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# TRANSVERSE AURORAL ION ENERGIZATION OBSERVED ON DE-1 WITH SIMULTANEOUS PLASMA WAVE AND ION COMPOSITION MEASUREMENTS

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Abstract. The abundance of oxygen ions observed flowing into the magnetosphere cannot be explained by a single-step, parallel acceleration mechanism. Some transverse energization of ionospheric ions is required and has been observed from ionospheric altitudes to the plasma lobes in the earth's magnetotail. Progress in understanding the nature of the various transverse energization mechanisms has been slow because of the relative lack of examples with sufficiently resolved (in time, energy, and frequency) particle and wave data.

Starting in early 1984, the Dynamics Explorer-1 satellite systematically acquired a coordinated set of high time resolution plasma and plasma wave observations from the earth's auroral zone. We have selected several intervals from the 0 to 10 kHz wideband data from the Dynamics Explorer-1 satellite with intense low frequency emissions and evidence of harmonic structure and have examined in detail the high resolution ion data obtained simultaneously. In this report we present detailed data from events in the cusp and evening auroral zone and comment briefly on how these data can be used to more fully understand auroral acceleration processes.

## Introduction

Energetic (> 100 eV) ionospheric ions are observed in abundance in the earth's magnetosphere. Johnson [1983] has compiled a set of papers reviewing the work of the last decade in magnetospheric ion composition, which has shown that the ionosphere and solar wind make approximately equal contributions to the ambient magnetospheric plasma. Shelley [1985], in a survey of the available data on the circulation of energetic ionospheric plasma in the magnetosphere, concluded that during magnetically active times the primary source of ionospheric ions in the magnetosphere is the auroral zone. Shelley also noted that the relatively minor terrestrial component of the plasma sheet during magnetically quiet periods could be supplied from either the auroral zones or polar caps. Hultqvist [1983] concluded from the dynamic changes observed in the energetic ionospheric plasma component in the magnetosphere that the only possible sources were at ionospheric altitudes (i.e., less than 1000 km). Hultqvist noted that a transverse energization or acceleration mechanism is probably required to extract ions from these low altitudes. Transverse acceleration of plasma is not limited, however, to ionospheric altitudes; it has been observed in all regions of the magnetosphere (e.g., Johnson, 1983).

The systematic theoretical investigation of the coupling of the magnetospheric and ionospheric plasmas was started with the the work of Kindel and Kennel [1971], who explored a class of plasma instabilities in the ionosphere which were driven by field-aligned currents. Kindel and Kennel pointed out that these instabilities lead to transverse energization of ions. Progress in plasma wave theory in ionospheric-magnetospheric coupling has been relatively slow due to the limited capabilities of instruments in providing the detailed, high resolution, in situ diagnostics required to test the theories. Our current understanding of the many different kinds of magnetospheric acceleration processes is reviewed in this volume by Cornwall [1986]. One of the goals of the the Dynamics Explorer program is to provide detailed, high resolution diagnostics of the plasma environment in the auroral acceleration region. The purpose of this paper is to describe a data set assembled from Dynamics Explorer-1 and illustrate its relevance to studies of the auroral acceleration processes.

## Data

Many of the instruments on the DE-1 satellite have the capability to cover relatively wide ranges with high spectral resolution. These instruments are programmed to optimize the combination of spectral range, spectral resolution and time resolution for specific scientific studies. A program to acquire a systematic and extensive collection of low frequency (0 to 10 kHz) wideband data from the DE-1 Plasma Wave Instrument [Shawhan et al., 1981] and high time resolution ion composition data from the Energetic Ion Composition Spectrometer [Shelley et al., 1981] in the auroral zones was started in January 1984. The analysis of this coordinated data set was be

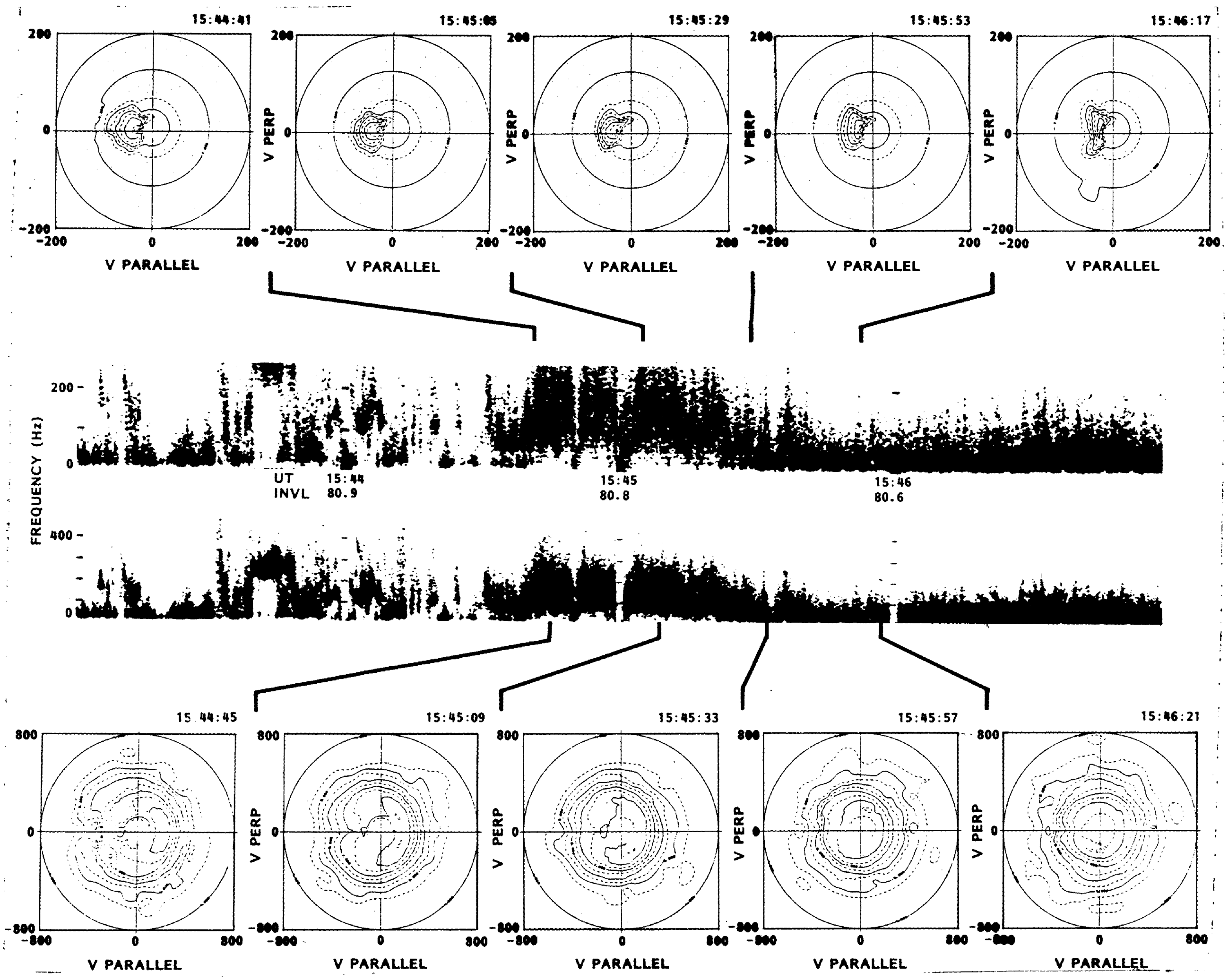

Fig. 1 High time resolution plasma wave (center panels) and ion composition data from an interval on March 15, 1984. See text for a description of the format.

gun using analog wideband data because digital ion and plasma wave data were available for only a small number of events. Kinter et al., [1979] have shown, however, that plasma wave emissions near multiples of the hydrogen cyclotron frequency are, at times, associated with transverse ion energization. We have scanned the first ~300 days of the Plasma Wave Instrument (PWI) wideband data set for intense low frequency emission events with evidence of harmonic structure lasting tens of seconds and then obtained high time resolution Energetic Ion Composition Spectrometer (EICS) data and digital swept frequency receiver (SFR) data from the PWI instrument.

Approximately 200 data acquisition intervals constituting over 300 hours of wideband data were scanned. Thirty–one events lasting on the order of tens of seconds or more were identified from the wideband data. No harmonic structures spaced at the oxygen gyrofrequency were found in this initial visual survey. More sensitive, and therefore more time consuming, methods will be used to search intervals identified in this inital survey for oxygen cyclotron waves. The 300 days scanned included complete local time coverage, but the 31 intense events were observed primarily in the evening auroral zone (17) and in the cusp region (7). The remaining events were in the midnight sector (5) or polar cap (2). One event was observed below 2000 km and two events were observed above 19,000 km.

Energetic ion composition and SFR (swept frequency receiver, Shawhan et al., 1981) data for 10 of these events were available at the time this report was prepared. The SFR data for these events shows considerable power at low frequencies (less than 1 kHz) from the electric dipole antenna and very little power from the magnetic loop antenna, indicating that the low frequency plasma waves observed are electrostatic.

We have selected two representative events, one from the cusp and one from the evening auroral zone, to present here.

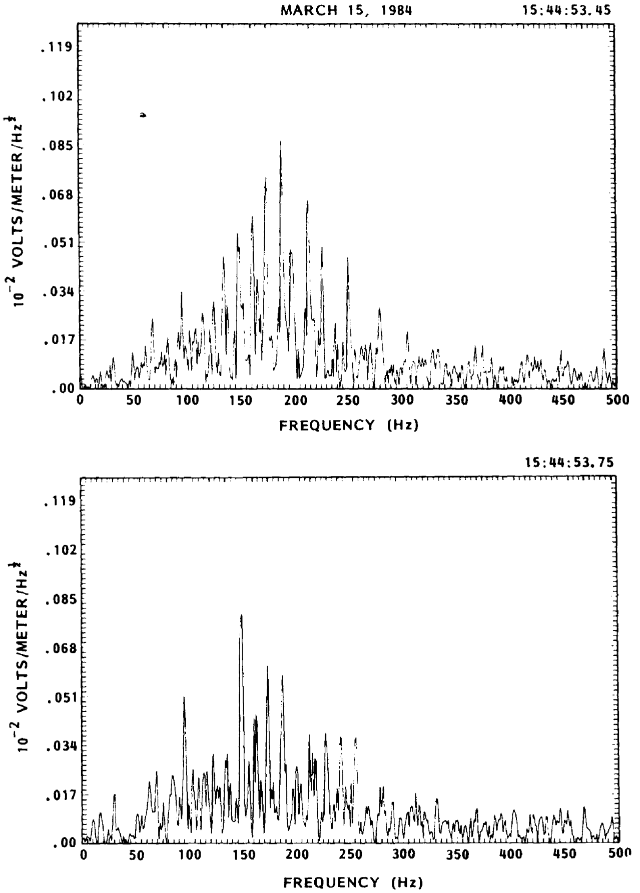

Fig. 2. Electric field strength *vs.* frequency from the wideband receiver for two intervals on March 15, 1984. Note that the absolute values indicated are accurate only within a factor of 4.

## A Magnetospheric Cusp Crossing.

The cusp crossing selected is from March 15, 1984. when the DE–1 satellite was at an altitude of 19,500 km and 10:55 magnetic local time. An overview of the time dependence of the low frequency emissions for this interval is shown in the center panels of Figure 1 which displays the wave intensity for two frequency ranges 0 to 500 and 0 to 250 Hz encoded in gray scale as a function of frequency and time for the period 15:44 to 15:46. Black indicates the highest intensity. Universal time (UT) and invariant latitude (INVL) are indicated at one–minute intervals between the two center panels. Intense, banded, low frequency emissions are seen from ~15:44:30 to ~15:45:30 and intermittently before 15:44:30 in the 0 to 250 Hz (top) spectrogram. Figure 2 shows the electric field strength as a function of frequency (from 0 to 500 Hz) from the wideband receiver for two times during this interval. The intense, banded, low frequency emissions near multiples of the hydrogen gyrofrequency (~13 Hz) are clearly visible in this high resolution data. The lower hybrid frequency was estimated to be in the range 240 to 300 Hz between 15:44 and 15:46. This estimate was based on plasma density measurements derived from the upper cutoff of the whistler mode radiation (Ann Persoon, private communication) and relative $H^+$ and $O^+$ densities determined from the energetic ion composition spectrometer. The calculation of the lower hybrid frequency was based on cold plasma theory [Stix, 1962] and assumed propagation perpendicular to the magnetic field.

High time resolution, mass analyzed ion data are presented above and below the central spectrograms in Figure 1 in the form of contours of constant phase space density. The end of the time interval over which the data for each contour plot were acquired is indicated by the heavy solid lines. Oxygen data (above) and hydrogen data (below) were obtained in alternate satellite spin periods (6 seconds). Twenty-four seconds or four complete spin periods were required to cover the full energy–angle range for both hydrogen and oxygen ions.

The contour lines are spaced at half decade intervals and are plotted in a coordinate system aligned with the local magnetic field. Velocities parallel (horizontal axis) and perpendicular (vertical axis) to the magnetic field for ± 200 km/sec for oxygen and ± 800 km/sec for hydrogen are displayed. The oxygen ions shown in the top panel

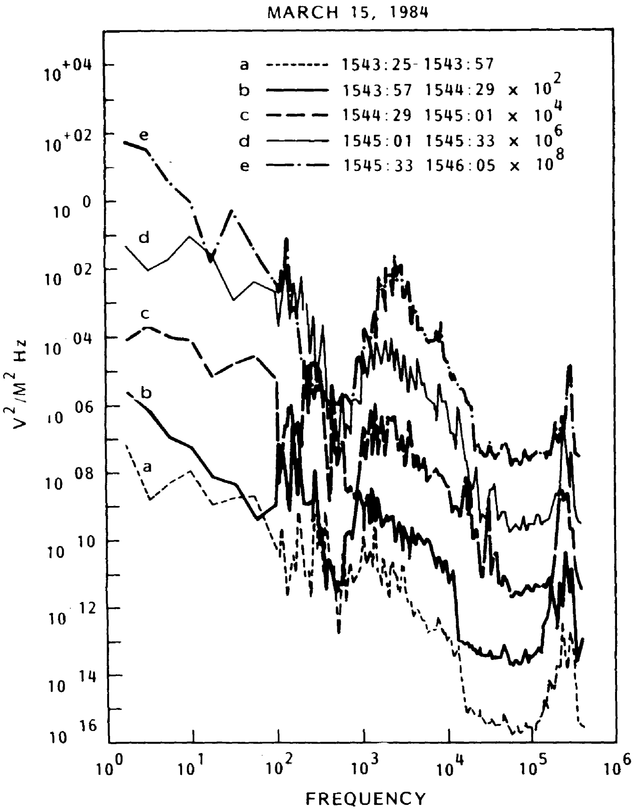

Fig. 3. Stacked plot of power spectral density as a function of frequency observed in the electric antenna (in units of $v^2/m^2$–Hz) from the SFR for a cusp crossing on March 15, 1984. The frequency resolution is 30% below and 1% above 100 Hz.

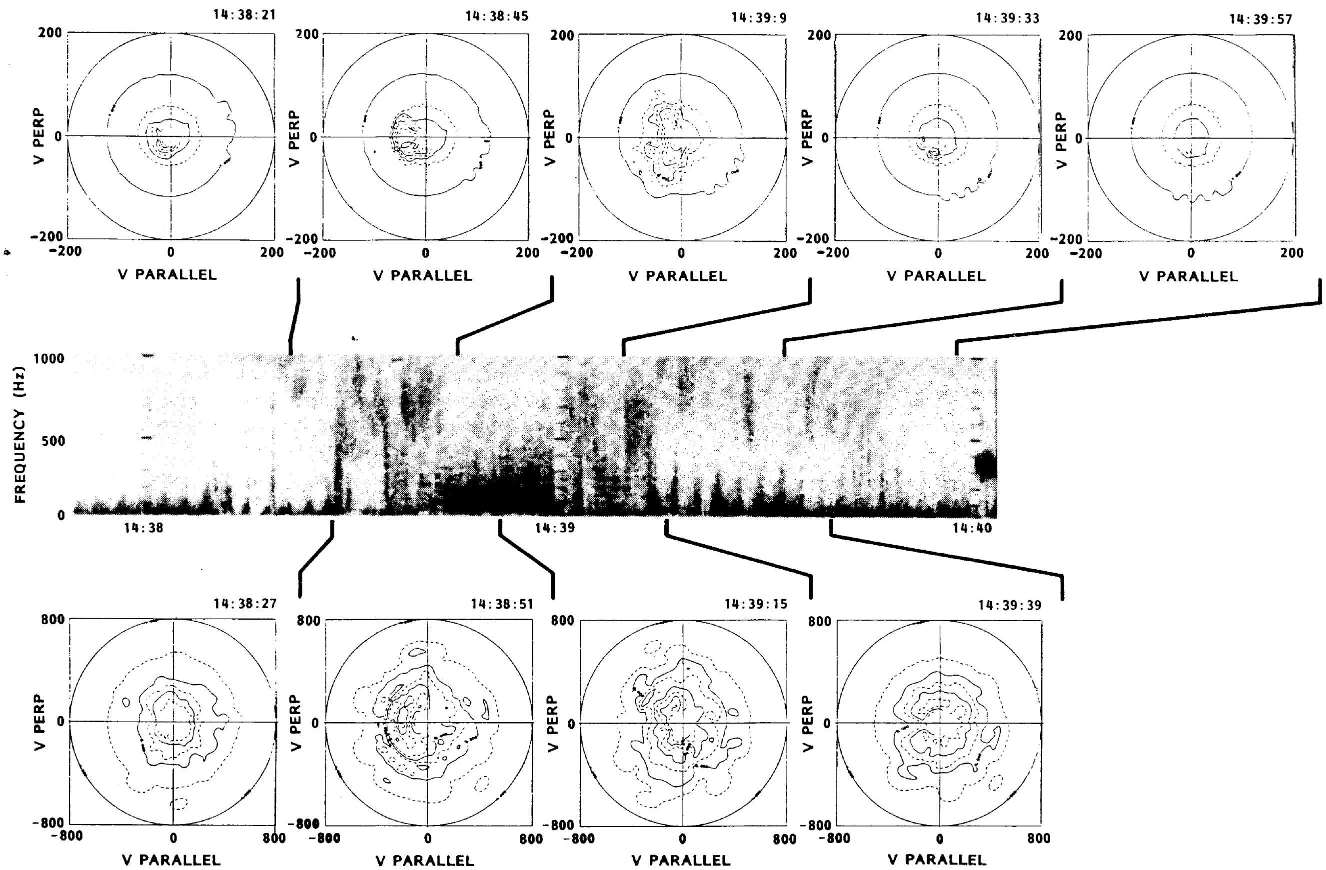

Fig. 4. High time resolution plasma wave and ion composition data from an interval on January 4, 1984. The format is similar to that of Figure 1.

are flowing from the ionosphere below. The contour plots are produced by contouring the surface defined by the larger of the one-count response of the instrument or the actual measurement at each sample point. The 'real' distribution then 'pokes through' the one-count-per-sample surface; thus the full circles and large arcs centered on the origin in the oxygen contour plots (top) are from the one-count-per-sample surface.

The sequence of hydrogen contour plots in the bottom panel of Figure 1 shows the evolution in energy and angle of injected magnetosheath $H^+$ ions which is the result of the combined effects of convection electric fields and spreading in pitch angle of the downward flowing cusp ion beam because of the magnetic mirror force. These effects have been described in detail by Peterson [1985], Roth and Hudson [1985], and Burch et al. [1982]. The hydrogen data for the period ending at 15:44:45 show the collimated, down flowing, high energy magnetosheath ions typically observed on the edge of the cusp. In the next two accumulation intervals, the distribution retains a peak in velocity which increases in angular extent. At the end of the interval shown in Figure 1, the hydrogen distributions are essentially isotropic. Since latitude is decreasing with time during this interval, the convection direction is sunward. Gorney [1983] and Roth and Hudson [1985] have pointed out that hydrogen ion distributions such as those for the intervals ending at 15:45:09 and 15:45:33 are unstable and could be the source of plasma waves of the type observed in the wideband data at this time.

The character of the upflowing oxygen distribution also changes over the time interval shown in Figure 1 from approximately isotropic in a frame of reference moving with the bulk flow velocity up the magnetic field line to a distribution which, for the interval ending at 15:45:29, has more thermal energy perpendicular to the magnetic field than parallel to it. Ungstrup et al. [1986] have also presented data from the ISEE-1 satellite suggesting transverse energization in the moving frame of reference of one of the plasma ion components.

Ions are expected to interact only with low (less than 1 kHz) plasma waves, but the higher frequency components can provide additional information about the local plasma environment. Figure 3 is a stacked plot of power spectral density as a function of frequency observed in the electric antenna from the swept frequency receiver. With the exception of the auroral kilometric radiation above $10^5$ Hz, the cusp SFR spectra in Figure 3 are similar to those presented by Lin et al. (1984) obtained from DE-1 on magnetic field lines populated with magnetosheath ions. The power spectral density in the 100 to 200 Hz range measured in the magnetic loop antenna for the same intervals presented in Figure 3 is approximately 100 times lower than that from the electric dipole antenna, indicating that the low frequency plasma waves shown in Figure

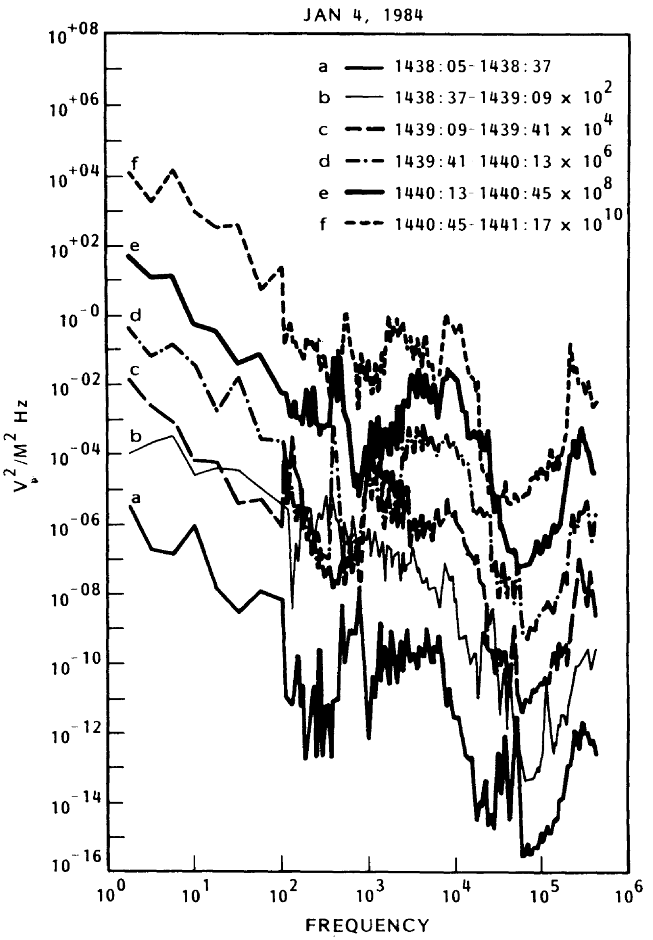

Fig. 5. Stacked plot of power spectral density as a function of frequency from the SFR for an evening auroral zone crossing on January 4, 1984. The format is similar to that of Figure 3.

2 are electrostatic. In fact below $\sim 10^5$ Hz, most of the power spectral density is seen in the electric antenna.

## An Evening Auroral Zone Crossing.

Figure 4 presents high time resolution EICS and PW1 data in a format similar to that of Figure 1 for an interval on January 4, 1984, when the satellite was at an altitude of 10,000 km near the poleward edge of the energetic ion precipitation zone at 17:40 magnetic local time and an invariant latitude of 78 degrees, moving equatorward. Intense bands of wave emissions spaced at the local hydrogen gyrofrequency (~60 Hz) below about 400 Hz are clearly visible from 14:38:40 to 14:39:10 in the central panel. Because of uncertainties in determining the plasma density (Ann Persoon, private communication) and the indication that most of the ion density is from ions with energies below the 10 eV lower limit selected for the EICS instrument at this time, we can only establish a broad range for the lower hybrid frequency. For equal hydrogen and oxygen densities the lower hybrid frequency would be ~725 Hz. If only 10% of the density is oxygen and the rest hydrogen, then the lower hybrid frequency would be ~1 kHz.

The contours of hydrogen phase space density in the lower panel show isotropic distributions for the the intervals ending at 14:38:27 and 14:39:39 and higher mean energies transverse to the magnetic field direction during the period of intense wave emissions near 14:39.

While there is clear evidence for upward flowing oxygen ions above the EICS 10 eV cut-off energy from 14:38:21 through 14:39:09, it is only for the interval ending at 14:39:09 that the data are adequate to provide meaningful phase space density contours. As noted above, the nearly circular contours centered on the origin are the contours of the one-count-per-sample instrument response. The series of oxygen contours in the top panel thus suggest that a low intensity upflowing oxygen ion beam exists until at least 14:39:33 which has its maximum energy and/or intensity during the measurement cycle ending at 14:39:09. Oxygen contours for the interval ending at 14:39:09 show that most, but not all, of the ion energy above the instrument threshold is perpendicular to the local magnetic field. Because of the wide energy width of the lowest energy channel, the magnitude of this parallel energy is not as well known as the magnitude of the perpendicular energy. Conservation of the first adiabatic invariant and the relative magnitudes of the parallel and perpendicular energies leads to the conclusion that this distribution is consistent with the transverse energization of the oxygen ions occurring between 1000 km below the spacecraft and locally.

Figure 5 is a stacked plot of power spectral density as a function of frequency from the electric antenna of the SFR. Data from the magnetic loop antenna do not show intense power spectral density below $\sim 10^5$ Hz. We conclude that the 0–1 kHz waves displayed in Figure 4 are electrostatic and that the plasma waves above ~1 kHz are typical of those seen in the high altitude auroral zone from DE-1 [Gurnett et al., 1983].

## Discussion

Stix [1962], in the introduction to his book on plasma physics, noted that a plasma is distinguished from other states of mater primarily by its collective properties. Transverse energization of ions by plasma waves and growth of plasma waves at the expense of particle energy are two of the central topics of space plasma physics. The detailed investigation of plasma processes associated with perpendicular ion heating in existing data sets has proven to be difficult, primarily because of the small number of well documented examples (see, for example, Kintner and Gorney, 1984).

Starting in 1984, the Dynamics Explorer-1 satellite systematically acquired a coordinated set of high time resolution plasma and plasma wave observations from the auroral zone. We have begun a program to use this data set to study the plasma processes associated with perpendicular ion heating. The relatively small scale nature of perpendicular ion energization, the vast amount of data to be searched, the established association of plasma wave emissions near multiples of the hydrogen cyclotron frequency with transverse ion energization (e.g., Kinter et al., 1979), and the ready availability of wide band plasma wave data lead us to limit our initial investigation to intervals with intense low frequency (less than 1 kHz) emissions with evidence of harmonic structure lasting tens of seconds. When digital ion data are available, they will also be searched for regions of transverse ion energization and compared with simultaneous plasma wave data. The present results, while preliminary, do provide some new insights into the study of collective plasma interactions

We have presented above two representative examples obtained from the Dynamics Explorer-1 satellite which show an increase in the transverse (to the magnetic field) ion energy in association with intense low frequency plasma waves with harmonic structure. The Plasma Wave Instrument digital swept frequency receiver data and the Energetic Ion Composition Spectrometer data for both examples presented were typical of other cusp and auroral zone intervals encountered by the DE-1 satellite.

There have been previous reports of simultaneous measurements of plasma waves and ion distribution functions (e.g., Kintner, 1980; Kintner and Gorney, 1984; or Yau et al., 1986); however, the data from Dynamics Explorer extend the energy range for ion species identification to the thermal range and extend the altitude range sampled to over 22,000 km. In addition to the data presented here, data from two other Dynamics Explorer-1 instruments, a fluxgate magnetometer [Farthing et al., 1981] and a second generation cold plasma analyzer [Chappell et al. 1981], are also available for most of the intervals considered. Analysis of these data are in progress. Unfortunately, no electron plasma data are available for the period of this study.

The data presented above for the cusp crossing of March 15, 1984, are qualitatively similar to the first order analysis of the energy balance between incoming magnetosheath and accelerated ionospheric cusp ion distributions and plasma waves using published data from S3-3 and DE-1 by Roth and Hudson [1985]. A complete analysis of the full DE-1 data set for several cusp crossings, including the thermal plasma composition and field-aligned currents, will provide the in situ diagnostics for a more detailed investigation of the energy balance in this and similar events. Presentation of such an analysis is beyond the scope of this first report.

One of the more important tools in the study of the collective behavior of plasma particles and waves is the identification of the mode(s) of the plasma waves. For example, the difference in the mathematical descriptions of electrostatic ion-cyclotron and lower hybrid waves are in the approximations used to account for electron motions (e.g., Chang and Coppi, 1981). Roth and Hudson [1985] have noted that plasma wave data similar to that shown in Figures 1-3 indicate that the lower hybrid description of electron motion must be considered in models of cusp plasma.

We note also that the $O^+$ distribution in Figure 1 for the period ending at 15:45:29 is not what is generally referred to as a conic distribution (see, for example, Sharp et al., 1977 and Gorney et al., 1981) because the distribution shows a considerable velocity parallel to the magnetic field. In fact, the $O^+$ distribution in Figure 1 for the measurement interval ending at 15:45:29 can be approximately represented by a bi-maxwellian distribution with temperatures of 180 and 250 eV parallel and perpendicular to the local magnetic field and a bulk flow velocity of 27 km/sec up the magnetic field line. Klumpar et al. [1984] have presented bi-modal $O^+$ distributions which they describe as the result of both parallel and perpendicular energization occurring on the same magnetic field line. In the examples presented by Klumpar et al., the $O^+$ distributions were 'folded' toward the magnetic field direction. This folding was interpreted as the result of the gradient in magnetic field strength between the region where the ions acquired their transverse energy and the satellite observation position. The $O^+$ distribution for the interval ending at 15:45:29 does not show evidence of 'folding' toward the magnetic field direction, suggesting that the region of transverse $O^+$ energization is quite near to the satellite.

The data from the auroral zone presented in Figures 4 and 5 show the simultaneous increase in transverse energy in both $H^+$ and $O^+$ plasma components in the presence of plasma wave emissions at multiples of the hydrogen gyrofrequency. This is not the only such example found in the DE-1 data set to date. However, as noted above, the $O^+$ contours in Figure 4 are consistent with the oxygen having acquired most of its transverse energy below the satellite position. It is hoped that detailed examination of the field aligned currents inferred from the magnetometer data and thermal plasma data from the RIMS instrument will resolve some of the ambiguities and lead to a more complete understanding of the plasma processes associated with perpendicular ion heating.

Lennartson [1983], in a systematic listing of the known or postulated ion acceleration mechanisms operating in the auroral regions, concludes with the remark: "Even though certain mechanisms have received more attention than the others in the literature, it is probably fair to say that the 'basic' mechanisms have yet to be agreed upon." It is clear that the high resolution data and large number of events in the Dynamics Explorer data set introduced here will provide a good body of data to test the limits and establish the relative importance of these auroral acceleration mechanisms.

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