Radiative Balance and the Faint Young Sun Paradox

- Solar Irradiance
- Inverse Square Law
- Faint Young Sun
- Early Atmosphere

Earth, Water, and Life

1. Water - essential medium for life.
2. Water - essential for tectonics
3. Sedimentary rocks and stable isotope data at $3.8 \times 10^9$ yr indicate the presence of liquid water.
4. Earth is unusually wet.
   - Venus: very dry, water vapor
   - Mars: ice
   - Earth: ice, vapor, liquid

Is Earth just the right distance from the Sun to have liquid water?

The root of the paradox

[Graph showing increased He burning in the Sun's core over time]
Modern Global Mean T ~ 15°C (288 K)
4.5x10^9 yr - Effective T would be ~87% present (~22°C or 251 K)

The Faint Young Sun Paradox

- Atmosphere traps heat - Greenhouse
- Steady state - energy balanced!

http://www.science.uwaterloo.ca/~cchieh/cact/applychem/atmosphere.html

Atmosphere Structure

How hot is (was) Earth?

At steady state: Energy in = Energy Out

A. How much energy does the Earth get from the Sun?
1. The Sun emits electromagnetic radiation across a wide range of wavelengths.
   - 40% - infrared/microwave (longwave radiation)
   - 50% - visible
   - 10% - ultraviolet and x-ray/gamma ray (shortwave radiation).

   We'll soon understand why the sun emits so strongly in the visible range.
2. The amount of energy arriving on Earth is a function of distance from the sun.

Flux: the amount of energy (or material) that passes through a given area, measured perpendicular to that area, per unit time.

Solar energy flux ($S$) varies with distance according to the Inverse Square Law

$$ S = S_0 \left( \frac{r_0}{r} \right)^2 $$

- $S$ = solar flux
- $S_0$ = solar flux at ref point (e.g., Earth)
- $r$ = distance (AU)

At 1 AU/Earth’s orbit (~1.50x10^8 km), the mean solar flux ($S_2$) is: ~1370 W/m² (Watt = unit of power = J/s = N*m/s)

For Jupiter ~ 5.2 AU, ~$(1/5)^2 \sim 4\%$

3. Solar flux intercepted by Earth = area of a disk with Earth’s radius ($\pi r^2$) less the flux reflected (to space).

Energy in = solar flux$_{sun}$ - reflected

Energy in = $\pi r_E^2 S_0 - \pi r_E^2 S_0 A$

- $r_E$ = earth’s radius (6370 km)
- $A$ = Earth’s albedo

Albedo - reflectivity of a surface, expressed as a fraction of total incident energy
- low albedo (water ~ 0.07-0.20)
- high albedo (ice ~ 0.5 - 0.9)

$A_{Earth} = 0.3$

Energy in = $\pi r_E^2 S_0 (1-A)$
B. How much energy does the Earth radiate back to space?
1. The wavelength of radiation emitted is related to the temperature.

Wien’s Law: radiation flux emitted by a body peaks at a wavelength ($\lambda$) that is inversely proportional to its $T$ (K).

$$\lambda \text{ (\mu m)} \approx \frac{b}{T} \text{ (K)}$$

$$\lambda \approx 2898 \text{ (\mu m/K)} / T \text{ (K)}$$

- Sun radiates mostly at visible wavelengths
  - Sun’s $T$ is 5780 K; radiates at what $\lambda$?
- Earth radiates at longer, infrared wavelengths
  - Earth’s $T$ is 288 K; what is $\lambda$?

2. The flux of energy from a body is proportional to its temperature.

**Stefan-Boltzmann Law:**

$$F = \sigma T_e^4$$

- $F$ = energy flux (W/m$^2$)
- $T_e$ = effective radiating $T$ (K) (no atmosphere)
- $\sigma$ = Boltzmann constant: $5.67 \times 10^{-8}$ (W/m$^2$/K$^4$

3. Energy reradiates over Earth’s entire surface (as a sphere).

Energy out $= 4\pi r_E^2 \sigma T_e^4$

- $r_E$ = Earth’s radius
- $T_e$ = Earth’s surface temperature

**Energy balance equation**

At steady state (Radiative equilibrium),

Energy absorbed = Energy emitted

$$4\pi r_E^2 S_e (1-A) = 4\pi r_E^2 \sigma T_e^4$$

solve for $T_e$

$$T_e (1-A) = \sigma T_e^4$$

$$\sigma T_e^4 = S_e (1-A) / 4$$

If $A = 0.3$ and $S = 1370$ W/m$^2$ $T_e$ of 255 K (-18°C).

The mean surface temperature ($T_e$) of Earth

$\sim 288$ K (+15°C).

- extra 33 K of heat?

**Greenhouse Gases**
Atmosphere Composition

H$_2$O, Trace Gases - absorb (trap) energy

<table>
<thead>
<tr>
<th>Gas</th>
<th>Concentration (ppm)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$</td>
<td>780,840</td>
<td>78.084</td>
</tr>
<tr>
<td>O$_2$</td>
<td>209,470</td>
<td>20.947</td>
</tr>
<tr>
<td>Ar</td>
<td>9340</td>
<td>0.934</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>380</td>
<td>0.038</td>
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<tr>
<td>Ne</td>
<td>18.2</td>
<td>0.00182</td>
</tr>
<tr>
<td>He</td>
<td>5.2</td>
<td>0.00052</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>1.7</td>
<td>0.00017</td>
</tr>
<tr>
<td>Kr</td>
<td>1.1</td>
<td>0.00011</td>
</tr>
<tr>
<td>H$_2$</td>
<td>0.5</td>
<td>0.00005</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>0.3</td>
<td>0.00003</td>
</tr>
<tr>
<td>Xe</td>
<td>0.1</td>
<td>0.00001</td>
</tr>
<tr>
<td>O$_3$</td>
<td>0 to 8.0</td>
<td>0.000080</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>0.1 to 40,000</td>
<td>0.0001 to 4</td>
</tr>
</tbody>
</table>

A more detailed Energy Balance at Earth’s surface

Incoming shortwave solar radiation?
- 30% reflected back (Albedo)
  - air
  - clouds
  - land/water
- 23% absorbed - atmos.
  - vapor, CO$_2$
  - clouds
- 47% absorbed - land/ocean

Outgoing long wave radiation
- 70% absorbed eventually returns to space

Absorption Characteristics of Gas Molecules are variable

Greenhouse gas: absorb and emit IR radiation

EM wave (w/ specific frequency) is absorbed by a molecule, increasing rotation rate.
- frequency $\sim$ molecule’s structure.
Earth's IR emissions peak at ~15µm. This is why CO$_2$ is an important greenhouse gas.

Global Warming: Why worry about trace gasses?

- H$_2$O - broadest absorption spectrum
- Absorption in those bands ~ saturated!
- **THE GAP** (6-15 µm) filled by trace gases such as CH$_4$, O$_3$, CFCs, sulfide gasses
Into Earth: $S(1-A)/4 + \sigma T_e^4$
Out of Earth: $\sigma T_e^4$
1) Energy balance for Earth: $S(1-A)/4 + \sigma T_e^4 = \sigma T_s^4$

Into Atmosphere: $S/4 + \sigma T_s^4$
Out of Atmosphere: $2\sigma T_e^4$
2) Energy balance for Atmosphere: $\sigma T_s^4 = 2\sigma T_e^4$

Substitute 2nd equation into 1st: $S(1-A)/4 + \sigma T_e^4 = 2\sigma T_e^4$
3) $S(1-A)/4 = \sigma T_e^4$

Rearrange 2nd equation: 4) $T_s = 2^{0.25}T_e$

If 3rd equation says $T_e = 255$ K, then 4th equation says surface temperature is 303 K.

$\Delta T_s = 48$ K, 15 K higher than actual Greenhouse.

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Evolution of Earth’s Climate

- First shelly fossils (Cambrian explosion)
- Snowball Earth ice ages
- Warm
- Rise of atmospheric O$_2$ (Ice age)
- Ice age (?)
- Warm (?)

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Solar luminosity (relative to today)

Time (byr B.P.)

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The Faint Young Sun Paradox

Solar Solutions?
- Sun more massive? Greater luminosity? Lost mass via solar wind?
- Stronger solar wind, lower cosmic ray flux, lower albedo?

Terrestrial solutions to the FYS Paradox
- Albedo changes?
  - Less cloudiness on warm early Earth?
    - Unlikely
- Increased greenhouse gas concentrations
  - NH₃: Doesn’t work (photolyzes rapidly)
  - CO₂: Works! (supplied by volcanoes)
  - CH₄: Also works (probably requires life)
- Important to understand climate feedbacks

Systems Notation

= system component
-> = positive coupling
--- = negative coupling
Positive Feedback Loops (Destabilizing)

Surface temperature \[\rightarrow\] Atmospheric \(\text{H}_2\text{O}\) \[\rightarrow\] Greenhouse effect

What keeps the climate system stable?
The carbonate-silicate cycle

Negative feedback loops (stabilizing)

So what was the $pCO_2$ of the early atmosphere?

And how do we know this?
Estimates of CO$_2$ and CH$_4$ through time?

Several proxies can be used to estimate pCO$_2$

![Graph showing CO$_2$ and CH$_4$ concentration through time]

Ohmoto et al., 2004

$pCO_2$ from Paleosols (2.8 Ga)?

Fe$_3$SiO$_4$(OH)$_4$(gelato) + 3CO$_2$g + 2H$_2$O

= 3FeCO$_3$(gelato) + 2H$_2$SiO$_4$(gelato)

Absence of siderite (FeCO$_3$) places upper bound on $pCO_2$ (factor of 20 lower than needed to offset 25% reduction in SL)

Need other Greenhouse gases (CH$_4$).

Other reasons for CH$_4$ instead of (or in addition to) CO$_2$

- Early atmospheres thought to be reduced (see lecture on Hadean world)
- Methane-producing archaea are evolutionarily ancient
  - Substrates for methanogenesis were widely available,
    - CO$_2$ + 4H$_2$ $\rightarrow$ CH$_4$ + 2H$_2$O
    - CH$_3$COOH (acetate) $\rightarrow$ CH$_4$ + CO$_2$
  - Acetate supplied by fermentation of organic matter
- Serpentinization of ocean crust supplied CH$_4$

$\langle Fe, Mg \rangle_2SiO_4 + sH_2O + CO_2 \rightarrow Mg_8Si_2O_5(OH)_4 + Fe_3O_4 + CH_4$
Furthermore...

- Atmospheric O$_2$ absent/low prior to 2.3x10$^9$ year ago
- Photochemical lifetime of CH$_4$ is ~10 years today, but in a low-O$_2$ atmosphere would be $\sim$1000 times longer

**CH$_4$-climate positive feedback loop**

- Surface temperature
- CH$_4$ production rate
- Greenhouse effect

A Negative feedback....?

- If CH$_4$ becomes more abundant than CO$_2$, organic haze begins to form (via polymerization/photolysis)....
**CH₄- Haze-climate feedback loop**

- CH₄ production
  - Surface temperature
  - Haze production
  - Atmospheric CH₄/CO₂

- (+)

- (-)

- Greenhouse effect

**Titan’s organic haze layer**

- Hydrocarbon Haze from photolysis (and charged particle irradiation) of CH₄
- Cools the planet - Negative feedback loop!

(Picture from Voyager 2)

**High pCH₄ end with Irreversible Oxidation of the Earth’s Surface?**

- H⁺ escapes, thereby lowering the reducing capacity of atmospheres and oceans
- Net Photosynthesis + Methanogenesis:
  \[ \text{CO}_2 + 2\text{H}_2\text{O} \rightarrow \text{CH}_4 + 2\text{O}_2 \]
- Reduction + Photolysis
  \[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + \text{O}_2 + 4\text{H}^+ \]
**Conclusions**

- CH₄ may also have contributed to keeping the Archean climate warm.
- Ultimately switched to CO₂ as greenhouse gas once surface became more oxidized (end Archean?).