GEOPHYSICAL RESEARCH LETTERS, VOL. 9, NO. 9, PAGES 937-940, SEPTEMBER 1982

THE DISCOVERY OF NITROGEN IONS IN THE EARTH'S MAGNETOSPHERE

C. R. Chappell
Solar-Terrestrial Physics Division, NASA/Marshall Space Flight Center, AL 35812
R. C. Olsen
Physics Dept., University of Alabama in Huntsville, Huntsville, AL 35899
J. L. Green, J. F. E. Johnson, and J. H. Waite, Jr.
Magnetospheric Physics Branch, NASA/Marshall Space Flight Center, AL 35812

Abstract: Operating in a mass scanning mode, the Retarding Ion Mass Spectrometer (RIMS) has measured N+ and N++ ions in the magnetosphere. Both N+ and N++ are observed in the plasmasphere with N+ ions also seen flowing out of the northern polar cap at altitudes up to 3 R_E. The N+ fluxes are 5 to 10% of the O+ fluxes with the N++ fluxes at 1 to 5% of the N+ fluxes.

Introduction

In the past decade research on the Earth's magnetosphere has seen a progression of emphasis on the study of the Earth as a fundamental source of the magnetospheric plasmas. Beginning with the initial discovery of energetic He+ and O+ [Shelley et al., 1972] in the early 1970's, the Earth's ionosphere has been found to be a rich varietal source of ions for the magnetosphere above. The application of mass spectrometry techniques to high-altitude magnetospheric satellites has disclosed the broad presence of energetic 0+ ions throughout the magnetosphere and has resulted in the discovery of such minor ion species as 0++, He, and D+ in the plasmasphere and beyond [Young et al., 1977; Johnson, 1979].

However, until the flight of Dynamics Explorer 1 (DE-1) the mass spectrometers used in the magnetosphere were not able to resolve masses near the 0+ (mass 16) peak in the mass spectrum. Previous designs had been optimized for the study of ions over a broad energy range rather than a concentration on high mass resolution. The Retarding Ion Mass Spectrometer (RIMS) instrument on DE-1 was designed to have an excellent mass resolution ($\Delta m/m = 3\%$) and gives information on the mass, energy, and angle of ions in the range of 1 to 32 AMU for energies of 0 to 50 eV. In this paper we report the first observation of N+ and N++ ions in the Earth's magnetosphere. Both of these ions measured by the RIMS instrument are present in the plasmasphere with N+ also present in the polar cap up to altitudes as high as 3 RE.

With the benefit of hindsight one could expect to see N+ in the magnetosphere. Early measurements of ionospheric composition from Explorer 31 [Hoffman, 1969], Explorer 32 [Brinton et al., 1971], Ogo 2, 4, and 6 [Taylor et al., 1968] , and ISIS 2 [Hoffman et al., 1974] showed that N+ and 0+ were generally the two dominant ion species at altitudes around 1000 km for the higher latitudes above the plasma-pause (A > 60°). In these ionospheric investigations the N+ density was found to be 5 to 10% of the 0+ density and to track the 0+ profile both in altitude between 500 and 1500 km [Brinton et al., 1971] and in latitude at 1400 km [Hoffman et al., 1974]. Typical N+ densities range from 102 to 104 ions/cm^3 at the F peak and above and are strongly dependent on latitude, season, and magnetic activity. In magnetic storm times Hoffman et al. [1974] found that N+ could become the dominant ion at invariant latitudes above 60°. With this amount of N+ present in the high-latitude F-region it is not surprising that the same processes which apparently act to accelerate 0+ ions out of the ionosphere into the magnetosphere would have a similar effect on the N+ ions.

The production and loss of N+ in the ionosphere is controlled by the photoionization of N and N2 and by the reaction of He+ + N2 with the loss dominated by reactions of N+ with 02 and NO (see Schunk and Raitt [1980] ; and Torr and Torr [1979] for more detail). Extensive models by Schunk and Raitt [1980] and Sojka et al. [1981a,b; 1982] which involve both diffusion of ionization along the magnetic field and the magnetospheric convection of ions at high latitudes show that the expected densities of N^+ can be highly dependent on diurnal, seasonal, universal time, solar cycle, and magnetic activity conditions. Their early models show good agreement with experimental data at altitudes of 800 km with the N^+ density being 5 to 10% of the O^+ densities.

Description of the RIMS Instrument and Data Display

The RIMS instrument consists of three sensor heads each containing a retarding potential analyzer followed by a magnetic ion mass spectrometer which has two channel electron multiplier detectors located behind the magnet to measure masses in the ratio of 1 to 4 simultaneously. The instrument is described in detail by Chappell et al. [1982a]. The radial sensor head views perpendicular to the DE-1 space-craft spin axis and samples the complete range of pitch angles in a 6-s rotation of the spacecraft with an angular resolution of ±10° in the spin plane and ±55° perpendicular to the spin plane. The DE-1 spacecraft is in a cartwheel orientation with the spin axis perpendicular to the orbit plane. The ±Z heads of the RIMS instrument are directed parallel and anti-parallel to the spin axis. In this paper we will present data from the radial head only.

The instrument covers the mass range of 1 to 32 AMU with the low and high mass channels covering 1 to 8 and 4 to 32 AMU, respectively. The instrument mass scan can be programmed to cover any set of masses in this range, in 32 steps. In the data presented here, the instrument was scanning from mass 2 to 32 with the 32 steps spread approximately exponentially across the mass range. This provided several mass steps around each mass peak. A mass scan was completed every 0.5 s, or 12 times per rotation of the spacecraft. During this particular mass scan mode, no energy analysis was carried out by the retarding potential analyzer. However, it is possible to gain some information on the ion energies through analysis of the individual mass peak locations as discussed below.

The discovery of magnetospheric nitrogen (N^+ and N^{++}) was made during a full orbit mass scan conducted on December 30, 1981 (Day 364), a disturbed day with Kp's for the orbital period being 6-, 5, and 4-. The DE-1 orbit on that day is shown in Figure 1. The orbit plane is in the 0400 to 1600 local time sector with apogee at approximately 50° latitude over the northern hemisphere. In such an orbit the satellite moves from apogee in the dawn sector across the polar cap, the dusk auroral zone, and into the plasmasphere. Perigee occurs in the plasma-sphere and southern polar cap region. The satellite then reenters the plasmasphere on the dawn side, traverses the middle of the plasmasphere and exits through the northern dawn side auroral zone and back into the polar cap.

A full orbit of RIMS mass scan data on December 30, 1981, is shown in part A of Color Plate 1. In this mass-time spectrogram format masses in the range of 2 to 8 and 8 to 32 are shown in the top and bottom panels, respectively. The horizontal axis, for time, is divided into 180 increments, and the data are spin averaged over the 2-minute bins for this plot. The data are sorted by mass for the 32

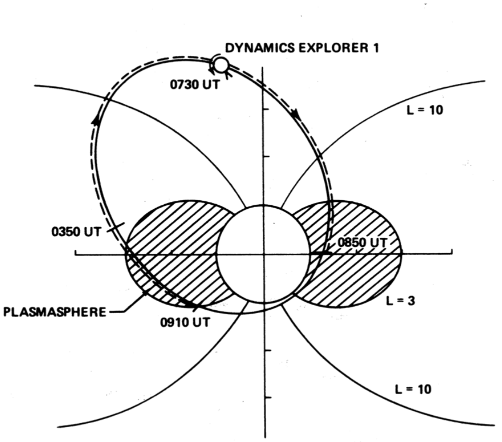


Fig. 1. A schematic diagram of the DE-1 orbit in the 0400 to 1600 local time plane on December 30, 1981, looking from the solar direction. The data cover a nearly complete orbit from 0350 UT prior to apogee to 1120 UT approaching apogee. There is a data gap between 0850 and 0910 UT around perigee. A sketch of the L = 3 plasmapause location is also shown.

vertical bins, and the scale is logarithmic, reflecting the data mode. The average counts per 12 ms accumulation are color-coded according to the scale on the left-hand side of the plot ranging from 1 count in blue to 10,000 in red. The mass per unit charge (AMU/Q) is noted on the vertical axis.

The region of enhanced fluxes between 0825 and 1007 UT is the plasmasphere. Note that there is evidence for m/q = 2, He+, N++, 0++, N+, 0+, and Ne+. The fluxes of He+, N+, and 0+ are particularly significant up to altitudes of almost 2 RE. The section of missing data

between 0850 and 0915 UT is around perigee where the radial head shuts itself off to protect the electron multipliers from excessively high ionospheric fluxes. Nitrogen ions (N+ and N++) have never before been reported in the plasmasphere as seen here. Perhaps the most surprising aspect of this figure is the presence of N+ at high altitudes across the polar cap as shown by the fluxes between 0735 and 0820 UT. As we will see in a later plot, the N+ is observed to altitudes greater than 3 RE above the polar cap. Note that the 0+ also extends to high altitudes across the polar cap with fluxes evident out to the satellite apogee position. These data represent the first observations ever made of magnetospheric N+ and N++.

Figure 2 shows two mass spectra measured simultaneously in both the high mass and low mass channels. The mass spectrum (solid line) was taken in the plasmasphere at 1005, during the outbound part of the orbit. Note that in the top panel the N+ and 0+ peaks are clearly resolved. The N++ and 0++ data form two distinct plateaus at the left hand side of the lower panel. These data were taken from the radial head when it was looking within 15° of the ram direction. These fluxes are therefore roughly proportional to the densities, multiplied by the space-craft velocity. The ratio of the N+/0+ count rates is 0.1, which represents a relative density of the same level. This is consistent with previous low-altitude ionospheric measurements and theoretical predictions [Hoffman et al., 1974; Brinton et al., 1971; Schunk and Raitt, 1980] .

The mass spectrum (dashed line) was measured at 0737 UT in the polar cap. Again the N+ and 0+ peaks are clearly resolved. Note that there is no He+ observed at this high altitude in the polar cap on this day. These data are taken at a pitch angle of 145°, about 20° off the ram direction. This was the direction of peak flux for the polar cap ions (see below for a discussion of the flow direction and energy).

The N+ and 0+ peaks for this polar cap mass spectrum are very close in mass step location to the spectra for the plasmasphere case. In the RIMS instrument the mass peak location is determined by an accelerating volt-age located in front of the mass spectrometer. Hence the peak location can shift directly with the kinetic energy of the incoming ions. The total width of the N+ peak is about 30 V. In this mode, we could expect to see peak shifts on the order of 10 V or greater if they were present. The nearly coincident location of the N+ peaks for the plasmasphere and polar cap spectra indicate that the ions have very similar energies in the two regions of space. The ratio of the N+ and 0+ peak fluxes is also very similar in the two regions, with N+/O+ = 10% in the plasmasphere and 6% in the polar cap.

Nitrogen Ion Characteristics

The characteristics of the N+ and N++ ions can be displayed very effectively through the use of spin angle-time spectrograms. This technique has been discussed in the two companion papers in this issue (Chappell 1982; Chappell et al., 1982b). Part B of Color Plate 1 shows a spin-time spectrogram of N+ in the top panel and N++ in the lower panel. Here, the counts for the nitrogen data are sorted according to angle with respect to the spacecraft ram direction, with zero degrees across the center of the plot. The counts are averaged within an angular bin of about 10° width over a time interval period of 2 min.

The highest fluxes of N+ are seen in the plasmasphere region (0825 to 1007 UT). Here the fluxes are centered around the ram direction indicating a cold-rammed plasma where the ion thermal energy is less than the ram energy. During the outbound portion of the orbit, from perigee to the plasmapause (0915 to 1007 UT), the nitrogen and oxygen ions initially have higher fluxes than the helium, then drop below the helium as the spacecraft moves out of the high-latitude topside ionosphere and into the plasmasphere at lower 'L' values. There is an enhancement in the N+ flux at the outer edge of the plasmasphere (1000 to 1007 UT). This may be a nitrogen torus signature in the outer plasmasphere as has been found for 0+ and 0++ by Chappell et al. [1982b]. This enhanced density could also be caused by unsteady convective flow in the outer plasmasphere during this period of high magnetic activity, possibly a detached plasma region. At 1005, the spacecraft velocity of 4.6 km/s gives the nitrogen a ram energy of 1.6 eV and an approximate density of 2 ions/ cm^3.

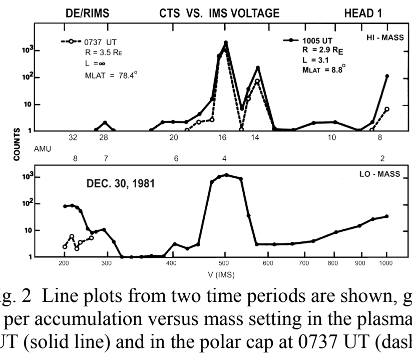
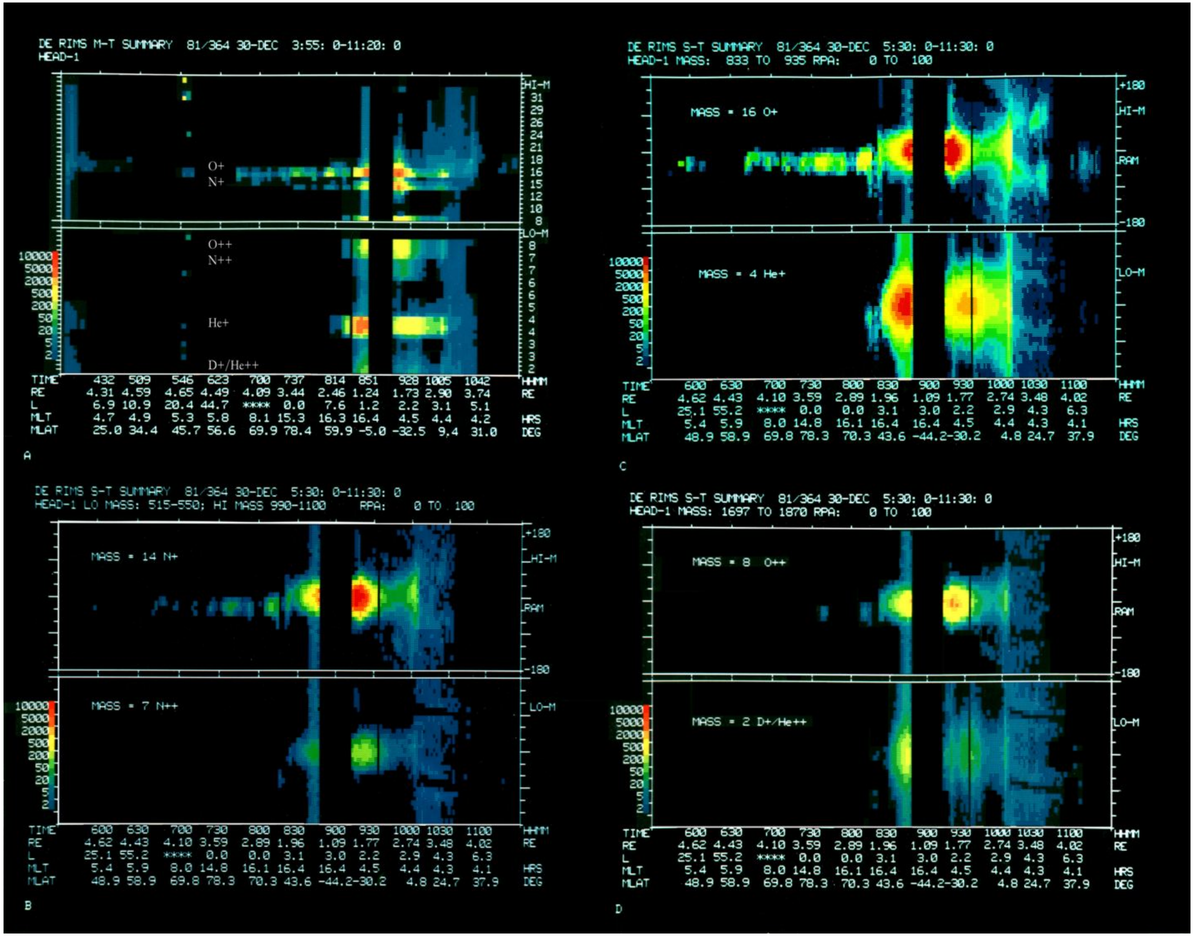


Fig. 2 Line plots from two time periods are shown, giving the counts per accumulation versus mass setting in the plasmasphere at 1005 UT (solid line) and in the polar cap at 0737 UT (dashed line).



Color Plate I. A) A mass-time spectrogram covering the mass range of 2 to 32 AMU over a nearly complete orbit showing the presence of m/q = 2, He^+, N^{++}, O^{++} in the lower panel (LO-Mass channel) and 0^{++}, N^+, and O^+ in the upper panel (HI-Mass channel). B) Spin-time spectrograms for N^+ in the upper panel and N^{++} in the lower panel on December 30, 1981. C) Spin-time spectrograms for O^+ in the upper panel and He^+ in the lower panel. D) Spin-time spectrograms for O^{++} in the upper panel and m/q = 2 in the lower panel.

At higher altitudes in the polar cap (0640 to 0820 UT) the N+ ions are peaked off the ram direction. Examination of the pitch angle shows that this peak in the nitrogen flux is located at a pitch angle of about 145°, an intermediate angle between upward flow out of the ionosphere along the field line (180° pitch angle), and the ram direction at this orbital position (127° pitch angle). These data therefore suggest that the N+ ions are flowing along the field line out of the northern hemisphere below the satellite. If the flow is field aligned, we can use the angle of the resultant vector given by the spin peak location and the spacecraft velocity at this location of 3.8 km/s to calculate the flow velocity of the N+ along the field line. This calculation gives an N+ velocity of 2.1 km/s corresponding to a flow energy of 0.3 eV. This is very close to the ram energy of the plasmaspheric N+ at 1005 UT, which would place the mass peak at the same position in the spectrum, in agreement with the line plot in Figure 2. If the peak N* flux and flow velocity are used to make an approximate calculation of density the result is .8 ions/ cm^3. The polar cap data are therefore consistent with a 0.3 eV beam of N+ ions with density .8 ions/ cm^3 moving along the field line direction to the spacecraft, which apparently has a relatively small (< 1 V) potential at this time. The N++ spin angle-time spectrogram is shown in part B of Plate 1 in the lower panel. The N++ fluxes are quite evident in the plasmasphere region, with fluxes of 1 to 5% of the singly-charge nitrogen value.

To place the nitrogen ion measurements in context we have included spin-time spectrograms of the other major ions observed in the 2 to 32 mass range. In addition to the N+ and N++ ions, part C shows 0+ ions in the top panel and He+ ions in the bottom panel. As with N+ and N++, the He+ and 0+ ions show the plasmasphere between 0825 and 1007 UT to be a cold-rammed plasma. The He+ ions are the best indicator of the plasmapause location at L = 3.3 inbound and L = 3.1 outbound. Just prior to the plasmasphere entry at 0820 both the He+ and 0+ show count rate enhancements in the off-ram direction. These are probably associated with upward flowing field-aligned He+ and 0+ fluxes in the dusk side auroral zone. These flows have energies of several hundred eV, and it is difficult to separate the energized nitrogen and oxygen in the mass spectra. Note that there is a peak in the oxygen flux all the way across the polar cap, beginning at apogee (0545 to 0815 UT). As in the case of nitrogen, this is consistent with a flow of thermal plasma out of the polar region along the magnetic field. This 0+ ion beam has a flow energy of 0.35 eV. The similarity of the plasmasphere and polar cap signatures of the 0+ and N+ is strongly suggestive that similar processes are controlling the transport of these two ions from the ionosphere into the magnetosphere.

Part D of Color Plate 2 shows the 0++ and m/q = 2 ions. As with the other ion species, these ions are present throughout the plasmasphere. There is also an indication at 0737 and 0810 UT that the 0++ is present in the field-aligned flow regime of the polar cap. The spin curve of the m/q = 2 data is consistent with these ions being He++, but this has not been fully determined.

Discussion and Summary

Measurements by the RIMS instrument on DE-1 have shown that nitrogen ions can be a prominent feature of the Earth's magnetosphere. They are present as N+ and N++ in the plasmasphere and N+ in the polar regions. The low-energy N+ ions exhibit characteristics very similar to the low-energy 0+ magnetospheric ions with a flux ratio of about 5 to 10% of the 0+. This ratio is similar to that observed in the topside ionosphere at altitudes ranging from 300 to 1500 km. The N++ ions are observed with fluxes at about 1 to 5% of the N+ fluxes. The observations reported here were made on a relatively disturbed day with the peak Kp at 6-during the period of time covered by the orbit.

Because of the similarities between N+ and 0+ signatures in the magnetosphere and ionosphere, it seems appropriate to speculate that the ionosphere is the direct source of these ions. Within the plasma-sphere the ions may diffuse up the field line and be accumulated in the plasmasphere region through processes similar to 0+. Thermal diffusion may be important for N+ as it appears to be for 0+. At high latitudes outside the plasmasphere one might expect that the parallel electric fields which are known to exist in the auroral zone might accelerate both the N+ and 0+ ions up the field lines when the potential drops are located in the N+ and 0+ dominated topside ionsophere. Once the N+ ions are transported up into the magnetosphere their lifetime due to charge exchange should be on the order of months or longer. There-fore, their loss could be expected to be controlled by magnetospherically-driven transport processes.

It is interesting to note that there is no He+ measured flowing along field lines in the polar cap on this day. The reaction He+ + N2 -> N + N+ + He can lead to a loss of He+ and the creation of N+ in its place thus enhancing the relative percentage of N+ to He+. However, the detailed altitude profiles of N+, 0+, and He+ are highly dependent on specific magnetospheric location and conditions [Sojka et al., 1981a] and the comparison of observations such as these with theoretical explanation must await the modeling of this specific case including parameters such as the terminator location and geomagnetic conditions.

These initial N+ and N++ observations reopen the question of the composition of different magnetospheric regions. It is clear that previous measurements of 0+ ions will have to be reexamined using mass spectrometry techniques capable of resolving masses 14 and 16 and masses 7 and 8. One can anticipate that the understanding of magnetospheric plasma composition in the future will ultimately have to include the complete variety of ions that presently characterize the low-altitude regions of the Earth's ionosphere.

Acknowledgments: The authors are indebted to the engineering and science staff of the University of Texas at Dallas and to the RIMS team at MSFC. We are grateful to the Intergraph and Boeing Corporations for assistance with data reduction software and to the MSFC/ NEEDS network for support of the graphics analysis.

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(Received May 21, 1982;
accepted May 27, 1982.)