Utah State University

From the Selected Works of Bela G. Fejer

January 1, 1984

Electric field and plasma density measurements in the auroral electrojet

R. Pfaff

M. C. Kelley

Bela G. Fejer, *Utah State University*

E. Kudeki

C. W. Carlson, et al.

Electric Field and Plasma Density Measurements in the Auroral Electrojet

R. F. PFAFF,¹ M. C. KELLEY,¹ B. G. FEJER,¹ E. KUDEKI,¹ C. W. CARLSON,² A. PEDERSEN,³ AND B. HAUSLER⁴

Intense electrostatic waves in the auroral *E* region have been detected simultaneously on two payloads launched in a mother-daughter configuration from Kiruna, Sweden. The data sets comprise electric field and density measurements from the ambient (dc) conditions to fluctuations as high as 50 kHz. The dc electric field measured by both payloads was 54 mV/m northwest, which corresponded to an electron drift velocity of 1080 m/s. This electric field drove two-stream waves perpendicular to both **B** and **E** observed by both spacecraft throughout an altitude region which agrees quite well with the range predicted by linear two-stream theory. The power in the waves depended on the electron density gradient, diminishing near 107 km where the gradient changed direction for a few kilometers. This observation is consistent with a gradient drift wave contribution to the instability process, since the auroral zone geometry does permit a component of the electric field perpendicular to **B** to be parallel to the vertical electron density gradient. Electric field spectra corroborate these results, as a strong component was detected at longer wavelengths (several hundred meters), the spectral regime associated with this instability. The spectra measured on both payloads also reveal an enhanced nearly coherent wave of a few meters wavelength at the topside of the layer (120 km), which also appears as electrostatic and parallel to the current. This spectral feature may be the consequence of a narrow range of wavelengths excited near the two-stream instability threshold. Descending through the layer, the fluctuations fill out to a broadband, turbulent spectrum, extending to scale sizes down to the order of centimeters. Long wavelength waves form the strongest spectral component below 105 km. Power observed perpendicular to the direction of the current may indicate the presence of secondary plasma waves.

1. INTRODUCTION

Auroral and equatorial electrojet irregularities have been the subject of extensive experimental and theoretical research for the last two decades [e.g., *Lange-Hesse*, 1967; *Unwin and Baggaley*, 1972; *Kennel and Arnush*, 1973; *Fejer*, 1979]. Auroral radar backscatter measurements of *E* region (95–120 km) electron density fluctuations have been made in Alaska, Canada, Greenland, the Soviet Union, New Zealand, the northeastern United States, and Scandinavia. Most of the equatorial radar data have been accumulated at the Jicamarca Radio Observatory in Peru, though measurements have also been made in Africa and India. In the past 15 years, a number of instrumented sounding rockets have made observations in both the auroral and equatorial electrojets. A review paper by *Fejer and Kelley* [1980] describes many of these recent measurements.

It is now well accepted that the plasma irregularities in the equatorial and auroral electrojets are associated with electrostatic waves and turbulence driven by plasma instabilities. The theory of these instabilities has been discussed by several authors [e.g., *Rogister and D'Angelo*, 1970; *Sudan et al.*, 1973; *Fejer et al.*, 1975], primarily for the equatorial case. Taking the geometrical differences into account, the same theories can be readily applied to the auroral electrojet case [e.g., *Greenwald*, 1974; *Wang and Tsunoda*, 1975; *Moorcroft*, 1979; *Schlegel and St.-Maurice*, 1982; *St.-Maurice and Schlegel*, 1983]. There remain, however, important differences between the two regions, as described by *Fejer and Kelley* [1980].

Linear instability theories have been successful in explaining many features of the observations. *Farley* [1963] and *Buneman* [1963] simultaneously published theories for a "two-stream" instability which occurs when the streaming velocity

of electrons relative to ions exceeds a value of the order of the ion acoustic velocity. In the auroral and polar cap regions and near the magnetic equator, sufficiently large electric fields exist for electrons to achieve such velocities via $\mathbf{E} \times \mathbf{B}$ drifts. A second instability mechanism occurs when a plasma gradient and an applied electric field exist perpendicular to the magnetic field, as initially proposed by *Simon* [1963] and by *Hoh* [1963], and later applied to space plasmas by *Rogister and D'Angelo* [1970]. This "gradient drift" instability does not have a well-defined threshold electric field, but rather, a linear growth rate which depends on the electric field, the electron density gradient, and the angle between these two vectors. In addition, recombination damping imposes a small threshold electric field for the onset of the gradient drift instability [*Fejer et al.*, 1975].

Most electrojet turbulence at the equator involves either a pure gradient drift process or a mixture of the two instabilities. An exception at the equator may occur during daytime counter-electrojet conditions when only two-stream echoes are present [*Crochet et al.*, 1979]. In the auroral zone and polar cap, where the magnetic field lines are nearly vertical, the large electric fields and small horizontal plasma density gradients perpendicular to the magnetic field, may permit the two-stream process to be the dominant instability present (see review by *Fejer and Kelley* [1980] for details). However, it appears likely, as will be shown in this paper, that both instability processes can act simultaneously to produce a turbulent *E* region in the auroral zone ionosphere.

Because the basic instability mechanisms are the same in both the auroral and equatorial electrojets, similar experiments conducted in both regions are important for comparing the nature of the irregularities in the two vastly different geophysical situations. One important difference between the auroral and equatorial Doppler spectra at meter scale wavelengths is that the latter saturate at the ion acoustic speed, C_s , while the auroral irregularities seem to have phase velocities which sometimes exceed this value. In addition, in the auroral region the ion acoustic speed is considerably enhanced in the presence of large electric fields [*Schlegel and St.-Maurice*, 1982]. Several VHF radars now use this property oper-

¹School of Electrical Engineering, Cornell University.²Space Sciences Laboratory, University of California, Berkeley.³European Space Research and Technology Center (ESTEC).⁴Max-Planck-Institut für Extraterrestrische Physik.

ationally to measure high-latitude electric fields. Besides their inherent interest as a plasma turbulence phenomenon accessible to detailed study, the irregularities act as a scattering screen for communication applications, they may be important to anomalous heating in the *E* region [St.-Maurice *et al.*, 1981; St.-Maurice and Schlegel, 1983] and may also effect riometer measurements [Siren, 1982].

Several previous rocket experiments have performed wave measurements in the auroral electrojet, though only a limited portion of the spectrum of the instabilities has been reported thus far. Kelley and Mozer [1973] showed from measurements in a strongly driven case in the auroral oval that the waves were electrostatic, that irregularities existed at wavelengths much less than the ion mean free path (0.1–1.0 m), and that the wave intensity was largest parallel to the current. Holtet [1973] reported similar results as well. Spectra of δE and $\delta N/N$ (fluctuating quantities) produced by Kelley and Mozer [1973] indicated a broad spectrum in the frequency range of 50–1000 Hz in the rocket reference frame. At 110 km, they reported broadband values of 2.3 mV/m for δE and 0.08 for $\delta N/N$ for this frequency band. In a series of papers, Olesen *et al.* [1976] and Bahnsen *et al.* [1978] reported measurements made in the polar cap which showed that strong waves were present even where the vertical component of *E*, the ambient electric field, was antiparallel to ∇n , the electron density gradient, and only weak signals were present in the opposite case. The region of strong waves was thus stable to the gradient drift process, and the waves detected were primarily generated by the two-stream mechanism. Bahnsen *et al.* [1978] reported a signal at 3–6 m wavelength, using a cross-correlation analysis of simultaneous electric field waveforms. Observations of six sounding rockets flown in the Antarctic *E* region have been reported by Ogawa *et al.* [1976]. They measured electron density irregularities from a few hertz to 160 Hz under a variety of visual conditions. In this bandwidth, waves were observed between 90 and 120 km with amplitudes of 10% or smaller and spectral slopes between -1 and -3 .

In this paper, we discuss electric field and plasma density fluctuation measurements made on board the Porcupine II sounding rocket and on a free-flyer ejected from the main spacecraft. Simultaneous radar backscatter, dc electric field, and plasma density measurements are available. The data are presented next, followed by theoretical analysis and conclusions.

2. EXPERIMENT AND OBSERVATIONS

2.1. Experiment Description

The Porcupine II sounding rocket payload, a part of project Porcupine that involved four Aries rocket flights, was launched at 1922:00 UT from Kiruna, Sweden, on March 20, 1977, during a positive magnetic bay of 87 nT. The main vehicle was heavily instrumented for particle and field studies, as were two ejected instrument packages. Two more ejected payloads included barium-shaped charge experiments.

Simultaneous data were obtained with the STARE radar system, located in Trondheim, Norway, and Sauvamaki, Finland. As the barium clouds drifted away from their release point at 460 km near apogee, comparison of the STARE velocity data with the cloud drifts showed reasonably good agreement [Rieger *et al.*, 1979]. Although experimental problems precluded a Doppler radar drift measurement at precisely the rocket location, the general flow pattern resolved by the

Fig. 1. Smoothly varying sine wave due to $E_{\text{ambient}} + V_{\text{rocket}} \times B$ with superimposed low-frequency fluctuations detected by the free-flyer payload as it transverses the electrojet.

radar was consistent with drifts derived from the dc electric fields measured on the rocket. On the downleg of the trajectory, just above and in the *E* region, these fields were independently measured on the main payload and on one of the free flyers to be 54 mV/m with a direction 37° west of geomagnetic north in an earth-fixed reference frame [R. Grabowski, personal communication, 1980; Mallinckrodt, 1980]. This value is well above observed threshold levels for radar aurora [Moorcroft, 1979; Fejer and Kelley, 1980].

On the main payload, the electric field detector was a 5.0-m (tip-to-tip) dipole with spherical electrodes extended perpendicular to the spin axis. The electric field wave instrument had an automatic gain control (AGC) feature, which has been accounted for in the data, and a high pass filter with a response of -18 dB/octave below the 3-dB point at 50 Hz. The density probe was a fixed-bias cylindrical Langmuir probe operated in the electron saturation mode (0.4 cm in diameter, 10 cm long). The density fluctuation high pass filter was 9 Hz (3-dB point) and, as it had no AGC, was less sensitive. FM/FM telemetry was used to transmit the waveforms and determined the high-frequency response of each detector output.

Electric field data presented from the free-flyer were measured with a 3.0-m (tip-to-tip) dipole antenna. The telemetry system was digital and only allowed waveform measurements up to a Nyquist frequency of 250 Hz for the low-frequency channel. An on-board swept-frequency analyzer provided spectra extended to 50 kHz every 2.05 s. The bandwidth of the swept filter was 300 Hz. Both of the electric field experiments on the main payload and free-flyer were similar to instruments described by Fahleson [1967]. The main spacecraft and free-flyer were separated by about 2 km horizontally but were virtually at the same altitude in the electrojet on the downleg. Boom and instrument deployment precluded upleg measurements in the electrojet by either payload.

2.2. Data Presentation

Data from the ELF dc electric field detector on the free-flyer payload are presented in Figure 1. The smoothly varying sine wave (due to $E_{\text{ambient}} + V_{\text{rocket}} \times B$) is abruptly interrupted by superimposed intense low-frequency fluctuations detected as the vehicle entered the electrojet. The rocket began to tumble at 654 s (1932:54 UT), which accounts for the amplitude change in the sinusoid. It is, nevertheless, clear that the fluctuation strength decreased rapidly at about 655 s. By using techniques of Fourier analysis, the spin component was subtracted from the data shown in Figure 1, and the higher frequency residual ($2.5 \text{ Hz} < f < 250 \text{ Hz}$) is plotted versus height in Figure 2a. The broadband rms fluctuation strength of the waves is seen to be several millivolts per meter. Unfortunately, for this payload, the angles between the dipole, the spin plane,

Fig. 2. (a) Electric field wave intensity (between 2.5 and 250 Hz) from the free-flyer after the sine wave in Figure 1 was subtracted. (b) Electron density measured by the main payload. The values have been normalized by using an on-board RF probe experiment. The large nulls at the spin frequency are due to instrumental effects and should be ignored. The presence of waves between these nulls represents long wavelength irregularities. (c) Electric field wave intensity from the main payload from 50 Hz (3 dB) to 1000 Hz. (d) Delta N/N fluctuations from the main payload. The data include wave frequencies up to 1000 Hz. All waves with frequencies less than 35 Hz have been subtracted. The null effects seen in Figure 2b also create the apparent loss of power at the spin frequency here.

and the magnetic field are not known, and thus it is difficult to ascertain the component of the perturbed electric fields perpendicular to $\mathbf{B}$. Comparison with Figure 1 shows that this representation displays most of the low-frequency (long wavelength) turbulence power, since power at frequencies below the spin rate would show modulation of the sine wave envelope which is not readily apparent. In addition, as the primary direction of the rocket velocity was vertical, measurements of long horizontal wavelengths were restricted by the small horizontal velocity and the limited time spent in the E region. The residuals below about 97 km are dominated by effects of tumbling and neutral turbulence.

Langmuir probe data (main payload) are plotted in Figure 2b. The deep nulls in the density data occurring at the spin frequency of 2.7 Hz are not geophysical and may be due to a magnetic end effect on the cylindrical Langmuir probe, as discussed by *Szuszczewicz and Takacs* [1979]. Between the nulls, low-frequency density fluctuations can be seen corresponding to the same region in which the electric field fluctuations are present. The time resolution of this channel was 4.25 ms. The probe was normalized between the end effect regions using the absolute density measured by an on-board radio frequency probe experiment (L. Storey, private communication, 1979).

Higher frequency measurements of electric field (δE) and density ($\delta N/N$) fluctuations made on the main payload are shown in Figures 2c and 2d. Both wave receivers show the well-defined electrojet layer between 121 and 96 km. The main payload spin axis was tipped 28° off the magnetic field. The electric field fluctuation levels (Figure 2c) have been adjusted to yield the corresponding signal strength for the waves in the plane perpendicular to the magnetic field, assuming for our purposes here that $k_{\parallel} = 0$. Note the slight mid-electrojet decrease in fluctuation strength in Figures 2a, 2c, and 2d at 107 km and the correspondence to the change in the electron density gradient in Figure 2b. In addition to the fact that the two electric field instruments had different orientations, all three fluctuation channels had different bandpass characteristics and should be quantitatively compared with care.

The apparent spin modulation in the $\delta N/N$ channel (Figure 2d) is due to instrumental effects as discussed earlier. In order to suppress the spin effects and hence delineate the electrojet waves from the instrumental effects, the data in Figure 2d have had all Fourier components less than 35 Hz subtracted. Thus the $\delta N/N$ levels plotted cannot be construed as containing the full low-frequency fluctuation strength.

Sonograms of the electric field data from both the main payload (Figure 3a) and the free-flyer (Figure 3b) are presented in Figure 3, along with integrated power profiles from 102.5 to 1501.5 Hz and 3.9 to 250.0 Hz, respectively. Note that the majority of the power is at the lower frequencies (longer wavelengths) in the lower half of the electrojet layer. Both power profiles show modulation at twice the spin rates (which were different for the two vehicles). Inspection shows that the peak signals occur when the detectors were oriented roughly parallel to the $\mathbf{E} \times \mathbf{B}$ direction and hence nearly parallel to the electrojet Hall drift. This result has also been reported by *Kelley and Mozer* [1973] and by *Holtet* [1973].

In both sonograms, a distinct enhancement in the spectral density occurs at about 220 Hz in the upper portion of the layer (indicated by an arrow in Figures 3a and 3b). This spectral peak then broadens in the lower half of the unstable layer. In the free-flyer data, the signal in the region where the spectrum displays a peak is modulated at twice the spin frequency (again showing that the strongest fluctuations are aligned with the current). The simultaneous detection of this feature by two independent instruments clearly shows that these electrojet waves were relatively uniform on a horizontal scale of several kilometers. The coherent nature of this waveform is shown in Figure 4. The rms amplitude is about 0.5 mV/m. Power in the spectral peak is 10 dB above that of neighboring frequencies, as shown in more detail in the spectral presentation below, but is considerably less than the integrated broadband power in the heart of the electrojet, as shown in the power profiles in Figures 3a and 3b.

Electric field spectra from 25 Hz to 10 kHz from the main payload are shown in Figure 5 for six heights spaced 4 km apart in the electrojet region. The spectra each cover 1.092 s of

Fig. 3. (a) Frequency-time sonogram (0–1875 Hz) of the electric field variations from the main payload plotted in Figure 2c. Power is out of the page, with the darkest shades corresponding to the largest power values. The integrated power from 103 to 1502 Hz is plotted on top and shows the twice-per-spin modulation created when the instrument was aligned with the current. The spin frequency of the main payload was 2.68 Hz. (b) Frequency time sonogram (0–250 Hz) of the electric field waves plotted in Figure 2a. The integrated power from 4 to 250 Hz again shows a twice-per-spin modulation. The spin frequency of the daughter payload was 1.1 Hz. The arrow in both sonograms indicates the enhanced spectral peak discussed in the text.

data and thus contain more than two complete spin periods. The high pass filter of the wave receiver has been unfolded in this presentation. As mentioned above, throughout the electrojet most of the power is at low frequencies below 1 kHz. In addition, below the local inflection in the density profile at 107 km mentioned earlier, there is a further increase in power at long wavelengths, marked by a rise in the spectral density below roughly 50 Hz. The detailed nature of the spectra below 25 Hz is difficult to ascertain due to the large contribution at the spin rate of 2.7 Hz. A plateau in the spectra is seen between approximately 50 and 800 Hz throughout most of the electrojet region. The spectrum changes form at roughly 1000 Hz, above which the power decreases sharply until the background noise level is reached.

Although part of the change in spectral form at approximately 1000 Hz is undoubtedly due to a falling off in the power of the waves at shorter wavelengths, an instrumental effect must be taken into account, since the wavelengths measured are becoming increasingly less than the probe separation distance at frequencies above roughly 200 Hz. As discussed by Kelley and Mozer [1973], for arbitrary wavelengths and k parallel to the dipole, the power in the waves will be altered via the relation

$$V^2(k) = d^2 E^2(k) \frac{\sin^2(kd/2)}{(kd/2)^2} \quad (1)$$

where $V(k)$ is the measured voltage and d is the probe separation distance. Interference effects, or “bite-outs,” in satellite electric field power spectra of high-latitude, “zero-frequency” (i.e., in the rest frame of the plasma, the frequency is approximately zero) electrostatic turbulence have been shown by Temerin [1978] to be due to the insensitivity of the double probe to wavelengths which are integral divisors of the probe separation distance. The absence of such bite-outs in these electric field spectra suggests that the phase velocity of the electrojet turbulence for wavelengths less than 5 m dipole length is not constant but changes as a function of frequency (and, hence, wavelength).

The expected change in power due to equation (1) begins to become noticeable at wavelengths roughly smaller than twice the probe separation distance, and eventually produces a change in spectral index of about -2 (M. Temerin, private communication, 1982). Although, qualitatively, this effect is similar to what we see in the present data, because the power is also naturally decreasing for shorter wavelengths, we refrain from parameterizing the upper portion of the spectrum with a

power law index. The plateau mentioned earlier between 50 and 800 Hz is more pronounced below the inflection in electron density at 107 km, as is the knee in the spectral power at approximately 1000 Hz.

Measurements by the swept frequency analyzer on the free-flyer payload show spectra extended to 50 kHz. Figure 6 displays six consecutive instrument sweeps taken above and in the electrojet region. For electrostatic waves, these spectra will also show a falling off in power for wavelengths shorter than the 3-m probe separation distance of the daughter payload. Aside from effects of different dipole lengths and orientations, the data shown in this figure may be considered as the output of the convolution of the spectra in Figure 5 with the 300-Hz bandwidth filter of the swept frequency analyzer. The sweep at 122 km shows a remnant of a broadband VLF electromagnetic hiss band detected throughout the flight. As the low-frequency part of the spectrum broadens when the electrostatic turbulence is encountered, the higher frequency hiss dies out, possibly scattered by the turbulence. The spikes in the data at 97 km are either due to interference or reception of ground-based transmitters.

Conversion of frequency spectra such as those plotted in Figure 5, which correspond to the Fourier transform of the time series measured in the rocket frame, to frequency and wave number spectra in the plasma frame, is not a straightforward matter, as discussed by *Fredricks and Coroniti* [1976] and by *Temerin* [1979]. The Doppler shift of the frequency of the measured waves due to the rocket motion may be described by

$$\omega_{\text{meas}} = \mathbf{k} \cdot \mathbf{v}_\phi - \mathbf{k} \cdot \mathbf{v}_r \quad (2)$$

where ω_{meas} is the measured wave frequency in the rocket frame, $\mathbf{k}$ is the wave vector, $\mathbf{v}_\phi$ is the phase velocity of the waves in the plasma frame, and $\mathbf{v}_r$ is the rocket velocity. In the plane horizontal to the magnetic field, the component of the rocket velocity is roughly 562 m/s toward magnetic south. If, following linear theory, we assume the dominant waves are traveling at the $\mathbf{E} \times \mathbf{B}$ velocity, we find that the relative velocity of the waves in the rocket frame is 742 m/s in the $\mathbf{E} \times \mathbf{B}$ direction. Thus, under these assumptions, the wavelength of the waves corresponding to the peak in Figure 5a would be approximately 3–4 m.

At lower altitudes in the electrojet region, wavelength determination is further complicated by the decrease of the phase velocity, as is discussed later in the paper. For the measured frequency discussed above, if the waves traveled instead at the acoustic velocity of (say) 550 m/s, their wavelength would be approximately 1 m. Thus although high frequencies indicate high k values, the converse is not necessarily true, and power measured at low frequencies may still have contributions from short wavelength waves.

Fig. 4. Raw electric field from the main payload showing the coherent nature of the enhanced frequency waves at 120 km.

Fig. 5. Six electric field spectra spaced 4 km apart from the main payload as it descended through the electrojet. The high pass filter (3 dB at 50 Hz) has been unfolded in this presentation. The spectra represent 1.092 s of data each.

3. DISCUSSION

3.1. General Characteristics of the Unstable Layer

The observations reported here, particularly the electric field data, show that the unstable layer in the auroral electrojet is sharply defined at both the upper and the lower edges. Such a result is consistent with characteristic measurements made by the Millstone Hill radar which also show the height range of the auroral electrojet instabilities to be sharply defined at the edges [e.g., *Abel and Newell*, 1969]. Radar data from the Jicamarca Radio Observatory [*Fejer et al.*, 1975] and rocket data [*Pfaff et al.*, 1982a] have shown similar properties for the equatorial electrojet unstable layer.

As mentioned earlier, the mechanisms responsible for these waves are due to the two-stream and gradient drift instabilities [*Rogister and D'Angelo*, 1970; *Sudan et al.*, 1973] which are part of the same dispersion relation. The growth rate for waves propagating perpendicular to the magnetic field obtained from fluid theory is given below, using the notation of *Fejer et al.* [1975],

$$\Gamma(k) \cong \frac{1}{1 + \psi_0} \left\{ \frac{\psi_0}{v_i} \left[\left(\frac{\mathbf{k} \cdot \mathbf{V}_a}{1 + \psi_0} \right)^2 - k^2 C_s^2 \right] + \frac{1}{L_N} \frac{v_i}{\Omega_i} \frac{V_a}{(1 + \psi_0)} \right\} - 2\alpha N_0 \quad (3)$$

Fig. 6. Electric field power spectra from the swept frequency analyzer on board the free flyer. The spectra represent 2.048 s of data each.

where v_e and v_i are the electron and ion collision frequencies, Ω_e and Ω_i are the electron and ion gyrofrequencies, $\psi_0 = (v_e v_i)/(\Omega_e \Omega_i)$, V_d is the mean electron drift velocity (normal to $\mathbf{B}$) relative to the ions, L_N is the component of the electron density gradient perpendicular to $\mathbf{B}$ and parallel to $\mathbf{E}$, C_s is the ion acoustic velocity, $\mathbf{k}$ is the wave vector, α is the recombination rate, and N_0 is the ambient electron density. For a vertical ambient density gradient, $L_{N_0} = N(\delta N/\delta z)^{-1}$, we have $L_N = L_{N_0}/\cos \phi$, where ϕ is the magnetic dip angle. The electron density gradient is destabilizing (stabilizing) when $L_N \cdot \mathbf{E}$ is positive (negative).

This fluid theory result is valid only for wavelengths much larger than the ion mean free path (i.e., for λ greater than a few meters) and when $v_i \gtrsim \Omega_i$. For smaller wavelengths, kinetic equations should be used [e.g., Ossakow *et al.*, 1975; Schlegel and St.-Maurice, 1982; St.-Maurice and Schlegel, 1983]. However, since the largest amplitude fluctuations were observed for wavelengths larger than a few meters, we use the existing fluid approach. Considering only the two-stream case, and waves with scale sizes between a meter and a few tens of meters (frequencies > 30 Hz) propagating perpendicular to the earth's magnetic field, the threshold velocity is simply

$$V_d \cos \Theta \cong C_s(1 + \psi_0) \quad (4)$$

where Θ is the angle between the wave vector and the electron drift velocity. Since the instability is most easily excited for waves propagating parallel to the drift velocity, we concentrate on this case.

By using the neutral atmosphere model of Jacchia [1977] to calculate the collision frequencies, gyrofrequencies, and the ion acoustic speed C_s (with $T_e = T_i$), and the measured electric field to calculate the relative drift speed V_d , we obtained the theoretical unstable layer to be between 92 and 128 km for waves with $\lambda = 5$ m. The theoretical values exceed somewhat the measured height range values. Higher collision frequency values would raise the bottom height of the unstable layer. Taking recombination damping into account [e.g., Fejer *et al.*, 1975] brings down the top edge of the predicted unstable layer by about 2 km. In addition, near the top of the electrojet, fluid theory is no longer strictly valid for meter-scale irregularities.

Furthermore, the electron and ion temperatures can be considerably higher in the auroral zone during strong electric field events [e.g., Schlegel and St.-Maurice, 1981; Wickwar *et al.*, 1981], resulting in a larger ion-acoustic speed and consequently increased damping. Thus within these limitations, the fluid two-stream plasma instability theory accounts quite well for the observed altitude range of unstable waves in the auroral E region.

Although the two-stream driving term is the most important throughout the electrojet, the contribution due to the gradient drift term cannot be ignored, particularly for λ greater than or equal to a few tens of meters. In this case, the driving term increases when the ambient electric field $\mathbf{E}$ has a component parallel to the electron density gradient. In the E region during diffuse aurora conditions, this gradient should be strictly vertical. Since the magnetic field has a dip angle of 77.2° for the rocket trajectory coordinates at 110 km, a poleward directed electric field will have a component parallel to the electron density gradient in the E region whenever the density gradient is upward. It is clear from Figure 2 that when the gradient reverses sign briefly above 107 km, the broadband wave power decreases slightly, indicating that the driving term was weakened as the gradient became anti-parallel to the vertical component of the electric field. Above about 120 km, the electron density gradient length is very large and so the gradient drift does not affect the driving term appreciably.

3.2. Spectral Characteristics

As shown in Figures 4 and 5, near the top of the unstable layer the spectrum has a well-defined peak and a nearly coherent waveform in the several meter wavelength range. Other examples of this enhanced spectral peak on the topside of the unstable auroral E region have been presented by Pfaff *et al.* [1982b]. It is clear that this occurs in the altitude range where the instability is near the threshold condition. The linear fluid theory shows that for k parallel to the streaming velocity, the two-stream growth rate

$$\gamma(k) \propto k^2(V_d^2 - C_s^2) \quad (5)$$

increases with decreasing wavelength. Kinetic effects [e.g., Lee and Kennel, 1973; Ossakow *et al.*, 1975; Schlegel and St.-Maurice, 1982; St.-Maurice and Schlegel, 1983] result in a greater threshold, however, and show that $\gamma(k)$ begins to decrease with increasing k in the few meter range. It seems reasonable that a detailed calculation will show a maximum for $\gamma(k)$ when the instability is near marginal stability at the top of the layer where a smaller range of wavelengths will be excited. This would be even more the case with $k_{\parallel} \neq 0$, since both the threshold drift velocity and the growth rate would be larger, as indicated by kinetic theory calculations. Figure 5 shows that the smaller scale waves are more heavily damped in the upper part of the unstable region in agreement with the theory.

For electrojet instabilities, the real part of the frequency predicted by the linear fluid theory in an earth-fixed frame for waves perpendicular to the magnetic field is given by

$$\omega_r \cong (\mathbf{k} \cdot \mathbf{v}_e + \psi_0 \mathbf{k} \cdot \mathbf{v}_i)/(1 + \psi_0) \quad (6)$$

For altitudes larger than about 105 km, where $\psi_0 \ll 1$, and $\mathbf{k}$ parallel to $\mathbf{v}$, $\omega_r = kE/B$. Below 100 km, ψ_0 increases rapidly with decreasing altitude. In addition, the phase velocity decreases for waves with $k_{\parallel} \neq 0$. In this flight, the coherent wave frequency band (at 3-dB points) was 190–260 Hz, which, as-

suming the same relationship holds for these waves, corresponds to wavelengths from 4 to 3 m. For shorter wavelengths (λ less than a few meters), the fluid theory overestimates the phase velocity [see *Schlegel and St.-Maurice*, 1982].

Our results indicate the presence of coherent waves in the topside of the electrojet unstable region which could be a consequence of a narrow range of k values that are excited near the two-stream instability threshold. Kinetic theory calculations (J.-P. St.-Maurice, private communication, 1983) indicate that such waves should have $k = 4$ ($\lambda \sim 1.5$ m), in fair agreement with our observations. Therefore these topside narrow band waves are not inconsistent with the results of recent linear kinetic theories.

Recent data from the 50-MHz Ithaca auroral radar show a very narrow Doppler spectra at 3 m with shifts ranging from 70 to 120 Hz [*Fejer et al.*, 1984]. The radar is oriented at an angle of 20° east of geomagnetic north. Further results from this radar have shown additional examples of such narrow spectra which probably occur at altitudes above the center of the electrojet scattering region (J. Providakes, personal communication, 1983). This Doppler shift is suggestive of the coherent wave feature reported here. Of course, a better comparison between radar and rocket results would require simultaneous measurements in the same scattering volume.

As the rocket descended through the electrojet, the spectrum "filled in" around the initial unstable wave number, resulting in a very broad spectrum. In the time domain, the waveforms are much more turbulent than the nearby quasi-sinusoidal signals discussed above. Similarly, typical auroral E -region backscatter radar signals indicate a broad range of frequencies for the single radar wave number, another indication of turbulence. At shorter wavelengths, the spectrum may correspond to an "inertial subrange" wherein energy cascades to smaller scales. The interpretation of this part of the measured electric field spectrum is difficult, however, since the response of the detector falls off for $kd > 1$.

As seen in the sonograms in Figure 3 and in the spectra in Figure 5, below about 105 km, the power in the waves is largest at very low frequencies, corresponding to long wavelengths, roughly between tens and hundreds of meters. This is the spectral regime in which the strongest gradient drift wave contributions are expected. Similar enhancements at long wavelengths have been reported in equatorial electrojet rocket data by *Pfaff et al.* [1982a], and Jicamarca radar data have shown the existence of kilometer-scale waves throughout the electrojet layer [*Kudeki et al.*, 1982].

3.3. Secondary Waves and Heating Effects

The existence in the in situ data of turbulent power perpendicular to the current implies the existence of secondary waves. The change in power levels between the spectra perpendicular and parallel to the current is best seen in the twice-per-spin modulation evident in the power profiles and sonograms in Figures 3a and 3b. It is possible that part of the spectral power measured by the rocket perpendicular to the current came from waves propagating obliquely to the direction of the current, and we also note that the expected rocket Doppler shift will be different for parallel and perpendicular traveling waves. Despite these uncertainties, power from waves observed perpendicular to the current is a likely indication of the presence of secondary waves.

The generation of secondary electrostatic plasma waves in the equatorial and auroral electrojets has been discussed by

several authors [e.g., *Sudan et al.*, 1973; *Greenwald*, 1974; *Moorcroft*, 1979]. The waves are generated by the primary waves which are driven by the ambient electric field. Depending on the perturbed electric fields created by the primary waves, the secondary waves are either of the gradient drift or two-stream type.

The condition for the onset of secondary two-stream waves for $\mathbf{k} \perp \mathbf{B}$ between about 105 and 115 km, where the ions are essentially at rest and $\psi_0 \ll 1$, is given by

$$\delta E \gtrsim C_s B \quad (7)$$

Since the ion acoustic velocity is usually about 400 m/s in the electrojet region, secondary two-stream waves will be excited only when the fluctuation electric field level exceeds about 20 mV/m. Enhanced temperatures and, for shorter wavelengths, kinetic effects would increase the threshold electric field. This value is considerably larger than the broadband rms electric fields measured during our experiment. Although the actual component of the perturbed fields perpendicular to the magnetic field are uncertain, it appears that no secondary two-stream waves would be expected to be generated in spite of the large dc electric field.

Secondary gradient drift waves are thus a more likely candidate for a cross current wave component. The gradient drift secondary waves require small perturbed drift velocities and operate more efficiently at longer wavelengths. Calculations are complicated by the broadband nature of the instability, since it is not clear how energy is shared between the various wave numbers [e.g., *Sudan et al.*, 1973; *Greenwald*, 1974]. Thus we postpone formulating more detailed conclusions concerning these effects until the relationship of the data with the nonlinear theory is better understood.

A number of recent theoretical papers have been published suggesting that the auroral electrojet waves can efficiently heat electrons [*St.-Maurice et al.*, 1981; *St.-Maurice and Schlegel*, 1983], and some experimental data suggest that this is the case [*Schlegel et al.*, 1981; *St.-Maurice and Schlegel*, 1982]. Unfortunately, the present data set is not optimized to study the short-wavelength regime invoked by these authors. As discussed earlier, because it is difficult to ascertain the power in the waves when the wavelength is less than the probe separation distance, comparison between theory and experiment is complicated. However, it is clear that the spectrum is not peaked in the tens of centimeters range in the center of the electrojet as the theory suggests. Furthermore, it is unlikely that the correction for the boomlength effect is sufficiently great that the intensity of the waves in the short wavelength regime is as high as required by the present anomalous heating theory.

The experimental difficulties can be circumvented by a more sensitive $\delta N/N$ experiment, since its probe size can be small compared to tens of centimeters. As well, future electric field experiments in the auroral electrojet are planned which will include very short double probes in order to better measure the full spectrum and to parameterize the instrumental effect of spatial filters on the electric field spectra. Theoretical efforts which include the reality of a broad spectrum for the electrojet waves are required for a better understanding of the electrojet heating process.

4. CONCLUSIONS

The results presented here show electrostatic turbulence in the unstable auroral E region confined to a layer between 96 and 121 km. The similarities between the observations of two

simultaneous payloads spaced a few kilometers apart indicate that on a large scale, the electrojet turbulence displays uniform characteristics. However, an investigation of the turbulence as a function of altitude reveals differentiation within the layer, from which we make the following further conclusions:

1. The two-stream instability is one mechanism thought to produce the irregularities. The altitude range in which the waves were detected agrees quite well with the range predicted by linear two-stream theory.

2. The gradient drift instability also contributes to wave generation in the event, as evidenced both by the large power at long wavelengths and by the tendency for the power profile to diminish as the gradient in electron density becomes antiparallel to E .

3. In the heart of the electrojet, the waves cover a broad spectrum from roughly hundreds of meters to a few centimeters wavelength, with broadband fluctuating rms electric fields of several millivolts per meter. The specific nature of this spectrum is dependent on height within the layer. The power in the waves is strongly k dependent.

4. A sharply peaked spectrum of waves ($\lambda \sim 3\text{--}4$ m) was detected at the top of the layer, which may be caused by the two-stream process at marginal stability.

5. Spectral power observed perpendicular to the direction of the current implies the presence of turbulence associated with secondary plasma waves.

The strong dependence on altitude and background plasma parameters seen in the spectral differentiation of the waves indicate that the unstable auroral E region is far from being a layer of homogeneous turbulence. Rather, we conclude that it is a complex domain, whose characteristic waves are a signature of several plasma processes operating simultaneously.

Acknowledgments. We thank J.-P. St.-Maurice and M. Temerin for many helpful discussions. The Porcupine project was an undertaking of the German Ministry for Science and Technology and the Max-Planck-Institute at Garching, Federal Republic of Germany. We gratefully acknowledge the support of G. Haerendel as well as all the Porcupine experimenters. This research was supported at Cornell by the Atmospheric Sciences Division of the National Science Foundation.

The Editor thanks J.-P. St.-Maurice and another referee for their assistance in evaluating this paper.

REFERENCES

- Abel, W. J., and R. E. Newell, Measurements of afternoon radio aurora at 1295 MHz, *J. Geophys. Res.*, **74**, 231, 1969.
- Bahnsen, A., E. Ungstrup, C.-G. Falthammer, U. Fahlson, J. K. Olesen, F. Primdahl, F. Spanglev, and A. Pedersen, Electrostatic waves observed in an unstable polar cap ionosphere, *J. Geophys. Res.*, **83**, 5191, 1978.
- Buneman, O., Excitation of field aligned sound waves by electron streams, *Phys. Rev. Lett.*, **10**, 285, 1963.
- Crochet, M., C. Hanuise, and P. Broche, HF radar studies of the two-stream instability during an equatorial counter-electrojet, *J. Geophys. Res.*, **84**, 2523, 1979.
- Fahlson, U. V., Theory of electric field measurements conducted in the magnetosphere with electric probes, *Space Sci. Rev.*, **7**, 238, 1967.
- Farley, D. T., A plasma instability resulting in field-aligned irregularities in the ionosphere, *J. Geophys. Res.*, **68**, 6083, 1963.
- Fejer, B. G., and M. C. Kelley, Ionospheric irregularities, *Rev. Geophys. Space Phys.*, **18**, 401, 1980.
- Fejer, B. G., D. T. Farley, B. B. Balsley, and R. F. Woodman, Vertical structure of the VHF backscattering region in the equatorial electrojet and the gradient drift instability, *J. Geophys. Res.*, **80**, 1313, 1975.
- Fejer, B. G., R. W. Reed, D. T. Farley, W. E. Swartz, and M. C. Kelley, Ion cyclotron waves as a possible source of resonant auroral radar echoes, *J. Geophys. Res.*, **89**, in press, 1984.
- Fejer, J., Ionospheric instabilities and fine structure, *J. Atmos. Terr. Phys.*, **41**, 895, 1979.
- Fredricks, R. W., and F. V. Coroniti, Ambiguities in the deduction of rest frame fluctuation spectrums from spectrums computed in moving frames, *J. Geophys. Res.*, **81**, 5591, 1976.
- Greenwald, R. A., Diffuse radar aurora and the gradient drift instability, *J. Geophys. Res.*, **79**, 4807, 1974.
- Hoh, F. C., Instability of Penning-type discharge, *Phys. Fluids*, **6**, 1184, 1963.
- Holtet, J. A., Electric field microstructures in the auroral E -region, *Geophys. Norv.*, **30**, 1, 1973.
- Jacchia, L. G., Thermospheric temperature, density, and composition: New models, *Spec. Rep. 375*, Smithsonian Astrophys. Observ., Cambridge, Mass., 1977.
- Kelley, M. C., and F. S. Mozer, Electric field and plasma density fluctuations due to the high-frequency Hall current two-stream instability in the auroral E region, *J. Geophys. Res.*, **78**, 2214, 1973.
- Kennel, C. F., and D. Arnush, Type 1 irregularities in the auroral and equatorial electrojets, *AGARD Conf. Proc.*, **138**, paper 16, 1973.
- Kudeki, E., D. T. Farley, and B. G. Fejer, Long wavelength irregularities in the equatorial electrojet, *Geophys. Res. Lett.*, **9**, 684, 1982.
- Lange-Hesse, G., Radio aurora, in *Aurora and Airglow*, edited by B. M. McCormac, p. 519, Reinhold, New York, 1967.
- Lee, K., and C. F. Kennel, Effects of propagation parallel to the magnetic field on the type 1 electrojet irregularity instability, *Planet. Space Sci.*, **21**, 1339, 1973.
- Mallinckrodt, A. J., Rocket observations of natural and artificially stimulated phenomena within a quiet auroral arc, Ph.D. dissertation, Univ. of Calif., Berkeley, 1980.
- Moorcroft, D. R., Dependence of radio aurora at 398 MHz on electron density and electric field, *Can. J. Phys.*, **57**, 687, 1979.
- Ogawa, T., H. Mori, and S. Miyazaki, Rocket observations of electron density irregularities in the antarctic auroral E region, *J. Geophys. Res.*, **81**, 4013, 1976.
- Oleson, J. K., F. Primdahl, F. Spanglev, F. Ungstrup, A. Bahnsen, U. Fahlson, C.-G. Falthammer, and A. Pedersen, Rocket borne wave and plasma observations in the unstable polar cap E region, *Geophys. Res. Lett.*, **3**, 399, 1976.
- Ossakow, S. L., K. Papadopoulos, J. Owens, and T. Coffey, Parallel propagation effects on the type 1 electrojet instability, *J. Geophys. Res.*, **80**, 141, 1975.
- Pfaff, R. F., M. C. Kelley, B. G. Fejer, N. C. Maynard, and K. D. Baker, In situ measurements of wave electric fields in the equatorial electrojet, *Geophys. Res. Lett.*, **9**, 688, 1982a.
- Pfaff, R. F., M. C. Kelley, B. G. Fejer, and M. Smiddy, Rocket observations of coherent electrostatic waves on the topside of the auroral electrojet turbulent region (abstract), *Eos Trans. AGU*, **63**, 393, 1982b.
- Rieger, E., H. Foepl, G. Haerendel, A. Valenzuela, I. A. Zhulin, V. I. Gaidansky, V. S. Dokoulin, Yu. Ya. Ruzhin, and T. J. Hallinan, The barium ion jet experiment of Porcupine 2, *Space Res.*, **19**, 367, 1979.
- Rogister, A., and N. D'Angelo, Type 2 irregularities in the equatorial electrojet, *J. Geophys. Res.*, **75**, 3819, 1970.
- Schlegel, K., and J.-P. St.-Maurice, Anomalous heating of the polar E region by unstable plasma waves, 1, Observations, *J. Geophys. Res.*, **86**, 1447, 1981.
- Schlegel, K., and J. P. St.-Maurice, Note on the parallel propagation effects of unstable Farley-Buneman waves at high latitudes, *Planet. Space Sci.*, **30**, 315, 1982.
- Simon, A., Instability of a partially ionized plasma in crossed electric and magnetic fields, *Phys. Fluids*, **6**, 382, 1963.
- Siren, J. C., Do ionospheric plasma instabilities affect a high-latitude riometer?, *J. Geophys. Res.*, **87**, 6271, 1982.
- St.-Maurice, J.-P., and K. Schlegel, Estimates of plasma wave amplitudes in the turbulent high-latitude E region using electron temperature measurements, *J. Geophys. Res.*, **87**, 5197, 1982.
- St.-Maurice, J.-P., and K. Schlegel, A theory of coherent radar spectra in the auroral E region, *J. Geophys. Res.*, **88**, 4087, 1983.
- St.-Maurice, J.-P., K. Schlegel, and P. M. Banks, Anomalous heating of the polar E region by unstable plasma waves, 2, Theory, *J. Geophys. Res.*, **86**, 1453, 1981.
- Sudan, R. N., J. Akinrimisi, and D. T. Farley, Generation of small-scale irregularities in the equatorial electrojet, *J. Geophys. Res.*, **78**, 240, 1973.

- Szuszczewicz, E. P., and P. Z. Takacs, Magnetosheath effects on cylindrical Langmuir probes, *Phys. Fluids*, **22**, 2424, 1979.
- Temerin, M., The polarization, frequency, and wavelengths of high-latitude turbulence, *J. Geophys. Res.*, **83**, 2609, 1978.
- Temerin, M., Doppler shift effects on double-probe-measured electric field power spectra, *J. Geophys. Res.*, **84**, 5929, 1979.
- Unwin, R., and W. J. Baggaley, The radio aurora, *Ann. Geophys.*, **28**, 111, 1972.
- Wang, T. N. C., and R. T. Tsunoda, On the crossed field two-stream instability in the auroral plasma, *J. Geophys. Res.*, **80**, 2172, 1975.
- Wickwar, V. B., C. Lathuillere, W. Kofman, and G. Lejeune, Elevated electron temperatures in the auroral *E* region measured with the Chatanika radar, *J. Geophys. Res.*, **86**, 4721, 1981.
- C. W. Carlson, Space Sciences Laboratory, University of California at Berkeley, Berkeley, CA 94720.
- B. G. Fejer, M. C. Kelley, E. Kudeki, and R. F. Pfaff, School of Electrical Engineering, Cornell University, Ithaca, NY 14853.
- B. Hausler, Max-Planck-Institut für Extraterrestrische Physik, Garching, Federal Republic of Germany.
- A. Pedersen, European Space Research and Technology Center (ESTEC), Noordwijk, The Netherlands.

(Received February 16, 1983;
revised September 28, 1983;
accepted September 29, 1983.)