Sodium salts in cryo-volcanic ice particles

Evidence for liquid water on Enceladus

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Some Parameters

- **Eff. Diameter:** $D = 504 \text{ km/s}$
- **Density:** $\rho = 1610 \text{ kg/m}^3$
- **Surface Temp.:** $T_{\text{equator}} \approx 80K$
  
  $T_{\text{Tiger Str.}} \approx 180K$
- **Production rate**
  
  $\approx 200 \text{ kg/s Gas}$
  
  $\approx 20 \text{ kg/s Ice-dust}$
- **Escape Speed:**
  
  $V_{\text{Escape}} \approx 230 - 300 \text{ m/s}$
  
  $V_{\text{Gas}} \approx 500 \text{ m/s}$
  
  $V_{\text{Dust}} \approx 150 \text{ m/s}$
- **Gas and particle flow are decoupled**
- **1 - 5 % of the ice grains are emitted into the E-ring (0.2 – 1 kg/s)**

Kempf et al., Icarus 2009
Saturn’s E-ring, the largest known planetary ring

Cassini crosses the E ring in most of its orbits:
- In situ sampling of Enceladus’ plume grains
- Excellent statistics
- Particle sizes 0.1 – 1.5 µm
Why Sodium is important

- If liquid water on Enceladus is in contact with a rocky planetary core:
  
  ⇨ Na-salts are the major dissolved solids (Zolotov, 2007)
  
  ⇨ Na-salts don’t stay in the ice during slow freezing (phase separation)

Na – detection

= Litmus test for liquid water as plume source
Our detector: the Cosmic Dust Analyser (CDA)
Na-rich water ice

- ~ 6% of E ring ice particle spectra
- Na abundance far above level of possible instrument contamination

**Type III - Spectrum**

- \((\text{NaOH})_n\text{Na}^+\) cluster prove alkaline water and high Na content \((\text{Na/H}_2\text{O} > 10^{-3})\)
- \((\text{NaCl})_n\text{Na}^+\) and \(\text{Na(Na}_2\text{CO}_3)\) \(\text{Na}^+\) cluster:
  - \(\text{NaCl}\), \(\text{NaHCO}_3\) / \(\text{Na}_2\text{CO}_3\), minor K component
  - Compounds predicted to be most abundant in an Enceladus ocean (Zolotov, 2007)
Reproducing CDA spectra in the laboratory
- No ice with embedded salt grains, but frozen saltwater.

Best agreement with
- NaCl: 0.1 - 0.2 M/l
- NaHCO₃: 0.05 - 0.1 M/l
- pH - value: ~ 9.0
- Na/K: 100 - 200

Predictions for early Enceladus Ocean (Zolotov, 2007)
- NaCl: 0.05 - 0.1 M/l
- NaHCO₃: 0.01 - 0.05 M/l
- pH - value: 8 - 11
- Na/K: 10 - 100
- Aerosol like droplets (sub-micron spray) form and freeze
- Salt content of the ocean water is preserved
- Rapid acceleration in the vent
- Condensation of additional water from the supersaturated water vapour
How to create a spray of water droplets?

Turbulences are mandatory

→ sizzling water from bubbles of up-streaming volatile gases \( \rightarrow \) Cassini- INMS (Waite et al., 2009)

Possible sources:
- Dissolved bicarbonate: \( \text{CO}_2 \)
- Clathrate decomposition at water/ice interface:
  \( \text{CO}_2, \text{CH}_4, \text{N}_2, \text{NH}_4, \) organic gas
- Hydrothermal processes:
  \( \text{N}_2, \text{CH}_4, \) organic gases
Na-poor water ice (Type I+II)

- ~ 90% of E ring particle spectra
- \((\text{H}_2\text{O})_n\text{Na}^+\) cluster prove water ice with low Na content \((\text{Na}/\text{H}_2\text{O} < 10^{-5})\)

Laboratory calibration experiments indicate \(\text{Na}/\text{H}_2\text{O} = 10^{-7} - 10^{-9}\)

K minor component
- Na-poor grains by homogenous nucleation from vapour

- Water vapour above a salty liquid is heavily depleted in salt components

\[ n_{\text{gas}}(NaCl) = n_{\text{liquid}}(NaCl) \exp \left( \frac{W_{\text{sol}}}{k_B T} \right) \]
- Na-poor grains by homogenous nucleation from vapour

- Ice grains form from vapour when the gas is compressed (e.g. at nozzles in the vent)

- This has been modelled for Enceladus’ vents and reproduces observed plume dynamics (Schmidt et al. 2008)
Why not detected by other instruments?

A) Direct detection of Na in plume vapour:
- Na concentration in the plume vapour $\leq$ Na-poor grains ($\text{Na/H}_2\text{O} \sim 10^{-7}$)
  ⇒ below detection limit of other instruments

B) Detection of Na from sputtered E ring grains:
- Average content in Na-poor (~90%) + Na-rich (~6%) E ring grain: $\text{Na/H}_2\text{O} \sim 10^{-4}$
- Enceladus Emission into E ring: $\sim 0.5 \text{ kg/s ice grains} \sim 200\text{kg/s water vapour}$
  ⇒ Sputtered Na is diluted by a factor of $\sim 400$
  ⇒ below detection limit of Earth bound spectroscopy (Schneider et al., 2009)

C) Detection of salts on Enceladus surface:
- Most ice grains fall back to the Tiger Stripes
  ⇒ Deposition of Na-rich and Na-poor grains: $\text{Na/H}_2\text{O} \sim 10^{-4}$
• How does the liquid reservoir look like?

• Evaporation from liquid water:
  - Evaporation of 200 kg/s cools the water surface
  - To avoid freezing due to latent heat:
    \[ R_{\text{out}} \ll R_{\text{in}} \]
  - \( R_{\text{out}} \approx 1 \text{ m} \)
  - Exact surface area depends on amount of convection in reservoir
  - \( 1 \text{ km}^2 < A_{\text{in}} < 10,000 \text{ km}^2 \)
Self-limiting process: Cannot maintain observed steady jets
Would expel sodium with liquid: Not seen by KECK
Would create only Na-rich grains: Not observed by CDA

Ice fracture crosses salty ice layer (frozen from ancient ocean?)
- Self-limiting process: salt-near the crack soon exhausted
- Geophysically unlikely

Heat flow problem: vents would rapidly freeze
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Upper part of liquid enriched by salt evaporation?
- Diffusion would rapidly smooth salinity gradient

John Spencer
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Heat flow problem: vents would rapidly freeze

Large liquid/gas interface

Gas-flow back-pressure in cracks

Supersaturated gas (Na-poor grains)

Na-rich grains from aerosols above liquid

Good agreement with prediction for ocean composition

Consistent with KECK non-detection of Na

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- Multiply connected archings and pillars?
- 1.2% Earth's gravity → No principal stability problem
Plume Reservoir = Ocean?

Salt-ice grains:
- Reservoir is (or has been) in enduring contact with rock.

Geophysical stability:
- ‘Stable’ cracks cannot go deeper than few kilometers = maximum depth of water surface

Three principal models:

a) Large & deep (60 km) ocean under thin ice crust
b) Small isolated salt water pockets ($V > 1 \text{ km}^3$)
c) Shallow ocean which supplies plume reservoir(s)

But:
- NO geysers! Better: jets
- NO water surface in narrow ice channels
Summary I

- **Na-rich E ring ice grain population**
  - ~ 6% of E ring particles
  - Main sodium bearing compounds are NaCl and Na-(bi)carbonate ("Soda")
  - K salts minor component
  - Total salinity ~ 0.5 - 2% (Na/H₂O > 10⁻³), alkaline pH
  - not consistent with a clathrate decomposition model
  - not consistent with ice sublimation model
  - very good agreement with liquid water in contact with rocky core

- **Na-poor E ring ice grain population**
  - ~ 90% of E ring particles
  - Na/H₂O = 10⁻⁵ - 10⁻⁹
  - good agreement with liquid water vapour above salty liquid
Two particle formation processes likely

- **Na-rich**: direct freeze out of submicron ocean water droplets
- **Na-poor**: nucleation of salt-depleted water vapour (Schmidt et al. 2008)

Results in agreement with Na non-detection by spectroscopy (Schneider et al., 2009)

Evaporation from liquid requires large water surfaces

- No violent boiling of near surface geysers
- More likely: evaporation into vapour chambers which narrow down to cracks

Connection to large Ocean? Three principal possibilities:

- Large & deep (60 km) ocean under thin ice crust
- Small isolated salt water pockets ($V > 1 \text{ km}^3$)
- Shallow ocean which supplies plume reservoir(s) \(\rightarrow\) Most plausible...
  ... at the moment ...