VOL. 80, NO. 31 JOURNAL OF GEOPHYSICAL RESEARCH NOVEMBER 1, 1975

VLF Line Radiation in the Earth's Magnetosphere and Its Association With Power System Radiation

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In a recent experiment, discrete VLF emissions from the magnetosphere were triggered by a transmitter at Siple Station in Antarctica. Spectrograms of these signals as received at the conjugate point, Roberval, Quebec, showed changes in slope, entrainments, and cutoffs at frequencies (several kilohertz) close to the harmonic induction lines from the local 60-Hz power system. This observation led to the suggestion that harmonic radiation from the power system enters the magnetosphere and interacts with the triggered emissions. New evidence supporting this suggestion has been found in spectrograms of simultaneous recordings made at Roberval and at Siple Station in Antarctica. It is shown that line radiation, near harmonics of 60 Hz, travels along the earth's magnetic field in the whistler mode and is received in the conjugate hemisphere at Siple Station. Echoing of the line radiation between Siple and Roberval is often observed. The magnetospheric lines are usually shifted in frequency by 20–30 Hz with respect to the adjacent induction line, but their spacings are near 120 Hz. They may trigger and cut off emissions as do signals from VLF transmitters. Occasionally, magnetospheric lines are seen with spacings of only 20–30 Hz. This smaller frequency separation and the frequency shift of other lines spaced 120 Hz apart are related to the positive frequency offset of emissions triggered by VLF signals from the Omega navigation transmitters. Harmonic lines of reasonable amplitude ($\sim 10^{-3}\ \gamma$) are shown to enhance significantly the precipitation of 2-keV electrons over the eastern parts of the American continents near $L \sim 4$. Some mid-latitude hiss bands appear to consist of sets of magnetospheric lines and their associated triggered emissions.

INTRODUCTION

VLF waves in the magnetosphere are excited by natural lightning discharges (the source of whistlers), by VLF transmitters, and by energetic electrons trapped in the radiation belts. In the last class are the short ($\sim$1 s), narrow band, variable-frequency signals known as discrete VLF emissions [*Helliwell*, 1965].

In a recent experiment, discrete VLF emissions were triggered by VLF signals from a transmitter at Siple Station in Antarctica and were received at Roberval, Quebec [*Helliwell and Katsufrakis*, 1974]. One of the results from this experiment is the basis for this paper. It was the finding that emissions triggered by Siple pulses often showed cutoff, entrainment, and variations in df/dt when the frequency of an emission approached the frequency of a subsequent Siple pulse. These wave-wave interaction effects were striking and unmistakable. Similar effects were observed at frequencies associated with harmonics of the Canadian power system, as illustrated in Figure 1. The lines appearing between 2.5 and about 4 kHz in Figure 1 are harmonic induction lines from the Canadian power system. Near 2.8 s the falling tone is turned into a rising tone near a power line harmonic. Between 3.2 and 3.5 s the emission appears to be entrained near a power line harmonic frequency. A few other examples can be seen on the record.

To explain these associations, it was postulated that harmonic radiation from the Canadian power system near Roberval enters a whistler duct in the magnetosphere. It then stimulates new radiation as it crosses the equatorial plane, and this new radiation is partially reflected at the conjugate point. The process is continuous, giving rise to a more or less steady signal level in both directions, as illustrated by the sketch in Figure 2. As this stimulated radiation travels northward through the interaction region, it interacts with emissions stimulated by the Siple signals, causing the wave-wave interaction effects noted in the data.

The amount of harmonic power radiated from a power system depends on the effective dipole moment for the current distribution and the distortion of the current wave form. A fairly large dipole moment could be achieved in several ways. There can be substantial ground currents associated with single-phase branch lines. Also, currents flow cross-country in the ground between different single-phase branch lines connected to the same three-phase system (suggestion from one of the referees). The Alcan aluminum refineries at Arvida (about 70 miles (44 km) from Roberval) use a large amount of dc power, which is rectified by 12-phase bridge-connected ignitrons (A. Boily, personal communication, 1975). It is well known that heavy-duty rectifiers produce wave form distortion [e.g., *Woodland*, 1970]. It is likely therefore that the action of these rectifiers produces the strong harmonics up to several kilohertz that are almost always observed in the power line induction fields at Roberval. Sample measurements made below 1800 Hz show that the harmonic amplitudes may be relatively large. For example, at the station St. Felicien, the twenty-fifth harmonic (1500 Hz) had an amplitude equal to 0.22% of the fundamental in a test conducted in 1968 (A. Boily, personal communication, 1975).

The power radiated at a given harmonic frequency depends on the amplitude of the harmonic current and the radiation efficiency at that frequency. Experiments conducted with the Siple transmitter indicate that magnetospheric signals can be received at Roberval even when the estimated power output from the Siple antenna is less than 10 W (for Siple antenna efficiencies see the paper by *Raghuram et al.* [1974]). The power lines to the Alcan aluminum refineries carry about 1000 MW of power. Hence even for small harmonic contents and low radiation efficiencies, significant amounts of radiation ($\sim$10 W) might be obtained at frequencies as high as 5 kHz. Furthermore, this power line radiation (PLR) is expected to be amplified as it crosses the equatorial plane in the magnetosphere. Gains as high as 30 dB can be expected [*Helliwell and Katsufrakis*, 1974].

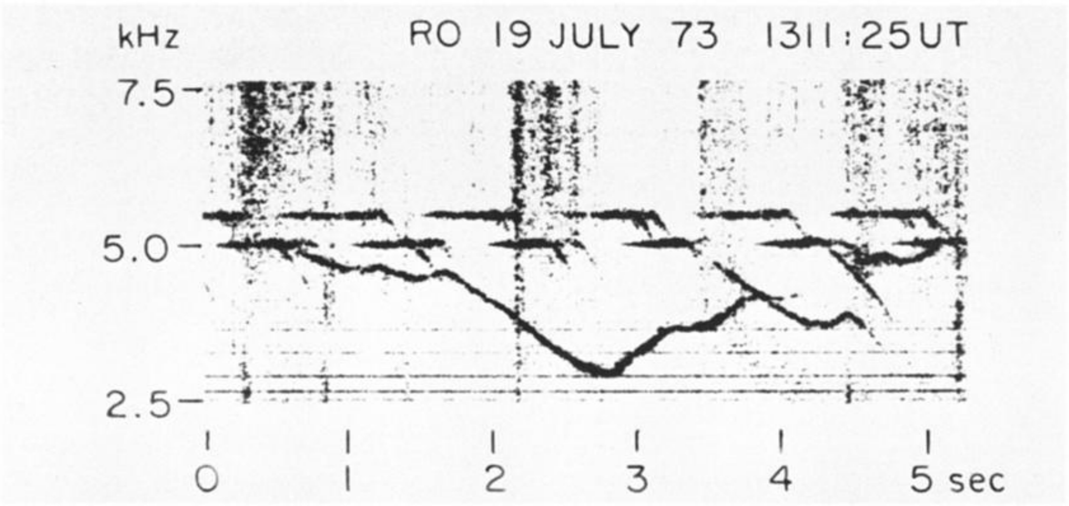

Fig. 1. Spectrogram showing an emission triggered by a pulse from the Siple transmitter interacting with PLR. The emission is turned around near a power line harmonic at 2.8 s. Between 3.2 and 3.5 s the frequency is held constant near a power line harmonic frequency [after *Helliwell and Katsufrakis*, 1974].

To test the hypothesis that harmonic radiation from the Canadian power system is entering the magnetosphere, a search was made for direct evidence of magnetospheric radiation associated with power line harmonics. In the next section of this paper we report our findings. We believe that they demonstrate the existence of magnetospheric line emissions that are initiated by signals from the Canadian power system. In addition, we show that the frequencies of the line emissions are usually offset 20–30 Hz above the power line harmonics. We also report evidence of fine structure in the spectrum, with line spacings of 20–30 Hz. We suggest that mid-latitude hiss may be excited by PLR. In the section on particle scattering we consider the effect of line radiation on particle scattering and the consequent precipitation of electrons into the ionosphere.

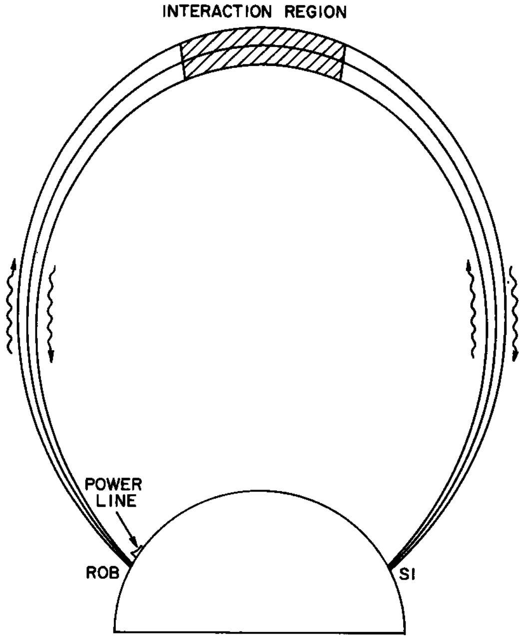

Fig. 2. Schematic figure showing how radiation from power lines travels between the conjugate stations at Roberval and Siple in a field-aligned duct in the magnetosphere. Amplification and emission triggering are postulated to occur in the equatorial plane through a feedback process based on electron cyclotron resonance.

RESULTS

First, we present spectra of various PLR phenomena. Simultaneous conjugate spectra from Siple Station and Roberval, Quebec, are shown in Figure 3. Two types of lines are discernible on the Roberval record. The first is thin and relatively constant in frequency and amplitude. This is called an 'induction' line and results from direct pickup of the harmonic fields from the power transmission lines near Roberval. The absence of such thin lines on the Siple record confirms this interpretation. The second type of line exhibits a much larger bandwidth (~30 Hz) and varies slowly in amplitude and frequency. Lines of this type are present on both the Siple and the Roberval records. Furthermore, they have the same frequencies and show the same gross variations in amplitude at the two ends of the path. We propose that these lines were originally excited by power lines in the vicinity of Roberval and that the waves echo back and forth along field-aligned ducts linking Siple and Roberval (Figure 2). Accordingly, we call them 'magnetospheric' lines. The nearly vertical echoing bands present on both records in Figure 3 are whistlers.

The induction lines appear at exact multiples of 60 Hz. At Roberval the induction lines are almost always at odd harmonics of 60 Hz. Although the magnetospheric lines are spaced roughly 120 Hz apart, they do not appear exactly at harmonics of 60 Hz. On the record of Figure 3 most of the magnetospheric lines are at frequencies slightly above odd harmonics of 60 Hz (on some records, not shown, the magnetospheric lines are below the nearest induction line). This remarkable circumstance is difficult to explain but resembles similar shifts in frequency observed in magnetospheric signals from transmitters like Omega [*Stiles and Helliwell*, 1975].

It might be thought that the lines seen at Siple could have traveled in the earth-ionosphere wave guide rather than through the magnetosphere. Both their drift in frequency and their large bandwidth exclude this possibility. In addition, the subionospheric signals from the Siple transmitter are not observed at Roberval, showing that this signal component is highly attenuated with respect to the magnetospheric component.

Further evidence of the magnetospheric origin of the lines observed at Siple is found in two recordings made on different

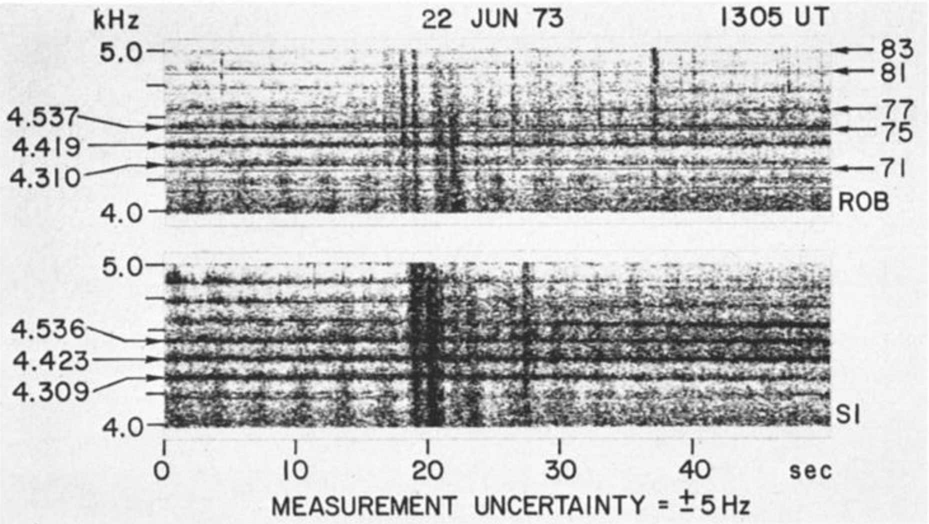

Fig. 3. Simultaneous spectra from the conjugate stations Siple and Roberval. The frequencies of prominent magnetospheric lines are given. The harmonic numbers of the induction lines seen at Roberval are given. Note the difference in bandwidth between magnetospheric and induction lines.

days and illustrated in Figure 4. The local conditions under which these two recordings were made were essentially identical. The upper panel shows a different frequency range of the same recording as is illustrated in the lower panel of Figure 3. The absence of lines above 2 kHz in the lower panel indicates that the lines above 2 kHz in the upper panel are of magnetospheric origin. Furthermore, the lines of the upper panel show a weak amplitude modulation at the two-hop echoing period of the whistlers on the same record, which is further evidence of their magnetospheric origin. In most cases it is fairly easy to distinguish between induction and magnetospheric lines because of their different structures. (On Figure 4 some weak induction lines of local origin are seen below 1 kHz.)

Control of periodic emissions by magnetospheric lines is suggested by the conjugate spectra of Figure 5. On the Roberval record a 'hook' emission starts at about 0.5 s near 2 kHz, just below an induction line. It then echoes between Roberval and Siple with an average two-hop period of 4.25 s, the same as that of one of the whistlers on the same record. The starting

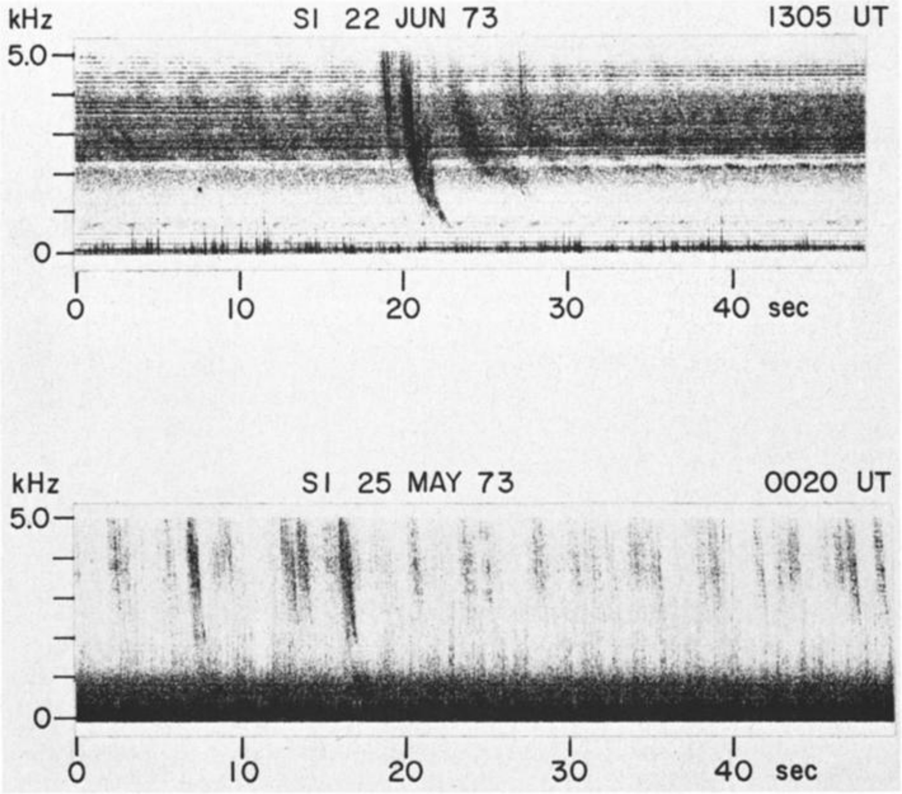

Fig. 4. The lower panel shows that induction lines are absent at Siple. Thus the lines in the upper panel are magnetospheric. The gains were equalized to improve the comparison.

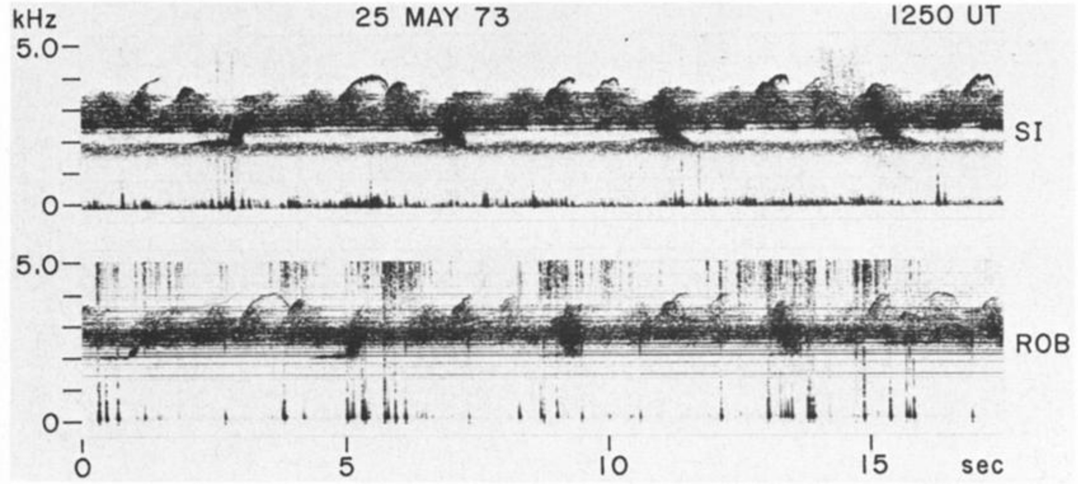

Fig. 5. Echoing emissions are triggered near 2 kHz, possibly by PLR. Note the cutoff of emissions at an induction line near 4 kHz on the Roberval record.

frequency moves up slightly, appearing to lock on to the frequency of the adjacent induction line on the Roberval record. Another induction line, near 4 kHz, corresponds closely with the upper cutoff frequency of a number of periodic 'inverted hook' emissions.

Between 2.5 and 3.5 kHz on Figure 5 there appears a typical mid-latitude hiss band, showing line structure. It seems likely that the entire hiss band is caused by PLR and emissions triggered by PLR at closely spaced frequencies. A better example of a hiss band showing line structure appears in the upper panel of Figure 4. The spacings between the lines in Figure 4 are also roughly 120 Hz. Their spacing is better shown on the expanded frequency scale of Figure 3. A distribution of measured spacings is plotted in Figure 10, including measurements made between 1305 and 1306 UT on June 22, 1973, and provides further evidence that the lines in Figure 4 are spaced roughly 120 Hz apart. Thus the PLR may provide a natural explanation for the commonly observed association between discrete emissions and mid-latitude hiss.

Another example of apparent power line control is shown in Figure 6*a*. A dispersive periodic emission of falling frequency is triggered near 2.4 kHz. The presence of a number of other periodic emissions starting at the same frequency suggests that they may be controlled by PLR. The record in Figure 6*b*, from Byrd Station in Antarctica, shows a burst of chorus initiated by a whistler. At about 17 s on the time axis the chorus starting frequency settles down to a roughly constant frequency near 5.8 kHz. This again could be a PLR effect.

If PLR does indeed travel through the magnetosphere, it should be possible to see PLR-associated phenomena in satel-

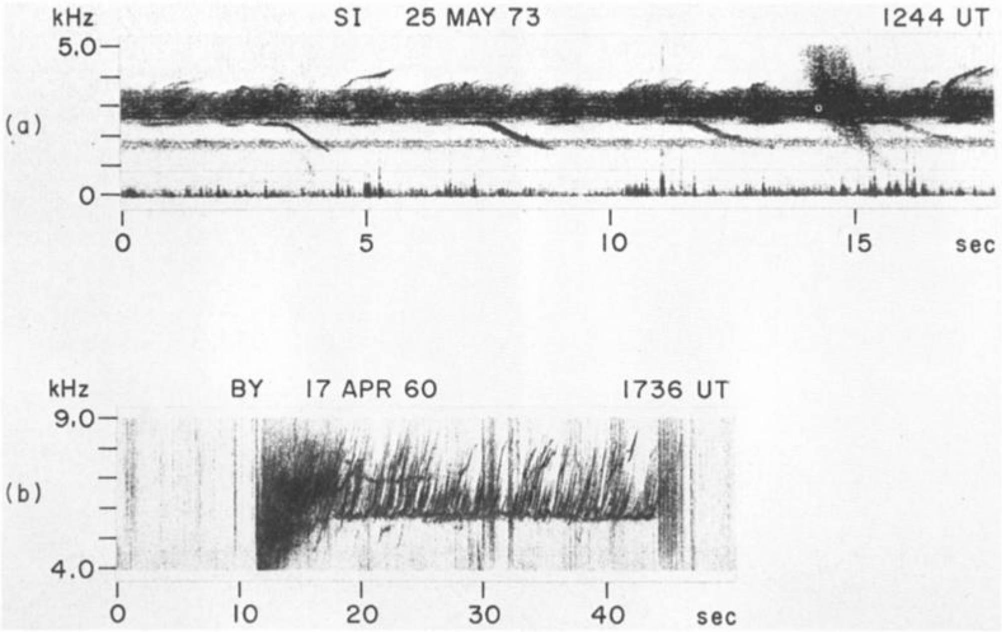

Fig. 6. (*a*) Siple spectrogram showing echoing dispersive emissions triggered near 2.4 kHz. The number of echoing narrow band emissions near the same frequency suggests control by PLR. (*b*) The nearly constant lower cutoff frequency of the chorus burst on the Byrd record might be due to PLR.

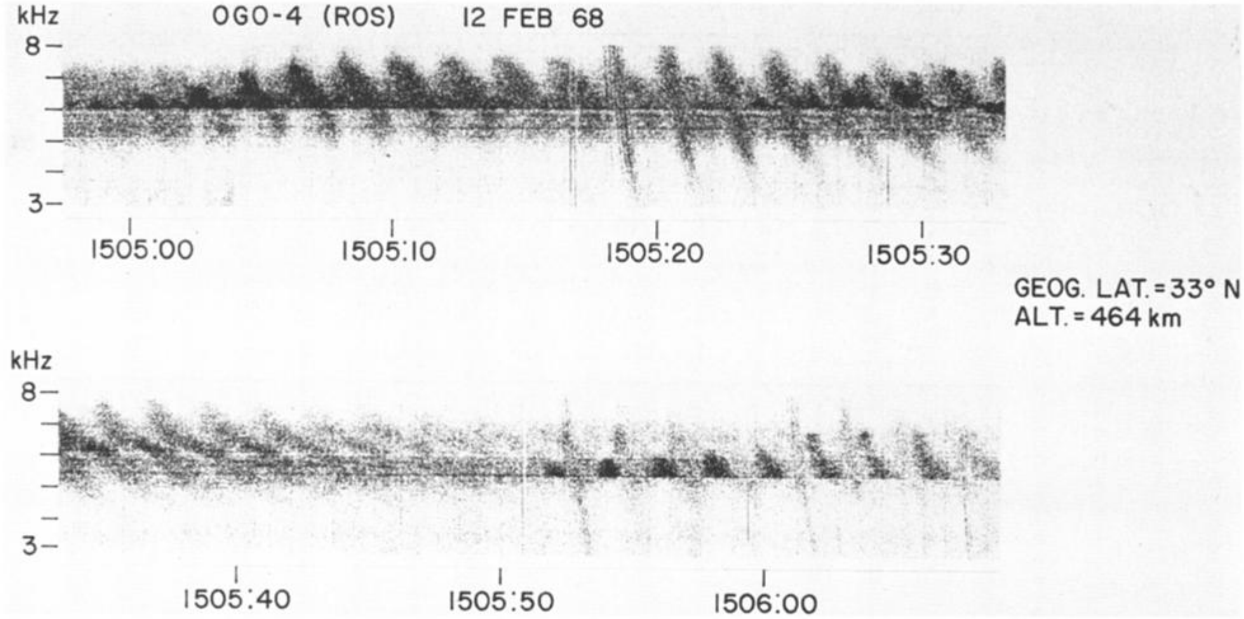

Fig. 7. Satellite record showing periodic emissions with a constant lower cutoff frequency. Two such cutoffs occur at 5.4 and 6 kHz. Note that the whistlers are not cut off.

lite data. Figure 7 shows a spectrogram of VLF noise received on the Ogo 4 satellite. The echoing emissions show a constant lower cutoff frequency, possibly a power line harmonic.

Fine structure in the magnetospheric line radiation is shown by the spectrograms of Figure 8 by means of an expanded frequency scale. There are two prominent lines on the 1235 UT Roberval record, at 2.70 and 2.82 kHz. The line at 2.70 kHz is seen also on the conjugate record from Siple. The line at Siple must be of magnetospheric origin, since induction lines are not seen at Siple at these frequencies. It is probable therefore that the line at 2.70 kHz at Roberval has a magnetospheric component as a result of whistler mode echoing. The line on the Roberval record at 2.82 kHz might also have a small magnetospheric component corresponding to the magnetospheric line seen at Siple at this frequency beginning at about 12h 35m 45s UT. In any case, the induction component dominates in both of these lines at Roberval, as is evident from their relatively constant amplitude. The two weak lines at 2.64 and 2.76 kHz at Roberval appear to be induction lines of even order. Lines spaced about 20–30 Hz apart appear between these induction lines and seem to be associated with the induction line at 2.70 kHz. These lines are not quite so prominent, suggesting that they might have in some way originated from the power line harmonic at 2.70 kHz. The fact that the fine structure first appears at a frequency close to the power line harmonic frequency lends credence to this viewpoint. Their magnetospheric origin is again demonstrated by the two-hop intensity modulation that is out of phase at the conjugate points. Figure 8*a* shows one of the rare instances when induction and magnetospheric lines coincide in frequency. Figure 8*b* shows how these lines have changed in a period of 15 min. While Figure 8*a* shows magnetospheric lines on the Siple record at 2.70 and 2.82 kHz (odd harmonics), Figure 8*b* shows magnetospheric lines slightly below these two frequencies, as is indicated by the induction lines at Roberval.

Close inspection of Figure 8*b* reveals an interesting fact. The induction lines at both 2.70 and 2.82 kHz drift with respect to the magnetospheric line structure. In the first 10 s of the record, both induction lines fall about 8 Hz and then remain fairly steady. If this change in apparent frequency were caused by tape speed variations, then the magnetospheric lines would be expected to show the same change. As the magnetospheric lines are essentially unchanged, we are forced to conclude that the induction lines themselves are changing frequency. The change of 0.3%, though large, is within maximum deviations observed in the power system frequency near Roberval. The deviations are within ±0.17% (A. Boily, personal communication, 1975); thus changes as large as 0.34% in the frequency are possible.

Although the magnetospheric lines in Figure 3 are fairly constant in frequency, there were a few cases in which magnetospheric lines drifted in frequency. In most of these cases a number of lines drifted up or down in frequency together, so that they appeared to be parallel in the spectrograms. The lines drift up in frequency more often than they drift down. In one case (not shown) the drift was as high as 50 Hz/min. Magnetospheric lines drift far more in frequency than induction lines, and the two drifts in general do not appear to be related. The fact that the induction lines can change frequency independently of the magnetospheric lines shows that these two kinds of lines can be relatively uncoupled over periods of the order of 1 min.

In a few cases (not shown here) we found that there was a noise-free band 50–200 Hz wide just below the transmitter frequency when Siple transmissions were received at Roberval. The transmitter signals, by perturbing the energetic particle distribution function, seem either to suppress the generation of noise or to attenuate the noise once it has been generated. Similar noise-free bands sometimes appear in connection with PLR. For example, in Figure 7 there is a noise-free band centered around 6 kHz, which is just below the frequency at which the echoing emissions are cut off. The band is best defined between 15h 05m 15s and 15h 05m 25s. Further details on noise-free bands will be reported later.

Having reviewed several PLR phenomena in terms of intensity-modulated dynamic spectrograms, we now employ a fast Fourier transform method [*Stiles and Helliwell,* 1975] to provide better definition of relative amplitudes. This method

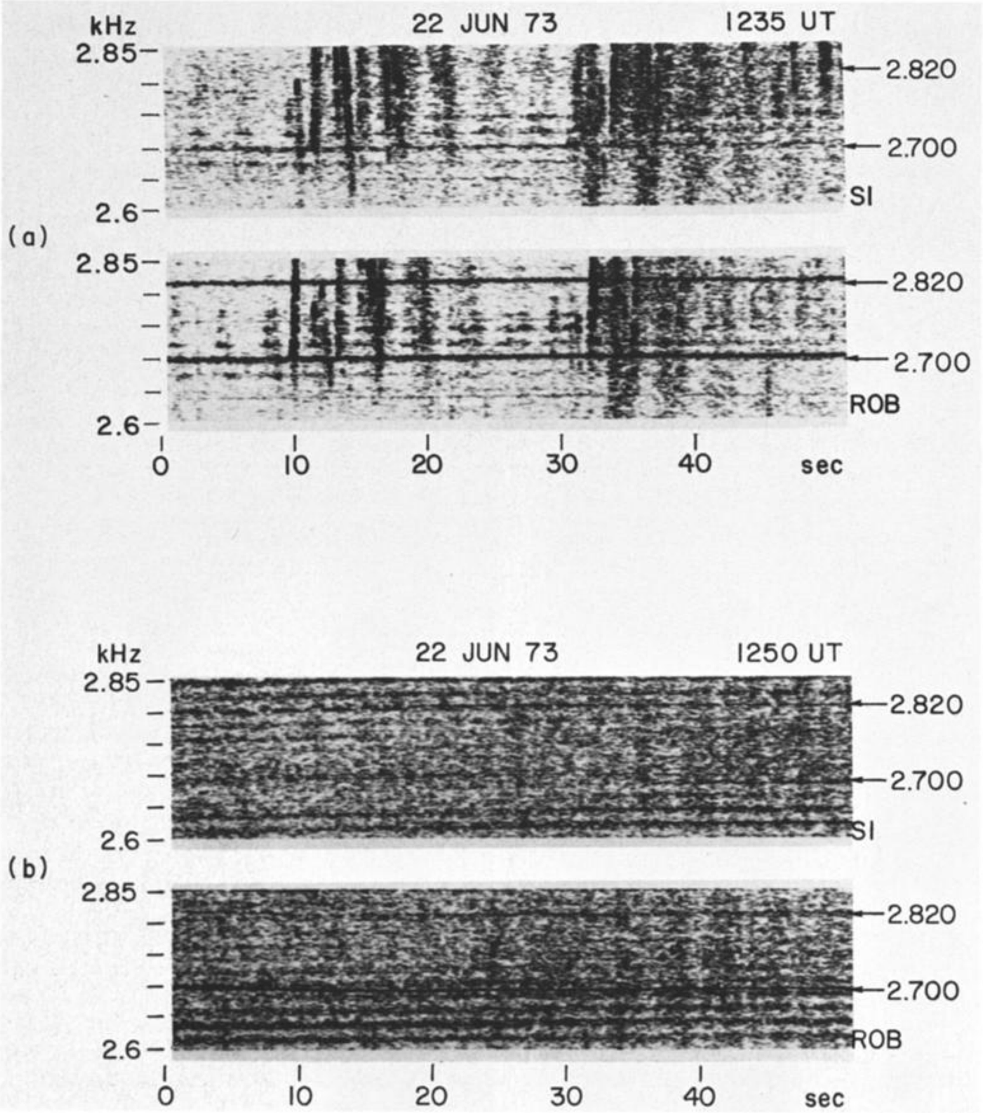

Fig. 8. Spectrograms on an expanded frequency scale showing the presence of lines at frequencies other than harmonics of 60 Hz. The locations of odd harmonics of 60 Hz are shown by arrows at the right of the panels. (*a*) There are magnetospheric lines very close to odd harmonics of 60 Hz, as can be seen from the Siple record. (*b*) The induction lines seem to have shifted down in frequency with respect to the magnetospheric lines.

was applied to the Roberval data illustrated in Figure 3, and the results are shown in Figure 9. Figure 9*b* shows five A scans (amplitude versus frequency plots), each scan representing an average over 10.24 s. The 3-dB bandwidth of each individual filter is ~1.6 Hz. To resolve adjacent lines, the filter spacing in frequency must be at least equal to twice the filter bandwidth, or about 3.2 Hz.

Most of the features of Figure 3 are reproduced in Figure 9*b*. There are induction lines at 4140, 4260, 4500, 4620, and 4980 Hz. These lines vary a little in frequency because of tape flutter or shift in power line frequency. Their bandwidth is relatively small. There are magnetospheric lines at 4300, 4420, and 4530 Hz. These lines are much broader than the induction lines and usually show more than one intensity peak. However, it is difficult to observe any systematic changes in the spectrum with time; i.e., the variations in the spectrum are random. The amplitudes of the magnetospheric lines are greater than those of the induction lines on these records. An average spectrum over the entire 51.2-s period is given in Figure 9*a*, showing the effect of further smoothing. Induction lines (some marked with short arrows and labeled with harmonic order) can be seen at 4140, 4260, 4500, 4620, and 4860 kHz. Magnetospheric lines, marked with long arrows, are seen at 4295, 4415, and 4525 Hz. These values of frequency are smaller than those of the corresponding lines on Figure 3 by 15, 4, and 11 Hz, respectively. Inspection of Figure 9*b* shows the reason. Each line spectrum is skewed in such a way that the peak, used in Figure 9*b*, falls below the visual average used in Figure 3.

One feature which we looked for but could not find in these A scans (Figure 9) was a clear-cut relationship between magnetospheric and induction lines. There is no evidence of a link between the induction line at 4260 Hz and the magnetospheric line near 4300 Hz. They exist as two separate lines. If continuous data with small tape speed error had been available for this period, it might have been possible to see two peaks evolve out of one peak at the induction line frequency. This would have established immediately the connection between induction and magnetospheric lines. Similar spectra of *Stiles and Helliwell* [1975] show such a connection for emissions triggered by signals from the transmitter on 14.7 kHz.

An approximate calculation was made of the paths along which the magnetospheric line radiation propagates by using methods described by *Park* [1972]. A 45-min portion of data recorded at Siple between 1230 and 1315 UT on June 22, 1973, was chosen for analysis. The calculations are only approximate because all of the whistlers received during this time were multipath. There were a number of echoing emissions during this period of time, many of them being of the type shown in Figures 5 and 6. The one-hop time delay was measured for a number of these emissions at different frequencies. These measurements indicated that the emissions, like the whistlers, were multipath. However, for frequencies above 4 kHz the one-hop time delay for emissions coincided with that of whistlers having well-defined nose frequencies. Measurements of the nose frequencies showed that most of the magnetospheric lines traveled along magnetospheric paths with L values between 3.5 and 4.0.

Numerous techniques were employed to ascertain whether the various phenomena described above were indeed due to PLR. The primary problem was our inability to measure frequencies accurately enough. In most cases because of finite emission bandwidth it is difficult to say precisely at what frequency an emission reverses slope, starts, or stops. It is necessary to determine this frequency to an accuracy of a few hertz in order to say whether the frequency at which such an event occurred is close to a power line harmonic frequency. For this reason most of our measurements were made on lines of relatively small bandwidth and long duration. Another source of error in measuring frequencies is variation in tape speed. Because of finite tolerances in tape recorder specifications the tapes were usually played back at a speed somewhat different from the recording speed. Frequencies were sometimes shifted up or down by as much as 300 Hz on this account. This error was removed by observing the shift in frequency of Omega ground wave transmissions at 10.2 kHz recorded on the same tape. Tape flutter caused an ac fluctuation in the frequency on top of this dc error. However, tape flutter was less serious and in most cases did not cause significant error in our measurements.

As Figure 3 indicates, magnetospheric lines often do not appear at harmonics of 60 Hz. However, it might be expected that the offsets of two adjacent magnetospheric lines from their associated power line harmonics would tend to be the same. If so, the spacings of the lines should be close to a multiple of 60 Hz. Because the Canadian power system radiates most strongly at odd harmonics, the minimum spacing is expected to be 120 Hz. A sample of data to test this hypothesis was obtained from records made at Siple Station between 1230 and 1315 UT on June 22, 1973. The results are shown in Figure 10, where the peak in frequency of occurrence occurs a little above 120 Hz (the mean occurs at 129 Hz). This shift could be due to the small size (133 samples) of our sample. On the other hand, the occurrence of the peak a little above 120 Hz could be real. This would mean that higher frequencies were raised more in frequency as they traveled through the magnetosphere. The difference in the frequencies of the lines was measured instead of the frequencies themselves because of the relatively large errors in tape speed. (In the case of Figures 3, 4, and 8, obtained from the same time period, the error was less because a higher tape speed was employed during recording.)

Measurements (not shown) were also made on a spectrogram from Eights Station in Antarctica between 2027 and 2041 UT on October 17, 1963. Errors in tape speed were small enough that absolute frequencies could be measured to within 5 Hz. However, there was no tendency for lines to occur at frequencies near harmonics of 60 Hz.

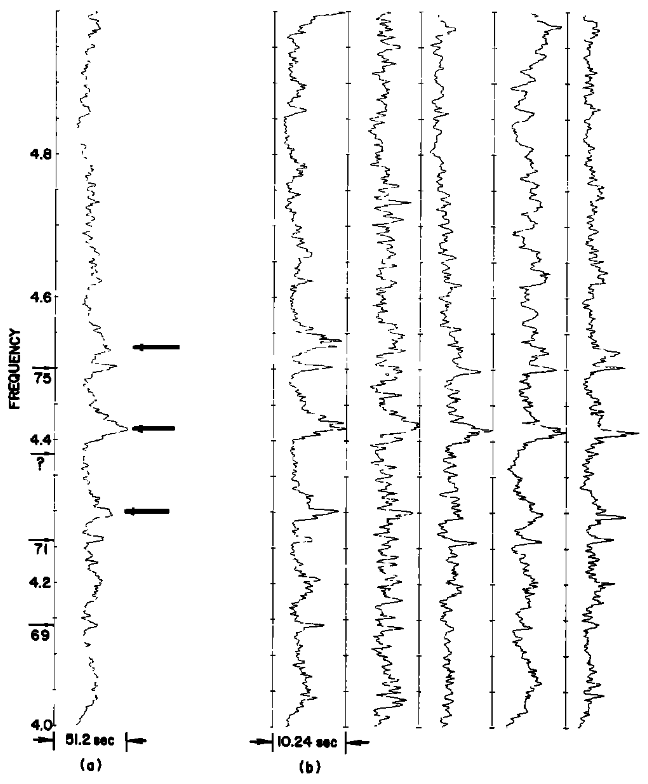

Fig. 9. Amplitude versus frequency plots (A scans) made from data received at Roberval for a period of 51.2 s starting at 1305 UT on June 22, 1973. (*a*) The A scan is an average over the entire 51.2-s period. (*b*) Each A scan is an average over 10.24 s.

As the power line frequency in most parts of the world is 50 Hz, observations at appropriate locations should show magnetospheric lines associated with harmonics of 50 Hz. So far, most of our study has been confined to the western hemisphere, and we have seen few phenomena which occur at harmonics of 50 Hz. However, measurements made on a spectrogram from Suffield, Alberta, did show some tendency

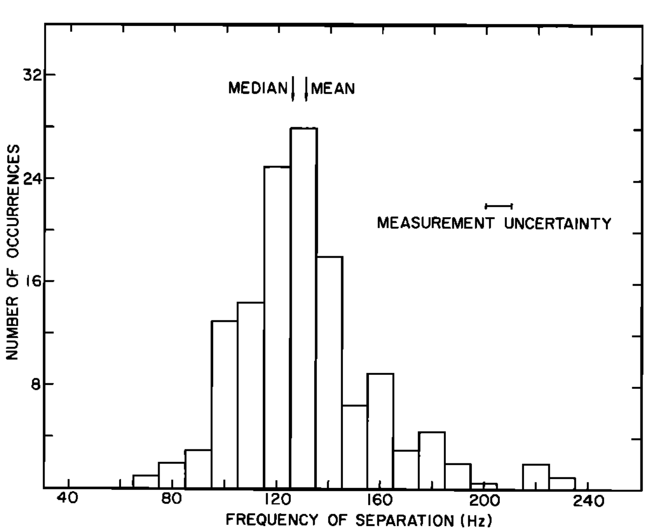

Fig. 10. Distribution of the frequency spacing between adjacent magnetospheric lines observed at Siple Station from 1230 to 1315 UT on June 22, 1973.

for lines to occur at multiples of 50 Hz. The evidence is not conclusive. Fifty-eight of 113 measurements occurred within 10 Hz of a harmonic of 50 Hz. One possible source of 50-Hz harmonic radiation is the power system of New Zealand.

PARTICLE SCATTERING

A practical aspect of line radiation in the magnetosphere is its effect on pitch angle scattering and the consequent precipitation of electrons into the ionosphere. We now consider possible precipitation effects of a broad spectrum of lines, such as those shown in Figures 4 and 8*b*.

For the sake of discussion we assume that the line spectrum consists of waves of equal amplitude B_L whose frequencies are odd multiples of 60 Hz and which lie in the range 3–5 kHz. We also assume that the waves propagate approximately along the $L = 4$ magnetic shell within a range of longitude of ±30° about the field lines linking Roberval and Siple. This range of illumination is consistent with satellite observations of field line illumination from ground-based VLF transmitters. Energetic electrons which occupy this illuminated region of the magnetosphere will be scattered in pitch angle by line spectrum elements whenever their parallel velocity $v_{||}$ satisfies the general resonance condition

$$\omega - k_{||}v_{||} = n\omega_H \qquad n = 0, \pm 1, \pm 2, \cdots \tag{1}$$

where ω and ω_H are the angular wave frequency and electron gyrofrequency, respectively, and $k_{||}$ is the component of the wave propagation vector which is locally parallel to the earth's magnetic field $\mathbf{B}_0$. For simplicity we consider here only the fundamental gyroresonance ($n = 1$). As a further simplification we assume that to a rough approximation the particle scattering due to the line spectrum is equivalent to that produced by a white noise spectrum in the 3- to 5-kHz band whose power spectral density is equal to the average power spectral density of the line spectrum. For a white noise spectrum the resonant encounters between the energetic electrons and the waves result in pitch angle scattering and a local pitch angle diffusion coefficient given approximately by the relation [*Roberts,* 1968]

$$D_\alpha \simeq \eta^2\beta_\omega[1 + (v_p v_{||}/v^2)]^2[1 + (v_{||}/v_g)]^{-1} \tag{2}$$

where β_ω is the average power spectral density of the harmonic waves; η is the electron charge to mass ratio; v_p and v_g are the local whistler mode phase and group velocities, respectively; $v_{||}$ is the electron parallel velocity; and v is the total velocity of the electrons. (A closely related result is given by *Gendrin* [1968].) The quantities v_p and $v_{||}$ are not independent but are related through (1) with $n = 1$.

In order to calculate average particle diffusion rates D_α the expression in (2) must be averaged over a bounce period, account being taken of the fact that $\beta_\omega \equiv 0$ for frequencies outside the range 3–5 kHz. This averaging depends upon particle energy and pitch angle. Consider the case of low-energy particles of total energy 2.5 keV which are within 30° of the equatorial loss cone at $L = 4$, and assume that $B_L \sim 1$ mγ, a value that is consistent with satellite measurements of field strengths of injected waves, in the equatorial plane. For these particles, $\beta_\omega \simeq 10^{-8}$ γ^2/Hz, $D_\alpha \simeq 2 \times 10^{-5}$ s^{-1}, and the particles will diffuse into the loss cone in a time $\tau \sim (D_\alpha)^{-1} \sim 5 \times 10^4$ s. Since the drift time of the same particles through the illuminated region (60° longitude) is also approximately 5×10^4 s, it can be expected that a large fraction of the 2.5-keV electrons of low pitch angle in the equatorial plane will be precipitated during their transit across the illuminated field lines. Thus the presence of harmonic waves of 1-mγ amplitude on the $L = 4$ shell in the magnetosphere could conceivably create a sink for low-energy particles and produce a marked asymmetry in the distribution of low-energy electrons between the 50° and the 110°W longitude meridians.

DISCUSSION

In spite of the puzzling frequency relationship between the power line harmonics and the other related broader lines, there can be no doubt that the latter are of magnetospheric origin. They are observed simultaneously at conjugate points; they show whistler mode echoing, in the form of amplitude modulation, with modulation phases reversed at conjugate points (Figure 3); and they are seen only when there is other evidence of whistler mode echoing and/or emission activity.

For example, consider the line whose frequency is near 2.72 kHz in Figure 8*a*. This line is present in both the Siple and the Roberval spectrograms. There is also an echoing whistler present in both spectrograms starting from 12h 35m 32s UT at Siple. Its average two-hop time delay at 2.72 kHz is 3.72 s at Siple. The average time period of the intensity modulation of the line at Siple is 3.74 s, the measurement uncertainty being ±0.1 s. At Roberval the two-hop time delay is 3.65 s for the whistler, while the time period of the intensity modulation of the line is 3.67 s. The phase difference between the modulation at Siple and that at Roberval is 175°, the measurement uncertainty being ±10°.

Thus within experimental error the period of the intensity modulation is the same as the two-hop whistler mode travel time. Furthermore, the modulation is in antiphase at the conjugate stations. These facts demonstrate that the intensity modulation is caused by whistler mode echoing and hence that the lines are of magnetospheric origin. It is not possible to measure the expected dispersion over the small frequency range displayed in the spectrogram. Frequencies within 100 Hz of 2.72 kHz would show a difference in two-hop time delay well under the measurement accuracy of 0.1 s. We conclude therefore that these lines are maintained in much the same way as periodic emissions. Reflections from each end of the path provide an input signal that triggers the growth of a new wave near the equatorial plane. This growth process is thought to be similar to that observed in the Siple transmitter experiments [*Helliwell and Katsufrakis,* 1974].

Initiation of the magnetospheric line may be related to a phenomenon observed in connection with Omega triggering [*Stiles and Helliwell,* 1975]. In that experiment, rising tones triggered by the amplified input signal form a plateau that often develops into a narrow band emission. In the present experiment the magnetospheric line becomes self-sustaining through continuous excitation and reflection. It may then slowly drift higher in frequency as a result of the same kind of triggering mechanism postulated to explain the initial positive offset in the frequency of Omega-stimulated emissions. However, it usually cannot cross a frequency band already occupied by another line, because the electrons that it requires for growth have already been trapped by the other wave [*Helliwell and Crystal,* 1973].

The fine structure (lines spaced 20–30 Hz apart) further shows that each individual line is self-sustaining as a result of whistler mode echoing. The PLR may serve to start this process and to regulate the frequency. Since lines generally do not cross one another, the first magnetospheric line either stays just above its parent line or rises to a frequency just below the next power line harmonic. In the latter case, new magnetospheric lines form and rise to a frequency just below that of the previous line (20–30 Hz). This process may continue until the spectrum between two odd harmonics is filled (for example, on Figure 8 there are five lines between 2.70 kHz and 2.82 kHz, the average spacing being 24 Hz). Then it is not possible for the lines to drift, and hence their frequencies become constant. This model might account for the unusual situation shown in Figure 8*a*, in which the magnetospheric lines fall on exact harmonics of the power line frequency. The fine structure prevents the magnetospheric line closest to the parent line from rising in frequency.

The existence of a minimum spacing between lines may depend on the effective frequency bandwidth of the resonant electrons that cause growth. According to the criterion stated by *Helliwell* [1967] the minimum bandwidth is determined by the deviation in parallel velocity from resonance required to shift the phase of an electron by π rad in one resonance length. For $L = 4$ and $f = 2.7$ kHz this bandwidth is $\pm 0.228\%$ in parallel velocity, corresponding to ± 7.05 Hz. As the wave field intensity increases above the value required to make the bunching length equal to the interaction length, the bandwidth increases as $B_L^{1/2}$, where B_L is the wave amplitude. The observed bandwidth of 20–30 Hz is thus somewhat greater than the estimated minimum of 14 Hz and hence is in satisfactory agreement with this model.

Another explanation for the fine structure of Figure 8 lies in the whistler mode side-band instability [*Das*, 1968; *Brinca*, 1972; *Nunn*, 1973]. In this instability the resonant particles trapped in the potential well of the parent whistler mode wave of frequency f achieve a quasi-steady state that is unstable to the presence of perturbing waves at frequencies $f + f_T$, where f_T is the approximate frequency of oscillation of the trapped particles in the potential well of the parent wave. Depending upon conditions, either or both of these side-band waves can grow to amplitudes of the order of that of the parent wave. Necessary conditions on the distribution function for the occurrence of growth are given by the above-mentioned authors. If we assume that these conditions are sometimes satisfied when a set of magnetospheric lines is initially generated by PLR, then this set may generate additional lines through the side-band instability. The fine structure between the original parent-line frequencies could then be a result of the original side bands subsequently producing side bands of their own.

By means of the parameters of *Brinca* [1972] it is found that a parent-wave amplitude of ~ 4 mγ is necessary to produce a value of $f_T \sim 20$ Hz. This amplitude is well within the range of amplitudes commonly observed in the inner magnetosphere; however, the theory takes account of only a single set of side bands. A generalization of the theory to multiple side bands is necessary before we can properly assess the role of this type of instability in producing a structure like that of Figure 8.

As was mentioned in the section on results, there are several cases in which magnetospheric lines were observed to drift slowly in frequency. Although we believe this drift to be due to a triggering effect, as mentioned above, we should point out that frequency drifts can also be produced through a Doppler shift phenomenon. In monitoring the frequency of whistler mode signals from northern hemisphere VLF stations, *McNeill* [1967] measured a Doppler shift of about one part in 10^5 which he attributed to the motion of the whistler ducts which carried the VLF signals. The velocity of these ducts was estimated by McNeill to be about ½° of latitude per hour, a value much lower than the peak convection duct motions during substorms of 5°/h reported by *Carpenter et al.* [1972].

Assuming the maximum drift rate, we might expect to measure a Doppler shift of approximately one part in 10^4 for a one-hop transmission such as that observed by McNeill. Furthermore, assuming a one-hop bounce time of approximately 1 s for an echoing wave packet, we would expect to see a frequency change in the internally reflected wave of one part in 10^4 per second. For a 3-kHz magnetospheric line this change would amount to ~ 20 Hz/min. Thus Doppler shift frequency changes can conceivably approach the values of the magnetospheric line frequency drifts observed to date. However, our observations of magnetospheric line frequency drifts were made for the most part during very quiet periods, when the Doppler shift mechanism should produce very little frequency shift. Thus we conclude that the Doppler shift produced by convective motion of ducts played little part in the observed frequency shift of the magnetospheric lines.

We have noted that the presence of harmonic line radiation in the magnetosphere may affect the energetic particle population. In order to assess these effects the electron diffusion rate must be calculated as a function of L shell, particle energy, and pitch angle. The model should include all the cyclotron resonances. Such calculations are presently underway and will be reported in a subsequent paper.

The harmonic line radiation from the Canadian power system may create a sink for low-energy particles on the $L \sim 4$ field lines. This effect might be detectable by using appropriate particle counters on an equatorially orbiting satellite, such as Explorer 45, which intersects the $L \sim 4$ field lines. At the present time a study of Explorer 45 VLF wave and particle data is underway in order to determine if such an effect does exist (D. A. Gurnett and P. Smith, personal communication, 1974).

In future studies of the magnetosphere it will be desirable to know the input radiation from power systems in order to interpret properly wave and particle phenomena connected with whistler mode signals.

Acknowledgments. This research was supported in part by the National Aeronautics and Space Administration under grant NGL-05-020-008; in part by the National Science Foundation, Atmospheric Sciences Section, under grant GA-32590X; in part by the National Science Foundation, Office of Polar Programs, under grant GV-28840X; and in part by the Air Force Office of Scientific Research under grant F4462-72-C-0058.

The Editor thanks R. Gendrin and M. G. Morgan for their assistance in evaluating this paper.

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(Received September 3, 1974;
revised March 13, 1975;
accepted May 8, 1975.)