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Discovery of nitrogen in Saturn's inner magnetosphere

H. T. Smith,[1] M. Shappirio,[2] E. C. Sittler,[2] D. Reisenfeld,[3] R. E. Johnson,[1]
R. A. Baragiola,[1] F. J. Crary,[4] D. J. McComas,[4] and D. T. Young[4]

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[1] We detected N^+ in Saturn's magnetosphere in the range L ~ 3.5 to ~9.5 Saturn Radii (Rs) using data collected by the Cassini Plasma Spectrometer during Saturn Orbit Insertion and the following orbit (Rev A). The presence of N^+ in Saturn's magnetosphere has been a source of much debate since Voyager's detection of unresolved mass/charge 14–16 amu ions in this region. Two principal nitrogen sources have been suggested: Titan's atmosphere and nitrogen compounds trapped in Saturn's icy satellite surfaces (Sittler et al., 2004; E. C. Sittler et al., Energetic nitrogen ions within the inner magnetosphere of Saturn, submitted to *Journal of Geophysical Research*, 2004). The latter may contain primordial nitrogen, likely as NH_3 in ice (Stevenson, 1982; Squyers et al., 1983) or N^+ that has been implanted in the surface (Delitsky and Lane, 2002). In addition to our nitrogen detection results, we also present an initial examination of possible sources of these ions. **Citation:** Smith, H. T., M. Shappirio, E. C. Sittler, D. Reisenfeld, R. E. Johnson, R. A. Baragiola, F. J. Crary, D. J. McComas, and D. T. Young (2005), Discovery of nitrogen in Saturn's inner magnetosphere, *Geophys. Res. Lett.*, *32*, L14S03, doi:10.1029/2005GL022654.

1. Introduction

[2] Saturn, with its elaborate rings, numerous satellites and dusty plasma, is an evolving planetary system. This ringed planet has a co-rotating magnetosphere through which the inner icy satellites (Mimas, Enceladus, Tethys, Dione and Rhea) orbit. In addition, Titan, the second largest moon in the solar system, spends much of its time within Saturn's magnetosphere. Until recently, our analysis of this system relied on limited data gathered from terrestrial and Hubble Space Telescope observations and from three spacecraft (Pioneer 11 and Voyager 1 & 2) that passed through Saturn's magnetosphere. These data indicated both thermal and energetic plasmas composed of a light ion component (protons) and a heavier ion component. However, the earlier instruments were not able to determine if the heavy ions were oxygen and/or nitrogen.

[3] Our detection of nitrogen ions (throughout this paper "nitrogen ions" refers to atomic nitrogen (N^+) and not molecular or doubly charged ions, etc., unless explicitly stated) in Saturn's magnetospheric plasma gives the first measure of nitrogen's relative importance to water products from the icy ring particles and satellites in the inner magnetosphere. *Sittler et al.* [2004] and E. C. Sittler et al. (Energetic nitrogen ions within the inner magnetosphere of Saturn, submitted to *Journal of Geophysical Research*, 2004, hereinafter referred to as Sittler et al., submitted reference, 2004) suggested two principal sources of nitrogen ions: Titan's nitrogen-rich atmosphere and nitrogen species trapped or implanted in the icy satellite surfaces. If the detected N^+ originated in Titan's atmosphere, this would give insight into the plasma transport processes in the magnetosphere. Alternately, if a local source created the N^+, this would be the first indication of nitrogen-containing molecules on the surfaces of these satellites. Such molecules may contain primordial nitrogen, possibly from NH_3 trapped in ice [*Stevenson*, 1982; *Squyres et al.*, 1983], or nitrogen ions that have been implanted in the surface [*Delitsky and Lane*, 2002], possibly originating from Titan's atmosphere [*Sittler et al.*, 2004, also submitted reference, 2004]. In this paper we first describe the detection of nitrogen ions and then examine their spatial distribution with the ultimate goal of identifying their origin.

[4] Data from Cassini's arrival on June 30, 2004 is rapidly advancing our understanding of the plasma in Saturn's inner magnetosphere. The orbiter carries 12 instruments and is on a nominal 4-year mission. Here we present results from the Ion Mass Spectrometer (IMS), which is one of three sensors on the Cassini Plasma Spectrometer (CAPS) [*Young et al.*, 2004].

[5] CAPS data can be used to determine ion mass/charge (M/Q) between 1 eV and 50 keV and 1–100 amu/e. Energy resolution ($\Delta E/E$) is 0.17 while mass/charge resolution ($M/\Delta M$) is ~8 or ~60 amu/e depending on detector [*Young et al.*, 2004]. An electrostatic analyzer selects ions in energy-per-charge (E/Q) after which they enter a time-of-flight (TOF) analyzer. In the TOF section, ions are pre-accelerated by 14.6 keV, pass through a carbon foil and emerge as neutral or charged particle fragments. Any molecular ions entering the IMS are completely broken up in the carbon foil and only their atomic fragments reach the detectors. A linear electric field (LEF) deflects positive ion fragments leaving the foil (of external E/Q < ~15 keV/e) toward one set of detectors (called the LEF) while neutral and negative particles impact another detector (called the ST). The ion species and incident energy determine the fraction of particles leaving the foil. Knowledge of the incident ion E/Q and TOF are used to calculate the ion M/Q. The LEF detector records high-resolution ($M/\Delta M$ ~ 60) spectra while the ST records low-resolution ($M/\Delta M$ ~ 8) spectra (see *Young et al.* [2004] for more detail). Flight unit calibrations and a still-available identical prototype unit determine the locations and shapes of the TOF peaks used for ion species identification. The data presented here are primarily collected by the LEF detector. The energy range mentioned

[1]Engineering Physics, University of Virginia, Charlottesville, Virginia, USA.
[2]Goddard Space Flight Center, Greenbelt, Maryland, USA.
[3]Department of Physics and Astronomy, University of Montana, Missoula, Montana, USA.
[4]Southwest Research Institute, San Antonio, Texas, USA.

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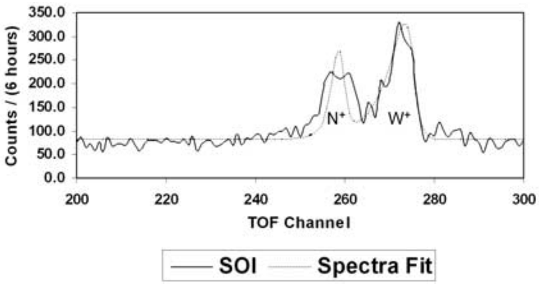

Figure 1. LEF spectrum for SOI orbit (day 182) from 18:00 to 24:00 UTC. The solid line shows ion counts corrected for fixed-pattern noise and integrated over 6 hours at 333 eV. The dotted line shows our model fit to the spectrum with the N^+ peak on the left and the water group ion (W^+) peak on the right. The one sigma fractional uncertainties are ~1.5% for both peaks with a chi-squared value of 3.8.

above is divided into 64 logarithmically spaced channels sequentially cycled every 4 s. In the data used here adjacent energy channels are summed together to form a total of 32 separate channels each with an effective resolution of $\Delta E/E = 0.34$.

2. N^+ Detection

[6] We first detected of N^+ in the magnetosphere just before Saturn Orbit Insertion engine firing [*Young et al.*, 2005]. We examined IMS data collected from 18:00 until 24:00 UTC on 30 June, 2004 (DOY 182) covering the in-bound trajectory from ~8.3 to ~3.4 Saturn radii (R_S) from the planet. As mentioned above, we first consider LEF data integrated over a 6-hour period to accumulate significant counts. The initial data showed a peak in the spectrum where we expected to see N^+, but here we present two sets of results validating the nitrogen detection because the spectral region around this N^+ peak is noisy.

[7] First, we focus our analysis on ions with energies around 333 eV because they produce the largest number of counts during the 6-hour period. Figure 1 shows an LEF spectrum corrected for fixed-pattern noise and integrated over 6 hours in the vicinity of the peak in nitrogen flux at 333 eV. The dotted line shows our model fit to the spectrum with the N^+ peak on the left and the water group ion (referred to as W^+ representing the sum of O^+, OH^+, H_2O^+ and H_3O^+) peak on the right. The one sigma fractional uncertainties are only ~1.5% for both peaks with a chi-squared value of 3.8. We also examined all other species in the calibration data (at 375 eV) that could produce a peak in the vicinity of N^+. Specifically, we considered N_2^+, CH_4^+, O_2^+ and CO^+ however all of these species require a peak to the left of N^+ that is not present in our spectra. Although not present in the calibration data, it is important to note that N^+ detected as fragments of molecules containing nitrogen (such as NH_3^+) would create a peak slightly shifted to the left (shorter TOF) of the N^+ calibration peak. This occurs because as the NH_3^+ is broken into atomic fragments, the energy is distributed among the four fragments so that the nitrogen fragment is less energetic than an atomic N^+ counterpart. Thus the nitrogen fragment from NH_3^+ does not penetrate as far into the electric field, giving a shorter LEF TOF than N^+.

[8] We use another characteristic of the LEF sensor to test the above identification. For each species of LEF ion, a fixed fraction strikes the detector's suppression grid and grid holder. In this case, no LEF stop signal is produced but instead a secondary electron is usually generated. These electrons are accelerated back to the ST sensor generating a false ST peak at approximately the same TOF channel that appeared in the LEF data. We refer to these peaks as "echoes" [*Young et al.*, 2004]. This serendipitous effect has proven useful for confirmation of ion detections. We have recorded the ratio of echo counts to LEF counts vs. channel number in Figure 2 for 333 eV as well as other nearby energy levels. The ratio is very noisy except close to the region of valid detections, where we also indicate the ratio obtained from the calibration data (~1.7). This correlation strongly supports the identification of N^+ because the ratio only corresponds to the calibration ratio in the vicinity of the N^+ peak and appears as noise elsewhere. Note the ratio noise is also reduced in the vicinity of the water group ion LEF peak. This result combined with the results discussed above help validate the identification of a nitrogen peak associated with the plasma in the inner magnetosphere.

[9] We also detected N^+ in the magnetosphere during the next orbit (Rev A) around Saturn when the spacecraft returned to the inner magnetosphere. We examined IMS data collected from 12:00 until 24:00 UTC on 28 October 2004 (DOY 302), covering the out-bound trajectory from ~6.2 to ~9.5 Rs from Saturn. We integrate counts at the peak in the energy spectrum (~330 eV) over the 12-hour period. Figure 3 shows our model fit to the spectra with an N^+ fractional one sigma uncertainty of ~7% and a chi-squared value of 2.5. All other species in the calibration data at 375 eV in the vicinity of the N^+ peak again do not appear present. Figure 4 shows the ST echo to LEF peak ratio for N^+ indicating valid ion detection similar to that suggested by Figure 2. Therefore, these results indicate the presence of N^+ on two trajectories through the inner magnetosphere.

3. N^+ Initial Characterization

[10] To obtain the spatial distribution of N^+, we examined the data for the nitrogen peak as a function of distance from Saturn. The solid line in Figure 5 shows the average energy of the ions in relation to the spacecraft as they enter the IMS

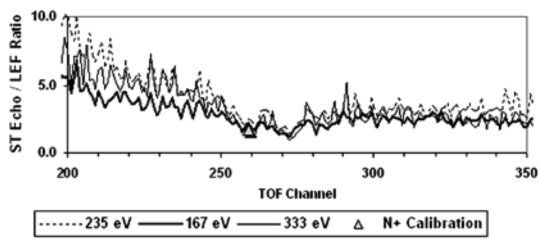

Figure 2. Ratio of ST "echo" peak ion counts to the associated LEF ion counts (TOF channels 200 to 350) integrated over the 6-hour SOI period at three energy levels. The shaded triangle represents the ST echo peak to LEF peak ratio derived from N^+ prototype calibration data.

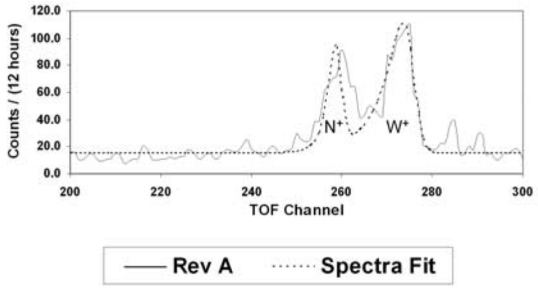

Figure 3. LEF spectrum for Rev A orbit (day 302) from 12:00 to 24:00 UTC. The solid line shows ion counts corrected for fixed-pattern noise and integrated over 12 hours at 333 eV. The dotted line shows our model fit to the spectrum with the N^+ peak on the left and the water group ion (W^+) peak on the right. The one sigma fractional uncertainty for N^+ is $\sim$7% and 16% for W^+ with a chi-squared value of 2.5.

during the SOI orbit (as function of radial distance in Saturn's equatorial plane). Inside 4 R_S, radiation background was removed from the data. The estimated average energy of N^+ is the sum of its co-rotation and thermal energies. As shown by *Sittler et al.* [2005], the water group ions have thermal energies $T_W \sim 100$ eV near Rhea's L shell and $T_W \sim 40$ eV just outside Mimas' L shell. Also, *Sittler et al.* [2005] show that the water group ions are approximately co-rotating and the same must be true for the nitrogen ions. Therefore, the measured curve is expected to be greater than the co-rotation energy curve, as observed. Similar to Figure 5, the solid line in Figure 6 represents the ion counts (per 8 second LEF collection cycle) as a function of radial distance for the same time period. The lower portion of Figure 6 shows Cassini's location normal to the orbital plane. Notice the counts for this period begin to appear when the spacecraft is vertically within $\sim$1 R_S of the orbital plane and when Cassini is closer than $\sim$7 R_S to Saturn. This implies a vertically confined distribution suggesting a local source. In addition, the average energy of these ions at the beginning of this period is about 600 eV and slowly decreases as the spacecraft moves closer to Saturn, following a trend similar to that of the co-rotation energy.

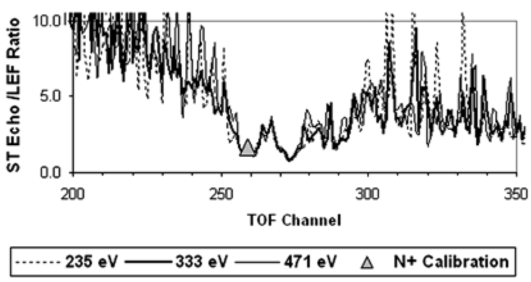

Figure 4. Ratio of ST "echo" peak ion counts to the associated LEF ion counts (TOF channels 200–350) collected during Rev A (12 hour integration) at three energy levels. The shaded triangle represents the ratio of the ST echo peak to the LEF peak derived from N^+ prototype calibration data.

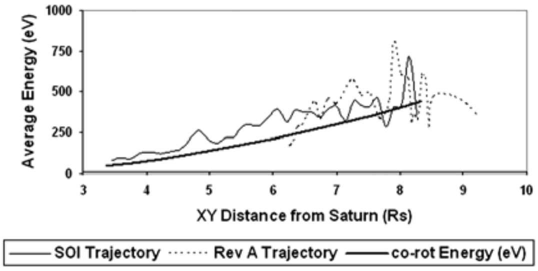

Figure 5. Average energy of ions entering N^+ (TOF channel 257) as a function of radial distance from Saturn along its equatorial plane for 6 hours of the SOI orbit (solid line) and 12 hours of Rev A (dotted line). The heavy solid line represents co-rotation energy.

[11] The dotted lines in Figures 5 and 6 represent the average ion energies and counts (per LEF collection cycle) respectively for Rev A. The average energy follows the same decreasing trend toward Saturn observed during the first orbit. Similar to SOI, the nitrogen signal does not become apparent until Cassini is vertically within $\sim$1 R_S of the orbital plane (within 6.5–9.5 R_S of Saturn for this orbit). The distribution again appears to be vertically confined within $\sim$1 R_S of Saturn's equatorial plane.

[12] We also used CAPS to search for N^+ near Titan, which might be expected as a byproduct of atmospheric sputtering on its nitrogen-rich atmosphere [*Johnson*, 1990; *Shematovich et al.*, 2003]. In contrast to N^+ detection in the inner magnetosphere, CAPS has yet to definitively detect N^+ in the outer magnetosphere near Titan's orbit (20 R_S). Specifically, we examined the in-bound and outbound passes around Titan's torus (SOI & Rev A) and could not identify atomic N^+ in the LEF spectrum. Because the N^+ we do detect is low energy, close to the local co-rotation energy, it cannot be generated from nitrogen ions picked-up in the outer magnetosphere and then diffused inward as examined by Sittler et al. (submitted reference, 2004). Such a population would have energies $\sim$>100 keV and would not be detectable by IMS. The ions detected with the LEF appear,

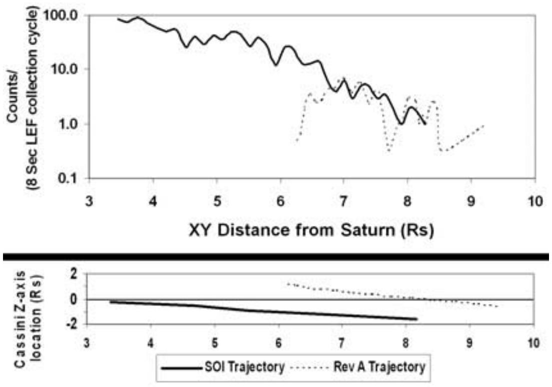

Figure 6. Ion counts (per 8 second LEF collection cycle) for detected N^+ as a function of radial distance from Saturn along its equatorial plane for 6 hours of the SOI orbit (solid line) and 12 hours of Rev A (dotted line). The lower portion shows Cassini's location normal to the orbital plane in Saturn Radii (Rs).

therefore, to be locally produced and picked-up and are seen only close the satellite orbit plane, suggesting the inner icy satellites are a likely source.

[13] Titan could also be an indirect source of the N^+ formed in the inner magnetosphere [*Smith et al.*, 2004] when neutral nitrogen atoms and molecules ejected from Titan's atmosphere with very low inclinations are ionized in the inner magnetosphere and form close to the orbital plane. Based on our model, a possible Titan N^+ source locally ionized in the inner magnetosphere would be about 3×10^{24} N^+/s, which is more than three orders of magnitude smaller than the entire H_2O source ($\sim 10^{28}$ per second) (S. Jurac and J. D. Richardson, A self-consistent model of plasma and neutrals at Saturn: Neutral cloud morphology, submitted to *Journal of Geophysical Research*, 2004). The N^+ source size needs to be eventually re-evaluated using Cassini data on the loss of Titan's atmosphere. Additionally, Jurac and Richardson estimate an icy satellite H_2O source of $\sim 1 \times 10^{26}$/s. Assuming only 3% nitrogen contamination of this source, the possible satellite N^+ source becomes comparable to the Titan source.

4. Summary

[14] We used CAPS data to show the presence of N^+ in Saturn's inner magnetosphere. In particular, CAPS detected N^+ from ~ 3.5 to ~ 9.5 R_S from Saturn and within ~ 1 Rs vertically of the orbital plane. This is consistent with the heavy ion scale heights suggested by existing plasma models [*Richardson and Sittler*, 1990; *Richardson and Jurac*, 2004]. Additionally these ions show an energy distribution that peaks well below 1 keV, suggesting that they are formed locally. In future work, we plan to specifically relate our findings to the results derived from Voyager observations.

[15] The discovery of nitrogen ionized in Saturn's inner magnetosphere requires an examination of its origins. The icy satellites provide an obvious source because N^+ is detected in the inner magnetosphere with energies lower than inwardly diffusing nitrogen ions from Titan (Sittler et al., submitted reference, 2004). *Krimigis et al.* [2005] set a limit on energetic N^+ at no more than 5% relative to O^+. If nitrogen originates from these moons, it would provide the first identification of a surface species other than H_2O. In particular, N^+ could be a product of radiolytically altered NH_3 in the icy satellites [*Johnson and Sittler*, 1990; *Lanzerotti et al.*, 1984], consistent with the presence of a volatile species required for the apparent resurfacing of these icy moons [*Stevenson*, 1982]. However, the lack of identification to date of other nitrogen containing ions (e.g., NH_x^+, NO^+, etc.), could suggest the nitrogen is from Titan but is locally ionized [*Smith et al.*, 2004]. The latter source should appear strongly peaked between about 6–11 Rs, whereas the signal detected here appears to increase with decreasing distance from Saturn with the largest values close to the orbit of Enceladus, strongly suggesting an icy satellite source. This first detection of ionized nitrogen in Saturn's inner magnetosphere dramatically increases our knowledge of this region and continued observation will allow us to separate the icy satellite and Titan sources.

[16] **Acknowledgment.** This work is supported by JPL contract 1243218 for CAPS operations and data analysis, the NASA Planetary Atmospheres, NASA GSRP, and the Virginia Space Grant Consortium.

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R. A. Baragiola, R. E. Johnson, and H. T. Smith, Engineering Physics, University of Virginia, Charlottesville, VA 22904, USA. (hts4f@virginia.edu)

F. J. Crary, D. J. McComas, and D. T. Young, Southwest Research Institute, San Antonio, TX 78228-0510, USA.

D. Reisenfeld, Department of Physics and Astronomy, University of Montana, Missoula, MT 59812, USA.

M. Shappirio and E. C. Sittler, Goddard Space Flight Center, Greenbelt, MD 20771, USA.