Simulations and Observations of Heating of Auroral Ion Beams

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In the auroral zone, quasi-static parallel electric fields produce beams of ionospheric ions (e.g., H\textsuperscript{+}, He\textsuperscript{++}, and O\textsuperscript{+}), which flow outward into the magnetosphere, providing a significant source of ions for the ring current and plasma sheet. Because the velocities to which these beams are accelerated is dependent on the mass of the ions, differential flows between the various ion species can develop which are unstable to an ion-ion streaming instability. Particle simulations and observations from DE 1 are used to investigate the heating of the ion beams produced by this instability. It is shown that there is net transfer of energy from the light ions to the heavy ions, with the heavy ions reaching maximum velocities near the beam velocity of the light ions. Bulk heating of the heavy ions occurs when their relative density is low while high-energy tails are produced when their relative density is high. The heating is primarily parallel to the magnetic field if the difference in the heavy and light ion beam velocities is subsonic while both perpendicular and parallel heating can occur if it is supersonic. In the latter case, very strong heating of an intermediate ions species such as He\textsuperscript{+} can also occur. Comparison with observations shows features consistent with heating via the ion-ion instability including perpendicular heating in the supersonic regime and parallel heating in the subsonic regime and a change in the heating between these regimes as the ratio of the H\textsuperscript{+} beam speed to the local sound speed is observed to decrease. This heating is, however, not always observed in association with enhanced wave emissions. This lack of waves is attributed to reabsorption of the waves as the ions become heated.

1. INTRODUCTION

Along auroral field lines, ionospheric ions are observed to be accelerated outward into the magnetosphere and are consequently a significant source of ions for the ring current and plasma sheet [Chappell et al., 1987]. This ion outflow is in part produced by quasi-static parallel electric fields known to occur along auroral field lines [Hoffman and Evans, 1968; Whalen and McDermid, 1972; Arnould et al., 1974; Evans, 1974; Chiu and Shue, 1978]. This potential drop accelerates ions along the magnetic field to produce field-aligned ion beams with energies of several keV [Shelley et al., 1976]. Such beams are rarely observed below 5000 km and appear to be heated appreciably in both parallel and perpendicular directions [Collin et al., 1986; Ghelometti et al., 1986].

Ionospheric ions can also experience strong perpendicular acceleration. Evidence for this comes from observations of ion conic distributions where the pitch angles of the ions are confined to angles nearly perpendicular to the magnetic field [Sharp et al., 1977; Gorney et al., 1981; Klumpar, 1986]. Conics typically have energies less than about 500 eV. Due to the mirror force associated with gradients in the geomagnetic field, this perpendicular energy can be converted to parallel energy and thereby lead to enhanced ionospheric outflow.

On occasions, “bimodal” distributions are observed where the outflowing ions show evidence of both strong perpendicular and parallel acceleration [Klumpar et al., 1984]. Such distributions can also be produced by extended transverse heating and velocity-filter effects.

Several mechanisms for this perpendicular acceleration or heating utilizing wave-particle interactions have been proposed. These mechanisms include heating by (1) electrostatic ion cyclotron waves [e.g., Lyak et al., 1980; Dusenberry and Lyons, 1981; Ashour-Abdalla and Okuda, 1984], (2) lower hybrid waves [Chang and Coppi, 1981] and (3) shear Alfven waves [Chang et al., 1986; Wingele et al., 1987, 1988b]. While many of these waves have been observed on auroral field lines, observations from S3-3 [Kintner and Gorney, 1984; Kintner, 1986] and DE 1 [Peterson et al., 1988] have yet to establish a direct association between conics and these waves.

Recently, Wingele et al. [1988a] used particle simulations and observations from DE 1 to show that conics could easily be generated by the quasi-static perpendicular electric fields associated with V-shaped potentials in discrete auroral arcs. Within these potentials there is an enhanced upward current and the magnetoospheric electrons are accelerated downward by the quasi-parallel electric field. In adjacent regions, ionospheric electrons are accelerated outward, forming the return current. Plasma ions are accelerated across the field lines to close these spatially separate currents. This acceleration creates ion conics in velocity space and, in coordinate space, plasma cavities in the return current regions and plasma enhancements in regions of enhanced upward current. Strong broadband electrostatic bursts (BEB) with spectral maxima near the local plasma and lower hybrid frequencies were shown to be associated with these potential structures. These simulations were limited in that they were not run sufficiently long to investigate the properties of the ion beams produced by the quasi-static parallel electric field.
The properties of the ion beams produced by the quasi-static parallel electric field have received much less attention even though observations show that they can undergo significant parallel and perpendicular heating [Klumpar et al., 1984; Collin et al., 1986; Ghiselmetti et al., 1986]. An understanding of the dominant processes governing this heating is important if the characteristics of the outflowing ionospheric ions are to be fully understood.

One mechanism for the heating of auroral ion beams which has been recently proposed is heating via an ion-ion two-stream instability [Bergmann and Lotko, 1986; Dusenbery and Martin, 1987]. A schematic diagram for the processes involved is shown in Figure 1. A quasi-static parallel electric field accelerates ionospheric ions, including H⁺, He⁺ and O⁺, upward. For a quasi-static electric field, the energy gained ΔE is independent of the ion mass. However, the corresponding change in the ion velocity Δv is then approximately inversely proportional to the square root of the ion mass. Thus, the lighter ions, like H⁺ and He⁺, are accelerated to higher velocities than the heavier ions, such as O⁺. This differential ion flow can lead to ion-ion streaming instabilities, which can lead to strong heating of the ions with net energy being transferred from the lighter ions to the heavier ions.

The linear theory for the ion-ion two-stream instability under auroral conditions has been evaluated by Bergmann et al. [1988] and Dusenbery et al. [1988] and references therein. Kaufmann et al. [1986] made the first attempt to identify observationally whether heavy ionospheric ions were being heated by this instability. They were able to show that the O⁺ ions tended to have a more extended high-energy tail than the H⁺ ions, which is expected if energy is being transferred from the light ions to the heavy ions by the ion-ion instability. More recently, Reiff et al. [1988], using near-magnetic conjugate crossings of DE 1 and DE 2 to study auroral potentials and associated particle acceleration, showed that the characteristic temperature of the upflowing ionospheric ions was (weakly) correlated with the relative drift velocity between the H⁺ and O⁺ ions but not with the locally measured current. This correlation although weak was interpreted as further evidence for heating of ionospheric ions by the ion-ion instability rather than by a current driven instability. Yau et al. [1985], Collin et al. [1987] and W. K. Peterson (Auroral ion composition, submitted to Journal of Geophysical Research, 1988; hereinafter Peterson, submitted, 1988) have also noted that the heating is also dependent on the solar cycle.

The purpose of this paper is to use two-dimensional particle simulations to determine the nonlinear evolution of the distributions of the ion beams and thereby to determine quantitatively signatures in the ion distributions produced by the ion-ion instability for the variety of plasma conditions in the auroral zone. These signatures, as determined from the simulations, are then compared with observations from DE 1 to test whether there is any direct evidence for the heating of heavy ionospheric ions via the ion-ion instability. Such a direct comparison not only allows the heating of the ionospheric ions to be characterized semiquantitatively in terms of the local plasma parameters but also allows some insight into the variability seen in the observations of Reiff et al. [1988] as well as with solar cycle.

The outline of the paper is as follows. In section 2, a review is given of the linear theory relevant to the simulations. Simulation results for the ion-ion instability for a two-ion-component plasma are presented in section 3 for supersonic and subsonic ion flows, and changes in the heating with electron temperature are examined in section 4. It is shown that the beams undergo preferential perpendicular heating during supersonic interactions while preferential parallel heating occurs during subsonic interactions. In both cases, the ions with the smallest relative concentration experience strong bulk heating while the other ion species experience mainly tail heating. The most efficient transfer of energy occurs when the ratio of the electron to ion temperature is largest. This dependence of the heating on relative density and electron temperature can account for the scatter in the heating versus beam speed observed by Reiff et al. [1988] as well as variations in the heating with solar cycle as observed by Yau et al. [1985], Collin et al. [1987] and Peterson (submitted, 1988).

The results are then generalized in section 5 to the case when three ion species such as H⁺, He⁺ and O⁺ are present. These three species are often observed in the auroral zone so that for the most complete comparison between the simulations and observations, an intermediate ion species between the light and heavy ions needs to be included. It is shown that the heating of the light and heavy ions is as described above but that the intermediate ions can undergo much stronger heating than the heavy ions due to interactions with both the heavy and light ions.

The simulation results are then compared with observations from DE 1 in section 6. It is shown that the observed ion beam speeds can be larger than the local sound speed and that the heavy ions tend to have extended high-energy tails, similar to the earlier observations of Kaufmann et al. [1986]. In addition it is shown that the maximum velocity of the He⁺ ions approaches the H⁺ beam speed and that of the O⁺ ions approaches the He⁺ beam speed, with the heating changing from perpendicular to parallel heating as the

![Fig. 1. Schematic diagram of an auroral zone acceleration region, illustrating the development of differential ion flows and the development of the ion-ion instability.](image-url)
beam speed of the ions decreases from supersonic to subsonic. These features are all consistent with the predictions of the simulation, which gives support to the hypothesis that strong perpendicular and parallel heating of ionospheric ions can be produced by the ion-ion instability. A summary of results is given in section 7.

2. CONDITIONS FOR THE ION-ION INSTABILITY

Growth of the ion-ion two-stream instability depends upon the relative concentration of the various ion species and requires that (1) the electron temperature $T_e$ be much greater than the H+ temperature $T_{H+}$, and that (2) the drift speed of the H+ ions relative to the heavier ions be greater than about the sound speed in the auroral zone.

For example, at high altitudes where there is little electron acceleration, the ambient plasma electrons have temperatures of a few hundred electron volts. As these electrons are accelerated downward to lower altitudes they can reach energies of several keV, depending on the strength of the parallel electric fields. Wave-particle interactions, which are responsible for intense auroral emissions such as auroral hiss, auroral kilometric radiation and broadband electrostatic bursts (BEB), tend to convert some of this energy into thermal energy so that the electron temperature tends to increase with decreasing altitude [e.g., Reiff et al., 1988; Dusenbery et al., 1988]. These conditions can be strongly dependent on altitude in the auroral zone.

As an example of the changes in the characteristics of the instability with ion beam speed, Figure 2a [from Dusenbery et al., 1988] shows the maximum growth rate of the ion-ion instability for a H+–He+ plasma with equal amounts of H+ and He+ and $T_{H+} = T_{He+} = 0.01 T_e$. The H+ beam speed $v_{H+}$ is normalized to the sound speed $c_H = (m_e/m_{H+})^{1/2} v_p e$ and $\theta$ is the wave normal angle. The He+ ions are assumed to have the same streaming energy as the H+ ions. The magnetic field strength has been taken to be such that the ratio of the H+ plasma to cyclotron frequencies $\omega_H/\Omega_H$ is equal to 4, which is typical of the auroral cavity region [Calvert, 1981]. It is seen that when $v_{H+}/c_H \leq 1$ (i.e., the H+ ions are subsonic) growth is peaked along the magnetic field, with the maximum growth rate being only fractionally smaller than $\Omega_H$. As $v_{H+}/c_H$ increases (i.e., as the H+ ions become supersonic), the growth becomes strongly peaked at angles oblique to the magnetic field, although
the maximum growth rate is not significantly different.

As wave growth occurs, the H\(^+\) ions, which provide the free energy, are expected to become heated. An estimate for the final temperature of the H\(^+\) ions can be obtained from conditions for marginal stability. (Marginal stability does not provide any insight into the heating or acceleration of the heavier ions since the growth rate is not sensitive to the temperature of the heavier ions, assuming that the thermal velocity of the heavy ions does not become comparable to the H\(^+\) beam speed.) Results from the marginal stability analysis [Dusenbery et al., 1988] are shown in Figure 2b. It is seen that, as the relative concentration of H\(^+\) decreases, the temperature of the ions relative to the beam energy increases. In other words, the largest heating of the H\(^+\) ions is expected when their relative concentration is lowest while only small heating is expected when their relative concentration is high. As a result, different signatures in the observed ions distributions are expected as the relative concentration of the various ion species changes.

3. Two-Ion-Beam Interactions

3.1. Simulation Model

In order to examine the nonlinear evolution of the particle distributions due to the ion-ion instability, two-dimensional (three velocity) electrostatic particle simulations were employed. The simulations utilized the beams-in-geospace (BIG) code which has been used extensively to study active beam injection [Winglee and Pritchett, 1988]. In the present application periodic boundary conditions are utilized. The primary objective of the simulations is to identify signatures in the distribution as a function of the (1) beam speed, (2) relative concentration of the various ion species and (3) electron temperature relative to ion temperature.

The plasma is assumed to have two ion components. The light ion species is assumed to be H\(^+\) and the heavier ion is assumed to be He\(^+\). The results when the heavier ion is O\(^+\) are essentially the same as described in the following so that the ions represented by He\(^+\) can be considered as being any heavy auroral ion. The results from the two-ion-component plasma, while important in identifying the signatures in a light-ion/heavy-ion beam interaction, are not sufficient to make a detailed comparison with observations since, along auroral field lines, three ion species, H\(^+\), He\(^+\) and O\(^+\), are often observed with nonnegligible concentrations. Differences in the properties of the evolution of the particle distributions when all three ion species are present are investigated in section 5.

The system size for the simulations is 128\(\Delta\) x 128\(\Delta\) where \(\Delta\) is the grid spacing which is taken to be 0.2 \(v_T H /c_H\) where \(v_T H\) is the thermal speed of the H\(^+\) ions. For numerical simplicity, the simulations are conducted in the rest frame of the heavy ion species. For a direct comparison with the linear theory in section 2 [cf. Dusenbery et al., 1988] where both ions are assumed to be streaming with equal energy, the value of the beam speed \(v_B\) in the simulations should be multiplied by a factor of 2 when the heavy ion is He\(^+\) and a factor of 1.333 when the heavy ion is O\(^+\). The ambient plasma electrons are given a small drift velocity to match the current carried by the light ions so that the simulation system is current free. The results for a system with net current are essentially the same, provided that the drift speed of the electrons is small compared with their thermal velocity. The electrons do not play an important role in the ion-ion instability except for providing quasineutrality so that for numerical simplicity an artificially heavy electron mass \(m_e = 0.01 m_H\) is assumed. The electron temperature \(T_e\) is assumed to be 100 \(T_H\) except in section 4 where effects due to a reduction in \(T_e/T_H\) are investigated.

The magnetic field which is taken to be in the z direction of the simulations is assumed to be such that for plasma with equal amounts of H\(^+\) and He\(^+\), the H\(^+\) plasma frequency is equal to 7 \(\Omega_H\). This magnetic field strength is fractionally higher than assumed in the linear theory of Dusenbery et al. [1988] but allows the maximum time step of \(dt = 0.2/\omega_{pe}\) to be taken without modifying the physics. Fractional charges for the ions are used so that the minimum number of particles per cell representing an ion species is no smaller than two, independent of their relative charge density. Typically, a total of about 150,000 particles are used in the simulations.

3.2. Supersonic Ion-Ion Beam Interactions

In this section, the modification of the ion distributions via the ion-ion instability is investigated for a H\(^+\)-He\(^+\) plasma with \(v_B = 1.5 v_H\), i.e., for a supersonic interaction. The initial distributions for the He\(^+\) and H\(^+\) ions are shown in Figure 3a. The final ion distributions are shown in Figures 3b, 3c, and 3d for three different relative concentrations of H\(^+\): \(n_H/n_e\) equal to 20%, 50%, and 80%.

It is seen that for the smallest concentration of H\(^+\) there is very strong heating of the H\(^+\) ions, with the final distribution being similar to a ring distribution centered at \(v_H \simeq 0.5 v_H\) and radius \(v_H \simeq v_H\). As a result, the H\(^+\) ions have an effective velocity spread comparable to the initial beam velocity. On the other hand, the He\(^+\) ions show only weak heating with a tail being pulled out along a pitch angle of about 45\(^\circ\), giving the heavy ions the appearance of a bimodal distribution, similar to that observed by Kumpar et al. [1984]. The reason that there is preferential perpendicular heating is that for supersonic light-ion beams, wave growth and hence the wave electric field via which the particles interact are at angles oblique to the magnetic field (see Figure 2a).

Only little heavy ion heating is evident for the low relative H\(^+\) density because there is available relatively little free energy per heavy ion. However, as the relative H\(^+\) density is increased and that of the He\(^+\) ions is decreased, there is relatively more free energy available so that much stronger heavy ion heating is possible. This enhanced heavy ion heating in both the parallel and perpendicular directions is evident in the lower panels in Figure 3. In Figure 3d some of the heavy ions reach velocities as high as the light ions, i.e., energies nearly 4 times that of the H\(^+\) ions.

This enhanced heavy ion heating is associated with a decrease in the heating of the light ions. For example,
Thus, it can be concluded for supersonic beam interactions that for low relative densities of H\(^+\), strong heating of the H\(^+\) ions is expected with only weak heavy ion heating and this heating occurs preferentially perpendicular to the magnetic field. For high relative densities of H\(^+\) the reverse is true with only weak H\(^+\) heating and strong heavy ion heating. The heavy ion heating in this case occurs both in the parallel and perpendicular directions.

As seen from the above, the amount of heating and hence the ability to couple H\(^+\) beam energy into the heavy ions is sensitive to the relative density of the H\(^+\) ions. This is illustrated quantitatively in Figure 4, which shows time histories of the parallel and perpendicular energies \((E_\parallel, E_\perp)\) of the H\(^+\) ions normalized to their initial parallel (beam) energy \(E_{H0}\). For the lowest relative H\(^+\) density (Figure 4a), nearly 70\% of \(E_{H0}\) is lost with about 0.3 \(E_{H0}\) going into the perpendicular energy of the H\(^+\) ions, and the remaining 0.4 \(E_{H0}\) going primarily into the heavy ions. For the highest relative H\(^+\) density (Figure 4c), the H\(^+\) ions lose only about 20\% of \(E_{H0}\) of which nearly 75\% (i.e., \(\approx 0.16 E_{H0}\)) goes back into the H\(^+\) ions as perpendicular beam energy; the He\(^+\) ions gaining only about 4\% of \(E_{H0}\).

While the efficiency of coupling the H\(^+\) beam energy to the heavy ions decreases with increasing H\(^+\) relative density, the increase in the heavy ion energy relative to its initial energy in fact increases. This is illustrated in Figure 5, which shows the time histories of the He\(^+\) ions normalized to their initial parallel energy \(E_{He0}\). In all three cases, there is substantial parallel and perpendicular heating of the He\(^+\) ions with the ratio of max\((E_\perp/E_\parallel)\) decreasing with increasing H\(^+\) relative density. For the lowest H\(^+\) density (Figure 5a), the total increase in the He\(^+\) energy relative to their initial total energy is about 8.5 while for the highest H\(^+\) density (Figure 5c) the total increase is nearly double, being about 19.

These energy increases are in the frames where the He\(^+\) ions are at rest. In the spacecraft reference frame, these energy increases correspond to the He\(^+\) ions having an average energy 1.4 (1.8) times that of the H\(^+\) ions for the lowest (highest) H\(^+\) relative density. This variation in the energization of the heavy ions with relative density...
can easily account for the scatter in the heating as a function of relative beam speed observed by Reiff et al. [1988]. Moreover, if it is assumed that the average scale height of O$^+$ is highest during solar maximum, then the energization of the heavy ions relative to the H$^+$ ions is expected to be at a minimum which is consistent with the observations of Yau et al. [1985], Collin et al. [1987] and Peterson (submitted, 1988).

The characteristics of the wave emissions produced are illustrated in Figure 6, which shows time histories of the electrostatic wave energy normalized to the parallel H$^+$ beam energy $E_{H0}$. In all three cases, the waves are initially generated oblique to the magnetic field (i.e., $E_\perp > E_\parallel$) with a growth rate of the order of $\Omega_{H'}$. However, as the particle distributions become heated, the initially growing waves become damped and growth shifts to waves more field-aligned. This is seen in all three cases in Figure 5 as a reduction in both the absolute value of the wave intensities and in the ratio $E_\perp / E_\parallel$ after about $\Omega_{H'} \sim 5$. It is this shift from oblique waves to parallel waves which produces the parallel heating in Figure 3, especially for the case of relatively high H$^+$ density. Eventually, the bulk of the waves are reabsorbed and the peak wave amplitude never exceeds more than a few percent of $E_{H0}$, even though tens of percent of parallel beam energy can be lost by the H$^+$ ions.

Thus, the waves provide a medium by which energy can be transferred but energetically they do not play an important role themselves. Further, if the observed beams are near saturation then large wave amplitudes in association with the ion-ion instability are not expected since they would be heavily absorbed. If, on the other hand, observations are made during the growth phase of the waves then the typical wave spectrum that might be observed is shown in Figure 7, which was obtained by integrating over the full length of the simulation for the case where $n_H/n_e = 0.5$. The spectra for the other H$^+$ densities are qualitatively the same and are not shown. The spectrum extends from about the H$^+$ cyclotron frequency $\Omega_H$ to the H$^+$ plasma frequency $\omega_H$ with a
The relative increase in the He$^+$ energy as well as the preferential parallel heating is illustrated in Figure 9, which shows the time histories of the energy of the He$^+$ ions, normalized to their initial energy. (The time histories of the energy of the H$^+$ ions are similar to that in Figure 4 and are not shown.) In all three cases, the increase in parallel energy dominates. For the lowest H$^+$ relative density (Figure 9a), the final energy of the He$^+$ ions is about 3 times their initial total energy (in their rest frame). This change is about a third of that for the supersonic case since the H$^+$ beam speed and hence free energy are smaller. Note, however, that in the spacecraft frame the average energy of the He$^+$ ions is about 1.5 times their initial velocity (in their rest frame), which corresponds to the He$^+$ ions having an average energy of nearly twice that of the H$^+$ ions in the spacecraft frame. Thus, in both supersonic and subsonic cases, the average energy of the heavy ions relative to the H$^+$ ions increases with increasing H$^+$ relative density, being about 2 for a H$^+$ relative density of 80%.

For subsonic ion-ion beam interactions, the dominant growing modes are field-aligned rather than oblique to the magnetic field as in the previous section (e.g., Figure 2). The distributions and waves produced in this regime are now investigated. The plasma parameters are assumed to be the same as in section 3.2 except that $v_H$ is half as small, i.e., $v_H = 0.75 v_H$. The initial H$^+$ and He$^+$ ion distributions are shown in Figure 8a while the final distributions at saturation at $v_H = 7.5$ are shown in the lower panels for the same relative H$^+$ densities in Figure 3. It is seen that similar to the supersonic case, strongest heating of the H$^+$ ions occurs when their relative density is small. In Figure 8b, the initial beam is no longer evident and there is even a local maximum in the distribution about $v_H = 0$ (i.e., at the center of the He$^+$ distribution). For the highest relative H$^+$ density, the initial beam can still be seen with a tail extending to lower parallel velocities. In the intermediate case in Figure 8c there are local maxima at both the initial beam speed and at $v_H = 0$.

For the heavy ions, bulk heating again occurs when their relative density is low, as seen in Figure 8d. In this case, the interaction produces a local maximum in the heavy ion distribution at $v_H \approx 0.4 v_H$. For the cases of high relative density (Figures 8b and 8c), high-energy tails are created in the heavy ion distribution, with the maximum velocity being approximately equal to the initial H$^+$ beam speed. Thus, irrespective of whether the interaction is supersonic or subsonic, high-energy tails tend to be produced when the relative density of the heavy ions is high and bulk heating when their relative density is low.

However, unlike the supersonic case, the heating is primarily parallel to the magnetic field with very little perpendicular heating, as seen on comparing the distributions in Figures 3 and 8. This difference is due to the fact that for subsonic interactions the fastest growing modes are field-aligned (e.g., section 2) while for supersonic interactions they are oblique (at least in the initial phases). This difference in the heating of the ions is important as it can provide a clear signature between supersonic and subsonic interactions.

Fig. 7. Wave spectra for the electrostatic field components for the case shown in Figure 6. The spectrum extends from about the H$^+$ cyclotron frequency $\Omega_H$, to the H$^+$ plasma frequency $\Omega_{pe}$ with a spectral peak near $\Omega_{pe}$. This frequency range is consistent with that predicted by linear theory.

Fig. 8. Similar to Figure 3 except that a subsonic ion-ion interaction is considered ($v_H = 0.75 v_H$). In this case the heavy ions experience primarily parallel heating with little perpendicular heating.
In order to show that the change from preferential perpendicular heating to parallel heating as the beam speed decreases from supersonic to subsonic is associated with a change in the wave properties, Figure 10 shows the time histories of the electrostatic wave energies corresponding to Figure 9. On comparing with the supersonic case in Figure 6, it is seen that the wave fields are predominantly field-aligned in the subsonic case rather than oblique as in the supersonic case. Nevertheless, the wave fields are similar in that they reach comparable amplitudes over similar times scales and are absorbed as the particles become heated. Thus, intense wave emissions are again only expected if the observations are made before the heating has saturated. The power spectra for the wave fields determined from integrating over the total duration of the simulation for $n_H/n_e = 0.5$ are shown in Figure 11. The upper frequency limit of the waves is similar to the supersonic case but there is a tendency for the spectral maximum and the lower limit to extend to lower frequencies below $\Omega_H$.

4. MODIFICATIONS DUE TO CHANGES IN THE ELECTRON TEMPERATURE

As the ions propagate up the field lines, their beam speed is increasing while the electron temperature and hence local sound speed are decreasing (as discussed in section 2). Thus, the ratio $v_H/C_H$ is increasing but $T_e/T_H$ is decreasing and the characteristics of the ion-ion instability and associated ion heating can therefore change with altitude. The effects on the ion heating due to changes in the electron temperature are now investigated.

Figure 12 shows the final distributions for the same plasma parameters in Figures 3c and 8c except that the electron thermal speed has been reduced by a factor of 2 (i.e., $T_e/T_i = 25$) while keeping the beam speed relative to the ion thermal speed the same. As a consequence, $v_H/C_H$ is equal to 3 and 1.5, respectively, even though the ion plasma parameters are exactly the same as in Figures 3c and 8c. It is seen on comparing Figures 3c and 12a that the amount of parallel heating has substantially decreased even though the ion plasma...
Wave Spectra

![Wave Spectra](image)

Fig. 11. Wave spectra for the electrostatic field components for the subsonic case in Figure 10. The waves have a similar spectrum to the supersonic case except that there is a tendency for the spectrum to extend to slightly lower frequencies.

parameters are identical in the two figures. Moreover, the \( H^+ \) ion distribution has experienced considerably less distortion as \( T_e/T_i \) is decreased, with a well defined "kidney-bean"-shaped beam being evident in Figure 12a in the light \( H^+ \) ions and a conic or bimodal distribution (depending on the frame of reference) in the heavy ions. The total energy lost by the \( H^+ \) ions is about half that of the example in Figure 3c. A similar reduction in the parallel heating for the lower beam speed is also seen on comparing Figures 8c and 12b. The final distribution in Figure 12b resembles more closely the distribution in Figure 3c where \( v_{H}/c_H \) is the same but \( v_{H}/c_T \) is twice as large. However, the fractional amount of energy lost by the \( H^+ \) ions is again much smaller, being only 40% of that in Figure 3c.

Thus, in both cases, the amount of parallel heating and the efficiency of coupling the \( H^+ \) beam energy to the heavier ions depends not only on the relative beam speed but also on the electron temperature relative to the ion temperature. As a result, if the instability is not completely suppressed by wave-particle interactions at lower altitudes, then the ions observed at high altitudes may have a tendency to show stronger perpendicular heating than at lower altitudes. However, if the heating tends to saturate at low altitudes then the perpendicular heating may be suppressed and parallel heating would dominate. The final result depends on the strength of the auroral electric field which provides continual acceleration of the ion beams, while the ion-ion instability attempts to smear out and destroy the ion beam distributions. The effects arising from the competition between these two processes have yet to be determined.

5. Three-Ion-Beam Interactions

The above analysis assumes that the plasma has only two dominant ion species so that the properties of the ion-ion instability could be clearly identified as a function of beam speed, relative density and electron temperature. However, in the auroral zone, there are three dominant ion species, \( H^+ \), \( He^+ \) and \( O^+ \) [Collin et al., 1988], with the intermediate ion \( He^+ \) having possible interactions with both the light ion \( H^+ \) and the heavy ion \( O^+ \). In this section, such interactions are investigated and it is shown that the heating of the heavy and light ions is qualitatively similar to that determined in the previous sections. However, the intermediate ion can show a mixed behavior between that of the heavy and light ions and can, under certain conditions, become substantially more heated than either the light or heavy ions.

As an example, it is assumed in the following that \( n_{H^+}/n_O = 0.8 \) and \( n_{He^+}/n_O = 0.2 \) and \( T_{He} = T_{He} = T_O \) (the relative densities being similar to that in the observations presented in the following sections). Time histories of the ion and wave energy are shown in Figure 13 for the case of a supersonic interaction with \( v_{H} = 2v_{He} = 1.5c_H \). It is seen that, just as in the corresponding supersonic interaction in section 3.2 (i.e., Figure 4b), the \( H^+ \) ions lose about 50% of their initial beam energy, with about one half going into the perpendicular heating of the \( H^+ \) ions and the other half going into the other ions. The energy time history of the \( O^+ \) ions is also similar (viz. Figure 5b) except that there is fractionally less parallel acceleration since the relative drift between the heavy and light ions is larger.

The energy of the \( He^+ \) ions shows a behavior intermediate between that of the light and heavy ions as seen in Figure 13b. At early times (i.e., \( \Omega_{He} \leq 6 \)), the \( He^+ \) ions gain energy in both the parallel and perpendicular components, similar to the \( O^+ \) ions. They gain more parallel energy than perpendicular energy since their interaction with the \( H^+ \) ions is subsonic (i.e., \( v_{H} - v_{He} \leq c_H \)). However, at later times the \( He^+ \) ions like the \( H^+ \) ions start to lose parallel energy to the heavier \( O^+ \) ions. The net result is that there is little net increase in the parallel energy of the \( He^+ \) ions.

Despite the small net increase in the parallel \( He^+ \) energy, there is substantial heating in both the parallel and perpendicular components. This is illustrated in Figure 14, which shows the evolution of the \( He^+ \) ion distribution. It is seen that the initial increase in the parallel energy of the \( He^+ \) ions is associated with the
acceleration of He$^+$ ions with velocities $v_{\parallel} > v_{\text{He}}$, in a similar fashion as the H$^+$–He$^+$ interaction described in sections 3 and 4. By the time $\Omega_{H^+} = 7.5$ (Figure 14c), there has been bulk acceleration of this part of the distribution to $v_{\parallel} \approx 1.5 v_{\text{He}}$ where the distribution has a maximum. This feature remains approximately unaltered at later times so that the energy loss indicated in Figure 13b is not associated with the deceleration of these fast He$^+$ ions.

Instead, the loss of parallel energy in the He$^+$ ions is associated with the deceleration of the slow He$^+$ ions. In Figure 14b, the He$^+$ ions with $v_{\parallel} < v_{\text{He}}$ show little acceleration, but at later times when there is a net loss of parallel energy, these slow ions are seen in...
Fig. 15. Initial and final ion distributions for the case considered in Figure 13 showing that He$^+$ can become significantly more heated than either O$^+$ or H$^+$ ions due to its dual interaction with these two ions.

Figures 14c-14e to be strongly decelerated in the parallel direction. As these ions are decelerated in $v_T$, they also experience strong perpendicular acceleration with some of the ions having $v_L \approx v_{He}$. This heating of the slow He$^+$ ions is similar to that described in section 3 with the He$^+$ ions acting as the light ions and the O$^+$ ions acting as the heavy ions.

Due to the combined H$^+$-He$^+$ and He$^+$-O$^+$ interactions, the He$^+$ ions have a much larger velocity spread than in any of the other previous examples. This is also illustrated in Figure 15, which shows the initial distributions of all three ion components in the top panel and the final distributions in the lower panel. The velocity spread in the He$^+$ ions is comparable to that of the H$^+$ ions, so that the final thermal energy of the He$^+$ ions is nearly 4 times that of the H$^+$ ions. The O$^+$ ions appear much less heated, having a conic or bimodal distribution (depending on the frame of reference).

For the subsonic three-ion interaction, He$^+$ again experiences strong accelerations from both H$^+$-He$^+$ and He$^+$-O$^+$ interactions. However, in this case the H$^+$-O$^+$ interaction tends to dominate so that the He$^+$ ions can lose net parallel energy and the development of a local maximum at higher velocities does not occur. This is illustrated in Figure 16, which shows the time histories of the ion and wave energies for the same parameters as in Figure 13 except that the H$^+$ and He$^+$ beam speeds are half as small, i.e., $v_{He} = 2 v_{He} = 0.75 c_H$. In this case, the He$^+$ energy history has a similar profile as the H$^+$ ion energy, i.e., the He$^+$ ions are acting as a light ion species losing energy to the heavy O$^+$ ions. Because both the H$^+$ and He$^+$ ions are losing energy to the O$^+$ ions, the O$^+$ ion energy and peak wave energy can increase to a much larger fraction of the beam energy, as seen by comparing Figures 11c and 11d with 16c and 16d.

The initial and final distributions corresponding to this case are shown in the top and bottom panels in Figure 17, respectively. It is seen that the He$^+$ ions have been strongly heated in the parallel direction with $v_T$ extending from zero velocity to $v_{He}$ similar to the supersonic case except that there is no local maximum at high velocities and the perpendicular heating is substantially reduced. Even though the He$^+$ ions lose net parallel energy, some of the He$^+$ ions are nevertheless accelerated to velocities comparable to the H$^+$ beam speed. The O$^+$ ions have a much larger average parallel velocity than in the supersonic case, reaching peak parallel energies comparable to the He$^+$ beam speed, i.e., approximately 4 times the initial beam energy.

6. Observations

In this section, observations from DE 1 during a high-altitude crossing of the nightside auroral zone are compared with the simulation results in order to determine whether there is any direct evidence for heating via the ion-ion instability. It is shown that, even through one auroral crossing, conditions are highly variable and the features in the distributions vary rapidly, possibly on time scales faster than can be resolved by some of the instruments. Nevertheless, some but not all of the features in the simulations are seen, the difference being possibly due to the limited parameter space considered in both the simulations and observations.

Data obtained by DE 1 during several auroral crossings were examined. In the following, a case study for the crossing on day 319, November 15, 1981, is presented. For this crossing, the measured ion fluxes were sufficiently intense that features in the measured ion distributions could be most easily resolved. The data for this day also have the advantage that they are taken near apogee where the crossing of L shells is relatively slow thereby
1. Electron Properties

The characteristics of the electrons and ions during the time period of interest are summarized in the high altitude plasma instrument (HAPI) [Burch et al., 1981] energy spectrograms shown in Figure 18. The electrons (top panel) are essentially divided into two populations: (1) an energetic (\( \gtrsim 100 \text{ eV} \)) population of presumably magnetospheric origin and (2) a low-energy (\( \lesssim 50 \text{ eV} \)) component. This latter component has an almost constant density of about 1 cm\(^{-1}\) and is probably due to secondary electrons from the spacecraft rather than a true component of the ambient plasma. This conclusion is consistent with the measured current density, ion densities and the density inferred from the whistler cutoff (see below and sections 6.2 and 6.3).

Several inverted-V events (which may be associated with discrete auroral arcs) are seen in the flux of the energetic component (e.g., 1205-1210, 1213-1216, 1218-1220, 1221-1223 and 1225-1228 UT). During these events, energetic upflowing ions beams are also observed. Their energy ranges from several hundreds of electron volts to about 2 keV. The most intense ion events which will be examined in the following occur between about 1205 and 1210 UT and between 1221 and 1228 UT.

The number density, current density and average energy of the electrons obtained from integrating the distribution of the electrons detected by HAPI in the energy range of 74-2339 eV are shown in Figure 19. The lower cutoff of 74 eV has been made to exclude any secondary electrons. It is seen that the density of these electrons has local maxima of about 0.2-0.3 cm\(^{-3}\) during inverted-V events, these maxima representing an increase in density of nearly a factor of 4 relative to adjacent regions [cf. Winglee et al., 1988a]. The maximum current carried by these electrons is about 0.05 \( \mu \text{A m}^{-2} \) is relatively small compared with that seen at lower altitudes since the electrons have only fallen through a small fraction of the potential drop. These small currents are similar to that inferred from the magnetometer (J. A. Slavin, private communication, 1988), which suggests that the energy cutoff assumed for the integration of the HAPI data has not excluded a significant portion of the ambient plasma electrons.

The average energy of the electrons for the period ranges from about 150 to 300 eV. If the electron temperature is assumed to be such that the thermal energy is equal to the observed average energy (which is not a bad approximation since only small directed flows, i.e., current, are present) then the local sound speed ranges from about 100 to 140 km/s.

6.2. Ion Properties

Figure 20 shows the densities of H\(^+\), He\(^+\) and O\(^+\) inferred from the energetic ion composition spectrometer (EICS) [Shelley et al., 1981] for the first of the intense ion events during the auroral crossing. The error in the density estimates is about 30%. Throughout the period, O\(^+\) is the dominant ion species, with H\(^+\) having about half the density of O\(^+\), and He\(^+\) having about a quarter of the O\(^+\) density. The total density agrees well with that determined from the HAPI electrons, which suggests that the bulk of the ions have indeed been accounted for.
Fig. 17. Initial and final ion distributions corresponding to the subsonic, three-ion interaction considered in Figure 16. The maximum speed of the He$^+$ ions is approximately the H$^+$ beam speed, and that of the O$^+$ ions is that of the He$^+$ beam speed.

Data from the retarding ion mass spectrometer (RIMS) were also examined to verify whether there were any appreciable ion fluxes at low energies not detected by EICS. No significant levels of ions were detected during the intense ion events (T. E. Moore, private communication, 1988). This implies that either the bulk of the ions have been accelerated above the 50-eV limit of RIMS (in which case the bulk of the ions would be detected by EICS) and/or that the spacecraft is positively charged, preventing any low-energy ions from reaching the spacecraft. While there is always the latter possibility of an unseen cold ion component, an appreciable cold component is unlikely since (1) the EICS ion densities are in agreement with the HAPI electron density and (2) any cold component must be of ionospheric origin and would have been accelerated to keV energies by the auroral electron fields.

The measured EICS ion distributions taken at 48-s intervals between 1205 and 1210 UT are shown in Figure 21. The distributions have been rotated 180$^\circ$ from the usual EICS format so that upward flowing ions have a positive $v_{\parallel}$, similar to the simulations. The velocity scales have been chosen such that beams of the different ion species with the same ion energy would appear at the same distance from the origin. It is seen that at the earliest time (1205:37-1206:25 UT), beams are observed in all three ion species. Local maxima in these distributions appear at the same energy of about 2 keV (i.e., $v_{\parallel} \approx 300$ km/s for the H$^+$ ions). This energy is probably indicative of the potential that the ions have fallen through.

The distribution of the H$^+$ ions falls sharply beyond this energy. However, some of the He$^+$ and O$^+$ ions have high-energy tails indicating that they have undergone some additional acceleration [cf. Kaufmann et al., 1986]. Moreover, the maximum parallel velocity of the He$^+$ ions is approximately equal to the velocity of the H$^+$ ions, and the maximum O$^+$ velocity is approximately equal to the He$^+$ beam velocity. This is exactly what is expected for heating via the ion-ion instability (section 5).

There is also evidence of some perpendicular acceleration particularly in the O$^+$ ions which have the appearance of a weak bimodal distribution. This heating, if it is to be explained by the ion-ion instability, requires that the relative drift velocity of the H$^+$ ions be supersonic.

Acceleration of the heavy ions is also seen in the next two time intervals, although appearing to weaken in time. In the last two time intervals, there is very little evidence of acceleration of the heavy ions; much of the apparent velocity spread is probably due to variations in time during the sampling period rather than heating. This lack of heating is associated with a reduction in the average speed of the ions. For example, the peak in the O$^+$ distribution decreases from about 90 km/s in the second panel to about 60 km/s in the bottom panel.

If the above ion heating is to be interpreted as heating via the ion-ion instability, then the drift speed of the H$^+$ ions needs to be greater than about the sound speed. From Figure 21, $v_{\parallel}$ ranges initially between about 300 and 340 km/s and then decreases to about 200 km/s. At the same time the local sound speed (from Figure 19) increases from about 110 km/s to about 150 km/s. Thus, initially when large heavy ion heating is observed the H$^+$ beams are supersonic and unstable to the ion-ion instability. On the other hand, near the end of the
period when there is little heavy ion heating observed, the H+ beam speed only just exceeds the sound speed (and the relative drift speed between the ion species is below the sound speed) so that the plasma is only expected to be weakly unstable to the ion-ion instability in the subsonic regime, if at all.

Note, however, that if the heating observed in the first few periods in Figure 21 is occurring near the satellite then the interaction would be supersonic, and much stronger perpendicular heating than observed is predicted by the simulations (e.g., Figure 15). This discrepancy may be due to the fact that the interaction is possibly occurring at a lower altitude and any perpendicular heating is being partly masked by folding of the distributions by the mirror force. Moreover, if the interaction is occurring at lower altitudes then the local sound speed is probably higher and the beam speed lower than observed at the spacecraft so that the interaction may not be as supersonic in the source region. This would also produce more parallel heating at the expense of the perpendicular heating.

Clear evidence for both supersonic and subsonic interactions appears in the next period of strong ion beams between 1221 and 1229 UT. The densities of the H+, He+ and O+ ions for this period are shown in Figure 22. It is seen that O+ is in general again the dominant ion species with H+ and He+ having comparable densities, being about half that of O+. The relatively large O+ and He+ densities appear to be correlated with inverted-V events with the dropout in their densities during the period 1223-1224 UT being associated with the spacecraft moving between inverted-V events. The total densities are again in agreement with that inferred from the HAPI electrons.

The corresponding EICS distributions are shown in Figure 23 for four consecutive 96-s periods. During the first time interval, an inverted-V event starting at 1221 UT as seen by HAPI (Figure 18) is encountered. It is seen that there is strong perpendicular heating of all three ion species, with their perpendicular temperature being larger than their parallel temperature. Moreover, the average parallel energies of the heavy ions tend to be greater than that of the H+ ions, which again indicates that the heavy ions have undergone some additional acceleration. Some variations in the ion properties may also be occurring on time scales shorter than the resolution of EICS, as suggested by the two different features in the O+ ions at \( v_\parallel \approx 110, 160 \) km/s.
During the second time period, the dropout in the detected heavy ions is clear, as the spacecraft moves between inverted-V events. In the next time period, the heavy ions are again detected but at relatively lower energy than in the first time interval and there appears only slight parallel heating in the O$^+$ and He$^+$ ions. However, in the final period where intense ion beams are last observed, the H$^+$ beam velocity has increased to about 70% of that in the first time period and some of the O$^+$ ions have parallel velocities comparable to the beam velocity of the He$^+$ ions, indicating strong parallel acceleration of the heavy ions.

We suggest that the heating in the first interval in Figure 23 is due to the ion-ion instability in the supersonic regime. The observed distributions are qualitatively similar to those in Figure 15, with the peak velocities of the O$^+$ and He$^+$ ions being similar to the observed velocities. Moreover, the ratio $v_H/c_H$ is about 2 (and the relative drift speeds are supersonic) so that the ion beams can indeed be unstable to the ion-ion instability in the supersonic regime and become perpendicularly heated. We shall show in the next subsection that these ion beams are observed in association with an enhancement in the waves in the frequency range expected for the ion-ion instability, adding more evidence that these beams have been heated by the ion-ion instability.

In the later periods in Figure 23, the ratio $v_H/c_H \approx 1.4$ and the relative drift speeds are subsonic. In this case, the simulation results predicted that the ions should undergo primarily parallel heating via the ion-ion instability (Figure 17), in agreement with the observations. Thus, the heating via the ion-ion instability is able to semi-quantitatively account for the different types of heating seen in auroral beams through changes in the beam speed relative to the sound speed.
6.3. Wave Observations

The simulation results in sections 3 to 5 show that although the ion-ion instability can produce strong heating of the ions, large waves are not expected to be observed in association with the ion beams unless the heating has not reached saturation because the waves tend to be reabsorbed as the ions become heated. The wave observations from the University of Iowa plasma wave instrument (PWI) [Shawhan et al., 1981] are now presented to investigate any correlations of waves with the ion beams.

Figure 24 shows a swept frequency spectrogram of the electric field covering the period of interest. (Essentially no magnetic wave fields are seen except for very weak emissions during the most intense broadband electrostatic bursts, BEB.) The dark lines across the spectrogram show the electron, hydrogen and oxygen cyclotron frequencies, respectively. Note that most of the time the waves have a cutoff between about 4 and $8 \times 10^3$ Hz. If this cutoff is an indication of the local plasma frequency [cf. Persoon et al., 1988; Winglee et al., 1988a] then the local plasma density is between about 0.2 and 0.8 cm$^{-3}$. These densities are comparable to that inferred from the EICS and HAPI data.

During the period of interest, there are several very intense bursts, e.g., 1202, 1218 and 1223 UT. These bursts are associated with the discrete inverted-V events in the electron data (Figure 18) and have spectral characteristics of broadband electrostatic bursts investigated by Winglee et al. [1988a]. However, the ion beam events are not necessarily associated with these intense waves, e.g., the ion beams observed between 1205 and 1210 UT occur at a relatively quiet time in the observed wave emissions. During the intense ion beam event between 1221 and 1229 UT there is more wave activity but it is not clear from the spectrogram whether these waves are associated with the inverted-V electrons or the ion beams.

In order to examine the waves in more detail, power spectra taken at 32-s intervals were examined. The results for portions of the two periods during the ion beam events in Figures 21 and 23 are shown in Figures 25a and 25b, respectively. The times indicated on the figures denote the central time over which the spectra are calculated. Just prior to the ion beam events, BEB characterized by three spectral peaks (at about $2 \times 10^2$, $2 \times 10^3$ and $1 \times 10^4$ Hz) are observed. However, during the first ion beam event, the wave spectra, as shown in Figure 25a, remains fairly quiet with no obvious enhancements in the wave emissions. If the observed ion heating is due to the ion-ion instability then the lack of waves can only be accounted for by assuming that the heating has saturated at lower altitudes and the associated waves have been reabsorbed. This is also consistent with the observation that the ion beams, while appearing to have been perpendicularly heated, also appear to have been folded over by the mirror force.

There is much more wave activity during the second intense ion beam event as shown in Figure 25b. The dotted lines show the (frequency) averaged spectrum to indicate the waves seen at relatively quiet times similar to Figure 25a. The approximate value of $\omega$ as estimated from the plasma frequency is indicated in the lower part of the figure. BEB is not only seen prior to the beam event but also during the period 1223-1225 UT where essentially no ion beams are observed. During the actual period of the strong ion beam event between 1221 and 1223 UT there are clear enhancements in the wave emissions in the frequency range 0.2-2 $\times 10^3$ Hz. This frequency range includes that expected for the ion-ion instability (e.g., Figure 7). Doppler shifts between the
Fig. 21. Measured EICS velocity space ion distributions for five consecutive 48-s intervals during the first period. Initially, strong heavy ion heating is seen when the beam speeds are supersonic but, at later times, as the beam speed decreases and the ions become subsonic this heating becomes less apparent.

Simulation frame and the spacecraft frame may account for the higher frequencies in the observations. Some waves in this frequency range are expected since the ions show little evidence of folding by the magnetic field. Thus these waves could well be evidence for the ion-ion instability. However, there are other possible sources for these waves, including propagation of waves from the source region of the BEB, so that an absolute association of these waves with the ion-ion instability cannot be made.
7. Summary

In the auroral zone, a quasi-static parallel electric field accelerates ionospheric ions outward, providing a significant source of ions for the magnetosphere. Acceleration by such an electric field accelerates the ions to approximately the same energy irrespective of their mass. However, the corresponding change in velocity is approximately inversely proportional to the square root of the ion mass which produces a differential ion flow, with the lighter ions having a higher beam speed than the heavier ions. This differential ion flow can lead to an ion-ion streaming instability which can produce strong heating of the ions, with net energy being transferred from the light ions to the heavy ions. The ion heating produced by this instability is investigated in this study through a comparison between two-dimensional (three-velocity) electrostatic particle simulations and observations from DE 1.

The simulation results for a plasma with only two dominant ion species present are presented in sections 3 and 4. It is shown that the type and amount of heating depends on three factors: (1) the relative ion density; (2) the relative ion drift speed and (3) the temperature of the ions relative to the electron temperature.

The strongest heating of an ion species occurs when its relative density is small, irrespective of whether it is the light or heavy ion. In this case, there is bulk heating of the ions, and the original beam feature becomes very much less pronounced. When the relative density of an ion is large, tails in the distribution tend to be produced and the original beam can still be distinguished. The maximum velocity of the heavy ions produced by the instability can be as high as the beam speed of the light ions.

It is proposed that this variation in the energization of the heavy ions with relative density produces the scatter in the heating observed by Reiff et al. [1988] as a function of relative beam speed. Moreover, if it is assumed that the average scale height of O+ is highest during solar maximum, then the energization of the heavy ions relative to the H+ ions is expected to be at a minimum which is consistent with the observations of Yau et al. [1985], Collin et al. [1987] and Peterson (submitted, 1988).

The relative drift speed plays an important role in determining the type of heating produced by the instability. Both perpendicular and parallel heating of the ions can be produced. For interactions where the difference in the beam speeds of the ions is less than about the sound speed (i.e., subsonic interactions), heating occurs primarily along the magnetic field. For supersonic interactions, heating is initially oblique to the magnetic field. However, as the ions become heated, wave growth shifts to more field-aligned angles, so that strong parallel heating can occur, particularly in the later phases of the instability.

Because the electron temperature tends to decrease with increasing altitude in the auroral zone, the interaction can become more supersonic as the ion beams propagate upward (provided they are not strongly heated or decelerated at lower altitudes). The results in section 4 show that, with such a reduction in electron temperature, enhanced perpendicular heating occurs but the efficiency of coupling the light ion beam energy to heating and acceleration of the heavy ion decreases. For a change in $T_e/T_i$ of a factor of 4, the coupling efficiency decreases by nearly 50% (section 4).

When there are three ions present (e.g., H+, He+ and O+), the heating of the light and heavy ions is similar to that for a two-ion component plasma. The intermediate ion (i.e., He+) can participate in interactions with both the light ion H+ and the heavy ion O+. This dual interaction can accelerate some of the He+...
ions to velocities comparable to the H\textsuperscript{+} beam speed while decelerating some of the He\textsuperscript{+} ions down to the O\textsuperscript{+} speed, with the result that the He\textsuperscript{+} distribution can become much more heated than that of the O\textsuperscript{+} ions. In the supersonic case in section 5, there is initially a net gain in the He\textsuperscript{+} parallel energy due to the H\textsuperscript{+}–He\textsuperscript{+} interaction but, as these ions become heated, this interaction is suppressed and the He\textsuperscript{+} ions start to lose parallel energy to the O\textsuperscript{+} ions. As a result, there is little net change in the parallel energy of the He\textsuperscript{+} ions, with the velocities extending from the O\textsuperscript{+} beam speed to the H\textsuperscript{+} beam speed. For the subsonic interaction, the He\textsuperscript{+}–O\textsuperscript{+} interaction dominates so that there is a net loss of parallel energy from the He\textsuperscript{+} ions, although a few ions are still accelerated to the H\textsuperscript{+} beam speed.

Intense electrostatic waves can be generated during the interaction. Peak wave energies can reach a few percent of the H\textsuperscript{+} beam energy (e.g., section 3). These waves have frequencies between about the H\textsuperscript{+} cyclotron frequency and the H\textsuperscript{+} plasma frequency. Note, however, that these waves are reabsorbed as the ions become heated. In other words, intense waves need not be associated with the ion heating if the instability and heating are near saturation.

Observations from DE 1 during a nightside auroral crossing were examined for any evidence for heating.
Fig. 24. DE 1 swept frequency receiver data associated with the ion beam events shown in Figures 18-23.
Fig. 25. Sample wave spectra for ion beam events in Figures 21 and 23. Essentially no enhancement in the wave emissions is seen during the first event while in the second event there is much more wave activity with broadband electrostatic bursts and some enhancement during the ion beam events in the frequency range $10^2 - 10^3$ Hz, which is the expected range for the ion-ion streaming instability. The dotted lines show a typical spectra from the first period for comparison.

of the ions by the ion-ion instability. The observations show that often some of the He$^+$ ions are accelerated to the H$^+$ beam speed and that some of the O$^+$ ions are accelerated up to about the He$^+$ beam speed while the H$^+$ do not have any such high-energy tails. The presence in the heavy ions but absence in the H$^+$ ions of these high-energy tails is consistent with the simulation results for the ion-ion instability. It was also shown that there was strong perpendicular heating when the ion beams were observed to be in the supersonic regime and that this heating changed to parallel heating as the beam speed decreased into the subsonic regime, again consistent with the simulation results. This is probably the strongest evidence that the ion-ion streaming instability is accelerating and heating heavy ions in the auroral zone.

The wave data showed no clear association of enhanced waves with ion heating. During one event when there was strong ion heating, essentially no enhanced waves were detected. In another event, some enhanced wave emissions over the frequency range for the ion-ion instability were detected in association with strong heavy ion heating but propagation of waves from neighboring regions of intense wave activity could not be ruled out. However, a one-to-one correspondence between enhanced wave emissions and ion heating is not expected since the simulations clearly show that the waves generated by the instability tend to be reabsorbed as the ions become heated.

Acknowledgments. One of us (R. M. W.) gratefully acknowledges help and encouraging discussions on the DE data from T. E. Moore, W. K. Peterson, J. L. Burch and J. A. Slavin. We acknowledge D. A. Gurnett for the PWI data. 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, NSG-7287 and NAGW-998 to the University of Colorado; by NASA grant NAS5-28710 to Lockheed and by the Lockheed Independent Research Program; by NASA grant NAS5-28711 to Southwest Research Institute; by NASA grant NAG5-310 to the University of Iowa. The simulations were performed on the CRAY X-MP at the San Diego Supercomputer Center which is supported by the National Science Foundation.

The Editor thanks J. L. Horwitz and H. E. J. Koskinen for their assistance in evaluating this paper.
REFERENCES

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(Received September 13, 1988; revised November 16, 1988; accepted November 18, 1988.)