Relative fractions of water-group ions in Saturn’s inner magnetosphere

$O^+, OH^+, H_2O^+, H_3O^+$

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The plasma in Saturn’s inner magnetosphere

- Water ions comprise the bulk of Saturn’s plasma.
  - Nitrogen from Titan is less than 10%.
- From the Cassini Plasma Spectrometer (CAPS), know the temperature, density, and velocity distribution of the ions.
  - The water source is Enceladus, so neutral and ion densities peak near 4 Rs, and decay outward and inward.
  - Saturn’s inner magnetosphere is neutral dominated.
- Since the four water-group ions have similar masses and energies, it is challenging to extract the detailed composition of the water-group ions from CAPS data.
- The water-group fractions are sensitive probes of the source, transport, and loss mechanisms that govern Saturn’s magnetosphere.

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Water group fractions

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Water group fractions

Velocity-space densities at 4-4.5 Rs (Tokar 2008)
INMS measures ion mass, directly

- Cassini’s Ion and Neutral Mass Spectrometer (INMS) measures the individual ions separately.
  - No assumptions or fitting required.
  - One mass, one velocity at a time.
- Each measurement samples a small portion of velocity space at a time.
  - Narrow FOV (2° radius); ±1 km/s.
  - Limitation 1: Densities and count rates are low, sometimes requiring the aggregation of 10,000 measurements (IPs) for a 2σ result.
  - Limitation 2: velocity-space variations are convolved with changes due to other factors, complicating interpretation.
  - Maximum velocity for water ions: 20 km/s.

**Quadrupole mass spectrometer**
Mass range: 1-8, 12-99 u (AMU or Da)
Mass resolution: 0.12 AMU

**Closed Source Neutral (CSN)**

**Open source (OSI)**

**Ion aperture (OSI)**

**Energy sorting**

**Mass filter**

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Water group fractions
Raw data

- Uncertainty due to shot noise (low number of counts), not fitting.
- Later data are sampled at higher rate.

![Graph showing water group fractions with labels for $\text{H}_2\text{O}^+$ and noise level.](image)
Data from single orbits

- Uncertainty due to shot noise (low number of counts), not fitting.
- Later data are sampled at higher rate.

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H$_2$O$^+$ ion fractions from INMS

- 19 orbits with INMS data of sufficient quality to measure the relative fractions of water-group ions.
- The highest fractions of H$_2$O$^+$ are near 4 Rs, the orbit of Enceladus, the source of neutral water.
  - Fraction of H$_2$O$^+$ falls with increasing distance from Enceladus.
- Total density of ions also falls from a peak at 4.5 Rs.
- INMS densities, both total and velocity space, agree with CAPS.

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Relative fractions for the water-group ions

- The INMS results show trends that are used to constrain magnetosphere models.
- Far from Enceladus, more O\(^+\) than early models.
- H\(_3\)O\(^+\) is usually inseparable from the noise floor, but can be 5%.
- H\(_3\)O\(^+\) abundance from INMS has the greatest discrepancy with analysis of CAPS data and their early models.
  - Prompted by INMS results, H\(_3\)O\(^+\) reactions reviewed and corrected.
- What drives ion abundances?
  - An important factor is the local abundance of neutrals.
  - Transport timescales longer than most lifetimes.
Ion fractions have dependencies other than radial distance

- Measurement uncertainty causes some variation, but there is also true separation, particularly near 4.0 Rs.
- With such sparse data, it is difficult to isolate the many factors that affect fractions.
  - No apparent dependence on velocity, location in velocity space, azimuth, Enceladus orbit phase, or density.
  - Each INMS measurement is a spot sample of these factors.
- Fractions are constant through most of velocity space.
Velocity is fully defined by two parameters: $V_{\text{PAR}}$ and $V_{\text{PERP}}$

- When a neutral is ionized, it enters velocity space with $V_{\text{PAR}} = 0$
  $V_{\text{PERP}} = \text{pickup velocity}$

- Pickup velocity is
  $$V_{\text{PICKUP}} = V_{\text{MAG FIELD}} - V_{\text{KEPLAR}}$$

- $V_{\text{MAG FIELD}} = 38.5 \text{ km/s}$
- $V_{\text{KEPLAR}} = 12.6 \text{ km/s}$
- $V_{\text{PICKUP}} = 25.9 \text{ km/s}$
Location of INMS measurements in velocity space

• This plot of CAPS data from Tokar et al. 2008 shows the water-group ion densities near 4 $R_S$.

• INMS measurements (white circles) cover a broad portion of velocity space.
  – Radial distances range from 3.5 to 7 $R_s$.
• Plot shows detection of pick-up ions, which are marked by white box.
• INMS found higher fractions of $H_2O^+$ for the pickup ions near the pick-up velocity and near Enceladus.

Water group fractions
Tokar 2008
Relationship to pick-up velocity

• Expect ions close to the pickup velocity to have fractions that reflect the local neutral abundance.

• Near 4Rs, the local neutrals are mostly \( \text{H}_2\text{O} \), and the ions near the pick-up velocity have the highest fraction of \( \text{H}_2\text{O}^+ \).

• Core ions have higher fractions of \( \text{OH}^+ \) and \( \text{O}^+ \).
  – Core ions are older, processed; some converted to \( \text{OH}^+ \) or \( \text{O}^+ \).
  – Charge exchange with neutrals is slower for core ions.
  – Scatter is still large, indicating that other factors are relevant.

INMS found highest fractions of \( \text{H}_2\text{O}^+ \) for the ions near Enceladus and near the pick-up velocity.
New, self-consistent modeling

- What can we do with these data?
- Smith and Richardson are using INMS data to calibrate their new models that are self-consistent between neutrals and ions.
- Also aids in understanding neutral distribution.

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Water group fractions
Mean mass of water-group ions

- CAPS data provide accurate measurement of the mean mass of the water-group ions.
- CAPS trend (red, from Crary and Cassidy, EGU2018) shows mean mass decreases from 5 to 10 Rs.
- INMS data (blue) show similar trend.
Summary

- INMS measured water group fractions, unambiguously.
  - The fractions differ from previous models and measurements.
- Some evidence that the relative fractions differ between the pick-up region and the ions closer to the core of the velocity distribution.
- The fractions are used to calibrate the next generation of neutral and plasma models of Saturn’s inner magnetosphere.

Water-group ion fractions

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