The Faint Young Sun Paradox
&
The Geochemical C Cycle
&
Climate on Geologic Time Scales

12.007 Geobiology
Paleoclimate Lec. 1
Spring 2007
Paleoclimate: outline

- Incoming and outgoing radiation balance; greenhouse effect
- Faint Young Sun Paradox
- Global carbon cycle
- Weathering and “reverse weathering”
- Snowball earth climate considerations: can the earth escape from a snowball?

- Climate change examples:
  - Permo-Carboniferous glaciations
    - Continental arrangement
    - Land Plants and carbon cycle
  - Mesozoic warmth:
    - warmer equator, decreased equator-pole temperature gradient, higher CO₂?
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    - Lower CO₂? (early maybe, but not later). Roles of mountain uplift, weathering, seafloor spreading rates?
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    - Oxygen isotope paleoclimatology
    - Milankovitch insolation cycles
    - Ice cores and greenhouse gas changes
    - Abrupt climate change
The Electromagnetic Spectrum

**Figure 15.16** The electromagnetic spectrum.
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Please see Fig. 3 in Rottman, Gary, and George, Vanessa. “An Overview of the Solar Radiation and Climate Experiment (SORCE).” *The Earth Observer* 14 (May/June 2002): 17-22.
Greenhouse Gases absorb IR radiation efficiently.
(1) Molecules acquire energy when they absorb photons.
(2) This energy will be released later as re-emitted photons.
(3) Atmospheric molecules are rotating rapidly (and in aggregate, randomly), so the re-emitted energy is random in direction.
(4) So: half of the re-emitted radiation is directed back towards the earth.
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Please see Fig. 10.1.4 in Sarmiento, J. and Gruber, N. *Ocean Biogeochemical Dynamics*. Princeton, NJ: Princeton University Press, 2005.

Contemporary Solar Variability

- Contemporary Solar Variability ~0.1%
- Associated with 11-year sunspot cycle

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Please see Fig. 9 in Fröhlich, C. “Solar Irradiance Variability since 1978.” *Space Science Reviews* 125 (August 2006): 53-65.
Heat trapping in the atmosphere dominates the earth's energy balance. Some 30% of incoming solar energy is reflected (left), either from clouds and particles in the atmosphere or from the earth's surface; the remaining 70% is absorbed. The absorbed energy is reemitted at infrared wavelengths by the atmosphere (which is also heated by updrafts and cloud formation) and by the surface. Because most of the surface radiation is trapped by clouds and greenhouse gases and returned to the earth, the surface is currently about 33 degrees Celsius warmer than it would be without the trapping.
Courtesy of NASA
http://www.nasa.gov/images/content/136048main_bm_012004.jpg
Simple Planetary Energy Balance

\[ E_{\text{emitted}} = E_{\text{absorbed}} \]

1. **E_{\text{emitted}}**
   - Blackbody with effective radiating temperature, \( T_e \)
   - Stefan-Boltzmann Law
     \[ E = \sigma T^4 \quad (\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}) \]
     \[ E = \frac{2 \pi k^4}{h^3 c^2} \frac{\pi^4}{15} = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \]
   - Energy emitted per unit area
   - For entire surface of Earth
     \[ E_{\text{emitted}} = 4 \pi R_{\text{Earth}}^2 \times \sigma T_{\text{Teff}}^4 \]

- Likely solution to FYSP requires understanding of Earth’s energy balance (& C cycle)

Adapted from Kump et al. (1999)
2. Energy Absorbed

\[ E_{\text{absorbed}} = E_{\text{intercepted}} - E_{\text{reflected}} \]
\[ = \pi R_E^2 S - \pi R_E^2 S \times A \]
\[ = \pi R_E^2 S (1-A) \]

\[ E_{\text{emitted}} = E_{\text{absorbed}} \]
\[ 4 \pi R_E^2 \times \sqrt[4]{T_{\text{eff}}} = \pi R_E^2 S (1-A) \]
\[ \sqrt[4]{T_{\text{eff}}} = \frac{S}{4} (1-A) \]

\[ \Rightarrow \text{If } S \downarrow, \text{ then } \downarrow T_{\text{eff}} \text{ or } \downarrow A \]

Adapted from Kump et al. (1999)
Neither albedo
nor geothermal
heat flux
can keep the earth
from freezing
with 30% lower S

Adapted from
Kump et al. (1999)
Lower S compensated by larger greenhouse effect?

\[ \sqrt[4]{T_{\text{eff}}} = \frac{S}{4} (1 - A) \]

\[ \times \text{Geothermal Heat Flux} \]
\[ \times \text{Mass Loss of Sun} \]

\[ T_{\text{eff}} = \sqrt[4]{\frac{S}{40} (1 - A)} \]

Today: \[ 255 \text{ K} = -18^\circ \text{C} \]

Earth surface Temp = 15\(^\circ\)C

\[ T_s - T_{\text{eff}} = \Delta T_g \text { Greenhouse Effect} \]

15\(^\circ\) - (-18\(^\circ\)) = 33\(^\circ\)C

\[ \downarrow \text{s Compensated by } \uparrow \Delta T_g \]

Adapted from Kump et al. (1999)
But: the atmosphere is a leaky greenhouse...

If we assume that the atmospheric gas composition is what it is today, and then do the full radiative calculations assuming that the atmosphere does not convect, then the earth would be ~30°C warmer than it is. That is, the earth’s greenhouse effect is only ~50% efficient.

The difference is due to convection: when the near-surface air warms up, it rises in the atmosphere and can lose radiation to space more effectively.
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The ‘Faint Young Sun Paradox’
Faint Young Sun Paradox

\[ ^4\text{He} \rightarrow ^1\text{H} \]
Incremental density = incremental luminosity

Solar luminosity ~ 30% less 4.6 Byr BP

\[ \Rightarrow \text{Earth should have been frozen until } \sim 2 \text{ Byr BP} \]

Liquid H\textsubscript{2}O existed >3.5 Ga (sed. rocks, life, zircon $\delta^{18}$O)
Enhanced CO$_2$ Greenhouse Effect seems Necessary!

Image removed due to copyright restrictions.


http://www.geosc.psu.edu/~kasting/PersonalPage/Pdf/Scientific_American_88.pdf

shaded region shows greenhouse effect (incl. water vapor feedback and const. O$_2$ of 340 ppm)
Precambrian $p\text{CO}_2$ Estimates

Image removed due to copyright restrictions.

Please see Fig. 3 in Kaufman, Alan J., and Xiao, Shuhai. "High CO$_2$ levels in the Proterozoic atmosphere estimated from analyses of individual microfossils." *Nature* 425 (September 18, 2003): 279-282.
Earth’s Climate History:

Mostly sunny with a 10% chance of snow

• What caused these climate perturbations?

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Please see Fig. 1 in Lubick, Naomi. “Palaeoclimatology: Snowball Fights.” Nature 417 (May 2, 2002): 12-13.
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1. CO₂ Feedbacks: Geochemical Carbon Cycle

- Transfer of C between rocks and ocean/atmosphere (>10⁶-yr) can perturb CO₂ greenhouse effect
- Ocean/atmosphere C reservoir small w.r.t. rock reservoir and the transfer rates between them

2. Evidence for Long-Term CO₂-Climate Link

3. Case Studies:
   - Late Proterozoic Glaciations
   - Permo-Carboniferous Glaciations
   - Warm Mesozoic Period
   - Late Cenozoic Cooling
Earth's Carbon Budget

Biosphere, Oceans and Atmosphere: \(3.7 \times 10^{18}\) moles

Crust:
- Corg: \(1100 \times 10^{18}\) mole
- Carbonate: \(5200 \times 10^{18}\) mole

Mantle: \(100,000 \times 10^{18}\) mole
<table>
<thead>
<tr>
<th>Species</th>
<th>Amount (in units of $10^{18}$ gC)</th>
<th>Residence Time (yr)*</th>
<th>$\delta^{13}$ C % PDB**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary carbonate-C</td>
<td>62400</td>
<td>342000000</td>
<td>~ 0</td>
</tr>
<tr>
<td>Sedimentary organic-C</td>
<td>15600</td>
<td>342000000</td>
<td>~ -24</td>
</tr>
<tr>
<td>Oceanic inorganic-C</td>
<td>42</td>
<td>385</td>
<td>~ +0.46</td>
</tr>
<tr>
<td>Necrotic-C</td>
<td>4.0</td>
<td>20-40</td>
<td>~ -27</td>
</tr>
<tr>
<td>Atmospheric-CO$_2$</td>
<td>0.72</td>
<td>4</td>
<td>~ -7.5</td>
</tr>
<tr>
<td>Living terrestrial biomass</td>
<td>0.56</td>
<td>16</td>
<td>~ -27</td>
</tr>
<tr>
<td>Living marine biomass</td>
<td>0.007</td>
<td>0.1</td>
<td>~ -22</td>
</tr>
</tbody>
</table>

* Residence times are approximate and based on various factors including biological and geochemical processes.

** $\delta^{13}$ C values are relative to the PDB (Pee Dee Belemnite) standard.
Steady State & Residence Time

**Steady State:** Inflows = Outflows
Any imbalance in I or O leads to changes in reservoir size

Inflow: 60 Gton C/yr
Respiration

Atmospheric CO₂
760 Gton C

Outflow: 60 Gton C/yr
Photosynthesis

1 Gton = $10^9 \times 1000$ kg = $10^{15}$ g

The *Residence time* of a molecule is the average amount of time it is expected to remain in a given reservoir.

Example: $t_R$ of atmospheric CO₂ = $760/60 = 13$ yr
The Geochemical Carbon Cycle

1. Organic Carbon Burial and Weathering

\[ \text{Burial} \quad \frac{\text{CO}_2 + \text{H}_2\text{O}}{\text{weathering}} \rightarrow \text{CH}_2\text{O} + \text{O}_2 \]

2. Tectonics: Seafloor Spreading Rate
   - Mantle CO\(_2\) from Mid-Ocean Ridges

3. Carbonate-Silicate Geochemical Cycle
   - Chemical Weathering **Consumes** CO\(_2\)
   - Carbonate Metamorphism **Produces** CO\(_2\)
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Chemical Weathering = chemical attack of rocks by dilute acid

\[ \text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{“H}_2\text{CO}_3” \]

1. Carbonate Weathering:

\[ \text{CaCO}_3 + \text{“H}_2\text{CO}_3” \rightarrow \text{Ca}^{2+} + 2 \text{HCO}_3^- \]

2. Silicate Weathering:

\[ \text{CaSiO}_3 + 2 \text{“H}_2\text{CO}_3” \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- + \text{SiO}_2 + \text{H}_2\text{O} \]

• Carbonates weather faster than silicates

biogeochemical carbon cycle #2
Carbonate rocks weather faster than silicate rocks…
Products of weathering precipitated as $\text{CaCO}_3$ & $\text{SiO}_2$ in ocean

Image removed due to copyright restrictions.

CaCO₃ weathering is cyclic (CO₂ is not lost from the system), but calcium silicate weathering results in the loss of CO₂ to solid CaCO₃:

**CaCO₃ weathering cycle**

CaCO₃ weathering:

\[ \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2 \text{HCO}_3^- \]

CaCO₃ sedimentation:

\[ \text{Ca}^{2+} + 2 \text{HCO}_3^- \rightarrow \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \]

**Silicate weathering cycle(?)**

Silicate weathering:

\[ \text{CaSiO}_3 + 2 \text{CO}_2 + 2\text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + \text{Si(OH)}_4 + 2 \text{HCO}_3^- \]

CaCO₃ and SiO₂ sedimentation:

\[ \text{Ca}^{2+} + 2 \text{HCO}_3^- + \text{Si(OH)}_4 \rightarrow \text{CaCO}_3 + \text{SiO}_2\cdot\text{H}_2\text{O} + \text{CO}_2 + \text{H}_2\text{O} \]
The weathering of other aluminosilicates results in the loss of CO$_2$ AND makes the ocean saltier and more alkaline:

**Potassium feldspar weathering “cycle”**

**weathering:**

$$2 \text{KAl}_2\text{Si}_2\text{O}_8 + 2 \text{CO}_2 + 2\text{H}_2\text{O} \Rightarrow 2 \text{K}^+ + 2 \text{HCO}_3^- + 2 \text{Si(OH)}_4 + \text{Al}_2\text{O}_3$$

(solid)

**sedimentation:**

$$2 \text{K}^+ + 2 \text{HCO}_3^- + 2 \text{Si(OH)}_4 + \text{Al}_2\text{O}_3 \Rightarrow 2 \text{SiO}_2\cdot2\text{H}_2\text{O} + \text{Al}_2\text{O}_3 + 2 \text{K}^+ + 2 \text{HCO}_3^-$$
Problem:

As CO$_2$ is buried as CaCO$_3$ in sediments, why doesn’t CO$_2$ eventually vanish from the atmosphere?

(It would take only ~400,000 years of silicate weathering to consume all of the carbon in today’s ocean/atmosphere system)
Net Reaction of Rock Weathering +
Carbonate and Silica Precipitation in Ocean

\[ \text{CaSiO}_3 + \boxed{\text{CO}_2} \rightarrow \text{CaCO}_3 + \text{SiO}_2 \]

• CO₂ consumed

• Would deplete atmospheric CO₂ in 400 kyr

• Plate tectonics returns CO₂ via Metamorphism and Volcanism

-------------------------------------

Carbonate Metamorphism

\[ \text{CaCO}_3 + \text{SiO}_2 \rightarrow \text{CaSiO}_3 + \boxed{\text{CO}_2} \]

• CO₂ produced from subducted marine sediments

Net reaction of geochemical carbon cycle
(Urey Reaction)
Carbonate-Silicate Geochemical Cycle

- Mantle-Derived CO₂
- Mid-ocean ridge
- Deep-sea trench
- Magma
- Carbonate metamorphism
- CO₂ release
- CO₂ + SiO₂
- Weathering
- Metamorphic (+ mantle) CO₂

Figure by MIT OCW.
Carbonate-Silicate Geochemical Cycle

- CO₂ released from volcanism dissolves in H₂O, dissolves rocks
- Weathering products transported to ocean by rivers
- CaCO₃ precipitation in shallow & deep water
- Cycle closed when CaCO₃ metamorphosed in subduction zone or during orogeny.
• Geologic record indicates climate has rarely reached or maintained extreme Greenhouse or Icehouse conditions....

• Negative feedbacks between climate and Geochemical Carbon Cycle must exist

• Thus far, only identified for Carbonate-Silicate Geochemical Cycle:

  Temp., rainfall enhance weathering rates
  (Walker et al, 1981)

(i.e., no obvious climate dependence of tectonics or organic carbon geochemical cycle.)

Adapted from Kump et al. (1999)
The Walker (1981) feedback for CO$_2$ regulation

- (1) CO$_2$ emitted by volcanoes
- (2) CO$_2$ consumed by weathering
- (3) If (1) is greater than (2), CO$_2$ levels in the atmosphere increase.
- (4) As atm. CO$_2$ rises, the climate gets (a) warmer and (b) wetter (more rainfall).
- (5) Warmer and wetter earth weathers rocks faster. CO$_2$ is removed from the atmosphere faster.
- (6) CO$_2$ levels rise until the weathering rate balances volcanic emissions. Steady-state attained (until volcanic CO$_2$ emissions rise or fall).
The (modified) BLAG [Berner, Lasaga and Garrels) mechanism for long-term CO₂ regulation

- Walker mechanism plus consideration of changes in sea floor spreading rate (induces ~100 myr lag time between CO₂ emissions and ultimate recycling via Urey reaction), volcanism, and other factors influencing carbon cycle (organic deposition and weathering).
- Modified by J. Edmond to include irregularity of CaCO₃ deposition (shallow sediments and some basins get “more of their fair share” of CaCO₃ deposition, and spreading and subduction are not closely linked spatially (e.g. Atlantic spreads but has little subduction).
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Long-Term Climate Cycles & The Proterozoic Glaciations (‘Snowball Earth’)

Assigned Reading:
Climate Controls - Long & Short Timescales

- Solar output (luminosity): $10^9$ yr
- Continental drift (tectonics): $10^8$ yr
- Orogeny (tectonics): $10^7$ yr
- Orbital geometry (Earth -Sun distance): $10^4$-$10^5$ yr
- Ocean circulation (geography, climate): $10^1$-$10^3$ yr
- Atmospheric composition (biology, tectonics, volcanoes): $10^0$-$10^5$ yr
What caused these massive perturbations to the carbon cycle during the late Proterozoic?

- Carbon Isotopic Excursions 800-500Ma

Late Proterozoic Glaciations: Evidence

~4 global glaciations followed by extreme greenhouses 750-580 Ma

- Harland (1964); Kirschvink (1992)

Snowball Events:
- Breakup of equatorial supercontinent 770 Ma
- Enhanced weathering from increased rainfall (more land close to sea)
- Drawdown atmospheric CO$_2$ → Global cooling
- Runaway albedo effect when sea ice < 30° latitude
- Global glaciation for ~10 Myr (avg T ~ -50°C)
- Sea ice ~1000 m thick, geothermal heat flux (0.07 W/m$^2$) keeps ocean liquid

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Please see Fig. 3 in Hoffman, Paul F., and Schrag, Daniel P. “Snowball Earth.” *Scientific American* 282 (January 2000): 68.

http://www.eps.harvard.edu/people/faculty/hoffman/pdfs/Snowball_Earth--Hoffman_Schrag_.pdf
Late Proterozoic (~0.9-0.6 Ga) Glaciations

Image removed due to copyright restrictions.


http://www.gps.caltech.edu/~jkirschvink/pdfs/pprg.pdf
How to explain glaciers on all continents when those continents appear to have been close to the equator?
High Obliquity Hypothesis
Williams (1975)

- Earth’s tilt (obliquity) controls seasonality
- At high tilt angles (> 54°) the poles receive more mean annual solar radiation than the tropics (sun constantly overhead in summer)!
- Glaciers may be able to form at low latitudes

Problems:
- Even the tropics get quite warm at the equinoxes
- Moon stabilizes obliquity
- Would need v. large impact to destabilize; moon orbit doesn’t support this

Image from P. Hoffman
### Snowball Earth Hypothesis

~4 global glaciations followed by extreme greenhouses 750-580 Ma

- Harland (1964); Kirschvink (1992)

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Please see Fig. 1 in Lubick, Naomi. “Palaeoclimatology: Snowball Fights.” *Nature* 417 (May 2, 2002): 12-13.
Prologue to Snowball

- Breakup of equatorial supercontinent
- Enhanced weathering from increased rainfall (more land close to sea)
- Drawdown atmospheric CO₂ → Global cooling

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Deep Freeze

• Global cooling causes sea ice margin to move equatorward

• Runaway albedo effect when sea ice <30° latitude

• Entire ocean possibly covered with ice

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Carbonate-Silicate Geochemical Cycle

Mantle-Derived CO₂

Mid-ocean ridge

CaCO₃ + SiO₂

Deep-sea trench

CO₂ release

Carbonate metamorphism

Magma

Metamorphic (+ mantle) CO₂

CO₂ release

Weathering

CO₂ Consumed

CO₂

CaCO₃ + SiO₂ ↔ CaSiO₃ + CO₂

Weathering

Figure by MIT OCW.
Breaking out of the Snowball

- Volcanic outgassing of CO₂ over ~10⁶ yr may have increased greenhouse effect sufficiently to melt back the ice.

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Please see Fig. 2 in Lubick, Naomi. “Palaeoclimatology: Snowball Fights.” Nature 417 (May 2, 2002): 12-13.
Bring on the Heat: Hothouse follows Snowball?

Hothouse Events
• Slow CO₂ buildup to ~350 PAL from volcanoes
• Tropical ice melts: albedo feedback decreases, water vapor feedback increases
• Global T reaches ~ +50°C in 10² yr
• High T & rainfall enhance weathering
• Weathering products + CO₂ = carbonate precipitation in warm water

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http://www.eps.harvard.edu/people/faculty/hoffman/pdfs/Snowball_Earth--Hoffman_Schrag_.pdf
Image removed due to copyright restrictions.
Please see Prof. Hoffman's site on the Snowball Earth hypothesis,
http://www.snowballearth.org/
Enhanced Weathering of Rocks Results in Precipitation of Minerals in Ocean

- High T & CO₂ cause increase in weathering rate of continents
- Products of weathering carried to ocean by rivers
- Precipitated as CaCO₃ and SiO₂ minerals in ocean
Geologic Evidence for Hothouse Aftermath:
“Cap Carbonates”

Thick sequences of inorganically precipitated CaCO$_3$ overly Neoproterozoic glacial deposits globally.
Summary of Snowball-Hothouse Sequence

Image removed due to copyright restrictions.

Please see Fig. 6 and 7 in Hoffman, Paul F., and Schrag, Daniel P. “The Snowball Earth hypothesis: testing the limits of global change.” *Terra Nova* 14 (2002): 129-155.

http://www.eps.harvard.edu/people/faculty/hoffman/pdfs/TerraNova.PDF

Note: T estimated from E balance model.
One
Complete
Snowball-Hothouse
Episode

Image removed due to copyright restrictions.
Please see Prof. Hoffman's site on the Snowball Earth hypothesis, http://www.snowballearth.org/

Image from P. Hoffman
Evidence for Snowball / Hothouse

• **Stratigraphy**: globally-dispersed glacial deposits overlain by thick sequences of inorganic (cap) carbonates.

• **Carbon isotopes**: negative $\delta^{13}C$ excursions through glacial sections ($\delta^{13}C$ reaches $\sim$ -5 to -7‰). Little or no biological productivity (no light). Remain low through most of cap carbonate deposition.

• **Banded iron formations w/IRD**: only BIFs after 1.7 Ga. Anoxic seawater covered by ice.

• **Cambrian explosion**: Rapid diversification of multicellular life 575-525 Ma expected to result from long periods of isolation and extreme environments (genetic "bottleneck and flush").
Potential Problems with the ‘Snowball Earth hypothesis’

- Ocean/atmosphere climate models cannot seem to keep entire ocean covered with ice.
- No evidence for lower sea level.
- Weathering reactions are slow..... Maybe too slow to be the source of cap carbonates.

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Text removed due to copyright restrictions.


Alternate Cause for Cap Carbonate Deposition & $^{13}$C Depletions: Gas Hydrate Destabilization


- CaCO$_3$ precipitation does not require increased weathering flux of minerals.
- Can be caused by increased seawater alkalinity resulting from CH$_4$ consumption by sulphate-reducing bacteria.

$$\text{CH}_4 + \text{SO}_4^{2-} \rightarrow \text{HCO}_3^- + \text{HS}^- + \text{H}_2\text{O}$$
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