Plumes on Enceladus: The Ocean Debate

Nick Schneider, LASP, U. Colorado


Art by Michael Carroll
Outline for the Talk

I. How Salty is the Material Escaping Enceladus?
II. How Well Do Plume Models Explain Ejecta Composition?
Key Observations of Enceladus’ Plumes

- Mostly escaping
- Mostly gaseous, ~0.5% particles by mass

- Escaping gases:
  - Mostly water
  - CO$_2$, NH$_3$
  - Miscellaneous organics
  - Sodium <10 ppm

- Escaping particles:
  - mostly low-salt
  - small fraction salty (1% salinity)
Searching for Minor Species
Why sodium?

- Cosmically abundant
- 2nd, 3rd most common ejecta from Europa, Io
- Extraordinarily detectable - in atomic form

- Tracer of refractories
- Potential astrobiological significance
  - Associated with oceans or aquifers
  - A major electrolyte in terrestrial biology
Ocean Modeling: \textit{water}+\textit{rock} +\textit{time}=\textit{saltwater}

\textit{Figure from Postberg et al.}

\textit{Zolotov et al. 07}

\textbf{Figure 3.} Equilibrium concentrations of (a) major solutes and (b) pH in ocean-entering fluids cooled to 0°C at the ocean-rock interface on early Enceladus at 100 bar. The horizontal axis represents temperature of original fluids shown in Figure 2.
Internal Structure of Enceladus: Ocean?

- Plume composition is a strong constraint on interior structure and chemistry
  - Salt-rich particles strongly suggest presence of liquid, perhaps from a salty ocean, near the source (Postberg et al. 2009)
  - Non-water-soluble gases (e.g. N$_2$) may indicate clathrates (Keiffer et al. 2006)
  - Where do the organics come from?
Sodium in the Solar System

Io, Schneider et al.

Mercury, Wilson et al.

Europa, Brown et al.

Moon, Potter et al.
Conclusive Proof of Sodium’s Unsurpassed Visibility

Emission spectra of sodium in the range 585–595 nm. The bottom (dashed) trace is due to a flame test with NaCl. The upper (solid) trace is due to sodium emission from a dill pickle.
Sodium - the most easily detected element?

- Io
  - Na escape ~20kg/sec
  - 1-few% mixing ratio
  - ~2-hour lifetime
  - ~200kiloRayleighs peak

- Europa
  - Na escape ~0.1kg/sec
  - ~1% mixing ratio
  - Few-hour lifetime
  - ~10kiloRayleighs peak

[Brown & Hill 96]
## Minor Species

<table>
<thead>
<tr>
<th></th>
<th>Io</th>
<th>Europa</th>
<th>Enceladus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Escape rate</strong></td>
<td>$\sim 10^{28}$ SO$_2$/sec</td>
<td>$\sim 5 \times 10^{26}$ O/sec</td>
<td>$\sim 10^{28}$ H$_2$O/sec</td>
</tr>
</tbody>
</table>
| **Sodium escape**| $\sim 10^{26}$ Na/sec
20 kg/sec | $\sim 3 \times 10^{24}$ Na/sec
$\sim 0.1$ kg/sec | ? |
| **Sodium fraction** | 1-few % | $\sim <1\%$? | ? |
| **Sodium origin** | Volcanic NaCl? | Oceans? | ? |
The Search for Enceladus Sodium

Keck and Anglo-Australian Telescope Observations

- Deep searches in the E-ring and at Enceladus
- Feb & March 2007
- Spatially-resolved spectra
- Resolving power 50,000-100,000
Enceladus reflected light

scattered light from Saturn & rings

sodium emission from Earth's atmosphere

Solar spectrum sodium absorption
Sources Considered
• Atomic Na in plume
• Sodium-bearing molecules
• Na released from E-ring

Dominant processes:
• Photoionization
• Photodissociation
• Electron impact ionization
• Resonant scattering
• Radiation pressure
• Impact on rings
Molecule/Particle escape

Model mixing ratio = $1 \times 10^{-5}$ Na/H$_2$O

Actual upper limit = $7 \times 10^{-6}$ Na/H$_2$O (=7 ppm)
Atomic escape

Model mixing
ratio=$2 \times 10^{-6}$ Na/$\text{H}_2\text{O}$

Actual upper limit=$4 \times 10^{-7}$ Na/$\text{H}_2\text{O}$
($=0.4$ ppm)
Observational Conclusions

- The sodium content of the vapor plumes is <7ppm if sodium is released in molecular or particulate form, and <0.4ppm if released in atomic form.
- Enceladus has the lowest sodium escape rate among small bodies with escaping atmospheres.
- These upper limits are consistent with the small fraction of salty-bearing particles observed in the E-ring by Cassini’s CDA experiment.
II. How Well Do Plume Models Explain Ejecta Composition?
Plume Vent Models

- **Near-Surface Geysers**
  - Saline Liquid water
  - Violent boiling

- **Shallow Vents**
  - Saline Liquid water
  - Vapor under pressure

- **Tectonic Meltwater**
  - Low-salinity meltwater

- **Ice Sublimation**
  - Warm, fractured ice
  - Brine pocket

- **Deep Misty Caverns**
  - Saline Liquid water
  - Vapor under pressure
Near-Surface Geysers

- The boiling liquid can produce a cloud of gas and ice if some of the liquid is carried along with the vapor and freezes as it expands out of the vent …” [Porco et al. 2006]
- Source of water: ocean? Meltwater?
1. Near-Surface Geysers

**Strengths**
- Terrestrial analog
- Physics well understood

**Weaknesses**
- Sodium vapor and/or very salty particles would be easily observed
- *Plumes cannot come from complete vaporization of ocean water including its dissolved salts, as might occur from a near-surface geyser boiling into a vacuum.*
2. Shallow Vents (water-filled cracks)

- Evaporation occurs near equilibrium at the interface of small vents
- Particles can come from the liquid or spalled from the vent walls
- Preferential evaporation of water may enrich non-volatiles in the vent
2. Shallow Vents (water-filled cracks)

**Strengths**
- Could explain water vapor & salty particles

**Weaknesses**
- Preferential evaporation of H$_2$O in the vent plumping may lead to “salt clogging”
  - Choking off the vent?
  - Ejecting too-salty particles?
- Difficult to provide heat flux
3. Tectonic Meltwater

- Heating along fractures caused by tidal flexing (Nimmo et al. 2007, Hurford, DPS ‘09)
- Meltwater could collect in cracks
- Preferential evaporation of $\text{H}_2\text{O}$ could enrich vent water to $\sim 1\%$ salinity
3. Tectonic Meltwater

- **Strengths**
  - Heating mechanism common to most scenarios
  - Explains water vapor, salty particles, and potentially other gases

- **Weaknesses**
  - Not modeled well enough to evaluate
4. Ice & Clathrate Sublimation

- Icy crust is cracked and warmed by tectonic activity
- Sublimation and clathrate decomposition release “cometary” gases
- Particles are entrained in the flow
- Kieffer et al., 2006
4. Ice & Clathrate Sublimation

Strengths:
- Naturally explains low-sodium water vapor, comet-like gases (Waite et al. 2009)

Weaknesses:
- Source of salt-bearing particles is an ad hoc assumption and may not match observations
- What composition & conditions match INMS results?
- Cold temperatures may not yield high enough vent velocity
5. Deep Misty Caverns

- Evaporation occurs at the interface of a large liquid/vapor reservoir many km below the surface.
  - Equilibrium evaporation under pressure explains low-sodium vapor
- Flow out the vent is slow, “like a small leak in a balloon”
- Droplets entrained in the flow freeze on ejection
- Postberg *et al.*, Nature 2009
  (read online Supplementary Material!); Schmidt *et al.* Nature 2008

*Cavern actually within crust above ocean*
5. Deep Misty Caverns

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5. Deep Misty Caverns

Strengths

- Model contains most physically rigorous components
- Explains low-sodium water vapor
- Explains salty particle entrainment
- Explains vent velocities
5. Deep Misty Caverns

Weaknesses/Concerns

- Some model components* based on ad hoc assumptions
- Are km-scaled caverns realistic?
- What process makes droplets? *Do droplets evolve as brownian motion carries them for km’s?
- *What makes salt-poor particles?
- *Can underwater clathrate decomposition make escaping gases observed by Cassini’s INMS?
- Do these processes affect D/H?
### The Scorecard So Far

<table>
<thead>
<tr>
<th>Observable Model</th>
<th>Low-salt vapor</th>
<th>Salty particles</th>
<th>Other gases</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near-surface ocean geyser</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>F</td>
</tr>
<tr>
<td>Ocean-filled cracks</td>
<td>X?</td>
<td>X?</td>
<td>X</td>
<td>D</td>
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<tr>
<td>Freshwater-filled cracks</td>
<td>✔</td>
<td>✔?</td>
<td>?</td>
<td>B</td>
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<tr>
<td>Ice/Clathrate vaporization</td>
<td>✔</td>
<td>X?</td>
<td>✔</td>
<td>B</td>
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Plume Vent Models

Near-Surface Geysers: Ruled Out
Shallow Vents: Unlikely
Tectonic Meltwater: Possible?
Ice Sublimation: Possible?
Deep Misty Caverns: Possible?

- Violent boiling
- Vapor under pressure
- Brine pocket
- Warm, fractured ice
- Saline Liquid water
- Saline Liquid water
- Low-salinity meltwater
- Saline Liquid water
The Bottom Line: Don’t Jump on Any Bandwagons

- A wide variety of observational constraints & physical limitations argue against near-surface geysers and deep ocean-filled cracks
- Several viable scenarios (and hybrids) remain: sublimation/clathrate decomposition, meltwater evaporation, deep misty caverns

- More rigorous modeling needed to bring alternative scenarios to same level as “deep misty caverns” scenario.
The Big Debate: Oceans, Puddles, Ice or ???

- Saltwater, Freshwater or Ice?