The Icy Moons and the Extended Habitable Zone
Europa Interior Models
Other Types of Habitable Zones

Water requires heat and pressure to remain stable as a liquid
Extended Habitable Zones

• You do **not** need sunlight.
• You **do** need liquid water
• You **do** need an energy source.
Selected Moons of the Solar System, with Earth for Scale

- Earth (Moon)
- Mars (Phobos, Deimos)
- Asteroid Ida (Dactyl)
- Jupiter (Io, Europa, Ganymede, Callisto)
- Saturn (Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus, Phoebe)
- Uranus (Puck, Miranda, Ariel, Umbriel, Titania, Oberon)
- Neptune (Proteus, Triton, Nereid)
- Pluto (Charon, Dysnomia)

Scale: 1 pixel = 25 km
Saturn and its Satellites

- Saturn is nearly twice as far from the Sun as Jupiter
- Saturn gets ~30% of Jupiter’s sunlight:
  It is commensurately colder
- Saturn has 82 known satellites (plus the rings)
  • 7 major
  • 27 regular
  • 4 Trojan
  • 55 irregular
  • Others in rings
- Titan is nearly as large as Ganymede
Titan

The second-largest moon in the Solar System

The only moon with a substantial atmosphere

90% N$_2$ + CH$_4$, Ar, C$_2$H$_6$, C$_3$H$_8$, C$_2$H$_2$, HCN, CO$_2$
**Equilibrium Temperatures**

Recall that \( T_{EQ} \sim (L_*/d^2)^{1/4} \)

<table>
<thead>
<tr>
<th>Planet</th>
<th>Distance (au)</th>
<th>( T_{EQ} ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.38</td>
<td>400</td>
</tr>
<tr>
<td>Venus</td>
<td>0.72</td>
<td>291</td>
</tr>
<tr>
<td>Earth</td>
<td>1.00</td>
<td>247</td>
</tr>
<tr>
<td>Mars</td>
<td>1.52</td>
<td>200</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.20</td>
<td>108</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.53</td>
<td>80</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.2</td>
<td>56</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.1</td>
<td>45</td>
</tr>
</tbody>
</table>
The Atmosphere of Titan

Pressure: 1.5 bars
Temperature: 95 K

Condensation sequence:
• Jovian Moons: H₂O ice
• Saturnian Moons: NH₃, CH₄

2NH₃ + sunlight → N₂ + 3H₂
CH₄ + sunlight → CH, CH₂
Implications of Methane

Free CH$_4$ requires replenishment
  • Liquid methane on the surface?

Hazy atmosphere/clouds may suggest methane/ethane precipitation.

The freezing points of CH$_4$ and C$_2$H$_6$ are 91 and 92K, respectively. (Titan has a mean temperature of 95K)

(Liquid natural gas anyone?)

This atmosphere may resemble the primordial terrestrial atmosphere.
Near-IR image penetrates the haze, revealing surface features.
Near-IR image (933 nm)
Aside: Radar Imaging

- **Bright** implies:
  - Rough surfaces, or
  - Highly reflective surfaces

- **Dark** implies:
  - Smooth surfaces, or
  - Absorbing surfaces
The Sea?
The Lake?
The Huygens Probe

Part of the Cassini mission
Landed on Titan 1/14/05
The
Descent Imager / Spectral Radiometer
During the Descent of Huygens
onto Titan on January 14, 2005

Erich Karkoschka, University of Arizona,
the DISR Team, NASA, ESA

© 2006 University of Arizona
The View from Above

A Coastline?
Rivers?
Panoramic view from 8 km

The surface in true color

“Rocks” are probably water ice

The Surface
Lessons

• At 8 km, the atmosphere is saturated with CH$_4$

• Surface features look like lakes and riverbeds

• H$_2$O rocks show evidence of erosion

• Photochemical smog is due to organic molecules

• **Titan is a dynamic world**, with CH$_4$ and C$_2$H$_6$ precipitation

*Titan has all the building blocks for life*
Life on Titan?

Probably not. Titan is cold.

But \( \text{C}_2\text{H}_2 \) (acetylene) could be a source of energy.

Titan does have subsurface water oceans heated tidally, beneath a thick crust of water ice \( \text{(Science 319, 1649. 3/21/08)} \)
Enceladus
Enceladus up close
“Tiger Stripes”

blue: young H$_2$O ice
Tiger Stripes

IR-bright emission near the south pole of Enceladus
Geysers

Gas and dust plumes from occultation photometry. 
V=600 km/s

March 2008 Cassini flyby
Geyser Plumes backlit
Cassini Enceladus Flyby

12 March 2008
Came within 30 km of surface
Flew through geysers at 120 km altitude

Geysers suggest subsurface water at 0°C
Enceladus Model

Ocean 10 km thick
Below 30-40 km ice

Science, 4/4/14
Organic Molecules in Enceladus Plumes

Cassini mass spectrometer observations

• C, N, O–bearing molecules detected
  – Dimethylamines and ethylamines
  – Carbonyls
    • Acetic acid or acetaldehyde
  – Aromatics

Precursors of amino acids
Mimas

Closest of the large moons.
Mimas Librates (wobbles)

6 km wobble suggests
  – a liquid interior, or
  – an oval core

See
  – Science 346 (2014)
What’s Next?

**Europa Clipper** (NASA)
- Proposed for launch 2025
- Flyby mission

**JUICE**: Jupiter Icy Moons Explorer (ESA)
- June 2022 launch

**TSSM**: Titan/Saturn System Mission (NASA/ESA)
- Concept only
- Titan orbiter
- Balloon floating in Titan’s atmosphere
- Saturn orbiter, focusing on Enceladus
Further Out

- Triton
Pluto

CH$_4$, NH$_3$ ice
Reds suggest Tholins
Endor
Implications for $N_H$

Planets and moons create their own habitable zones

Habitable zones change with time

Only Venus is in the unmodified Habitable Zone

Earth is habitable

Venus and Mars were probably habitable

Europa, Ganymede, Titan, Enceladus, Mimas, and other icy satellites are potentially habitable

$N_H > 1$ seems reasonable
Implications for $f_{\ell}$

Life started at least once in the Solar System

The basic ingredients for biochemistry are common in the Solar System

We will not know whether life started more than once in the Solar System without more detailed investigations.

$f_{\ell} = 1$ seems reasonable
N Update

\[ N = N_\ast f_s f_p n_H f_\ell \cdots \]

- \( N_\ast = 4 \times 10^{11} \)
- \( f_s = 0.2 \)
- \( f_p = 1.0 \)
- \( n_H = 4 \)
- \( f_\ell = 1.0 \)

\[ N = 3.2 \times 10^{10} \]
Redox Reactions

• H₂ → 2H⁺ + 2e⁻ (reduction)
• 1/2 O₂ + 2H⁺ + 2e⁻ → H₂O (oxidation)

• Aerobic respiration
• 2Fe⁺⁺ + 1/2 O₂ + 2H⁺ → 2Fe⁺+++ + H₂O
• C₆H₁₂O₆ + 6O₂ → 6H₂O + energy