Enceladus: A Habitable Environment?

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Southwest Research Institute
May 23, 2017
Hydrogen: So what...it’s everywhere!

<table>
<thead>
<tr>
<th>Element</th>
<th>(N(E)_{0})</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>(2.431 \times 10^{10})</td>
</tr>
<tr>
<td>He</td>
<td>(2.343 \times 10^9)</td>
</tr>
<tr>
<td>Li</td>
<td>55.47</td>
</tr>
<tr>
<td>Be</td>
<td>0.7374</td>
</tr>
<tr>
<td>B</td>
<td>17.32</td>
</tr>
<tr>
<td>C</td>
<td>(7.079 \times 10^6)</td>
</tr>
<tr>
<td>N</td>
<td>(1.950 \times 10^6)</td>
</tr>
<tr>
<td>O</td>
<td>(1.413 \times 10^7)</td>
</tr>
<tr>
<td>F</td>
<td>841.1</td>
</tr>
<tr>
<td>Ne</td>
<td>(2.148 \times 10^6)</td>
</tr>
<tr>
<td>Na</td>
<td>(5.751 \times 10^4)</td>
</tr>
<tr>
<td>Mg</td>
<td>(1.020 \times 10^6)</td>
</tr>
<tr>
<td>Al</td>
<td>(8.410 \times 10^4)</td>
</tr>
<tr>
<td>Si</td>
<td>(\equiv 1.00 \times 10^6)</td>
</tr>
<tr>
<td>P</td>
<td>8373</td>
</tr>
<tr>
<td>S</td>
<td>(4.449 \times 10^5)</td>
</tr>
<tr>
<td>Cl</td>
<td>5237</td>
</tr>
<tr>
<td>Ar</td>
<td>(1.025 \times 10^5)</td>
</tr>
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\(\sim 90\% \text{ H}_2\)

Lodders (2003)
But, $\text{H}_2$ is relatively rare on Ocean Worlds

0.55 ppm $\text{H}_2$ in Earth’s atmosphere

It’s hard to hang on to $\text{H}_2$

Water-rock hydrothermal processes produce of order 1 M tonnes $\text{H}_2$ per year (Sherwood Lollar et al., 2014)
H$_2$ on Ocean Worlds: An Energy Source for Life

\[
\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}
\]

Chemical energy $\rightarrow$ Ecosystem

Shock & Canovas (2010)
Hydrothermal ultramafic rock alteration (serpentinization) on Enceladus

Silica particles (Hsu et al., 2015) form when hot vent fluids mix with cold ocean water at the ocean floor.

Alkaline ocean (Glein et al., 2015)
What exactly is serpentinization?

A Geochemical Process

For example:

\[ \text{Mg}_2\text{SiO}_4 + \text{MgSiO}_3 + 2\text{H}_2\text{O} \rightarrow \text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4 \]

Ultramafic Rock

Serpentine (aka asbestos)

Serpentinization leads to high pH (rock enriched in bases) and...
Serpentinizing hydrothermal systems on Earth produce large quantities of $\text{H}_2$

Lost City as a geochemical analogue of Enceladus

<table>
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<th>Value</th>
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<td>Temperature</td>
<td>90°C</td>
</tr>
<tr>
<td>pH</td>
<td>9-11</td>
</tr>
<tr>
<td>$\text{H}_2$ conc.</td>
<td>10 mM</td>
</tr>
<tr>
<td>$\text{CH}_4$ conc.</td>
<td>1 mM</td>
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Kelley et al. (2001; 2005), Proskurowski et al. (2006), Reeves et al. (2014)

mM = mmol per kg of $\text{H}_2\text{O}$
Model of hydrothermal serpentinization suggested by previous data

$\text{H}_2$ is the key missing piece
Cassini E21 Flyby – The Search for H₂

Plume

49 km from the surface

Porco et al. (2014)
H$_2$ counts detected
Signal shows structure
Mass 2 Counts Observed in OSNB Mode

$H_2$ & $H_2O$ enter the OPEN SOURCE

1. $H_2$ from Enceladus
2. $H_2^+$ generated from dissociative ionization of $H_2O$ in the open source

Cross section obtained from Itakawa and Mason, J. Phys. Chem. Ref. Data, Volume 34, Number 1, 2005

Is the detected $H_2$ real?

Instrument Background Estimation

Fig. 11. Recommended values of the partial ionization cross sections of $H_2O$ for the production of $H_2O^+$, $OH^+$, $O^+$, $O^-$, $H^+_2$, and $H^-$. 
Mass 2 Counts Observed in OSNB Mode

**H₂ & H₂O enter the OPEN SOURCE**
1. H₂ from Enceladus
2. H₂⁺ generated from dissociative ionization of H₂O in the open source
   Cross section obtained from Itakawa and Mason, J. Phys. Chem. Ref. Data, Volume 34, Number 1, 2005

**H₂ & H₂O enter the CLOSED SOURCE**
3. H₂ and H₂O gas ionized in the closed source and H₂⁺ leaks through the potential barrier on the quad lenses and into the quadrupole (Measured in INMS lab)
4. H₂ and H₂O gas (not yet ionized in the closed source) travels into the open source ionization region (Measured in INMS lab)

**Thermal gas in the instrument**
5. Thermal H₂ & H₂O gas measured during OSNB mode (Measured in INMS lab)

**INMS surface effects**
6. H₂ created from interactions with the surfaces of the instrument

**Other sources of Mass 2 counts**
7. H⁺ crosstalk
8. Radiation background

Is the detected H₂ real?

Instrument Background Estimation
Statistics of $\text{H}_2$ signal vs. instrument background

Many counts are above the estimated background
Model of plume outflow to derive the $\text{H}_2$ fraction

Waite et al. (2017)
Model of plume outflow to derive the $H_2$ fraction

Waite et al. (2017)
H₂ = Hydrothermal?
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<td>Enceladus too small (&gt;10M(_{\text{E}})), He not detected in plume</td>
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<td>Trapping of H(_2) in amorphous ice (&lt;20 K)</td>
<td>No evidence of such cold material in comets (OPR), lack of Ar, Ne, CO/N(_2) in plume</td>
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## H₂ = Hydrothermal?

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<td>Radiolysis of water ice on surface</td>
<td>Would not be concentrated in plume, low radiation fluxes at Enceladus, O₂ not detected in plume</td>
</tr>
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<td>e.g., Cooper et al. (2009)</td>
<td></td>
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<tr>
<td>Radiolysis of liquid water in interior</td>
<td>Low Cl chondritic radionuclide abundances, H₂/CH₄ ratio too high in plume</td>
</tr>
<tr>
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A Bottom-Up Test of the Hydrothermal Model

- Main idea: \( H_2 \) production from \( H_2O \) is coupled to Fe oxidation

- As in hydrothermal systems on Earth because of the high abundance of Fe

- Key geochemical reactions in the Fe-Si-O-H system:
  
  a. \( 3Fe^0 + 5H_2O + 2SiO_2 \rightarrow Fe\text{-serpentine} + 3H_2 \)
  
  b. \( 3\text{Fe-olivine} + 2H_2O \rightarrow 2Fe_3O_4 + 3SiO_2 + 2H_2 \)
  
  c. \( Fe\text{-serpentine} \rightarrow Fe_3O_4 + H_2O + 2SiO_2 + H_2 \)

- Approach: Estimate \( H_2 \) yield from amounts of Fe minerals on Enceladus
A Bottom-Up Test of the Hydrothermal Model

- Mass of rock from the internal structure model of McKinnon (2015)

Rock = Source of electrons to make $H_2$ from $H_2O$
A Bottom-Up Test of the Hydrothermal Model

• Mass of rock from the internal structure model of McKinnon (2015)

• Mineralogy of rock based on solar elemental abundances (Lodders, 2003) and alteration phases in carbonaceous chondrites (Brearley, 2006)

• **Example:** 1% anhydrous accreted rock in the core can sustain ~1% H\(_2\) in the plume at today’s outgassing rate (Hansen et al., 2011) for ~500 Myr

• The presence of appreciable H\(_2\) in the plume does not require a large amount of anhydrous rock. Less if outgassing is only episodic

• Compatible with a low density core (McKinnon, 2015) that may be dominated by hydrated silicates containing some pore water
$H_2/CH_4$ ratio similar to Lost City vents

$H_2/CH_4 = 9$

$H_2/CH_4 = 1 \text{ to } 14$
The hydrothermal model is supported by the data.
## Comparative Deep Energy

**Earth vs. Enceladus**

<table>
<thead>
<tr>
<th>Body:</th>
<th>Earth</th>
<th>Enceladus</th>
<th>Enceladus/Earth</th>
</tr>
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<tbody>
<tr>
<td><strong>Production Rate:</strong></td>
<td>$1 \times 10^{12}$ mol H$_2$/yr (Sherwood Lollar et al., 2014)</td>
<td>$3 \times 10^9$ mol H$_2$/yr ($\sim$1% H$_2$ in plume)</td>
<td>0.003</td>
</tr>
<tr>
<td><strong>Surface Flux:</strong></td>
<td>2000 mol H$_2$/yr km$^2$</td>
<td>4000 mol H$_2$/yr km$^2$</td>
<td>2</td>
</tr>
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H$_2$ links the inorganic and organic/living worlds

- **Organic synthesis**
  
  \[ \text{CO}_2 + \text{H}_2 \rightarrow \text{Organics} + \text{H}_2\text{O} \]

**Organic Signatures**
H₂ links the inorganic and organic/living worlds

• **Organic synthesis**
  \[ \text{CO}_2 + \text{H}_2 \rightarrow \text{Organics} + \text{H}_2\text{O} \]

• **Prebiotic chemistry**
  Current model: Life began at *alkaline* hydrothermal vent

• **Chemical energy for life**
  H₂/CH₄-based metabolisms

Weiss et al. (2016, Nat. Microbiol. 1, 16116)
Methanogenesis

\[ \text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \]

Is there enough chemical energy to support life??

Waite et al. (2017)
The reaction

$$\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$$

Methanogenesis

The amount of free energy available

$$\Delta G = \Delta G^0 + RT \ln(Q)$$

Theory

Exploration

(aka, death)

Waite et al. (2017)
CO₂ + 4H₂ → CH₄ + 2H₂O

The energy demands of Earth microbes...

Affinity (kJ/mol CH₄)

H₂/H₂O Ratio

Growth
Equilibrium
Maintenance

Hoehler (2004)

Waite et al. (2017)
$\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$

Estimated range based on previous Cassini data

Waite et al. (2017)
Is there enough chemical energy to support life?  

**YES!**

Energy supply > demand  
Enceladus energetically habitable

Waite et al. (2017)
$H_2$ evidence that Enceladus is energetically habitable

Inhabited?
That’s the $1B question!

Free Energy

Liquid Water

Essential Elements: C, N, O, S? P?

Caloric equivalent of ~300 pizzas every hour!
H₂ and the drive to life as the next theme of Enceladus exploration

McCollom & Seewald (2013)
Energy availability sets the stage for future missions exploring relationships between habitability and the presence of life on ocean worlds.
Conclusions

• Geochemical model of hydrothermal serpentinization

• Identified native $H_2$ in the plume from INMS

• Hydrothermal source of $H_2$

• $H_2$ is a potent and ancient energy source for microbes

• Made the first calorie count of an alien ocean

• Follow the $H_2$!