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Auroral E Region Plasma Waves and Elevated Electron Temperatures

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INTRODUCTION

Auroral E region plasma irregularities have been studied extensively with VHF and UHF coherent radars [e.g., Balsley and Ecklund, 1972; Greenwald et al., 1973; 1975; Haldoupis and Sofko, 1976; Moorcroft and Tsunoda, 1978; Unwin and Johnston, 1981; Timofeev and Miroshnikov, 1982; Nielsen et al., 1984; Fejer et al., 1984a; Providakes et al., 1985]. At radar frequencies of 40–50 MHz the spectra are usually broad with widths of the order of the mean Doppler shift, i.e., similar to type 2 spectra obtained from the equatorial electrojet [e.g., Fejer and Kelley, 1980], but the auroral echoes often have larger mean Doppler shifts and spectral widths. Narrow spectral peaks similar to the type 1 (two-stream) equatorial echoes are also sometimes seen [Balsley and Ecklund, 1972; Haldoupis and Sofko, 1976]. There have been a few observations of other narrow (~10 Hz or even less) peaks at frequencies between about 30 and 80 Hz, independent of the E region cross-field plasma drift. These have been labeled type 3 and appear to be associated with ion cyclotron waves [Fejer et al., 1984a; Providakes et al., 1985; Haldoupis et al., 1985].

The phase velocity of the so-called type 1 spectral peak varies much more in the auroral zone than it does at the equator [Balsley and Ecklund, 1972; Tsunoda, 1976; Moorcroft and Tsunoda, 1978]. Comparisons between Scandinavian Twin Auroral Radar Experiment (STARE) or Sweden And Britain Radar Experiment (SABRE) and European Incoherent Scatter (EISCAT) observations [Nielsen and Schlegel, 1983, 1985; Reinleitner and Nielsen, 1985] imply that the unstable waves travel at approximately the ion-acoustic velocity, which can vary due to temperature changes in regions of strong electric fields, where heating by the strongly unstable waves themselves can occur [Schlegel and St.-Maurice, 1981; Wickwar et al., 1981; St.-Maurice et al., 1981; St.-Maurice and Laher, 1985]. Recently, in fact, electron temperatures higher than 2000 K were observed with the Sondre Stromfjord [Stauning, 1984] and EISCAT (I. Haggstrom, private communication, 1985) radars. The ion-acoustic speeds corresponding to such temperatures are significantly larger than the phase velocities (400–600 m/s) of typical two-stream waves.

It is these waves (which we shall call type 4) with exceptionally high phase velocities that we will examine here using a radar interferometer with high temporal and spatial resolution during periods with strong auroral electric fields and currents. They are observed only during periods of very strong auroral currents (or intense electric fields). On these occasions the power spectra are usually very broad with average phase velocities and spectral widths sometimes larger than 600 and 800 m/s, respectively, and at times the narrow peaks appear with phase velocities of almost 1000 m/s. We will argue here that the latter are seen when the radar wave vector is roughly parallel to the current direction when the electric field is very large and that they are caused by the two-stream instability acting in regions of highly elevated electron temperatures. The more commonly observed broad Doppler spectra are probably due to secondary gradient drift waves. These can have unusually large phase velocities because the drift velocity threshold for the direct excitation of short wavelength instabilities is very high in these periods of strong plasma heating. In other words, the type 1 waves (mixed with type 2) will be observed only when the radar is properly oriented with respect to the current direction (i.e., inside the two-stream unstable cone); at other times only the type 2 will be detected. This overall picture provides a plausible explanation for our results, but the details of these processes are complicated and are still far from fully understood.

EXPERIMENTAL PROCEDURE

The data were obtained with the 49.92-MHz Cornell University Portable Radar Interferometer (CUPRI) system located in Ithaca, New York (76.5°W, 42.5°N). The antenna consisted of two 26-element colinear arrays of half-wave dipoles placed end to end and 1.5 wavelengths above the ground. There was a backplane wire about 0.25 A behind each antenna. The horizontal (one way) beamwidth of each

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array was about 5.5° but the vertical beamwidth was much broader [Providakes, 1985]. The radar beams were pointed about 20° east of geomagnetic north, or 7° east of geographic north, as is shown in Figure 1. The radar wave vector was within 3° of normal to the magnetic field for ranges between 350 and 700 km at an altitude of 110 km [Providakes, 1985].

The radar was operated usually with a 50 μs pulse and was cycled between an range time intensity (RTI) and a spectral mode. In the RTI mode the interpulse period (IPP) was 10 ms. For spectral observations the IPP was usually reduced to 2 ms, which causes range aliasing (echoes from 150, 450, 750 km, etc. are combined), but the unaliased RTI data can be used to resolve the ambiguities. The Doppler spectra become frequency aliased when the phase velocities in the scattering region are larger than 750 m/s. In such cases, we alternate between two slightly different IPPs (e.g., 1.8 and 2.0 ms) to unravel the spectral features.

For the interferometer observations one antenna is used for transmission and two for reception. The signals from each antenna were synchronously detected, and the two quadrature outputs were recorded on a FM analog tape recorder for later digital processing. All data channels were sampled simultaneously for 30 range gates separated by 7.5 km every IPP, providing data over a range of about 225 km. Sets of 128 consecutive quadrature sample pairs from each range gate from each receiver were fast Fourier transformed, and then cross spectra and power spectra were calculated. For each Doppler shift the magnitude (coherence) of the normalized cross spectrum provides an estimate of how localized the corresponding scattering region is within the radar scattering volume [Farley et al., 1981], and the phase gives the mean angular position. With the baseline of 52 m, a change in the phase angle of 2π at a range of 450 km corresponds to an east-west displacement of about 55 km. If a scatterer has a larger displacement, the corresponding phase angle will be aliased (wrapped around). The rate of change of the phase with time gives an estimate of the velocity transverse to the radar beam. More details of the interferometer data analysis are given in the works by Farley et al. [1981] and Providakes et al. [1983, 1985].

RESULTS

We will concentrate here on the unusual type 4 spectra described in the introduction that are measured only in highly disturbed periods. Figure 2 shows some early examples from a period when the Kp index was about 8. The integration time was 2 s, and each spectrum was normalized with its own maximum value. Data from the same period were examined by Fejer et al. [1984a], but that paper was concerned primarily with another spectral feature, namely,
narrow type 3 spectral peaks with a Doppler shift of about 70 Hz. In the data set shown here, the occurrence of the positively shifted peaks is usually preceded by a systematic broadening of the negative component of the spectrum, sometimes to the point of aliasing. The whole process of the appearance and disappearance of these peaks lasts typically only a few tens of seconds. Fejer et al. pointed out that both their time evolution and the corresponding magnetometer data from Ottawa suggested that the peaks were probably frequency aliased and that actually they represented Doppler shifts of about −300 Hz (phase velocities of 900 m/s away from the radar). Observations to be presented below confirm this conclusion.

Similar echoes were also observed during very disturbed periods on September 6, 1982, and April 25, 1984, when the Kp indices were 8+ and 7−, respectively. We will examine here radar data obtained at about 0830-0910 UT (0330-0410 EST) on September 6, 1982. Figure 3 shows the Ottawa magnetogram for this period and also the times when measurements were made with the radar interferometer. The darkened areas indicate observations of the aliased (as we shall see later) type 4 spectral peaks. As is shown in Figure 1, Ottawa corresponds to a slant range of about 350 km north of Ithaca for a scattering altitude of 110 km. On this night, the storm reached its maximum amplitude at about 0900 UT (0400 EST), with negative deflections in the X component as large as −1500 γ, corresponding to a very strong westward electrojet. The Z component indicated rapid northward and southward movements of the westward electrojet. The type 4 echoes were observed only during periods when the electrojet current near Ottawa was very strong. These echoes are also usually associated with a large Y component (a north-south component of current). However, a more detailed comparison between the radar data with data from a single magnetometer is not meaningful, since the latter is sensitive to the average auroral currents extended spatially in range.

Figure 4 shows some radar spectra obtained during this period with an integration time of about 6.5 s. The radar was switched to the RTI mode between 0334:01 and 0334:10; hence the gap in the data. The peaks with apparent phase velocities of about +700 m/s occur only when the broad negative spectral component has a large mean phase velocity (usually between −300 and −600 m/s) and width (up to about 800 m/s). The occasional apparent decreases in the amplitude of the broad component are just a consequence of the normalization process. In fact, as we shall see, as the amplitude of the narrow peak increases, so usually does the power in the broad component.

The ambiguity in the Doppler shift can be resolved by using two slightly different IPPs. The change will not affect unaliased features but will shift any aliased part of the spectrum. A number of these tests were performed, and all of them supported the conclusion that the phase velocity of the narrow peaks has the same sign as that of the broad component. Figure 5 shows one such example, with the complete power and cross spectral information displayed. Note the change in position of the peak when the smaller IPP

Fig. 3. Ottawa magnetogram during a period of very large currents and strong auroral echoes. Periods of spectral observations are also shown. Shaded areas indicate the presence of type 4 echoes.

Fig. 4. Selected spectra during a period of strong type 4 echoes. Integration time was 6.5 s. There is a gap in the spectral observations between 0334:01 and 0334:10. Positive velocities are toward the radar.
(faster sampling rate) was used. The IPP was still not small enough to remove the aliasing, but one can easily calculate that the true phase velocity was about \(-840\) m/s. The phase spectrum at 0400:26 also shows an example of phase aliasing for negative velocities. The coherence of the spectral peaks is usually close to unity, indicating that these radar returns come from regions much smaller than the scattering volume in east-west extent. The coherence of the broad type 2-like component is more variable and is fairly low in this figure, but sometimes it too is high.

Since the temporal evolution of the spectra and the use of two different IPPs both clearly indicate that the type 4 peaks were frequently aliased, we can reconstruct the true spectra by wrapping the 32 largest positive Doppler shifts around to the negative side, so the frequency range covered becomes \(-375\) to \(+125\) Hz, representing velocities from \(-1125\) to \(+375\) m/s. Figure 6 shows a set of these reconstructed power and phase spectra during a period of very strong westward current, according to the Ottawa magnetogram. Note the very sudden appearance of narrow peaks with phase velocities of \(800-900\) m/s at all but the furthest range. The phase spectra show examples of both significant spatial averaging (e.g., at 0400:35 at all ranges) and very slight averaging (e.g., at 0400:48 at the two furthest ranges). The power spectra are the sum of contributions from scatterers at different azimuthal positions that are moving with different radial velocities. The data from 435 and 457.5 km show, for example, that the region generating the type 4 peak can be separated by as much as 20 km from the region contributing the broad component. The apparent structure of the echoing region is quite variable. For example, several of the plots from ranges of 435 and 442.5 km suggest a smooth shear in radial velocity of about 1 km/s in 30 km or so of transverse distance. On the other hand, the upper right-hand panel indicates that all phase velocities originate within a transverse extent of at most a few kilometers, suggesting either violent turbulence or a very strong shear. One final important point to note from Figure 6 is that the type 4 structures are usually quite well aligned with the radar beam. At 0400:35, for example, all the type 4 echoes come from a transverse position of \(-20\) to \(-25\) km.

Figure 7 gives several additional examples of the sudden (transition times of less than 10 s) appearance and disappearance of the narrow peaks at large Doppler shifts. Their occurrence is again preceded by substantial broadening of the type 2-like component to widths of up to about 800 m/s. The spectra at the two closest ranges also show that type 4 peaks sometimes appear even when the backscattered power is very small, presumably because of low electron densities.

Figure 8 shows examples of the temporal and spatial variations of the type 4 phase velocity. For example, the velocity of 517.5 km changed from about 600 m/s to about 850 m/s during the period from 0340:35 to 0341:16, and the velocity at 0340:51 changed from about 650 to 850 m/s between the ranges of 472.5 and 532.5 km. The southernmost ranges show very weak echoes with wide spectra.

The temporal and spatial variation of the backscattered power at four adjacent ranges is shown in Figure 9, in which all the spectra are now normalized to the same value rather than to their own maximum. This figure illustrates quite dramatically the sporadic appearance of strong type 4 echoes lasting a few tens of seconds and preceded by large increases of the mean velocity and spectral width of the broad component. Large power increases of the type 4 echoes are not associated with large changes in the type 2 power, but they are correlated with increases in the phase velocity of these waves. Although the power of the broad component increases with the average phase velocity, the converse is not always true; there can be large changes in echo power without significant changes in the spectrum, suggesting large variations of the electron density in the scattering region.

As was described earlier, the interferometer technique can determine the position and transverse drift velocity of individual scatterers if the scatterers remain coherent for a few
Fig. 7. Selected spectra showing the appearance and disappearance of type 4 spectra. Integration time was 5.5 s.

seconds. Figure 10 shows this sort of data measured at two adjacent ranges. Following the procedure described in the work by Providakes et al. [1985], the power spectrum was divided into eight frequency bins, and for each the position of any localized scatterer was determined from the phase spectrum. Four symbols, corresponding to different Doppler shift ranges as shown at the bottom of the panels, are used to represent the position of the scatterers. A symbol is plotted only if the coherence in the frequency bin is greater than 0.7. This figure shows, in a way slightly different from the presentation of Figure 6, the highly localized and sometimes complex nature of the unstable regions, particularly for the type 4 echoes, and the frequent occurrence of velocity shears. Note also that sometimes the interferometer technique detects highly coherent type 4 echoes (e.g., the circled crosses between about 0401:17 and 0402:10) that are too weak to be seen in the power spectra; the normalization suppresses them even though they are strong enough to have a high coherence value.

The transverse velocity of the irregularities can be derived from the slope of the horizontal (transverse) distance plots in Figure 10 [Farley et al., 1981; Providakes et al., 1985]. In the period 0403 to 0404, for example, the velocity is about 500 m/s in a mainly eastward direction. We will argue later that we see type 4 echoes only when the transverse component of the drift velocity is much smaller than the line-of-sight velocity. The figure also shows that the lifetime of the type 4 peaks at any particular range interval is often too short, and the appearance and disappearance too abrupt, to be attributed to motion of the scatterers into or out of the radar beam. The changes must be related to substantial and rapid changes in the electric field.

Finally, the influence of the radar magnetic aspect angle on the occurrence of type 4 echoes is illustrated in the
modified RTI plot shown in Figure 11. The ranges from which type 4 echoes were received during this highly disturbed period are shown as squares. Echoes with a broad type 2 spectrum were received over the entire range from 330 to 547.5 km and often beyond. The magnetic aspect angles, for an altitude of 110 km, are shown at the right of the figure. Echoes were received from regions where the aspect angle differed from 90° by as much as 5°, but for the type 4 echoes the difference was only about 1°; the aspect sensitivity was much greater.

Fig. 9. Examples of the temporal and spatial variations of the backscattered power. Spectra were normalized to the same value and the integration time was about 6 s.

Fig. 10. Horizontal interferometer data for two consecutive range intervals as a function of time. Time increases from top to bottom. Symbols for the positions correspond to the frequency bins shown at the bottom of the spectra plots. Slope of a line drawn through a set of scatterers represents the transverse velocity (eastward for scatterers moving left to right).
DISCUSSION

Other Radar Observations

Doppler spectra similar to those reported here were observed with the 42-MHz CW bistatic radar at Saskatoon, Canada during the morning sector of an exceptionally disturbed period ($Ap = 48$) [Haldoupis and Sofko, 1979]. Figure 12 shows some of their spectra. The mean Doppler velocity of the narrow component was about $1050 \pm 70$ m/s and the half-power width about 175 m/s; the broad component had a mean phase velocity of $500 \pm 100$ m/s and a half-power width of $650 \pm 200$ m/s. Note the relationship between the changes in the broad component and the appearance of the type 4 peak. The CW observations had no frequency aliasing problems, and so these results support our dealiasing procedure. On the other hand, their observations had poor spatial resolution, and so the spectra represent considerable spatial averaging. Even so, the type 4 peaks lasted only a short time, as can be seen in Figure 12. Ogawa and Igarashi [1982] showed a few examples of aliased type 4 spectra obtained with a 50-MHz radar at Syowa Station, Antarctica during a period of very strong magnetic activity (see their Figure 5a), but they did not discuss the echo characteristics. Large changes in the phase velocity of type 1 waves were observed at the same time.

Spectra measured with the 140-MHz STARE system usually are broad, with a width in velocity of 500-1200 m/s [Nielsen et al., 1984]. When the radar is pointed within about $60^\circ$ of the direction of the electron flow, however, a narrower component is also sometimes seen, usually centered at about 400-600 m/s, but occasionally at much higher velocities [Reinleitner and Nielsen, 1985]. The width is hard to determine accurately because the frequency resolution is about 300 Hz, or about 300 m/s. This poor frequency resolution and the greater temporal and spatial averaging (covering typically 20 x 20 km$^2$) may explain why the highly localized and short-lived type 4 echoes that we see have not been clearly detected by STARE.

Interpretation

How do we explain the type 4 observations? Our hypothesis is that the first step is a large increase in the electric fields, leading to a similar increase in the currents, or more precisely in the velocity of the electrons relative to the ions. This velocity, sometimes in combination with electron density gradients, is what drives the electrojet instabilities, as can be seen from the familiar fluid theory results [e.g., Fejer et al., 1984b; Farley, 1985], namely,

$$\omega = k \cdot \mathbf{V}_e/(1 + \psi)$$  \hspace{1cm} (1)

$$\gamma = \frac{1}{1 + \psi} \left[ \frac{\psi (\omega_e^2 - k^2 C_s^2)}{\nu_i} + \frac{\nu_e \omega_e}{\Omega_e k L_{eff}} \right] - 2\alpha N_0$$  \hspace{1cm} (2)

where $\mathbf{V}_d = \mathbf{V}_e - \mathbf{V}_i$ is the plasma drift velocity, $\psi = (\nu_i/\Omega_e \omega_e) (1 + \nu_e^2 k_i^2 / \nu_e^2 k_i^2)$; $\nu_i$ and $\nu_e$ are the ion-neutral and electron-neutral collision frequencies; $\Omega_e$ is electron (ion) gyrofrequency, $k_i$ is the component of the wave vector that is parallel to the magnetic field; $C_s$ is the ion-acoustic speed; $L_{eff}$ is the characteristic length of the electron density gradient perpendicular to the magnetic field; and $(2\alpha N_0)^{-1}$ is the recombination time. Here we have assumed $k$ is parallel to $\mathbf{V} \times \mathbf{B}$ for convenience. The first term on the right-hand side of (2) is the ion inertial or two-stream term, the second describes diffusive damping, the third is the stabilizing or destabilizing (when $E \cdot V$ is negative or positive, respectively) gradient drift term, and the last gives the damping due to recombination. For wavelengths of about a meter or less, kinetic theory is required for accurate results.

The first two terms in (2) are proportional to $k^2$ and so are most important for short wavelengths. As the drift velocity increases and reaches values somewhat greater than the ion-acoustic velocity, short wavelength waves become linearly unstable and hence reach large amplitudes. Depending upon geometry, these waves may or may not be detected by radar (the Bragg condition requires that $k_{wave} = -2k_{radar}$ for backscatter observations), but their dissipation will heat the electrons if they are driven strongly enough [e.g., St.

Fig. 11. Range time plot of the occurrence of type 4 echoes (denoted by squares). Magnetic aspect angles for an altitude of 110 km are also shown.

Fig. 12. Example of 42.1 MHz CW radar power spectra data during type 4 conditions. Integration time for a single spectrum is about 2.0 s (adapted from Haldoupis and Sofko [1979]).
Maurice et al., 1981; Primdahl and Bahnsen, 1984; St. Maurice and Laher, 1985; Robinson, 1986. The temperature increase broadens the scale of the Doppler spectrum, since the characteristic velocity is the ion-acoustic velocity, which is proportional to the square root of a weighted (see below) sum of the ion and electron temperatures. The broad type 2 (as we have been calling it) part of the spectrum, which always corresponds to velocities below the ion-acoustic, now will extend to higher than normal Doppler shifts. The ion-acoustic waves, if detected, will be at the new higher Doppler shift corresponding to the increased marginal phase velocity (approximately the new ion-acoustic velocity).

The only tricky point to keep in mind here is that in this model which we are proposing, the directly excited, short wavelength ion-acoustic waves (which we refer to here generally as type 1 or type 4), depending upon whether or not they are associated with normal or substantially elevated temperatures) must be present first to cause the heating, but often they will not be detected by the radar because their wave vectors will not be oriented parallel (or antiparallel) to the radar wave vector. These plasma wave vectors will be directed more or less in the same direction as the electron drift (as well as perpendicular to B of course), but the Ithaca radar, as well as most of the other auroral radars, is pointed more or less northward, i.e., roughly perpendicular to the usual direction of the current. Said another way, we suggest that they very broad spectra can exist only when short wavelength ion-acoustic waves are very strongly driven by electron drift velocities well above the normal ion acoustic speed, but these waves propagate in a relatively narrow cone of angles (cos \( \theta > C_i/V_a \)), where \( C_i \) itself increases with \( V_a \) due to electron heating) which only occasionally and briefly rotates into a direction which allows the radar to detect them.

Drift velocities less than the normal ion-acoustic velocity produce 3-m and shorter wavelength waves only via a nonlinear cascade from longer wavelengths excited primarily by the gradient drift term [Sudan et al., 1973; Keskinen et al., 1979; Sudan, 1983]. We believe that this process alone will not lead to appreciable electron heating, but this point is probably controversial. For example, St.-Maurice and Laher [1985] suggest, on the basis of their calculations, that electron heating can be caused by the long wavelength waves for which the gradient drift mechanism is the most effective, if their wave vector is a few \( (2^\circ-5^\circ) \) degrees away from perpendicularity. But the long wavelengths are always easily excited, and yet the extreme heating is rare. It is our opinion that although the longer wavelengths clearly will be affected for strong drift conditions, driving the instability unusually strongly affects mainly the short wavelength end of the \( k \) spectrum, and that this is where the heating will occur. This is consistent with the ideas advanced by Primdahl and Bahnsen [1985] and Robinson [1986]. Further theoretical work on this point is certainly needed, however.

If the short wavelength waves are the important ones, how do they cause the heating? One good possibility is the model of Sudan [1983], in which wave particle collisions add to the usual electron-neutral collisions, leading to a substantial increase in the diffusion rate perpendicular to the magnetic field and hence to an increase in \( J\cdot E \), the Joule heating of the electrons. And, of course, the temperature increase itself will raise the electron-neutral collision frequency. Alternatively, recent studies by E. Kudeki and D. T. Farley (private communication, 1986) at the magnetic equator have shown that strongly driven ion-acoustic waves appear to couple to longer wavelength waves which are propagating at slower phase velocities and are less perpendicular to \( B \) (larger \( |k|/k \) ratios). These suffer greater diffusive damping, thereby limiting wave growth, and St.-Maurice and Laher [1985] have shown that strong waves propagating at only slight angles to the magnetic field normal can cause substantial electron heating. They applied this idea to long wavelengths, as was mentioned in the previous paragraph, but it is equally valid for shorter wavelengths. An alternative short wavelength heating process relying on the role of anomalous electron collisions for heating the electrons was proposed by Primdahl and Bahnsen [1985] and Robinson [1986]. This second process assumes that the waves propagate exactly perpendicular to \( B \) \( (k || = 0) \). So either of these short or long wavelength mechanisms or a combination of both appears to offer a plausible explanation for the heating, and the second also might explain why the narrow type 4 peaks seem to be more aspect sensitive than the broad component, as is shown in Figure 11.

The ideas above imply that strongly driven ion-acoustic waves must be present, even if the radar doesn’t detect them, whenever strong heating occurs. Is this idea defensible? First of all, there are equatorial measurements that show that the intensity of (echo power from) the type 1 waves decreases by roughly 0.3 dB/deg for 3-m waves as the \( k \) vector departs from parallel to the direction of mean electron flow [Iterkic et al., 1980], and about 0.3-0.6 dB/deg for 1-m auroral waves [Andre, 1983; Haldoupis et al., 1984]. Linear theory suggests an even more drastic dependence on angle (a sharp cutoff); it is the always present large-scale waves at the equator which spread the type 1 waves over all angles with respect to the mean electron flow direction [Kudeki et al., 1982]. These waves depend upon density gradients of the proper sign and so will not always exist in the auroral zone. Second, we have shown evidence from the interferometer observations that the type 4 waves often exist even when they don’t show up on the power spectra. The circled crosses plotted in the top half of Figure 10, for example, show that the signal at the type 4 Doppler shift was highly coherent, implying a high signal-noise ratio, even though it was much weaker than the broad Doppler component and was therefore suppressed by the normalization.

Next we ask what values of electron temperature are required to explain the radar observations if we assume that the type 4 waves are propagating at their threshold phase velocity, which is close to \( C_i \). It is not clear exactly what expression is most appropriate for the ion-acoustic velocity in this case. The fluid theory described by (1) and (2), which is what is quoted most in the literature, gives \( [(K_T e + K_T i)/m_i]^{1/2} \) as the velocity, but this assumes isothermal ions and electrons an assumption, which is not correct for electrons and short wavelengths. It probably is not correct for ions either, since for a phase velocity of 1000 m/s the oscillation frequency for 3-m waves is about 2-3 times the ion collision frequency near the height of maximum heating (about 110 km). Collisionless kinetic theory [e.g., Ichimaru, 1973] gives the velocity as \( [(K_T e + 3K_T i)/m_i]^{1/2} \) for \( T_e \) much greater (a factor of three is probably enough) than \( T_i \), but, of course, the plasma is not collisionless. We do not wish to pursue here the question of exactly what the correct expression should be, but perhaps these two possibilities
give reasonable bounds. For an assumed value of $T_e$ of 400 K, say, and a mean ion mass of 31 amu, an ion acoustic velocity of 900 m/s would imply an electron temperatures of 2600 K or 1800 K in the two cases. As was mentioned in the introduction, incoherent scatter measurements in the $E$ region [Stauning, 1984; I. Haggstrom, private communication, 1985] have shown temperatures of this order during very disturbed conditions. Nielsen and Schlegel [1983] have estimated the ion acoustic speed as a function of height and drift velocity, assuming isothermal electrons and ions. For example, at 115 km, for a drift velocity of 2000 m/s, they calculated $T_e = 2191$ K, $T_i = 764$ K, and $C_s = 890$ m/s.

If 3-m two-stream waves are excited in the $E$ region (above 110 km) where intense electric fields are present, and $\Omega / \nu_i > 1/6$, then the drift velocity of the ions also must be taken into account. The threshold phase velocity in the radar frame, ignoring neutral winds, is given by

$$V_p = C_s + \frac{\nu_0 \Omega_e}{\nu_i^2 + \Omega_e^2} \frac{k \cdot E}{Bk}$$

(3)

However, the ion drift correction is not important when $k$ is nearly parallel to $V_d$, since, in this case, $k \cdot E \approx 0$.

Our observations indicate that these plasma heating events associated with very large auroral currents (with $\Delta H$ over Ottawa about 5–6 times the typical value for normal type 1 observations) can occur at much lower latitudes ($L = 3.5$ in our case) than reported previously. During the observations discussed above we had no supporting observations to study in detail the ambient conditions for the occurrence of strongly enhanced electron temperatures. However, the characteristics of eastward drifting Omega bands with a westward background electrojet and circular Hall current vortices [e.g., Oppenoorth et al., 1983] would be consistent with our observations. Such bands could explain the occasional rotation of the drift velocity so that the radar wave vector is inside the two-stream unstable cone.

**Conclusions**

Very strong and highly variable auroral radar echoes were observed from Ithaca in the postmidnight sector during periods of extremely strong magnetic activity over Ottawa. Most of the Doppler spectra were similar to those of the equatorial gradient drift waves, but often with considerably larger average phase velocities and spectral widths. On these occasions, relatively narrow Doppler spectral peaks with very large phase velocities (between about 650 and 900 m/s) are observed frequently. These narrow spectral peaks (labeled type 4) have typical turn on and turn off times smaller than a few seconds and usually last only a few tens of seconds at a given range.

These type 4 spectra resemble those of equatorial type 1 (two stream) spectra but have phase velocities considerably larger than the nominal ion acoustic speed (about 360 m/s) near the center of the electrojet scattering region. The time evolution of the broad type 2 component prior to the appearance of the type 4 spectra is also similar to that seen at the equator prior to the occurrence of type 1 waves.

The auroral backscattered echo is often strong and highly variable in range and with time during these extremely disturbed events. The power from the type 4 echoes sometimes varies more than 20 dB in less than a minute and/or between consecutive ranges. These waves are sometimes generated even in regions where the echoes are very weak, due to small electron densities. When the type 4 power increases, so usually does the power from the broad spectra, but the converse is not true. The type 4 echoes are considerably more aspect sensitive than the broad type 2 echoes and are rarely observed at aspect angles differing by more than a degree from normal to $E$.

The interferometer data show that the radar returns, particularly the type 4 echoes, come from north-south aligned scattering regions highly localized (scale sizes somewhat smaller than 10 km) in east-west extent. There are frequently large transverse shears in the line of sight velocities inside these localized patches. The discrete patches may have transverse drift velocities of up to about 1000 m/s, but much smaller velocities are also observed.

These observations at $L = 3.5$ are consistent with the interpretation that the type 4 echoes are due to highly field-aligned two-stream waves generated during periods of very large plasma drifts (perhaps 1500 m/s or more) and, consequently, highly enhanced electron, and perhaps also ion temperatures. These echoes are probably observed only when the drift velocity is closely aligned with the radar line of sight.

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