Synthesis of Elements in Stars

Hao Liu
Zetian Ma

Element Abundances and Nuclear Structure

- There are many stable and radioactive nuclei, each has unique properties.
- All nuclei are made of proton and neutron.
- Only at very high energies can nucleons be produced or annihilated.
- As long as the energy is below meson production threshold, all ”prompt” nuclear process can be seen as recombination of protons and neutrons. At low energies s-process allows the interchange between protons and neutrons.

What has been the history of the matter?

Element Abundances and Nuclear Structure

It seems probable that all elements evolved from **hydrogen**, since:

- Proton is stable while the neutron is not.
- Hydrogen is the most abundant element, and helium is the next. (from pp chain and CN cycle)

Element Abundances:

- Iron and nickel comprise less than 1% of the total mass while they are most stable.
- Atomic abundance curve has an **exponential decline** to $A \approx 100$ and is **approximately constant** thereafter. (ignores many details)

Element Abundances and Nuclear Structure

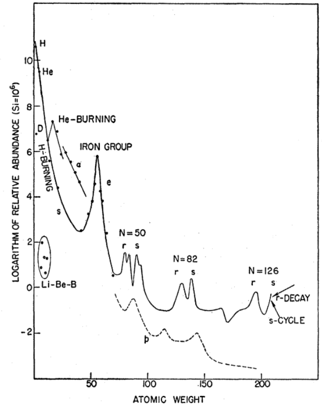


FIG. I,1. Schematic curve of atomic abundances as a function of atomic weight based on the data of Suess and Urey (Su56). Suess and Urey have employed relative isotopic abundances to determine the slope and general trend of the curve. There is still considerable spread of the individual abundances about the curve illustrated, but the general features shown are now fairly well established. These features are outlined in Table I,2. Note the overabundances relative to their neighbors of the alpha-particle nuclei $A=16, 20, \cdots 40$, the peak at the iron group nuclei, and the twin peaks at $A=80$ and 90, at 130 and 138, and at 194 and 208.

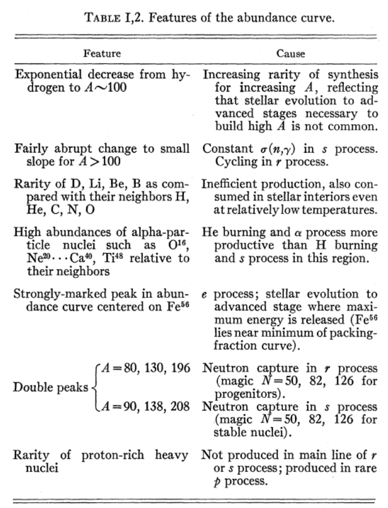


TABLE I,2. Features of the abundance curve.

Feature	Cause
Exponential decrease from hydrogen to $A \sim 100$	Increasing rarity of synthesis for increasing A, reflecting that stellar evolution to advanced stages necessary to build high A is not common.
Fairly abrupt change to small slope for $A > 100$	Constant $\sigma(n,\gamma)$ in s process. Cycling in r process.
Rarity of D, Li, Be, B as compared with their neighbors H, He, C, N, O	Inefficient production, also consumed in stellar interiors even at relatively low temperatures.
High abundances of alpha-particle nuclei such as O^{16}, $Ne^{20} \cdots Ca^{40}$, Ti^{48} relative to their neighbors	He burning and α process more productive than H burning and s process in this region.
Strongly-marked peak in abundance curve centered on Fe^{56}	e process; stellar evolution to advanced stage where maximum energy is released (Fe^{56} lies near minimum of packing-fraction curve).
Double peaks $A=80, 130, 196$	Neutron capture in r process (magic $N=50$, 82, 126 for progenitors).
Double peaks $A=90, 138, 208$	Neutron capture in s process (magic $N=50$, 82, 126 for stable nuclei).
Rarity of proton-rich heavy nuclei	Not produced in main line of r or s process; produced in rare p process.

Four Theories of the Origin of the Elements

Three theories assume elements were built in a **primordial state of the universe:**

Nonequilibrium theory of Gamow; the polyneutron theory of Mayer; equilibrium theory of Klein.

They need very special initial conditions for the universe which has no evidence.

Although they distribute elements on a cosmic scale, they are spatially uniform.

The fourth theory: the **stars** are the seat of origin of the elements

Evidence: nuclear transformations are currently taking place inside stars.

To distribute elements on cosmic scale: explosive ejection in **supernovae**, the less energetic but more frequent **novae**, and the less rapid and less violent ejection from **stars in the giant stages of evolution** and from **planetary nebulae**.

It was not known whether all of the atomic species heavier than hydrogen are produced in stars. In this paper, only focus on synthesis in stars .

General Features of Stellar Synthesis

Temperature needs to be adjusted so that the **outflow of energy** through the star is balanced by **nuclear energy** generation.

H $\rightarrow$ He$\rightarrow$ C$\rightarrow \ldots$ $\rightarrow$Fe , rising temperature.

The temperature rise is brought about by the conversion of **gravitational energy** into thermal energy.

Heavier and heavier nuclei will be synthesis.(Since penetrations of Coulomb barriers occur more readily as the temperature rises)

General Features of Stellar Synthesis

Other factors needs to be considered: **details of rising temperature; barrier effects at low temperatures.**

The temperature is **not** everywhere the same inside a star: nuclear evolution is most advanced in central regions .

Process that produces special nuclear effects:

- Mixing of central and outer layers.
- Material ejected from one star may subsequently become condensed in another star.

These complications show that the stellar theory cannot be simple.

The elements evolve by a whole series of processes: H burning, He burning, n, e, r, s, p and x processes.

Modes of Element Synthesis

if we believe only hydrogen is primeval, at least eight different types of synthesizing processes are demanded to explain the abundance curve.

(1) Hydrogen Burning: H $\rightarrow$ He, and C,N,O,F,Ne,Si that are not produced by (2) and (3). Provide most energy.

(2) Helium Burning: He $\rightarrow$ C, and ^{16}O, ^{20}Ne, ^{24}Mg

(3) α **process:** ^{20}Ne +α, synthesize the four-structure nuclei ^{24}Mg, ^{28}Si, ^{32}S, ^{36}A, ^{40}Ca, and probably ^{44}Ca and ^{48}Ti.

(4) e process: synthesize elements comprising the iron peak in the abundance curve (vanadium, chromium, manganese, iron, cobalt, and nickel)

Modes of Element Synthesis

(5) s process: (n,γ).

- Takes place on a long time-scale, from 100 years to 1000 years for each neutron capture.
- Occurs at a slow rate compared to the beta decays.
- Produce of the majority of the isotopes in the range 23$\leq$A$\leq$ 46 (excluding those by the α process), and for a considerable proportion of the isotopes in the range 63$\leq$A$\leq$ 209.
- The s process produces the abundance peaks at A =90, 138, and 208.

Modes of Element Synthesis

(6) r process:

neutron capture on a very short time-scale.

- 0.01—10 sec for the beta-decay processes interspersed between the neutron captures.
- The neutron captures occur at a rapid rate compared to the beta decays.
- Produce a large number of isotopes in the range $70 \leq A \leq 209$, also uranium and thorium.
- The s process produces the abundance peaks at A =90, 138, and 208. Also produce some light element synthesis, e.g., ^{36}S, ^{46}Ca, ^{48}Ca, and perhaps ^{47}Ti, ^{49}Ti, and ^{50}Ti.
- Produces the abundance peaks at A =80, 130, and 194.

Modes of Element Synthesis

(7) p **process:**

(p, γ) or (γ, n). Synthesis of a number of proton-rich isotopes .

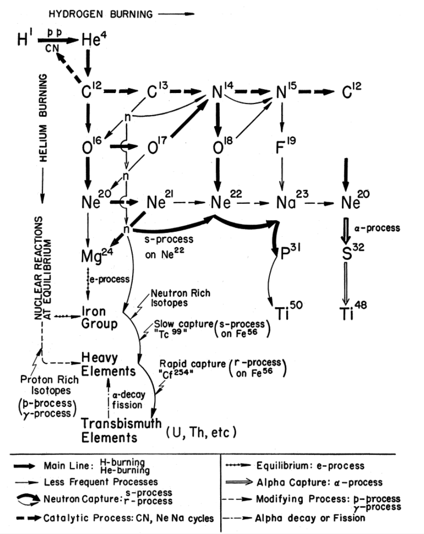
(8) x **process:**

Synthesize D, Li, Be, B. More than one type of process may be demanded.

They are very unstable at the temperatures of stellar interiors, so they are probably produced in regions of 1ow density and temperature. (But there is some observational evidence against this)

Auxiliary process: ^{13}C(α,n)^{16}O, ^{13}C(α,n)^{16}O to provide proton and neutron for s and r process.

Modes of Element Synthesis



Modes of Element Synthesis

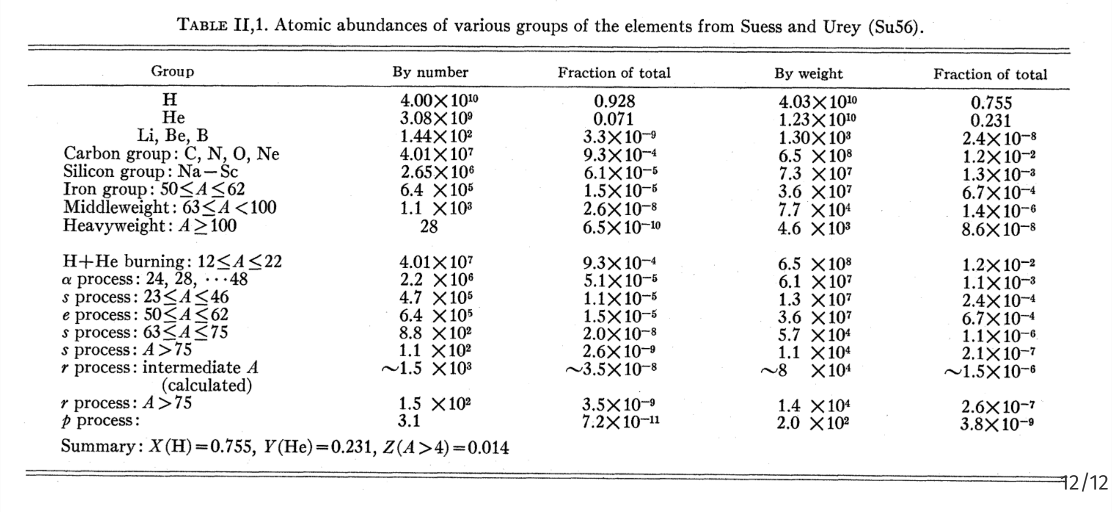


TABLE II,1. Atomic abundances of various groups of the elements from Suess and Urey (Su56).

Group	By number	Fraction of total	By weight	Fraction of total
H	4.00×10^{10}	0.928	4.03×10^{10}	0.755
He	3.08×10^{9}	0.071	1.23×10^{10}	0.231
Li, Be, B	1.44×10^{2}	3.3×10^{-9}	1.30×10^{3}	2.4×10^{-8}
Carbon group: C, N, O, Ne	4.01×10^{7}	9.3×10^{-4}	6.5×10^{8}	1.2×10^{-2}
Silicon group: Na$-$Sc	2.65×10^{6}	6.1×10^{-5}	7.3×10^{7}	1.3×10^{-3}
Iron group: $50\leq A\leq62$	6.4×10^{5}	1.5×10^{-5}	3.6×10^{7}	6.7×10^{-4}
Middleweight: $63\leq A<100$	1.1×10^{3}	2.6×10^{-8}	7.7×10^{4}	1.4×10^{-6}
Heavyweight: $A\geq100$	28	6.5×10^{-10}	4.6×10^{3}	8.6×10^{-8}
H+He burning: $12\leq A\leq22$	4.01×10^{7}	9.3×10^{-4}	6.5×10^{8}	1.2×10^{-2}
α process: 24, 28, $\cdots$48	2.2×10^{6}	5.1×10^{-5}	6.1×10^{7}	1.1×10^{-3}
s process: $23\leq A\leq46$	4.7×10^{5}	1.1×10^{-5}	1.3×10^{7}	2.4×10^{-4}
e process: $50\leq A\leq62$	6.4×10^{5}	1.5×10^{-5}	3.6×10^{7}	6.7×10^{-4}
s process: $63\leq A\leq75$	8.8×10^{2}	2.0×10^{-8}	5.7×10^{4}	1.1×10^{-6}
s process: $A>75$	1.1×10^{2}	2.6×10^{-9}	1.1×10^{4}	2.1×10^{-7}
r process: intermediate A (calculated)	$\sim1.5\times10^{3}$	$\sim3.5\times10^{-8}$	$\sim8\times10^{4}$	$\sim1.5\times10^{-6}$
r process: $A>75$	1.5×10^{2}	3.5×10^{-9}	1.4×10^{4}	2.6×10^{-7}
p process:	3.1	7.2×10^{-11}	2.0×10^{2}	3.8×10^{-9}

Summary: $X(\mathrm{H})=0.755$, $Y(\mathrm{He})=0.231$, $Z(A>4)=0.014$