Astrophysics I: Stars and Stellar Evolution

AST 4001

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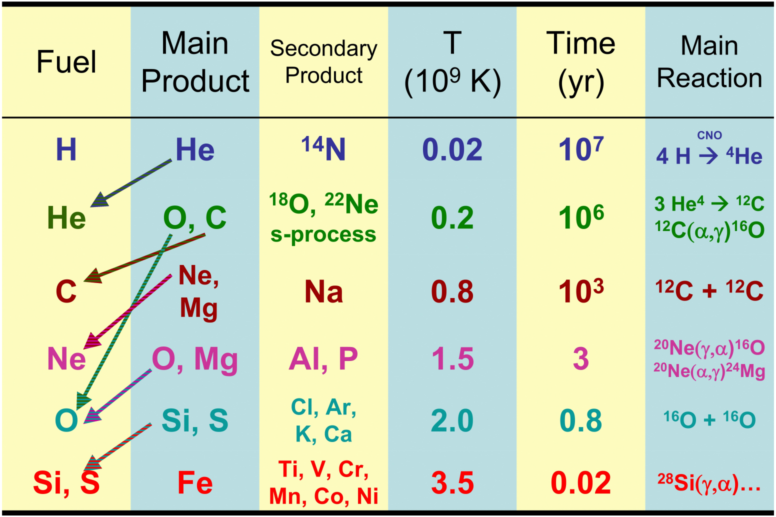
Stars and Stellar Evolution, Fall 2008

Overview

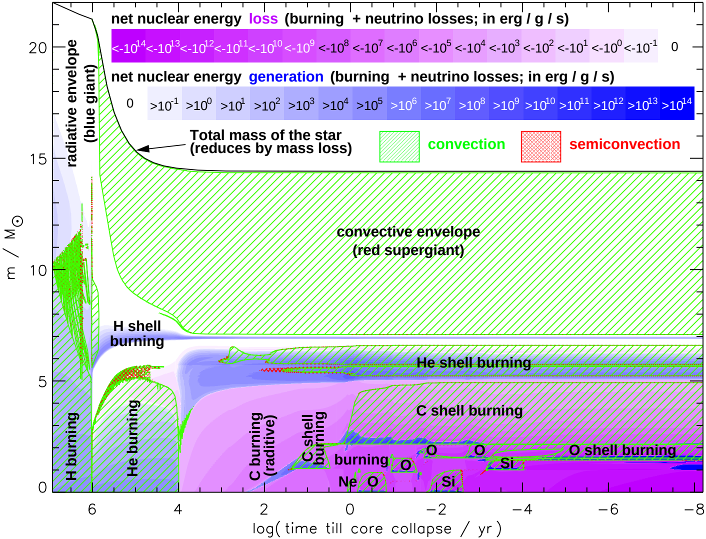
Overview - Burning Phases in Stars

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**	**$4\,H \xrightarrow{CNO} {}^4He$**
He	**O, C**	**^{18}O, ^{22}Ne** **s-process**	**0.2**	**10^6**	**$3\,He^4 \rightarrow {}^{12}C$** **$^{12}C(\alpha,\gamma)^{16}O$**
C	**Ne, Mg**	**Na**	**0.8**	**10^3**	**$^{12}C + {}^{12}C$**
Ne	**O, Mg**	**Al, P**	**1.5**	**3**	**$^{20}Ne(\gamma,\alpha)^{16}O$** **$^{20}Ne(\alpha,\gamma)^{24}Mg$**
O	**Si, S**	**Cl, Ar, K, Ca**	**2.0**	**0.8**	**$^{16}O + {}^{16}O$**
Si, S	**Fe**	**Ti, V, Cr, Mn, Co, Ni**	**3.5**	**0.02**	**$^{28}Si(\gamma,\alpha)$...**

Overview - Burning Phases in the Stellar Interior



Stellar Structure Equations - Nuclear Burning

stationary terms time-dependent terms

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho} \tag{1}$$

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} - \frac{1}{4\pi r^2}\frac{\partial^2 r}{\partial t^2} \tag{2}$$

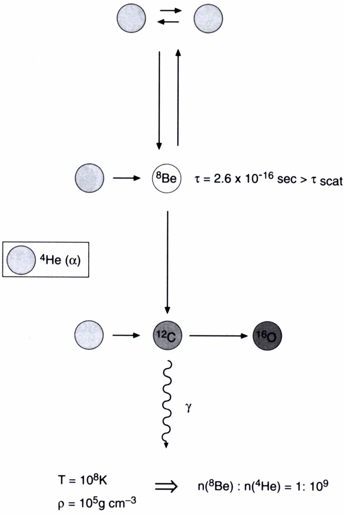
$$\frac{\partial F}{\partial m} = \varepsilon_{\mathrm{nuc}} - \varepsilon_{\nu} - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t} \tag{3}$$

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\nabla \left[1 + \frac{r^2}{Gm}\frac{\partial^2 r}{\partial t^2}\right] \tag{4}$$

$$\frac{\partial X_i}{\partial t} = f_i(\rho, T, \mathbf{X}) \tag{5}$$

where $\mathbf{X} = \{X_1, X_2, \ldots, X_i, \ldots\}$.

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!

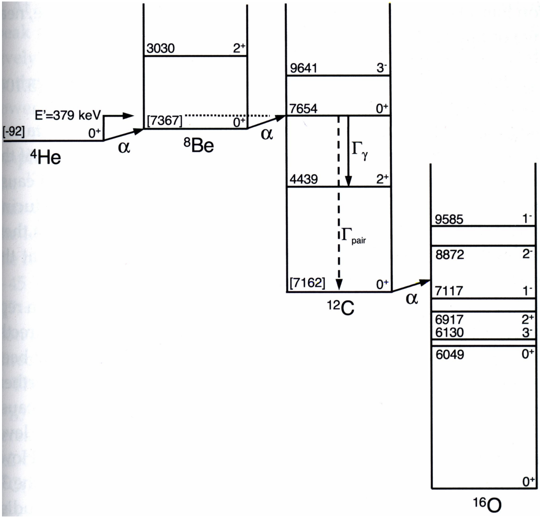
Step 2:

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

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

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

Helium Burning level scheme



Additional Reactions of Helium Burning

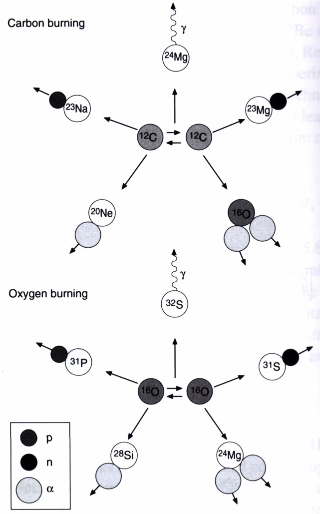
Oxygen Production

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

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

$\langle \sigma v \rangle \;\propto \rho T^{40}$
The final abundance of carbon is set by the competition of 3α and $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reactions;
The production of $^{16}\mathrm{O}$ can only start when a sufficient amount of $^{12}\mathrm{C}$ has been made.

Carbon and Oxygen Burning



Carbon Burning

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

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

Oxygen Burning

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

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

Neon Burning

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

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

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

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

“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”.

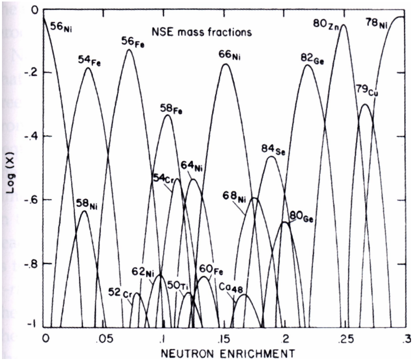
Typical burning temperature is $3 \ldots 3.5 \times 10^9$ K.

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.

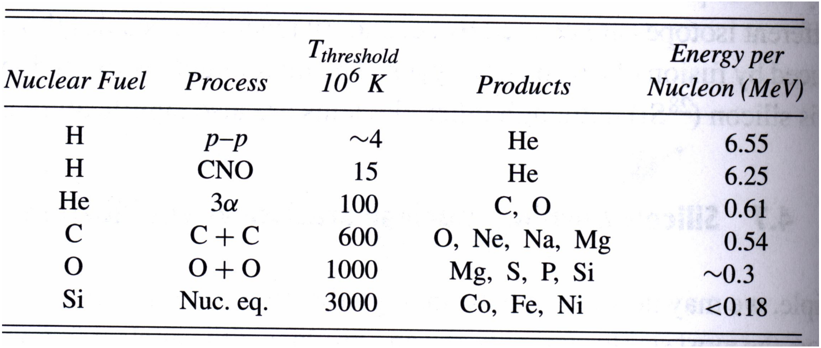
Beyond Silicon/Sulfur Burning



NSE distribution for $T = 3.5 \times 10^9$ K, $\rho = 10^7$ 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