Stellar Evolution

- **protostar, pre-main sequence, main sequence, post-m-s**

- **evolution determined primarily by mass**
  - Small chemical evolution effect
  - (although Pop III may be very different…)

- “evolution” = how luminosity and surface temp vary with time.
  - Plot “evolutionary track” on H-R diagram
Main Sequence

• 90% of all stars lie on M-S.
  – Longest lived portion
  – Nuclear Fusion

• What type of stars?
  – Let’s derive a luminosity function
    • Start by looking at number counts for the brightest stars
• Most are brighter than the sun… why?
  – Selection effects: easier to see more luminous objects at large distances than it is to see faint things nearby

• What about number counts for nearest stars?

Most stars are faint.
Definition of Luminosity Function

- Relative number of stars in successive intervals of luminosity within any given volume of space.
- Can infer the initial mass function from the luminosity function and the evolution of stars.

2 common forms of the IMF:

- Salpeter (1955): \( \xi(M) = c \left( \frac{M}{M_\odot} \right)^{-2.35} \)
- Miller-Scalo (1979): \( \xi(M) = c_1 \left( \frac{M}{M_\odot} \right)^{-1.25} \quad 0.1 \text{ -- } 1 \ M_\odot \)
  \[ = c_2 \left( \frac{M}{M_\odot} \right)^{-2} \quad 1 \text{ -- } 2 \ M_\odot \]
  \[ = c_3 \left( \frac{M}{M_\odot} \right)^{-2.3} \quad 2 \text{ -- } 10 \ M_\odot \]
  \[ = c_4 \left( \frac{M}{M_\odot} \right)^{-3.3} \quad 10 \text{ -- } 125 \ M_\odot \]

Most stars are low mass and long lived.
Evolution off Main Sequence

- Zero-age main sequence
- Termination of core hydrogen fusion

Luminosity ($L_\odot$)

Temperature (K)

- 9 $M_\odot$
- 5 $M_\odot$
- 3 $M_\odot$
- 2 $M_\odot$
- 1 $M_\odot$

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HR Diagrams for Star Clusters
Evolution off Main Sequence

• Hydrogen burning eventually depletes inner core.
• For lower main sequence – the hydrogen burning shell begins to move into a region of declining density; shell surrounds a Helium core, which grows outward, in mass, through the star.
• However, He core must be supported against its own gravity, as well as support weight of remaining star.
• But, the energy sources are all outside!
  – Impossible to establish a temperature gradient within core. Only gravitational contraction can produce energy within core \(\rightarrow\) results in slow contraction of helium core (and also slow increase in stellar luminosity due to temperature rise).
As the isothermal core grows (through addition of He from the H-burning shell), the core temperature rises in order for the core to remain in equilibrium and support the outer layers of the star. → limit to the amount of material an isothermal core can support.

Chandrasekhar – Schönberg (C-S) limit:

$$q_{C-S} = 0.37 \left( \frac{\mu_o}{\mu_i} \right)^2$$  
where $\mu$ = mean molecular weight.

And

$$q_{C-S} = \frac{M_c}{M}$$

→ Isothermal core can support ~ 37% of the mass; if the core is primarily He, this limit is reduced to ~ 10%.

In terms of physical size, the isothermal degenerate core is very small (a few earth radii).
• As H-burning continues, an equilibrium is established that results in a higher shell temperature, higher luminosity, and temperature gradient.

→ star moves upward and to the right in H-R diagram.

• Eventually, outer envelope becomes convective; Hayashi tracks are once again relevant.
Decline in available H supply leads to a steady increase in the shell temperature and a rise in luminosity. Star expands rapidly to accommodate energy flow

→ Red Giant

![Graph showing L vs temp with RG indicating Red Giant phase]
Helium Flash

- Temp. of core eventually reaches $10^8$ K, the ignition temp of He via triple $\alpha$ process.
- Since core is degenerate, the electron pressure is only weakly dependent on temperature.
  - Rather than expanding and decreasing rate of triple $\alpha$, high temperature increases rate of triple $\alpha \rightarrow$ thermal runaway
  - Runaway limited by removing degeneracy from the core; at sufficiently high T, the equation of state will revert to ideal gas law.
  - The core expands rapidly, cools, and reaches equilibrium with He $\rightarrow$ C in center
  - Duration of flash $\sim$ few minutes.
Helium Burning = Horizontal Branch

- Star moves down the giant branch and onto horizontal branch. The helium burning core is surrounded by a hydrogen burning envelope.

Asymptotic Giant Branch (AGB)

- When He fuel exhausted in core, He burning continues in shell around it. Similar to the red giant phase, star now ascends the AGB.
Thermal Pulses

- Helium burning is very T dependent. As T increases, pressure also increases, and the star expands. Expansion leads to T decrease and sharp drop in He burning. Star then contracts; expands; contracts; etc. Explosions occur every few thousand years.

Planetary Nebula Ejection

- After He burning, a hot core is left behind. The expelled material forms a PN. Core will eventually become a white dwarf.
Ring Nebula
• For higher mass stars, $M > 7 \, M_{\odot}$
  – He core is greater than C-S limit.
    $\rightarrow$ Core contraction
  – Helium burning while H burning in an envelope.
  – Large convective zone, which dredges material up from inner regions.
  – Star moves to the left, but maintains similar luminosity.
Mass Loss for high mass stars

- Stellar winds blow off the outer envelopes at rates of $10^{-7}$ to $10^{-6} \, M_\odot/yr$
  - can lose a few $M_\odot$ while on M-S

Outer layers are removed, leaving core and heavy elements exposed.