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Observations of Molecular Ions in the Earth's Magnetosphere

P. D. CRAVEN,[1] R. C. OLSEN[2] C. R. CHAPPELL,[1] AND L KAKANI[1]

. The retarding ion mass spectrometer on Dynamics Explorer 1 operating over the polar cap during a large magnetic storm has measured fluxes of up to 10^0 ions cm-^{2} s-^{1} of the molecular ions $N2^+$, NO. and 02^+. These ions were measured beginning low in the satellite orbit (1.1 RE) and extending to about 3 RE geocentric altitude. Near perigee, the ions have a rammed distribution indicating a cold Maxwellian plasma (1000°-2000°K). The molecular ions gradually shift to a field-aligned distribution at the higher altitudes. An upward flow of 5-10 km/s is found in these field-aligned measurements. The density of the molecular ions is on the order of 2 cm-^{3} at all altitudes, and the energy of the ions generally increases as the satellite moves sunward across *the* southern polar cap. Kinetic energies of at least 20 eV were found at 2.5 *RE* geocentric distance.

INTRODUCTION

Molecular ions are normally considered to be a feature of the ionospheric E and *F* regions. In these regions, they peak in density at about 150 km. Their density falls rapidly with altitude above about 200 km, reaching a density of 1 ion/cm^3 around 500 km *[Hanson and Carlson, 1977; Banks and Kokarts,* 1973]. Because of their low densities at higher altitudes, they have seldom been detected by the mass spectrometers that have been flown on satellites with perigees above 1000 km. During magnetically disturbed times these ions have been observed above the *F* region of the ionosphere up to 1400 km altitude at high geomagnetic latitudes *[Taylor, Hoffman et al.,* 1974]. The positive identification and measurement of molecular ions at higher altitudes have not been reported before. We report in this paper the first positive measurement of these ions at geocentric distances up to 3 R_E over the polar cap.

The context of our observations is set by the work of Taylor and Hoffman. *Taylor [1974]* reported that the occurrence of the molecular ions of nitrogen, nitric oxide, and oxygen at high latitudes can be highly localized in time and/or space. He suggested that because of this localization, their appearance at the high latitudes may be related to activities in the polar cusp. While neither *Taylor [1974]* nor *Hoffman et al.* [1974] emphasized the relative abundance of the three minor ions, the latter authors did note the unusual dominance of N_2^+ over the other molecular ions in the higher latitudes. This is unusual in the sense that in the normal *E* and *F* region, N_2^+ is quickly lost through interactions with 0 and 0_2, forming O_2^+ and NO^+. *Schunk and Raitt* [1980], however, in modeling the high-latitude F, region for conditions of summer and winter solstice, high geomagnetic activity, and solar maximum, show that above about *400* km the molecular ion concentration is such that N_2^+ is usually the most abundant of the three molecular ions and 0_2^+ is the least abundant. The relative abundances obtained from the model can vary significantly with season and position, however, at least below 800 km *[Sojka et al.,* 1982].

The retarding ion mass spectrometer (RIMS) and its operation in the mass scan mode have been described else-where *[Chappell et al.,* 1982] and will not be repeated in detail here. We should note that the range of masses which is measured in a particular operation is programmable. Independent of the mass range chosen, it is covered in *32* steps that are not necessarily equally spaced in the ion mass spectrometer (IMS) voltage. For the measurement of the molecular ions the instrument was programmed to scan (with zero retarding potential) from M/q = 20 to M/q = 46 in the high mass channel (The low mass channel measures ions with 1/4 the mass of the ions measured in the high mass channel) Near the masses 28 to 32, the mass voltage steps were set closer together than at other masses in order co improve the resolution for determining the molecular species and their kinetic energy.

In the following sections, we will first show the orbit of Dynamics Explorer 1 and briefly describe the geomagnetic conditions under which the molecular ions were observed. We will then describe the data display which shows the observations of molecular ions near perigee and over the polar cap. Lastly, we will examine the energy and relative abundances of the molecular ions detected over the polar cap.

OBSERVATIONS

The orbit of DE 1 on the pass under study is shown in Figure 1. The satellite orbit plane for this pass was close to the noon-midnight meridian. On the inbound part of the orbit, the satellite passed over the north polar region, reaching a maximum invariant latitude of 83° at about 1920 MLT and then continued on to its perigee of about 1.08 R_E (geocentric) at 2300 MLT, 30° north magnetic latitude. On the outbound part of the orbit, the satellite passed over the south polar cap, reaching an invariant latitude of about 84° at a geocentric altitude of 2.3 R_E around 0500 MLT. It then continued equatorward on the dayside of the orbit but remained at high geomagnetic latitudes through the end of the pass at about 1000 MLT.

September *6,* 1982 (day 249*)* was a very active day with the sum of *Kp* reaching 69. *A* magnetic storm took place on days 248, *249,* and *250* as shown by the *Dst* index in Figure *2.* The *Dst* index reached its most negative value of *303* gammas on day *249* during this storm. The observations-

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[1] Space Science Laboratory, NASA Marshall Space Flight Center, Huntsville, Alabama.

[2] Physics Department, University of Alabama in Huntsville.

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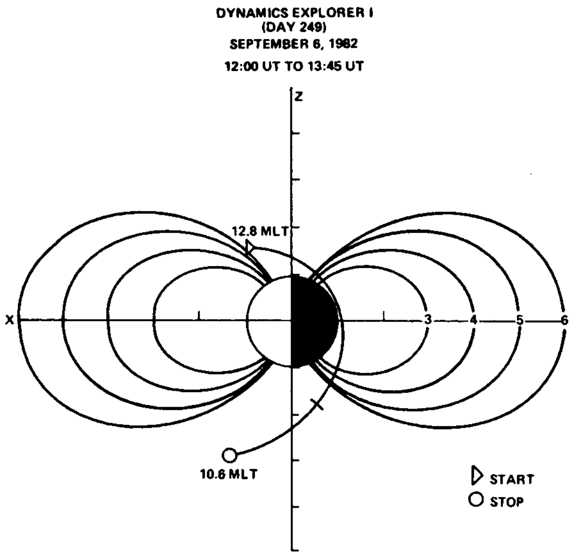

Fig. 1. The orbit of DE 1 in solar magnetic coordinates for 1200 to 1345 UT.

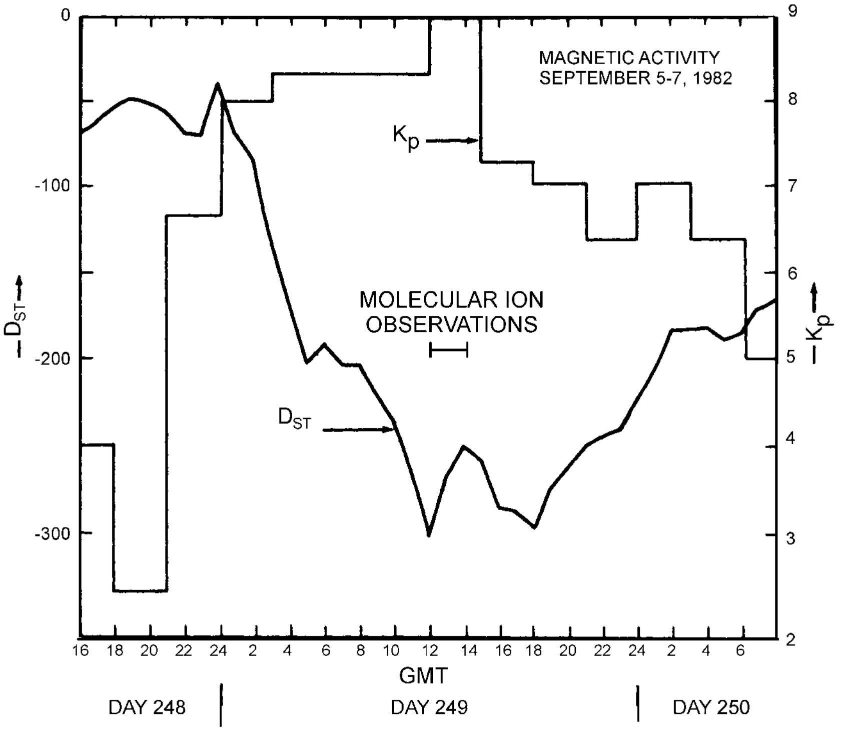

Fig. 2. The Dst and Kp indices plotted as a function of UT for day 249. The last 8 hours of day 248 and the first 8 hours of day 250 are shown for reference. The Kp indices are plotted on the right hand scale, the Dst on the left.

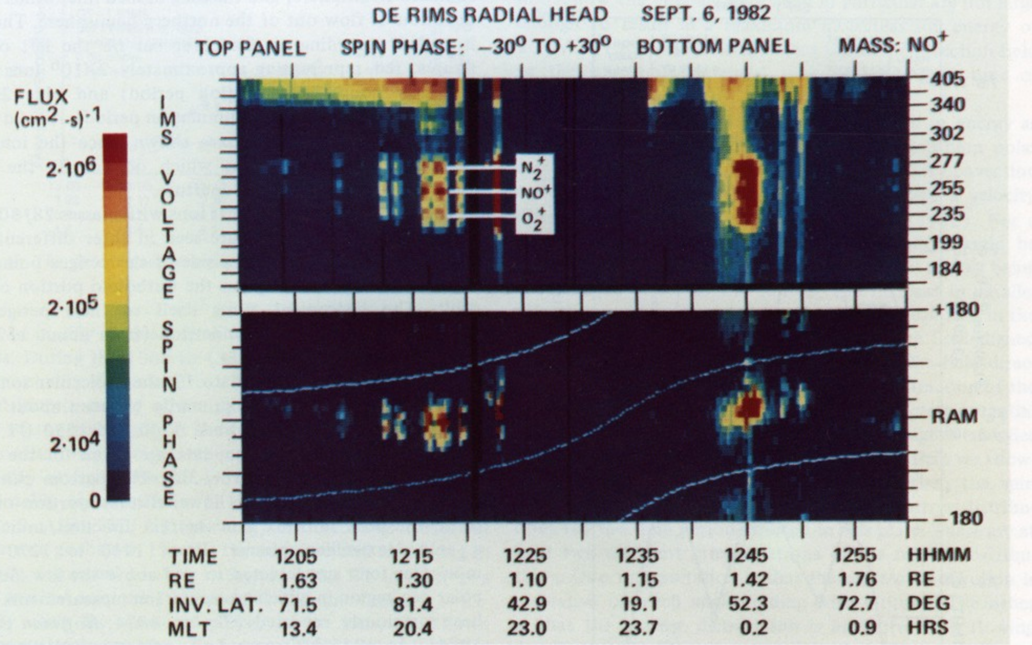

Plate 1. (Top) Mass-time spectrogram for a rammed plasma. (Bottom) Spin-time spectrogram for NO$^+$. The flux contour scale is shown by the color bar on the left.

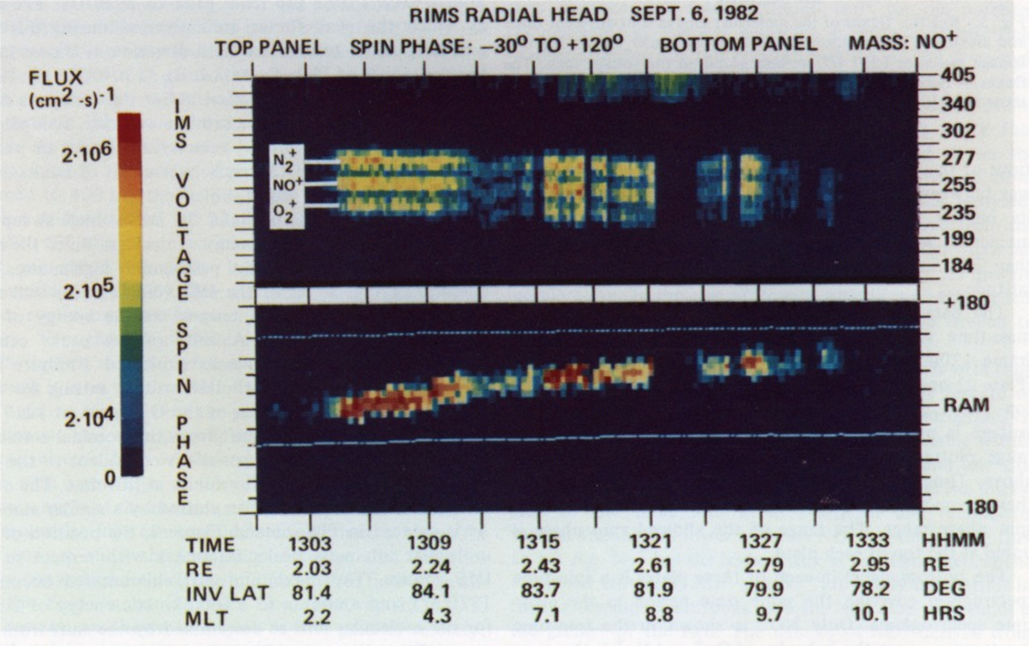

Plate 2. (Top) Mass-time spectrogram for a field-aligned plasma. (Bottom) Corresponding spin-time spectrogram for NO$^+$.

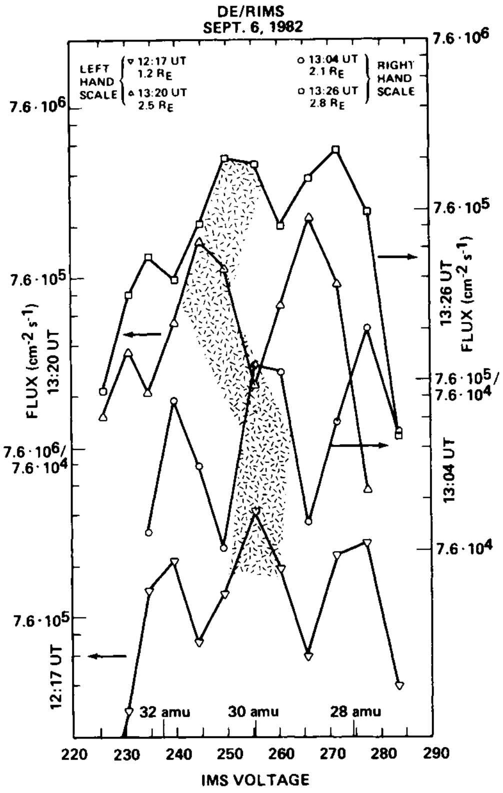

Fig. 3. Relative fluxes of the molecular ions at four different times and altitudes. The position of the three molecular ions in the IMS voltage sweep at 1217 UT are also noted on the voltage scale. The fluxes at 1217 UT, or 1.2 R_E, are shown in the bottom curve; those at 1326 UT, or 2.8 R_E, are shown in the top curve.

of the molecular ions took place while the *Dst* index was between about -250 and -300 gammas and *Kp* was at its highest value (9). Most of the observations of the molecular ions were made at invariant latitudes greater than 70°. Some observations were made near 50° invariant latitude.

The data are displayed in Plates 1 and 2, which are mass-time and spin-time spectrograms covering the time frame 1200 to 1300 UT (Plate 1) and 1300 to 1336 UT (Plate 2) on September 6, 1984. In both Plates 1 and 2, the top panel is the mass-time spectrogram, in which IMS voltage is plotted on the vertical axis. The IMS voltage range plotted covers the.masses from 20 to 46 as noted above. Time is plotted along the horizontal axis. Data for these mass-time spectrograms were taken over a limited spin phase range. The range of the allowed spin phase is noted at the top of each plate.

The bottom panel in each of these plates is a spin-time spectrogram covering the same time period as the mass-time spectrograms. Only NO^+ is shown in the spin-time spectrogram since the behavior of 0_2^+ and N_2^+ is the same as the NO^+. The minimum and maximum pitch angles in these spin-time spectrograms are shown by the short dashed white line, which represents the direction of flow out of the southern hemisphere, and the long dashed line, which is the direction of flow out of the northern hemisphere. The flux is coded according to the color bar on the left of the figures; red representing approximately $2X10^6$ ions cm^{-2} s^{-1} (200 counts/accumulation period) and blue $2X10^4$ ions cm-^{2} s ^{1} (2 counts/accumulation period). A solid angle is not included in the fluxes shown since the ions are measured in narrow beams which do not fill the wide dimension of the 20° X110° aperture.

Plates 1 and 2 indicate that ions with masses 28, 30, and 32 (N_2^+, NO^+, and 0_2^+) are seen in three different segments of the orbit, on either side of the perigee point and over the south polar cap on the outbound portion of the orbit. The instrument turns itself off near perigee to prevent damage to the channeltron (from about 1222 to 1236 UT in Plate 1).

In the perigee region (Plate 1), the molecular ions are detected in brief segments primarily between about 1210 UT and 1222 UT and between 1240 and 1250 UT. The spin angles from which the data are taken for the mass spectrogram are limited to +/-30°. The bottom panel of Plate 1 shows that for this lower-altitude portion of the orbit, the peak ion flux is in the ram direction, indicating a cold Maxwellian plasma. From 1210 to 1220 UT, molecular ions are detected in and above the low-altitude polar cap region in which molecular ion measurements have been previously reported *[Taylor,* 1974; *Hoffman et al.,* 1974]. At 1245 UT, near L=3, cold rammed plasma is found mixed with a trapped distribution.

At higher altitudes over the southern polar cap (1300-1336 UT, Plate 2), molecular ions are found almost continuously except for a gap from 1321 to 1324 UT. The angle at which the peak fluxes are measured during this time gradually shifts toward the field direction as shown in the bottom panel of Plate 2. At 2.1 R_E (1304 UT) the fluxes are peaked in the ram direction. After this time, as a result of the combination of the satellite velocity, field-aligned flow velocity and *EXB* drift velocity, the fluxes are peaked at a spin phase angle that is between that of the rammed and field-aligned spin angles.

The position of the peaks in the IMS voltage sweep can be used to determine the energy of the ions. Since the mass analyzer has a limited energy passband at high masses, the position of the curves in the IMS voltage sweep will shift to lower voltages (higher masses) as the energy of the incoming ions increases. A shift of the peaks can be seen in Figure 3, where we have plotted 1-minute time averages of the flux at each IMS voltage setting for four different times. The position of the 0_2^+ peak at 1217 UT represents about a 12-eV shift from the nominal zero drift energy position. This voltage shift is equivalent to the ram energy due to the spacecraft velocity at this time. The other two molecular ions have been shifted by a similar amount. As is evident in Plate 2 and Figure 3, the position of the molecular ion mass peaks fluctuates with respect to the IMS voltage. The maximum shift encountered occurs at 1320 UT and amounts to a total kinetic energy of 20 eV for the molecular ions as determined by the shift from the zero drift position. At 1326 UT, the total kinetic energy of the ions is about 15 eV, 3 eV higher than in the 1200 to 1300 UT time frame. In the 1200 to 1300 UT time frame, the energy of the ions remains nearly constant (see Plate 1)

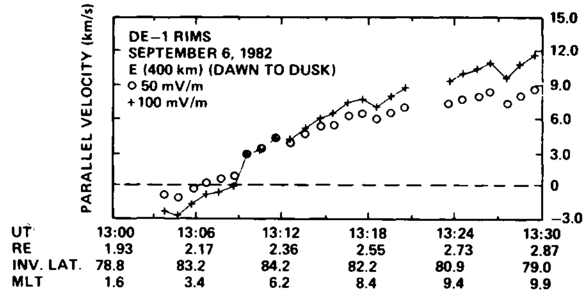

Fig. 4. The field-aligned velocity of NO^+ as a function of time.

and is mainly derived from the satellite velocity of 8-9 km/s. During the 1300 to 1330 UT time frame, the spacecraft velocity decreases from 6.6 km/s to 4.7 km/s, yet the total kinetic energy of the molecular ions is greater at the end of the time than at the beginning. It is clear that the molecular ions have greater convection or parallel (or both) velocity as the spacecraft moves in time. The energy most noticeably increases from 1315 UT to 1321 UT as seen in Plate 2. After 1321 UT the energy of the ions decreases but does not go below 15 eV. The ions are still increasing in energy compared to their energy at 1300 UT but not at a rate as great as in the 1315 to 1321 UT time frame.

By using the measured energy of the ions, the known spacecraft velocity, the spin angle of the peak ion flux, and the angle between the B field and the spacecraft velocity, one can calculate both the field-aligned flow velocity and that due to a convection electric field. If we assume zero potential on the spacecraft, then the parallel and perpendicular (perpendicular to B in the plane defined by B and the spacecraft velocity vector) velocities found for the ions at $2.8\ R_E$ (1327 UT) geocentric altitude are about 9 and 4 km/s, respectively. A positive spacecraft potential of 10 V will increase these values to about 10 and 6 km/s, respectively. A 4-km/s convection velocity corresponds to an approximately 10-mV/m electric field at the satellite. Mapped to 400 km the field is about 40 mV/m. Data from the ion drift meter on DE 2 indicate that from about 1300 to 1320 UT, the antisunward component of the convection drift velocity is nominally 1-2 km/s (R. Heelis, private communication, 1985). For a B field of 0.5 gauss, these values correspond to a convection electric field of 50-100 mV/m. Thus the electric field magnitude derived from the RIMS data is reasonably close to that found from DE 2 although it is on the low end of the range.

To get an idea of how the parallel flow velocity changes throughout this time period, we can assume that the convection electric field is nonvarying with time or latitude. Then with knowledge of the magnetic field direction and the spin angle of the maximum flux, the parallel velocity of the molecular ions can be calculated. We used a 50-mV/m field and, to show the sensitivity of the parallel velocities to the convection field strength, a 100-mV/m field to calculate the field-aligned velocities from 1300 to 1330 UT. The results are shown in Figure 4. The parallel velocity, and therefore the energy, of the ions increases in time for both assumed values of the convection electric field. This is consistent with the general trend indicated in Plate 2 and Figure 3. However, the calculated flow velocities do not follow the detailed shifts and in particular are not large enough to result in a maximum molecular ion energy of 20 eV at 1320 UT. This indicates that the convection field or the spacecraft potential may be varying in time or latitude or both.

These molecular ions are seen to increase in energy as the spacecraft travels sunward across the southern polar cap. Such a trend could be explained by EXB convection acting on ions with different parallel energies, a velocity filter effect, as suggested, by *Burch et al.* [1982]. For a given species, ions with lower parallel energy would be encountered first, with ions of higher parallel energy being encountered closer to the source. The increase in parallel velocity would also explain the shift of the peak flux in the spin phase diagrams from the ram toward the field-aligned direction. The peak flux will move toward the field direction, as the parallel velocity becomes a larger fraction of the spacecraft velocity. If, as is likely, the spacecraft potential is increasing with altitude, the trend to higher energies toward the dayside polar cap is even greater than we show.

The variation in flux with spin phase (i.e., the spin curve) shown in Plate 2 reveals extremely narrow distributions for the time period covered in this plate. There are at least two different interpretations of the narrow distributions. One interpretation is that the narrow distribution is indicative of pitch angle folding with altitude. The other is that the narrow distribution is indicative of a flowing distribution. The amount of pitch angle folding experienced by the particles depends on the altitude at which the particles originate and the pitch angle of the particles at that altitude. Particles with a 90° pitch angle at 1.1 R_E geocentric distance will fold to about 160° (in the northern hemisphere) at 2.8 R_E, assuming a dipole magnetic field and accounting for the gravitational force. This is enough to account for the narrow angular distribution observed at 2.8 R_E. However, at 2.0 RE the observed width of the angular distribution is slightly less than the width that would be expected from pitch angle folding. If on the other hand, the narrow distribution is indicative of flowing Maxwellian plasma, then the spin curves represent highly supersonic flow. The temperature inferred from the Mach curve is less than 2000°K, suggesting that there has been little heating of the molecular ions during the upward acceleration. In the case of flowing plasma, a positive spacecraft potential of approximately 10 V is also needed to match the observations.

The relative abundance of the three ions varies with time and altitude as shown in Figure 3. A notable feature of these observations that can be seen in the spectrograms of Plates 1 and 2 is that the fluxes are highly variable within time intervals of a few minutes at both high and low altitude. For the times shown in Figure 3, 0_2^+ has the lowest flux of the three ions at each altitude and records its highest flux at the lower altitude. NO^+ has the highest flux at $1.2\ R_E$. N_2^+ has the highest flux at the higher geocentric distances. However, NO^+ and N_2^+ are nearly compatible in flux at the higher altitudes, and the NO^+ flux sometimes is the greater of the two. The density of NO^+ derived from the maximum flux and the flow velocity is on the order of 2 ions/cm^3 throughout the period covered in Figure 3. The N_2^+ density would be similar to the NO^+, with the density of 0_2^+ just slightly lower. The relative concentrations reported by *Hoffman et al.* [1974] were in descending order, N_2^+, NO^+, 0_2^+, except at the higher latitudes where the 0_2^+ concentrations were equal to those of N_2^+ and NO^+. Our observations are different with regard to the 0_2^+ in that the RIMS observations indicate that the dominance of N_2^+ and NO^+ over 0_2^+ continues to higher altitudes and higher latitudes. The difference may be seasonal [*Sojka et al.,* 1982] or may be due to the highly variable nature of conditions in the geomagnetic storms. The observations of both *Hoffman et al.* [1974] and those reported here represent different single events. Each observation is only a limited glimpse of a complex process. More observations of such events are needed before a complete picture of the relative abundances can be formed.

SUMMARY AND CONCLUSIONS

We have shown that the molecular ions N_2^+, NO^+, and 0_2^+ are measured with the RIMS on DE at geocentric distances up to about 3.0 R_E over the polar cap region during a large magnetic storm. The density of the molecular ions, assuming zero spacecraft potential, is about 2 ions/ cm^3 over the measured range. The molecular ions were also measured at altitudes as low as 700 km and down to about 50° invariant latitude. The field-aligned flow velocities of the molecular ions increase as the spacecraft travels sunward across the southern polar cap. Such behavior is consistent with ions of a given species having a range of parallel velocities drifting across the polar cap under the influence of crossed electric and magnetic fields. The observed total energy is probably a lower limit because of spacecraft potential effects which can reasonably be expected to add up to 10 eV to the energy that was observed.

The molecular ions seen in the polar cap could have been generated in the cusp region and transported to the position where they were seen. This transport would depend on the convection electric field across the polar cap and would be similar to the effects observed in the 0^+ ions discussed by *Lockwood et al.* [1985] and *Waite et al.* [1985]. Because the ions observed here have nearly the same molecular weight, they do not show any of the effects of a geomagnetic mass spectrometer [*Lockwood et al.,* 1985].

If we use the characteristics of the ions at 2.8 R_E (geocentric), and a 50-mV/m convection electric field, and then trace the ion trajectories to a source altitude of 700 km using the program developed by *Horwitz* [1984], we find the location of the source region in the noon-midnight meridian plane to be about 70° geomagnetic latitude on the dayside. Because of the geomagnetic storm taking place at the time of the observations, the cusp could be expected to have moved toward the equator [*Meng,* 1982]. In fact, from DE 2 data the cusp is located at 63°-68° at 1313 UT (N. Maynard, private communication, 1985). The closeness of the source position to that of the cusp position indicates that the molecular ions may well originate in or on the edges of the cusp as suggested by *Taylor* [1974]. In order to more accurately trace the ion trajectories, the variation of the convection electric field with time and latitude needs to be included in the models and flow in planes other than the noon-midnight plane should be considered.

Based on the fact that molecular ions are usually found at altitudes of the *F* region and below, it is probable that the ions seen here at high altitudes have been subjected to an energization process that started in the *F* region. To what altitude the energization process continues cannot be determined from these data. However, if as suggested by *Spjeldvik and Fritz* [1981], ionospheric molecular ions with tens of MeV of energy have been observed in the radiation belt, then the energization process apparently continues after the ions leave the polar cap region.

The dynamics of the ions seen at perigee at mid-latitudes may be different from that of the ions seen over the polar cap. The ions seen at 1245 UT are on the nightside and the angular distribution is quite different from those seen at the same altitude over the northern polar cap. The appearance of the trapped molecular ions at 1245 UT suggests that the ions at 1245 UT may be experiencing transverse heating. Because the activity on this day is so high, the auroral zone has probably expanded to low invariant latitudes. In this case, the ions observed at 53° may be in the auroral zone. The ions could have been transported to this position from the dayside cusp region or may actually originate there due to nightside auroral activity.

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C. R. Chappell, P. D. Craven, and L. Kakani, NASA Marshall Space Flight Center, Huntsville, AL 35812.

R. C. Olsen, Physics Department, University of Alabama in Huntsville, Huntsville, AL 35899.

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