Radioactivity

Lecture 15
The Origin of Life
The origin of life
through building of complex molecules

The scientist definition:

Life is a complex, self-organizing, adaptive chemical system!

The adaptive chemical system is an extensive network of interactions and feedback mechanisms between its different components. The feed-back component allows to adapt to changing environmental situations.

Self-organization means that collective patterns evolve out of simple basic rules operating at the local level. No single molecule has the master-plan the dynamic pattern defines the ensemble.

The simple rules are the chemical (an physical) laws, that each complex molecule desires to be in the lowest energy configuration, which is facilitated through chemical reactions forming more complex systems.
Life and Energy

• Life requires energy to maintain the physiological functions of the bodies.
• The main energy source of the biological system of animals (includes us) is chemical energy that is generated by the chemical conversion of food in the gastro-intestinal system.
• The main energy source of the biological system of plants is solar energy that is converted through photosynthesis in nutrient plant food.
• The energy source of less developed microbiological systems are also different chemical mechanisms.
• Three ingredients of life, Water, Organic Molecules (Carbon), Energy!
• The question is, what is the energy source for generating the first self-sustaining biological systems that can be identified as life. Options, solar light, heat and fire in Hadean period, electrical discharges (lightening) in a methane atmosphere during the first two billons years of Earth?
The First Two Billion Years

Water
Energy
Organic Molecules

How did that come about???
Early Experiments

- Urey-Miller experiment with artificial ammonium, methane, and hydrogen atmospheres exposed to electrical discharges, generates amino-acids as base for complex molecules.
- Carl Sagan took a similar experimental approach that produced by phosphorus enrichment Adenosin-Tri-Phosphat (ATP), an important building block of protein, RNA and DNA.
- A challenge remains the building of more complex chemical molecules that requires long time and sustained chemical conditions.
- Two theories are presently being discussed: Heaven and Hell!
Heaven and Hell

**Astrobiology**: formation of complex molecules in carbon enriched ices in comets, asteroids, planets through constant bombardment by intense cosmic radiation that provides the energy. The molecules are deposited on earth at more moderate conditions for further development.

**Deep ocean vents**: volcano heated deep sea vents that pump hot mineral rich material into ocean water at conditions that allow catalytic building of more complex Sulphur and phosphate rich organic molecules. Possible source of mineral component in biological systems.
Astrobiology

Space is not only an active nuclear laboratory, breeding new elements, but it is also an active chemistry laboratory breeding new molecules with ever increasing complexity. These molecules can clearly be observed and identified by molecular spectroscopy in the infra-red radiation range. Complex molecules as building blocks of life are also found in meteoritic inclusions.
Cosmic ice composition

Ices Matching the Observed Spectra

- Carbon
- Carbon dioxide
- Carbon monoxide
- Methane
- Ammonia plus
- Water components make a perfect mix for further synthesis if energy is supplied.

*Ice templates used:* $\text{C}_2\text{H}_2$, $\text{C}_2\text{H}_4$, $\text{C}_2\text{H}_6$, $\text{C}_3\text{H}_8$, $\text{NH}_3$, $\text{NO}$, $\text{NO}_2$, $\text{SO}_2$, $\text{CH}_3\text{OH}$, $\text{CH}_4$, CO, CO$_2$, H$_2$O, N$_2$. 
Energy Distribution in Solar Flare

Overall x-ray and gamma radiation flux, generated in solar flares. Gamma radiation is generated by nuclear processes.
Molecule Synthesis

Either direct radiation, or decay heat from deposited radioactive isotopes can provide the energy for the molecule synthesis, unlike sudden lightening with sporadic powerful electrical discharges, the continuous flow of decay heat as a likely energy source. This would prevent the dissociation of complex molecules.

Synthesis is most likely facilitated through gradual build-up of molecules with growing complexity with numerous catalytic and intermediate step to provide intermittent stability of molecules as building stones of organic macro-molecules such as RNA and DNA.

Left: organic structure produced in interstellar ice by irradiation
Right: organic components found in the Murchinson meteorite
Interstellar Amino-Acids

Interstellar grain chemistry. Radiation causes the release and ionization of hydrogen atoms that get added to unsaturated low complexity organic molecules generating radicals gradually building up more complex organic chemistry such as β-Alanine and amino-methanols and amino-ethanols.

Amino acids formed from β-Alanine through chemical interaction with amino-methanols and amino-ethanols.
Chirality in Amino Acids, a Cosmic Signature?

While both chirality options can be made in the chemical laboratory, biological proteins are nearly exclusively made of L amino acids, known as *left-handed proteins*. D-amino acids are very rare in nature and have only been found in small peptides attached to bacteria cell walls. This phenomenon is called Enantiomerism.

(S)-Alanine (left) and (R)-alanine (right) or levorotatory (L) and dextrorotatory (D).
The Supernova Explanation?

Possible explanation is the large neutrino flux from supernova a nearby supernova triggering the formation of the solar system and the magnetic field of the remaining neutron star.

- the spin of the $^{14}$N in the amino acids, or in precursor molecules from which amino acids might be formed are coupled to the chirality of the molecules
- The $^{14}$N nuclei align in the magnetic field and the high anti-neutrino flux cause the right handed $^{14}$N to be concerted to $^{14}$C destroying the dextrorotatory version of the molecule:
  \[ \bar{\nu}_e + ^{14}\text{N} \rightarrow e^+ + ^{14}\text{C} \]
- Chemical evolution transfers dexterity to more complex organic molecules.
- The mechanism might be universal for life origins in our universe.

If this model is correct, molecules of life would appear to have been created in the molecular clouds of the galaxy, with their Enantiomerism determined by processes induced by a near-by supernovae, and subsequently either transported to Earth in meteorites, swept up as the Earth passed through molecular clouds, or included in the mixture that formed Earth when the planets were created.
Seeding Earth

Enormous flow of meteoritic material during the Hadean period of the solar system. Probably not enough time for having formed complex molecules by early cool sun. Seeding within first Billion of years or long-term seeding according to Panspermia Theory.

Present Frequency of Impactors:
- Pea-size meteoroids - 10 per hour
- Walnut-size - 1 per hour
- Grapefruit-size - 1 every 10 hours
- Basketball-size - 1 per month
- 50-m rock that would destroy an area the size of New Jersey - 1 per 100 years
- 1-km asteroid - 1 per 100,000 years
- 2-km asteroid - 1 per 500,000 years

A "nemesis" comet impactor would give us only a 6-month warning.
Conan the Bacterium

Arguments against panspermia or any other theses suggesting life is from space are the exceedingly cold temperatures in interstellar environments and the extremely high level of radiation near stars.

*Deinococcus radiodurans* is one of the most radiation-resistant organisms known. It can survive cold, dehydration, vacuum, and acid, and is therefore listed as the world's toughest bacterium in *The Guinness Book of Records!* It can survive a radiation level of 1.5 million rads. It will survive into a post-nuclear world.

*Deinococcus* accomplishes its resistance to radiation by having multiple copies of its genome and rapid DNA repair mechanisms. It usually repairs breaks in its chromosomes within 24 hours by a 2-step process. First, *D. radiodurans* reconnects chromosome fragments by a process called single-stranded annealing. In the second step, multiple proteins mend double-strand breaks through homologous recombination. This process does not introduce any more mutations than a normal round of replication would, but could lead to less radiation safe DNA and chromosome composition in a less radiation prone environment.
Alternative Origin or further Processing?

Hydrothermal vents are the result of seawater percolating down through fissures in the ocean crust in the vicinity of spreading centers or subduction zones (places on Earth where two tectonic plates move away or towards one another). The cold seawater is heated by hot magma and reemerges to form the vents. Seawater in hydrothermal vents may reach temperatures of over 700°F Fahrenheit. Hot seawater in hydrothermal vents does not boil because of the extreme pressure (~300 atm) at the depths where the vents are formed.

When the fluid rises up through the seafloor, it carries many new chemicals with it, such as copper and zinc. These chemical reactions also remove chemicals from the seawater, such as oxygen and magnesium. These elements are important catalysts and ingredients for building complex organic molecule systems.
Admixtures also contain radioactive elements, but most of the energy comes as thermal energy from the hot (magma heated) vents. In this hot mineral rich environment lots of chemical reactions can occur that may serve either as first steps to life or as a breeding ground for Conan the bacterium and his descendants.
A venting black smoker emits jets of particle-laden fluids. The particles are predominantly fine-grained sulfide minerals formed when the hot hydrothermal fluids mix with near-freezing seawater. These minerals solidify as they cool, forming chimney-like structures. “Black smokers” are chimneys formed from deposits of iron sulfide, which is black. “White smokers” are chimneys formed from deposits of barium, calcium, and silicon, which are white.
The Chemistry of Hydrothermal Vents
Concentrations of main molecules in vent gases

Shown are the concentrations of CO₂ (a), He (b), Cl (d), H₂ (f), H₂S (g) and CH₄ (h); also shown are the ratios Li/Cl (c) and ³He/heat (e).

Magmatic events can produce rapid changes in hydrothermal vent chemistry
Marvin D. Lilley, David A. Butterfield, John E. Lupton and Eric J. Olson
Nature 422, 878-881 (24 April 2003)
The Locations of Hydrothermal Vents

Newly formed organic materials will become part of the freshly formed deep-sea crust.
Multiple probes have been taken from asteroid and meteorite space samples as well as from hydrothermal vents, the question about the original site remains open.

No life found here. The search for the origin of life is still on!
The solar system circles around the galactic center once every 226 Million years on a tilted orbital plane in a swinging motion. On its trajectory it passes through different regions of density and activity, regions of star formation and star death. Presently it moves through the so-called local bubble, an area of low activity. There was nearby supernova activity in the past and there will be areas of supernova activity in the future.
Cobalt-rich ferromanganese crusts are solid layers that form when manganese and iron precipitate out of cold seawater. They may contain cobalt, nickel, and some rare earth elements and could provide up to 20% of the global cobalt demand.
The evidence of near-by supernovae

Measurements of isotope distribution as a function of depth in the ferro-manganese crust as well as in magnetotactic bacterial found in deep sediments indicates an enrichment in $^{60}$Fe ($T_{1/2} = 2$ million years) at a depth level that corresponds to a deposition time between 2 and 3 Million years ago. 1 Million years of crossing a supernova remnant.
Galactic distribution of $^{60}$Fe

The radiation flux from supernova on earth surface depends on the shielding power of atmosphere is typically 99%, Q=1% reaches the surface. However high radiation intensity breaks-up the protective Ozone layer and transmission increases transmission to Q=10%=0.1. In that case a supernova closer than 35pc would generate more than 10Gy in dosage, deadly for the normal human being. In distances between 35 and 100 pc, the average dose varies between 10 and 1 Gy, causing considerably enhanced mutation rates in biological systems. There is no strong evidence for large extinction between 2 and 3 Million years, but possibly some evidence for mutational change in pre-hominide creatures.
Any Global Evidence in Extinction Record?

2.6 Million years ago is the transition from Pliocene to Pleistocene, characterized by the decline of ocean species. Temperatures had suddenly dropped and a cooling period caused expansion of arctic zones. The shift of ocean currents was assumed to provide the explanation, but a cataclysmic supernova event near-by might offer a different cause. Nearby stellar systems at a distance between 50-100 pc was the Scorpion Centaurus association near the star Antares, with high supernova activity rate.
2.5 M years ago?

Could be the sudden development of bi-pedalism, talking ability, and language a reflection of an enhanced mutation rate 2.5 Million years ago?

This is a speculation like the speculation about an extinction event. More research is needed.
Biological evidence?

Fine-grained debris from a supernova explosion could pass through Earth’s atmosphere, rapidly oxidizing in the process. The nano-particles would rapidly dissolve in oxygen, form rust, and eventually settle in the sediment along the ocean floor, where the bacteria would suck them up for their crystal chains.

When the bacteria eventually die, those chains remain behind in the sediment, and $^{60}$Fe would be locked inside. So any traces of $^{60}$Fe found in that sediment would constitute a kind of biogenic signature of a supernova event, preserved in the fossil record.
The path to the bottom

- Upper Atmosphere Deposition (Fig. 3, this paper)
- Mesosphere/Lower Thermosphere Winds (Fig. 1, Plane, Feng, & Dawkins 2015)
- Mean Atmospheric Iron Deposition (Fig. 3b, Dhomse, et al. 2013)
- Mean Annual Iron Concentration at 0 - 103 m (Fig. 11d, Moore & Braucher 2008)
- Mean Annual Iron Concentration at 103 - 502 m (Fig. 12d, Moore & Braucher 2008)
- Mean Annual Iron Concentration at 502 - 945 m (Fig. 13d, Moore & Braucher 2008)
- Mean Annual Iron Concentration at > 945 m (Fig. 14d, Moore & Braucher 2008)

- $^{60}$Fe dust enters the atmosphere and is nearly completely ablated/vaporized.
- $^{60}$Fe oscillates in north/south & east/west winds as it descends through atmosphere.
- $^{60}$Fe rains out of atmosphere to surface.
- Highly soluble $^{60}$Fe is consumed by plankton and other ocean life.
- $^{60}$Fe descends along a "conveyor belt" remaining in the same fluid element.
- $^{60}$Fe reaches sample location and is incorporated into sediment/Fe-Mn crust/magnetosomes.

- Magnetosomes

- sediment age [Myr]

- 2.8 Myr