Exploring the Habitability of Enceladus’ internal ocean

Hunter Waite, Chris Glein, Rebecca Perryman, Sean Hsu, Luciano Iess, and Peter Thomas
Past Observations of Enceladus

HABITABILITY

Salts

Complex Organics

Recent Observations of Enceladus

Global Oceans: Geysers

Global Oceans: Internal Structure

Hydrothermal Systems: Silica

Hydrothermal Systems: H₂

Summary
What Defines Habitability?

NASA’s Astrobiology Roadmap:

1. Extended regions of liquid WATER
2. Conditions favorable to the assembly of complex ORGANIC MOLECULES
3. ENERGY SOURCES to sustain metabolism
What we knew about Enceladus Habitability at the time of the Decadal

Salts as an indication of INTERIOR WATER

The existence of COMPLEX ORGANICS
A subsurface ocean in contact with the rocky core

NaCl  $\sim 0.5 - 1.0\%$
NaHCO$_3$  $\sim 0.2 - 0.5\%$
$pH$  $\sim 8.5 - 9$

Organics at Enceladus
What we have learned about Enceladus Habitability after the time of the Decadal

WATER: Global Oceans

ENERGY SOURCE: Hydrothermal Systems
What we have learned about Enceladus Habitability after the time of the Decadal

WATER: Global Oceans

ENERGY SOURCE: Hydrothermal Systems
Geysers on Enceladus

Enceladus Radius: 252 km
5 GW thermal power

Can gravity measurements help unveil the interior structure of the tiny moon?
Cassini Enceladus Observations

E9 Flyby
Closest Approach = 28-APR-2010 00:10:17 UTC
**Altitude ≅ 100 km**, Lat ≅ -89° Incl. ≅ 85°
Relative velocity ≅ 6.5 km/s, SEP angle ≅ 141°

E12 Flyby
Closest Approach = 30-NOV-2010 11:53:59 UTC
**Altitude ≅ 48 km**, Lat ≅ 62° Incl. ≅ -62°
Relative velocity ≅ 6.3 km/s, SEP angle ≅ 54°

E19 Flyby
Closest Approach = 2-MAY-2012 09:32:34 UTC
**Altitude ≅ 70 km**, Lat ≅ -72° Incl. ≅ 108°
Relative velocity ≅ 7.5 km/s, SEP angle ≅ 162°
Early Cassini data showed that Enceladus had erupting material from the south polar region, and further sampling and analysis indicated a liquid water reservoir as the ultimate source.

Gravity analysis is consistent with local reservoir (less et al., 2014) and with reinterpretation is consistent with a thin global liquid layer (McKinnon 2015).

Possible dynamical implications of maintaining an ocean on such a small object was a strong motivation to get better constraints on the interior of Enceladus, especially the extent of the liquid reservoir.
One route to interior structure is the physical libration amplitude which can indicate whether the object’s surface is rigidly connected to the interior. (Van Hoolst et al., 2009 etc.)

Basically, if a surface shell is not rigidly connected to the remainder, it will be subject to larger forced libration than a fully rigid object.

Cassini’s long orbital tour provides multiple observations throughout Enceladus’ orbit, thus allowing for accurate characterization of any forced libration.

Physical libration $= 0.12 \pm 0.014^\circ$ (3σ)
Meaning of libration amplitude: Solid Models

Homogeneous distribution of mass, depends only on the satellite’s measured shape:
\[ \gamma = 0.032^\circ \]

Two-layer in hydrostatic equilibrium:
\[ \gamma = 0.032^\circ - 0.034^\circ \]
(Shell density: 700-930 kg/m\(^3\)
Core density: 2000-3300 kg/m\(^3\))

None of the solid models tested were consistent with observed libration.
Global ocean model fits the measurements

<table>
<thead>
<tr>
<th>Interior Model</th>
<th>Amplitude of forced libration</th>
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<tbody>
<tr>
<td>Homogenous ellipsoid</td>
<td>0.032°</td>
</tr>
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<td>2-layer hydrostatic</td>
<td>0.032° - 0.034°</td>
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<td>2-layer hydrostatic, including “polar sea” and depression</td>
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<tr>
<td>Ellipsoidal core, global ocean, ellipsoidal shell (23 km) (2300, 1000, 850 kg/m³)</td>
<td>0.120°</td>
</tr>
<tr>
<td><strong>Measured Value</strong></td>
<td><strong>0.120° ± 0.014° (3σ)</strong></td>
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Ellipsoidal shape: 256.2, 251.4, 248.6 km
Thomas et al., 2016, Icarus 264, 27-47.

Libration measurements using ISS data confirmed suspicions that the liquid reservoir on Enceladus is global.

Thickness of layers is not to scale.
Thomas et al., 2015

Beuthe et al., 2016

Iess et al., 2014

Beuthe et al. reinterpreted the gravity and shape data using minimum stress isostasy and second order figure of equilibrium, showing that gravity and libration measurements can be reconciled.

Core density is in the range 2300-2500 kg/m³. Core radius is about 190 km.
In summary...

A coherent picture of the interior structure of Enceladus emerges from the combination of gravity, topography and rotation measurements:

- Core density: 2300-2500 kg/m³
- Core radius: 190-200 km
- Water + ice mantle: 50-60 km thick
- Ice shell thickness: 20-25 km (from librations), thinning out to 10-15 km in the southern polar region. This is lower but still consistent with G-T estimates (30-40 km).
- Thickness of global ocean: 25-30 km (+10 km at the south pole)

It is surprising how much Cassini has been able to tell us about the interior of Enceladus.

Although Cassini has essentially completed its observation of the moon, we may still expect a more refined tomography from theoretical work.
What we have learned about Enceladus Habitability after the time of the Decadal

WATER: Global Oceans

ENERGY SOURCE: Hydrothermal Systems
Hydrothermal activities within Enceladus

- CDA observation of fast (>100 km/s), tiny (a few nm) silica particles originating from Enceladus.

- Spontaneous, homogenous nucleation of nano-phase silica colloids occurs when the super-saturation is achieved by the pH and/or temperature changes.

\[
\text{SiO}_2^{(\text{mono})} \xrightarrow{k_1} \text{SiO}_2^{(\text{cn})} \xrightarrow{k_{\text{fast}}} \text{SiO}_2^{(\text{nano})} \xrightarrow{k_2} \text{SiO}_2^{(\text{ppt})}
\]

- \( \text{SiO}_2 \) is an indicator of hydrothermal reactions on Earth & Mars.
Nano-Silica Formation vs. Rock Composition

Image of nano-silica formed in hydrothermal experiments.

Hsu et al, 2015

Graph showing solubility of silica at 0°C as a function of temperature for different pH levels (pH 8.4, pH 8.8, pH 9.3, pH 10). The graph compares the solubility of Si-rich (chondrite-like) and Si-poor (Earth's mantle-like) conditions.
Cassini-INMS

E21 Data Set

H₂ in the Plume

Possible H₂ Sources

Chemical Affinity of H₂

Does "Abundant H₂" = "No Life"?

Alternative H₂ Affinity Interpretation

Limiting Growth Factors

Coupled Metabolisms

Summary
INMS utilized two operating modes during the E21 Enceladus Flyby:

**Closed Source Neutral (CSN)**
- Measures non-reactive species only
- Subject to wall reactions, such as titanium reacting with H$_2$O to form H$_2$

**Open Source Neutral Beaming (OSNB)**
- Sensitivity 1/400 of closed source
- Material entering the open source does not directly interact with the walls
Observations of $\text{H}_2$, $\text{H}_2\text{O}$, and $\text{CO}_2$ by INMS during the E21 flyby

**Velocity range** sampled (Panel C, black points) corresponds to the field of view of the sampled region and affects both the speed and angle of the measured molecules.
The detected count rates and estimated background rates are plotted as a function of time from closest approach to Enceladus (2015-301T15:22:42).

Data show a low-level H\textsubscript{2} population together with several extreme H\textsubscript{2} signal spikes reaching intensities of tens to hundreds of counts. The low-level H\textsubscript{2} population was used in the calculation of H\textsubscript{2} to H\textsubscript{2}O ratio.
## What is the Source of the Observed $\text{H}_2$?

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| Trapping of H$_2$ in amorphous ice (<20 K)  
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| Radiolysis of liquid water in interior  
e.g., Chyba & Hand (2001) | Low CI chondritic radionuclide abundances, predicts low H$_2$/CH$_4$ ratio in plume |
Serpentinizing hydrothermal systems on Earth produce large quantities of H$_2$

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<th>Parameter</th>
<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>H$_2$ conc.</td>
<td>10 mM</td>
</tr>
<tr>
<td>CH$_4$ conc.</td>
<td>1 mM</td>
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mM = mmol per kg of H$_2$O
Kelley et al. (2001; 2005), Proskurowski et al. (2006), Reeves et al. (2014)
A Bottom-Up Test of the Hydrothermal Model

H$_2$ production from H$_2$O 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. $3\text{Fe}^0 + 5\text{H}_2\text{O} + 2\text{SiO}_2 \rightarrow \text{Fe-serpentine} + 3\text{H}_2$

b. $3\text{Fe-olivine} + 2\text{H}_2\text{O} \rightarrow 2\text{Fe}_3\text{O}_4 + 3\text{SiO}_2 + 2\text{H}_2$

c. $\text{Fe-serpentine} \rightarrow \text{Fe}_3\text{O}_4 + \text{H}_2\text{O} + 2\text{SiO}_2 + \text{H}_2$

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 $\text{H}_2$ from $\text{H}_2\text{O}$
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% \( \text{H}_2 \) in the plume at today’s outgassing rate (Hansen et al., 2011) for ~500 Myr.

The presence of appreciable \( \text{H}_2 \) 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.
Hydrothermal Mineral Alteration as a Source of $\text{H}_2$

$\text{H}_2$ production from $\text{H}_2\text{O}$ is coupled to Fe oxidation

Similar to hydrothermal systems on Earth because of the high abundance of Fe

This geochemical model was used to estimate the $\text{H}_2$ yield ($\leq 20 \times 10^{19}$ moles) of Enceladus’ core (Waite et al., 2017)

Steady-state plume requires $\sim 1 \times 10^{19}$ moles $\text{H}_2$ over 4.56 Gyr
Thermogenesis as a Complementary Source of H₂

Accreted rocks on Enceladus could be rich in organic matter.

Those organics would contain H.
Comet Halley: $C_{100}H_{80}N_{4}O_{20}S_{2}$ (Kissel & Krueger, 1987)

Heating organic matter from the Murchison meteorite generates $H_2$ (Okumura & Mimura, 2011)

![Graph showing the heating timescale of minutes against temperature (°C)]

Heating timescale of minutes
Thermogenesis as a Complementary Source of H$_2$

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Heating organic matter from the Murchison meteorite generates H$_2$ (Okumura & Mimura, 2011)

Thermogenesis $\leq 3.5 \times 10^{19}$ moles H$_2$

Mineral Alteration $\leq 20 \times 10^{19}$ moles H$_2$

Steady-state plume requires $\sim 1 \times 10^{19}$ moles H$_2$ over 4.56 Gyr

Hydrothermal processing of rocks may produce H$_2$ from both minerals and organics

Heating timescale of minutes
H₂ links the inorganic and organic/living worlds

**Organic synthesis**

CO₂ + H₂ → Organics + H₂O

**Prebiotic chemistry**

Current model: Life began at *alkaline* hydrothermal vent (shout out to Mike Russell!)

**Chemical energy for life**

H₂/CH₄-based metabolisms

Weiss et al. (2016, Nat. Microbiol. 1, 16116)
## Enceladus Plume Composition

- **Major plume constituents**

### Ice Grains (CDA)

<table>
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<tr>
<th>Component</th>
<th>Concentration (mol/kg H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>0.05-0.2</td>
</tr>
<tr>
<td>NaHCO₃+Na₂CO₃</td>
<td>0.01-0.1</td>
</tr>
<tr>
<td>KCl</td>
<td>~0.001</td>
</tr>
</tbody>
</table>

Postberg et al. (2009)

### Gas Phase (INMS)

<table>
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<tr>
<th>Species</th>
<th>Molar Percentage</th>
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<tr>
<td>H₂O</td>
<td>~98</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.3-0.8</td>
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<tr>
<td>CH₄</td>
<td>0.1-0.3</td>
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<tr>
<td>NH₃</td>
<td>0.4-1.3</td>
</tr>
<tr>
<td>H₂</td>
<td>0.4-1.4</td>
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Waite et al. (2017)

### Terrestrial seawater:

- 0.5 m NaCl
- 0.03 m SO₄⁻²
- 0.01 m KCl
- 0.002 m HCO₃⁻
Chemical Affinity of H\(_2\)CO\(_2\) + 4H\(_2\) → CH\(_4\) + 2H\(_2\)O

Methanogenesis

Is there enough chemical energy to support life???

The amount of free energy available

\(\text{H}_2/\text{H}_2\text{O} \text{ Ratio} \)

Waite et al. (2017)
The energy demands of Earth microbes…

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

**Chemical Affinity of H$_2$**

- **Hoehler (2004)**
  
- **Waite et al. (2017)**

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**Diagram Details**

- **Y-axis**: Affinity (kJ/mol CH$_4$)
- **X-axis**: H$_2$/H$_2$O Ratio

- **Growth**
- **Equilibrium**
- **Maintenance**

---

**Equation**

$$\text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$$
Apparent chemical affinity for hydrogenotrophic methanogenesis in the ocean of Enceladus (273 K, 1 bar)

The major species composition of Enceladus’ plume gas (Waite et al., 2017)

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<th>Constituent</th>
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<td>H₂O</td>
<td>96 to 99</td>
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<tr>
<td>CO₂</td>
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\[ 4\text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \]

Enceladus H₂ Affinity: 40 to 130 kJ/(Mol CH₄)

These nominal model results are based on CH₄/CO₂ = 0.4, a chlorinity of 0.1 molal, and 0.03 molal total dissolved carbonate (Hansen, et al., 2011). Reported ranges in these parameters propagate to give an uncertainty in the computed affinities of ~10 kJ (mol CH₄)⁻¹.
Does "Abundant H₂" = "No Life"?

The paper adopts an agnostic position on whether the result indicates or negates the presence of life – the argument against life asks if there is so much H₂ why wouldn’t microbes have eaten it.

H₂ utilization in Earth microbial systems stops at a value that maintains a small negative Gibbs free energy (vGc). This critical value is explained by the coupling to the energy-generating system of the cell that has a threshold of about 1/3 ATP or approximately -23 kJ/mol of the energy-generating reaction. 

Life on Enceladus may not rely on ATP as an energy transfer molecule, which would imply the H₂ affinity threshold for microbial growth may be different.

Primitive life in the ocean of Enceladus may choose a simpler organic molecule for phosphate to bind to such as acetic acid or enolpyruvate – the simplest alpha ketone – or it may choose a completely different energy transfer mechanism.

This cannot be determined apriori. Therefore we cannot know the critical Gibbs free energy threshold for microbes in the ocean of Enceladus.

### Measured Enceladus

**H₂ Affinity:** 40 to 130 kJ/(Mol CH₄)

**[best guess: 100 kJ/(Mol CH₄)]**
Effect of Growth Factors on $\text{H}_2$ Consumption

Several factors affect the microbial growth rate in Earth based methanogens:

1. $\text{H}_2$ must not fall below the level of 17-23 $\text{M}$ [H.C. Ver Ecke et al., PNAS, August 21, 2012, vol.109(34), 13674-13679] for methanogenesis to take place in Earth microbes. Our inferred ocean level ranged from 100 $\text{M}$ (pH9) to 0.1 $\text{M}$ (pH11). Note also that the concentrations of $\text{H}_2$ produced in the hydrothermal system would double if we assume that the observed $\text{CH}_4$ is biogenic in origin.

2. H.C. Ver Ecke et al., Environmental Microbiology Reports, doi:10.1111/1758-2229.12065, 2013 also studied growth rate for methanogenons as a function of temperature, pH, chloride content, and $\text{NH}_4^+$ availability.

One of the most likely scenarios is that microbial growth is limited by environmental growth factors.
## Coupled Metabolic Systems

Metabolic pathways found in the Earth’s oceans:

1. **Methanogenesis:**
   
   \[
   4\text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}
   \]

   Subject of the present finding

2. **Anaerobic Oxidation of Methane:**
   
   \[
   \text{CH}_4 + \text{SO}_4 + \text{H}^+ \rightarrow \text{CO}_2 + \text{H}_2\text{S} + 2\text{H}_2\text{O}
   \]

   Could be investigated on a future mission

3. **Sulfate Reduction:**
   
   \[
   4\text{H}_2 + \text{SO}_4 + 2\text{H}^+ \rightarrow \text{H}_2\text{S} + 4\text{H}_2\text{O}
   \]

4. **Hydrogen Oxidation:**
   
   \[
   2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}
   \]

   Difficult to measure directly due to the low concentrations expected for \(\text{O}_2\) in the ocean environment

5. **Methane Oxidation:**
   
   \[
   \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}
   \]

6. **Sulfide Oxidation:**
   
   \[
   \text{H}_2\text{S} + 2\text{O}_2 \rightarrow \text{SO}_4 + 2\text{H}^+
   \]

This limited set of metabolic pathways illustrates the possible effects of coupled metabolic pathways on the interpretation of the chemical affinity of \(\text{H}_2\).
In summary...

Waite et al., Science 356, 155–159 14 April 2017: Cassini INMS has observed H$_2$ emanating from the plume, which is inferred to originate in the interior ocean.

The H$_2$ implies a hydrothermal source in the ocean of Enceladus.

The H$_2$ affinity interpreted in terms of the chemical equilibrium represented by the methanogenesis reaction: $4\text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$ indicate a potential source of chemical food for microbes.

The published results are agnostic with regard to the existence of life in the ocean of Enceladus – a Search for Life must be pursued through a future mission.
Overall Summary

1. Measurements in the last five years of internal structure firmly establish a global ocean with a thin ice crust separation near the south pole.

2. Composition of the ice grains and gas from the plume strongly indicate the existence of hydrothermal systems at the rock ocean interface that produce molecular hydrogen and provide evidence for chemical energy for methanogenic microbes.

3. Next step: SEARCH FOR LIFE
Supplementary Slides
Hydrogen gas is discovered coming from Saturn’s moon Enceladus, suggesting reaction of rock with warm water at the base of a subsurface ocean.

Cassini Finds Molecular Hydrogen in the Enceladus Plume: Evidence for Hydrothermal Processes

The major species composition of Enceladus’ plume gas

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</tbody>
</table>

Apparent chemical affinity for hydrogenotrophic methanogenesis in the ocean of Enceladus (273 K, 1 bar). The orange lines bracket the observed range in the mixing ratio of H₂ in the plume gas (0.4% to 1.4%). The blue lines are contours of constant ocean pH, a key model parameter. The cyan region indicates affinities for a pH range that may provide the greatest consistency between literature results. The dashed red line designates chemical equilibrium, where no energy would be available from methanogenesis. These nominal model results are based on CH₄/CO₂ = 0.4, a chlorinity of 0.1 molal, and 0.03 molal total dissolved carbonate. Reported ranges in these parameters propagate to give an uncertainty in the computed affinities of ~10 kJ (mol CH₄)^−1.

Waite et al., Science 356, 155–159 14 April 2017
The accumulated signal mass spectra for E5 and E7 representative of the high and low velocity distributions described in the text. The spectra have been normalized so that the signal in other masses can be compared to the H$_2$O signal at 18 Da. The lower bound of the plot window represents the noise level for both data sets. A significant velocity dependence is observed when comparing the two spectra. The E5 spectrum shows composition with complexity up to C$_6$H$_6$ (78 Da) whereas E7 complexity peaks in the C$_3$ group (around 40 Da).