Today in Astronomy 106: Life, and its components

- The Drake equation: an accounting measure that suggests a path of inquiry into the emergence of life.
- Life as we know it.
- Definition of Life: how might we know life when we see it or seek it.

(SSC/NASA)
Review. Radioisotope dating can be used to determine

A. how long ago the elemental ingredients – silicon, oxygen, magnesium, iron… – of the rock were made.

B. how long ago an igneous rock was last melted.

C. how long ago the ingredients of a sedimentary rock were deposited on the ocean floor.

D. how long ago the last radioactive atom in the rock decayed.
One of these sets of experimental measurements of Rb and Sr ratios is of lava from a recent eruption of Mauna Loa. Which one?

A. 
B. 
C.

Astronomy 106, Fall 2015
The emergence of life and intelligence: Drake’s Equation

So how did life and its components come into existence, during the billions of years of the past?

During the rest of the semester, we will be guided by the equation formulated in the 1960s by Frank Drake as an accounting measure for the universal factors important in the emergence of life and civilization in the Universe.

- Drake phrased the expression in terms of the number of civilizations with which we could eventually communicate, but each factor in the equation is related to the development of an important component of life as we have tentatively defined it.

- Also of importance but not a term in the equation: $r$, the average distance to the nearest civilizations.

No astronomy or biology in it, just bookkeeping, but it’s a useful way to think about Life.
The Drake equation

\[ N = R_\ast f_p n_e f_\ell f_i f_c L \]

\( N \) = number of communicable civilizations in our Galaxy
\( R_\ast \) = rate at which stars form.
\( f_p \) = fraction of stars that have planetary systems.
\( n_e \) = number of planets, per planetary system, that are suitable for life.
\( f_\ell \) = fraction of planets suitable for life, on which life actually arises.
\( f_i \) = fraction of life-bearing planets on which intelligence develops.
\( f_c \) = fraction of intelligence-bearing planets which develop a technological phase during which there is a capacity for, and interest in, interstellar communication.
\( L \) = average lifetime of communicable civilizations.

See also Evans, appendix 5.
The result after 13.7 Gyr: Life As We Know It.

As far as we know, things that are alive are composed of **organic molecules**, based upon long chains and rings of carbon atoms, and **water**.

- This endows living things with a distinctive mix of ion-molecule and neutral-neutral chemical processes, as we will discuss in the middle third of the course.

- It might also seem like an eccentric choice, considering how Earth’s surface differs from the rest of the Solar system.

**Abbreviation**: Gyr = $10^9$ years = 1 billion years.

PAHs. Green = carbon, gold = hydrogen. (SSC/NASA)
# Chemical composition of Life As We Know It

Much of LAWKI is similarly composed.

By atom, per hundred oxygen atoms,

<table>
<thead>
<tr>
<th>Element</th>
<th>Bacteria</th>
<th>Human</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>217.2</td>
<td>234.6</td>
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<tr>
<td>Carbon</td>
<td>22.1</td>
<td>40.4</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>4.8</td>
<td>9.2</td>
</tr>
<tr>
<td>Oxygen</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Calcium</td>
<td>&lt; 0.2</td>
<td>0.9</td>
</tr>
</tbody>
</table>

i.e. CHONSP, as one learns in high-school biology.
Chemical composition of Life As We Know It (continued)

But this is different from Earth’s composition…

<table>
<thead>
<tr>
<th>Element</th>
<th>Interior</th>
<th>Crust</th>
<th>Ocean</th>
<th>Air</th>
<th>Human</th>
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<tbody>
<tr>
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<td>0.002</td>
<td>232.0</td>
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<tr>
<td>Carbon</td>
<td>&lt; 0.1</td>
<td>0.1</td>
<td>0.004</td>
<td>0.1</td>
<td>37.9</td>
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<tr>
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<td></td>
<td>372.1</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
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<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Sodium</td>
<td>4.2</td>
<td>0.9</td>
<td></td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>Magnesium</td>
<td>30.4</td>
<td>3.0</td>
<td>0.1</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.8</td>
<td>10.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon</td>
<td>28.6</td>
<td>33.9</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Argon</td>
<td></td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Potassium</td>
<td>2.3</td>
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<td></td>
<td>0.3</td>
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<tr>
<td>Calcium</td>
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<td>3.1</td>
<td></td>
<td></td>
<td>0.9</td>
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<tr>
<td>Iron</td>
<td>30.6</td>
<td>3.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(by atom, per 100 oxygen atoms)
Chemical composition of Life As We Know It (continued)

... and in fact closer to the solar system at large.

<table>
<thead>
<tr>
<th>Element</th>
<th>Earth</th>
<th>Sun</th>
<th>Comets</th>
<th>Human</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>147058.8</td>
<td>200</td>
<td>232.0</td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>&lt; 0.1</td>
<td>44.1</td>
<td>44.1</td>
<td>37.9</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>13.4</td>
<td>13.4</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Sodium</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>30.4</td>
<td>4.3</td>
<td>4.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.8</td>
<td>0.3</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Silicon</td>
<td>28.6</td>
<td>3.7</td>
<td>3.7</td>
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<tr>
<td>Phosphorus</td>
<td>0.03</td>
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<td>0.8</td>
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<td>Sulfur</td>
<td>4.8</td>
<td>1.4</td>
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<td>0.2</td>
</tr>
<tr>
<td>Potassium</td>
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<td>Calcium</td>
<td>2.0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.9</td>
</tr>
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<td>Iron</td>
<td>30.6</td>
<td>1.2</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>1.6</td>
<td>0.2</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

(by atom, per 100 oxygen atoms)
Take a guess. Carbon and silicon atoms can both make four covalent bonds. There’s a lot more silicon on Earth’s surface than carbon. Why aren’t we made of silicon instead?

A. Life began in comets, not on Earth’s surface.

B. Life must have evolved on a planet with more carbon, and then been transplanted.

C. Silicon life came first and was gradually replaced by carbon life.

D. Long molecules made of silicon chains are unstable; basically it was carbon-chain molecules or nothing.

Answer in lecture on 20 October.
Other prominent attributes of LAWKI

In addition, living things tend to...

- ...engage in **metabolism**, thus requiring supplies of chemicals and chemical energy.
- ... **reproduce**.
- ... **mutate**: they adapt and evolve.
- ... exhibit **sensitivity**: they respond to changes in their environment.
What is Life?

We will take these five attributes as a *provisional definition of life*, and use them to guide our search. But we must remember that…

- …it’s really Life As We Know It.
- …as we explore the Universe, we find many unexpected environments in which things could have progressed quite differently, considering the billions of years they had to do so.
- …even as we explore Earth, we find **extremophiles**: life forms adapted to chemicals and environments way past where we thought the limits were.

Grand Prismatic Spring, Yellowstone National Park, where a lot of interesting extremophiles live.
Mid-lecture Break

- Homework #1 is (still) available on WeBWorK; due 7PM, 16 September.

Identify the correct statement.

A. After visiting Pluto, the New Horizons probe is on its way back to Earth with the samples it collected.

B. There have been five mass extinctions in Earth’s history, and a sixth may be under way.

C. On the average, 55% of our DNA was inherited from the Neanderthals.

D. The “RNA World” picture of the origin of Earth’s life has been decisively disproven.
Exceptions to the LAWKI-based definition

- Mules and hinnies are undoubtedly alive, but do not reproduce. (Very often, anyway.)
- Fire is undoubtedly not alive, but all it would seem to lack is organic composition.
- Viruses are considered by most to be a life form, but they do not metabolize or exhibit sensitivity.
- Robots are not considered alive, but: we can endow them with sensors; program them to build other robots (reproduce) or change themselves or others (mutate, adapt). They require energy and materials to keep going (metabolism).
A definition exercise: water

So let’s see what happens when we try to make a sharper, more general definition to guide us. As an exercise in this activity:

Suppose that this is the 17th century, and although we have great experience with the physical and chemical world, we can’t identify individual atoms and molecules, and don’t know for sure that matter is made of such things.

What is Water?
Water As We Know It

To take it as is from the terrestrial environment:

- Colorless, odorless clear liquid
  - except seawater, pond water, lake water…
- Vaporizes at $T = 373 \text{ K}$ under 1 atmosphere pressure.
  - except if not particularly clear and colorless.
- Freezes at $T = 273 \text{ K}$ under 1 atmosphere pressure.
  - except if not particularly clear or colorless.
- Nonpoisonous; quenches thirst; very mildly flavored.
  - except with certain special trace additives.

Many exceptions! Is there an essence of water that we may seek in a more sophisticated fashion?
We can make **distilled** water by boiling ordinary water and recondensing the vapor under clean conditions. Then we get:

- Colorless, odorless clear liquid
- Vaporizes at $T = 373$ K under 1 atmosphere pressure.
- Freezes at $T = 273$ K under 1 atmosphere pressure.
- Nonpoisonous; quenches thirst; flavorless.
- When cooled below 273 K under suitable conditions, crystallizes in a distinctive hexagonal pattern, as seen for example in snowflakes.

In all a restrictive definition but perhaps still not uniquely definitive.
The true essence of water

With 19th-century hindsight, of course, we know that water is a molecule which contains two hydrogen atoms and one oxygen atom, covalently bonded as shown here:

Does Life admit to such a uniquely restrictive definition? How might we find out if it does?
Are there better ways to define Life?

Many have tried to come up with more general definitions that have fewer exceptions. Notable is Claire Folsome (1979, quoting Onsager and Morowitz), who focused on life as an ecological process:

Life is that property of matter that results in the coupled cycling of bioelements in aqueous [watery] solution, ultimately driven by radiant energy to attain maximum complexity.

Biosphere 2
Are there better ways to define Life? (continued)

And Feinberg and Shapiro (1980):

Life is fundamentally an *activity* of the biosphere. A biosphere is a highly ordered system of matter and energy characterized by complex cycles that maintain or gradually increase the order of the system through an exchange of energy with its environment.

Digging for ice on Mars (*Phoenix/U. Ariz.*)
Are there better ways to define Life? (continued)

Perhaps the ultimate nerdy definition, from famous physicist Erwin Schroedinger (1944):

Life is a class of phenomena in open thermodynamic systems, able to decrease their internal entropy at the expense of increasing the entropy of its surroundings, and avoids the decay into equilibrium.

(Entropy is a measure of disorder in a physical system; according to the second law of thermodynamics, entropy can never decrease in a closed system.)

Schroedinger
(Nobel Foundation)
Are there better ways to define Life? (continued)

And The Chords (1954):

Hey nonny ding dong,
   alang alang alang
Boom ba-doh, ba-doo
   ba-doodle-ay
Oh, life could be a dream,
   sh-boom.

The more general the definition, the more cryptic life tends to look.
Is there an Essence to life?

Is there a unique, definitive descriptor for life, analogous to the atomic composition of water?

- We don’t know for sure. But:

- the idea that the basic attributes of life, like the five for LAWKI, could be encoded in the contents, may suggest a way to look for an essence.

- So, as suggested by many scientists over the last 150 years, we may look for analogues and generalizations of the genetic code common to LAWKI, as an essence of life.

  - Schroedinger, again, suggested such a generalization in the form of “aperiodic crystals”, a decade before Watson and Crick found the structure of DNA.