The Faint Young Sun Problem

Long-term climate/
Solar luminosity changes/
Constraints on atmospheric CO$_2$/
The methane greenhouse

J. F. Kasting
<table>
<thead>
<tr>
<th>Era</th>
<th>Period</th>
<th>Epoch</th>
<th>Duration in millions of years ago</th>
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<td>First shelly fossils</td>
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<td>Age of fish</td>
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<tr>
<td>Ice age</td>
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<td>First vascular plants on land</td>
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<td>First dinosaurs</td>
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<td>Dinosaurs go extinct</td>
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<td>Ice age (Late Cenozoic)</td>
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<td>Ice age (Warm)</td>
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<td>First dinosaurs (Warm)</td>
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<td>Phanerozoic Time</td>
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### Geologic time

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- **First shelly fossils (Cambrian explosion)**
- **Snowball Earth ice ages**
- **Rise of atmospheric O$_2$ (Ice age)**
- **Ice age**
- **Warm (?)**
- **Origin of life**
• From a theoretical standpoint, it is curious that the early Earth was *warm*, because the Sun is thought to have been *less bright* ⇒
Why the Sun gets brighter with time

- H fuses to form He in the core
- Core becomes denser
- Core contracts and heats up
- Fusion reactions proceed faster
- More energy is produced
  \[ \Rightarrow \] more energy needs to be emitted

Figure redrawn from D.O. Gough, Solar Phys. (1981)
Enhanced solar mass loss?

- Are we sure that the Sun was less bright back in the past?
- What if the young Sun was more massive than today?
  - Brian Wood and colleagues at Univ. of Colorado have derived empirical constraints from observations of nearby young stars (see backup slides)
  - Their conclusion is that any massive solar mass loss must have occurred very early, within the first 100-200 m.y.; hence, it does not affect the Earth during the time period of interest to geologists or astrobiologists

- One cannot measure (fully ionized) stellar winds directly, but one can look at neutral hydrogen that builds up the stellar astrosphere
• So, I will assume that the young Sun was really faint, as predicted by the standard model.

• This has big implications for planetary climates, as first pointed out by Sagan and Mullen (1972)…
The faint young Sun problem

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

$T_S = \text{average surface temperature}$

Kasting et al., *Scientific American* (1988)
The faint young Sun problem

- The best solution to this problem is higher concentrations of greenhouse gases in the distant past (but not H\textsubscript{2}O, which only makes the problem worse).
Greenhouse gases

- Greenhouse gases are gases that let most of the incoming visible solar radiation in, but absorb and re-radiate much of the outgoing infrared radiation.

- Important greenhouse gases on Earth are CO$_2$, H$_2$O, and CH$_4$.
  - H$_2$O, though, is always near its condensation temperature; hence, it acts as a feedback on climate rather than as a forcing mechanism.

- The decrease in solar luminosity in the distant past could have been offset either by higher CO$_2$, higher CH$_4$, or both. Let’s consider CO$_2$ first.
The carbonate-silicate cycle

- Silicate weathering slows down as the Earth cools
  ⇒ atmospheric CO$_2$ should build up
- This is probably at least part of the solution to the faint young Sun problem
In the simplest story, atmospheric CO$_2$ levels should have declined monotonically with time as solar luminosity increased.
But, various geochemists have attempted to place limits on past CO\textsubscript{2} levels.

According to these authors, the absence of siderite (FeCO\textsubscript{3}) places an upper bound on pCO\textsubscript{2}.
More recently, Rosing et al. (Nature, 2010) have tried to place even more stringent constraints on past CO$_2$ using banded iron-formations (BIFs).

I actually don’t believe any of these constraints.

Nevertheless, there are reasons to think that other greenhouse gases were present.
Sagan and Mullen liked ammonia (NH$_3$) and methane (CH$_4$) as Archean greenhouse gases.

As a result of Preston Cloud’s work in the late 1960’s, they were aware that atmospheric O$_2$ was low on the early Earth.
• “Conventional” geologic indicators show that atmospheric O₂ was low prior to ~2.2 Ga

H.D. Holland (1994)

• Mass-independently fractionated sulfur isotopes strongly support this conclusion
--- I’ll return to this topic in the next lecture
• But Sagan and Mullen hadn’t thought about the photochemistry of ammonia
Problems with Sagan and Mullen’s hypothesis

• Ammonia is *photochemically unstable* with respect to conversion to $N_2$ and $H_2$ (Kuhn and Atreya, 1979)

\[
\begin{align*}
(R70) & \quad \text{NH}_3 + h\nu \rightarrow \text{NH}_2 + H \\
(R75) & \quad \text{NH}_2 + \text{NH}_2 + M \rightarrow \text{N}_2\text{H}_4 + M \\
(R81) & \quad \text{N}_2\text{H}_4 + H \rightarrow \text{N}_2\text{H}_3 + \text{H}_2 \\
(R80) & \quad \text{N}_2\text{H}_4 + h\nu \rightarrow \text{N}_2\text{H}_3 + H \\
(R83) & \quad \text{N}_2\text{H}_3 + \text{N}_2\text{H}_3 \rightarrow \text{N}_2\text{H}_4 + \text{N}_2\text{H}_2 \\
& \quad \rightarrow \text{N}_2\text{H}_4 + \boxed{\text{N}_2 + \text{H}_2}
\end{align*}
\]

-- $N_2$ and $H_2$ do not readily recombine to form $NH_3$
-- $N_2$ ($N\equiv N$) is stable, and the $H_2$ escapes to space
-- This said, $CH_4$ remains a viable candidate…
Other reasons for liking CH₄ in addition to CO₂

- Substrates for methanogenesis should have been widely available, e.g.:
  \[ \text{CO}_2 + 4 \text{H}_2 \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O} \]

- Methanogens (organisms that produce methane) are evolutionarily ancient
  - We can tell this by looking at their DNA
  - In particular, we look for that part of the DNA that codes for the RNA in their ribosomes
Ribosomal RNA

- Ribosomes are organelles (inclusions) within cells in which proteins are made.
- Surprisingly (or not), ribosomes contain their own RNA (ribonucleic acid).
  - The RNA is also the catalyst for protein synthesis, indicating that life may have passed through an “RNA World” stage.
- The RNA in ribosomes evolves very slowly, so looking at differences in the RNA of different organisms allows biologists to look far back into evolution.

Methanogenic bacteria

“Universal” (rRNA) tree of life

Courtesy of Norm Pace
• Back to climate...
Feedbacks in the methane cycle

- Furthermore, there are strong feedbacks in the methane cycle that would have helped methane become abundant.
- Doubling times for thermophilic methanogens are shorter than for mesophiles.
- Thermophiles will therefore tend to outcompete mesophiles, producing more CH$_4$ and further warming the climate.
CH$_4$-climate positive feedback loop

- Methanogens grow faster at high temperatures
Furthermore,

- If CH₄ becomes more abundant than about 1/10ᵗʰ of the CO₂ concentration, it begins to polymerize ⇒
Organic haze photochemistry

This leads to the formation of ethane \((\text{C}_2\text{H}_6)\), ethylene \((\text{C}_2\text{H}_4)\), and acetylene \((\text{C}_2\text{H}_2)\)

**Ethane formation:**
1) \(\text{CH}_4 + \text{hv} \rightarrow \text{CH}_3 + \text{H}\) or
2) \(\text{CH}_4 + \text{OH} \rightarrow \text{CH}_3 + \text{H}_2\text{O}\)
3) \(\text{CH}_3 + \text{CH}_3 + \text{M} \rightarrow \text{C}_2\text{H}_6 + \text{M}\)

- “Standard”, low-\(\text{O}_2\) model from Pavlov et al. (*JGR*, 2001)
- 2500 ppmv \(\text{CO}_2\), 1000 ppmv \(\text{CH}_4\) \(\Rightarrow\) 8 ppmv \(\text{C}_2\text{H}_6\)
Ethane (C$_2$H$_6$) is a good greenhouse gas because it absorbs within the 8-12 $\mu$m “window” region. It can provide several degrees of greenhouse warming.
• If the CH$_4$:CO$_2$ ratio exceeds about 0.1, however, *organic haze* begins to form, as it does on Saturn’s moon, Titan ⇒
Titan’s organic haze layer

- The haze is formed from UV photolysis of CH$_4$
- It creates an *anti-greenhouse effect* by absorbing sunlight up in the stratosphere and re-radiating the energy back to space
- This *cools* Titan’s surface
Possible Archean climate control loop

- CH₄ production
- Haze production
- Atmospheric CH₄/CO₂ ratio
- CO₂ loss (weathering)
- Surface temperature

(−)
• When one puts all of this together, one can estimate surface temperature as a function of $f_{\text{CH}_4}$ and $p_{\text{CO}_2}$
• When atmospheric $O_2$ went up at 2.4 Ga, $\text{CH}_4$ would have gone down, possibly triggering the *Paleoproterozoic glaciations* ⇒

Huronian Supergroup (2.2-2.45 Ga)

S. Roscoe, 1969
Conclusions

• The Sun really was ~30% dimmer during its early history
  – Any deviation from this would have been too short-lived to be meaningful

• CO$_2$, CH$_4$, and C$_2$H$_6$ may all have contributed to the greenhouse effect back when atmospheric O$_2$ levels were low

• High atmospheric CH$_4$/CO$_2$ ratios can trigger the formation of organic haze. This has a cooling effect.
  – Stability arguments suggest that the Archean climate may have stabilized when a thin organic haze was present

• The Paleoproterozoic glaciation at ~2.4 Ga may have been triggered by the rise of O$_2$ and loss of the methane component of the atmospheric greenhouse
• Backup slides (stellar mass loss constraints)
Was the young Sun really faint?

- Solar luminosity is a strong function of solar mass: $L_{\odot} \sim M_{\odot}^4$
- Planetary orbital distance varies inversely with solar mass: $a \sim M_{\odot}^{-1}$
- Solar flux varies inversely with orbital distance: $S \sim a^{-2}$
- Flux to the planets therefore goes as $S \sim M_{\odot}^6$
Estimating stellar mass loss

• The question of stellar mass loss has been addressed empirically by Brian Wood and colleagues at Univ. of Colorado
• They looked for evidence of bow shock interactions around nearby young solar analog stars
  – Stellar winds themselves are fully ionized and impossible to see, but neutral hydrogen builds up at the bow shock

http://www.answers.com/topic/heliosphere
Ly $\alpha$ spectrum of $\varepsilon$ Eridani (from HST)

Estimated mass loss rate vs. stellar age

Wood et al. (2002)
Wood et al. (2002)

⇒ The Sun was probably back on the standard solar evolution curve by \(\sim 4.4 \text{ Ga (i.e., 4.4 Gyr ago)}\)