Nuclear fusion and stars

Physics HL Presentation

Eric, Jerrie, Louis and Tom

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Creation of Light Elements

Proton–Proton (p–p) Chain

- Proton-Proton (p–p) chain is the most dominant reaction in the **low mass main sequence stars** like the sun.
- Reactions:

$$
\begin{aligned}
{}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{1}e^{+} + {}^{0}_{0}\nu_e \\
{}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} &\rightarrow {}^{3}_{2}\mathrm{He} + \gamma \\
{}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} &\rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H}
\end{aligned}
$$

- Net reaction (p–p chain):

$$
4 \times {}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{0}_{1}e^{+} + 2 \times {}^{0}_{0}\nu_e + \gamma
$$

Creation of Light Elements

CNO Cycle

- Dominates in **more massive stars** since greater Columb barrier is overcame.
- Reactions:

$$
\begin{aligned}
{}^{12}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{13}_{7}\mathrm{N} + \gamma \\
{}^{13}_{7}\mathrm{N} &\rightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{1}e^{+} + \nu_e \\
{}^{13}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{14}_{7}\mathrm{N} + \gamma \\
{}^{14}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{15}_{8}\mathrm{O} + \gamma \\
{}^{15}_{8}\mathrm{O} &\rightarrow {}^{15}_{7}\mathrm{N} + {}^{0}_{1}e^{+} + \nu_e \\
{}^{15}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He}
\end{aligned}
$$

- Net reaction (CNO cycle):

$$4 \times {}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2e^{+} + 2{}^{0}_{0}\nu_e + \gamma$$

Creation of Light Elements

Triple alpha process

- Occurs **after the main-sequence phase** ($T \sim 10^8\,\mathrm{K}$, $M > 0.5M_\odot$).
- $0.8M_\odot < M < 2.2M_\odot$:helium flash; $M > 2.2M_\odot$:smooth start.
- Reactions:

$$^4_2\mathrm{He} + ^4_2\mathrm{He} \rightleftharpoons ^8_4\mathrm{Be}$$
$$^8_4\mathrm{Be} + ^4_2\mathrm{He} \rightarrow ^{12}_6\mathrm{C} + \gamma$$

High mass stars

- After helium burning, temperatures become high enough for successive fusion stages:
- Carbon burning: $^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow ^{20}\mathrm{Ne}, ^{23}\mathrm{Na}, ^{24}\mathrm{Mg}, \ldots$
- Oxygen burning: $^{16}\mathrm{O} + ^{16}\mathrm{O} \rightarrow ^{28}\mathrm{Si}, ^{31}\mathrm{P}, \ldots$

"Life choices" of stars

The Chanderasekhar Limit

- Electron-degenerate matter is present in white dwarfs.
- The Chandrasekhar limit: $1.4\,M_\odot$.
- The largest mass a white dwarf star can have.

The Oppenheimer-Volkoff Limit

- Neutron-degenerate matter is present in neutron stars.
- The Oppenheimer-Volkoff limit: $3\,M_\odot$.
- The largest mass a neutron star can have.

Black holes

- Happens when the mass of the star remnant reaches the OV limit.
- Mainly depends on the initial mass of the star ($M > 20M_\odot$ makes it possible, usually $M > 40M_\odot$).

"Fate" of stars

Mass ($M_\odot$)	**Main Sequence**	**Giant Phase**	**After Giant**	**Remnant**
0.08–0.25	(pp chain)	—	—	He white dwarf
0.25–2.2	(pp chain)	Red giant (triple–alpha)	Planetary nebula	C white dwarf
2.2–8	($\rightarrow$ CNO)	Red giant / AGB (He, C)	Planetary nebula	C white dwarf
8–12	(CNO)	Supergiant (He, C, Ne)	Supernova	O/Ne/Mg WD
12–40	(CNO)	Supergiant (He, C, Ne)	Supernova	Neutron star
40–150	(CNO)	Supergiant (full fusion chain to Fe)	Core-collapse supernova	Black hole

Ending

"We are not figuratively, but literally stardust."

— Neil deGrasse Tyson.

Each atom in our body, everything we see around us, originated from a magnificant dying of a main sequence star. The star shined for millions of years before its final certain call, and the interstellar dust traveled light years before forming the world in which we live.