Life Beyond Earth

Ediacaran Fossil, one of the first multicellular organisms
Life As We Know It

How do we define life?

When did life arise on Earth and how do we know?

What factors are required for life?

Where are the best places to look for extraterrestrial life in our Solar System and beyond?

How will we know ‘life’ if/when we find it?
**Bacteria** - One of the three domains on the phylogenetic tree of life; this domain used to be synonymous with ‘prokaryote’ (no nucleus), but then *archaea* were identified as a distinct group.

**Archaea** - Prokaryotes that are distinct from bacteria. Originally thought to only occur in extreme environments, we now know that they are widespread in many habitats.

**Eukaryote** - An organism with a complex cell structure and a membrane-bound cell nucleus that contains genetic material; plants, animals, fungi, etc.; most (but not all) of the members utilize oxygen.
“Primordial soup again?”
On Earth, we have examined the ancient rock record in great detail to determine when and how life first arose on this planet.

As far as we can tell, the oldest putative microbial life is about the same age as the oldest known rocks.

Some of these detections are highly controversial, but if they are correct then it would suggest that life has been around for much of the history of the Earth.

However, it’s important to remember that Earth is dominated by plate tectonics, so most of the truly ancient rock record has been destroyed!
Life: The Early Years

Oldest Microfossils in Apex Chert from Western Australia? ~3.5 Ga

Oldest Eukaryotes ~1.8 Ga?
Some are found in the iron formations in northern Michigan, Wisconsin, Canada

Microbial Life?
Is There Any Evidence for Life Beyond Earth, Perhaps in the Rock Record on a Place Like Mars?
Searching for Life on Early Earth

Search for compositional indicators of past or present life

Chemical

Isotopes, Redox gradients

\[ \delta^{13}C \]

\[ \delta^{33,34}S \]

Molecular

Morphological

[Image of chemical structure]

[Image of morphological feature]

[Image of ruler for scale]
Searching for Life on Early Earth

Stromatolites
- Organo-sedimentary accretionary layers

Microfossils
- Preserved cell walls, skeletons, cysts, etc.

Biomarkers
- Molecular compounds specific to certain organisms

Geochemical/Mineralogic evidence
- Shifts in isotopes that correspond to enzymatic systems,
- Microbially mediated deposits (Banded Iron Formation?)

Molecular Clocks
- Backtracking based on mutations in genes
Stromatolites: Evidence for Life on Early Earth

Stromatolites are layered, accretionary structures that are preserved in the rock record (commonly in carbonate rocks or chert).

They are believed to be formed by the trapping and binding of sediment by biofilms composed of microorganisms (e.g., algae). Their shapes are quite diverse and they were apparently much more common on the ancient Earth.

Modern examples of stromatolites are extremely rare.

The stromatolite type "Conophyton" (image to the left) is hailed as a biogenic stromatolite, formed by photosynthetic cyanobacteria ~3.4 billion years ago....but could it instead be formed by an abiotic process??

Some stromatolites may form by simple accretion of sediment, no ‘life’ needed.
Microfossils

- Direct evidence of the presence of organisms.
- This could be soft cell walls that are remineralized, hard shells, or cysts and resting stages.
- Particular forms are diagnostic of specific species.
- Presence or absence can (but does not have to) be indicative of certain environmental conditions.
- Abundance can also indicate environmental conditions or shifts due to evolution.
Microfossils

“Eoentophysalis” - oldest fossil cyanobacteria? 
~1.9 billion years old

Cyanobacteria generate oxygen by photosynthesis. They ultimately led to the rise of oxygen on Earth.
The faded red curve shows a ‘classical, two-step’ view of atmospheric evolution, while the blue curve shows the emerging model (pO$_2$, atmospheric partial pressure of O$_2$). Right axis, pO$_2$ relative to the present atmospheric level (PAL); left axis, log pO$_2$. Arrows denote possible ‘whiffs’ of O$_2$ late in the Archaean; their duration and magnitude are poorly understood. An additional frontier lies in reconstructing the detailed fabric of ‘state changes’ in atmospheric pO$_2$, such as occurred at the transitions from the late part of the Archaean to the early Proterozoic and from the late Proterozoic to the early Phanerozoic (blue boxes). Values for the Phanerozoic are taken from refs. 96 and 97.

Summary of carbon (black) and sulphur (red and grey) isotope data through Earth’s history.

[Lyons et al., 2014]
Cell-like microspheres can be formed by agitating proteins and lipids in a liquid medium.

Each microsphere in the photo below is about 5 micrometers (µm) in diameter.

Pre-biotic chemists have synthesized molecules known as proteinoids, some of which consist of more than 200 linked amino acids when dehydrated, concentrated amino acids are heated.
Microfossils: Did Microspheres Enclose Early Cells?

The heated, dehydrated, concentrated amino acids spontaneously polymerize to form proteinoids.

Perhaps similar conditions for polymerization existed on early Earth, but the proteinoids needed to be protected by an outer membrane or they would break down.

Experiments show that proteinoids spontaneously aggregate into microspheres which are bounded by cell-like membranes.

In addition, proteinoids grow and divide much as bacteria do (see images below).
To verify that something is truly a ‘fossil’, we need to know the origin and age of the rock/sediment, that the object in question is indigenous to and deposited with the surrounding rock, and that it is clearly biologic in origin.

The oldest putative microfossils are in the Apex chert from western Australia and are 3.465 billion years old (published in 1993 in *Science*).

- 11 diverse species of filamentous objects similar to cyanobacteria-like organisms
- distinct ‘septa’ were present (dividing walls between objects)
- isotopic C signature indicated biological carbon fixation
- laser-Raman spectra were consistent with the presence of kerogen

*(kerogen = insoluble organic material) (bitumen = soluble organic material)*
Other scientists looked at the same rocks and found no evidence for fossils!

- Some shapes follow crystal ‘ghosts’ or are part of complex branching structures.
- The ‘septa’ may have been made by quartz interspersed into graphite (graphite is pure carbon).

Both the structures and the isotopes can be explained by non-biogenic hydrothermal processes.

Laser-Raman spectra are not characteristic of only kerogen... so was it really organic material?

**Figure 3** Automontages of inferred artefacts from the Apex chert. **a.** New image of putative beegiatoan *Eoleptonema* apex Holotype (ref. 3), combining the most sharply focused images from successive focal planes; **b, c,** digital image and interpretative sketch in the style of ref. 3 that omits the lower structure; **d, e,** new single image frames showing continuity of original and newly imaged structures. **f,** Topographic map showing computer-selected focal planes (plus scale in μm) of a; **g,** new image of putative cyanobacterium *Archaoscillatoriopsis disciformis* Holotype (ref. 3) showing rhombic ghost (arrow); **h, i,** digital image and interpretative sketch in the style of ref. 3 that omits the lower structure and side branch; **j, k, l,** new single image frames showing continuity of original and newly imaged structure. Scale bar, 40 μm.
The problems associated with arguing for life based primarily on morphology are perhaps best exemplified by the supposed ‘fossils’ in the martian meteorite ALH84001.

The identification of bacteria-like shapes in the meteorite caused a huge stir in the public and kicked off a decades-long debate in the scientific community.

The objects of interest (bottom image) looked roughly like connected cells and were argued to be biologic in origin. However, later studies showed that similar features with similar properties could be reproduced in the lab under abiotic conditions.
**Grypania**: The first "compelling" eukaryote, ~1.8 billion years old.

Some excellent examples are found in the iron formation deposits (bottom right) in the upper peninsula (Michigan) and Canada.
**Biomarkers**

**Biomarker:** An organic compound in natural materials (e.g., sediment, rock, water, soil, fossils, oil, etc.) that is unambiguously linked to specific precursor molecules made by living organisms.

**Diagenesis:** The transformation of sediments and organic material by low-temperature reactions and/or microbial activity; generally precedes metamorphism.

**Lipids:** Chemical compound that is insoluble in water but soluble in organic solvents. These compounds make up cellular membranes and become relatively enriched during diagenesis, and they are important starting material for the generation of petroleum.

**Biomarkers are characteristic of certain organisms or processes:**
- pigments reflect photosynthesis
- membrane lipids can indicate species

These compounds are often derived from lipids and can be very stable, and diagenesis can alter the compounds into more stable forms.

Not all organisms leave clear biomarkers; some are generated only during certain conditions.
Just as animals are transformed into ‘traditional’ fossils, so too can complex molecules be transformed into ‘chemical fossils’.

As with other fossils, the final product is not identical to the original product, but it is similar enough that there are telltale clues to its origin.
Creation is Hard, Preservation is Even Harder

Organic matter passes through a series of reduction-oxidation (‘redox’) reactions in the water and sediments. In a very general sense, oxidation destroys organic matter.

- **O₂ respiration:** \( \text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{H}_2\text{O} + \text{CO}_2 \)

- **Denitrification:** \( 4/5\text{H}^+ + \text{CH}_2\text{O} + 4/5\text{NO}_3^- \rightarrow \text{CO}_2 + 2/5\text{N}_2 + 7/5\text{H}_2\text{O} \)

- **Manganese reduction:** \( 4\text{H}^+ + \text{CH}_2\text{O} + 2\text{MnO}_2 \rightarrow 2\text{Mn}^{2+} + 3\text{H}_2\text{O} + \text{CO}_2 \)

- **Iron reduction:** \( 8\text{H}^+ + \text{CH}_2\text{O} + 4\text{FeOOH} \rightarrow 4\text{Fe}^{2+} + \text{CO}_2 + 7\text{H}_2\text{O} \)

- **Sulfate reduction:** \( \text{H}^+ + \text{CH}_2\text{O} + 1/2\text{SO}_4^{2-} \rightarrow \text{CO}_2 + 1/2\text{H}_2\text{S} + \text{H}_2\text{O} \)

Only ~5% of organic matter reaches sediments, and <1% is actually buried.

Proteins & sugars are lost first; the more stable lipids remain.

Eventually the lipids are geopolymerized to kerogen (insoluble organic material) and converted to oil/natural gas.

As temperature increases, you pass through the oil & gas windows and ultimate the organic material breaks down to pure carbon (graphite); at ~225°C.
Biomarkers (chemical fossils) are detected and identified using the technique of gas chromatography (GC) and mass spectrometry (MS).

The GC technique separates components and can tell us abundances of individual components.

The MS technique allows us to break unknown complex molecules into fragments; the mass of the fragments lets us determine the identity of the unknown molecules.

These 2 techniques are often combined into one instrument: the GC-MS.

This is the primary way we identify biomarkers.

Though the method is complex, a GC-MS is being flown on the 2011 MSL rover and will be the primary instrument used in the search for organic material on Mars.
Contamination is a serious issue when searching for ancient life on Earth, and it is certainly an issue when searching for life beyond Earth.

Indeed, if a mission like the MSL rover actually detects organic material on a place like Mars, the first question will be “Is it actually indigenous to Mars?”

Followed by “Is it biological in origin?”
For all the diversity of life on Earth, the basic biochemistry of life isn’t really that diverse at all. To make life possible, you need **water**, **energy**, and the **right elements (CHNOPS)**.
What Does Life Need?

Life alleviates chemical disequilibrium in the environment.

Earth is dynamic, with many niches of chemical disequilibrium.