Astrobiology

- Astrobiology (sometimes called Exobiology) is the study of life in the Universe
  - Origin of Life
  - Distribution of Life
  - Ultimate Fate of Life

- Astrobiology today is an extrapolation from the one known example (Earth life), using the basic principles of chemistry & physics and observing the Universe around us...

But first...What is Life?

- The question is philosophical, poetic, spiritual, intangible... but also scientific!
- To find life we must define what we seek...
- "Intuitive" definition:
  - “I know it when I see it”
  - Not very rigorous
  - Applies only to Earth life?
What is Life?

- A more rigorous definition:
  - Something is alive if it has the ability to ingest nutrients, give off waste products, & reproduce
  - But what are nutrients?
  - What are waste products?
  - Is growth important? (mountains "grow"...)

- Clearly the definition must acknowledge that life is hard to define and that there are likely to be exceptions to any rules proposed...

Attributes of Living Systems...

- Rather than defining life, can we describe it in terms of specific attributes?
  - Life has at least two unique attributes:
    1. A living system must be able to reproduce, to mutate, and to reproduce its mutations
    2. A living system must be able to convert external energy sources into useable internal energy sources

But even this gets dicey...

- There are systems with one attribute but not both
  - Chemical Reactions
    - CO₂ "reproduces"
    - But it's not alive!
  - Crystals
    - "reproduce" in regular patterns, get distorted (mutated)
  - Fire
    - Uses "nutrients", converts energy, "grows", "reproduces", ...
  - Many other "fuzzy" cases...

The Essential Requirements

- Liquid Water
  - "Medium" for the chemistry of life (mobility, nutrients)
  - Stable over wide range of temperatures
  - Unique freezing properties help maintain stability
  - Complex organic compounds don't dissolve in water!

- Source of Excess Energy
  - Sunlight (photosynthesis)
  - Chemical (oxidation)
  - Thermal or geothermal...

- Source of Organic Molecules
  - C, H, N, O, P, S combined in both simple and complex ways
  - "Simple" organic molecules appear to be abundant out there...
Origin of Life on Earth?

- Key Questions:
  1. Did life originate on Earth or in space?
  2. If life originated on Earth:
     a. What were the conditions like on early Earth that made possible the origin of life?
     b. Did life originate on or near the surface, below the surface, or in the oceans?

"Panspermia"

- Swedish chemist Svante Arrhenius proposed in 1908 that life is ubiquitous in the Cosmos and that "spores" or the seeds of life were delivered to Earth essentially by accident
- No attempt to explain how life originated, only how it got to Earth
- How did the "spores" get off other planets? (impacts?)
- How did the "spores" survive harsh interstellar radiation?
- More recent variation: "intentional" panspermia
  - Life was planted on Earth by space travelers
  - Popular among science fiction fans and conspiracy groupies
  - Still doesn’t explain how life originated though...

Organic Molecules in Meteorites

- Some complex organic molecules (molecules containing carbon) have been found in some of the most primitive carbonaceous chondrite meteorites
  - Alkanes, benzene, paraffins, amino acids, ...

Organic Molecules in Exotic Places

- Complex organic molecules have also been found or inferred to exist in:
  - Interstellar molecular clouds
  - Comets
  - Interplanetary dust particles
  - Some dark asteroids, rings, & planetary satellites
  - Some other “anomalous” meteorites (e.g., ALH84001)
- Did life on Earth originate from raw materials brought in by the early "rain" of debris from asteroid, comet, and cosmic dust impacts?
Could Life Have Originated on Earth?

- Hypothesized environment of the early Earth:
  - Heating of interior, release of volatiles
    - $H_2$, $H_2O$, $CH_4$ and $NH_3$
  - $H_2O$ forms liquid ocean at Earth's $P$, $T$
  - $NH_3$ dissolves in water
  - Result is a highly-reducing atmosphere
    - $H_2$, $CH_4$ abundant
    - Little if any free $O_2$
  - Can simulate this environment in the lab...

Life on Earth

- The Miller-Urey experiments were perhaps too simplistic, but they demonstrated that the interactions of liquid water, natural energy sources, and organic molecules leads to the production of complex organic molecules
- Even if the Urey/Miller process was not efficient enough to produce large quantities of organics, remember that organics formed elsewhere were still being delivered to the early Earth by impacts...
- The building blocks of life are abundant in the Cosmos!
- But how did the building blocks become alive ???

The Miller-Urey Experiments
(early 1950s, U. Chicago)

- Water = primitive ocean
  - $CH_4$, $NH_3$, $H_2$ = primitive atmosphere
- electrical discharge = lightning
- cycling through ocean...

- RESULTS:
  - complex organic molecules
  - simple amino acids!
  - life's building blocks!

Making Primordial Soup

Life on Earth

- Very soon after the early Earth cooled and the impact rate slowed, life appeared
- How? No one knows...
- Miller-Urey and more than 50 years of subsequent experiments have not been able to reproduce the result
- Life has slowly increased the amount of free $O_2$ in Earth's atmosphere over time
- Atmosphere is in disequilibrium

Jakosky (1998)
**Starting Simple...**

- Life on Earth started simple
- Most life on Earth remains simple
- All life on Earth is similar at a basic level

*Tree of Life* for Earth, based on similarity in RNA sequences among all life forms (past and present) on this planet (Woese, 1987)

**Complexity is rare...**

- A census of life on Earth today or 3 billion years ago would reach the same conclusion: life on Earth is dominated by simple bacteria!

**...and Accidents Happen!**

- Evolution towards more complex life forms is not necessarily inevitable
  - bacteria are very efficient life forms...
- External, even random forces play a role
  - e.g., Gould's theory of "punctuated equilibrium"
- Starting over again with the same initial conditions, could the experiment be repeated?
  - Would life form at all? (hmm...)
  - Would evolution follow the same path? (probably not)

**Some Big Questions**

- Has this happened elsewhere?
  - in the solar system?
  - in the Galaxy?
  - in the Universe?
- Can we use our knowledge of the formation and evolution of life on Earth to make predictions about the nature, distribution, and abundance of life "out there"?
- Should we seek simple life, or complex life?
Life in Extreme Environments

Evidence of the diversity of life is provided by groups of microorganisms known as extremophiles (lovers of extreme conditions). These life forms occupy niches of:
- Extreme temperature
- Extreme acidity
- Extreme salinity
- Greatest range: prokaryotes
  - Simple, single-celled organisms
- Substantial range: eukaryotes
  - More complex, nucleated, and/or multicellular organisms

Life on Earth

- Life developed early on the Earth
- Conditions have not always been ideal...
  - Changing atmospheric chemistry
  - Large-scale variations in climate
  - Active geology
  - Impacts
- The result of life’s adaptability to these variations is a dizzying array of diversity

Life in Extreme Environments!

- From permafrost to hot springs
- From battery acid to salty lakes
- Deep under the ocean
  - Life relies on geothermal energy
  - Deep under the ground
    - Life using geochemical energy
- Some organisms have even survived long-duration exposure to the vacuum and radiation of space

Extremophiles

Nealson (1997)
Life Elsewhere in Our Solar System?

- The enormous range of diversity and ruggedness of life on Earth has only recently been recognized.
- The idea of simple life beyond Earth is not as crazy as it used to be!
- We can make a "short list" of places to look:
  - Mars
  - Europa
  - Titan
  - Enceladus
- And there may be more that we could add...

Life on Mars?

- Mars preserves clues that its climate may once have been very different...
- And that there is still a substantial (?) inventory of water at or near the surface...
- And that there were abundant volcanic, impact, and/or geothermal heat sources...
- Liquid water, heat sources, organic molecules... the requirements for life as we know it!

Evidence of Life on Mars from a Meteorite?

- A small number (~50) of meteorites are thought to have come from Mars
- Special one: ALH84001
- Found in Antarctica in 1984
- Thought to be a sample of ancient Martian crust: radiometric age around 3.5 billion years
- Cosmic ray exposure indicates ejection from Mars around 15 million to 20 million years ago
- Outer chemical evidence indicates that it fell to Earth about 13,000 years ago

Evidence of Life on Mars from a Meteorite?

- Four pieces of evidence presented by scientists that ALH84001 preserves signs of past life on Mars:
  - Carbonate minerals: precipitated from a once thicker, warmer, atmosphere?
  - Magnetite grains: similar in shape to magnetite formed bacterially
  - Complex organic molecules: specifically PAH molecules
  - Segmented, "bacterial" shapes

Landmark paper published by McKay et al. (1996) Science, 273, p. 924
But Much Skepticism!

- Is the rock from Mars?
- Was it contaminated by Earth life while sitting in Antarctica for 13,000+ years?
- There have been abiologic explanations proposed for each piece of "biologic" evidence
- No "controls" on some new methods used
- "Extraordinary claims require extraordinary evidence" --Carl Sagan
- Proponents remain steadfast, despite more than a decade of skepticism and criticism...

The Real Message of ALH84001...

- Whether or not ancient fossil microbes actually exist in this Mars meteorite may be secondary
- ALH84001 and data from telescopes and space missions appear to show that:
  - liquid water existed in the Martian subsurface
  - complex organic molecules were there too
  - energy was provided by volcanoes, impacts, geothermal
  - The ingredients for life all appear to have existed at one time on Mars. Do they still exist today??

But: Growing prospects that there was (is?) life on Mars...

**NEWSFOCUS**

Growing Prospects For Life on Mars Divide Astrobiologists

As discoveries on Mars, including warm spots and salty soil, raise the chances of finding life there, scientists consider how best to look for it within their budget.

Science magazine, October 1, 2010...

BUT: Growing prospects that there was (is?) life on Mars...

- Discovery of "young," potentially-active gullies
- Discovery of pervasive subsurface ice deposits
- Discovery of minerals formed in water
- Evidence for "plumes" of methane gas
- Discovery of perchlorate (X\(\cdot\)ClO\(_4\)) in the soil/dust
- 2012 arrival of MSL...
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- 2012 arrival of MSL...
Possible abodes for life discovered in the Jupiter system by the Voyager and Galileo missions...

**Europa**
- Ice-covered Moon
- flat flat flat!
- Crust broken up into moving plates!
- "salty" deposits well up between plates
- Subsurface ocean??

**Ganymede**

**Callisto**

**Galilean Satellite Interiors**
- Iron-rich core
- Molten silicate interior
- Thin ice crust

**Europa**
- Silicate lower mantle
- Icy upper mantle
- Ice crust

**Ganymede**
- Partly differentiated ice-rock interior

**Callisto**
- Ice-rich outer layer

* Ridges show different compositions: hydrated sulfate salts that appear to have "erupted" from the interior (ocean?...
**Life on Europa?**

- Europa may have a subsurface **liquid water** ocean
- The ocean may be warmed by **tidal energy**
- **Organic molecules** delivered by comets over time?
- Could there be life down there?
- Finding out will not be easy
  - First, we must prove that there’s an ocean
  - Then, we must figure out how to access it
- And there are **ethical** issues to face as well, especially if we find evidence for life there

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**Titan**

- **Mercury-sized “planet”!**
- Thick, hazy atmosphere, with lots of hydrocarbons
  - formed by sunlight breaking up CH₄ molecules
  - similar to early Earth?
- Surface pressure: 1.5 bars!
- Surface temp.: 95K (-290°F)
**Life on Titan?**

- Complex organic chemistry in the clouds
- Molecules should sink and accumulate on surface
- Could be seas/lakes of liquid ethane ($\text{C}_2\text{H}_6$)?
- What happens to the organics on the surface?
  - Simple accumulation?
  - Geologic "recycling"?
  - "Evolution"?
- At $T=90\text{K}$, chemistry likely to be sluggish...
- The Huygens Probe studied Titan up close!

**Enceladus**

A tiny moon (only 500 km), but surprisingly active!

- Only 500 km diameter, yet internally active!
- Subsurface liquid water? Newest astrobiology “hotspot” in the solar system...
Other Possible Places for Clues

- "Hospitable" planetary atmosphere levels
- High up on Venus?
- Near the 1 bar level on Jupiter, Saturn?
- Subsurfaces of small bodies
  - Comets
  - Asteroids
  - Other planetary satellites
- What surprises await?