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 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) ⇒ 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 - <u>shell hydrogen burning</u>).**
- **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)

$$E = f\ Mc^2$$

- 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

$$t = \frac{fMc^2}{L}$$

– 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
- $25M_\odot \Rightarrow 3\text{x}10^6$ 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 ($10^{-7}\ M_\odot\ yr^{-1}$ compared to $10^{-14}\ M_\odot\ yr^{-1}$ 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).**

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be}$$

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

$$^{8}\mathrm{Be} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

    - **Three ^{4}He have formed to produce ^{12}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.

$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma$$

- Helium burning produces more energy and <u>creates</u> 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 ($>2M_{\odot}$) helium burning starts gradually as $T \rightarrow 10^8$K.
- In low mass stars He burning is sudden (a few minutes). Called the <u>helium flash.</u>
- In <u>ideal gases</u> pressure, temperature and density are related simply

$$P = \rho kT$$

- P:pressure
  ρ: density
  T: temperature
- Pressure increases ⇒ Heats ⇒ Expands ⇒ 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 <u>independent</u> of temperature).
- Helium ignites, temperature increases (pressure doesnt 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 dont see the flash).
- He burning causes luminosity to decrease.
- The core expands, cools and doesnt 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

↓ Gravity

Protostar

3000K, High Luminosity, Large

↓ H ignition

Zero Age MS

Core T=10^6K, Small

↓ H usage

Main Sequence

10^7K, stable

↓ H depletion

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