Conditions on Early Earth and the Search for Other Earth-like Planets

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Talk outline

- **Part 1**: Conditions on the early Earth
- **Part 2**: The search for Earth-like planets and life outside the Solar System (only covered if questions arise...)
When did life arise?

- This question is currently in controversy.
- Until the 1940’s, geologists thought that life only began around 540 m.y. ago at the dawn of the Phanerozoic Eon.
- But we now know that the record of life extends well back into the Precambrian Eon.

Artist’s depiction of life in the Cambrian oceans

http://www.fas.org/irp/imint/docs/rst/Sect20/A12.html
# Geologic time

<table>
<thead>
<tr>
<th>EON</th>
<th>ERA</th>
<th>Duration in millions of years</th>
<th>Millions of years ago</th>
</tr>
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<tbody>
<tr>
<td>PHANEROZOIC</td>
<td>CENOZOIC</td>
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<td></td>
<td>MESOZOIC</td>
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<td></td>
<td>PALEOZOIC</td>
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<td>543</td>
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<td>PROTERZOIC</td>
<td>LATE</td>
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<td></td>
<td>MIDDLE</td>
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<td>1600</td>
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<tr>
<td></td>
<td>EARLY</td>
<td>900</td>
<td>2500</td>
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<tr>
<td>PRECAMBRIAN</td>
<td>LATE</td>
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</tr>
<tr>
<td></td>
<td>MIDDLE</td>
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<td>3400</td>
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<tr>
<td></td>
<td>EARLY</td>
<td>400</td>
<td>3800</td>
</tr>
<tr>
<td></td>
<td>HADEAN</td>
<td>800</td>
<td>4600</td>
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</table>

- First shelly fossils (Cambrian explosion)
- Snowball Earth ice ages
  - Warm
  - Rise of atmospheric $O_2$ (Ice age)
    - Ice age
      - Warm (?)
    - Origin of life
Archean microfossils

Summary of evidence

- Taken as a whole, the evidence supports the idea that life had evolved by 3.5 Ga, and possibly earlier
- What were the environmental conditions at this time?

1. What was the *atmospheric composition* during the Hadean/early Archean?
Early atmospheric composition

- **Old idea**: Early atmosphere was dominated by *methane* and *ammonia*
- This was based, in part, on Harold Urey’s observations of Jupiter and Saturn
  - He thought that Earth should have resembled these planets before its hydrogen had time to escape
- Earlier thinkers: Oparin and Haldane
Miller-Urey experiment

- This hypothesis was supported by the famous Miller-Urey experiment.
- Organic compounds were formed in the atmosphere by electrically and/or photochemically driven reactions.
- Requires a strongly reduced atmosphere (CH₄, NH₃, H₂O).
Why you can’t have a dominantly methane-ammonia atmosphere

- Ammonia is *photochemically unstable* with respect to conversion to N\textsubscript{2} and H\textsubscript{2} (Kuhn and Atreya, 1979)

\[
\begin{align*}
\text{(R70)} &: \quad \text{NH}_3 + h\nu \rightarrow \text{NH}_2 + \text{H} \\
\text{(R75)} &: \quad \text{NH}_2 + \text{NH}_2 + \text{M} \rightarrow \text{N}_2\text{H}_4 + \text{M} \\
\text{(R81)} &: \quad \text{N}_2\text{H}_4 + \text{H} \rightarrow \text{N}_2\text{H}_3 + \text{H}_2 \\
\text{(R80)} &: \quad \text{N}_2\text{H}_4 + h\nu \rightarrow \text{N}_2\text{H}_3 + \text{H} \\
\text{(R83)} &: \quad \text{N}_2\text{H}_3 + \text{N}_2\text{H}_3 \rightarrow \text{N}_2\text{H}_4 + \text{N}_2\text{H}_2 \\
& \quad \rightarrow \text{N}_2\text{H}_4 + \text{N}_2 + \text{H}_2
\end{align*}
\]
Why you can’t have a dominantly methane-ammonia atmosphere

**Ethane formation:**

1) \( \text{CH}_4 + \text{h} \xrightarrow{\text{UV}} \text{CH}_3 + \text{H} \)  
   or  
2) \( \text{CH}_4 + \text{OH} \xrightarrow{\text{reaction}} \text{CH}_3 + \text{H}_2\text{O} \)

Then

3) \( \text{CH}_3 + \text{CH}_3 + \text{M} \xrightarrow{\text{reaction}} \text{C}_2\text{H}_6 + \text{M} \)

• \( \text{CH}_4 \) also photolyzes, although at a slower rate than does \( \text{NH}_3 \)
• This leads to the formation of longer-chain hydrocarbons by a process termed *polymerization*...
Titan’s organic haze layer

- The net result is formation of organic haze, like the haze that exists on Saturn’s moon, Titan
- It can produce an anti-greenhouse effect if it gets too thick

(Picture from Voyager 2)
Weakly reduced atmosphere

Furthermore

- Modern volcanic gases are relatively oxidized
  - Mostly CO$_2$ and H$_2$O, little CH$_4$ or NH$_3$
- For all these reasons, the early atmosphere is thought to have been only *weakly reduced*
- Such an atmosphere is not very conducive to Miller-Urey type synthesis

2. What was the *climate* like during the Hadean/early Archean?

- The young Sun was significantly (25-30%) *fainter* than today.
The faint young Sun problem

\[ T_e = \text{effective radiating temperature} = \left[ \frac{S(1-A)}{4 \, \text{W}} \right]^{1/4} \]

\[ T_S = \text{average surface temperature} \]

Kasting et al., *Scientific American* (1988)
The best solution to this problem is higher concentrations of greenhouse gases in the distant past.

Kasting et al., *Scientific American* (1988)
In the simplest story, atmospheric CO$_2$ levels should have declined monotonically with time as solar luminosity increased.

Various geochemists have challenged this hypothesis, but I now think that those challenges are all baseless.
• Despite the theoretical expectation for cool temperatures based on low solar flux, oxygen isotopes predict extremely high surface temperatures 🌋️
O isotopes—the last 900 k.y.

- Oxygen isotopes are used routinely to infer paleotemperatures on the glacial-interglacial time scale

after Bassinot et al. 1994
Marine carbonate $^{18}$O vs. time
(detailed, time axis reversed)

- When one looks at long time scales, however, one finds a very large negative shift in $^{18}$O, suggesting high surface temperatures

Shields & Veizer, G$^3$, 2002
\( ^{18}\text{O} \) of modern and ancient cherts (\( \text{SiO}_2 \))

- Cherts, which are better preserved, tend to show the same trend, *i.e.*, they get isotopically lighter (in O) as they get older

**Chert data:**

- Mean surface temperature was $70\pm 15^\circ C$ at 3.3 Ga
  

**Carbonate data:**

- Surface temperatures remain significantly elevated until as recently as the early Devonian (~400 Ma)
• Biological data *seem* to support the idea of a high-temperature origin of life, and possibly a hot early Earth

• We see this in *ribosomal RNA* and in *proteins*
“Universal” (rRNA) tree of life

Red shading indicates hyperthermophiles ($T_{\text{growth}} > 80^\circ C$)

Courtesy of Norm Pace
• I don’t believe that the Archean Earth was hot, however, because there were glaciations at ~2.4 Ga and 2.9 Ga
Geologic time

First shelly fossils (Cambrian explosion)

Snowball Earth ice ages

Warm

Rise of atmospheric O₂ (Ice age)

Ice age

Warm (?)

Origin of life
Possible explanations for the oxygen isotope data

- All ancient carbonates and cherts have been altered by *diagenesis*
  - The $^{18}$O values represent the temperature in the sediments, not in the ocean
- Seawater $^{18}$O has varied with time
- The high temperatures derived from the cherts are a result of widespread hydrothermal activity on the seafloor (van den Boorne et al., Geology, 2007)
Possible explanations for thermophilic common ancestors

1. Phylogenetic data may be *biased* (?)  
2. Surface temperatures on the early Earth were uniformly *hot*  
3. Life originated at high temperatures, perhaps in a midocean ridge hydrothermal vent  
4. Life originated at low temperatures in some surface environment, then colonized the midocean ridge vents  
   - Surface life was then wiped out by a *big impact*, and life recolonized the Earth from the vents
Hydrothermal vent model for life’s origin

- Organic synthesis took place in hydrothermal vents at midocean spreading ridges
- Liquid-solid interfaces available
- Strong free energy gradients
- “Pyrite-pulled” reactions (Wächtershauser)

“Black smoker”

(Photo taken from Alvin)

T $\geq$ 350°C
pH = 4-5
Conclusions

- Earth’s early atmosphere was probably weakly reduced
  - Mostly N₂ and CO₂ with a little H₂ and CO
- The climate was probably relatively cool by the time that life originated
- Life may have originated in an off-axis hydrothermal vent environment
  - Such environments may have been widespread on the ancient seafloor
- A promising way to investigate the origin of life is to search for habitable worlds around other stars and see if life has originated elsewhere
Ancestral elongation factor proteins (EF-Tu) of all organisms (panel a) and even of mesophiles (panel b) indicate a thermophilic common ancestor for extant life (40-80°C).
Palaeotemperature trend for Precambrian life inferred from resurrected proteins

Eric A. Gaucher¹, Sridhar Govindarajan² & Omjoy K. Ganesh³

Nature, Feb., 2008

- More recent work by this group proposes a detailed time scale for surface temperature evolution, based on two different molecular clock techniques.
- Ancestral genes were synthesized and cloned into *E. coli* to allow them to be expressed as proteins.
- Protein *melting points* were then measured in the lab.

![Graph showing O isotope data](image)

**Figure 3**: Plot of ancestral EF melting temperatures against geological time. Molecular clock estimates are shown with their confidence intervals (horizontal bars) from ref. 16, using a 2.3-Ga minimum constraint for the Great Oxidation Event. Solid lines are temperature curves of the ancient ocean inferred from maximum δ¹⁸O (light grey⁴, dark grey⁵). Although not shown, an analogous trend is seen with δ³⁰Si isotopes⁶.
• **Part 2:** The search for Earth-like planets and life outside the Solar System
Radial velocity (Doppler) method

- Many extrasolar planets (over 500) have been detected already, most by using the *radial velocity*, or Doppler, method
- None of these RV planets are as small as Earth, however
  - Detecting Earth-mass planets around solar-type stars may or may not be possible with this technique (ongoing debate)
“Hot Jupiters”

G. Marcy and P. Butler (circa 2002)

Mayor and Queloz (1996)
Known extrasolar planets

- 548 extrasolar planets identified as of May 11, 2011
  - 500 by radial velocity
  - 128 transiting planets
  - 12 microlensing
  - 24 direct imaging
  - 12 pulsar planets
  - 60(?) multiple planet systems

- Few, if any, of these planets are very interesting, however, from an astrobiological standpoint
  - Gliese 581g (the “Goldilocks planet”) is probably not real

Info from *Extrasolar Planets Encyclopedia* (Jean Schneider, CNRS)

http://exoplanets.org/massradiiframe.html
Transit method

- The light from the star dims if a planet passes in front of it.
- Jupiter's diameter is 1/10th that of the Sun, so a Jupiter transit would diminish the sunlight by 1%.
- Earth's diameter is 1% that of the Sun, so an Earth transit decreases sunlight by 1 part in $10^4$.
- The plane of the planetary system must be favorably oriented.
  - Transit probability is $\pi R_*/a$.

Image from Wikipedia
Kepler Mission

• This space-based telescope will point at a patch of the Milky Way and monitor the brightness of ~160,000 stars, looking for transits of Earth-sized (and other) planets
• $10^5$ precision photometry
• 0.95-m aperture capable of detecting Earths
• Launched: March 5, 2009

http://www.nmm.ac.uk/uploads/jpg/kepler.jpg
Kepler target field: The stars in this field range from a few hundred to a few thousand light years in distance.
February 2011 data release

Table 5. Number of Candidates versus Size.

<table>
<thead>
<tr>
<th>Candidate Label</th>
<th>Candidate Size $(R_p)$</th>
<th>Number of Candidates plus known planets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth-size</td>
<td>$R_p \leq 1.25$</td>
<td>68</td>
</tr>
<tr>
<td>super-Earth-size</td>
<td>$1.25 &lt; R_p \leq 2.0$</td>
<td>288</td>
</tr>
<tr>
<td>Neptune-size</td>
<td>$2.0 &lt; R_p \leq 6.0$</td>
<td>662</td>
</tr>
<tr>
<td>Jupiter-size</td>
<td>$6.0 &lt; R_p \leq 15$</td>
<td>165</td>
</tr>
<tr>
<td>very-Large-size</td>
<td>$15.0 &lt; R_p \leq 22.4$</td>
<td>19</td>
</tr>
<tr>
<td>Not considered</td>
<td>$R_p &gt; 22.4$</td>
<td>15</td>
</tr>
</tbody>
</table>

- 1235 “planet candidates” total orbiting 997 stars
- 54 planets within the habitable zone (as defined by the Kepler team), 4 or 5 of which are probably rocky
Kepler habitable zone planets

Borucki et al., Ap. J., v2, submitted Mar., 2011 (Fig. 4)
• What we’d really like to do is to build a big TPF (Terrestrial Planet Finder) telescope and search directly for Earth-like planets.
• We can also look for spectroscopic biomarkers (O₂, O₃, CH₄) and try to infer the presence or absence of life on such planets.
• Need a lot of money ($5B or more) to do this!