($>2M_{\odot}$) helium burning starts gradually as $T \rightarrow 10^8\text{K}$.
- In low mass stars He burning is sudden (a few minutes). Called the helium flash.
- In ideal gases pressure, temperature and density are related simply

$$P = \rho kT$$

- P: pressure
 ρ : density
 T: temperature
- Pressure increases \Rightarrow Heats \Rightarrow Expands \Rightarrow Cools (safety valve).

– Helium Flash

Figure 21-5

- In red giant the core is very compressed
- Atoms are ionized and the free electrons cannot be compressed any more (Pauli exclusion principle).
- Core acts as a degenerate electron gas (pressure is independent of temperature).
- Helium ignites, temperature increases (pressure doesn't increase to compensate) and a runaway effect occurs.
- Eventually temperature increases so that the electrons are no longer degenerate and core expands.
- Energy generated is used in core heating and expansion and absorbed by outer layers of the star (we don't see the flash).
- He burning causes luminosity to decrease.
- The core expands, cools and doesn't heat the surrounding H shells (energy production drops). Outer shells contract.
- After He flash star is hotter, smaller and less luminous.

Life as a Star

Molecular Cloud

<100 K, low density



Protostar

3000K, High Luminosity, Large



Zero Age MS

Core $T=10^6\text{K}$, Small



Main Sequence

10^7K , stable

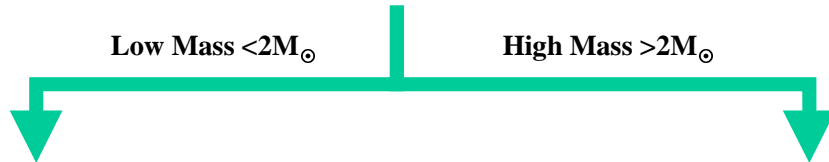


Red Giant

H depleted, Large, Cool

Low Mass $<2M_{\odot}$

High Mass $>2M_{\odot}$



Helium Flash

Core 10^8K , sudden He burning

Helium Burning

Core 10^8K , gradual He burning