ORIGIN OF THE ELEMENTS

Fundamental to understanding-the history & content of the solar system, galaxies, and the universe. It is also an important issue for this course.

What is the cosmic abundance of the elements?

Figure 1 - Relative abundances

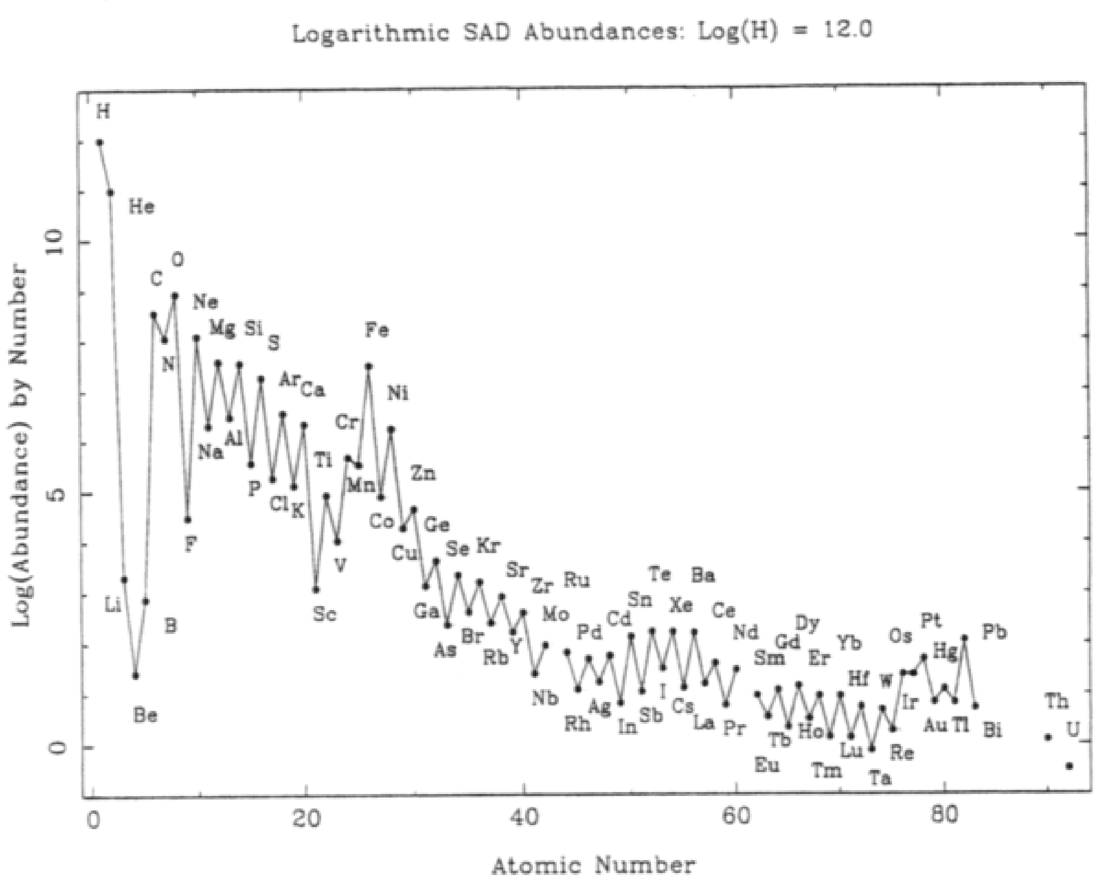


Figure 1.1. Elemental Abundances of the SAD. (Anders and Grevesse 1989.)

Figure 2- Shape of the abundance curve

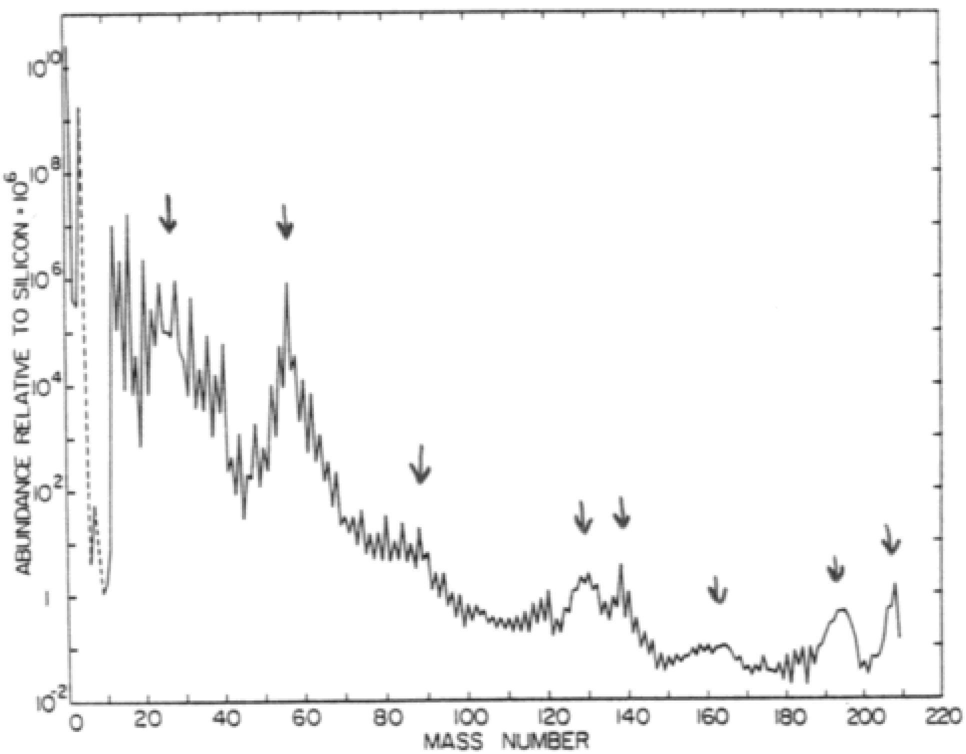


Figure 7.6. The SAD: Abundances vs. Mass Number (Cameron 1982, with permission).

Figure 3 - Abundances in Earth’ crust

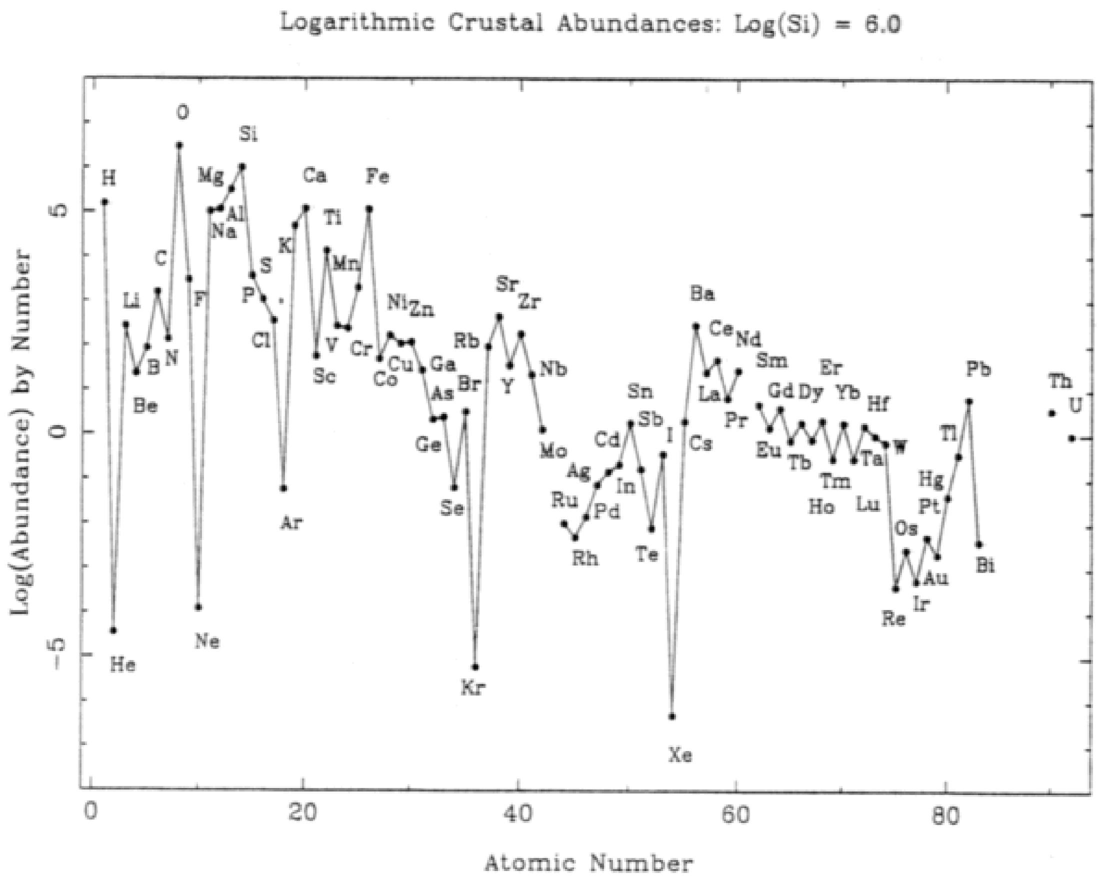


Figure 5.1. Abundances in the Earth’s Crust (Carmichael 1982). Logarithms are base 10.

How can we understand the observed relative abundances of the elements? Where did they come from and why are the light elements so much more abundant than the heavier elements? These are questions we were not even able to pose until the late 1940s and not able to make much progress on until our understanding of stellar structure and evolution and the big bang were understood, at least in broad outline.

Two possibilites:

1) The Big Bang, and/or
2) Stellar nucleosynthesis

The Big Bang: Origin of the Light Elements

Late 1940s- George Gamow and students Ralph Alpher and R. Herman postulated that the elements were created in the Big Bang during the period when the Universe was hot and dense enough to sustain nuclear reactions.

Predicted the CBR-- T~5 K!

Problem: atoms of mass 5 and 8 are unstable

This work was ignored for more than 15 years

i) Few scientists took the Big Bang theory seriously at that time.

ii) The mass 5 and 8 problem seemed fatal

iii) Recognition that stars can synthesize elements diverted attention from this.

Return to the Big Bang as a source of element production was motivated by:

i) Detection of the CBR in the early 1960s

ii) Realization that stars are net users of hydrogen, and deuterium, and they cannot produce nearly enough helium

iii) Improvements in our understanding of the the Big Bang by Robert Wagner, David Schramm, Steven Weinberg and others who had expertise in cosmology and high energy physics.

Figure 4 --BB element abundances

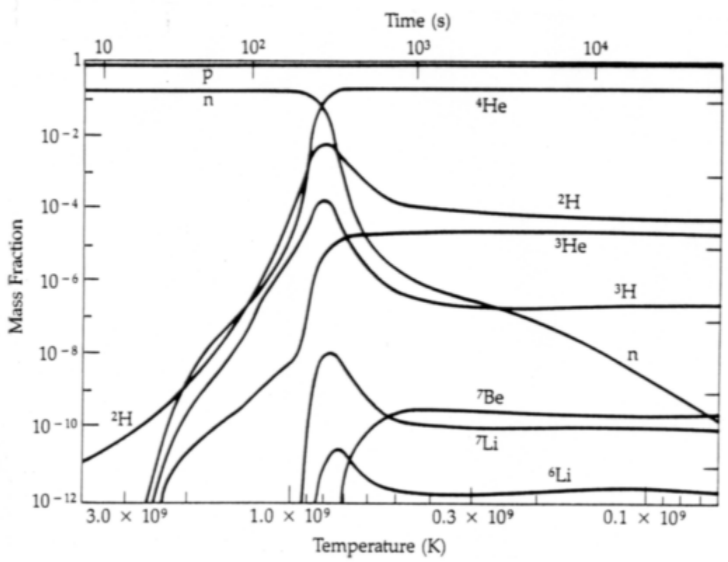


FIGURE 26–1 Nucleosynthesis in the Big Bang. The top axis gives the age of the Universe; the bottom gives temperature; the vertical axis is abundance in terms of the fraction of total mass. *(Adapted from a diagram by R. V. Wagoner)*

Conclusions:

1) H and D formed entirely in the BB--slowly decreasing due to stellar nucleosynthesis
2) He formed primarily in the BB with a small fraction added by stellar nucleosynthesis.
3) Li essentially all in the BB--slowly decreasing due to stellar nucleosynthesis
4) Be and B -- BB and stars
5) The relative abundances of H, D, Li, Be, and B in the Sun, other stars, and the interstellar medium appears entirely consistent with formation in the BB plus small modifications by stars.
6) Li, Be, and B have low cosmic abundances and are present only because they were produced in very small abundances in the BB.

Stellar Nucleosynthesis: Elements Heavier than Boron

The BB could not produce elements heavier than Boron because the Universe had too low a density to produce these elements by the time their progenitors were synthesized.

How do stars produce heavy elements? To address this question, we must first consider the possible energy sources available to stars.

Chemical and Gravitaional Energy

The issue here is how can stars produce the prodigious amounts of energy required to account for their luminosities for billions of years.

Chemical energy can keep the Sun radiating at most for a few thousand years even if it could convert all H->H_2.

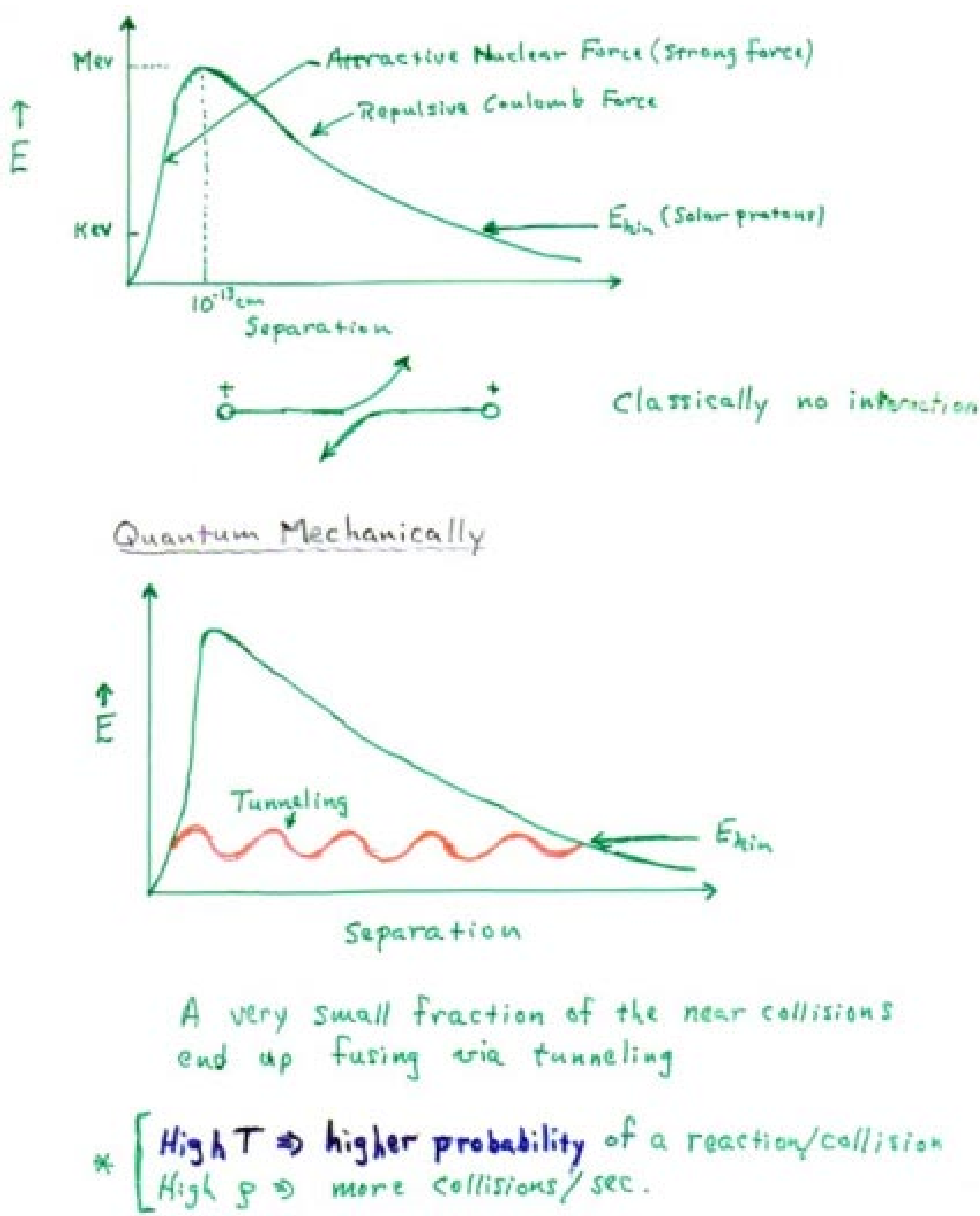
Gravitational energy can keep the Sun radiating at its present luminosity for at most 15 million years. Too short!

Nuclear Energy

Fission: Energy derived from the break-down of heavy unstable nuclei into lighter nuclei. Most of the heavy, energy rich nuclei such as Uranium, Plutonium, Thorium, etc. have long half-lives. In order to supply the required 2 erg/gm/s the Sun would have to be composed essentially entirely of Uranium, Thorium etc. and their decay products. However the mean density of the Sun is only about 1.4 gm/cm^3 (just a little more than that of water). The Sun cannot have even a small fraction of its mass composed of such heavy elements with this mean density. Fission cannot be a viable source of energy for stars!

Fusion: Synthesis of heavy elements from lighter ones.

Figure 5 --Fusion requires a miracle



Hydrogen Burning

Figure 6 --The P-P Chain

Low mass stars (M<2 solar masses)

Hydrogen Burning

I. Proton-Proton Chain

von Weisächer (1937)

Bethe + Critchfield (1938)

[$T \sim 10^7 - 2\times10^7 K$

$\tau \sim 10^{10} yr$

rate $\propto T^4$]

A.	$H^1 + H^1 \longrightarrow H^2 + e^+ + \nu$	1.44 Mev − 0.263 Mev
	$H^2 + H^1 \longrightarrow He^3 + \gamma$	5.49 Mev
	$He^3 + He^3 \longrightarrow He^4 + 2H^1$	12.859 Mev
B.	$He^3 + He^4 \rightarrow Be^7 + \gamma$	1.586 Mev
	$Be^7 + e^- \rightarrow Li^7 + \nu$	0.861 − 0.80 Mev
	$Li^7 + H^1 \rightarrow He^4 + He^4$	17.347 Mev
C	$Be^7 + H^1 \rightarrow B^8 + \gamma$	0.135 Mev
	$B^8 \rightarrow Be^8 + e^+ + \nu$	17.980 − 7.2 Mev
	$Be^8 \rightarrow He^4 + He^4$	0.095 Mev

Branches B+C require a significant amount of He^4 to be present

⇒ only important in old stars that have He^4-rich cores.

The proton chain dominates energy production in the Sun + lower mass stars.

Figure 7 --The CNO Cycle
Massive stars only (M>2 solar masses)

rate $\propto T^{18}$
$T > 2 \times 10^{7} K$

II. CNO Cycle

A. $C^{12} + H^{1} \rightarrow N^{13} + \gamma$

$N^{13} \rightarrow C^{13} + e^{+} + \nu$

$C^{13} + H^{1} \rightarrow N^{14} + \gamma$

$N^{14} + H^{1} \rightarrow O^{15} + \gamma$

$O^{15} \rightarrow N^{15} + e^{+} + \nu$

$N^{15} + H^{1} \rightarrow C^{12} + He^{4}$

$\sim 4 \times 10^{-4}$

B. $N^{15} + H^{1} \rightarrow O^{16} + \gamma$

$O^{16} + H^{1} \rightarrow F^{17} + \gamma$

$F^{17} \rightarrow O^{17} + e^{+} + \nu$

$O^{17} + H^{1} \rightarrow N^{14} + He^{4}$

von Weizäker (1938)
Bethe (1939

C, N, O have higher coulomb barriers than H, D, + He and therefore CNO only occurs in the cores of massive stars whose central temperatures are much higher than in low-mass stars.

Figure 8 -P-P and CNO rates versus temp.

410 PRINCIPLES OF STELLAR EVOLUTION AND NUCLEOSYNTHESIS

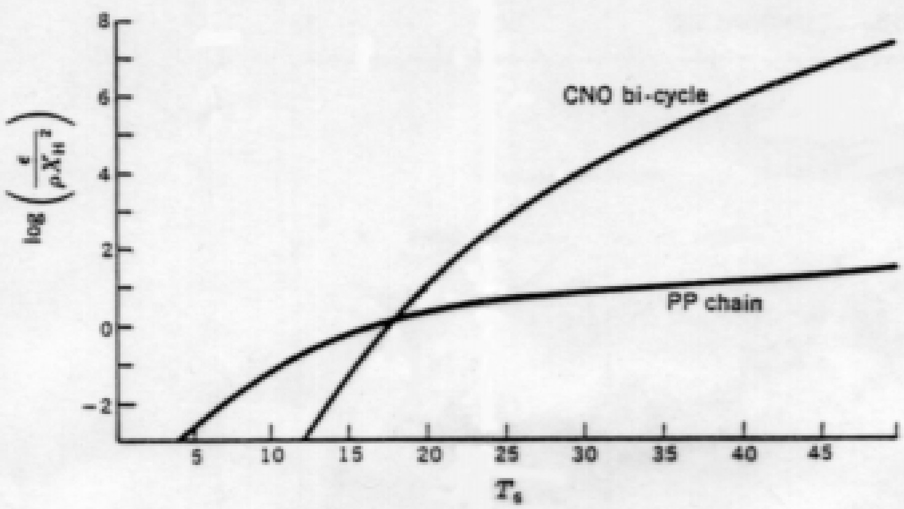


Fig. 5-16 A comparison of thermonuclear power from the PP chains and the CNO cycle. Both chains are assumed to be operating in equilibrium. The calculation was made for the choice $X_{CN}/X_H = 0.02$, which is representative of population I composition.

Helium Burning

Figure 9 -Triple Alpha process

Helium Burning

3-α Process

$T \gtrsim 10^8 K$

$\tau \lesssim 10^7 yr$

$He^4 + He^4 \rightarrow Be^8$	-0.092 Mev
$Be^8 + He^4 \rightarrow C^{12} + \gamma$	$+7.37$

Also when enough C^{12} is present:

$C^{12}(\alpha,\gamma)O^{16}$	7.161
$O^{16}(\alpha,\gamma)Ne^{20}$	4.730
$Ne^{20}(\alpha,\gamma)Mg^{24}$	9.317
	9.981

Carbon, Oxygen, and Heavier Element Burning

Figure 10-Carbon and Oxygen burning & Higher temp reactions

Carbon Burning $T > 10^8 K$

$\tau \sim 10^5 yr$

$$
\begin{aligned}
C^{12} + C^{12} &\rightarrow Mg^{24} + \gamma \\
&\rightarrow Ne^{23} + p \\
&\rightarrow Ne^{20} + He^4 \\
&\rightarrow Mg^{23} + n \\
&\rightarrow O^{16} + 2He^4
\end{aligned}
$$

A : 16 - 24

Oxygen Burning $T \geq 10^9 K$

$\tau < 10^5 yr$

$$
\begin{aligned}
O^{16} + O^{16} &\rightarrow S^{32} + \gamma \\
&\rightarrow P^{31} + p \\
&\rightarrow S^{31} + n \\
&\rightarrow Si^{28} + He^4 \\
&\rightarrow Mg^{24} + 2He^4
\end{aligned}
$$

16

A : 32 - 24

Other higher T reactions:

neutron capture + β decay:

- Silicon burning
- s - process (slow)
- r - process (rapid) : $T > 10^{10} K$,
- p - process : $T > 2 - 3 \times 10^9 K$,

What happens when a star uses up all available fuel?

Low mass stars: $M \leq 1.4\ M_o$

He or C/O core white dwarf

Most processed matter remains in the WD remnant.

=> not much enrichment of the ISM, certainly not of elements heavier than He

Intermediate mass stars: $1.4\ M_o < M < 5\text{-}10\ M_o$

Most mass ends up in a neutron star. Only heavy element enrichment of the ISM occurs via stellar winds which is mostly unprocessed material, although some C and O might be added.

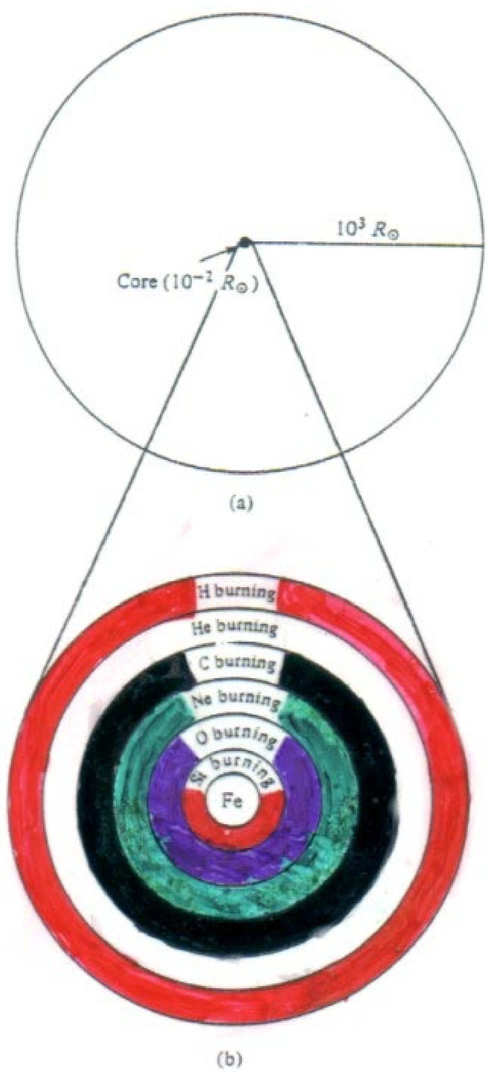
Stars in this range that are in close binary systems may become a Type I supernova, in which case, all the material could be blown back out into the ISM with heavy enrichment of processed elements.

Massive stars: $M > 5\text{-}10\ M_o$

These stars burn to Fe at the core with shells of lower mass buring outside. These stars will become supernovae and blow most of the processed matter out into space. This is the primary process of enriching the ISM.

Figure 11-Structure of a massive star before going supernova

A massive star just prior to going supernova



Envelope is about the size of Jupiter's orbit.

Core is about the size of the Earth

Figure 10.3 Shells in the core of a high-mass star as it evolves away from the main sequence. (a) The core is only a small fraction of the total radius. (b) In the core, there is a succession of shells of different composition. Each shell has exhausted the fuels that are still burning in shells further out.

Fe is the end of the line. Nuclei heavier than Fe require more energy to make synthesize than is returned.

Is the abundance curve consistent with this general picture?

Figure 12- Idnetification of particular nuclear processes with peaks in the abundance curve.

2.2 SOLAR SYSTEM ABUNDANCES 13

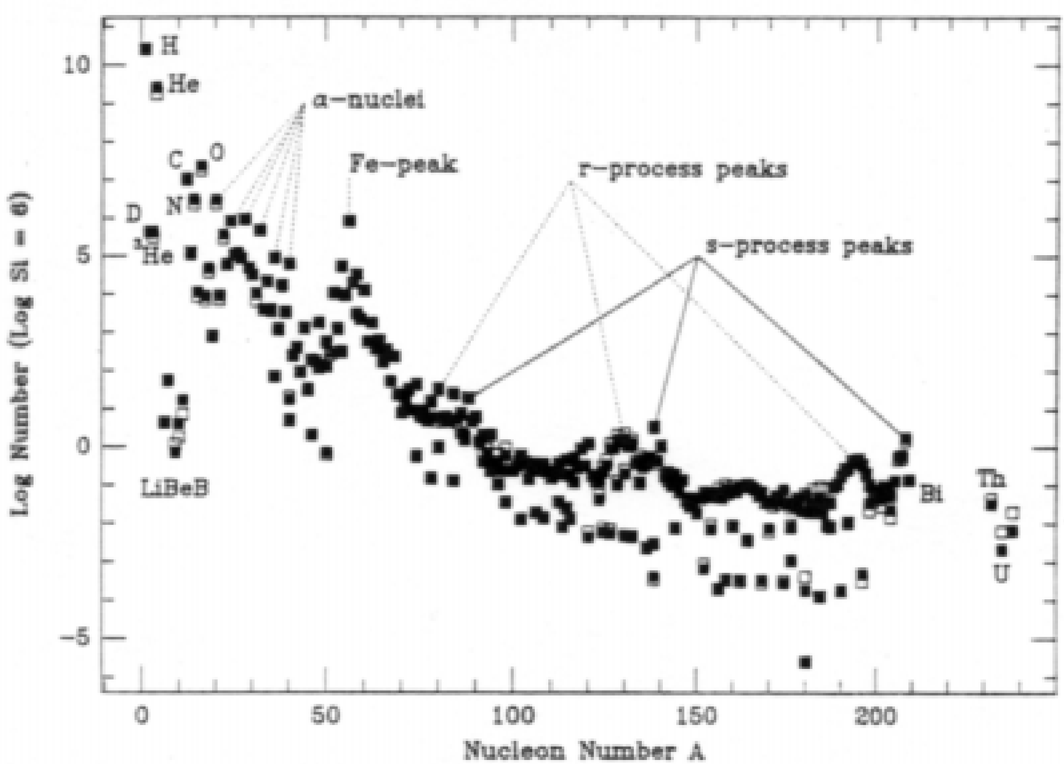


Fig. 2.1. Abundance Features

SUMMARY

1) ❄ The light elements H, D, ^{3}He, ^{4}He, Li, Be, and B are formed in the Big Bang. Some He is produced in stars, but this is small relative to that produced in the Big Bang.

2) ❄ Carbon and heavier elements are produced primarily in massive stars and returned to the interstellar medium (the space between the stars) via supernovae explosions.