Cassini Detection of Water Group Pick-up Ions in Saturn’s Toroidal Atmosphere

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Abstract

This study reports direct detection by the Cassini plasma spectrometer of freshly-produced water group pick-up ions within Saturn’s toroidal atmosphere and concentrated in the vicinity of the Enceladus orbit and within the Tethys orbit. These ions are most likely produced by charge exchange collisions between corotating thermal plasma and neutral atoms and molecules. Clear signatures of fresh pick-up (rings, shells) in the ion velocity distributions are observed and the ion data, along with Cassini magnetometer data, neutral cloud models, and hybrid plasma simulation are found consistent.

Introduction

One of the major discoveries of the Cassini mission is the plume of icy grains and gas emanating from the south polar region of the moon Enceladus (R ~ 4 Rₜ) [Porco et al., 2006]. Models predict [Johnson et al., 2006] that the icy plume results in a new feature at Saturn, a narrow (~0.5 to 1.0 Rₜ) and dense torus of water group (O, OH, H₂O, H₃O) neutral atoms and molecules centered on the Enceladus orbit. Subsequent scattering of these neutrals can produce a large “toroidal atmosphere”, consistent with the extended (2-8 Rₜ) OH neutral cloud observed by the Hubble space telescope [Shemansky et al. 1993]. Consequently, the missing source of water vapor necessary to understand the OH cloud observations and predicted by Jurac et al. [2002] to coincide with the Enceladus orbit is likely the plumes from the south polar region of the moon.
The scattering of the neutrals within the toroidal atmosphere is primarily a result of charge exchange collisions between water group ions and neutrals [Johnson et al. 2005]. The water group ions are a constituent of the thermal plasma that is approximately corotating with Saturn’s magnetic field. At the orbit of Enceladus the ion corotation speed is about 27 km/s larger than the neutral’s keplerian orbital speed. The relative collision speed for an individual ion-neutral collision varies both with radial distance from Saturn and with the thermal velocity spread of the ions, leading to a range in energy of the neutrals scattered out of the narrow neutral Enceladus torus. Properties of the thermal ion plasma have most recently been measured by the Cassini Plasma Spectrometer (CAPS) [Young et al. 2004], during Cassini’s Saturn orbit insertion (July, 2004) [Sittler et al. 2005].

Charge exchange collisions scatter neutrals and, of importance to this study, replace a fraction of the corotating ion core with a new and slower-moving ion population without changing the total ion content. The ions are expected to have initial speeds less than the corotation speed and are “picked up” by Saturn’s magnetic field, evolving into distinctive phase space velocity distributions referred to as rings and shells [e.g. see Sittler et al., 2004]. CAPS measures these distributions from which the ion source region can be mapped. The purpose of this study is to report direct detection by CAPS of these water group ions within their source region, Saturn’s toroidal atmosphere. Previously, CAPS observed water group pick-up ions during a close encounter with Enceladus [Tokar et al., 2006]; this study reports the first measurement of these ions throughout an extended region in Saturn’s inner magnetosphere and far away from individual moons. In so doing, both the narrow Enceladus torus and broader toroidal atmosphere are indirectly detected.
Data Analysis

Cassini plasma spectrometer data in the equatorial inner magnetosphere (3.5 \( R_S < R < 7.0 \) \( R_S \)) are analyzed in this study. These data were obtained by CAPS on Oct. 11 and 29, 2005, Nov. 27, 2005 and Dec. 24, 2005, during time periods when CAPS actuation was operational yielding excellent phase space sampling (see Young et al., [2004] for a description of CAPS). Figure 1 illustrates typical ion counting rate as a function of energy per charge and radial distance from Saturn obtained by a single CAPS anode. The data in the top panel were measured on October 11, 2005, near the orbit of Enceladus while the data in the bottom panel were measured on November 27, 2005, farther out near \( R \sim 6 \) \( R_S \). Enceladus was separated about 2 \( R_S \) longitudinally from Cassini at the time of the \( R \sim 4 \) \( R_S \) orbit crossing. Actuation of the CAPS instrument across the thermal plasma flow yields high count rate samples and provides the ion phase space sampling. The high counting rate at larger energies is predominantly due to water group ions, while the ion counts at lower energies are due to light ions, e.g. \( H^+ \), \( H_2^+ \), as revealed by CAPS time-of-flight data [Young et al., 2005]. Background counts, especially those due to Saturn’s radiation belts, are taken as the average of counts measured between 9.7 and 23 keV (where plasma is largely absent) and are subtracted from these data. The low energy boundary visible in the bottom panel results when the counting signal drops below the background.

Inspection of the ion counting data in Figure 1 does not reveal that the water group ion distribution measured close in, near \( R = 4 \) \( R_S \), is hotter than would be expected for flow speeds near rigid corotation. If these data are fit with Maxwellian or Kappa phase space density (PSD) functions the azimuthal flow speed is low, about 50 to 70% of rigid corotation. This is due to the high ion temperature and the interaction of temperature and flow speed for the CAPS electrostatic analyzer. Such low flow speeds are in contrast to the analysis of CAPS data from Saturn.
orbit insertion [Sittler et al. 2005] that found ion flow near corotation in this region. Here we establish that the fresh pick-up ion component leads to the anomalously high ion temperature, as illustrated in Figure 2. Shown are CAPS counting rates (blue data points) for a single anode and near R = 4.3 R$_S$ (top panel) and R = 5.7 R$_S$ (bottom panel). Both data slices are obtained when actuation of the detector yields a look direction into the corotational plasma flow (corresponding to the bright streaks in Figure 1). The broad peak in Fig. 2 is attributed to the water group, here assumed to be OH$^+$ (M/Q = 17) for modeling purposes.

In order to establish the presence of pick-up ions, simulated ion counting rates are calculated assuming azimuthal ion flow at the speed of rigid corotation [Sittler et al., 2005]. The OH$^+$ temperature is chosen to yield a maximum count rate at the energy of the peak measured by CAPS, and the ion density is chosen to match the counting rate peak value. These simulated counting rates (solid black curves) are subtracted from the measured data (blue circles) at the high energy end dominated by water group ions to yield a residual counting rate (red squares). The most striking aspect of these residual counting rates is that near R~4.3 R$_S$ they peak near the expected energies of water group pick-up ions, with no such correspondence further out near R~5.7 R$_S$. This is shown by the vertical dashed lines, denoting the expected upper limit energies of locally-produced ions, most likely via charge exchange with an orbiting neutral atom or molecule. In the frame of reference of CAPS, these ions have a speed of $V_{co} + V_{rel} - V_{sc}$ where $V_{co}$ is the rigid corotation speed, $V_{rel}$ is the relative speed of a corotating ion and orbiting neutral, and $V_{sc}$ is the azimuthal speed of Cassini. An important point is the effect of the assumption of rigid corotation on this analysis. It is well known that energy is required to accelerate the locally produced pick-up ion population, leading to a corotation lag. However, if a lower flow speed is assumed to calculate the CAPS counts, e.g. 80% of rigid corotation, the resulting residual counting
rates are largely unchanged from those in Figure 2 but the agreement with the pick-up energy at \( R = 4.3 \, R_S \) is poor (the pick-up energy is lower by about 100 eV). In our view, this does not argue against the presence of pick-up ions but instead is further evidence for flow near corotation in agreement with Sittler et al. [2005]. It should be noted that local pick-up of the water group at low energies \( (V = V_{co} - V_{rel} - V_{sc}) \) is difficult to observe by CAPS due to the presence of the light ion core. In addition, including multiple water group ion species or adopting a different (e.g. 16, 18, 19) average ion mass per charge does not significantly alter the results in Figure 2.

Figure 3 extends the analysis of Figure 2 by presenting energy distributions (vertical axis) covering the radial distance range from 3.5 to 7 \( R_S \). The average look direction of CAPS for the 127 data slices plotted is equal to 14.4° ± 6.8° from the corotation direction. Simulated counting rates are subtracted from maximum ion counting rates vs. energy per charge as described in Figure 2, with rigid corotation assumed throughout the radial distance range. The solid black curve is the energy in the instrument frame of an \( OH^+ \) ion with speed equal to \( V_{co} + V_{rel} - V_{sc} \) as discussed above. (Discontinuities in this curve are due to varying Cassini spacecraft speed.)

This figure shows that in the vicinity of the orbit of Enceladus (3.5 to 4.5 \( R_S \)) there is a large residual counting rate near the expected energy of water group pick-up ions. Between the orbits of Tethys and Dione, the residual signal near the pick-up ion energy is considerably reduced, suggesting the majority of local pick-up ions in these regions are too few to emerge above the instrument background. This transition in the pick-up ion counts from high to low just inside the Tethys orbit is observed on two of the four orbits analyzed in this study as Cassini traverses the region; the remaining two orbits achieve minimum radial distances of about 4.68 and 4.96 \( R_S \) and do not observe a strong pick-up ion counting signal. Outside of Dione’s orbit, the residual
counting rate increases at energies near and lower than the local pick-up energy, indicating some local pick-up ion production in this region.

The ion phase space density (PSD) as a function of velocity parallel and perpendicular to the magnetic field (assumed to lie in the Z direction) is plotted in Figure 4, with the PSD calculated in the corotating frame for the water group (energy range 90 eV to 1.7 keV) again assuming OH+. Data are accumulated over a radial range of 0.5 Rs and the plasma is assumed to be rigidly corotating. The black dashed semi-circle is drawn at the relative speed, $V_{\text{rel}}$, between an orbiting neutral and the corotating ions at the center of the radial bins, $R = 4.25$ and 6.60 Rs. For the bin centered at $R = 4.25$ Rs, the most striking feature is the strong enhancement in PSD near 90 degree pitch angle. This is the residual ion component illustrated in Figures 2 and 3 and is identified as locally produced water group pick-up ions that are characterized by their gyro-motion dominating their motion along the field lines. A similar but weaker signature is observed in the bin centered at 6.60 Rs, in agreement with Figure 3.

Figure 4 also illustrates that the CAPS ion counting data for the water group pick-up ions are consistent with a source region in the vicinity of the Enceladus orbit and subsequent transport of plasma to larger R. If we assume conservation of the ion first adiabatic invariant ($E_{\text{perp}}/B$) during transport from a source location $R_{\text{source}}$ outward to position R, the ions should be “adiabatically cooled”, with $v_{\text{perp}}$ reduced by the factor $(R_{\text{source}}/R)^{1.5}$ for a dipolar magnetic field. Point B in Figure 4 is the mapping of $v_{\text{perp}}$ from local pickup at $R = 4.25$ Rs (point A) to $R = 6.6$ Rs, conserving the first adiabatic invariant. Inspection of the PSD values at these two points show that they are roughly equal in magnitude, and this can be verified for source locations near $R = 4$ and mapped to larger R. The PSD at the mapped $v_{\text{perp}}$ values remains roughly constant outward
from the Enceladus orbit and well above the PSD at velocities corresponding to local pickup (dashed semi-circles in Figure 4).

Discussion

Using simple arguments, e.g. the discussion of Figures 2 and 3, the primary result of this study is the unambiguous direct detection by CAPS of locally produced water group pick-up ions over a broad spatial region in the vicinity of the Enceladus orbit and within the orbit of Tethys. These are freshly produced pick-up ions that are not yet thermalized, most likely produced by charge exchange between corotating thermal ions and neutral atoms and molecules in Saturn’s toroidal atmosphere. From the data shown in Figure 4, the density of these ions in the vicinity of the Enceladus orbit can be estimated by subtracting the core ion PSD from the total PSD and integrating the remainder over velocity space. Here we assume for the core ions a Maxwellian PSD function for OH+ with an isotropic ion temperature of 20eV and a typical ion density in this region of 70 cm$^{-3}$ [Persoon et al., 2006; Tokar et al., 2006]. The 20 eV temperature is that obtained in the analysis for the top panel of Figure 2, assuming rigid corotation and matching the energy of peak ion counts measured by CAPS. The resulting PSD velocity space distribution of the pick-up ions is shown in Figure 5, dominated by ions in a ring and near the velocity of local pick-up. Integration of this distribution yields $N_{pu} = 5.6$ cm$^{-3}$; that is, the non-thermalized pick-up ions are approximately 8% of the core ion density.

The ratio in density of pick-up to core ions can be used to estimate the ratio of the ion thermalization time to the loss time. We use ionization, charge exchange, and loss times obtained by Sittler et al. [2008] to obtain an expression for the thermalization time $(N_{pu}/N_{core})/(5 \times 10^{-5}$ s$^{-1})$, where $(N_{pu}/N_{core})$ is the fraction of nonthermalized ions in the local plasma. Using the percent
above at \( R = 4.25 \) \( R_S \) gives a thermalization time of 1600 s. Ion thermalization occurs by energy and pitch angle scattering. Here, these processes are simulated using a one dimensional hybrid (particle ions, fluid electrons) simulation code [Winske and Omidi, 1992] to obtain an independent check on the thermalization time extracted from the data. This simulation code has been successfully applied to ion pick-up at Io [Cowee et al., 2006]. The simulations are initialized with a core ion \( \text{OH}^+ \) population and uniform magnetic field corresponding to conditions on the equator at \( R = 4.25 \) \( R_S \). The results indicate that pick-up ion densities from 2.5 to 10% of the total ion population are sufficient to drive the instability to fluctuating field amplitudes measured by the Cassini magnetometer in this region (1 to 8 nT), [J. Leisner, personal communication, 2008]. The instability saturates in about 200 ion gyroperiods, before the estimated thermalization time of 1600 s (~470 ion gyroperiods). However, full thermalization of the pick-up population occurs on a somewhat longer time scale, about 1000 ion gyroperiods (~3500 s).

In our view, a consistent picture emerges from the CAPS data, the hybrid simulations, and the neutral cloud models. In the narrow Enceladus torus, where the neutral densities are very high [Johnson et al., 2006], charge-exchange-induced pick-up dominates. In this process, fresh ions replace thermalized core ions \textit{without} changing the total ion density. Based on the CAPS data and the modeling discussed here, the exchange of fresh ions for thermalized ions happens sufficiently rapidly in the Enceladus torus that a detectable, nonthermalized ion component is maintained.

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References


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Figure 1: CAPS ion counting data for one anode as a function of energy per charge and radial distance from Saturn. The data were measured near Saturn’s equatorial plane on Oct 11, 2005 (top panel) and Nov 27, 2005 (bottom panel). Actuation of the CAPS instrument provides the phase space sampling, with the highest ion counts identified as water group ions and observed when the instrument samples corotating plasma.
Figure 2: CAPS ion counting data as a function of energy per charge in the equatorial plane and near $R = 4.3 \, R_S$ (top panel) and $R = 5.7 \, R_S$ (bottom panel). The broad peak is identified as water group ions, with the lower energy counts due to light ions ($H^+$, $H_2^+$). CAPS simulated counting rates for corotating $OH^+$ described by a Maxwellian PSD function (black curves) are subtracted from these data to leave a residual ion counting rate component (red curves). In the vicinity of the Enceladus orbit this residual signal peaks at the expected energy of locally produced pick-up ions with no such correspondence further out. See text for further discussion.
Figure 3: Extension of the analysis in Figure 2 to the radial distance range 3.5 to 7.0 $R_S$. Plotted is CAPS OH$^+$ counting rate as a function of energy per charge and radial distance. A strong residual ion counting signal is observed by CAPS in the vicinity of the Enceladus orbit and near the expected energy of locally produced pick-up ions (solid black curve). This residual counting signal is largely absent between the orbits of Tethys and Dione. See text for further discussion.
Figure 4: CAPS OH+ PSD in the corotating frame as a function of velocity parallel and perpendicular to the magnetic field, assumed to lie in the z direction. Left (right) panel shows data accumulated over a 0.5 $R_S$ bin centered at $R = 4.25$ (6.60) $R_S$, respectively. See text for further discussion.
Figure 5: CAPS measured PSD of OH$^+$ ions identified as primarily the locally produced pick-up ion population in the vicinity of the Enceladus orbit. These data are obtained by subtracting the PSD of the OH$^+$ ion core population from the left panel of Figure 4. Integration of these data yields a pick-up ion population that is about 8% of the total ion density. See text for further discussion.