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Bela G. Fejer, *Utah State University*
R. W. Reed
D. T. Farley
W. E. Swartz
M. C. Kelley

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Ion Cyclotron Waves as a Possible Source of Resonant Auroral Radar Echoes

B. G. Fejer, R. W. Reed, D. T. Farley, W. E. Swartz, and M. C. Kelley

School of Electrical Engineering, Cornell University

Auroral backscatter radar observations were made from Ithaca, New York, at 50 MHz during the early morning of April 1, 1976, a period of high magnetic disturbance (Kp ~ 8). The backscattered power showed large rapid (time scale of a few minutes or less) variations, characteristic of discrete radar aurora, from L = 3.5-4. Doppler spectra of waves propagating in nearly the north-south direction from up to 28 different ranges were obtained simultaneously with good spatial (7.5 km) and temporal (2 s) resolution. Some unusual spectra with very narrow peaks at Doppler shifts between about 70 and 90 Hz were observed and were apparently associated with sheared flows of the auroral plasma. These echoes were observed at the southern edge of the scattering region, which moved poleward with a velocity which sometimes exceeded 800 m/s. There is evidence that the echoes were generated above about 140 km. Present electrojet instability theories cannot explain these narrow spectra, but the Doppler shift suggests that they might be caused by ion cyclotron waves generated by field-aligned currents (electron drifts). However, the excitation of ion cyclotron waves requires currents considerably stronger than typically quoted mean values (~10^{-2} µA/m^2). Furthermore, the most easily excited ion cyclotron waves have wavelengths longer than 3 m and do not propagate in quite the right direction for detection by our radar. The thresholds for the waves that we observe is considerably higher than the minimum. Intense localized currents, such as those known to be associated with auroral curls and vortices (J > 10^{-4} µA/m^2), appear to be sufficient to excite the longer (~10-20 m) ion cyclotron waves in the upper E region; whether or not the field-aligned electron drifts are ever large enough to excite directly the 3-m waves we observe is an open question, but there is at least some evidence which suggests that such drifts do exist in very localized regions during highly disturbed conditions.

EXPERIMENTAL PROCEDURE

The data to be presented were obtained with a 49.92-MHz radar located in Ithaca, New York (76.5°W, 42.5°N). This radar is very similar to that used by the NOAA group in Alaska [Balsley and Ecklund, 1972a, b]. The antenna consists of a horizontal 52-element colinear array of half-wave dipoles producing a horizontal beamwidth of 3° and a wide fan beam in the vertical plane. The beam was directed 8° east of geographic north, as shown in Figure 1, which corresponds to 18.5° east of geomagnetic north. The region observed is normally south of the auroral oval, but during disturbed periods (Kp > 5), strong scattering is observed. The radar wave vector k is within a degree of normal to the magnetic field at a height of 110 km from ranges of 500 to 1165 km (the farthest range being limited by the E region horizon). For ranges smaller than 500 km the aspect angle between k and B decreases and is about 82° at 300 km [Reed, 1980]. Similarly, this angle is less than 85° at all ranges for altitudes above about 140 km.

The received echoes were synchronously detected, and the two quadrature outputs were digitized and used to generate an online range-time-intensity (RTI) display. The data can also be recorded on analog tape for later spectral analysis. The RTI data are normally obtained with an interpulse period (IPP) of about 10 ms to avoid range ambiguity problems, but for the spectral mode the IPP was reduced to 2 ms to avoid (probably; see below) frequency aliasing. In more recent experiments the IPP has been decreased to 1 ms. By alternating the

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RTI and spectral schemes it is usually possible to resolve the range ambiguity implicit in the short IPP mode. In this paper we will be concerned mostly with some unusual examples of spectral data obtained within the 2-ms "window" between 300 and 600 km in range. The range resolution was 7.5 km (50-μs pulse). Power spectra were calculated by using a 64-point fast Fourier transform (FFT) routine and averaging 16 consecutive power spectra from a particular range, corresponding to an integration time of about 2 s. The frequency resolution was thus 500/64 = 7.81 Hz, which is equivalent to a line-of-sight Doppler velocity resolution of 23.4 m/s, since at a radar frequency of 50 MHz, a Doppler shift of 1 Hz corresponds to a velocity of 3 m/s.

OBSERVATIONS

Very strong auroral echoes were obtained between 0200 and 0500 EST (0700 and 1000 UT) on April 1, 1976, a period that was extremely active magnetically (Kp ~ 8). The Ottawa magnetogram for this period indicated a negative bay exceeding 1200 γ at one time, corresponding to a strong westward electrojet. The Z trace showed that the center of the electrojet was generally north of Ottawa but occasionally moved south.

The range of the radar echoes was primarily north of Ottawa, although this may be due at least in part to the large increase of the aspect angle (the angle between the radar beam and the normal to the magnetic field) for smaller ranges. The radar was operated mostly in the RTI (low pulse repetition frequency (PRF)) mode but was frequently changed to the spectral (high PRF) mode during periods of strong and/or highly variable echoes. In this work we concentrate on the spectral data and discuss the associated current system only briefly.

The Z trace of the Ottawa magnetogram indicated a rapid northward movement of the westward electrojet starting at about 0200 EST. RTI data for a 6-min period just after 0200 EST are presented in Figure 2, with the range measured from Ithaca. A broad region of diffuse aura, observed by the radar prior to 0201 EST, narrowed rapidly as it moved northward until its disappearance at about 0207 EST. The data to be presented here were obtained during this period. Figure 3 shows the corresponding self-normalized power spectra. The integration time was 42 s, and only every other range sampled is displayed. At the southern end of the scattering region, mostly type 2-like spectra were observed with small negative average Doppler shifts, indicative of an eastward drift and a westward electrojet. These small average Doppler shifts indicate that the radar wave vector was close to perpendicular to the direction of the current at the corresponding ranges. At many of the northerly ranges the echoes displayed broad peaks centered at about -160 Hz (i.e., a phase velocity of 480 m/s away from the radar). The peak Doppler shift of these latter echoes is of the order of the ion acoustic speed, but the spectral widths are sometimes considerably larger than the typical widths of the equatorial type 1 echoes. With our single-beam antenna observations we cannot be sure that these echoes with large Doppler shifts are in fact type 1 echoes, but for convenience we will describe their spectra as type 1-like.

In any case, it is a third class of echo, the narrow spectral component darkened in Figure 3, which we are particularly concerned in this paper. The Doppler shifts of these narrow peaks varied between -60 and -89 Hz with a mean value of -74 Hz. It can be seen that the narrow spectra usually were observed only in a limited-latitude region at any given time. The whole region moved poleward away from the

Fig. 1. Map showing the location of the Ithaca radar beam.

Fig. 2. RTI display showing the northward motion of the strong scattering region observed on April 1, 1976.
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radar, following the movement of the region of discrete radar aurora, with a velocity of about 800 m/s. As the region moved northward, the shape and Doppler shift of the narrow peaks did not change appreciably, even though the broader part of the spectra did change.

Figure 3 also shows some clearly aliased spectra between 412.5 and 487.5 km at 0201 EST. The time evolution of the aliased spectra observed with an integration time of 2 s indicates that their presence is preceded by a progressive broadening of the width of the spectra. Therefore the sharp peak with a Doppler shift of about 180 Hz corresponds to waves with a negative Doppler shift of about -320 Hz or a phase velocity of 960 m/s away from the radar.

There was a definite spatial relationship between the regions responsible for the different types of echo, and this relationship was maintained as the whole disturbance moved rapidly northward. The regions of type 2-like and type 1-like spectra were always to the south and to the north, respectively, of the region of very narrow spectra, as seen in Figure 3. Figure 4 shows this behavior in a slightly different way. The spectra are all from a particular range (398 km), and we see the spectral characteristics change with time as the echoing region moves northward past it. We see first the type 1-like echoes from the northern edge, then the echoes with the narrow spectra, and finally, the broad type 2 echoes before the echoes disappear entirely. Figure 5 shows that the narrow spectra did not change appreciably as the region from which they were obtained moved northward.

The width of these narrow peaks is equal to or smaller than the typical equatorial type 1 widths. Figure 6 shows the appearance of the narrow spectral component in a region where only type 1-like spectra were observed previously. Here the integration time was about 2 s and the range resolution was 7.5 km. There was no change in either the phase velocity or width of the type 1-like spectra before and after the appearance of the narrow, small-phase velocity peaks at a given range. This suggests that these two spectral components probably come from different scattering regions within the scattering volume defined by the radar.

The narrow spectra lasted at most 60 s at any particular range and were strong only a small fraction of that period. Figure 7 illustrates the variation of the backscattered power for 4 min at five selected ranges. The solid bars indicate the periods when at least half of the backscattered power from a given range came from the narrow spectral component. These peaks were observed, at any given range, only during periods of decreasing total power and changing line-of-sight drift velocity (see Figure 3).

Figures 3 and 6 also indicate that the power associated with the narrow spectra was very small between 367.5 and 382.5 km during the entire time period. The echo power from the broader spectral components, however, did not show a similar decrease. If the weakening of power associated with the narrow spectral component was a result of the antenna pattern and not just a fortuitous temporal variation, we can roughly estimate the height of the scattering region responsible for these echoes. Because of the effect of the ground reflection (the antenna image), there should be a moderate null in the pattern at an elevation angle of about 22° (the pattern was not measured; the rather temporary antenna in use when the measurements were taken was subsequently rebuilt). The range corresponding to this minimum in the antenna gain will depend upon the altitude of the echoing region. Figure 8 shows the estimated variation of the gain with range for scatterers at 110 and 140 km. During the April 1976 period the antenna was sagging somewhat and, as a result, the null was undoubtedly less pronounced and perhaps at a slightly higher elevation angle. In spite of these admitted uncertainties, these results suggest that the height from which these unusually narrow spectra were received was well above the 90–120 km region, from which the normal auroral echoes originate.

Recent observations with the Ithaca radar have confirmed the
Fig. 5. Spectra showing the nearly constant Doppler shift of the narrow spectral component at different ranges and times.

occurrence of discrete auroral echoes well above the center of the electrojet scattering region (J. Providakes, private communication, 1982).

We have mentioned earlier the question of spectral aliasing. Although the IPP for these observations was made short to avoid aliasing as much as possible, there is clear evidence of some aliasing in the first column of Figure 3. An important question then is whether the ultranarrow spectra could also be aliased. The fact that the frequency shift remained nearly constant for about 5 min and over a range of about 200 km argues against the aliasing possibility. Moreover, recent spectral observations by using the Ithaca radar with an IPP of 1 ms indicate that these narrow spectral peaks indeed have a Doppler shift in the range 70-100 Hz (J. Providakes, private communication, 1982).

**COMPARISON WITH OTHER OBSERVATIONS**

The spectra of auroral radar echoes have been studied in detail over the last 15 years (e.g., Abel and Newell, 1969; Balsley and Ecklund, 1972b; Haors, 1972; Greenwald et al., 1975; Moorcroft and Tsunoda, 1978; Haldoupis and Sofko, 1976, 1979). The spectral shape depends on the strength of the electrojet, on the frequency and azimuth of the observing radar, and on the characteristics (diffuse or discrete) of the echoing region. Most of the auroral echoes observed with the Ithaca radar have spectra similar to those of type 1 and type 2 equatorial irregularities. The very narrow spectra, however, are significantly different from the equatorial spectra and also from the double-peaked spectra reported by Greenwald et al. [1975]. These latter spectra (which we also observe, but do not discuss here) have an average phase velocity close to zero and a half-power width of about 150 Hz (velocity spread of 450 m/s), and are associated with diffuse rather than discrete echoes. Here we will discuss only observations of discrete echoes having Doppler spectra similar to our narrow spectrum.

*Balsley and Ecklund* [1972b] mention that about one third of their 50 MHz discrete echoes had narrow, two-stream-like spectra with phase velocities between about 160 and 520 m/s (i.e., Doppler shifts between 53 and 173 Hz). They suggested that most of these echoes were probably generated by the two-stream instability with the large range of Doppler shifts caused by large variations in the ion acoustic velocity (due to temperature variations) and/or strong neutral winds. Very narrow spectral peaks with Doppler shifts of about 70 Hz (phase velocities of about 250 m/s) were observed occasionally with the 42.1-MHz CW bistatic radar operated by the University of Saskatchewan [Haldoupis and Sofko, 1978; G. Sofko, private communication, 1979]. In this case the narrow spectral peaks occurred during a brief period preceded and followed by the presence of "normal" type 1-like spectra. It is possible that some of these previous small-Doppler narrow spectra were caused by the same mechanism responsible for our unusual spectral data.

Recently, in situ rocket observations have detected large-amplitude coherent waves with frequencies of a few hundred hertz in the upper part of the electrojet scattering region [Pfaff et al., this issue]. These waves have spectral characteristics considerably different from those of the normal electrojet irregularities observed at lower altitudes with the same rocket. Although we cannot directly compare the rocket and radar observations, the altitude and short wavelength of these waves suggest that they might be related to our present radar observations.

**DISCUSSION**

We begin by comparing the results presented above with the existing electrojet instability theories. Next, we discuss other plasma instabilities which might be important. We cannot fully explain our observations with any of these theories, but the ion cyclotron instability is the most promising.

**Electrojet waves.** It is clear that our narrow spectral data are not related to the type 2 irregularities which have velocity-dependent Doppler shifts and large spectral widths. Our observations cannot be explained by the two-stream instability
either, for several reasons. The spectral width is narrower than that of the usual two-stream-like spectrum, and the phase velocity is considerably smaller. Wind and temperature effects cannot explain the small Doppler shifts, since they do not seem to affect the normal type 1-like spectra which are frequently observed at the same time and range. Furthermore, we can see from Figure 3 that the “normal” spectrum (after subtracting the narrow spike) can change character from type 1 to type 2 without any significant change in the spike, suggesting that the electrojet with its associated instabilities is certainly not the sole cause of the spike. This conclusion is consistent with our observation that the echoes are probably coming from an altitude above the electrojet region. The generation of auroral echoes by irregularities above the center of the electrojet region has in fact been recognized for over two decades (see review by Chesnut [1972]), but the previous papers did not report spectral data and did not discuss generation mechanisms.

Ion cyclotron waves. Discrete auroral radar echoes come from regions in which upward field-aligned currents are present, during both afternoon and evening periods [Tsunoda et al., 1976a; McDermid and McNamara, 1978]. These echoes are also related to the presence of bright visual arcs and to the region of the Harang discontinuity [e.g., Greenwald et al., 1973; Tsunoda et al., 1976b]. Rocket observations also indicate that intense and highly localized field-aligned currents at 100–200 km are associated with auroral arcs [Arnoldy, 1974; Anderson and Vondrak, 1975]. Field-aligned currents are obviously a source of free energy and may be able to generate density irregularities through plasma instabilities such as the ion cyclotron instability.

Ion cyclotron waves have been studied in detail in connection with laboratory Q machines [e.g., D’Angelo and Motley, 1962], and various in situ observations have shown that such waves exist in the auroral ionosphere. For example, oxygen ion cyclotron waves were detected by rocket probes in the auroral F region [Kelley et al., 1975] at the southern edge of the westward electrojet in a 100-m-sized region characterized by an intense shear in the plasma flow [Kelley and Carlson, 1977]. Satellite instruments have detected proton ion cyclotron waves above about 1000 km [Kintner et al., 1978]. Recent auroral rocket observations from Antarctica suggested the presence of ion cyclotron waves below about 220 km and fairly monochromatic waves with an estimated wavelength of about 15 m at about 140 km near the edge of an auroral arc [Ogawa et al., 1981; Yamagishi et al., 1981].

A considerable amount of work has been done on the theory of ion cyclotron waves. Kindel and Kennel [1971], following earlier work by Drummond and Rosenbuth [1962], derived the linear dispersion relation for electrostatic waves in a collisionless, uniformly magnetized plasma by using kinetic equations. The wave frequencies are always slightly higher than multiples of the ion gyrofrequency. The difference can reach 20–30% for the most unstable wavelengths and large $T_e/T_i$ ratios, but it is usually considerably less, especially for wavelengths of 3 m. For any reasonable temperature ratio at this wavelength the first $O^+$ harmonic or the second NO$^+$ or O$_2^+$ harmonic has a frequency of about 57–64 Hz, which is close to what we observe. The field-aligned electron velocity required for instability in the collisionless case is $V_e \approx \omega/k_\perp$, where $k_\perp$ is the (small) component of the wave vector parallel to the magnetic field. For $O^+$ ions the minimum velocity for instability with $T_e/T_i = 1000$ and $B = 0.6$ G is about 15 km/s and occurs for a wavelength of about 12 m and an aspect angle of about 86°. The threshold is considerably larger for 3-m waves, particularly for aspect angles of 85° or less, which would be the case for our geometry at altitudes for which the collisionless theory is valid. The most unstable 3-m waves have aspect angles greater than 89° and require drift velocities $\sim 40$ km/s.

Adding the effect of collisions must be done carefully. Assuming a weakly collisional plasma, Kindel and Kennel [1971] found that ion-neutral collisions have a significant stabilizing effect for values of $\nu_i$ as small as 2% of $\Omega_i$. On the other hand, D’Angelo [1973] and Chatuvedi [1976] discussed the collisional electron case ($\nu_e > k_\parallel V_{Te}$, where $\nu_e$ and $V_{Te}$ are the electron collision frequency and thermal speed, respectively), and showed that instability is possible in the auroral upper $E$ region even when $\Omega_i$ and $\nu_i$ are comparable. In this case, the threshold oscillation frequency in the ion reference frame and the field-aligned drift velocity are given by

$$\omega^2 \approx \Omega^2 + k^2 \nu_e^2$$

and

$$V_\parallel \approx \left( \frac{\omega}{\nu_e} \right) \left[ 1 + \frac{\Omega_i}{\nu_e \Omega_i} \frac{k_\parallel^2}{k^2} \right]$$
where $k$ is the total wave number and $C_s$ is the ion acoustic velocity. Note that (1) predicts phase velocities larger than the ion acoustic speed, which is not what we observe. The formulas above, obtained from fluid equations, are valid only for wavelengths much larger than the ion gyroradius ($R_i \sim 3 \text{ m}$ for NO$^+$ ions at 150 km). In the auroral ionosphere at 150 km, by using $\Omega_e = 200 \text{ s}^{-1}$, $\Omega_i = 10^7 \text{ s}^{-1}$, $v_i = 4000 \text{ s}^{-1}$, $v_e = 10 \text{ s}^{-1}$, and $C_s = 500 \text{ m/s}$, the threshold velocity is about 16 km/s for $kR_i = 1 (\lesssim 16 \text{ m})$, which is not much different from Kidel and Kennel's results.

For an electron density of $10^6 - 10^8 \text{ cm}^{-3}$, a field-aligned drift velocity of 15 km/s corresponds to a current density of 24 - 240 $\mu\text{A/m}^2$. Most observations indicate field-aligned currents of about 10 - 20 $\mu\text{A/m}^2$, but much larger values ($\sim 100 - 200 \mu\text{A/m}^2$) are sometimes observed in highly localized regions by rockets [e.g., Whalen and McDiarmid, 1972; Ledley and Farthing, 1974; Bering et al., 1975] and satellites [Burke et al., 1983; R. A. Heelis et al., manuscript in preparation, 1983].

Therefore the excitation of ion cyclotron waves with wavelengths of 10 - 20 m can certainly be expected in regions of these very intense field aligned currents and/or small electron densities, but how do we explain the excitation of our 3-m ($kR_i < 5$) waves, which would require drifts substantially larger? (We have not calculated exactly how much larger, for the observed aspect angles, but 50 - 100 km/s or more is probably a reasonable guess.)

There is some evidence that extremely large but very localized field-aligned drifts do exist at times. It is well known, for example, that auroral optical emissions often exhibit curls with typical scale sizes of 1 - 10 km [Hallinan and Davis, 1970]. The flow of small-scale irregularities around these structures is invariably counterclockwise looking upward in the northern hemisphere. These have been discussed by Hallinan and Davis in terms of vortices created by the Kelvin-Helmholtz instability of an extremely sheared flow, with estimates of the associated shear frequency ($dV/dy$) of about 30 s$^{-1}$. This value is comparable to the shear frequency of 20 s$^{-1}$ reported by Kelley and Carlson [1977] at the equatorward edge of a westward electrojet which was indeed associated with O$^+$ ion cyclotron waves in the F layer. Maynard et al. [1982] measured electric fields which varied by as much as 200 mV/m from sample to sample (2000 m separation). This observation implies a shear of 8 s$^{-1}$ and probably larger. Burke et al. [1983] have reported more modest but still intense shears ($\sim 1 \text{ s}^{-1}$) at the edge of an auroral arc by using satellite data. We can estimate quite easily the value of $J_\parallel$ implied by this shear. Height integration of the current continuity equation shows that the field-aligned current can be derived from the expression

$$J_\parallel = -v_i E_p \Sigma_p$$

where $v_i$ is the perpendicular divergence operator, $E_p$ is the Pedersen component of the convection electric field, and $\Sigma_p$ is the height-integrated Pedersen conductivity (the Hall current is usually divergence-free). To estimate $J_\parallel$ we assume $\Sigma_p$ to be uniform at a value of 10 mhos and replace $v_i E_p$ by $\delta E/L$, where $L$ is a scale size and $\delta E$ corresponds to the observed change in convection speed over this distance. Recent data from the Dynamics Explorer satellite show that this assumption is not unreasonable for such an estimate [Sugiura et al., 1982]. We can estimate $\delta E/L$ from the velocity shear, since $dV_\parallel/dy = B^{-1}dE_\parallel/dy \sim \delta E/BL$. The shear value of 1 s$^{-1}$ from the work of Burke et al. [1983] yields a field-aligned current of 500 $\mu\text{A/m}^2$, and the values of 20 s$^{-1}$ and 30 s$^{-1}$ mentioned above give considerably larger results. Burke et al. reported a measured value of $J = 145 \mu\text{A/m}^2$ at the satellite altitude (800 km). Mapped to the ionosphere at 140 km, this current corresponds to 180 $\mu\text{A/m}^2$, which is of the same order as the value estimated from the shear. Changing $\Sigma_p$ somewhat would improve the agreement. Both larger and smaller values of $\Sigma_p$ are common. More recently, R. A. Heelis et al. (manuscript in preparation, 1983) observed field-aligned currents of about 100 $\mu\text{A/m}^2$ at 900 km with the DE 2 satellite in regions of large drift shear.

We thus conclude that there is ample evidence of localized field-aligned currents well in excess of 100 $\mu\text{A/m}^2$ in regions of active aurora, and much larger but very localized currents are apparently not out of the question. The fact that these even larger currents have never been directly observed is due to the difficulty of securing great luck to have a rocket pass through a very small but very intense current region, whereas the radar will always receive its strongest echoes from there.

We can estimate the average level of the large-scale field-aligned currents during the present experiment from the following rough argument. We observed a change in the broader part of the Doppler spectrum of about 125 Hz (375 m/s) within a latitude range of about 25 - 50 km (see Figure 3). Assuming the total velocity change to be a factor of 3 larger than the line-of-sight variation (since we were looking 18.5° east of geomagnetic north), the $J_\parallel$ estimate yields about 10 - 20 $\mu\text{A/m}^2$. The maximum value of $J_\parallel$ could, of course, be substantially higher if the currents were highly localized. Note that the requirement of a highly localized region of strong field-aligned currents is not inconsistent with the observation of the narrow spectra from several ranges. The echoes could come from a thin sheet, aligned more or less in the north-south direction (i.e., roughly parallel to the radar beam), which would be expected to have a quantum drift velocity of about 200 m/s. Recent radar interferometer observations from Ithaca have in fact shown several cases of exactly this sort of alignment (J. Providakes, private communication, 1982) and have also shown that the echoing regions were highly localized.

We should also mention that, since the auroral curls flow counterclockwise looking upward in the northern hemisphere, the electric field perpendicular to B is directed inward and therefore the field-aligned currents must flow downward (electrons move upward) to neutralize the net negative charge at the center of the curl. This upward electron motion is in agreement with the preferred negative Doppler shift of the narrow spectral peaks which we observe. Recall also that the expression (1) for the Doppler shift is in the ion reference frame, and if the echoes are from regions where $v_i \geq \Omega_i$, the ions might be expected to have a large Hall and/or Pedersen drift velocity. But, as we have pointed out, Figure 3 shows that the Doppler shift of the narrow spike remains approximately constant while the rest of the spectrum, and therefore presumably the electric field, varies. Can we reconcile this apparent contradiction? If, as we propose, the spike is produced by very localized, strong field-aligned currents, these echoes will originate from regions of strong precipitation where $E_p$ is small. The other echoes are known [e.g., Greenwald et al., 1973] to come from regions outside the auroral arcs where $E_p$ is much stronger. In other words, the spike and the broader spectral component must come from different field lines as well as
different altitudes. There is some preliminary evidence that this is the case (J. Providakes, private communication, 1983).

So, to sum up this discussion of ion cyclotron waves, there is ample evidence that currents sufficient to excite these waves at wavelengths of 10–20 m are often present and that such waves are observed in situ above the electrojet scattering region. Whether or not these waves can explain our radar observations of 3-m waves is less clear; very strong field-aligned drifts are needed, but these may exist at times. On the other hand, arguing against this explanation, perhaps, is the fact that we see no evidence of first harmonic NO+ and O2+ waves, only O+ waves (or second harmonic molecular ion waves). Furthermore, the radar geometry is not very favorable at altitudes of 140 km and above, where the aspect angle is less than 85°, and of course, at heights near 110 km where the angle is near 90°, collisions destroy the instability. It is conceivable that some sort of nonlinear cascade process is the source of the 3-m resonant waves. We know, for example, that type 1 and type 2 waves are seen in the auroral zone at aspect angles that cannot be explained by linear theory, and various cascade processes are known to produce short wavelength irregularities in the equatorial E and F regions. However, it is not obvious that any cascade could produce the sharp resonance we observe. Nonlinear mixing processes almost invariably broaden a spectrum, both in k space and in frequency.

Other F region instabilities. Ossakow and Chaturvedi [1979] showed that moderate field-aligned currents in the presence of density gradients can excite F region irregularities. This process cannot explain our results, however, since the unstable wavelengths are very long (about 1 km), and furthermore, the oscillation frequency is proportional to the drift velocity and is not related to a characteristic Doppler shift. St.-Maurice [1978] has shown that large-scale auroral electric fields (~85 mV/m) can cause significant distortions in the Maxwellian ion distribution function above about 150 km. This causes the plasma to be unstable [Ott and Farley, 1975], leading to the generation of electrostatic waves with wavelengths of about 50 cm and oscillation frequencies ranging from about the ion cyclotron frequency to about the lower hybrid frequency, depending on a variety of ionospheric parameters [St.-Maurice, 1978]. These frequencies cover the range of our results, but this mechanism cannot excite waves during periods when the perpendicular electric field is not very large.

SUMMARY

Our radar observations during a period of strong echoes showed the presence of a narrow spectral component at a Doppler shift of about -70 Hz which cannot be explained by existing electrojet instability theories. Evidence suggests that these echoes come from above the normal electrojet wave zone. This Doppler shift could perhaps be explained as the first harmonic component of O+ ion cyclotron waves or as the second harmonic component of NO+ waves. There is good evidence, during active periods, of the existence of field-aligned currents large enough to excite ion cyclotron waves with wavelengths 10–20 m. The 3-m waves propagating in the directions observed by our radar are more difficult to explain quantitatively, however; sufficiently intense currents (i.e., field-aligned electron drifts) have never been directly observed. Nevertheless, there is some evidence that such drifts may in fact occur in very localized regions, which is exactly what is needed to explain the radar data. Alternatively, some nonlinear cascade from the longer wavelengths may be involved, but then it is difficult to understand the sharply resonant shape of the Doppler echo spectrum.

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R. W. Reed, Raytheon Equipments Division, Waltham, MA 01778.

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