Ion energy distributions and densities in the plume of Enceladus

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Collaborators
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• Enceladus, Saturn’s inner magnetosphere and E ring
• Enceladus plume observations
  • Cassini INMS and CAPS
• Model description
  • Equation, chemical reactions, model settings…
  • Some cases of electric and magnetic field
• Results & Discussions
  • Model comparisons with CAPS, INMS and LP
• Summary
• Enceladus (~3.95 $R_S$)
  • Equatorial radius: 247 km
  • Orbital radius: $238.02 \times 10^3$ km
    • $\sim 3.95 \, R_S$
  • Mass: $7.0 \times 10^{19}$ kg
  • Atmosphere: (Thin) Water vapor
• Enceladus plume (~3.95 $R_S$)
  • Water gas
• E ring
  • 3 – 8 $R_S$ (overlapping with inner magnetosphere)
  • Water group ion
  • Dust
• Source: Mainly Enceladus plume
Cassini

• Outline
  • Launch date: Oct. 15, 1997
  • Development & Operation: NASA, ESA
  • Orbit Insertion: Jul. 1, 2004
  • Now Operating!
    • EOM: Sep. 15(?), 2017
  • Instruments (3 major)
    • Optical remote sensing
    • Electric-magnetic field, particles and wave observation
    • Microwave remote sensing
• Ion and Neutral Spectrometer (INMS)
  • Can measure the mass number of ions and neutrals (1 < amu < 99)
  • Two sources
    • Closed source: ex. N₂, CH₄
      • Species not to react with the antechamber surface
    • Open source: Radicals and ions

• Cassini Plasma Spectrometer (CAPS)
  • Electron spectrometer (ELS)
    • Electron energy distribution
  • Ion mass spectrometer (IMS)
    • Ion energy (and mass) distribution
  • Ion beam spectrometer (IBS)
- Enceladus plume encounter
- Cassini had 22 Enceladus orbits.
- E03 and E07 orbits are the focus of this presentation.
• Enceladus plume encounter
• Cassini had 22 Enceladus orbits.
• E03 and E07 orbits are the focus of this presentation.
• INMS observations in the plume for E03 orbit
  • \( \text{H}_3\text{O}^+ \) is dominant. \( \text{H}_2\text{O}^+ + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{OH} \)
• INMS counts

• $\text{H}_3\text{O}^+$ is dominant.

• Max.: $\sim$10

INMS (H$_2$O$^+$ & H$_3$O$^+$) for E03 & E07

Spacecraft
$V_x \sim 2.8$ km/s
$V_y \sim -7.2$ km/s
$V_z \sim 0.1$ km/s

INMS FOV

Co-rotational flow

INMS (H$_2$O$^+$ & H$_3$O$^+$)

a: $m/q = 18$ (H$_2$O$^+$)

b: $m/q = 18$ (H$_2$O$^+$)

c: $m/q = 19$ (H$_3$O$^+$)

d: $m/q = 19$ (H$_3$O$^+$)

e: E03

f: E07

INMS counts

$\text{H}_3\text{O}^+$ is dominant.

Max.: $\sim$10

[Sakai et al., 2016]
CAPS/IMS for E03 & E07

- CAPS energy spectrum
- Low energy plasma
- ~19:07 for E03; ~07:42 for E07

[CAPS/IMS E03 Anode 5, log([# s^{-1}])] [CAPS/IMS E07 Anode 4, log([# s^{-1}])]

[Sakai et al., 2016]
Investigation of the ion environment in Enceladus plume

- Where do low energy ions come from?
- What are the physical processes need to explain INMS (and CAPS) data?
  - Electric field or Magnetic field?

Method

- Test-particle simulation of water group ions
• Equation of motion

\[ m_i \frac{dv_i}{dt} = q(E + v_i \times B) \]

• Enceladus coordinate system
• Where do ions in the plume come from?
  1. Charge exchange between background ions and neutral plume
     • Charge eXchange front model (CX model)
  2. Photoionization in the plume
     • Photoionization Plume model (PP model)
• Where do ions in the plume come from?

1. Charge exchange between background ions and neutral plume
   • Charge eXchange front model (CX model)

2. Photoionization in the plume
   • Photoionization Plume model (PP model)
- Charge eXchange Front Model (CX)
  - Interaction of the background ion with the plume gas
  - Particle generator: H$_2$O$^+$ at X = -5 R$_E$
  - Initial V based on the bulk speed: V$_z$ = 0
    - Disk input (particle number of 5 millions)
  - Ion velocity is smaller than the co-rotation velocity in the inner magnetosphere [Holmberg et al., 2012, Sakai et al., 2013].
Simulation settings

• Area of simulation
  - $-5 \, R_E < X < 5 \, R_E; \ -5 \, R_E < Y < 5 \, R_E; \ -10 \, R_E < Z < 5 \, R_E$
  - Move to next particle when a particle is out of this area.

• Plume neutral density ($H_2O$ gas)
  - Based on Saur et al. [2008]

$$n_{plume} = n_0 \left( \frac{R_E}{r} \right)^2 \exp \left[ - \left( \frac{\Theta}{H_\Theta} \right)^2 - \frac{r - R_E}{H_d} \right]$$

- $n_0 = 2.5 \times 10^9 \, \text{cm}^{-3}$, $H_\Theta = 12 \, \text{deg.}$, $H_d = 948 \, \text{km}$
  - [Fleshman et al., 2010]
Reactions with the plume

- $\text{H}_2\text{O}^+ \& \text{H}_3\text{O}^+$
- Charge exchange & Chemical reactions
  
  $\text{H}_2\text{O}^+ + \text{H}_2\text{O} \rightarrow \text{H}_2\text{O} + \text{H}_2\text{O}^+$
  $\text{H}_2\text{O}^+ + \text{H}_2\text{O} \rightarrow \text{OH} + \text{H}_3\text{O}^+$
- Monte Carlo method for reactions
- $\text{H}_3\text{O}^+\text{-H}_3\text{O}^+$ collisions
  - Elastic scattering
  - The cross section is based on a $\text{H}^+\text{-He}$ cross section \cite{Krstic1999}, but we scale it by a factor of 10.

$\sigma_{\text{cx}} = 10^{-15}$ cm$^2$

$\text{H}_2\text{O}^+ + \text{H}_2\text{O} \rightarrow \text{OH} + \text{H}_3\text{O}^+$

$\text{H}_2\text{O}^+ + \text{H}_2\text{O} \rightarrow \text{H}_2\text{O} + \text{H}_2\text{O}^+$

$\sigma_{\alpha} = 10^{-15}$ cm$^2$

$\text{H}_2\text{O}^+ + \text{H}_2\text{O} \rightarrow \text{OH} + \text{H}_3\text{O}^+$

\cite{Sakai2016}
H$_2$O$^+$ -> H$_3$O$^+$ [Lishawa et al., 1990]

- Proton transfer channel

- Atom pickup channel

$\sigma_{pt} > \sigma_{api}$, so the proton transfer channel is adopted.

- One order of magnitude higher
\( \text{H}_2\text{O}^+ \rightarrow \text{H}_3\text{O}^+ \) [Lishawa et al., 1990]

- Proton transfer channel

- Atom pickup channel

\[ \sigma_{pt} > \sigma_{api}, \text{ so the proton transfer channel is adopted.} \]
- One order of magnitude higher
• Magnetic and electric fields used in this simulation

• Based on Omidi et al. [2012]

• 3 cases for E in the plume
  • 1) Omidi’s field
    • No changes
  • 2) Reduced $E_y$
    • 25% of Omidi’s $E_y$
  • 3) Reduced $E_y$ & $E_z$
    • 25% of Omidi’s $E_y$
    • $E_z = -10 \, \mu V/m$
What are outputs of this simulation?
- The number of particles into each bin
- Example of bin
- Convert this number to flux, total count for INMS comparison and density every bin.
Results
Results: Flux for E03 & E07

- Energy vs. Flux distribution (Cassini reference frame)

- $E_z$ is important for obtaining the low energy ion.

- Ions are moving to – $Z$ direction.

- $E_z$ can be generated by dust [e.g., Farrell et al., 2010] or pressure gradient of plasma in $Z$ direction.

- Note that the units of models are different from CAPS.
• Calculated ion counts: INMS: $\approx 10$, Model: 100-1000

E03, around 20 eV

- a: $\text{H}_2\text{O}^+ + \text{H}_3\text{O}^+$
- Omidi fields
- Reduced $E_y$ & $E_z$
- INMS counts

Counts [#] vs. Time

E07, around 6 eV

- b: $\text{H}_2\text{O}^+ + \text{H}_3\text{O}^+$
- Omidi fields
- Reduced $E_y$ & $E_z$
- INMS counts

Counts [#] vs. Time

[Sakai et al., 2016]
Models

• Where do ions in the plume come from?
  1. Charge exchange between background ions and neutral plume
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• Photoionization Plume Model (PP)
  • See ions generated by photoionization
  • Particle generator: $\text{H}_2\text{O}^+$ in the plume
  • Initial $V = 0$
  • Ion starts the gyromotion.

• Photoionization rate
  • $I = 5.1 \times 10^{-9} \text{ s}^{-1}$ [e.g., Moses and Bass, 2000]
**Ion counts: Comparison with INMS**

- Calculated ion counts: INMS: ≈10, Model: 100-1000

### E03, around 20 eV

- **a:** $\text{H}_2\text{O}^+ + \text{H}_3\text{O}^+$
- **b:** $\text{H}_2\text{O}^+ + \text{H}_3\text{O}^+$
- **c:** $\text{H}_2\text{O}^+$
- **d:** $\text{H}_2\text{O}^+$
- **e:** $\text{H}_3\text{O}^+$

**Omidi fields:** Reduced $E_y$ & $E_z$

### E07, around 6 eV

- **b:** $\text{H}_2\text{O}^+ + \text{H}_3\text{O}^+$
- **d:** $\text{H}_2\text{O}^+$
- **f:** $\text{H}_3\text{O}^+$

**Omidi fields:** Reduced $E_y$ & $E_z$

- **Calculated ion counts:** INMS: ≈10, Model: 100-1000

[Sakai et al., 2016]
- CAPS required the low energy ions in the plume!

<table>
<thead>
<tr>
<th>Ion energy (CAPS: $E &lt; 10$ eV)</th>
<th>Counts (INMS: ~10)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Omidi’s field</strong></td>
<td>$E &gt; 10$ eV</td>
</tr>
<tr>
<td><strong>Reduced E</strong></td>
<td>$1$ eV &lt; $E &lt; 10$ eV</td>
</tr>
</tbody>
</table>

- Why are INMS counts lower than model counts in reduced $E$?
• Why are INMS counts lower than model?
• Pointing direction of INMS is important.
• A slightly shift of the INMS phase-space volume would reduce the model counts.

[Sakai et al., 2016]
Ion density in the plume

- Ion density: 400-800 cm$^{-3}$
- Langmuir Probe: $\sim 10^4$ cm$^{-3}$ [Morooka et al., 2011]
- Previous model: 100-1000 cm$^{-3}$ [Kriegel et al., 2014]
- $E_y$ is still low?
Energy-Flux distribution: 25% vs. 10% of Omidí’s $E_y$

- 10% of Omidí’s $E_y$
  - Consistent with a velocity of ~1 km/s [Kriegel et al., 2011]
  - Fluxes did not have big changes in both cases.
  - Ions somewhat get stuck upstream.

[Energy flux distribution with elastic scattering $[m^{-2} s^{-1} eV^{-1}]$, $E_z = -10 \mu V/m$

[Sakai et al., 2016]
• Ion density: 500-1000 cm$^{-3}$
  • Langmuir Probe: $\sim 10^4$ cm$^{-3}$ [Morooka et al., 2011]
  • Still lower than LP
    • Other effect?: Critical ionization velocity effect [Meier et al., 2015]
  • Note that model ion count with 10% of $E_y$ is almost similar to 25% of $E_y$. 

[Graphs showing ion density over time with labels for 25% and 10% of $E_y$.]
Summary

- Energy vs. flux distribution
  - Vertical electric field is important for obtaining the low energy ion detected by CAPS.
  - The electric field could be generated by dust or pressure gradient of plasma in Z direction.

- Ion species
  - $\text{H}_3\text{O}^+$ is dominant which is consistent with INMS.
  - Our total count is not consistent with INMS results.
    - Direction where INMS is looking significantly affects it.

- Ion density
  - 400-1000 cm$^{-3}$ from our model
  - It is lower than LP even if more reduced $E$ is considered, but almost consistent with previous models.
References


• Meier, P. et al. (2015), Modeling the total dust production of Enceladus from stochastic charge equilibrium and simulations, *Planet. Space Sci.*, 119, 208-221.


