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 stars 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) ⇒ temperature, pressure and density rise.
    • Increased pressure ⇒ increase nuclear reaction (more energy). Pressure from photons pushes outer layers ⇒ 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 (~3x10^6 years).
- Low mass stars (M) burn slowly (~2x10^{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 $^4$He) 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) ⇒ 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
    • \( 25M_\odot \Rightarrow 3\times10^6 \) 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 \, yr^{-1} compared to 10^{-14} \, M_\odot \, yr^{-1} for Sun).

• For the Sun:

  Hydrogen depletion: 5 \times 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).
    
    \[
    ^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be}
    \]
    
    - $^8\text{Be}$ is very unstable (breaks down to $^4\text{He}$)
      A 3rd $^4\text{He}$ can collide before breakdown.
      
      \[
      ^8\text{Be} + ^4\text{He} \rightarrow ^{12}\text{C} + \gamma
      \]
      
    - 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 $^{12}\text{C}$ can be converted to $^{16}\text{O}$ releasing energy.
    \[^{12}\text{C} + ^{4}\text{He} \rightarrow ^{16}\text{O} + \gamma\]
  - Helium burning produces more energy and **creates** heavier elements (metals).
  - Know 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 ($>2\text{M}_\odot$) 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
    $\rho$: 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=10^6K, Small

Main Sequence
10^7K, stable

Red Giant
H depleted, Large, Cool

Helium Flash
Core 10^8K, sudden He burning

Helium Burning
Core 10^8K, gradual He burning

Low Mass <2M☉
High Mass >2M☉