

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 ($M < 4M_{\odot}$)**

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 (horizontal branch stars).
 - For a $1M_{\odot}$ star He is depleted in 10^8 yrs (core is not ^{12}C and ^{16}O).
 - Core contracts again (no energy production) until supported by degenerate-electron pressure.

– 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
 - $R_{\text{surface}} \sim 1.5 \text{ AU}$
 - $R_{\text{core}} \sim 6400 \text{ km.}$
 - $T \sim 3000 \text{ K}$
 - Mass loss $10^{-4} M_{\odot} \text{ yr}^{-1}$

– 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 ($M > 2M_{\odot}$) 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 \rightarrow heat \rightarrow 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 $1M_{\odot}$ 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 $10\text{-}30 \text{ km s}^{-1}$.
- Gas cools and becomes part of the ISM.

– Cores of low mass stars

Figure 22-10

- For $M < 4M_{\odot}$ 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} ($10^6 \times$ 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 $1.4 M_{\odot}$ (all WD have $M < 1.4M_{\odot}$).
- 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
- Hydrostatic Equilibrium (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 ($>4 M_{\odot}$)**

- **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 $> 1.4 M_{\odot} \rightarrow$ overcomes degenerate pressure and Carbon ignites ($T=6 \times 10^8$ K).
 - Process continues with Ne (10^9 K), O (1.5×10^9 K), Si (2.7×10^9 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. $25 M_{\odot}$: Carbon 600 yrs, Neon 1 yr, Oxygen 6 months, Si 1 day).

– Supergiant phase

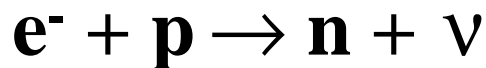
Figure 22-13

- H-Si burning (in $25M_{\odot}$ star) generates vast amounts of energy. Outer layers of star expand rapidly.
- Enter a supergiant phase
 - $L = 10^5 L_{\odot}$
 - $T = 3000\text{-}25000 \text{ K}$
 - $R = 5 \text{ AU}$
- 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 photodisintegrate the Fe core.
 - Density increases and the electrons and protons combine to form neutrons

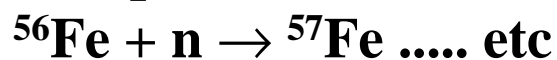
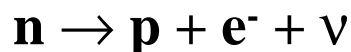


- e^- :electrons
p:protons
n:neutrons
 ν :neutrino
 - neutrinos carry off energy and the core cools and collapses further.
 - After 0.25s the core is 20 km in diameter and has a density of 4×10^{17} kg m⁻³ (nuclear density). A neutron rich core.
 - The neutrons cannot be compressed further and the contraction 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 → all heavier elements in the Universe.



- 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.

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

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

$$\begin{aligned} E_{\text{grav}} &= \frac{6.67 \times 10^{-11} \times (1.99 \times 10^{30})^2}{1.5 \times 10^4} \\ &= 1.8 \times 10^{46} \end{aligned}$$

- 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.