Neutrinos & Origin of Elements

PHY 8850

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Agenda

1. Burning in Stars

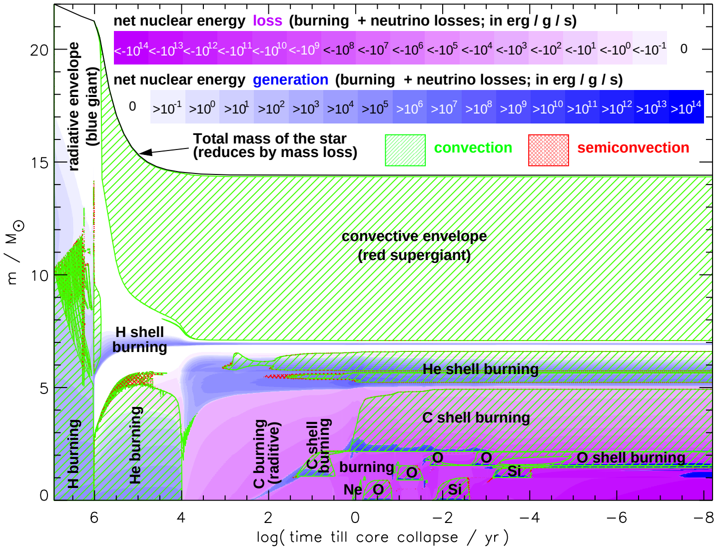
Overview

Burning Phases in Stars

$20\,M_\odot$ star

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,\mathrm{H} \xrightarrow{\mathrm{CNO}} {}^{4}\mathrm{He}$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,\mathrm{He}^4 \rightarrow {}^{12}\mathrm{C}$ $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$
C	Ne, Mg	Na	0.8	10^3	$^{12}\mathrm{C} + {}^{12}\mathrm{C}$
Ne	O, Mg	Al, P	1.5	3	$^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}$ $^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}\mathrm{O} + {}^{16}\mathrm{O}$
Si, S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}\mathrm{Si}(\gamma,\alpha)\ldots$

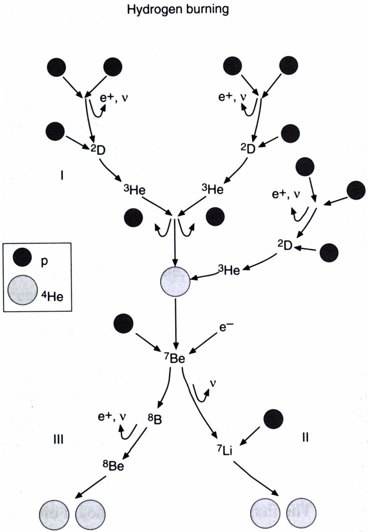
Burning Phases in the Stellar Interior

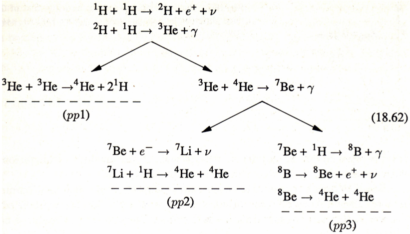


Hydrogen Burning - the two modes

- Two basic modes of hydrogen burning are distinguished
- The pp-chain in low-mass stars
- The Carbon-Nitrogen-Oxygen (CNO) cycle in high-mass stars

Hydrogen Burning - pp chains




$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu$

$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H$ (pp1)

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$ (18.62)

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$

$^{7}Li + {}^{1}H \rightarrow {}^{4}He + {}^{4}He$ (pp2)

$^{7}Be + {}^{1}H \rightarrow {}^{8}B + \gamma$

$^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$

$^{8}Be \rightarrow {}^{4}He + {}^{4}He$ (pp3)

Energy release:

$Q(pp1) = 26.20 MeV$

$Q(pp2) = 25.67 MeV$

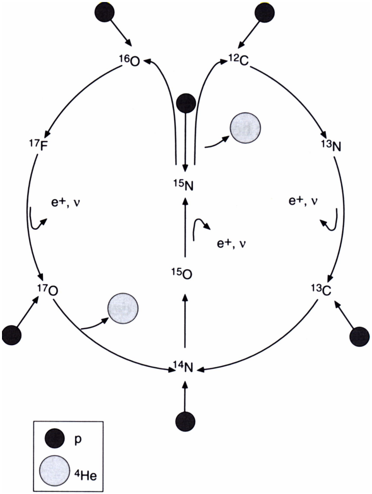
$Q(pp3) = 19.20 MeV$

Reaction rate: $\langle \sigma v \rangle \propto T^4$

Notes on pp hydrogen burning

- All four chains fuse 4 protons to one ^{4}He – and therefore have the same difference in mass excess. They have the same energy supply.
- Different Q-values (amount of energy release) due to different amounts of energy being *carried away by neutrinos*.
- With increasing temperature the dominant burning switches from pp1 to pp2 to pp3 chains.

Hydrogen Burning - CNO bi-cycle

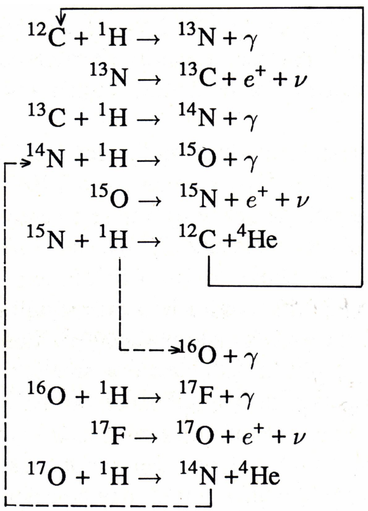


Energy release:
$Q(CNO) = 24.97 MeV$

Reaction rate: $\langle \sigma v \rangle \propto T^{16}$

Branching:
CNO-1 : CNO-2 $\sim$ 10,000 : 1

Hydrogen Burning - CNO bi-cycle



$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{1}\mathrm{H} &\rightarrow {}^{13}\mathrm{N} + \gamma \\
{}^{13}\mathrm{N} &\rightarrow {}^{13}\mathrm{C} + e^{+} + \nu \\
{}^{13}\mathrm{C} + {}^{1}\mathrm{H} &\rightarrow {}^{14}\mathrm{N} + \gamma \\
{}^{14}\mathrm{N} + {}^{1}\mathrm{H} &\rightarrow {}^{15}\mathrm{O} + \gamma \\
{}^{15}\mathrm{O} &\rightarrow {}^{15}\mathrm{N} + e^{+} + \nu \\
{}^{15}\mathrm{N} + {}^{1}\mathrm{H} &\rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He} \\
&\dashrightarrow {}^{16}\mathrm{O} + \gamma \\
{}^{16}\mathrm{O} + {}^{1}\mathrm{H} &\rightarrow {}^{17}\mathrm{F} + \gamma \\
{}^{17}\mathrm{F} &\rightarrow {}^{17}\mathrm{O} + e^{+} + \nu \\
{}^{17}\mathrm{O} + {}^{1}\mathrm{H} &\rightarrow {}^{14}\mathrm{N} + {}^{4}\mathrm{He}
\end{aligned}
$$

Energy release:
$Q(CNO) = 24.97 MeV$

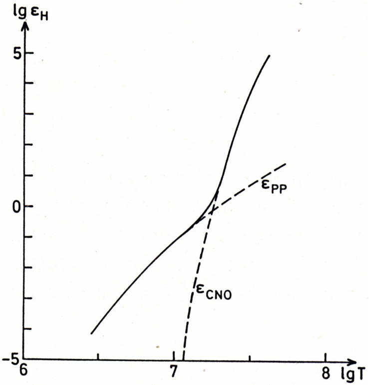
Reaction rate: $\langle \sigma v \rangle \propto T^{16}$

Branching:
CNO-1 : CNO-2 $\sim$ 10,000 : 1

Hydrogen Burning - CNO bi-cycle

- Usually the beta-decays are fast compared to the capture reactions, (p,γ).
- ^{14}O: $\tau_{1/2} = 70$ sec
  ^{15}O: $\tau_{1/2} = 122$ sec
  ^{13}N: $\tau_{1/2} = 10\,$min
  ^{17}F: $\tau_{1/2} = 64$ sec
  ^{18}O: $\tau_{1/2} = 110\,$min
- ^{14}N(p,γ)^{15}O usually is the slowest "bottleneck" reaction.
- CNO cycle burning converts most CNO isotopes into ^{14}N.

Competition of Hydrogen-Burning Modes



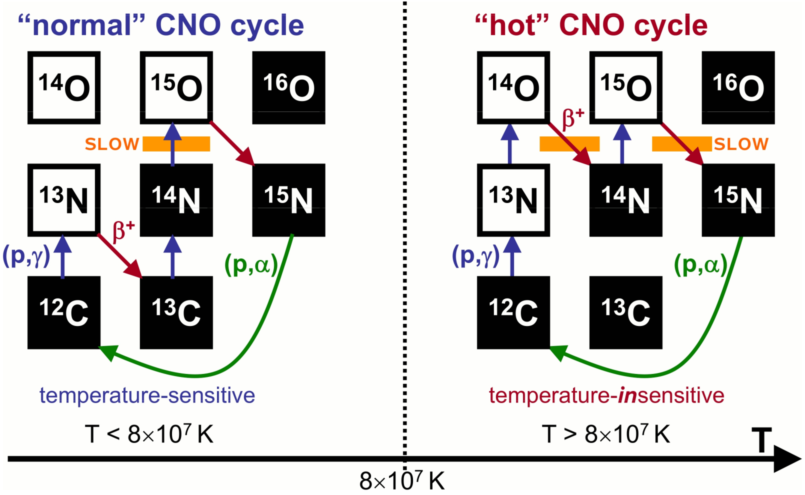
Transition from pp-chains
in low-mass stars (low *T*)
to CNO chains
in high-mass stars (high *T*)

Was that all of hydrogen burning...?

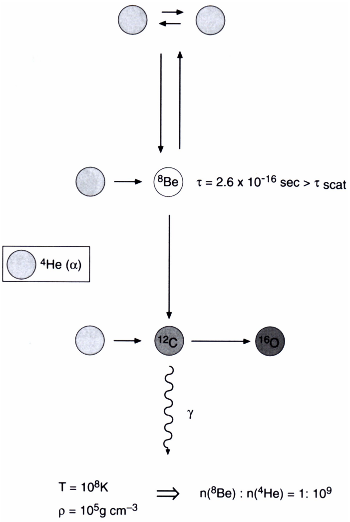
Future questions on hydrogen burning

- What happens at the first stars?
  (no initial CNO)
- What happens at high temperatures?

Normal and Hot CNO Cycles



The Triple-α Reaction



Step 1:

$^4\mathrm{He} + {}^4\mathrm{He} \rightleftharpoons {}^8\mathrm{Be}$

Built up equilibrium abundance of ^{8}Be

Lifetime of ^{8}Be is only 2.6×10^{-16} s!

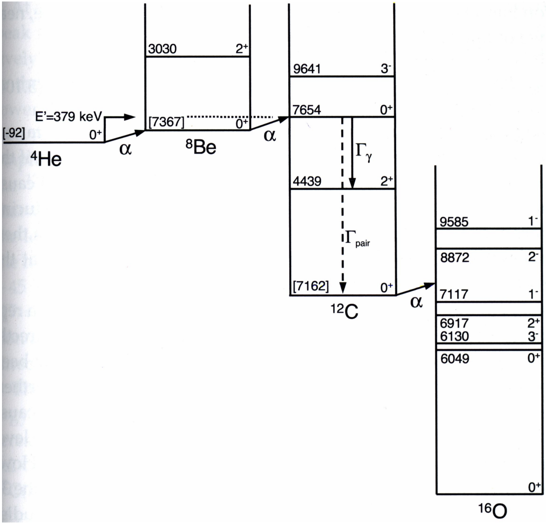
Step 2:

$^8\mathrm{Be} + {}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$

$$Q_{3\alpha} = 7.275\,\mathrm{MeV}$$

$$<\sigma v> \propto \rho^2 T^{40}$$

Helium Burning level scheme



Additional Reactions of Helium Burning

Oxygen Production

$^{4}\text{He} + {}^{12}\text{C} \rightarrow {}^{16}\text{O} + \gamma$

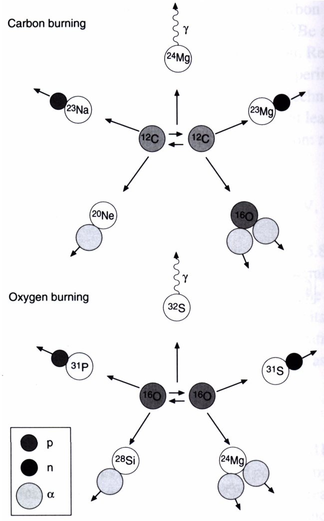
$Q = 7.162\,\text{MeV}$

$\langle \sigma v \rangle \ \propto \rho T^{40}$

The final abundance of carbon is set by the competition of 3α and $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reactions;

The production of ^{16}O can only start when a sufficient amount of ^{12}C has been made.

Carbon and Oxygen Burning



Carbon Burning

$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{12}\mathrm{C} &\rightarrow {}^{24}\mathrm{Mg} + \gamma \quad , & 13.931 \\
&\rightarrow {}^{23}\mathrm{Mg} + n \quad , & -2.605 \\
&\rightarrow {}^{23}\mathrm{Na} + p \quad , & 2.238 \\
&\rightarrow {}^{20}\mathrm{Ne} + \alpha \quad , & 4.616 \\
&\rightarrow {}^{16}\mathrm{O} + 2\alpha \quad , & -0.114
\end{aligned}
$$

Average $Q = 13\,\mathrm{MeV}$

Oxygen Burning

$$
\begin{aligned}
{}^{16}\mathrm{O} + {}^{16}\mathrm{O} &\rightarrow {}^{32}\mathrm{S} + \gamma \quad , & 16.541 \\
&\rightarrow {}^{31}\mathrm{P} + p \quad , & 7.677 \\
&\rightarrow {}^{31}\mathrm{S} + n \quad , & 1.453 \\
&\rightarrow {}^{28}\mathrm{Si} + \alpha \quad , & 9.593 \\
&\rightarrow {}^{24}\mathrm{Mg} + 2\alpha \quad , & -0.393
\end{aligned}
$$

Average $Q = 16\,\mathrm{MeV}$

Neon Burning

Neon burning proceeds by a combination of photo-disintegrations and α captures:

$$^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{4}\mathrm{He}\ , \qquad Q = -4.73\,\mathrm{MeV}$$

This reaction dominates over the inverse reaction known from helium burning for $T > 1.5 \times 10^{9}\,\mathrm{K}$.

Subsequently, the ^{4}He is captured on another ^{20}Ne nucleus:

$$^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{24}\mathrm{Mg} + \gamma.$$

The net result is

$$2\,{}^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{24}\mathrm{Mg} + \gamma\ , \qquad Q = +4.583\,\mathrm{MeV}$$

"Silicon" Burning

Actually, often we have more sulfur in the star than there is silicon, but it is custom to call this phase "silicon burning".

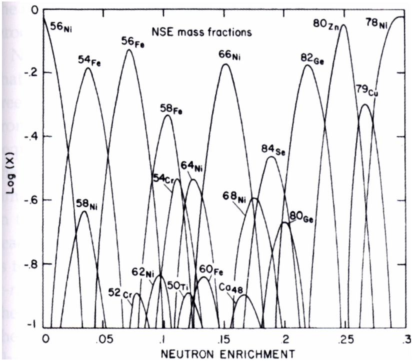
Typical burning temperature is $3 \ldots 3.5 \times 10^9$ K.

Similar to neon burning, silicon burning proceeds as a series of photo-disintegration reactions, mostly, (γ, α), and helium capture reactions, (α, γ) to build up iron group elements.

$$(\gamma, \alpha) \rightleftharpoons (\alpha, \gamma)$$

At the high T and ρ of these conditions, also *weak reactions* occur, converting protons into neutrons and leading to a *neutron excess*. This allows to actually make stable iron isotopes.

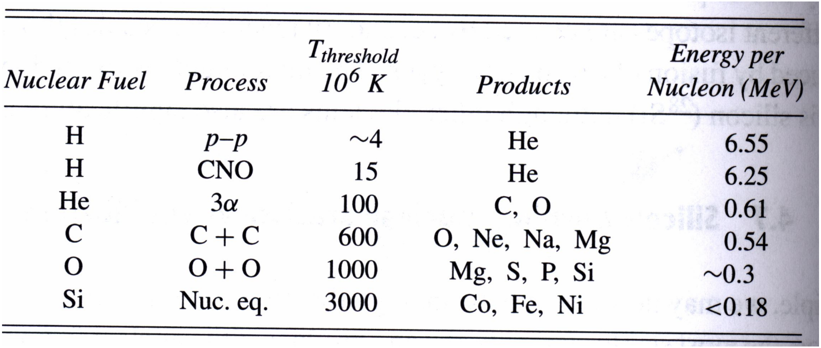
Beyond Silicon/Sulfur Burning



NSE distribution for
$T = 3.5 \times 10^9\,\mathrm{K}$,
$\rho = 10^7\,\mathrm{g/cm^3}$

After silicon burning T and ρ is so high that the nuclei are in **nuclear statistical equilibrium**, i.e., the reactions are fast compared to the evolution time-scale of the star, and the abundance distribution of the nuclei is given by a *Saha equation*.

Summary of Energetics



Nuclear Fuel	*Process*	$T_{threshold}$ 10^6 K	*Products*	*Energy per Nucleon (MeV)*
H	p–p	~4	He	6.55
H	CNO	15	He	6.25
He	3α	100	C, O	0.61
C	C + C	600	O, Ne, Na, Mg	0.54
O	O + O	1000	Mg, S, P, Si	~0.3
Si	Nuc. eq.	3000	Co, Fe, Ni	<0.18