Plume ionosphere of Enceladus as seen by the Cassini ion and neutral mass spectrometer

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[1]   The Cassini spacecraft passed within 168 km of the surface of Enceladus on 14 July 2005 during the E2 flyby and passed closer (50 km) during the E3 encounter on 13 March 2008. During both flybys the ion and neutral mass spectrometer (INMS) detected a plume atmosphere mainly composed of water. During the E3 flyby, the INMS measured an ion mass spectrum with a large peak at mass number of 19 Daltons (interpreted as H_3O^+ ions) but not at the mass numbers of other water group ion species (including H_2O^+, OH^+, O^+). In addition, the INMS observed ion species at mass numbers 36 and 37 - possibly the water cluster ion species H_2O^+ - H_2O and H_3O^+ - H_2O. The INMS detection of cold H_3O^+ in the plume combined with the almost complete absence of cold H_2O^+ ions is attributed to an active ion-neutral chemistry operating in a plume "ionosphere." **Citation:** Cravens, T. E., R. L. McNutt Jr., J. H. Waite Jr., I. P. Robertson, J. G. Luhmann, W. Kasprzak, and W.-H. Ip (2009), Plume ionosphere of Enceladus as seen by the Cassini ion and neutral mass spectrometer, *Geophys. Res. Lett.*, *36*, L08106, doi:10.1029/2009GL037811.

1.   Introduction

[2]   Enceladus is thought to be the source of both plasma and neutral gas for the inner magnetosphere of Saturn and E-ring near the orbital distance of $\approx 4\ R_S$ (Saturn radii) (see the discussions by *Kivelson* [2006], *Johnson et al.* [2006], and *Jurac and Richardson* [2005]). The Cassini Ion and Neutral Mass Spectrometer (INMS) in its neutral mode detected a plume atmosphere near Enceladus during the E2 encounter [*Waite et al.*, 2006] and demonstrated that the plume gas is mainly due to water vapor (91%) and also contains carbon dioxide (3.1%), a combination of carbon monoxide and molecular nitrogen (3.3%), and methane (1.6%). The maximum neutral density measured during E2 was $\approx 10^6$ cm^{-3}, but the spacecraft just skirted the "edge" of the plume. The Cassini Ultraviolet Imaging Spectrography (UVIS) also detected water vapor in the plume during E2 using the stellar occultation technique

[*Hansen et al.*, 2006], finding a near-surface column density of 1.5×10^{16} cm^{-2} (corresponding roughly to a density of $\approx 10^9$ cm^{-3} for a "scale-length" of about 175 km). During the E3 encounter, Cassini moved from north to south, and at a radial distance of about 3 Enceladus radii (R_{enc}) passed through a much denser part of the plume where the INMS measured neutral mass spectra with signal-to-noise ratios much larger than those obtained during E2 and found peak neutral densities of $\approx 10^8$ cm^{-3} at a radial distance of $r \approx 3\ R_{enc}$ (paper in preparation on INMS closed source neutral data) with an estimated total production of $\approx 10^{28}$ s^{-1} [cf. *Jurac and Richardson*, 2005]. Figure 1 is a schematic of the plume and the spacecraft trajectory.

[3]   The thermal plasma in the inner magnetosphere, as well as near Enceladus, was expected prior to Cassini to consist mainly of water group ions (H_2O^+, OH^+, O^+, H_3O^+....) [cf. *Ip*, 2000; *Jurac and Richardson*, 2005]. Cassini measurements of the plasma [*Tokar et al.*, 2006; *Jones et al.*, 2006; *Young et al.*, 2005] and the magnetic field [*Dougherty et al.*, 2006] near Enceladus during E2 and other flybys confirmed this. In particular, the Cassini Plasma Spectrometer (CAPS) observed a mixture of water group (WG) ions during E2, within a broad region of $\approx 30\ R_{enc}$ [*Tokar et al.*, 2006] and with a total ion density of ≈ 80 cm^{-3} that did not vary much. However, the spacecraft only skirted the "edge" of the plume during this encounter. The bulk flow far from Enceladus was observed to be approximately co-rotational (26 km/s with respect to Enceladus), but the flow speed near the E2 closest approach (CA) point was less than this ($u \approx 17$ km/s). The CAPS ion mass spectrometer (IMS) measured significant portions of ion phase space (i.e., velocity space) during E2, demonstrating that the distribution function was a ring (i.e., a torus), as would be expected for pick-up ions, albeit a "fat" ring with major and minor radii of $v_0 \approx 17$ km/s and ≈ 5 km/s, respectively [*Tokar et al.*, 2006]. The spatial trajectories of such pick-up ions are cycloids. Figure 2 is a schematic of phase space showing this ring distribution and also the INMS observational geometry. Note that the INMS only observes a fraction of the total ion density. Slower and colder plasma was detected by CAPS during the E3 encounter (R. L. Tokar et al., Cassini detection of Enceladus' cold water-group plume ionosphere, submitted to *Geophysical Research Letters*, 2009), suggesting that the ion density in the INMS field-of-view should be enhanced.

[4]   Magnetometer measurements demonstrated that the magnetic field for radial distances within a few R_{enc} exhibited an Alfven wing pattern with a field strength reduction of about 10% from an "expected" magnetospheric

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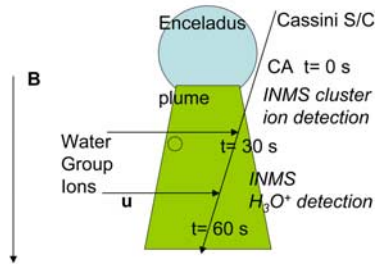
Figure 1. Schematic of the Enceladus gas plume and ionosphere. The external plasma flow with its water group (WG) ions approaches the plume from the left in the diagram (flow vectors labeled **u**). Not shown is a rather small velocity component perpendicular to the plane of the figure. A typical scale of a gyro-orbit (the circle) and an approximate E3 spacecraft trajectory with some times are shown.

value (B ≈ 330 nT) [*Dougherty et al.*, 2006; *Pontius and Hill*, 2006].

[5] Charge exchange and ion chemistry are important in the gas coma of Enceladus [*Tseng and Ip*, 2007] as well as in the "larger" inner magnetosphere region [*Johnson et al.*, 2005]. Water ion chemistry is also known to operate in many other environments including comets [e.g., *Rubin et al.*, 2009], interstellar clouds [e.g., *Duley*, 1996], the terrestrial D-region [cf. *Schunk and Nagy*, 2000], and in active experiments in the F-region [cf. *Mendillo et al.*, 2008].

[6] The current paper describes ion composition measurements made by INMS within the plume of Enceladus. In its ion mode, the INMS only observes "cold" ionospheric-type plasma. Three main points will be emphasized in the paper: (1) cold "ionospheric" plasma within the plume is overwhelmingly H_3O^+ and not composed of other water group ions, (2) water cluster ions might be present (H_2O^+ - H_2O and H_3O^+ - H_2O), and (3) the plume
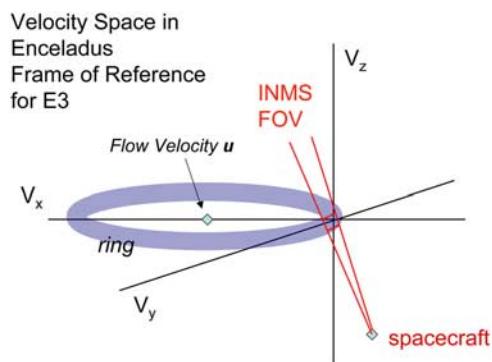

Figure 2. Schematic of phase space (i.e., velocity space) in the Enceladus frame of reference and near the edge of the plume. A ring distribution centered on the "local" flow velocity of $v_0 \approx 17$ km/s is shown. The spacecraft speed was close to 14.5 km/s with respect to the satellite. The INMS field of view (FOV) is shown in red, as is the phase space volume within which the INMS can detect ions. The center of this volume is at rest with respect to Enceladus.

ionosphere might be a significant H_3O^+ source for the entire inner magnetosphere.

2. INMS Open Source Ion Measurements in the Enceladus Plume

[7] The INMS is a quadrupole mass spectrometer with excellent mass resolution. The instrument in its ion mode has a narrow field of view (±4°) and detected for the E3 encounter ions that were within a narrow range (about ±1.5 km/s for this case) of speeds centered at a ram velocity of $v_r = 14.5$ km/s (or an energy of 20.7 eV for m = 19 ions) [*Waite et al.*, 2004, 2005; *Kasprzak et al.*, 1996]. Such ions were at rest with respect to Enceladus (see Figure 2).

[8] The INMS alternated between measuring neutrals and measuring ions during E3 with a sampling rate depending on the mass number. The integration period (ip) for each measurement was $\Delta t = 31$ ms. Figure 3 shows the INMS ion count rate (counts per ip) for m/q (mass per charge) = 18, 19, 36, and 37 Daltons for times near closest approach. The probable species identifications for these m/q values are: H_2O^+, H_3O^+, and the water cluster ions H_2O^+ - H_2O, and H_3O^+ - H_2O, respectively. The total number of counts was 62 in this time interval for m = 19.

[9] A combined mass spectrum for a time interval from closest approach (t = 0) to 120 s after CA (encompassing the passage through the neutral plume) is displayed in Figure 4. The most prominent peak is clearly at m = 19, identified as H_3O^+, although peaks are also present at m = 36 (H_2O^+ -
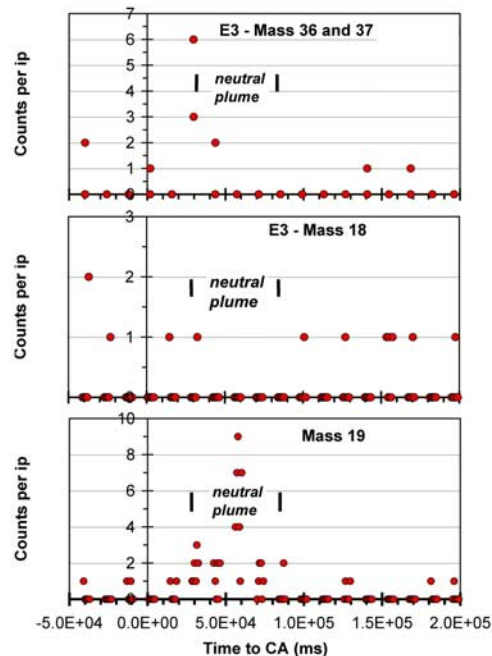

Figure 3. (top) Counts per integration period for both masses 36 and 37 (perhaps water cluster ion species H_2O^+ - H_2O, and H_3O^+ - H_2O) versus time from closest approach as measured by the INMS for the E3 Enceladus encounter. (middle) Same as Figure 3 (top) but for m = 18 (H_2O^+). (bottom) Same as Figure 3 (top) but for m = 19 (H_3O^+). The time interval within which the neutral density measured by INMS is greater than half its maximum value is denoted as "neutral plume".
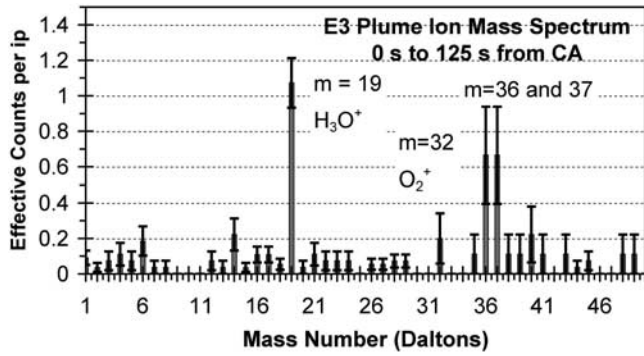
Figure 4. Mass spectrum measured by the INMS for a time period encompassing the plume encounter (from CA up to +120 s from CA). Effective count rates (counts per ip per measurement opportunity for a given mass) versus mass number are shown. One-sigma statistical error bars are shown.

H_2O) and m = 37 (H_3O^+ - H_2O). Note that there is little H_2O^+, OH^+, and O^+ present. Possible peaks also exist at m = 14 (perhaps N^+) and m = 32 (perhaps O_2^+). The background rate associated with energetic radiation impinging on the detectors was estimated at ≈0.013 counts/ip.

[10] A mass spectrum (not shown) measured outside the plume but not far from the satellite (−300 s to CA and +120 s to + 500 s), does not exhibit a large m = 19 peak and has no count rate for any mass number exceeding ≈0.1 counts/ip. The estimated upper limit (outside the neutral plume) to the effective count rate for all water group ions (m = 16, 17, 18, 19) is 0.5 C/ip. Converting this count rate to a phase space density near zero velocity in velocity space (relative to Enceladus) gives ≈ 1.5 × 10^{-6} s^3 m^{-6} just outside the plume for E3. The CAPS experiment during E2 measured a value twice this [*Tokar et al.*, 2006]. On the other hand, the maximum phase space density within the plume from INMS for m = 19 is 15 × 10^{-6} s^3 m^{-6} and this value is 5 – 10 times greater than the average value measured by CAPS during E2. But higher CAPS values are expected for E3 due to its closer proximity to the plume.

[11] To summarize, outside the plume CAPS observed all water group ion species, whereas in the plume the INMS mainly observed ions with a mass of 19, with other species having relative abundances less than ≈15%.

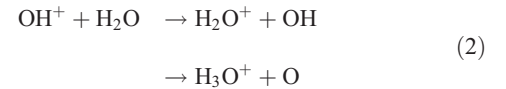## 3. Interpretation: Plume Ionosphere

[12] Water group ions (roughly equal abundances of H_2O^+, H_3O^+, OH^+, and O^+) present in Saturn's co-rotating E-ring plasma are convected into the dense plume atmosphere where they interact with the neutral gas. INMS data (current paper) demonstrates that the composition of plasma approximately at rest with respect to Enceladus is mainly (≈80% or more) H_3O^+ with a phase space density significantly exceeding that found in a ring distribution by CAPS during E2 just outside the plume [*Tokar et al.*, 2006]. The ring distribution apparently evolves into a colder (and slower) population inside the plume itself (Tokar et al., submitted paper, 2009).

[13] Some relevant time constants could help in the data interpretation. The gyrofrequency of a water group ion is

Ω = 1.7 s^{-1} for B ≈ 300 nT, the gyroperiod is T_g = 4 s, and the gyroradius is r_g ≈ 10 km for a u ≈ 15 km/s speed. The transport time through the plume is τ_T ≈ L/u ≈ 30 s where L ≈ $2R_{enc}$ is the approximate plume width. The ion-neutral collision time is given by τ_C ≈ $[k_{in} n_n]^{-1}$ ≈ 10 s with k_{in} ≈ 1 − 2 × 10^{-9} cm^3 s^{-1} [*McDaniel et al.*, 1970; *Johnson*, 1990] and a neutral density (for E3) for r ≈ 2–3 R_{enc} of n_n ≈ 10^8 cm^{-3}. With τ_T greater than τ_C, collisions are certainly important at this distance, and with the gyroperiod being less than τ_C it would seem that a ring distribution should be maintained. This will probably not be the case near the base of the plume. We estimate an electron-ion recombination time of ≈10^4 s, indicating that loss of plasma in the plume is not an important process.

[14] Laboratory measurements of ion-neutral chemical rate coefficients are typically quoted for a temperature of 300 K [cf. *Anicich and McEwan*, 1997]. However, the range of kinetic energies associated with the ring distribution observed by CAPS is large (0 eV − 200 eV). Nonetheless, ring distribution ions spend some fraction of their time at speeds near v ≈ 0, and the following reactions involving water group ions and neutral water (with k_{in} ≈ 1 − 2 × 10^{-9} cm^3 s^{-1} at thermal energies) are relevant:

$$O^+ + H_2O \rightarrow H_2O^+ + O \qquad (1)$$

$$OH^+ + H_2O \quad \rightarrow H_2O^+ + OH$$
$$\rightarrow H_3O^+ + O \qquad (2)$$

$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH \qquad (3)$$

O^+, OH^+, and H_2O^+ ions are converted into H_3O^+ by these reactions.

[15] Two questions come to mind. First, do fast water group ions react with water in the same way as thermal ions? Second, are H_3O^+ ions from the chemistry "cold" enough such that the phase space density near v = 0 is measurable by the INMS? Laboratory measurements [*Lishawa et al.*, 1990] indicate that fast water ions (or deuterated ions) in collisions with H_2O mainly undergo charge transfer with the chemical reaction channel (equation (3)) leading to H_3O^+ mainly occurring for collision energies less than about 2 eV. However, charge exchange collisions do contribute to the creation of slower and colder plasma (in which the chemistry can operate) by creating new ions that are initially at rest before they are "picked-up" by the flow.

[16] Neutral species other than water were detected by the INMS near Enceladus [*Waite et al.*, 2006] such that ion-neutral reactions other than those listed above should also take place. For example, $O^+ + CO_2 \rightarrow O_2^+ + CO$ and $OH^+ + CO_2 \rightarrow OCOH^+ + O$ reactions produce O_2^+ and $OCOH^+$ ions, respectively. Note that O_2^+ ions do not react with water or carbon dioxide and so should persist in the plume ionosphere and/or in the E-ring. The mass spectrum (Figure 4) has a possible (one-sigma) detection of O_2^+.

[17] The INMS data also suggests (at the 3-sigma level) that water cluster ions are present near the plume. Figure 3 shows that these ion species, unlike H_3O^+, were observed

just before the spacecraft entered the neutral plume rather than in the middle of the plume. The spacecraft then was located downwind of the dense plume near its base (Figure 1). Cluster ions are produced by three-body reactions of NO^+ and O_2^+ ions with water in the terrestrial ionosphere mainly below about 85 km, where the total neutral density is about 10^{14} cm^{-3} [cf. *Schunk and Nagy*, 2000]. The total plume density for Enceladus is several orders of magnitude less than this and so this mechanism will not work. Radiative association reactions, with rate coefficients of $\approx 10^{-16}$ cm^3 s^{-1}, also seem to be inadequate [*Petrie and Dunbar*, 2000]. Perhaps cluster ions can be formed by sputtering due to fast ion impact on ice surfaces associated with grains in the plume or with the satellite surface. The water molecule yield is quite large for 100 eV or so heavy ion impact on ice [*Johnson*, 1990], and perhaps some of the ejected particles are cluster ions [*Duley*, 1996].

4. Summary

[18] The three issues listed in the introduction are now revisited. First, INMS measurements have demonstrated that the cold plume ionosphere mainly consists of H_3O^+ ions. Other water group ion species, convected into the plume from outside, are efficiently converted by ion-neutral reactions into H_3O^+ ions. Second, water cluster ions (H_2O^+ - H_2O and H_3O^+ - H_2O) were observed by the INMS (with some uncertainty). The source of such ion species is not obvious but might involve sputtering from icy surfaces.

[19] The third issue is now considered – the possibility that the plume is an important source of H_3O^+ for the inner magnetosphere of Saturn. The ion population in the inner magnetosphere is known to include H_3O^+ ions along with the other water group ions [*Tokar et al.*, 2006]. The suggested source has been the well-known reaction (3) in which H_2O^+ reacts with H_2O, but in the magnetosphere itself [*Tseng and Ip*, 2007; *Jurac and Richardson*, 2005; *Johnson et al.*, 2005, 2006]. One possible problem is that reaction (3) is slow for fast water ions [*Lishawa et al.*, 1990]. By adopting a torus centered at the orbit of Enceladus (minor radius of 1 R$_s$) with both neutral and ionized water densities of 50 cm^{-3} (preliminary INMS measurements suggest that the neutral density might be much higher than this (M. Perry, private communication, 2008) [also see *Delamere et al.*, 2007]) and with a fast ion rate coefficient of $\approx 10^{-10}$ cm^3 s^{-1} [i.e., *Lishawa et al.*, 1990], we estimate the magnetospheric source to be $\approx 10^{24}$ s^{-1}. Within the plume the chemical conversion of ions to H_3O^+ can take place much faster, although the volume is much smaller. We estimate a total plume production rate of H_3O^+ that is also $\approx 10^{24}$ s^{-1} by using an external total ion flux ($F = n_e u \approx 10^8$ cm^{-2} s^{-1}) which interacts with a plume having a cross section of ≈ 1000 km by ≈ 500 km. This possible ion source should be further investigated as more data becomes available.

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