GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L14202, doi:10.1029/2008GL034749, 2008

Cassini detection of water-group pick-up ions in the Enceladus torus

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Received 21 May 2008; revised 16 June 2008; accepted 20 June 2008; published 24 July 2008.

[1] This study reports direct detection by the Cassini plasma spectrometer of freshly-produced water-group pick-up ions within the proposed Enceladus torus, a radially narrow toroidal region surrounding Saturn that contains a high density of water-group neutrals. This torus is produced by the icy plumes observed near the south pole of Enceladus. The ions are created by charge exchange collisions between water-group neutrals in the Enceladus torus and thermal ions corotating with Saturn. They are identified in the Cassini data via their characteristic ring-like signatures in ion velocity distributions. In the radial distance range of 4.0 to 4.5 R_S, the density of these non-thermalized ions is estimated to be at least 5.2 cm^{-3}, about 8% of the total ion density. The estimated density together with ionization, charge exchange, and loss times, yield an ion thermalization time of at least 3150 s, in reasonable agreement with hybrid particle simulations. **Citation:** Tokar, R. L., et al. (2008), Cassini detection of water-group pick-up ions in the Enceladus torus, *Geophys. Res. Lett.*, *35*, L14202, doi:10.1029/2008GL034749.

1. Introduction

[2] One of the major discoveries [*Dougherty et al.*, 2006; *Porco et al.*, 2006] of the Cassini mission is the plume of icy grains and gas emanating from the south polar region of the moon Enceladus (orbital radial distance R = 3.95 R_S, with R_S = Saturn radius = 60330 km). Models predict [*Johnson et al.*, 2006] that this plume produces a radially narrow (~1.0 R_S) and dense torus of water-group (O, OH, H_2O) neutral atoms and molecules centered on Enceladus' orbit and referred to as the Enceladus torus. Subsequent scattering of these neutrals produces an extended neutral cloud, consistent with the OH torus (2–8 R_S) detected by the Hubble space telescope (HST) [*Shemansky et al.*, 1993]. Both the ionization and the scattering are primarily a result of charge exchange collisions between water-group ions, nearly corotating with Saturn, and neutrals in the Enceladus torus [*Johnson et al.*, 2005]. The relative speed for an individual ion-neutral collision varies both with radial distance from Saturn and with the thermal velocity of the ions, leading to a range in energy of the neutrals scattered out of the narrow Enceladus torus.

[3] 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 newly-created ions are moving near the local Keplerian speed, slower than the corotation speed, and are "picked-up" by Saturn's magnetic field. The purpose of this study is to report the direct detection by the Cassini plasma spectrometer (CAPS) [*Young et al.*, 2004] of these water-group ions within their source region, the Enceladus torus. 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 their toroidal source region and far from Enceladus.

2. Data Analysis

[4] CAPS data in the equatorial inner magnetosphere (3.5 R_S < R < 7.0 R_S) are analyzed, obtained in 2005 on Oct. 11 and 29, Nov. 27, and Dec. 24, all near local noon. Figure 1 illustrates typical ion counting rates as a function of energy per charge, radial distance from Saturn, and time obtained by individual CAPS anodes during actuation. The data in the top panel were measured in the proposed Enceladus torus region (~4 R_S) and the bottom panel farther out near R = 5.7 R_S. The high counting rate at energies near 100 eV (Figure 1, top) and 500 eV (Figure 1, bottom) are mostly due to water-group ions, while the ion counts at lower energies are due to lighter ions, e.g. H^+, H_2^+, as revealed by CAPS time-of-flight data [*Young et al.*, 2005].

[5] Shown in Figure 2 are two slices of ion counts (blue data points) when actuation of the detector yields maximum counts, corresponding to the bright streaks in Figure 1. These slices are measured when the look direction of CAPS is nearly into the corotating ion direction. The broad peaks in Figure 2 are attributed to water-group ions, 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 for CAPS are calculated assuming Maxwellian phase space density functions and azimuthal ion flow at the speed of rigid corotation, as determined by *Sittler et al.* [2005]. The OH^+ temperature is chosen to yield a maximum count rate at the energy CAPS observes, and the OH^+ density is chosen to match the counting rate peak value. This yields for OH^+ core densities and temperatures: (24 cm^{-3}, 23 eV) and (35 cm^{-3},110 eV) at R = 4.3 and 5.7 R_S, respectively. The 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).

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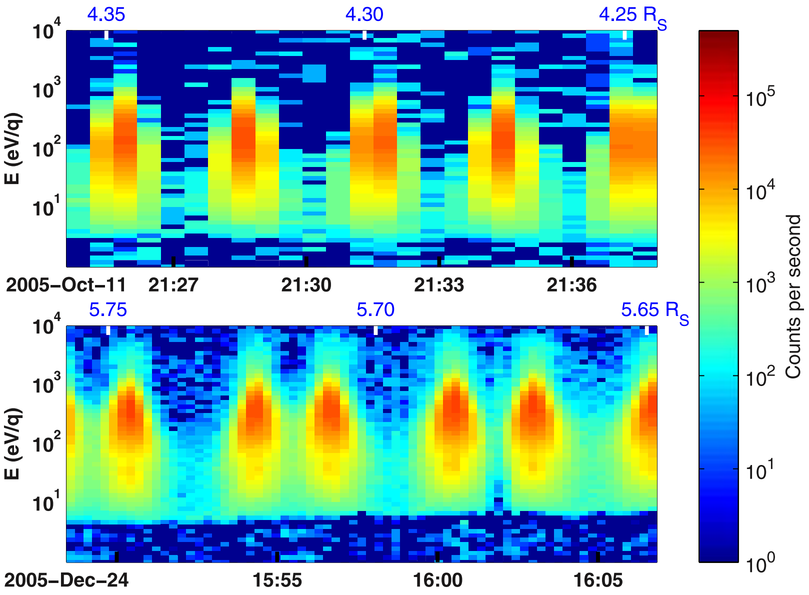

Figure 1. CAPS ion counting data for anode (top) 5 and (bottom) 4 as a function of energy per charge (eV/q), radial distance from Saturn (R_S) and time (UT). The data were measured in 2005 near Saturn's equatorial plane on (top) Oct 11th and (bottom) Dec 24th. Actuation of the CAPS instrument provides the phase space sampling, with the highest ion counts identified as water-group ions and observed when the instrument samples corotating plasma. The actuator sweeps through 150 deg of the full 360 deg around Cassini's main axis and moves at a nominal speed of about 1 deg/s with one full actuation cycle having a duration of about 347 s. The segment of phase space sampled by the instrument is dependent on both the actuator motion and the orientation of the spacecraft. For the Oct 11th example, the spacecraft was aligned such that the actuator motion yielded sampling in the north-south direction while actuator motion on Dec 24th sampled in the east-west direction. For the purposes of this study, both orientations provide sufficient ion phase space sampling. For the data in the top panel, Cassini was about 2 R_S downstream of Enceladus.

[6] The most striking aspect of these residual counting rates is that at R = 4.3 R_S they peak near the expected energy of water-group pick-up ions, with no correspondence further out near R = 5.7 R_S. This is shown by the vertical dashed lines, denoting the expected energy of OH^+ ions produced via charge exchange collisions between the corotating water-group ion core and orbiting neutral atoms or molecules. In the frame of reference of CAPS, the locally-produced ions have a speed $V = V_{co} + V_{rel} - V_{sc}$ 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. In the equatorial plane, $V_{rel} = V_{co}\,[1 - (1.85/R)^{3/2}]$, with R the radial distance in R_S. For example, near Enceladus' orbit V_{co} = 39.0 km/s and V_{rel} = 26.5 km/s, with typical V_{sc} = 14 km/s. The agreement in the energy of the residual count peak and the local pick-up energy indicates that within the high density neutral Enceladus torus pick-up ion production occurs rapidly so that a significant fraction of the ions are not yet thermalized.

[7] Figure 3 illustrates the residual counting rate vs. energy per charge and radial distance. As in Figure 2, simulated counting rates are subtracted from CAPS maximum water-group counting rates, with rigid corotation assumed throughout the radial distance range. The solid black curve is the OH^+ ion pick-up energy in the Cassini frame, with discontinuities due to varying Cassini speed. Figure 3 shows that in the vicinity of the proposed Enceladus torus (3.5 to 4.5 R_S) there is a large residual counting rate near the pick-up energy. Between Tethys and Dione's orbits, this residual signal is considerably reduced, suggesting few locally produced ions in this region. The pick-up ion boundary near Tethys' orbit is observed on two of the four Cassini orbits (Oct 11th and Nov 27th) analyzed in this study; the remaining two orbits (Oct 29th and Dec 24th) 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 mostly lower than the local pick-up energy, possibly indicating local ion production. However, this may also be due to the breakdown in the assumption of rigid corotation for the core in addition to the development of a temperature anisotropy for the core water-group ions. Further analysis of the ion data near and outside Dione's orbit is complex and beyond the scope of this study.

[8] The ion phase space density (f_i) as a function of velocity parallel and perpendicular to the magnetic field (assumed parallel to the planetary rotation axis) is plotted in Figure 4, with the ion velocities calculated in the corotating frame for the water-group (energy range 90 eV to 1.7 keV, CAPS frame) again assuming OH^+. Data are accumulated over a radial range of 0.5 R_S and the plasma is assumed to be rigidly corotating. The black semi-circles are drawn at the relative speed, V_{rel}, at the center of the radial bins, R = 4.25 and 6.60 R_S. For the bin centered at R = 4.25 R_S, the strong enhancement in f_i near 90 degree pitch angle is clear, identified as locally produced water-group pick-up ions that are characterized by their gyro-motion dominating their motion along the field lines. For the radial bin centered at 6.60 R_S, there is a weaker enhancement in f_i at V_{rel} and near 90 degree pitch angle than that observed near Enceladus'

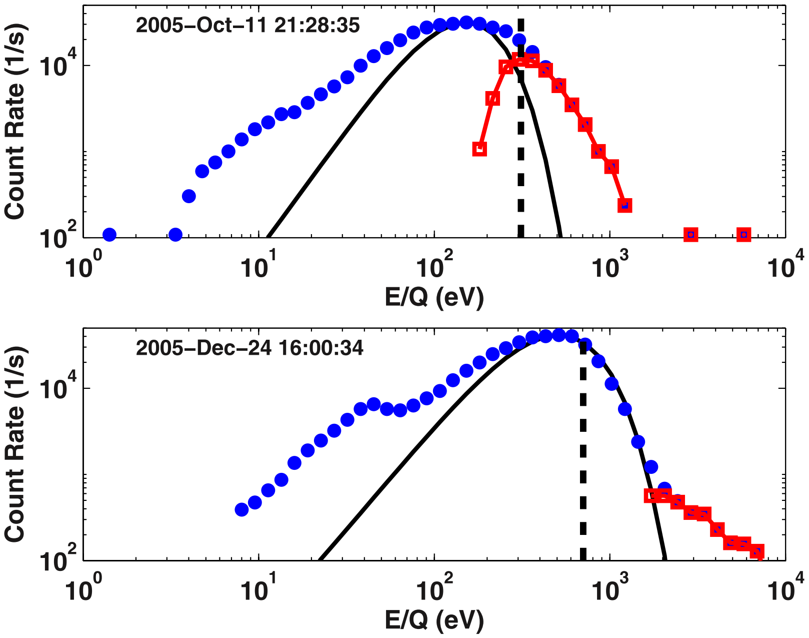

Figure 2. CAPS ion counting data (blue points) as a function of energy per charge near (top) R = 4.3 R_S and (bottom) R = 5.7 R_S. Within the Enceladus torus (top) the residual counting signal (red squares) peaks at the expected energy of locally produced pick-up ions (vertical dashed lines) with no such correspondence further out at R = 5.7 R_S. If a lower flow speed is assumed to calculate the residual counts, e.g. 80% of rigid corotation, the residual counting signal is similar but the agreement with the pick-up energy at R = 4.3 R_S is poor because the energy is lower by about 100 eV due to the smaller assumed V_{co}. This result is further evidence for flow near corotation as determined by *Sittler et al.* [2005]. It should be noted that local pick-up of the water-group at low energies (corresponding to $V = V_{co} - V_{rel} - V_{sc}$) 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 do not significantly alter the conclusions from this analysis.

orbit. This is consistent with reduced pick-up ion production in this region.

3. Discussion

[9] The primary result of this study is the unambiguous direct detection by CAPS of locally produced water-group pick-up ions near Enceladus' orbit. Consistent with a high density of neutrals in the radially narrow Enceladus torus, these ions are produced via charge exchange and not yet thermalized. The density of the pick-up ions over the range 4.0 to 4.5 R_S can be estimated by subtracting the core water-group f_i from the total f_i shown in Figure 4 (left). Employing a forward model of CAPS to match the measured data [*Tokar et al.*, 2005] while constraining the ion flow to rigid corotation yields for the water-group ion core: $N_{OH}+ = 29.4 \pm 2.6$ cm^{-3} and $T_{OH}+ = 23.7 \pm 2.8$ eV over the radial distance range 4.0 to 4.5 R_S. A Maxwellian f_i function is chosen for the thermalized core OH^+ with an isotropic temperature (24 eV). The density (33 cm^{-3}) is chosen to give the best fit to the binned ion data. The f_i velocity space distribution after subtraction of the ion core f_i is shown in Figure 5 as is the velocity of local pick-up (semi-circle). Using these data, a pick-up ion density of 5.2 cm^{-3} is obtained by integrating over a shell in velocity space with inner radius 27.1 km/s and outer radius 32.7 km/s, the V_{rel} values at 4.0 and 4.5 R_S. In addition, the total residual ion density is obtained by integrating the f_i in Figure 5 over all velocity space to obtain 20.6 cm^{-3}, corresponding to a total

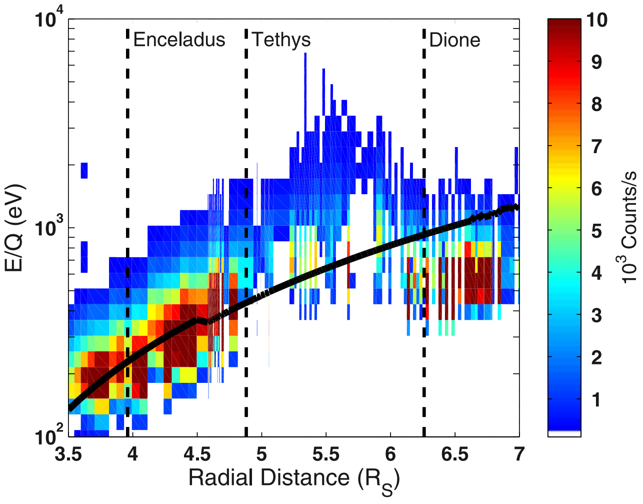

Figure 3. Extension of the analysis in Figure 2 to the radial distance range 3.5 to 7.0 R_S. Plotted is the CAPS residual ion counting rate as a function of energy per charge (eV) and radial distance (R_S). A strong residual signal is observed by CAPS in the vicinity of Enceladus' orbit and near the expected energy of locally produced pick-up ions (solid black curve). This residual counting signal is largely absent outside Tethys' orbit, and near Dione's orbit is most intense at energies lower than predicted for local pick-up.

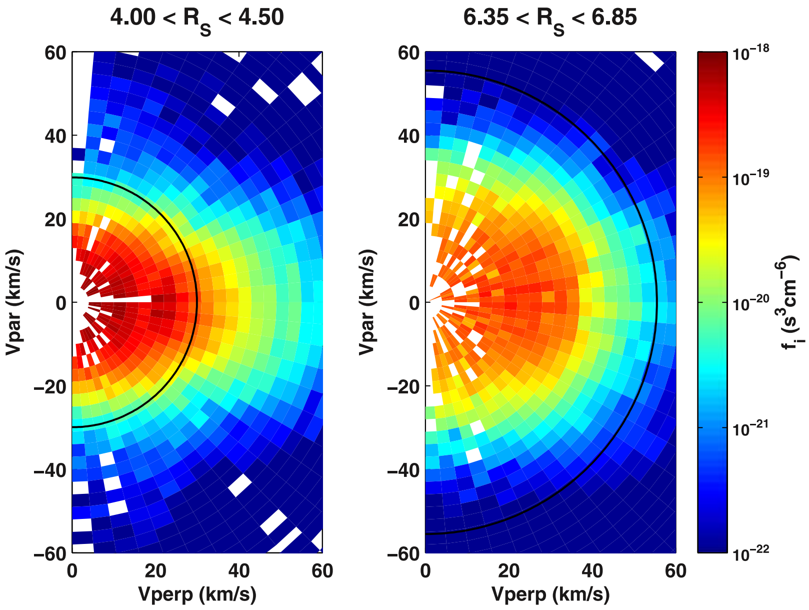

Figure 4. Phase space density for water-group ions (OH^+) in the corotating frame of reference as a function of velocity parallel and perpendicular to the magnetic field, assumed to lie in the z direction. Left (right) panel shows data accumulated over a 0.5 R_S bin centered at R = 4.25 (6.60) R_S, respectively. The semi-circles are drawn at the V_{rel} values for the midpoint of the radial bins. Data were obtained (left) on 11-Oct-2005 from 21:08:03 to 22:06:43 UT and (right) on 27-Nov-2005 from 03:01:13 to 04:13:45 UT.

ion density of 33 + 20.6 + 8.9 = 62.5 cm^{-3}, where the light ion density of 8.9 cm^{-3} from the forward model of these CAPS data is included. This total density is in good agreement with the Cassini radio and plasma wave science electron density measurements in this region [*Persoon et al.*, 2006] that found 60 ± 10 cm^{-3}. Therefore, in the radial range 4.0 to 4.5 R_S, the locally produced pick-up ions are estimated to be about 8% (5.2/62.5) of the total ion density.

[10] Ionization, charge exchange, and loss times obtained by *Sittler et al.* [2008] are used to estimate the thermalization time of the pick-up ions: $(N_{pu}/N_{core})/(5 \times 10^{-5}\ s^{-1})$, where (N_{pu}/N_{core}) is the ratio of pick-up to core water-group ion density. For the N_{pu}/N_{core} value of 5.2/33 = 0.16 obtained for fresh pick-up ions in the velocity space shell, the thermalization time estimate is 3150 s. To obtain an independent estimate of the ion thermalization time in this region, the energy and pitch angle scattering of the pick-up ions is simulated using a one dimensional hybrid code [*Cowee et al.*, 2006]. The simulations are initialized with a core ion OH^+ population, a cold ring of OH^+ at V_{rel}, and a uniform magnetic field corresponding to conditions at Saturn on the equator at R = 4.25 R_S. In the simulations, full thermalization of the pick-up ion population occurs in 3500 to about 10,000 s, in reasonable agreement with the time estimate above. In addition, the simulation results indicate that a pick-up ion density of 5.2 cm^{-3} is sufficient to drive the instability to fluctuating field amplitudes measured by the Cassini magnetometer in this region (0.1 to 0.8 nT) (J. S. Leisner, personal communication, 2008).

[11] A consistent picture emerges from the CAPS data, the neutral cloud models, and the hybrid simulations. 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 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.

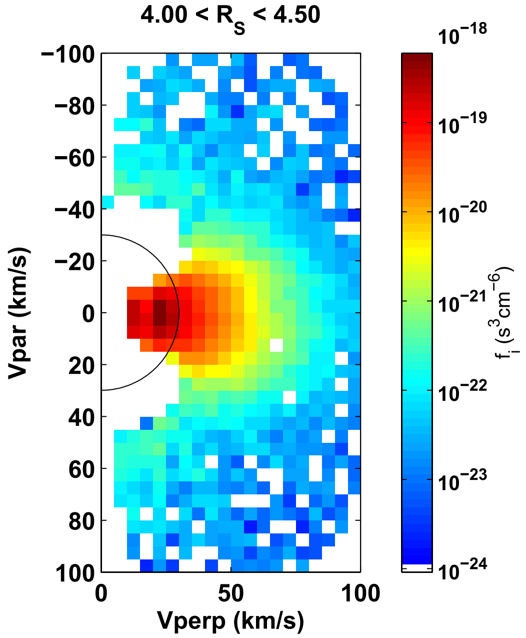

Figure 5. Phase space density obtained by subtracting the water-group ion core from the left panel of Figure 4. The semi-circle is drawn for V_{rel} at the center of the radial bin. Integration of these data over a shell in velocity space yields a local pick-up ion density of 5.2 cm^{-3}, or about 8% of the total ion density.

[12] **Acknowledgments.** The work at Los Alamos was performed under the auspices of the US DOE and was supported by the NASA Cassini program. The ion mass spectrometer is a component of the Cassini Plasma Spectrometer and was supported by JPL contract 1243218 with Southwest Research Institute. Cassini is managed by the Jet Propulsion Laboratory for NASA. The work at Virginia was also supported via this JPL contract.

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