Particle Acceleration and Wave Emissions Associated with the Formation of Auroral Cavities and Enhancements

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Observations from DE 1 and electrostatic particle simulations are combined in an effort to provide a unified model for (nightside) auroral particle acceleration and wave emissions and their association with plasma cavities and enhancements. The observations show that enhanced electron precipitation during inverted-V events is associated with broadband electrostatic bursts (BEB), increased upward field-aligned currents, and density enhancements. These regions are flanked by return current regions where the density is depleted (i.e., by plasma cavities). Perpendicular acceleration of ambient plasma ions can occur in both upward and return current regions. It is shown through the simulations that these processes are integrally related and are not independent of each other. The free energy for the auroral particle acceleration can be provided by energetic ion beams in the plasma sheet boundary layer with nonzero perpendicular energy. The perpendicular energy allows charge separation between the beam ions and costreaming electrons to occur. The resultant space charge fields accelerate electrons on the same field lines as the costreaming electrons downward toward the ionosphere, without the beam ions actually propagating down to auroral altitudes. Ambient plasma electrons on adjacent field lines are accelerated upward, forming a return current. Because these currents are spatially separate, a perpendicular electrostatic shock develops which accelerates the plasma ions across the field lines in an effort to close the currents. This accelerating current in velocity space and, in coordinate space, plasma cavities are formed in the return current regions and plasma enhancements in the enhanced positive current regions. Strong broadband electrostatic waves are generated with spectral maxima being generated near the local electron plasma frequency by the accelerated electrons and near the lower hybrid frequency by the accelerated ions, similar to that observed in BEB.

1. Introduction

Along auroral field lines, a variety of phenomena are observed, including upward acceleration of ionospheric ions, downward acceleration of magnetospheric electrons, perpendicular electrostatic shocks, and intense wave emissions. The upflowing ions are observed to experience not only parallel acceleration but also strong perpendicular acceleration. The presence of perpendicularly accelerated ionospheric ions (i.e., ion conics) was first discovered by the S3-3 satellite [Sharp et al., 1977]. Subsequent observations from S3-3 and the DE satellites have shown that these ions are present along high-latitude auroral field lines from altitudes of about 400 km to 18,000 km [Ghielmetti et al., 1978; Whalen et al., 1978; Gorney et al., 1981; Klumpar et al., 1984; Yau et al., 1983, 1984; Moore et al., 1985; Klumpar, 1986].

A number of mechanisms for this perpendicular acceleration or heating utilizing wave-particle interactions have been proposed. These mechanisms include heating (1) by current-driven electrostatic ion cyclotron waves [Ungstrup et al., 1979; Lysak et al., 1980; Dusenbery and Lyons, 1981; Ashour-Abdalla and Okuda, 1983a, b, 1984], (2) by current-driven lower hybrid waves [Chang and Coppi, 1981; Singh and Schunk, 1984], and (3) by shear Alfvén waves [Chang et al., 1986; Winglee et al., 1987, 1988c].

Many of these waves have been observed on auroral field lines [e.g., Bering et al., 1975; Kelly et al., 1975; Bering, 1984; Kintner and Gorney, 1984; Garrett et al., 1984]. However, Kintner and Gorney [1984] and Kintner [1986] from an examination of S3-3 data were unable to establish a direct association of ion conics with these waves. A detailed study of high resolution plasma data obtained from the Dynamics Explorer 1 (DE 1) satellite by Peterson et al. [1988] was also unable to establish a single event where there was an unambiguous signature for the enhanced transfer of energy from plasma waves to ambient plasma ions.

In the above theories for the perpendicular heating,
currents carried by streaming electrons are usually assumed to provide the free energy for the wave growth. Such currents are often observed in association with ion conics [e.g., Heelis and Winningham, 1984; Kintner and Gorney, 1984; Moore et al., 1985]. However, there is some experimental evidence which suggests that the magnitude of the electron drift speed may be smaller than the electron thermal speed and, as such, may be insufficient to drive these waves unstable [Kintner and Gorney, 1984].

Another problem with the above theories is that they do not take into account the quasi-static electric fields which are known to exist in the auroral region and drive the currents. Unambiguous signatures of quasi-static parallel electric fields were first obtained from observations of strongly field-aligned electron distributions [Hoffman and Evans, 1968; Whalen and McDermid, 1972; Arnoldy et al., 1974]. More recently, near-conjugate observations by DE 1 and DE 2 of particles associated with inverted-V events indicate the presence of field-aligned potential differences of several keV from DE 1 altitudes (8000–12,000 km) to DE 2 altitudes (500–1000 km) [Lin et al., 1985; Reiff et al., 1986, 1988]. The potential drop along the magnetic field line need not be monotonic but may contain local potential islands, as evidenced by the double layers observed by S3-3 [Temerin et al., 1982] and by examples of counterstreaming electron beams detected by DE 1 [Lin et al., 1982, 1984]. The electrons accelerated by the parallel electric field produce intense radio emissions including intense electrostatic emissions [Scarf et al., 1974; Gurnett et al., 1976; Gurnett and Frank, 1977], auroral kilometric radiation, z mode radiation, and auroral hiss [e.g., Gurnett et al., 1983, and references therein; Bohnsen et al., 1987].

Modification of the particle distributions produced by these quasi-static parallel electric fields was examined theoretically by Evans [1974] and Chiu and Schulz [1978]. Wu and Lee [1979] predicted that these parallel fields would produce a plasma depletion or cavity and that this cavity would be a crucial factor in the generation of auroral kilometric radiation. The presence of a plasma cavity was later verified by observations from ISIS 1, Hawkeye, and DE 1 satellites [Benson and Calvert, 1979; Calvert, 1981; Persoon et al., 1988]. Localized density enhancements within the auroral cavity can also be present [Benson and Calvert, 1979; Lin et al., 1985].

The first observations of strong quasi-static perpendicular electric fields were made by the S3-3 satellite, which established the presence of perpendicular electrostatic shocks [Mozer et al., 1980; Temerin et al., 1982; Mozer et al., 1985]. These shocks were characterized by large quasi-static electric fields of 100–1000 mV/m directed primarily perpendicular to the magnetic field and occurred in localized regions. In particular, at the satellite apogee of 8000 km, the shocks were observed to have a width of about 10–40 km (assuming stationary structures) with the corresponding potential drop across the shock being as large as several kilovolts. These shocks were observed in association with regions of field-aligned currents, upward accelerated ions, downward accelerated electrons, and intense ion cyclotron waves [Redfern et al., 1985]. Borovsky and Joyce [1983, 1986] and Borovsky [1984] have suggested that these shocks or oblique double layers can produce the observed perpendicular heating of ionospheric ions by direct particle acceleration.

A variety of mechanisms have been proposed for the origin of the potential drops on auroral field lines (for a review, see Kan and Lee [1981]). These processes include anomalous resistivity, single-particle motion, differential conductivity for upgoing and downgoing currents produced by the magnetic mirror force, and large-amplitude Alfvén waves. Lyons [1981] showed that the field-aligned potential drop and the associated current density could be explained by considering only single-particle motion along the magnetic field and that such motion was inconsistent with anomalous resistivity.

To date, theories for the generation of ion conics assume that either the potential structure or the current system is preexisting without considering how such structures are generated. Similarly, theories for radio emissions in the auroral region, in general, assume the presence of an unstable particle distribution without considering how such distributions are formed and their relation with the quasi-static electric fields and associated current systems. Moreover, the interrelation of the auroral particle acceleration with the formation of auroral plasma cavities and/or enhancements has not been addressed. Clear signatures in the particle or wave properties showing the interrelation between the particle acceleration and the associated wave emissions are difficult to identify due to the complexity of the processes involved [Kintner and Gorney, 1984; Kintner, 1986; Peterson et al., 1988].

Auroral particle acceleration is integrally tied to the overall coupling of energy between the ionosphere and the magnetosphere. In particular, processes in the magnetotail can provide a source of free energy for auroral particle acceleration. One possible means by which this magnetospheric-ionospheric coupling can occur was pointed out by Lyons and Evans [1984] using NOAA 6 data. They showed that the electron precipitation responsible for discrete auroral arcs often occurred at the outer boundary of the plasma sheet in association with spatial structures in streaming ion distributions arising from current sheet processes.

It is the purpose of this paper to provide a unified model which interrelates the various processes involved in auroral particle acceleration and the associated wave emissions and to thereby determine how energy is coupled from the magnetosphere into the ionosphere. The specific objectives of the paper are to identify (1) the phenomena in the magnetotail which can provide the source of free energy for the perpendicular electrostatic shocks and the associated potential structures in the nightside auroral region; (2) the characteristics of the particle acceleration produced by the shock, including efficiency and energy transport between magnetospheric and ionospheric plasmas, the properties of the particle distributions throughout the shock region and return current regions, and the associated wave emissions; (3) the source of free energy for the generation of ion conics; and (4) signatures for the formation of plasma cavities and/or enhancements.

The study utilizes observations from DE 1 (section 2) to determine the properties of the particles and wave emissions relative to the current systems and quasi-
static electric fields associated with discrete auroral arcs. Two-dimensional (three velocity) electrostatic particle simulations (section 3) are then used in sections 4–6 to determine how the above processes are interrelated.

Persoon et al. [1988] have previously used data from multiple instruments on the DE 1 satellite to examine the auroral cavity. In this study, the upper cutoff of auroral hiss was used to identify the auroral cavity, and it was shown that low-energy (< 1 keV) upflowing H⁺ ions are strongly correlated with the poleward edge of the auroral cavity. A detailed study of processes within the cavity was restricted due to interference from intense broadband electrostatic noise bursts. In the present study, it is shown from both observation and simulation that these electrostatic bursts can be used as a signature for the downward acceleration of electrons in association with density enhancements and cavities. This signature enables processes throughout the auroral region to be examined in greater detail than in previous studies.

Two-dimensional simulations which model the formation of V-shaped perpendicularly electrostatic shocks have been previously performed by Wagner et al. [1980, 1981, 1985] and Singh et al. [1983, 1987]. These simulations are able to easily generate V-shaped potentials. However, the origins of the magnetospheric-ionospheric coupling are unclear. In the simulations of Wagner et al., the magnetospheric plasma is loaded throughout the system so that there is no well-defined ionospheric plasma. In the simulations by Singh et al. [1987], positive charge is injected at one end of the simulation system, and negative charge at the other end. It is unclear how naturally occurring plasmas can produce this instantaneous charge injection in different regions.

These restrictions are removed in the present work. A possible free energy source for the magnetospheric-ionospheric coupling is specifically identified. This free energy source is shown in section 4 to be the perpendicularly energized ion beams in the plasma sheet boundary layer [Grabbe and Eastman, 1984; Eastman et al., 1984, 1985]. This perpendicular energy can cause charge separation between the beam ions and costreaming electrons which drives the formation of the electrostatic shock, which, in turn, produces the acceleration of the auroral plasma. Note, however, that the ion beams themselves do not have to actually propagate into the auroral region to produce a disturbance there, although such beams are occasionally seen entering the auroral region [Lyons and Evans, 1984; Peterson et al., 1988]. As the shock forms, electrons in the shock are accelerated downward to form beams while electrons on the edges of the shock are drawn upward into the magnetosphere to form the return current. The shock accelerates the plasma ions across the magnetic field in an effort to maintain quasi-neutrality. As a result of this acceleration, conic distributions develop in the ion velocity space and, in coordinate space, plasma cavities develop in the return current regions and plasma enhancements in the beam region.

A detailed understanding of auroral particle acceleration is not only important in itself but is of fundamental importance in determining energy transport associated with the propagation of particle beams in space plasmas, for example, during active injection of particle beams from spacecraft [Pritchett and Winglee, 1987; Winglee and Pritchett, 1987, 1988 and references therein] and the heating of the solar corona and chromosphere during solar flares [Winglee et al., 1986a, b]. The main differences between these problems are the spatial scale lengths of the beam and the source of the energetic particles.

2. Observations

2.1. Wave Emissions

We have examined data from DE 1 from several nightside auroral crossings at altitudes of about 3 RE geocentric. All show similar features, and we present results from only one of the case studies. Such a case study allows a detailed examination of the many processes occurring simultaneously on auroral field lines and thereby gives insight into how they are related. The data presented in the following are for day 292, October 19, 1981. The hourly averaged AE index during the auroral crossing (i.e., between 1000 and 1100 UT) was about 500. The corresponding values of AE an hour either side of the crossing was about 600. The nightside region 1 current system, as determined from the magnetometer, was encountered between 1015 and 1031 UT and the region 2 current system between 1031 and 1040 UT.

Plate 1 shows a frequency spectrogram for the electric field from the University of Iowa plasma wave instrument (PWI) during the auroral crossing on day 292, 1981. (Plate 1 can be found in the separate color section in this issue.) This instrument, which is described by Shawhan et al. [1981], provides a swept frequency spectrogram in the frequency range 1.78 Hz to 4 x 10⁶ Hz every 32 s. The white lines across the spectrogram show from top to bottom the electron (Ωₑ), hydrogen (Ω_H), and oxygen (Ω_O) cyclotron frequencies.

Auroral kilometric radiation (AKR) is seen as the intense emissions at frequencies of about 2 x 10⁵ Hz, between about 1012 UT and 1040 UT, which coincides with the auroral crossing. After 1040 UT, the spacecraft moves into the plasmasphere where plasmaspheric hiss is observed. A whistler funnel at frequencies less than about 2 x 10⁶ Hz, which is characteristic of auroral hiss, is seen propagating poleward from the auroral region starting at about 0950 UT and extending through the auroral region [cf. Persoon et al., 1988].

Within the hiss frequency band, intense bursts of emissions are seen during the auroral crossing. These bursts are highly structured with four very intense and discrete events at about 1014:00, 1017:30, 1020:30, and 1025:30 UT and three lesser intense events during the auroral crossing (e.g., at 1012:30, 1016, and 1023:30 UT). The upper cutoff frequency for these bursts is higher than that of the emissions on either side of the bursts and can extend to frequencies above the electron cyclotron frequency on occasions (e.g., at 1014:00 and 1020:30 UT). The most intense emissions are, however, not at these high frequencies but at frequencies less than about 10⁶ Hz. The power at any given frequency during one of these bursts on average decreases as the spacecraft moves equatorward. This is observed on other
auroral crossings, which suggests that the effect is spatial rather than temporal.

From an examination of the magnetic spectrograms (not shown), these bursts are primarily electrostatic. Only the two most intense bursts at 1014:00 and 1020:30 UT have (weak) magnetic signatures in the intermediate frequency range between $10^3$ and $10^4$ Hz. These signatures appear weaker than those of AKR, plasmaphess, hiss, and the whistler mode emission at about 1000 UT even though the electric field strength of the bursts is much higher than these other emissions. In this paper, these bursts are referred to as “broadband electrostatic bursts” (BEB).

These bursts may be related to the broadband electrostatic noise (BEN) seen in the tail. BEN can have frequencies extending up to about the electron plasma frequency [Scarf et al., 1974; Garrett et al., 1976; Garrett and Frank, 1977]. The most intense waves in BEN appear to be near the lower hybrid frequency [Cattell and Mozer, 1986], similar to the present case. However, BEN is usually attributed to ion beam instabilities [Grabbe and Eastman, 1984; Dosenbery and Lyons, 1985; Omidi, 1985]. It is shown here that BEB is associated with electron beams and perpendicular ion acceleration.

Although BEB is generated over a large frequency range, the power spectra show well-defined local maxima in certain frequency ranges. As an example, Figure 1 shows electric field spectra densities over consecutive 32-s periods (i.e., the time to complete a full sweep through the frequency range of the receiver). The times given are at the center of each period. The dashed lines at the top and bottom of the figure show the power (averaged in frequency) when BEB is not present. AKR appears as the spike at about $2 \times 10^3$ Hz. Narrow-band electrostatic emissions at about $5-6 \times 10^4$ Hz appear near the electron cyclotron frequency (which, in the auroral cavity, is approximately equal to the upper hybrid frequency).

A moderate BBE is seen at about 1012:34 UT, but by the next sample at 1013:06, very weak or no BBE is seen. A very strong BBE is then seen between 1013:38 and 1014:52 UT (this corresponds to the first of the major BBEs in the color spectrogram in Plate 1). At 1015:14 UT, BBE is no longer seen. Note that during times of BBE, the spectrum density has three local maxima at frequencies of about $1-2 \times 10^2$ Hz, $1-3 \times 10^3$ Hz, and $1-2 \times 10^4$ Hz. All three peaks tend to develop at the same time within the resolution of the instrument and are not present when BBE is absent. This is true for all the BBEs seen in the present case study and not just the two BBEs shown in Figure 1. In other words, the three local maxima are integrally related and not independent of each other.

The frequencies of these local maxima are well above the ion cyclotron frequencies and well below the electron cyclotron ($\Omega_e$) and upper hybrid ($\omega_{UH}$) frequencies. Thus, the main candidates for these local maxima are (1) the electron plasma frequency $\omega_{pe}$; (2) the $H^+$ and $O^+$ plasma frequencies $\omega_{pH}$ and $\omega_{pO}$, respectively; and (3) the whistler mode resonance frequency $\omega_{WR}$ which, for a $H^-O^+$ plasma with $\omega_{pe} < \Omega_e$, $\Omega_O$, $\Omega_{H} \ll \omega_{pH}$, and oblique propagation, is given approximately by $\omega_{WR} \approx (\omega_{pe}^2 \cos^2 \theta + \omega_{pH}^2 + \omega_{pO}^2)^{1/2}$

where $\theta$ is the angle of propagation. For exactly 90° propagation, $\omega_{WR}$ is equal to the lower hybrid frequency $\omega_{LH} = (\omega_{pH}^2 + \omega_{pO}^2)^{1/2} \approx \omega_{pH}$. However, for just a few degrees off perpendicular propagation, $\omega_{WR}$ can be significantly upshifted above $\omega_{LH}$ by the electron correction.

If a typical density of about 4 cm$^{-3}$ (cf. section 2.2) is assumed, the electron plasma frequency would correspond to about $2 \times 10^4$ Hz. This frequency corresponds closely

![Power spectra of the electric field from the swept frequency receiver (SFR) during the first 3 min of the auroral crossing, i.e., 1012-1015 UT. Each power spectra spans 32 s (i.e., the time to conduct a full frequency sweep) with the time given being at the center of the sweep. The dashed line shows the average signal detected in the absence of any strong BBE. Although the spectrum of BBE when it is present is broad, it is not monotonic with local maxima in the spectral density at about $1-2 \times 10^2$, $1-3 \times 10^3$, and $1-2 \times 10^4$ Hz.](image-url)
with the local maximum at the highest frequency; i.e., the highest-frequency peak may be a measure of the local electron plasma frequency and indicate the presence of electron acceleration. Note that the upper cutoff of this spectral peak can be 2 to 3 times the frequency where the spectral density peaks. This cutoff frequency can approach the electron cyclotron frequency, e.g., at 1013:38 UT in Figure 1.

The second spectral peak about $1-3 \times 10^3$ Hz overlaps with the frequency range in which Kintner and Gorney [1984] observed lower hybrid waves in association with ion conics. However, if a density of $4 \text{ cm}^{-3}$ is assumed with equal amounts of $H^+$ and $O^+$ present, the lower hybrid frequency is only about $300$ Hz, which is significantly smaller than the frequency of the second spectral peak. However, if the angle of propagation is only $5^\circ$ off perpendicular propagation, the resonant frequency is upshifted to a value near the second spectral peak. In the following, these waves are referred to as lower hybrid waves consistent with the nomenclature of Kintner and Gorney [1984] since they probably lie on the part of the whistler mode resonance near the lower hybrid frequency. These waves may provide a signature of the acceleration of $H^+$ ions (section 4.2).

The oxygen plasma frequency for the above parameters is approximately equal to $80$ Hz. This frequency lies near the third spectral peak at $1-2 \times 10^2$ Hz, so that the third spectral peak may be a signature of the acceleration of $O^+$ ions.

2.2. Electrons and Field-Aligned Currents

In order to determine the properties of the electrons and electric currents during the auroral crossing, data from the high altitude plasma instrument (HAPI) [Burch et al., 1981] and the DE 1 magnetometer [Farthing et al., 1981] were examined. Plate 2 shows data from these instruments in the interval 1010-1030 UT where the most intense particle acceleration and wave emissions are occurring. (Plate 2 can be found in the separate color section in this issue.) The top panel shows the electron energy spectrogram from HAPI while the bottom panel shows the perturbations in the measured east-west component of the magnetic field ($B_\phi$) after subtraction of the International Geomagnetic Reference Field (IGRF) 1980 model of the Earth's field. The field-aligned currents displayed in the middle panel are inferred from these magnetic perturbations, using the assumption that they are produced by an infinite current sheet oriented parallel to the local magnetic $L$ shells. The validity of this approximation for these observations is supported by the near-absence of associated perturbations in the radial and geomagnetic north-south components (not shown) during the period of these field-aligned currents. A positive current indicates a net flux of electrons downward from the magnetosphere into the ionosphere. The solid arrows in the bottom panels indicate the times (to within 30 s) of intense BEB, and the dashed arrows less intense BEB.

During the entire period shown, there is a net influx of energetic electrons from the magnetosphere to the ionosphere, as indicated by the net positive current inferred from the magnetometer data. This net positive current is associated with the crossing of the evening region 1 current system. (The region 2 current system (not shown) is encountered between about 1032 and 1040 UT.) The region 1 currents are seen in the electron spectrogram at the top of Plate 1 as a continual flux of electrons in the energy range about 1 keV after the auroral crossing at 1011:30 UT. During the auroral crossing, there are several intensifications of these precipitating electrons. These intensifications are associated with enhanced positive currents, e.g., at 1012:30, 1014, 1021, 1025:30, and 1029:30 UT. These regions are hereafter called "primary current regions" to indicate that they are associated with the primary acceleration of magnetospheric electrons down into the auroral zone. The velocity distributions of the electrons in these regions have not only an enhanced loss cone feature but also a hole feature adjacent to a beamlike feature, where there is a positive slope with respect to the parallel velocity in the distribution [Lin et al., 1986].

On each side of these intensifications, there are regions of either negative currents or at least regions of reduced positive currents. These regions provide return currents from the ionosphere to the magnetosphere. They can also be seen in the energy spectrograms as intensification of low-energy electrons at energies about 10 eV. Note that the times of BEB correspond with regions of positive or primary current rather than with regions of return current.

Most of the primary current regions are relatively small in width. For example, the primary current regions at 1012:30, 1021, 1025:30, and 1029:30 UT have widths of between about 20 and 40 km. This width is comparable to the scale sizes of the perpendicular electrostatic shocks observed by S3-3. The very broad inverted-V event at 1014 UT in Plate 1 has a width about 3 times as large. However, the current profile is far from homogeneous during this large event, with large currents being evident at the beam edges and only small currents near the center of the event. The width of these individual current structures is comparable to that seen in the simple events. This filamentary current structure or local intensification in the current is shown in section 6 to be a natural feature of the plasma requiring local neutralization of the charge carried by the energetic electrons precipitating into the ionosphere.

An independent measure of the current density as well as the plasma density can be obtained by integrating various moments of the electrons detected by HAPI. The results for the number flux, the number density, and the current density over the interval 1011 to 1023 UT integrated over the electrons in the energy range 18 eV to 13 keV are shown in Figures 2a-2c, respectively. The lower limit is set so as to exclude photoelectrons in the vicinity of the spacecraft from the count. As a result there is no information on the density of ambient plasma electrons with energies below 18 eV. The times of the BEB are again indicated by the solid and dashed arrows. It is seen that most of the features of the current (including the filamentary current structure about 1014 UT) are seen by both HAPI and the magnetometer. The main difference is that a large positive current at about 1016 UT seen by HAPI appears as a much broader feature by the magnetometer. The magnitudes of the observations from both instruments agree closely.
The difference in the energy discrimination between the RIMS and EICS instruments provides important information on the acceleration mechanisms and the sources of free energy. EICS is able to detect energetic ion flows from the magnetosphere as well as ionospheric ions which have been accelerated through a significant fraction of the auroral potential drop. RIMS, on the other hand, with its low-energy cutoff does not detect these energetic ions. Instead, the ions detected by RIMS have seen only a small fraction of the potential drop and therefore are presumably indicative of local acceleration processes.

Plate 3 shows spectrograms from RIMS for the H\(^+\) (top panel), He\(^+\) (middle panel), and O\(^+\) (bottom panel) ions. (Plate 3 can be found in the separate color section in this issue.) In each of these panels, the top portion shows an energy spectrogram while the lower portion shows the spin phase angle of the ions detected. The long dashed line near spin phase angles near 90\(^\circ\) indicates field-aligned flows up the field lines (i.e., pitch angles of 180\(^\circ\)). The solid arrows again indicate times of the more intense BEB, and the dashed arrows times of the weaker BEB similar to Plate 2. Just prior to the first of intense BEB events, ion conic distributions (i.e., ions with spin phase angles deviating significantly from 90\(^\circ\)) are evident in all three ion species. (The steady trace, especially for the H\(^+\) ions, near the 2–5 count level which starts near 105\(^\circ\) spin phase angle at 1000 UT is a Sun pulse as seen by the instrument and does not indicate ion outflow.) Similar ion conic distributions on nightside auroral crossings near the poleward edge of auroral density depletions have been reported by Persoon et al. [1988].

At the actual time of the first BEB, very few upflowing ions are detected. This indicates either that there is little ion acceleration and the ions are not seen due to their low energy (\(\lesssim 10\) eV) and the positive charging of the spacecraft (to +45 to +10 V) in the low-density environment of the auroral region or, more probably, that the bulk of the ions are accelerated (to energies higher than the few tens of electron volts which can be detected by the RIMS instrument). For the H\(^+\) ions, the dropout appears as a change in the energy spectrogram from intensities which appear nearly white down to either light blue or dark blue (i.e., null). For the O\(^+\) ions, the dropouts are seen as a decrease from light blue or white down to null. Perpendicularly accelerated ions as well as ion beams are seen again after the end of the BEB and the intensification of the precipitating electrons. This pattern is repeated about the other BEB with major dropouts in the RIMS data at about 1017–1018:30, 1020:30–1021:30, and after 1025:30 UT during times of BEB.

Although the different ion species show dropouts at about the same times, the accelerations appear different with respect to the angle of the magnetic field for the various ion species. For example, the velocities of the H\(^+\) and the He\(^+\) ions are relatively field aligned after the first conic is seen whereas the velocities of the O\(^+\) ions appear more coniclike. Moreover, the velocities for the O\(^+\) ions are not symmetric about the magnetic field but appear preferentially at about a spin phase angle of 45\(^\circ\), implying a convective flow. Such asymmetry about the
magnetic field suggests that a quasi-static perpendicular electric field is producing a directed flow rather than wave-particle interactions which would tend to produce isotropic heating (assuming quasi-linear acceleration).

The EICS data are shown in Plate 4. (Plate 4 can be found in the separate color section in this issue.) The top two panels show energy spectrograms for H⁺ and O⁺ ions. The lower four panels show the corresponding phase spectrograms for the H⁺ and O⁺ ions in the energy ranges 1 to 17 keV and 10 eV to 1 keV, respectively. The spectrograms are taken over a 96-s interval. In these diagrams, field-aligned flows up the field lines are again represented by spin phase angles at about 90°. The first three intense BEBs are indicated by the solid arrows while the fourth coincides with the 1 of the 1030 UT label. Energetic He⁺ (not shown) is also detected with a spectrogram similar to that of O⁺.

On entering the auroral region at 1012 UT a broad spectrum of energetic H⁺ ions (i.e., greater than 1 keV) is seen (panel 1). This component is probably of magnetospheric origin and is not evident in the other two ion species. These energetic ions are almost isotropic except possibly for a small loss cone at about 90° (panel 3).

Upflowing ion beams in the energy range of 10 eV to 1 keV are seen generally in both the H⁺ and O⁺ ions throughout the auroral crossing (panels 5 and 6). Energetic (> 1 keV) upflowing ion beams are occasionally seen, e.g., at 1015–1016:30 UT and 1021–1022:30 UT. These beams are probably indicative of strong parallel acceleration of ions below the spacecraft.

Strong perpendicular acceleration of the ions (where they have spin phase angles extending out to either 0° or 180°) in the energy range 10 eV to 1 keV is seen on four occasions in panels 5 and 6 at 1013:30–1015 UT, 1016:30–1018 UT, 1020–1021:30 UT, and 1025–1026:30 UT. These ions are probably of ionsospheric origin. The times correspond with the dropouts in the RIMS and are consistent with the hypothesis that these dropouts are due to the bulk (perpendicular) acceleration of the plasma ions above the RIMS energy range of 50 eV, rather than the absence of any particle acceleration. These times also correspond to those when intense BEB and electron density enhancements are seen.

Downgoing H⁺ ions with spin phase angles between 180° and 360° in the energy range 10 eV to 1 keV are also present on occasion, e.g., at 1013:30 UT and 1025 UT. These times coincide with two of the times when perpendicular acceleration of ions is seen. However, two of the conic events are not related to any downward ion flows. Peterson et al. [1988] have also reported the occasional presence of downflowing ions during auroral crossings which was sometimes associated with banded emissions below about the lower hybrid frequency.

The fact that these downflowing ions are predominantly H⁺ suggests that they are probably of magnetospheric origin, possibly associated with energetic plasma flows in the plasma sheet boundary layer [Eastman et al., 1984; Grabbe and Eastman, 1984]. However, the ionosphere cannot be completely ruled out as the source. Observations of ion beams being accelerated out of the auroral region, convecting to lower latitudes, and eventually precipitating into the conjugate hemisphere have been reported by Winningham et al. [1984] and Bosqued et al. [1986].

In summary, the observations show that during auroral crossing there are intense broadband electrostatic bursts (BEB) (besides auroral kilometric radiation, auroral hiss, and z mode radiation). These bursts have spectral maxima near the electron plasma frequency and possibly at the lower hybrid and oxygen plasma frequencies. These bursts are associated with (1) enhanced plasma density, (2) enhanced electron precipitation, (3) enhanced positive upgoing currents, and (4) bulk perpendicular acceleration of plasma ions to energies above several tens of electron volts. Return current regions appear on either side of these bursts and tend to occur in regions of low plasma density. The spatial width of these events tends to between about 20 and 40 km, which is comparable to the width of perpendicular electrostatic shocks observed by S3-3. On occasion, ions, presumably of magnetospheric origin, are seen flowing down into the auroral region.

3. Simulation Model

In order to provide a unified model for auroral processes, two-dimensional (three velocity) electrostatic particle simulations are used. The simulation code is similar to that of Pritchett and Wingale [1987] except that the boundary conditions have been modified so that the system is isolated along the magnetic field in the x direction but periodic across the magnetic field in the y direction. The use of periodic conditions across the magnetic field models the presence of a series of beams propagating toward the auroral region (consistent with observations) while the use of an isolated system along the magnetic field eliminates the possibility of unphysical attractions with repeated images of the system (i.e., between ionosphere and magnetosphere) as particles approach the simulation boundaries.

A schematic for the simulation model is shown in Figure 3a. The system is divided into 3 regions: magnetotail (magnetosphere) on the left-hand side where the density nme is relatively low; topside ionosphere on the right-hand side where the density nie is higher; and a boundary region in the middle of the system representing the auroral region where magnetospheric-ionspheric coupling occurs. The density increases approximately linearly with distance from the magnetospheric density nme to the ionospheric density nie, as indicated by the density profile in Figure 3b. This change in the plasma density is included so that there is a large plasma reservoir from which return currents out of the ionosphere can be drawn. In the simulations, the ratio of nie/nme is taken to be 4, which is about the limit in dynamical range afforded in the simulations for the given scale length along the magnetic field. This variation in density represents altitudes from about 3 Rg down to about 2 Rg. The model is not currently able to accurately treat interactions with the much denser and possibly collisional plasma at lower altitudes.

The simulation model also requires the identification of the free energy source. This has yet to be determined unambiguously by experiment. Nevertheless, there are observations which indicate a possible source of free energy. Lyons and Evans [1984] have shown, from NOAA
This power is comparable to the maximum power of $10^{11}$ W carried by auroral particles precipitating into the ionosphere [Gurnett, 1974]. In other words, these beams in the plasma sheet boundary layer carry sufficient power to drive auroral processes. It should be stressed that, as shown in the following simulations, the beams themselves do not have to propagate down to auroral altitudes ($\lesssim 3$ $R_E$) to produce the particle acceleration there.

The beams have the additional features that (1) they have a substantial amount of perpendicular energy with the perpendicular temperature $T_\perp$ greater than their parallel temperature $T_\parallel$ and (2) they are accompanied by costreaming electrons with $T_\parallel > T_\perp$ [Frank, 1985]. Such beams can be produced by current sheet acceleration [Lyons and Speiser, 1982]. Magnetspheric-ionospheric coupling via these beams is also suggested by the EICS data discussed in the previous section which show the presence of downflowing magnetspheric ions during the auroral crossing in occasional coincidence with conics.

The object of the simulations is to determine (1) how the energy of such beams can couple to the nightside auroral plasma without the ion beams actually entering the auroral region (since downward flowing ions are not always seen), (2) properties of the particle acceleration and wave emissions, and (3) whether they are consistent with wave-particle observations in the auroral region.

To this end in the simulations, an energetic ion beam with costreaming electrons is injected from the left-hand boundary representing the magnetotail, as indicated in Figure 3a. The beam density at injection $n_i$ is assumed to be $4n_i$. This relatively high density is assumed since magnetic focusing in the convergent geomagnetic field should substantially increase the density as the beam propagates in from ISEE 1 altitudes of several tens of Earth radii to a few Earth radii. Moreover, because the magnetspheric part of the simulation model is relatively short, the energy carried by the beam is relatively small compared with the auroral and ionospheric plasmas unless a relatively large density is assumed. Differences associated with changes in the beam density as well as beam energy are discussed in section 5.

The mass of the beam and plasma ions is assumed to be 50 $m_e$. The artificially small ion mass allows time scales of the order of an ion gyroperiod to be resolved during the length of the simulation while still maintaining differential motion between the ions and electrons. The parallel drift speed of the beam at injection $v_{b\parallel}$ is assumed to be $\Omega_E v_i$ for $v_i < v_{b\perp}$. The thermal speeds of both beam and plasma ions are assumed to be equal. With this distribution, the beam ions have a well-defined gyroradius $\rho_b = v_{b\perp}/\Omega_i$ (where $\Omega_i$ is the ion cyclotron frequency) which, as shown in the following sections, essentially determines the width of the primary and return current regions.

The thermal speed of the beam electrons is assumed to be equal to $\sqrt{2}$ of the thermal speed of the ambient plasma electrons $v_{Te}$. This difference in thermal speeds was made so as to be able to differentiate the two populations in velocity distributions. The results presented here are not dependent on this parameter.
because the electrons at injection carry very little energy into the system since they are essentially costreaming with the beam ions. The initial plasma electron temperature $T_e$ is assumed to be equal to the plasma ion temperature $T_i$. Assuming that the ambient plasma is at 10 eV, the beam energy is about 2.5 keV, which is relatively low compared with actual beam energies observed in the plasma sheet boundary layer.

The unit of length in the simulations is $\Delta = 2\lambda_{ie}$ where $\lambda_{ie} = \omega_{pe}/\omega_{ce}$ is the Debye length of the ionospheric plasma and $\omega_{pe}$ is the ionospheric plasma frequency. The system size is $L_x \times L_y = 512\Delta \times 128\Delta$, which for typical auroral parameters represents about $33 \times 16$ km. If it is assumed that the simulation distance across the field lines scales with the ion gyroradius rather than a Debye length (section 6), then the system actually represents a region $33 \times 64$ km, which is wider than the individual BEB events.

Unless otherwise stated, the beam width $w_b$ is assumed equal to a beam ion gyroradius $\rho_b$. The magnetic field strength is such that the electron cyclotron frequency $\omega_e$ is equal to $\sqrt{2} \omega_{pe}$. The corresponding beam ion gyroradius is $\rho_b = 36\Delta$. The properties of a beam where $w_b > \rho_b$ are discussed in section 6. It is shown that in this case the beam tends to filament, with each filament having similar properties for a beam with $w_b \lesssim \rho_b$.

The simulation system is symmetric about the beam center, which is placed at $y = L_y/2$. Because of this symmetry, computing time and memory can be saved by loading the beam and plasma particles in only the upper half of the system, $y \geq L_y/2$, and using symmetry to construct the plasma properties for $y < L_y/2$. This reduces the total number of particles needed in the simulations by a factor of 2. Typically, 131,000 particles are used for the 512 × 128 system. Plasma particles are reflected from all boundaries except for the right-hand boundary. At the latter boundary, the particles are re-injected at random so as to represent scattering by collisions in the ionosphere which can give rise to cross-field currents. If the particles near this boundary become depleted or a large number of accelerated particles start to cross this boundary, there is some uncertainty in the accuracy to which this approximation portrays the ionospheric boundary. It is for this reason that the simulations are stopped when the number of accelerated particles crossing the right-hand boundaries exceeds more than a few percent of the total number of particles in the system. This time corresponds to approximately $t \simeq 150/\omega_{pe}$, or equivalently $20/\omega_{pi}$, in the following results.

4. Simulation Results

4.1. Density Perturbations

The properties of the beam as it propagates into the system are indicated in Figure 4, which shows contours of beam charge density at $\omega_{pe}t$ equal to (Figure 8a) 50 and (Figure 8b) 150. The dotted contours indicate regions of negative charge density (i.e., where there are more beam electrons than beam ions) while the solid contours indicate regions of positive (or near zero) charge density. The densities are normalized to the initial ionospheric electron density $n_{ie}$. It is seen that, even though the beam charges are injected costripally, charge separation of the beam components occurs with regions of positive charge density lying on the outside of the beam and regions of negative charge density in the beam center. This charge separation is due to the gyroradius of a beam ion being much larger than that of an electron; the beam ions with their nonzero perpendicular energy are able to propagate across the field lines while the beam electrons remain tied to the field lines.

As a result of this charge separation, space charge fields develop which try to draw the beam ions back into the beam electrons in an effort to maintain quasineutrality. It is this electric field which produces the local ion maxima on the beam edges. A few of the ions on the outside edges are accelerated outward by a repulsive force from ions closer in toward the beam electrons, so that the beam ions can occupy a region much wider than the initial beam width. As the beam ions propagate outward, the ion beam density decreases, with the peak beam ion density being at most about $2n_{ie} = 0.5n_b$ on the flanks of the charge-separated beam electrons.

As the beam ions charge separate, a repulsive force associated with the excess negative charge in the beam center accelerates the beam electrons down the field lines. This is seen in Figure 4, where a region of negative charge density penetrates well into the auroral plasma, traveling at a speed much faster than the beam ions.
The space charge fields act not only on the beam particles but also on ambient plasma particles. The induced flows in the auroral electrons are illustrated in Figure 5, and those for the ionospheric electrons in Figure 6. Contours of their density at the beginning and end of the simulations are shown in Figures 5a and 6a and in Figures 5b and 6b, respectively. The solid contours indicate regions where the density is greater than about 0.5 \( n_{te} \) in Figure 5 and above 0.9 \( n_{te} \) in Figure 6 while the dotted contours indicate densities below these values. The arrows indicate the average flow of the particles.

Plasma electrons on the same field lines as the positive charge excess, associated with the charge-separated beam ions, are accelerated upward toward the magnetosphere. This is seen in the auroral electron density in Figure 5 as enhancements in their density in the magnetotail (i.e., the solid contours on either side of the beam region) and depletions at low altitude. It is also seen in the ionospheric electron density in Figure 6 where the electrons on these field lines have been drawn up into the auroral plasma region.

This electron flow leaves the charge-separated beam ions partially charge neutralized but effectively increases the net charge in the region of the beam electrons since their charge is no longer balanced by the same number of ions. In response to the repulsive force associated with this charge buildup, plasma electrons as well as beam electrons on these field lines are accelerated down toward the ionosphere. This is seen in the auroral electron density in Figure 5 as the expulsion of the bulk of the electrons from the beam region at high altitudes to low altitudes, producing the local maximum in the center of the system near the topside of the ionosphere. It is also seen in the ionospheric electron density in Figure 6 where densities greater than 90% of the initial density are present at much lower altitudes than the initial position of the ionospheric boundary. Note that these perturbations in the auroral and ionospheric plasmas occur even though the beam ions do not penetrate far into the system.

![Auroral Electron Density](image)

Fig. 5. Contours of the auroral electron density, for (a) initial profile and (b) final profile. The dotted contours denote regions where the density is below 0.5 \( n_{te} \), and solid contours indicate densities above this value. The arrows in Figure 5 indicate the direction of average flow. Electrons on the same field lines as the charge-separated ions are accelerated upward into the magnetosphere, producing the density enhancements in the magnetosphere and depletions at lower altitudes. Electrons on the same field lines as the beam electrons are accelerated downward, producing the density enhancement in the center of the system in the ionosphere.

![Ionospheric Electron Density](image)

Fig. 6. Contours of (a) the initial and (b) the final density of the ionospheric electrons. The dotted contours indicate densities below 0.9 \( n_{te} \). The ionospheric electrons are modified in a similar fashion as the auroral electrons in Figure 5 even though the beam ions do not penetrate far into the system.

As a result of these plasma flows, a region of primary current (i.e., net electron flow from magnetosphere to ionosphere) is present in the center of the system. This primary current is flanked on either side by return currents (i.e., net electron flow from ionosphere to magnetosphere). The maximum value of the primary current region determined from the simulations is about 3\( n_{te} v_{Te} \) while for the return current region it is about \( e n_{te} v_{Te} \). Note that the total primary and return currents are approximately balanced despite the fact that the magnitude of the return current density tends to be smaller than the primary current density because the total width of the (two) return current regions is wider than the (single) primary current region. This relative difference in the magnitudes of the currents is consistent with the observation described in section 4.2. The absolute value of the currents is also comparable with the observations with the maximum (primary) current in the simulations corresponding to \( 0.3 \times 10^{-6} \) A/m² assuming \( n_{te} = 1 \) cm⁻³ and \( T_e = 10 \) eV.

Because the primary and return currents are spatially separated, there is a tendency for a net buildup of positive charge in the return current region (associated with the ions left behind by the return current electrons) and a net negative charge in the primary current region.
(associated with the penetration or precipitation of beam and plasma electrons to lower altitudes). The electrons are not able to short-circuit this perpendicular field since they are tied to the field lines. As a result, a perpendicular electrostatic shock develops which tries to accelerate plasma ions across the field lines from the return current region into the primary current region in order to maintain quasi-neutrality.

The perturbations in the ion density produced by the shock is illustrated in Figure 7, which shows the contours of total plasma ion density. The initial profile is shown in Figure 7a and that at the end of the simulation in Figure 7b. The dotted and solid contours and arrows signify the same quantities as in Figure 5. It is seen that throughout the primary current region, the density is enhanced, with the density near the center of the system increasing by as much as about 50% over the duration of the simulation. On the other hand, a plasma depletion or cavity develops in the return current region with the density decreasing by about 20% over the duration of the simulation. The corresponding ratio of the density in the plasma enhancement is about twice that in the plasma cavity, which is comparable to that seen in the HAPI data (subsection 2.2).

There is also some net parallel acceleration of the plasma ions in the primary current region up into the magnetotail. However, it remains relatively small on the time scales of the simulations since the velocity of the plasma ions is so small that they are unable to propagate through much of the potential drop accelerating the plasma electrons.

![Electric Potential](image)

Fig. 8. Contours of the electric potential for the same times as in Figure 4. Dotted areas indicate negative potentials while solid contours indicate positive potentials. A perpendicular electrostatic shock quickly develops throughout most of the system and is then maintained at an approximately constant level except for the development of localized potential islands or double layers.

4.2. Electric Potential and Wave Fields

The electric potential corresponding to the above example is shown in Figure 8 for $\omega_{pe} t$ equal to (Figure 8a) 50 and (Figure 8b) 150. The dotted areas denote regions of negative potential while solid contours denote regions of positive potential. Large gradients in the potential are evident in the vicinity of the charge-separated beam ions. These gradients are enhanced due to the relative shortness of the magnetospheric section of the plasma treated in the simulation. The perpendicular electrostatic shock associated with the spatially separate primary and return current regions is seen as strong gradients in $y$ extending from the ion beam front down into the ionosphere. The gradients in the potential tend to be smaller in the ionosphere where there is more plasma available to respond to and thereby reduce the electric fields.

On comparing Figures 8a and 8b, it is seen that the perpendicular electric fields develop rapidly and then remain at an approximately constant level with the maximum potential being about $0.7n_i eT_i^2/2$. This quasi-static behavior of the electric fields is due to a competition between the charge separation of the beam ions which is driving the electric fields and the plasma response which is trying to reduce the electric field.

Within the auroral plasma region, the total potential drop across the shock is typically $0.3n_i eT_i^2/2$ over a distance of about $30 \Delta$ (i.e., over about an ion beam gyroradius). The corresponding perpendicular electric field has a magnitude of about 40 mV/m for the assumed simulation parameters. This is comparable to the lower range of values for perpendicular electrostatic shocks observed by S3-3 [Mozer et al., 1980; Temerin
et al., 1982; Mozer et al., 1985]. The electric field strength is relatively low in the present case because of the relatively low beam energy which was assumed in order to accommodate a few beam gyroradii across the simulation system and several hundred Debye lengths along the magnetic field. Larger potentials are possible if the beam energy or density is made larger.

Note that the parallel electric field within the shock remains relatively small due to the fast motion of the plasma electrons, which tends to short out the parallel electric field. The ions with their much larger inertia are slower to respond to the perpendicular electric field, which thereby allows the development of larger perpendicular fields. At later times, plasma turbulence in association with potential islands (i.e., double layers) or localized parallel electric fields can also develop, as seen in Figure 8b.

The power spectra for the induced waves near the center of the auroral plasma region (at \( x = 250 \Delta \)) at different positions across the magnetic field are shown in Figure 9. Spectra in the primary current and return current regions are shown in Figures 9a and 9b and in Figures 9c and 9d, respectively. Spectra near the boundary between these two regions are shown in Figures 9e and 9f. Spectra for the parallel electric field are shown on the left-hand side, and those for the perpendicular electric field on the right-hand side. The arrows mark the upper cutoff of the wave emissions except for narrow-banded emission about the electron cyclotron frequency in the perpendicular wave fields.

It is seen that the spectrum is broadbanded extending from near the ion cyclotron frequency to the electron cyclotron frequency (frequencies below about \( \Omega_i \) are not well resolved since the simulations are only run for about an ion gyroperiod). The waves are due to space charge oscillations associated with the acceleration of particles both along and across the magnetic field. The spectrum is broadbanded because the particles are undergoing nonnegligible accelerations on time scales of the order of their natural oscillation frequency, which can modify the actual oscillation frequency. Moreover, the quasi-static fields are producing macroscopic perturbations in the plasma density, so that well-defined plasma modes are not present. This situation differs from kinetic instabilities where gradients in the velocity distribution drive waves unstable, with the perturbations in both velocity and density remaining small during a wave period.

The highest wave frequencies are the narrow-banded emissions near the electron cyclotron frequency which are primarily directed perpendicular to the magnetic field (i.e., \( E_\perp \gtrsim E_\parallel \)). They are induced by the perpendicular electrostatic shock trying to drag the electrons across the field lines.

Apart from these narrow-banded emissions, the highest-frequency emissions are primarily directed along the magnetic field (i.e., \( E_\perp \ll E_\parallel \)) and occur in the primary current regions where the density is highest. The upper cutoff of these emissions, as indicated by the arrows, extends past the ionospheric plasma frequency \( \omega_{pe} \) which is greater than the local plasma frequency. However, the spectral maximum of these waves occurs near the local plasma frequency with the position of the spectral maximum shifting to lower frequencies from the primary current region to the return current region. These features are consistent with the high-frequency spectral maximum seen in BEB (subsection 2.1) and suggest that these waves are due to an electron beam-plasma interaction.

At frequencies below about \( \omega_{pi} \), the power in the parallel electric field tends to decrease, and the dominant wave fields are perpendicular to the magnetic field. These wave fields have a local maximum near \( \omega_{pi} \) which is approximately equal to the local lower hybrid frequency. They are more intense than the waves seen near the local electron plasma frequency, with the maximum field intensities being near the boundary between the primary and return current regions, and are produced by the perpendicular electrostatic shock and the perpendicularly accelerated ions. These wave fields are able to account for the second spectral maximum of BEB (cf. Figure 1).

The spectral maximum at the lowest frequency seen during BEB is not discernible in the present simulations since frequencies below about the ion cyclotron frequency are not well resolved. Moreover, only one ion species is treated in the present simulation which could give rise to a separate spectral maximum as the ions are accelerated.
across the shock. Despite this limitation the present simulations are able to reproduce several features of BEB including (1) its broad spectrum, (2) higher frequencies and intensities near the primary current region, and (3) local maxima in the spectra near the local electron plasma and ion plasma/lower hybrid frequencies.

4.3. Electron Energization

The energization of the beam electrons as charge separation occurs is illustrated in Figure 10, which shows the $v_x$-$x$ phase space (i.e., $v_x$ along the magnetic field integrated over all $y$) on the left-hand side and the $v_x$-$y$ phase (i.e., $v_x$ across the magnetic field integrated over all $x$) on the right-hand side for the beam electrons at $\omega_{pe}t$ equal to 50, 100, and 150. The arrows in the figures indicate the position of the ion beam front along the magnetic field. Beam electrons which are well behind the ion beam front and which experience little acceleration are seen as the dark patch of electrons at $x/\Delta \lesssim 80$ and $0 \lesssim v_x/v_T \lesssim 3$. However, beyond the ion beam front, the beam electrons are seen to be accelerated to higher velocities reaching peak speeds of about 10$v_T$ and with a mean speed of about 5$v_T$. Strong space charge oscillations (as indicated by the vortices in the $v_x$-$x$ phase spaces in Figures 10c and 10e) are seen to grow and propagate down the field lines.

The distribution of these accelerated electrons across the magnetic field can be seen from the $v_x$-$y$ phase spaces shown on the right-hand side of Figure 10. It is seen in the present case that the fastest electrons lie near the center of the beam, giving the phase space a similar appearance to that observed during inverted-V events. Near the edges of the beam, there is also strong acceleration as indicated by the vertical features in the phase space at $y/\Delta \simeq 45$ and 82. From an examination of the $v_x$-$x$ phase space, these electrons lie primarily behind the ion beam front at high altitudes and therefore are not expected to be observed in typical low-altitude observations of inverted-V events. The acceleration is due to space charge oscillations induced by the charge-separated ions as they try to drag the electrons across the field lines.

Figure 11 shows the $v_x$-$x$ and the $v_x$-$y$ phase spaces for the ambient plasma electrons at $\omega_{pe}t$ equal to 0, 50, and 150. The solid arrows again denote the position of the ion beam front while the dashed arrows represent the approximate position of the electron beam front (where the beam electron density first becomes appreciable). On comparing Figures 10 and 11, it is seen that the plasma electrons on the same field lines as the beam electrons are accelerated to similar velocities with a local

![Plasma Electrons: $v_x$](image)

Fig. 10. The $v_x$-$x$ (left side) and the $v_x$-$y$ phase spaces of the beam electrons at $\omega_{pe}t$ equal to 50, 100, and 150. The arrows indicate the position of the ion beam front. Electrons forward of the ion beam front are seen to be accelerated to higher velocities, reaching speeds as high as 10 $v_T$, and with a mean speed of about 5 $v_T$. Electrons behind the ion beam front near the edge of the beam also experience strong accelerations as the ions try to drag them across the field lines.

![Plasma Electrons: $v_x$](image)

Fig. 11. The $v_x$-$x$ (left side) and the $v_x$-$y$ (right side) phase spaces of the ambient plasma electrons at $\omega_{pe}t$ equal to 0, 50, and 150. The solid arrow indicates the position of the ion beam front, and the dashed arrow indicates the electron beam front. Plasma electrons in the primary current region (i.e., in the center with respect to $y$) are accelerated downward, reaching speeds comparable to the beam electrons. Strong return currents with bulk velocities of about 2 $v_T$ are seen on either side of the primary current region (i.e., the dark regions on either side of the primary current region in the $v_x$-$y$ phase spaces). Strong turbulence associated with the charge-separated beam ions produces heating of these electrons once they have passed the ion beam front, as seen by the tenuous high-energy component on either side of the primary current region.
maximum in $v_T \approx 7v_{Te}$ at $x$ near the electron beam front and at $y$ in the center of the beam region.

Strong return currents with bulk velocities of about $-2v_{Te}$ are seen on either side of the beam region (namely, $v_x-y$ phase space) extending from about the electron beam front back into the magnetosphere (namely, $v_x-x$ phase space). Strong turbulence associated with the charge-separated beam ions produces heating of these return current electrons up to speeds of about $10v_{Te}$ once they propagate past the ion beam front. It is this same turbulence which produces the heating of the beam electrons near the beam edge.

In order to show the type of electron distribution that would be observed, Figure 12 shows the total electron distribution as a function of position along the magnetic field in the primary current region. Each distribution has been taken over a region of $16\Delta \times 8\Delta$, centered at $y/\Delta = 68$ at spacings of $90\Delta$ along the magnetic field. The initial distribution of the ambient plasma electrons is shown in Figure 12a while Figures 12b–12e show the distributions at the end of the simulation. The distribution in Figure 12b consists of primarily beam electrons, with the ambient plasma electrons being accelerated down to lower altitudes (as evidenced by the lack of any cold component). The distribution at this point has a slight drift of about $2v_{Te}$. The large $v_{Te}$ relative to the initial ambient distribution is due to the higher initial thermal speed of the beam electrons rather than any appreciable perpendicular acceleration.

The distribution in Figure 12c is in the vicinity of the large space charge oscillation in Figure 10c. The distribution has two counterstreaming beams (and a slowly drifting background component), with the upward propagating beam having a small net drifts of about $-2v_{Te}$ and the downward propagating beam having a much greater drift speed of about $9v_{Te}$. Wagner et al. (1985) also generated similar counterstreaming beams in their simulation model by trapping via large-amplitude electrostatic waves produced through the two-stream instability. Such counterstreaming beams are on occasion seen on auroral field lines [Lin et al., 1982, 1984].

At the next lower altitude (Figure 12d), the distribution consists of a beam with a bulk drift speed of about $5v_{Te}$ as well as a drifting background component with a speed of about $1-2v_{Te}$. At the lowest altitude (Figure 12e), the electrons essentially have a single drifting distribution with an average speed of about $2-3v_{Te}$ and with its parallel temperature much greater than its perpendicular temperature. There is little perpendicular acceleration of the electrons as they remain tied to the field lines and are unable to fall through the potential drop associated with the perpendicular electrostatic shock.

The variations in the electron distributions across the ambient field lines are illustrated in Figures 13a–13d, which show the distributions at $x/\Delta = 212$ and $y/\Delta$ equal to 68, 80, 92, and 104, respectively. The first two distributions are in the primary current region while the lower two are in the return current region. The beam which is evident near the center of the system (Figure 13a) becomes less apparent as the boundary between the primary and return current regions is approached (Figure 13b). This is due to the canceling of the fields driving these two currents. Further across the field lines (Figures 13c and 13d) in the return current regions, well-defined upward drifting distributions with average speeds of about $2v_{Te}$ are seen.

Note that the temperature of these return current electrons is not significantly higher than that of their initial distribution in Figure 12a, unlike in the primary current region. This lack of heating is due to the absence of beam-plasma interaction and associated wave turbulence. Indeed, the power spectra of the parallel electric field (Figure 9) show nearly an order of magnitude decrease in wave intensity between the primary and return current regions at frequencies near the local electron plasma frequency.

This type of drifting electron distribution tends to be unstable to electrostatic ion cyclotron wave as well as shear Alfvén wave instabilities [Ashour-Abdalla and Okuda, 1984; Winglee et al., 1987, 1988c]. However, the time scale for the growth of these instabilities is several tens of ion gyroperiods, which is much longer than the duration of the present simulations.

4.4. Ion Energization

In contrast to the electron acceleration, the ions are primarily accelerated across the magnetic field rather than along the magnetic field. This is because the
Fig. 13. The total electron distribution in the auroral zone (at \( z/\Delta = 212 \)) as a function of position across the magnetic field. The energy of the beam decreases toward the beam edge due to cancelation of the fields driving the primary and return currents. The return currents themselves (Figures 13c and 13d) comprise a bulk drift in the electron distribution of about \( \sqrt{v_{Te}} \).

Electron motion tends to reduce the parallel electric field but not the perpendicular electric field. As a result, the ions over the duration of the simulation are more easily able to fall through the potential drop across the magnetic field rather than along it. This perpendicular acceleration occurs on much faster time scales than that associated with the above current-driven wave instabilities and can even suppress their growth due to the increase in the perpendicular ion energy.

As an example of the perpendicular acceleration of the ions, Figure 14 shows the perpendicular phase spaces of the plasma ions. The top panels show the initial perpendicular phase spaces. The middle and bottom panels show the final \( v_y \) and \( v_z \) phase spaces, respectively. On the left-hand side, the phase spaces as a function of \( x \) are shown while on the right-hand side the phase spaces as a function of \( y \) are shown. The velocity \( v_y \) is indicative of the \( y \) acceleration experienced by the ions. Some of this perpendicular energy appears in \( v_z \) through gyromotion, over which is superimposed the \( E \times B \) drift.

It is seen that the strongest ion acceleration occurs near the ion beam front and decreases down the field line. This is due to (1) the length of time the ions see the shock decreasing with distance from the ion beam front and (2) the density being higher at the lower altitudes so that the plasma is more easily able to respond to the space charge fields and thereby inhibit the necessity of large-amplitude fields and strong particle acceleration.

The highest-energy ions are seen in the primary current region between \( 45 \lesssim y/\Delta \lesssim 80 \), and they can reach energies as high as the beam energy. Besides this energetic component, there is also bulk acceleration of the ions extending from the return current regions into the primary current region. This acceleration occurs in association with the formation of plasma cavities in the return current region and a plasma enhancement in the primary current region. The bulk of phase space has been distorted from an initially flat distribution (Figure 14b) to an "N"-shaped distribution in Figure 14f and to a lesser extent in Figure 14d. The bulk drift velocity reaches a maximum near the boundary between the primary and return current regions, i.e., at \( y/\Delta \approx 45, 80 \). At these boundaries the ions have an average \( v_z \) of about \( 0.25v_{Te} \) and an average \( v_y \) of about \( v_{Te} \). This bulk acceleration may account for asymmetric cones and the dropouts seen in the RIMS data during crossings of primary current regions when intense BEBs are observed (section 2).

The total ion distributions for the same positions in Figure 13 are shown in Figure 15. (A speed of about 0.25 \( v_{Te} \) corresponds to about 120 km/s for a H\(^+\) ion or about 160 eV.) Strong perpendicular heating or coniclike distributions are evident in both primary current and return current regions (e.g., Figures 15b-15d), although...
from its injected or initial value is in the perpendicular energy of the beam ions (Figure 16b). It is this energy which drives the charge separation and the associated perpendicular electrostatic shock. Over the length of the simulation, the beam ions lose nearly a third of their perpendicular energy. Of this energy loss $\Delta E$, about 30% goes into acceleration of the beam particles: the parallel energy of the beam ions increases by about 0.1 $\Delta E$ while the parallel energy and perpendicular energy of the beam electrons increase by 0.12 $\Delta E$ and 0.07 $\Delta E$, respectively. At the end of the simulation, the beam electrons have more parallel energy than perpendicular energy.

The remainder of the lost beam energy, i.e., 0.7 $\Delta E$ (or about 20 $E_0$), is deposited in the auroral and ionospheric plasmas. The largest energy increases, as previously discussed, occur in the parallel energy of the plasma electrons and in the perpendicular energy of the plasma ions. At the end of the simulation, the electron parallel energy has increased by nearly a factor of 9 or equivalently by about 0.3 $\Delta E$ and exceeds the electron perpendicular energy by nearly a factor of 3. The ion perpendicular energy increases by a comparable amount.

4.5. Efficiency of the Magnetospheric-Ionospheric Coupling

The above results show that strong energization of the beam electrons and plasma particles can result from the formation of a perpendicular electrostatic shock which is driven by charge separation between the beam ions and electrons. In order to show the efficiency of the coupling, Figure 16 shows time histories of the parallel energy $E_\parallel$ (dotted curves), and the perpendicular energy $E_\perp$ (solid curves), normalized to the initial energy of the ionospheric electrons $E_0$ for the electron and ion components of the beam and auroral and ionospheric plasmas. The dashed curves in Figures 16a and 16b indicate the actual energy injected into the system. Since beam particles are being continually injected into the system, the total energy of the beam particles increases with time.

The only energy component that shows a decrease

Fig. 15. The total ion distribution as a function of position across the magnetic field in the auroral zone (at $z/\Delta = 212$). Conic distributions are present in both primary and return current regions, with the strongest perpendicular acceleration being present near the boundary between these two current regions. Bulk perpendicular acceleration of the plasma is indicated by the maximum of the distribution being shifted from the origin.

Fig. 16. Time histories of the energy of the various plasma species. The solid lines indicate the perpendicular energy $E_\perp$, and the dotted lines the parallel energy $E_\parallel$, relative to $E_0$, which is approximately the initial parallel energy of the ionospheric electrons. The dashed lines in Figures 16a and 16b indicate the amounts of beam energy actually injected into the system. The only component to lose energy is the perpendicular energy of the beam ions (about 30%) which is driving the charge separation and associated space charge fields. The electrons primarily gain parallel energy, and the ambient plasma ions primarily perpendicular energy.
The energies of the ionospheric plasma show a similar preferential heating in the electron parallel energy and the ion perpendicular energy. The absolute changes in magnitude are, however, smaller since the electric fields and the time of interaction with these fields are smaller in the ionosphere than in the auroral plasma region.

Note that the changes in the particle energies shown in Figure 16 account for nearly all the energy lost by the beam ions. The wave energy only accounts for less than about 1% of $\Delta E$. The reason for the relatively low energy in the wave fields is that, although strong electric fields are produced by the charge separation of the beam ions, they tend to be reduced by the plasma response to these fields. In other words, the field intensities, once established, remain approximately constant, with a continual transfer of energy from the beam to the ambient plasma via these electric fields. The wave fields, while they remain energetically unimportant, provide the mechanism by which energy is transferred from the magnetosphere to the ionosphere. This is consistent with the observations of Kintner and Gorney [1984] and Peterson et al. [1988].

5. Variations With Beam Energy and Density

The results from the previous section show that space charge fields arising from the charge separation of an initially charge-neutral ion beam with nonnegligible perpendicular energy can produce a perpendicular electrostatic shock. This shock in turn can lead to the strong acceleration of auroral and ionospheric plasma. As is now shown, the amount of coupling, or efficiency, is dependent on the perpendicular current associated with the charge separation of the beam ions rather than just on the beam energy. Variability in the intensities of the observed BEB and auroral particle acceleration is attributed to differences in the perpendicular current associated with different incoming beams.

As an example, Figure 17 shows the $v_x-y$ phase space of the beam electrons for the same parameters in Figure 10 except that (1) the beam density is half as large and (2) the perpendicular beam velocity $v_{\perp b}$ and beam width are $\sqrt{2}$ larger (which increases the perpendicular beam energy while keeping the ratio of the beam width to ion gyroradius the same). Thus, the perpendicular energy injected into the system is $\sqrt{2}$ larger than in Figure 10 but the (unneutralized) perpendicular current is $\sqrt{2}$ smaller. It is seen that the phase spaces are qualitatively the same, with the acceleration of the beam electrons to higher parallel velocities and the development of intense space charge oscillations (as evidenced by the vortex about $x/\Delta \approx 100$). However, the magnitude of the acceleration is smaller, with the average speed of the beam electrons at $x/\Delta \geq 160$ being only about 3–4 $v_T$, while it is about 5–6 $v_T$ in Figure 10.

The ability of the beam to couple energy into the ambient plasma is also reduced. This is illustrated in Figure 18, which shows the corresponding energy time histories of the beam and plasma particles. It is seen on comparing Figures 16b and 18b that the fraction of perpendicular energy lost by the beam particles is nearly half as small in the present case, being only about 15% of the total perpendicular energy. Moreover, the ambient plasma only reaches energies similar to those in Figure 16 after a time $t = 200/\omega_{pe}$ (compared with $150/\omega_{pe}$), even though much more energy is carried into the system by the beam.

The reason for this reduction in the efficiency of coupling energy from the magnetosphere to the ionosphere is that, with the smaller perpendicular current associated with the charge separation, the ambient plasma is more easily able to produce neutralization of the space charge fields without the need of being accelerated up to as high an energy. Despite this difference in the efficiency of the coupling, the acceleration of the ambient plasma is similar, with primarily parallel acceleration of the plasma electrons and perpendicular acceleration of the plasma ions.

6. Wide Beams and Current Filamentation

In the examples in sections 4 and 5, the beam width is equal to a gyroradius of a beam ion. This width is comparable to that in most of the primary current regions seen in the observations in Plate 2. However, on occasion the region of primary current can be a very broad event, for example, at about 1014 UT in Plate 2 (subsection 2.2). In this section, a beam with width greater than a beam ion gyroradius is examined. It is shown that the beam in this case tends to filament into elements, with each element having a width of the order of a beam ion gyroradius and similar properties as described in the previous sections.
As an example, Figure 19 shows (Figure 19a) the beam density, (Figure 19b) total (ambient) plasma parallel current, and (Figure 19c) the total plasma ion density at \( \omega_{pe} t = 150 \) for the same parameters as in section 4 except that the magnetic field strength and beam width are larger by factors of 2 and 1.5, respectively. The beam width is then equal to three beam ion gyroradii. The dotted (solid) contours in Figures 19a-19c indicate regions of negative (positive) charge density, primary (return) current regions, and densities below (above) 0.5 \( n_{ie} \), respectively.

As seen in Figure 19a, charge separation occurs on the outside edge of the beam as before and results in the acceleration of the beam electrons. However, due to shielding in the center of the beam, the electrons near the beam edge experience the strongest accelerations, as seen in Figure 19a where the edges have streamed out further than the center. Plasma ions (Figure 19c) on either side of these streams, including those ions in the center of the system, are drawn into these streams by the associated negative charge excess. As a result, the density enhancements develop on the edges of the beam and cavities on either side and in the center of the beam region. This ion motion leaves an excess electron density in the middle of the system. As a result, some of the beam ions begin to accumulate in the center of the beam (as evidenced by the net positive charge in the center of the beam in Figure 19a) and accelerate the electrons in the middle of the system upward into the magnetosphere.

As a consequence, a filamented current system develops with return currents not only on the flanks of the beam but also in the center of the beam, as seen in Figure 19b. Strong positive or primary currents are present at the edges of the beam region. This current profile is similar to that seen in the HAPI and the magnetometer data (Plate 2 and Figure 2) during the broad event about 1014 UT. Similar filamentation of even wider beams occurs in a similar fashion and does not appear sensitive to the initial conditions for the beam injection [Winglee et al., 1988b].

The difference in the particle acceleration in the filamented primary and return current regions is illustrated in Figure 20, which shows the \( v_x - x \) phase space for the

![Figure 18](image1.png)

Figure 18. As in Figure 16, for the parameters in Figure 17. The acceleration of the ambient plasma is qualitatively the same. However, the efficiency is much smaller, with only about 15% of the beam energy going into the ambient plasma, and it takes much longer to produce the same energization of the ambient plasma in Figure 16.

![Figure 19](image2.png)

Fig. 19. The beam density, total plasma parallel current, and total ion density at \( \omega_{pe} t = 150 \) for the injection of a beam where its width is 3 times the beam ion gyroradius. The magnetic field strength is twice as large as in Figure 10, and the beam width is 1.5 times larger. The dotted (solid) contours in the different panels indicate regions of (a) negative (positive) charge density, (b) primary (return) current regions, and (c) densities below (above) 0.5 \( n_{ie} \), respectively. Charge separation occurs as before, but due to shielding of the fields in the center of the beam, the strongest particle accelerations occur near the edge of the beam. As a result, the beam filament a series of primary and return current regions, each of the order of a beam ion gyroradius, with enhanced densities associated with the primary current regions and density cavities in the return current regions.
Fig. 20. The \( v_x - y \) phase space for the beam electrons (left side) and the ambient plasma electrons (right side) for the case in Figure 19 at \( \omega_{pe} t \) equal to 50, 100, and 150. The solid (dashed) arrows indicate regions of primary (return) currents. The energy reached by the particles is similar to that in Figures 10 and 11. However, with the wider beam and the resulting filamentation, electrons in the center of the beam experience even stronger acceleration down into the ionosphere and can actually be drawn back up into the magnetosphere.

beam and plasma electrons at \( \omega_{pe} t \) equal to 50, 100, and 150. The solid arrows indicate the approximate positions of the primary currents while the dashed arrows indicate the regions of return currents. The primary current regions coincide with a local maximum in \( v_x \simeq 10v_T e \) for the beam electrons near the edge of the beam. Near the center of the beam in one of the return current regions, the beam electrons have a local minimum in \( v_x \) with an average negative drift of about 1–2 \( v_T e \).

The plasma electrons show a similar series of local maxima and minima through the different current regions as is seen on the right-hand side of Figure 20. The bulk of the electrons are represented by the dark regions of phase space and have average bulk speeds of about 1–2 \( v_T e \) in the outside return regions as well as in the primary current region. In the central return current region, the bulk speed is about half this value. A tenuous high-energy component associated with the return current electrons interacting with the charge-separated beam ions is present in the vicinity of the charge-separated beam ions.

As an indication of the perpendicular velocities and spatial distribution of the plasma ions, Figure 21 shows the \( v_x - y \) phase space of the plasma ions for the same times as Figure 20. Bulk perpendicular acceleration of the ions is seen throughout the different current regions. The strongest acceleration occurs on the boundary between the outside return current regions and the primary current regions, at \( y/\Delta \simeq 40, 90 \). There is only weak bulk acceleration of the ions in the center of the beam. The few very energetic ions in this region are due to an overshoot of some very energetic ions through the primary current region into the center of the beam. These characteristics of the particle velocities about each filament are essentially the same as in the smaller single events discussed in the previous sections.

7. Summary

In this paper, observations from DE 1 and two-dimensional electrostatic particle simulations have been combined in an effort to provide a unified model for (nightside) auroral particle acceleration and wave emissions in association with the formation of plasma cavities and enhancements. The observations show that during auroral crossings, in addition to auroral hiss, auroral kilometric radiation, and z mode radiation, intense broadband electrostatic bursts (BEB) can be present. The bursts can extend from the ion cyclotron frequency to the electron cyclotron frequency. The bursts have local spectral maxima at frequencies near the oxygen plasma frequency, the lower hybrid frequency, and the electron plasma frequency.

These bursts are observed in association with enhanced precipitation of energetic electrons from the magnetotail.
in the model is in identifying a possible source of free energy of the auroral particle acceleration and wave emissions. One possible source is the ion beams observed in the plasma sheet boundary layer. This assumption has several advantageous features. The plasma sheet boundary layer is known to be one of the primary energy transport regions in the magnetosphere with much of the energy being carried by ion beams with nonnegligible perpendicular energy. The plasma sheet boundary layer lies on the same field lines as the nightside auroral region, and the energy in the beams is more than sufficient to produce the observed particle acceleration.

The results from the simulation model are summarized in the schematic diagram in Figure 22. Due to the nonzero perpendicular energy of the ions, charge separation occurs between the ions and costreaming electrons since the ions have a much larger gyroradius than the electrons. This charge separation sets up a U-shaped electric potential at the expense of the perpendicular energy of the beam ions. Disturbances associated with these space charge fields are able to penetrate well down the field lines without the beam ions actually needing to propagate down to auroral altitudes.

In particular, the electric field accelerates electrons on the same field lines as the beam electrons down into the ionosphere. The peak velocity of these electrons is about 10 $v_T e$ in the simulations in section 4, which would correspond to an energy of about 1 keV assuming that the auroral plasma has an initial temperature of 10 eV. Electrons on the same field lines as the charge-separated beam ions are drawn upward into the magnetosphere to form a return current. The maximum primary current density in the simulations in section 4 is about $3e n_e v_T e$ while the return current density is about $en_e v_T e$. The total primary and return currents are nevertheless balanced since the total return current region tends to be wider than the primary current region. The magnitude of these currents is comparable to that obtained from HAPI and the magnetometer.

Because the primary and return currents are spatially separate, local charge neutrality is violated. The electrons cannot close the current since they remain tied to the field lines. Ionospheric currents can also close the currents, but the time scale for the enhanced current to propagate from the magnetosphere down to the ionosphere and back up is of the order of a second, much longer than the ion plasma time scale, which is of the order of a few milliseconds. Thus, it is the plasma ions which are forced to provide current closure or charge neutralization of the spatially separate current regions.

These ions are accelerated perpendicularly across the field lines in an effort to maintain quasi-neutrality, which produces conic distributions in velocity space, and in coordinate space produces plasma cavities in the return current regions and plasma enhancements in the primary current regions. Ions in the density enhancement are eventually accelerated along the magnetic field by the same electric field which is producing the downward propagating electron beam. This dual acceleration of the ions may account for the "X"-shaped spin phase spectrograms observed by Moore et al. [1985] in association with inverted-V events and the bimodal acceleration observed by Klumpar et al. [1984].
The presence of conics in both primary and return current regions is consistent with observations from EICS and RIMS that conics are observed in association with both types of currents. Moreover, the resultant generation of plasma cavities and enhancements is consistent with the density profile obtained from HAPI data.

The width of each current region tends to about a gyroradii of an ion with the perpendicular beam energy. This is approximately the distance an ion can be accelerated across a field line by quasi-static electric fields. Beams with much greater widths tend to filament into elements of this width, with current closure being achieved between adjacent filaments. This filamentation is observed in current profiles of large inverted-V events (e.g., section 2.2).

Intense electrostatic waves are generated by the accelerated particles through induced space charge oscillations (rather than by kinetic instabilities). The accelerated electrons are associated with strong wave turbulence near the local electron plasma frequency, with the highest frequencies being generated in the plasma enhancements, i.e., in the primary current regions. The plasma ions as they are accelerated across the field lines generate lower hybrid waves. The spectrum of these waves tends to be broadened by the quasi-static electric fields, which produces continued acceleration of the particles. These results are able to account for several of the observed features of BEB (section 2.1) including (1) the broad frequency range, (2) two of the spectral maxima of BEB, and (3) the association of high-frequency cutoffs in BEB with primary current regions and density enhancements. The presence of a third spectral maximum in BEB at low frequency may be due to the presence of a heavy ion which is not treated in the present simulations.

Through the space charge fields, the beam ions are able to efficiently couple energy from the magnetosphere into the auroral region and ionosphere. In the example in section 4, the beam ions lose nearly 30% of their perpendicular acceleration, the bulk of which goes into the parallel acceleration of the beam and plasma electrons and the perpendicular acceleration of auroral and ionospheric ions. With the loss of perpendicular energy, the beam ions should propagate further into the convergent magnetic field since the mirror point decreases with pitch angle. As the ions do so, their perpendicular energy would be partially restored at the expense of their parallel energy. As a result, the convergent geomagnetic field could provide enhanced coupling of energy from the magnetosphere as well as allow the beam to penetrate further into the auroral region. Indeed, the lowering in altitude of the mirror point of the beam ions may account for the occasional presence of downflowing ions when perpendicular ion acceleration is observed.

The present simulations are not able to investigate this problem since the magnetic field is assumed to be homogeneous. The convergence of the field lines may also play a direct role in the particle acceleration. Such fields can lead to the focusing of the precipitating electrons and associated space charge fields, which can in turn lead to enhanced particle acceleration and currents. This focusing may account for the very high energy (\(\simeq 10\) keV) electrons observed at low altitudes which are not generated in the present simulations. We hope to address these and other problems related to the convergence of the field lines in a future paper.

The present simulations are also limited in that only one ion species is treated so that there is little information on the heating of heavy ion species such as \(\mathrm{O}^+\). Differential motion between heavy and light ions is difficult to simulate at present due to restrictions on the duration of the simulations imposed by the quick propagation of the beam electrons through the system. A related difficulty with the limited duration of the present simulations is that they can only investigate the initial formation of a discrete auroral arc. Much longer time scales can be possibly investigated when boundary conditions at the ionosphere (e.g., including collisional processes) are more accurately incorporated in the simulation model. Nevertheless, preferential perpendicular acceleration of the heavy ions is expected due to differences in the gyroradii of the different ions [cf. Borovsky, 1984] just as the differences in gyroradii between the ions and electrons produce preferential parallel electron acceleration and preferential perpendicular acceleration of the ions in the present simulations. This should be especially true in large events where the heavy ions can propagate more easily further across the field lines than the light ions.

In summary, observations from DE 1 and two-dimensional electrostatic particle simulations have been combined in an effort to provide a unified model for (nightside) auroral particle acceleration and wave emissions in association with the formation of plasma cavities and enhancements. It is shown through simulations that the different types of particle acceleration and wave emissions are integrally related and are not independent of each other. The downward acceleration of electrons into the ionosphere can be produced by space charge fields associated with ion beams in the plasma sheet boundary layer (which do not need to actually propagate down to the auroral altitudes to produce a disturbance there). Electrons on the same field lines as the charge-separated beam ions are drawn upward from the ionosphere to form the return current into the magnetosphere. Ambient plasma ions are drawn across the field lines to produce current closure between the spatially separate primary and return current regions. This acceleration produces conic distributions in velocity space and, in coordinate space, plasma cavities in the return current regions and plasma enhancements in the primary current regions. Broadband electrostatic bursts are associated with this particle acceleration. A local spectral maximum near electron plasma frequency is generated by the accelerated electrons, and a spectral maximum near the lower hybrid frequency by the perpendicularly accelerated ions.

Acknowledgments. One of us (R. M. W.) gratefully acknowledges M. M. Mellott for providing the initial wave data which enabled the comparison with observations to be undertaken, W. K. Peterson for many enlightening discussions on the EICS data and C. S. Lin for providing the HAPI data. We acknowledge C. R. Chappell, the RIMS PI, and D. A. Gurnett, the PWI PI, for use of their data and the DE program for data analysis. This work was supported by National Science Foundation grants ATM 87-19371, ATM 83-18203 and by NASA's Solar Terrestrial Theory, Solar Heliospheric Physics and Space Plasma Physics Programs under grants NAGW-91, NSEG-7287 and NAGW-998 to the
University of Colorado; by National Science Foundation grant ATM 85-21125 and NASA's Solar Terrestrial Theory Program grant NAGW-78 to the University of California, Los Angeles; by NASA grant NSS-28710 to Lockheed and by the Lockheed Independent Research Program; by NASA grant NSS-28711 to Southwest Research Institute; by NASA grant NAG-5310 to the University of Iowa. The simulations were performed on the CRAY-YMP at the San Diego Supercomputer Center which is supported by the National Science Foundation.

The editor thanks J. M. Bosqued and A. Morikza for their assistance in evaluating this paper.

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(Received March 14, 1988;
revised July 7, 1988;
accepted July 18, 1988.)
Plate 1 [Winglee et al.]. Frequency spectrogram for the electric field from the University of Iowa plasma wave instrument for October 19, day 292, 1981. The white lines indicate the electron, hydrogen, and oxygen cyclotron frequencies, from top to bottom. The auroral crossing occurs between 1012 UT and 1040 UT, after which the spacecraft moves into the plasmasphere. Several intense broadband electrostatic bursts (as indicated by the discrete bands of emissions between $10^4$ Hz and $6 \times 10^4$ Hz) are seen during the auroral crossing.

Plate 2 [Winglee et al.]. The top panel shows the HAPI electron energy spectrogram during the auroral crossing. The bottom panel shows the east-west component of the magnetic field as measured by the magnetometer, and the inferred parallel currents are shown in the middle panel. There is a net inflow of energetic electrons from the magnetosphere into the ionosphere (i.e., a net positive current). Superimposed on this net flow are several intensifications (as indicated by the yellow regions in the energy range 1–10 keV) which are associated with regions of enhanced positive currents. The times of these intensifications correspond to times of intense (solid arrows) and moderate (dashed arrows) BEB.
Plate 3 [Winglee et al.]. Ion energy and spin phase angle spectrograms from RIMS for the \( \text{H}^+ \), \( \text{He}^+ \), and \( \text{O}^+ \) ions. Field-aligned flows up the field lines would have spin phase angles near 90°. The solid white line indicates the ram angle. Perpendicular heating of the ions, particularly \( \text{O}^+ \), occurs about 1012–1013:30, 1016–1017, 1018–1020, 1022–1023, and 1024–1025 UT. These times correspond to crossings of return current regions. Between these times there are dropouts in the number of ions detected by RIMS. These dropouts correspond to crossings of primary current regions and probably reflect the acceleration of the bulk of the plasma to higher energies than can be detected by RIMS rather than the absence of any ion acceleration.

Plate 4 [Winglee et al.]. Energy spectrograms (top panels) and phase spectrograms for the energy ranges 1–17 keV (middle panels) and 0.01–1.0 keV (bottom panels) for the \( \text{H}^+ \) and \( \text{O}^+ \) ions detected by EICS. Upward field-aligned flows would have spin phase angles of 90°. Upward flowing perpendicularly accelerated ions are present at 1013:30–1015 UT, 1016:30–1018 UT, 1020–1021:30 UT, and 1025–1026:30 UT, which coincides with the dropouts in RIMS and the crossing of primary current regions.