Death of Stars

- **Goals:**
  - **Relation between the mass of a star and its death**
  - **White dwarfs and supernovae**
  - **Enrichment of the ISM**
- **Low Mass Stars (M<4M❤)**

Figure 22-1

  - **He Depletion**
    - **After the He burning starts the core of the star expands and cools while the shells continue to burn H.**
    - **The star as a whole contracts and the temperature increases (luminosity remains constant).**
    - **Stars move horizontally across the HR diagram (<u>horizontal branch stars</u>).**
    - **For a 1M❤ star He is depleted in 10^8yrs (core is not ^{12}C and ^{16}O).**
    - **Core contracts again (no energy production) until supported by <u>degenerate-electron pressure.</u>**

– Second Giant Phase

Figure 22-2

- **Contraction of the core (2nd time) heats outer shells causing shell He burning.**
- **Second red giant phase (outer layers expand and cool).**
- **Luminosity is greater than for red giants (x100).**
- **Asymptotic giant branch (AGB) - inert C, O core and HE and H burning shells.**
- **AGB star**
  - $R_{surface}$ ~ 1.5 AU
  - R_{core} ~ 6400 km.
  - T ~ 3000 K
  - Mass loss 10^{-4} $M_{\heartsuit}$ yr^{-1}

– Dredge-ups enrich the stars surface

- **Energy transport occurs through radiative diffusion and convection.**
- **In Red giants convection can be dominant process (only effects outer 30% of Sun).**
- **Convection currents "dredge-up" material (enriched with metals) from the core.**

– Dredge-ups

- First dredge-up after H depletion - C, N, O brought to stars surface.
- Second dredge-up after He depletion brings more C, O to surface.
- Third dredge-up possible in AGB phase (M> $2M_{\heartsuit}$) bringing C_2, CN, CH (Carbon star).

– Planetary Nebulae

Figure 22-6

- Shell burning depletes He in outer layers. reducing pressure support for outer H burning shells.
- These H shells contract → heat → re-ignite
- He generated by H burning fuels the inner He burning shells and they ignite.
- Repeated bursts of energy (thermal pulses) emanate through the star's interior.
- These pulses produce radiation pressure that pushes the outer layers of the star away.
- A $1M_{\heartsuit}$ star can lose 40% of its mass.
- End with an exposed hot (10^5 K) core emitting UV radiation that ionizes the ejected layers (a planetary nebulae).
- Ejected gas moves at 10-30 km s^{-1}.
- Gas cools and becomes part of the ISM.

– Cores of low mass stars

Figure 22-10

- For $M < 4M_{\heartsuit}$ the contracting C, O core does not have sufficient pressure or temperature to ignite.
- This relic is a white dwarf.
- The white dwarf supports its self not through the generation of energy but by the degenerate electron pressure.
- Pressure is independent of T so as the white dwarf cools the radius remains the same.
- Density of WD is 10^9 kg m^{-3} (10^6x water).
- As the mass of a WD increases the radius decreases (more compact).
- There comes a limit when the degenerate pressure cannot support the mass of a star: Chandrasekhar limit.
- Theoretical limit is 1.4 $M_{\heartsuit}$ (all WD have $M < 1.4M_{\heartsuit}$).
- As the WD cools its luminosity decreases and it move to the lower right on the HR diagram.

- **Degenerate Electron Pressure**
  - **Ideal gas**

$$P = \rho kT$$

    - Increase pressure → increase temperature
  - **Degenerate gas (non-relativistic)**
    - Density is so high that electrons don't behave like a gas - can exchange energy through collisions.
    - Finite number of energy level available Only 2 electrons per energy level.
    - Electrons take on a "crystalline form".
    - Pressure is independent of temperature

$$P \propto \rho^{1/3}$$

    - P:pressure
      ρ:density
    - <u>Hydrostatic Equilibrium</u> (gravity=pressure)

$$P \propto \frac{M^2}{R^4}$$

    - Substituting in the density

$$R \propto \frac{1}{M^{1/3}}$$

    - Mass increases → Pressure Decreases

- # High Mass Stars (>4 M❤)
  - ## Fusion of heavy elements
    - **Higher mass stars have a greater core pressure and temperature and can ignite heavier elements (more than He burning).**
    - **Core mass > 1.4 M❤ → overcomes degenerate pressure and Carbon ignites (T=6x10^{8} K).**
    - **Process continues with Ne (10^{9} K), O (1.5x10^{9} K), Si (2.7x10^{9} K) upto Fe.**
    - **Each of these core reactions is associated with shell burning of the lighter elements.**
    - **Onion rings of shell burning elements (Hydrogen through heaviest element).**
    - **Isotopes of elements (changes in numbers of neutrons) form due to bombardment by neutron capture.**
    - **To burn heavy elements requires progressively higher temperatures - nuclear reactions are more rapid (e.g. 25 M❤: Carbon 600 yrs, Neon 1 yr, Oxygen 6 months, Si 1 day).**

- **Supergiant phase**

Figure 22-13

- **H-Si burning (in 25$M_\odot$ star) generates vast amounts of energy. Outer layers of star expand rapidly.**
- **Enter a supergiant phase**
  $L = 10^5 L_\odot$
  T = 3000-25000 K
  R = 5 AU
- **Eventually gravity cant overcome the electromagnetic repulsion of atoms.**
- **Element burning stops at ^{56}Fe (Iron: 26 protons, 30 neutrons). Results in an inert Fe core.**
- **Generation of thermonuclear energy ceases within the stars core.**
- **Shell burning continues in a region 6000 km in radius.**

- **Supernovae ($M>8M_\odot$)**
  - **Rapidly core collapse**
    - **Gravity compresses the stars core and it collapses rapidly**
    - **Temperature within the core reaches 5×10^9 K (in 0.1 secs).**
    - **Gamma-rays are emitted that <u>photodisintegrate</u> the Fe core.**
    - **Density increases and the electrons and protons combine to form neutrons**

$$e^- + p \rightarrow n + \nu$$

    - **e^-:electrons**
      p:protons
      n:neutrons
      ν:neutrino
    - **neutrinos carry off energy and the core cools and collapses further.**
    - **After 0.25s the core is 20 km in diameter and has a density of 4×10^{17} kg m^{-3} (<u>nuclear density</u>). A neutron rich core.**
    - **The neutrons cannot be compressed further and the contraction halts (causing a bounce → core expands).**

– Supernova explosion

Figure 22-20

- Prior to bounce regions surrounding the core are contracting at 15% speed of light.
- When core bounces it creates shock wave that impacts inward moving material.
- Material is accelerated outwards to speeds > speed of sound (releasing 10^{46} J - 100x total energy from Sun). Star blown apart.
- The shock wave compresses outer material creating last generation of fusion. Outer layers bombarded by neutrons.
- Elements build up neutrons. These decay into protons $\rightarrow$ all heavier elements in the Universe.

$$n \rightarrow p + e^- + \nu$$
$$^{56}Fe + n \rightarrow {}^{57}Fe \text{ ..... etc}$$
$$^{61}Fe \rightarrow {}^{61}Co + e^- + \nu$$

- Metal rich gas is dumped into the ISM.
- Supernovae occur about 1 per galaxy per 100 years. A supernovae can be the brightness of a galaxy (easy to detect).

- **Energy from a Supernova**
  - **Energy from gravity**
    - **Collapse a star down to a core radius of R=15 km.**

$$E_{grav} \approx \frac{GM^2}{R}$$

- **E_{grav}:gravitational energy from collapse**
  R: radius of core (15 km)
  M: mass of star ($1M_\odot$)

$$E_{grav} = \frac{6.67x10^{-11} \text{ x } (1.99x10^{30})^2}{1.5x10^4}$$
$$= 1.8x10^{46}$$

- **Gravity provides sufficient energy to power a supernova explosion.**

Types of Supernovae

Figure 22-21

- Type I
  - Little or no Hydrogen lines (Hydrogen in core and shells depleted).
  - Further types Type Ia (strong ionized Si absorption), Ib (strong He absorption no Si) and Ic (no He and no ionized Si absorption).
  - Type Ib and Ic are from massive stars which have their outer envelopes stripped prior to exploding.
  - Type Ia are from white dwarfs that accrete mass from a red giant companion. Mass increases the temperature (run away process as the WD is degenerate). WD blows itself apart.
  - Rapid brightening and the gradual decline in light curve.
- Type II
  - Prominent Hydrogen lines.
  - Standard supergiant collapse and explosion.
  - SN 1987a was a Type II supernova.
  - Step-like light curve.