Handout 26
Stellar Evolution after the Main Sequence

- **Basic idea: As Hydrogen fuel is consumed, the star is no longer able to burn H at the center.**
  - » Recall,
    - T_{center} is the maximum T in the star
    - the energy generation rate ε is ~ T^4 for the p-p chain
  - » Therefore, to maintain **Thermal Equilibrium**
    - i.e. balance energy generation with Luminosity
- **The core of the star must contract**
  - » recall,
    - interior temperatures scale as M/R
      - hydrostatic equilibrium and the ideal gas EOS
- **Highly dense core produces so much energy that *Thermal Equilibrium* dictates envelope expansion**
  - » Recall, when luminosity was higher, stars followed nearly vertical **Hayashi tracks** on the H-R diagram

He burning -- AGB stars

- **Eventually, core contracts enough for He burning to occur**
  - » 3 ^{4}He ==> ^{12}C + energy requires 10^8 K to proceed
    - recall present sun, T_c about 0.16 10^8 K
- **Lot's of energy produced (much He at high densities and temperatures), very luminous, the *Asymptotic Giant Branch***
  - » $L \sim 10^4\ L_{sun}$, $T \sim 4000$ K, $R \sim 200\ R_{sun}$
- **Now, gravity is low enough and radiation pressure high enough at the surface to eject material from the star!**
  - » significant mass loss occurs, up to 1/2 of the original star is ejected into interstellar space
    - dust formation crucial, opacity > 3,000 cm^2/gm
- **Because star is fully convective, this mass is enriched by the nuclear processed materials created earlier**
  - » radioactive Technetium, with a half-life of only 10^5 y, is seen in the atmospheres of Mira variables (AGB stars).

Planetary Nebulae and White Dwarfs

- **Eventually, whole H-rich envelope is ejected into outer space, exposing the He and CNO core**
  - » surface T ~ 180,000 K, R ~ 0.1 R_{sun} , L still ~ 10^4 L_{sun}
- **High T produces copious UV photons, which ionize the surrounding gas**
  - » The ionized, optically thin gas gives off **emission lines**
  - » this configuration is called a **Planetary Nebula**
    - named by Wm. Herschel because their blue-green color reminded him of Uranus
      - blue-green color from very strong [OIII] 500.7 nm line
- **Soon, all nuclear processing stops. The core now cools eternally. The star is a *White Dwarf***
  - » R ~ 0.01 R_{sun} , about the size of the Earth

Age dating of clusters

- **We can apply our knowledge of stellar evolution to use the H-R diagram of a cluster to estimate its age**
  - » All stars in a cluster born at the same time
  - » M.S. lifetime ~ $(M/M_{sun})^{-3}$
    - from $L \sim M^4$ along M.S.

Spectrum	M/M_{sun}	Lifetime(y)
G5	0.9	$13\ 10^9$
G2	1	$10\ 10^9$
A8	2	$1.2\ 10^9$
A0	3.6	$2\ 10^8$
B8	4.5	$1\ 10^8$
B0	17	$2\ 10^6$

  - » So if A0 stars are present, the age is $< 2\ 10^8$ y
  - » If a lot of A0 stars are present, but no B8 stars are present, the age is $> 10^8$ y
- **Precise position of M.S. cutoff implies the age of a cluster**

Cluster ages

- **Using Fig. 16-8, open (galactic) clusters**
  - » Pleiades < 2 10^8 y
    - A0 (B-V = 0) stars are present
  - » Praesepe ~ 9 10^8 y
    - A0 absent, A8 (B-V = +0.2) present
  - » M 67 ~ 5 10^9 y
    - G2 (B-V = +0.6) present, A8 absent
- **Globular clusters in the galactic halo are the oldest. The universe should be older than the oldest clusters. Looking at M3, and using the B-V color at the M.S. turnoff**
  - » B-V ~ 0.5 at turnoff, slightly redder than M 67. a bit older
    - This is over-simplified, because the Globular Clusters have much lower metal abundance's Z, and this must be taken into account in the stellar evolution.
  - » Oldest globular clusters ~ 12 -15 10^9 y old, constraint on age of universe.

Dead stars -- degeneracy

- **Degenerate core**
  - » Earlier, we said a 1 Msun star left behind a core of He which stopped contracting. Why? It should be able to continue contracting, raising the temperature, and keep on burning until everything is iron (the most tightly bound nucleus), maintaining thermal equilibrium all the while.
- ***Degeneracy pressure* prevents further contraction!**
  - » Our scaling law for interior temperatures $T_c \sim M/R$ implies arbitrarily high temperatures for arbitrarily small sizes. But degeneracy pressure takes over, supports the star, prevents further contraction, and limits the interior temperature
- **White dwarfs have a CNO core and about 0.6 solar masses**

White Dwarfs

- **The interior temperature is not hot enough for further nuclear reactions, therefore these stars will cool eternally.**
  - » The only energy supply is stored interior heat
    - energy supply $E = (3/2)NkT$, where N is the total number of nuclei
  - » no gravitational contraction can occur!
  - » They travel down the 0.01 solar radius track on the H-R diagram to lower and lower temperatures
    - Least luminous white dwarfs used to estimate age of disk of our galaxy
      - about 10 billion years old

White Dwarfs -- Neutron stars

- **If mass > 1.4 solar, electron degeneracy pressure is not big enough to hold back gravity**
  - » Further collapse ensues
  - » "inverse beta decay" occurs
    - p+ + e- ==> n + ν
    - proton + electron ==> neutron + neutrino
  - » neutrons are spin 1/2 Fermions, therefore they supply degeneracy pressure to stop the collapse
    - i.e. set $P_{degeneracy} = P_{hydrostatic\text{-}equilibrium}$
    - R ~ 10 km
      - » since the electron mass is 1800 times smaller, the radius is reduced by this factor compared to the white dwarf
    - density ~ nuclear matter density
  - » Solar mass in region the size of a city!

neutron stars -- black holes

- **There is a limiting mass of a neutron star, if this is exceeded, a black hole will result.**
  - » consider the escape velocity from the surface of a star
    - i.e. set total energy = KE + PE equal to zero
    - $-(GMm/R) + 1/2\ mv^2 = 0$, solve for v, the escape velocity
    - $v = (2GM/R)^{1/2}$.
    - set v = c, this is the maximum possible! Solve for R
    - $R = 2GM/c^2$, the Schwartzschild Radius
      - $R = 3$ km for $M = M_{Sun}$
  - » For a given density (i.e. nuclear density), the radius only increases as $M^{1/3}$, for increasing mass, eventually the Schwartzschild Radius will exceed the stars radius, and we have a black hole!
    - simple estimate indicates $M_{max} = 8\ M_{Sun}$
    - taking into account the compressibility of nuclear matter the limit is $3\ M_{Sun}$

consequences of degenerate stars

- **Both of the compressed, degenerate states (white dwarfs and neutron stars/black holes) are important for Galactic evolution**
  - » the White Dwarf forms in the center of a **Planetary Nebula**
    - the PN results from the red-giants wind, i.e. stars lose up to half their mass in the evolved phases
      - This material has been processed through nuclear fusion reactions in the interiors and contributes material highly enriched in the heavy elements (C, N, O, etc.)
      - The dust dominates the opacity (and metallicity) of the ISM
  - » The collapse to a neutron star or black hole is even more spectacular -- a **Supernova**!
    - Large amount of energy released. Enough to lift off the outer layers to infinity at 10,000 km/s.
    - the star is very dense and hot during the collapse
      - fusion can proceed clear up to the “Fe peak”
      - heaviest elements in the ISM comes from supernovae