Origin of the Elements

Abundance of the elements of the Solar System. Six key observations to be explained:

1. H and He are by far the most abundant.
2. Elemental abundances generally drop with increasing atomic number.
3. Even Z (atomic number) elements are more abundant than odd Z elements.
4. Li, Be, B are anomalously rare.
5. Fe is anomalously abundant.
6. Tc, Pm, are elements Z > 83 (Bi) [except for Th, U] are extremely scarce or nonexistent.

Nearly all of the elements beyond H and He are products of nucleosynthesis (synthesis of nuclides in stars)

Big Bang

100 seconds after T cooled to $10^9$ K and then elements can form.

H originated from coulomb attraction of protons and electrons.

Strong forces hold He nuclei together. (Strong force dominates within range of $\sim 10^{-15}$ m)

Big Bang epoch results in: H (72%) He (28%)

All Z > 2 are made via nucleosynthesis. In stars (mass > 0.072 $M_{\odot}$)

Explains observation #1.

Proton – Proton Chain H-burning

$$2 \left( ^1H + ^1H \rightarrow ^2H + \text{positron} + \text{neutrino} + \text{thermal energy} \right) \text{[timescale} \sim 10^9 \text{years]}$$

$$2 \left( ^3H + ^1H \rightarrow ^3He + \text{gamma ray} + \text{thermal energy} \right) \text{[timescale} \sim 1 \text{second]}$$

$$^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} \text{(i.e. alpha particle)} + 2^1\text{H} + 2 \text{gamma ray} + \text{thermal energy} \text{[timescale} \sim 10^6 \text{years]}$$

Net: $4^1\text{H} \rightarrow ^4\text{He} + 2 \text{positron} + 2 \text{neutrino} + \text{thermal energy}$

$dE/dt$ (energy production rate) is proportional to $T^4$ ($T$ = temperature)

However, our sun is an evolved star: composed of elements synthesized by previous dead stars. Evolved stars primarily use the CNO cycle instead to synthesize He:

$$^{12}\text{C} + ^1\text{H} \rightarrow ^{13}\text{N} + \text{thermal energy}$$

$$^{13}\text{N} \rightarrow ^{13}\text{C} + \text{ positron} + \text{ neutrino} + \text{ thermal energy}$$

$$^{13}\text{C} + ^1\text{H} \rightarrow ^{14}\text{N} + \text{ thermal energy}$$

$$^{14}\text{N} + ^1\text{H} \rightarrow ^{15}\text{O} + \text{ thermal energy}$$

$$^{15}\text{O} \rightarrow ^{15}\text{N} + \text{ positron} + \text{ positron} + \text{ thermal energy}$$

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

Net: $4^1\text{H} \rightarrow 4\text{He} + 2 \text{positron} + 2 \text{neutrino} + \text{thermal energy}$

Catalyzed by C, N, O.

Both the p-p chain and the CNO cycle need $T > 10^7K$
**Triple Alpha Process – Helium Addition**

Radiation pressure (from fusion energy) balanced with self gravity determines the size of the star’s core. When a star’s core has consumed most of its hydrogen, it will collapse since it is no longer pressure supported by radiative energy produced by H-fusion. For stars with $M > 0.8 M_{\text{sun}}$, core pressure will reach temperatures ($T > 10^8 \text{K}$) and pressures sufficient for He fusion (red giant phase)

$^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be}$ (half life of only $10^{-16}$ sec)

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

Short half-life of $^8\text{Be}$ explains why you need high $T$, $P$

Skips Li, B, which explains observations #4.

Carbon is the first stable element made beyond hydrogen and helium.

At higher $T$, pressure, further He-addition occurs:

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

$^{16}\text{O} + ^4\text{He} \rightarrow ^{20}\text{Ne}$

$^{20}\text{Ne} + ^4\text{He} \rightarrow \ldots$

Increasingly difficult due to increasing Coulomb repulsion with increasing $Z$.

Explains observation #2

He-addition continue up to the production of:

$^{56}\text{Ni} \rightarrow$ decays to $^{56}\text{Co}$ decays to $\rightarrow ^{56}\text{Fe}$. He addition stops at $^{56}\text{Fe}$ due to Coulomb repulsion.

This explains observation #5.

He-addition also explains observation #3 (even $Z$ element preference in saw tooth pattern)

Ultimately this favorability for even $Z$ is determined by quantum mechanical laws.

Also partly explains observation #6: Tc, Pm have odd $Z$. Main reason for lack of Tc and Pm is that they form no stable isotopes.

Rest masses of individual nucleons in elemental nuclei up to $^{56}\text{Fe}$ are slightly higher than nucleus itself. This is the mass deficit $\Delta m$. Lower energy state in the nucleus rather than free.

**Binding energy** = $-\Delta mc^2$

Cannot fuse anything higher than iron. Anything outside the range of the strong force ($= 10^{-15}$ m) will not fuse.

Beyond iron:

Fusion of elements with $Z < 26$ releases energy

$Z > 26$ absorbs energy

due to enormous Coulomb repulsion.
The way to build higher Z elements is to add uncharged nucleons: neutrons!

**Beta – Decay and Chart of the Nuclides**

Once $^4\text{He}$ has finally consumed, $T \rightarrow 10^9 \text{ K}$ and C-burning occurs. This generates free protons:

$^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + ^4\text{He}$

$^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + \text{proton}$

$^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + \text{proton}$

Protons are consumed to make new elements via $P$- Process:

$^{12}\text{C} + \text{P} \rightarrow ^{13}\text{N} + \text{gamma ray}$

$^{13}\text{N} \rightarrow ^{13}\text{C} + \text{positron} + \text{gamma ray}$

$^{13}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O} + \text{neutron}$

**S-Process** – Slow neutron addition. Occurs in late stage red giants. It occurs by addition of one or a few neutrons to a nuclide in the valley of stability followed by $\beta^-$ decay back to the valley. Usually just one neutron addition. $\beta^+$ decay does not play a role in the s-process. This is “slow” because elements in valley of stability absorb neutrons only every $10^4 \text{ sec}$.

Sources of neutrons for s-process

$^{18}\text{O} + ^4\text{He} \rightarrow ^{21}\text{Ne} + \text{neutron}$

$^{18}\text{O} + ^4\text{He} \rightarrow ^{22}\text{Ne} + \text{gamma}$

$^{22}\text{Ne} + ^4\text{He} \rightarrow ^{25}\text{Mg} + \text{neutron}$