Stars and Life

To understand the role of life in the universe, we first have to look at where the ingredients for life come from. These are the percentage of atoms in a typical sample of:

<table>
<thead>
<tr>
<th></th>
<th>The Sun</th>
<th>Humans</th>
<th>Earth’s Crust</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>91%</td>
<td>H</td>
<td>O</td>
</tr>
<tr>
<td>He</td>
<td>9%</td>
<td>O</td>
<td>Si</td>
</tr>
<tr>
<td>O</td>
<td>0.078%</td>
<td>C</td>
<td>Al</td>
</tr>
<tr>
<td>C</td>
<td>0.033%</td>
<td>N</td>
<td>Fe</td>
</tr>
<tr>
<td>Ne</td>
<td>0.011%</td>
<td>Ca</td>
<td>Ca</td>
</tr>
<tr>
<td>N</td>
<td>0.010%</td>
<td>Ph</td>
<td>Na</td>
</tr>
<tr>
<td>Mg</td>
<td>0.004%</td>
<td>S</td>
<td>K</td>
</tr>
</tbody>
</table>
We see that C, N and O are enriched in living organisms by a factor of 300 relative to the typical stuff of stars and the universe as a whole, much of it in the form of water:

<table>
<thead>
<tr>
<th></th>
<th>The Sun</th>
<th>Humans</th>
<th>Earth’s Crust</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>91%</td>
<td>H</td>
<td>H 61%</td>
</tr>
<tr>
<td>He</td>
<td>9%</td>
<td>O</td>
<td>O 26%</td>
</tr>
<tr>
<td>O</td>
<td>0.078%</td>
<td>C</td>
<td>C 11%</td>
</tr>
<tr>
<td>C</td>
<td>0.033%</td>
<td>N</td>
<td>N 2.4%</td>
</tr>
<tr>
<td>Ne</td>
<td>0.011%</td>
<td>Ca</td>
<td>Ca 0.23%</td>
</tr>
<tr>
<td>N</td>
<td>0.010%</td>
<td>Ph</td>
<td>Ph 0.13%</td>
</tr>
<tr>
<td>Mg</td>
<td>0.004%</td>
<td>S</td>
<td>S 0.13%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>O 47%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Si 28%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Al 8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fe 5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ca 3.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Na 2.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K 2.6%</td>
</tr>
</tbody>
</table>
Cosmic Element Abundances

Main features are:

- H and He are dominant
- Second peak at C, N and O
- Third peak at Iron
- Overall saw-tooth pattern
- Extreme rarity beyond Iron
- Light element trough

How can we explain this?
Origin of the Lightest Elements

The lightest elements — hydrogen, helium, and a smattering of deuterium (heavy hydrogen isotope) and lithium — were from the big bang itself, produced by fusion in the first three minutes when the universe was as hot as the core of a star like the Sun!

If no stars had formed in the expanding universe, we would not be here to have this discussion, since hydrogen and helium can combine to form…. nothing! Chemistry & biology impossible.
How Do We Know This Happened?

1. Cosmic Expansion

   All galaxies moving away from each other, pointing to when the universe was hotter and denser, with an origin 13.7 billion years ago.

2. Microwave Background

   Expansion since the early hot phase has cooled the radiation to microwaves, seen all over the sky at a temperature of only 3K.
How do stars and planets form?

Stars are born in *molecular clouds* consisting mostly of hydrogen molecules, with some heavier elements and dust.
Stars form out of molecular clouds
Infrared light from Orion Nebula is one of the closest star-forming clouds.
Planets form in the solar nebula

In the warm inner region of the solar nebula, only metal and rock could condense.

In the cold outer regions, ices made from water, methane, and ammonia could also condense.

The vast majority of the cloud material consisted of hydrogen and helium, which remained gaseous.
### TABLE 3.1 Materials in the Solar Nebula

A summary of the four types of materials present in the solar nebula. The squares in the final column represent the relative proportions of each type (by mass).

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Examples</th>
<th>Typical Condensation Temperature</th>
<th>Relative Abundance (by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen and Helium Gas</td>
<td>hydrogen, helium in nebula</td>
<td>do not condense</td>
<td>98%</td>
</tr>
<tr>
<td>Hydrogen Compounds</td>
<td>water (H₂O)</td>
<td>&lt;150 K</td>
<td>1.4%</td>
</tr>
<tr>
<td></td>
<td>methane (CH₄)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ammonia (NH₃)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock</td>
<td>various minerals</td>
<td>500–1,300 K</td>
<td>0.4%</td>
</tr>
<tr>
<td>Metals</td>
<td>iron, nickel, aluminum</td>
<td>1,000–1,600 K</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

The solar nebula concentrates the heavy elements

Light gases and volatile compounds are driven from the inner solar system by solar radiation

Rocks and metals are not, so they are concentrated by a very large factor
A cluster of many stars can form out of a single cloud.
Why does a star shine?

4 Hydrogen atoms weigh more than 1 Helium atom ... Where does the mass go when you convert 4 Hydrogen atoms into Helium?

\[ E = mc^2 \]

Sunlight!
Why does a star shine?

Stars are gravity engines. The pressure of gravity in a star’s core raises the temperature to millions of degrees, so hot that atomic nuclei move fast enough to overcome electrical repulsion and “stick” in the process called nuclear fusion.

In fusion, the product is slightly lighter than the sum of the nuclei that went into the reaction. The mass difference is converted into energy that makes its way out of the star:

\[ E = mc^2 \]  

Sunlight!
Hydrogen is converted into Helium via nuclear fusion in core of the Sun
Very massive stars are rare.

Low-mass stars are common.
Stars more massive than $100 \, M_{\text{Sun}}$ would blow apart.

Stars less massive than $0.08 \, M_{\text{Sun}}$ can’t sustain fusion.
Red Giant Star

- Large, cool (red) star

- Near end of its stellar life ... *done* with main sequence burning

- In 5 billion years ... this will be our Sun!
Helium fusion requires higher temperatures than hydrogen fusion because larger charge leads to greater repulsion.

Occurrences at end of a star’s life.
A star like our Sun dies by puffing off its outer layers, creating a planetary nebula.

Only a white dwarf is left behind
**High mass stars make heavy elements**

Helium-capture reactions add two protons at a time
Advanced nuclear fusion reactions require extremely high temperatures, several billion degrees.

Only high-mass stars can attain high enough core temperatures to create elements up to iron.
Advanced nuclear burning occurs in multiple shells in a **high mass star**
(our Sun will never get to this stage)
Iron is a dead end for fusion because nuclear reactions using iron do not release energy.

Iron is the most stable element; energy must be put in to get fusion past Fe.
Evidence for helium capture:

Note the higher abundances of elements with even numbers of protons (the saw tooth...)
Elements made during supernova explosion

Secondary peak at iron, the most stable element

Elements made during supernova explosion
Crab Nebula: Remnant of supernova observed in 1054 A.D.
Supernova Remnant ~ 40,000 years old

140 light years across!
We can see supernova exploding in other galaxies. The rate of supernova explosions is \( \sim 1 \) per 100 years in the Milky Way Galaxy.
Cosmic Element Abundance

Cosmic chemistry:

H is fundamental and the He is fused in the early hot big bang

Elements from C to Fe fused in moderately massive stars

Elements beyond Fe are mostly fused in supernova blast waves

Sawtooth is He nucleus added, trough due to unstable atoms

Stars are chemical factories. The universe is built for life!
The Life Cycle of Massive Stars