

Cassini detection of Enceladus' cold water-group plume ionosphere

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[1] This study reports direct detection by the Cassini plasma spectrometer of freshly-produced water-group ions (O^+ , OH^+ , H_2O^+ , H_3O^+) and heavier water dimer ions ($H_xO_2^+$) very close to Enceladus where the plasma begins to emerge from the plume. The data were obtained during two close (52 and 25 km) flybys of Enceladus in 2008 and are similar to ion data in cometary comas. The ions are observed in detectors looking in the Cassini ram direction exhibiting energies consistent with the Cassini speed, indicative of a nearly stagnant plasma flow in the plume. North of Enceladus the plasma slowing commences about 4 to 6 Enceladus radii away, while south of Enceladus signatures of the plasma interaction with the plume are detected 22 Enceladus radii away. **Citation:** Tokar, R. L., R. E. Johnson, M. F. Thomsen, R. J. Wilson, D. T. Young, F. J. Crary, A. J. Coates, G. H. Jones, and C. S. Paty (2009), Cassini detection of Enceladus' cold water-group plume ionosphere, *Geophys. Res. Lett.*, 36, L13203, doi:10.1029/2009GL038923.

1. Introduction

[2] One of the major discoveries made during the Cassini mission is a plume of water vapor and icy grains emanating from Enceladus's south polar region. This plume, which in fact is produced by a number of localized small scale plumes, indicates ongoing geologic activity and is the dominant source of both Saturn's extended neutral cloud and magnetospheric plasma. This plasma in turn interacts with its source forming fresh ions, a remarkable process that we describe here using the data from the recent Cassini close flybys of Enceladus.

[3] Enceladus is small, with a radius of 252 km ($1R_E$), and orbits near Saturn's equatorial plane at a distance of 3.95 Saturn radii ($1R_S = 60286$ km). It is one of the intrinsically brightest objects in the solar system because large areas in the south polar region are covered in water ice (reflecting nearly all incident light) produced by plume ice grains settling on the surface. The plume was imaged by Cassini in 2005 [Porco *et al.*, 2006] and was shown to originate at surface fractures in the moon's south polar region [Spencer *et al.*, 2006] that are $\sim 100K$ warmer than

the surrounding surface. Finally, the plume location corresponds to the region where perturbations in Cassini magnetometer data [Dougherty *et al.*, 2006] suggested enhanced plasma production.

[4] In 2008, Cassini encountered Enceladus four times at altitudes < 200 km. During two of these, on March 12 and October 9, Cassini traversed the plume region and the Cassini Plasma Spectrometer (CAPS) [Young *et al.*, 2004] was oriented favorably for sampling the ion and electron plasma associated with the plume. Earlier we showed that ion-neutral chemistry is occurring as indicated by our detection of H_3O^+ [Tokar *et al.*, 2006]. Here we build on that discovery and report the detection by CAPS of a cold ionosphere consisting of water-group ions created from the plume's neutral exosphere. In addition and quite remarkably, the plume plasma also contained negative ions and heavier positively-charged water cluster ions. The presence of such ions close to the source region suggests a stagnation in the plasma flow as it penetrates the plume allowing ion-molecule reactions to dominate as in a cometary coma. Further, the close flybys gave a surprisingly clear picture of the evolution of the plasma composition and flow field as the spacecraft travelled from the ambient plasma into the moon's wake region, into the plume, and then back out into the ambient plasma. This traversal and its implications are described below.

2. Cassini CAPS Observations

[5] Figure 1 illustrates the trajectory of Cassini during the E3 encounter on March 12, 2008 (blue), and the E5 encounter on October 9, 2008 (red). Cassini flew past Enceladus at very low altitudes during both encounters (52 km and 25 km respectively), traveling directly through the south polar region as shown in Figure 1. The coordinate system (in units of R_E) has z parallel to Saturn's rotational axis (aligned roughly along the mean plume direction), x in the direction of the corotating plasma flow, and y (positive toward Saturn) completing a right-handed system with the cylindrical coordinate $\rho = (x^2 + y^2)^{1/2}$. The Cassini trajectories are also plotted in z - ρ along with positions (A,B,...) denoting features in the data that are discussed below. The closest approach to Enceladus was at 19:06:12 UT for E3 and 19:06:40 UT for E5. For both E3 and E5, Cassini was directly south of Enceladus at 19:07:09 UT. The spacecraft traverses the wake region produced by Enceladus in the corotational thermal ion flow (illustrated conceptually by dashed lines in Figure 1, right) from 19:05:59 to 19:06:17 UT for E3 and 19:06:16 to 19:06:47 UT for E5 (see Figure 1, right, for the timing of the geometric wake passage). The speed of Cassini with respect to Enceladus was 14.4 km/s for E3 and 17.7 km/s for E5.

[6] Figure 2 is an overview of CAPS electron and ion counting rates as a function of energy and time for the two

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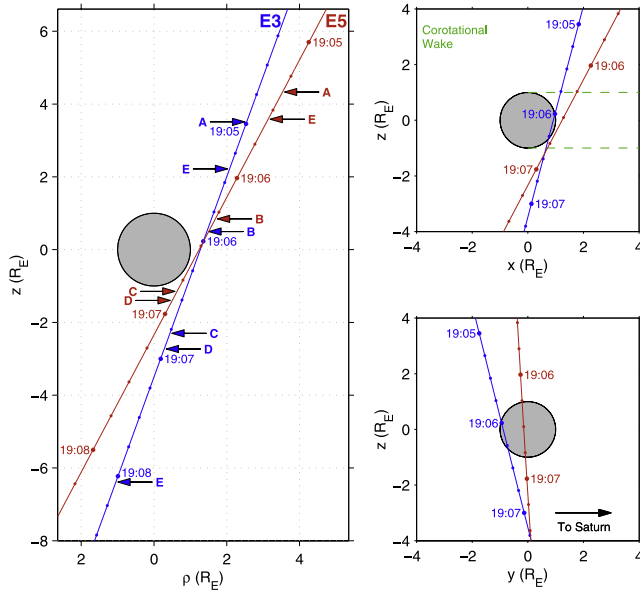


Figure 1. Illustrated is the trajectory of Cassini for both the E3 (blue) and E5 (red) encounters. The coordinate system has z parallel to Saturn's rotational axis, x in the direction of the corotating plasma flow, and y (positive toward Saturn) completing a right-handed system with the cylindrical coordinate $\rho = (x^2 + y^2)^{1/2}$.

encounters. (Although CAPS measures ion mass per charge using a time-of-flight mass spectrometer, the mass spectra are generated at 256-s resolution so that the diverse environments in the vicinity of Enceladus are all sampled in the same spectrum. No results from the time-of-flight mass spectra will be presented here, pending further efforts to separate ions from different regions.) Plotted is the color-coded counting rate of electrons and ions as a function of energy per charge (eV/q) and time (UT) for E3 (Figure 2, left) and E5 (Figure 2, right). In the top plot are electron data from the CAPS electron spectrometer. The spectrograms cover an energy range of 0.6–28,000 eV, measured in the spacecraft ram direction (anode 5) for both E3 and E5. For the ions, CAPS ion mass spectrometer anodes 5 through 7 are shown and the spectrograms cover an energy range of 1 eV to ~ 50 keV. The ion anodes have look directions covering the corotation direction (near anode 7) and the ram direction (anode 5). The first two solid vertical lines denote entrance and exit of the region where the corotating thermal ion plasma is fully shadowed by Enceladus and the third illustrates the position directly south of Enceladus, roughly below the region where the gas is emitted. Note that due south is later in time (further upstream, see Figure 1) than the peak plume signature for E3 and more coincident with this signature for E5. Closest approach for both encounters is within the wake region. The CAPS electron observations are discussed first, followed by the ions.

[7] It is immediately clear that the E3 and E5 electron data show consistent features. At the beginning of both plots (19:04 UT), the highest count rates are measured at energies $< \sim 10$ eV and are due to the ambient low energy electron population in Saturn's magnetosphere. The effect of penetrating energetic (> 1 MeV) particles appears as a relatively low count rate across all energies. The ambient electron

population also includes a less intense component at ~ 20 – 30 eV which may be photoelectrons from solar He(II) 30.4 nm interactions with the neutral and ice grain populations in Saturn's inner magnetosphere. This population is similar to that detected over Saturn's main rings [Coates *et al.*, 2005], during earlier Enceladus encounters [Tokar *et al.*, 2006], and due to interaction with N_2 in Titan's ionosphere [e.g., Coates *et al.*, 2007]. Cassini enters the solar shadow of Enceladus at 19:05:51 UT for E3 and 19:06:36 UT for E5. Reductions in the ambient population are observed (most clearly for E3) during that time due primarily to a change to a more negative spacecraft potential. In the plume itself, (times near the third vertical line) two additional interesting populations appear in the electron data. Between ~ 10 and ~ 500 eV, a population of negatively charged particles was present from $\sim 19:06:20$ – $19:07$ UT during E3 and between $\sim 19:06:40$ – $19:07:20$ during E5. These were interpreted (A. J. Coates *et al.*, Negative ions in the Enceladus plume, submitted to *Icarus*, 2008) as a population of short-lived primarily negatively charged water cluster ions in the plume ionosphere, superimposed on an ambient electron population. A second population of intense and highly time-variable fluxes of negative ions at energies > 500 eV is measured between 19:06:30–19:08:25 UT during E3 and 19:06:50–19:08:10 during E5. These heavy negative particles are consistent with the plume containing cold plasma with a composition and temperature different from the ambient plasma.

[8] The CAPS ion observations give a clear picture of the transition from the ambient plasma through the wake and then through the plume. Therefore, in addition to the vertical lines denoting the entrance and exit of the corotational shadow and due south relative to Enceladus, the transition features in the ion data are denoted with the letters A–E (see Table 1). The positions labeled A in Figures 1 and 2 are the first indication of ion slowing attributable to plasma interactions in the northern region at approximately 4.3 and 5.6 R_E in radial distance from Enceladus. For both encounters within the wake region the counting rate for the corotating water group ion population decreases dramatically and changes in character because Enceladus is an obstacle to the flow. A striking feature in these data is the appearance of narrow (in energy) ion counting signals between positions B and C. Because these ions are cold and detected primarily in the ram direction, they are interpreted as locally produced ions that are initially nearly at rest in the Enceladus frame and are rammed into the CAPS field-of-view by the spacecraft motion. Dust particle impacts on Cassini occurred during E3 [e.g., see Farrell *et al.*, 2009] and E5 and are denoted approximately by the position D almost due south of Enceladus and directly in the plume region. Positions E during both encounters denote a relatively sharp notch in the ion counting signal, possibly indicating crossing of a current layer or Alfvén wing. This notch is not observed for E5 at late times in the upstream region. Finally, an estimate of the size of the interaction region can be obtained from the observations of cold water group ions present during E3 in anode 5. These are seen in the CAPS data out to at least 19:12:37 UT, 22 R_E away from Enceladus.

[9] Figure 3 illustrates energy spectra for the cold ions (equivalent to a single slice of the spectrograms) at the position “C”. To analyze these data we make the assumption

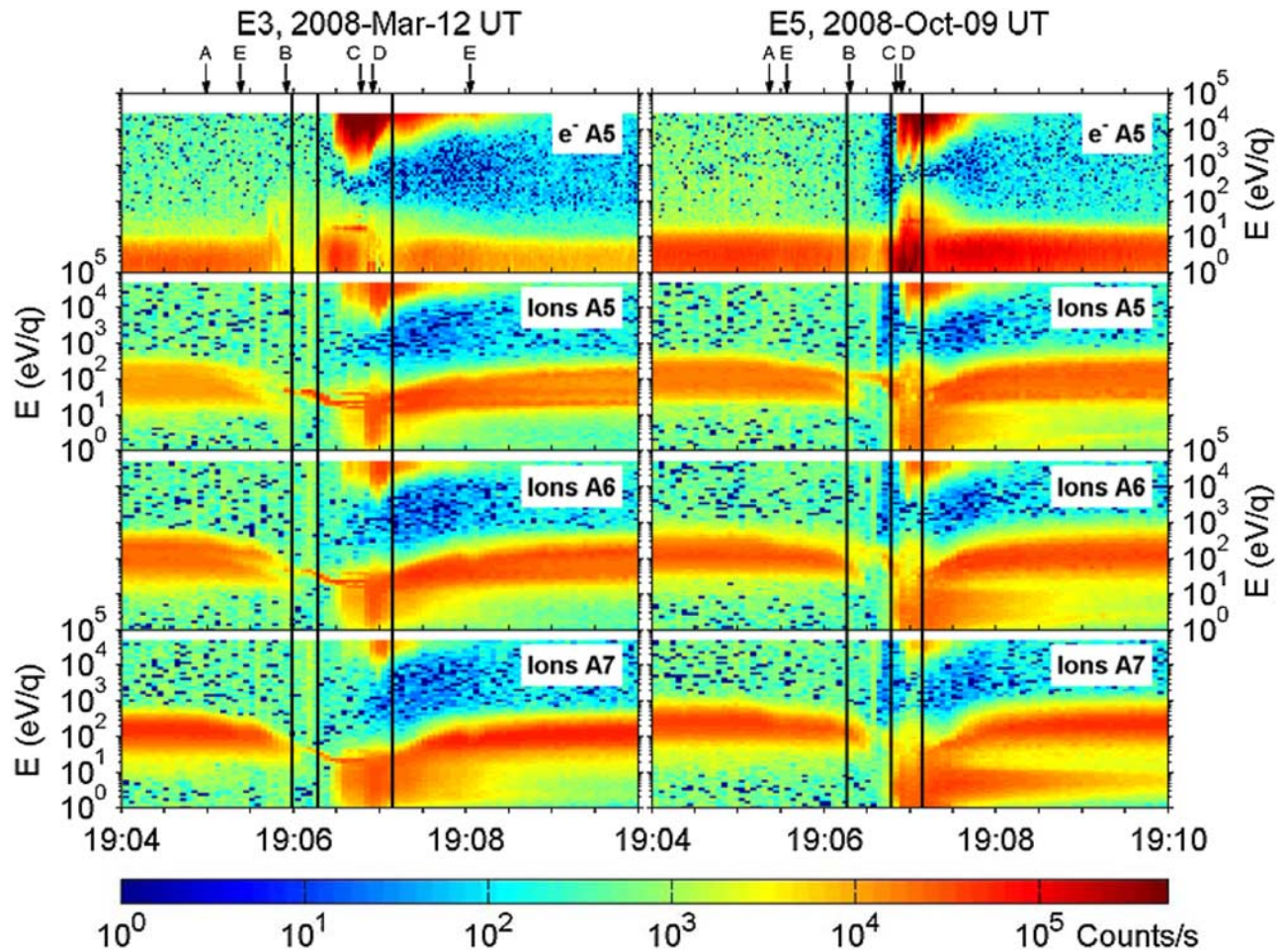


Figure 2. Electron and ion data measured by CAPS during both the E3 and E5 Enceladus encounters. The first two vertical lines denote entry and exit of Cassini in the geometric wake. The third vertical lines denote the position when Cassini is due south of Enceladus. The letters A-E along the top denote features in the ion data (Table 1).

that the cold ion populations are at rest with respect to Enceladus and anode 5 of CAPS is detecting a rammed ion population. Note that CAPS is not actuating and only a limited sample of ion phase space is available making more detailed modeling of these data difficult. With this assumption the detected ion energy per charge at the peak ion counting rate together with the CAPS energy passband $\Delta E/E = 17\%$ yield the mass ranges shown. (Also illustrated for reference are the ram energies of various ion species). These mass ranges, crudely estimated by this simple calculation, are interpreted as detection of a water group population (O^+ , OH^+ , H_2O^+ , H_3O^+) together with heavier water dimer ions ($H_xO_2^+$, $x = 1-4$, and possibly O_2^+). At the orbit of Enceladus we earlier identified each of the water-group ion

species including H_3O^+ [Tokar *et al.*, 2006]. In addition, Cravens *et al.* [2009] have recently reported that the Cassini ion neutral mass spectrometer (INMS) for E3 near time “C” confirmed the presence of mass 19 amu (H_3O^+) and also detected masses 36 and 37 amu. Due to the uncertainties in the exact masses, we tentatively associate the lowest mass peak for E3 with a water product. Although nitrogen is known to be present [Smith *et al.*, 2008] it is a minor species as is methane and other carbon species. Also note that for E3 there is no enhancement in the signal where light ions (H^+ , H_2^+) at ram energies are expected in contrast to E5 where a clearer light-ion signal is observed. This is probably due to both the lower ram speed for E3 vs. E5 and to a possible negative spacecraft potential.

Table 1. Summary of Features in the CAPS Ion Data^a

Position	Description	E3 Time (2008–Mar-12)	E3 R/R _E	E5 Time (2008–Oct-09)	E5 R/R _E
A	Interaction Starts	19:04:59	4.3	19:05:22	5.6
B	Rammed Ions	19:05:55	1.5	19:06:18	1.9
C	Multi-Ion Species	19:06:47	2.3	19:06:50	1.3
D	Dust Impacts	19:06:55	2.8	19:06:54	1.5
E	Ion Notch-Early	19:05:23	3.0	19:05:34	4.8
E	Ion Notch-Late	19:08:03	6.5	-	-

^aSee Figures 1 and 2.

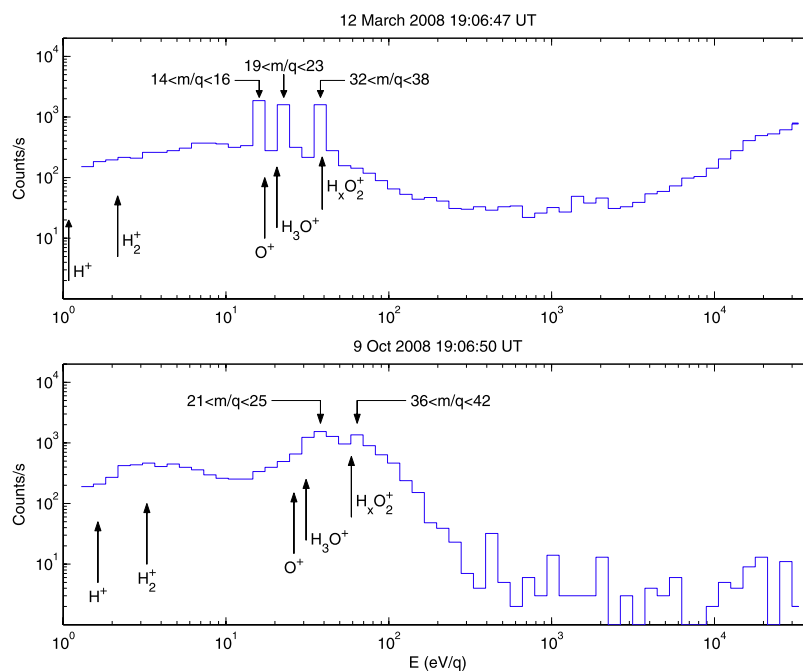


Figure 3. Individual ion counting rate versus energy per charge measured by CAPS anode 5 (including background) at the position “C”, within the plume, for both encounters. The anode 5 look direction is in the spacecraft ram direction, and the energy pass band of CAPS yields the mass ranges shown. These peaks are interpreted as detection of freshly-produced water-group ions and water dimer ions within the plume. Also shown are the expected ram energies of various ion species, including a water dimer ion for $x = 4$.

[10] When the cold ion peaks are analyzed as above by making the assumption that the ion species are at rest with respect to Enceladus, we obtain reasonable water-group and water dimer ion mass ranges. This result is consistent with the *Cravens et al.* [2009] INMS study as mentioned. This implies that for both encounters the upstream flow (~ 20 km/s with respect to Enceladus for E3 and ~ 16 km/s for E5, determined before the encounters when CAPS was actuating) is shielded by plasma production in the plume, causing the plasma flow to stagnate. This is further supported by the very low temperatures of the observed ions in the plume which is also a measure of the pick-up energy. Future work will model these processes in more detail. Also note that at earlier times, within and near the corotational wake, the energy of the cold populations increases, corresponding to an acceleration of the flow (a 5 to 10 km/s increase in speed).

3. Discussion

[11] The picture of the interaction derived from the CAPS data is as follows. Following the flow direction of the plasma (moving from right to left in Figure 2), the ambient plasma gradually slows on approach to the Enceladus region. As the plasma penetrates the plume, the flow rapidly slows increasing the ion-neutral molecule reaction cross sections so that at C, near where the spectra in Figure 3 are given, an incoming ion will have reacted at least once with the plume water vapor. Near and past due south of Enceladus (solid lines at 19:07:10 UT) is the densest region of the plume ionosphere, with the ion energy spectra exhibiting large masses and contamination at low energies, likely by the heavy dust impacts [Farrell et al., 2009]. On emerging through the plume center and moving toward the plume source, distinct

peaks of cool pick-up ions are observed nearly at rest with respect to Enceladus. The fact that predominantly cold ions have emerged from the plume close to the source and the relative speeds between the ions and the neutrals are small ($< \sim 0.5$ eV/amu), strongly suggest the ion mass flow is converted to fresh pick-up ions via ion-molecule interactions. That such interactions are occurring was shown earlier by the discovery of H_3O^+ in the Enceladus torus [Tokar et al., 2006], an ion that is only formed in very low energy ion-molecule reactions ($< \sim$ eV/amu).

[12] The formation of H_3O^+ competes with other ion-molecule interactions and, due to the presence of cold electrons, competes with electron-ion recombination [Sittler et al., 2008]. As the ambient ions (O^+ , OH^+ , H_2O^+ , H_3O^+ [Tokar et al., 2006]) penetrate from the upstream side of the plume they predominantly interact with H_2O as described earlier [Burger et al., 2007]. Using such a model of the plume along with an ion-molecule cross section \sim a few $\times 10^{-15}$ cm^2 , most of the ions will have reacted more than once if their path was through the center of the plume. For example, the OH^+ and H_2O^+ entering on the upstream side of the plume react with H_2O giving H_3O^+ . The O^+ component reacting with H_2O would give H_2O^+ , which would subsequently be converted to H_3O^+ depending on its path through the plume. These interactions have much in common with ion-neutral interactions in comet comas, where H_3O^+ is formed in the magnetic pile up region [Haberli et al., 1995]. Indeed, early CAPS measurements in Saturn's inner magnetosphere did resemble a comet-like mix of water-derived ions [Young et al., 2005]. As we continue to follow the Cassini trajectory backward along the ambient plasma flow direction, it is seen that ions formed in the plume are gradually accelerated without significant heating

and dragged into the magnetospheric wake. These ions are the principal source of the H_3O^+ for the magnetosphere and contribute to the ambient plasma torus, which interacts via charge exchange with Saturn's extended neutral cloud [Tokar et al., 2008], redistributing the neutrals throughout the magnetosphere [Johnson et al., 2006].

[13] What is also remarkable is the presence of a distinct peak at higher masses in this same region. Although much larger positive and negative masses, discussed elsewhere (Coates et al., submitted manuscript, 2008), are present in the plume, at position C for E3 and E5 a distinct mass ~ 32 – 38 amu emerges as a freshly formed ion (see Figure 3). Ions of such masses have been seen in comet comas, but have been identified with trace species involving carbon or sulfur species [e.g., Marconi et al., 1990, 1991]. However, here we interpret this as water dimer ions $(\text{H}_x\text{O}_2)^+$ with $x = 1$ – 4 . These may be formed by either charge exchange with a neutral dimer emerging from the plume or by an ion-molecule reaction in the stagnated plasma that, although cool by comparison with the ambient plasma, has non-negligible collision speeds with neutrals. CAPS data also suggest that the mass 32–38 amu ions disappear for E3 downstream, due to either large electron-ion recombination or dissociation. Therefore, for the first time we are able to give a detailed picture of the fate of the ambient plasma as it penetrates the predominantly water plume emanating from Enceladus. The data clearly show the morphology and stagnation of the plasma flow and the production of fresh ions that are characteristic of low energy ion-molecule interactions in the plume and which are subsequently accelerated into the ambient plasma.

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