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 (horizontal branch stars).
    – For a 1M☉ star He is depleted in 10^8 yrs (core is not ^12C and ^16O).
    – 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.
Death of Stars
– **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 during AGB phase (M > 2M☉) bringing C₂, CN, CH (Carbon star).

– **Planetary Nebulae**

  **Figure 22-6**
  • Shell burning depletes He in outer layers. This reduces the pressure support for the 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☉ star can lose 40% of its mass.
  • End with an exposed hot (10⁵ 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.
Expanding shell of ejected material

Star
Death of Stars

Survey of Astrophysics A110
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 itself 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$^{-3}$ ($10^6$ x 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 $1.4M_\odot$ (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.
Death of Stars

- **Degenerate Electron Pressure**
  - **Ideal gas**
    - Increase pressure $\rightarrow$ increase temperature
    \[ P = \rho kT \]
  - **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
    - \( \delta V \propto 1/\delta x \propto \rho^{1/3} \)
    - \( P \propto \rho \delta V^2 \propto \rho^{5/3} \)

- **Hydrostatic Equilibrium** (gravity=pressure)
  \[ P \propto \frac{M^2}{R^4} \]

- Substituting in the density
  \[ R \propto \frac{1}{M^{1/3}} \]

- Mass increases $\rightarrow$ Radius 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 (10⁹ K), O (1.5x10⁹ K), Si (2.7x10⁹ 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).
### Table 22-1: Evolutionary Stages of a 25-M$_\odot$ Star

<table>
<thead>
<tr>
<th>Stage</th>
<th>Core temperature (K)</th>
<th>Core density (kg/m$^3$)</th>
<th>Duration of stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen burning</td>
<td>$4 \times 10^7$</td>
<td>$5 \times 10^3$</td>
<td>$7 \times 10^6$ years</td>
</tr>
<tr>
<td>Helium burning</td>
<td>$2 \times 10^8$</td>
<td>$7 \times 10^5$</td>
<td>$7 \times 10^5$ years</td>
</tr>
<tr>
<td>Carbon burning</td>
<td>$6 \times 10^8$</td>
<td>$2 \times 10^8$</td>
<td>600 years</td>
</tr>
<tr>
<td>Neon burning</td>
<td>$1.2 \times 10^9$</td>
<td>$4 \times 10^9$</td>
<td>1 year</td>
</tr>
<tr>
<td>Oxygen burning</td>
<td>$1.5 \times 10^9$</td>
<td>$10^{10}$</td>
<td>6 months</td>
</tr>
<tr>
<td>Silicon burning</td>
<td>$2.7 \times 10^9$</td>
<td>$3 \times 10^{10}$</td>
<td>1 day</td>
</tr>
<tr>
<td>Core collapse</td>
<td>$5.4 \times 10^9$</td>
<td>$3 \times 10^{12}$</td>
<td>¼ second</td>
</tr>
<tr>
<td>Core bounce</td>
<td>$2.3 \times 10^{10}$</td>
<td>$4 \times 10^{15}$</td>
<td>milliseconds</td>
</tr>
<tr>
<td>Explosive (supernova)</td>
<td>about $10^9$</td>
<td>varies</td>
<td>10 seconds</td>
</tr>
</tbody>
</table>
– **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
  - $L = 10^5 \ L_\odot$
  - $T = 3000$-$25000$ 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_☉)**
  
  – **Rapid core collapse**
  
  • Gravity compresses the stars core and it collapses rapidly
  • Temperature within the core reaches 5x10⁹ 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

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

  • **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 4x10¹⁷ kg m⁻³ (**nuclear density**). A neutron rich core.
  • The neutrons cannot be compressed further and the contraction halts (causing a bounce core expands).
Outer ring
at edge of
swept-up gas
from earlier
mass loss.

Inner ring
of swept-up red-
supergiant gas.

Supernova
remnant.
A dark, invisible
outer portion
surrounds the
brighter inner
region lit by
radioactive
decay.
– **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.
  
  \[ n \rightarrow p + e^- + \nu \]
  
  \[ ^{56}\text{Fe} + n \rightarrow ^{57}\text{Fe} \ldots \text{etc} \]
  
  \[ ^{61}\text{Fe} \rightarrow ^{61}\text{Co} + e^- + \nu \]
- 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 $R=15 \text{ km}$.

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

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

  $$E_{\text{grav}} = \frac{6.67 \times 10^{-11} \times (1.99 \times 10^{30})^2}{1.5 \times 10^4}$$

  $$= 1.8 \times 10^{46}$$

  • 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
Death of Stars

Survey of Astrophysics A110

![Graph showing relative intensity vs. time for SN 1987N (Type Ia) and a diagram of a red giant turning into a white dwarf and exploding as a Type Ia supernova.](Image)
Death of Stars

Survey of Astrophysics A110

![Graph showing relative intensity with peaks labeled He I and SN 1984L (Type Ib).](Image)

Supergiant star with outer hydrogen removed → Core collapse, explosion.
Death of Stars

Survey of Astrophysics A110

Supergiant star with outer hydrogen, helium removed → Core collapse, explosion.

SN 1987M (Type Ic)

Relative intensity
Death of Stars

Survey of Astrophysics A110

d

Supergiant star with outer layers largely intact

Core collapse, explosion

SN 1992H (Type II)
Death of Stars

Survey of Astrophysics A110