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ISEE 1 OBSERVATIONS OF VLF LINE RADIATION IN THE EARTH'S MAGNETOSPHERE

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Abstract. A search has been carried out for magnetospheric line radiation in the VLF data acquired during the period October 1977 - August 1979 by the Stanford University VLF receiver on the ISEE 1 satellite, while the satellite position varied between L = 2 and L = 8 and the satellite longitude lay in the range 50°W to 110°W. This magnetopsheric region encompassed the magnetic field lines linking three stations, Eights, Siple and Roberval, from which most ground-based data on VLF line radiation has been obtained and also included one of the main regions in which the occurrence of VLF chorus has been actively linked to power line radiation. Line radiation was detected on only 5 of 90 orbits, and all examples occurred at frequencies below 4 kHz. The most clearly defined example of line radiation was acquired near L = 5 under conditions of very low magnetic activity during which the plasmapause was located at L ~ 7. In this particular case, the strongest lines in the spectrum exhibited a frequency change of approximately 22 Hz/min over a 9-min period, while weaker lines changed frequency as slowly as 6 Hz/min. The line radiation was detected during a period when whistler mode echoing was quite pronounced on lower L shells and may actually have been a scattered component of line radiation echoing between hemispheres on a magnetic shell of lower L value. In all instances the S/N ratio or the absolute intensity of the lines was quite low. Thus, in agreement with earlier work, we conclude that very little of the background VLF wave energy in the outer magnetosphere is contained directly in VLF line radiation. However, the catalytic role of line radiation in controlling VLF wave-particle interactions remains to be assessed.

Introduction

The presence of strong VLF line radiation (magnetospheric lines) in the magnetosphere has been reported in a number of recent papers [Helliwell et al., 1974; Park, 1977] in which a connection was demonstrated between the magnetospheric line radiation and harmonic radiation from electric power transmission lines that leaks into the magnetosphere.

The role of this man-made radiation in the interaction between waves and particles in the magnetosphere has been the subject of much debate in recent years. On one hand, there is strong, direct evidence from data received at ground stations that under the appropriate circumstances, VLF waves radiated by electric power transmission lines can leak into the magnetosphere and interact strongly with energetic electrons to produce wave amplification (30 dB) and energetic particle scattering and precipitation [Helliwell et al., 1975; Park, 1977; Park and Helliwell, 1978]. Furthermore, there is significant indirect evidence from Ariel III and OGO 3 satellite data that VLF chorus and other natural emissions can be triggered in the magnetosphere by power line radiation [Bullough et al., 1976; Luette et al., 1977]. On the other hand, the interpretation of the OGO 3 power line data has been questioned [Tsurutani et al., 1979], and it could not be demonstrated that power line radiation was a significant catalytic agent in the generation of VLF hiss or chorus as observed on OGO 5 and 6 [Tsurutani et al., 1979; Thorne and Tsurutani, 1979]. Questions concerning the importance of the role played by power line radiation have also been raised by other workers [Lyons and Williams, 1973].

Thus, although it is clear that power line radiation and associated magnetospheric lines [Helliwell et al., 1975] under the appropriate circumstances can exert considerable influence on a portion of the energetic particle population, there is no general agreement on the relative importance of power line radiation, vis-a-vis the natural VLF wave spectrum, in controlling energetic particle lifetimes over long time periods.

One seemingly straightforward method of resolving this impasse involves the direct measurement by satellite receiver of the amplitude of power line radiation and associated magnetospheric lines in the magnetosphere and the subsequent comparison of these amplitudes with that of natural VLF spectrum. Although these comparative methods tend to overlook the possible catalytic role of power line radiation in producing the 'natural' noise background [Park, 1977], they would serve to define the importance of the 'direct' role of power line radiation in controlling energetic particle dynamics.

Unfortunately, very few satellite observations of either power line or magnetospheric line radi-

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ation have been reported to date [Koons et al., 1978; Bell et al., 1978] in spite of extensive searches of large blocks of satellite VLF data. In view of this situation Tsurutani et al. [1979] have concluded that power line radiation in the magnetosphere is either very rare or generally below detectable levels, and thus the overall power of these waves would be too weak to affect significantly the radiation belt particles in any direct way.

In the present paper we attempt to elucidate further the role of power line radiation in magnetospheric wave-particle interactions by reporting a small set of recent ISEE 1 satellite observations of VLF line radiation. Our study indicates that the amplitude of VLF line radiation in the magnetosphere is generally low in comparison with broadband background noise also present in the data. However, the S/N ratio of these lines may be sufficiently high to allow these lines to act as catalytic agents during wave-particle interactions.

The observations reported here were carried out by the Stanford University VLF Wave-Injection Experiment on ISEE 1, which has been described in recent papers by Bell and Helliwell [1978] and Bell et al. [1981].

The Stanford University Experiment on ISEE 1 is an active experiment designed to study interactions between coherent VLF waves and energetic electrons in the magnetosphere. The main controlled source of coherent waves in this experiment is the Siple Station VLF transmitter, and in general the ISEE 1 receiver frequency range is varied as a function of satellite position to allow wideband reception of the transmitter signals as well as to insure an adequate S/N ratio in the analog telemetry channel [Bell and Helliwell, 1978].

As a consequence of these frequency range requirements, during the first two years after launch the lower cutoff frequency of the satellite receiver was usually set at 4 kHz when the satellite was within L = 4, at 2 kHz when the satellite was between L = 4 and L = 6, and at 1 kHz when the satellite was between L = 6 and L = 8. This arrangement may have tended to create a significant bias against detecting power line or magnetospheric line radiation on magnetic shells less than L = 4 since ground-based data indicates that VLF line radiation activity often occurs at frequencies lower than 4 kHz.

Nevertheless, our data should give a good representation of the type of line radiation activity that can be expected above 2 kHz in the region near the magnetic equatorial plane and on magnetic shells: L = 4-8.

Observations

During the period October 1977 - August 1979, the Stanford University VLF receiver on ISEE 1 acquired data on 90 near-equatorial orbits in which the satellite position varied between L = 2 and L = 8 and the satellite longitude lay in the range 50°W to 110°W.

This region of the magnetosphere encompassed the magnetic field lines linking the Eights, Siple and Roberval stations from which most ground-based data concerning VLF line radiation has been obtained, and one of the main regions in which the occurrence of VLF chorus activity had been linked to power line radiation [Luette et al., 1977]. Consequently, there was reason to expect that line radiation would be present in this region from time to time.

A search for the presence of line radiation was carried out by visual inspection of spectrograms depicting the entirety of the VLF wave data acquired during each of the 90 orbits. Evidence for the presence of line radiation was detected on 5 of the 90 orbits and each of these cases occurred on magnetic shells of L value greater than 4, where the lower cutoff frequency of the receiver was set to either 2 or 1 kHz. In all 5 cases the line radiation occurred below 4 kHz.

In general, the events consisted of the appearance for 2-15 min of three or more low-amplitude narrowband (less than 10 Hz) signals. The center frequencies of the lines were not exact harmonics of 60 (or 50) Hz and the lines tended to drift slowly in frequency. Thus the lines had the characteristics of magnetospheric lines [Helliwell et al., 1975].

In four of the five events the amplitude of the magnetospheric lines was quite low and the lines often disappeared into the background noise for long periods of time (10-30 s). In these cases the low S/N ratio made precise measurement of line amplitude and wave frequency difficult. In one event, however, the S/N ratio of the magnetospheric lines was relatively high, and precise frequency and amplitude measurements could be made. It is this event that is described in detail below.

The event of interest occurred on November 10, 1977, between 1605-1620 UT as the ISEE 1 satellite was moving inward from L = 5.4 to L = 4.8 at an average geomagnetic latitude of 7.5°N. The local electron gyrofrequency during this interval was approximately 6.8 kHz and the satellite longitude was approximately 54°W.

Three spectrograms of a portion of the data acquired during the event are shown in Figure 1. The upper spectrogram displays the entirety of the VLF data acquired in the 2-to-4-kHz channel of the Stanford experiment (HEM) over a time period of approximately 3.5 min. At least 10 separate magnetospheric lines can be seen in this panel, and it is also evident that these lines tend to rise slowly in frequency as time progresses.

Most of the magnetospheric lines were located in the 3-to-4-kHz range, while the signals in the 2-to-3-kHz range consisted mainly of unstructured hisslike noise. In general, the hiss exhibited pronounced amplitude fading with a period of approximately 1.5 s, a value equal to one half of the spin period of the satellite. This type of fading has been seen often in the ISEE 1 data [Bell et al., 1981]. It appears to be due to the rotation of the receiving antenna in the elliptically polarized electric field structure of the VLF waves.

Noticeable fading (~10 dB) also occurred in most of the magnetospheric lines, and this fading exhibited the same period and phase as the fading in the hiss, indicating that the propagation conditions for the lines may have been similar to that of the hiss. The signal dropouts occurring at 1614:10 and 1615:04 were not due to natural fading but were caused by programmed reductions

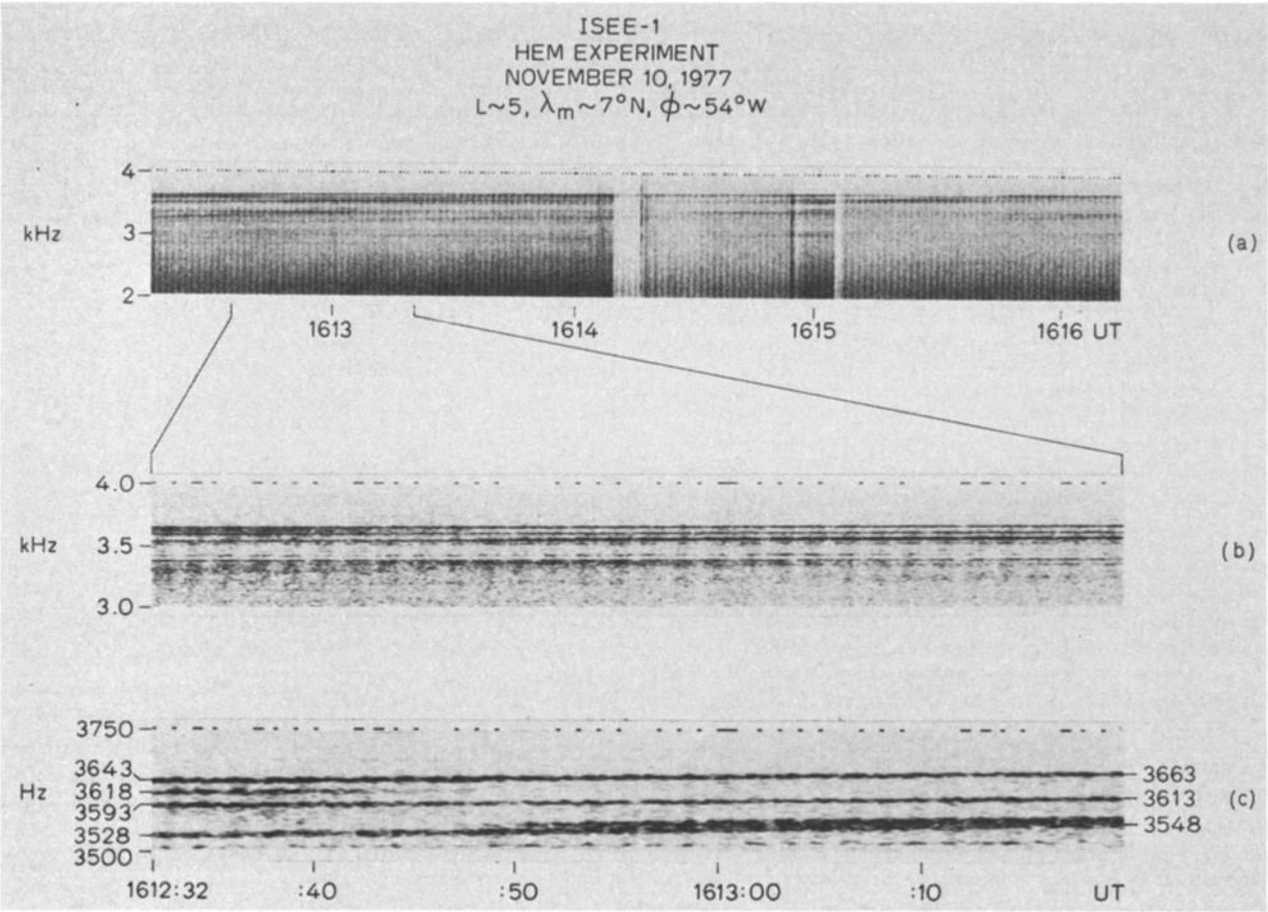

Fig. 1. Spectrograms of a portion of the VLF data acquired on November 10, 1977, as the ISEE 1 satellite was located near L = 5, at a geomagnetic latitude (λ_m) of approximately 7°N and at a geographic longitude (ϕ) of approximately 54°W. (a) Spectrogram showing the entirety of the VLF data acquired in the 2-to-4-kHz channel of the satellite receiver during the period indicated. (b) High resolution spectrogram showing VLF data in the 3-to-4-kHz range for the period 1612:32-1613:17. (c) High resolution spectrogram showing VLF data in the 3.5-to-3.75-kHz range.

in the receiver gain level. Further details of the line radiation can be seen in panel (b) where a portion of the data acquired near 1613 UT is shown with higher frequency and time resolution. Panel (b) contains all of the prominent lines in the spectrum and it can be seen that the highest amplitude lines do not fade out completely to background levels as the receiving antenna rotates in their wave fields. However, a few of the weaker lines do disappear completely into the background noise approximately every 1.5 s.

In general, the frequency spacings of the prominent lines remained constant as the line center frequencies increased with time. However, lines often disappeared into the noise for 30-40 s at a time, and new lines would sometimes appear. The average rate of change of frequency of the prominent lines was approximately 22 Hz/min and the total frequency change of the two most prominent lines (which were visible for approximately 9 min) was approximately 200 Hz. However, a few of the weaker, short-lived lines exhibited rates of change of frequency as low as 6 Hz/min. An example of the rapidity with which the higher amplitude lines could disappear into the background noise can be obtained by following in time the line of second highest frequency (~3618 Hz). This line begins to fade near 1620:40 UT, and within 10 s it has disappeared. It can be seen that the line of fourth highest frequency (slightly above 3.5 kHz) increases in bandwidth near 1612:45 UT. This increase is caused by the appearance of a new magnetospheric line at a slightly higher frequency. These details are brought out more clearly in panel (c), which shows the VLF wave data in the range 3.5-3.75 kHz with a higher frequency resolution.

The spectrogram in panel (c) begins at 1612:32 UT and ends at 1613:17 UT. The frequencies of the major lines (in the range 3500-3750 Hz) are as given on the frequency axis both at the start and end of the period shown. The average bandwidth of the prominent lines was approximately 6 Hz, about 4 times the filter bandwidth (~1.5 Hz) of the spectrum analyzer used to analyze the data and about 13 times the measurement uncertainty of 1/2 Hz. Since the time window of the analyzer was rather long, being approximately 500 ms, some of the apparent bandwidth of the lines could possibly have been produced by tape flutter in the playback tape recorder. According to specifications, tape flutter would have produced a line broadening of at most 2 Hz. Thus the average bandwidth of the lines must have been at least 2 Hz. As a result of the above mentioned factors the frequencies of the prominent lines shown in the figure could be determined only to within ±3 Hz.

Since the center frequency of the prominent lines increased by approximately 200 Hz during the period of observation, each line coincided at least 3 times with the harmonic lines that would be expected for direct power line radiation. Furthermore, the spacing between the three prominent lines at 3643 ± 3 Hz, 3593 ± 3 Hz, and 3528 ± 3 Hz was always close to multiples of 60 Hz. However, the spacing between any two adjacent lines in the spectrum was quite often much less than 60 Hz (or 50 Hz). For example, at 1613:32 UT, adjacent pairs of the prominent lines have the spacing 25 ± 6 Hz, 25 ± 6 Hz and 65 ± 6 Hz.

The spacing between adjacent lines was sometimes altered by the appearance of new lines in the spectrum, some of which lay close to the position of existing lines. For example, at 1612:50 UT a new line appears in the spectrum at 3541 ± 3 Hz, approximately 13 Hz above the line at 3528 ± 3 Hz.

Although the prominent lines appear to be relatively high in amplitude, they are actually quite weak and at the time of observation, the receiver was operating close to its maximum sensitivity. It is only because of the low level of the background noise that the lines appear as prominent features of the spectrum. The average amplitude of the upper three lines shown in Figure 1 was approximately 0.2 μV/m during the time indicated on the figure. This amplitude is approximately 20 dB below the integrated noise levels in the 2-4 kHz band that are usually observed by the Stanford experiment in this region of the magnetosphere.

The magnetospheric line event occurred during a period of moderate magnetic disturbance when the Kp index reached 3. However, the two previous days had been magnetically quiet and were designated 'quiet days,' on which the sum of the Kp indices was 7- and 6 respectively. Similar quiet conditions also existed on November 10 until approximately 1400 UT when, according to College, Alaska, magnetograms, a moderate substorm occurred, enduring until approximately 1800 UT.

As a result of the long period of quiet preceding the event, the outer boundary of the plasmasphere had expanded beyond 7 R_E. This expansion is evident in Figure 2, which shows the cold plasma density as a function of time and satellite position on November 10.

Figure 2 is based on data obtained by the electron density experiment on the spacecraft and was supplied through the courtesy of C. Harvey and J. Etcheto. A description of this experiment can be found in a recent paper [Harvey et al., 1976]. The plot of Figure 2 shows that the decrease of electron density between L ~ 3.5 and L ~ 6 is relatively slow and the the density level at L = 6 is approximately 100 cm^{-3}, a value consistent with those generally found inside the plasmasphere. Furthermore, a sharp transition to a low-density region does not take place until L = 7. Thus it appears that the magnetospheric line event of November 10 occurred well within the plasmasphere in a region of relatively high electron density.

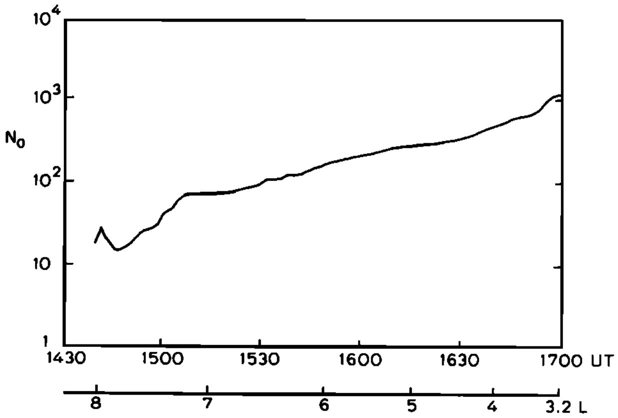

Fig. 2. Cold electron number density near the magnetic equatorial plane on November 10, 1977, as measured by the ISEE 1 electron density experiment (C. Harvey, private communication, 1981).

An important characteristic of the wave data acquired on November 10 was the fact that whistler mode echoing of both natural and man-made signals was very pronounced on magnetic shells below L = 4.5. Evidence of this phenomenon is shown in the lower panel of Figure 3, which consists of a spectrogram of ISEE 1 VLF wave data in the 3-to-8-kHz band acquired on November 10 at 1700 UT. Slightly before the 20 s mark an impulsive whistler trace (O^+ component) can be seen, which is followed by diffuse echoes which arrive approximately 1 s later and which endure for up to 4 s. Similar behavior was exhibited by all whistlers detected on the satellite during the period 1630-1715 UT as the satellite moved from L = 4.4 to L = 2.5 within 9° of the magnetic equator.

During the same interval, signals from the Siple transmitter also exhibited pronounced echoing effects and this behavior is clearly shown in the lower panel of Figure 3. The four continuous horizontal lines in the middle of the spectrogram in the lower panel (which appear to be magnetospheric lines) are actually temporally discrete signals from the Siple transmitter. The format for these signals is shown in the spectrogram of the upper panel which displays data acquired during an earlier orbit through the same region of the magnetosphere.

The discrete nature of the Siple signals is readily apparent in the upper panel, and it is apparent that wave echoing is not significant at this time. In the lower panel, however, it can be seen how the identical discrete signal format has been altered through echoing effects to produce continuous signals at all four transmitter frequencies. It is especially noteworthy that continuous signals have been produced at 4.25 kHz, even though the transmitter duty cycle at these frequencies is only 20%.

Discussion and Conclusion

The satellite-detected VLF line radiation shown in Figure 1 resembles closely the VLF line radiation detected at ground stations and

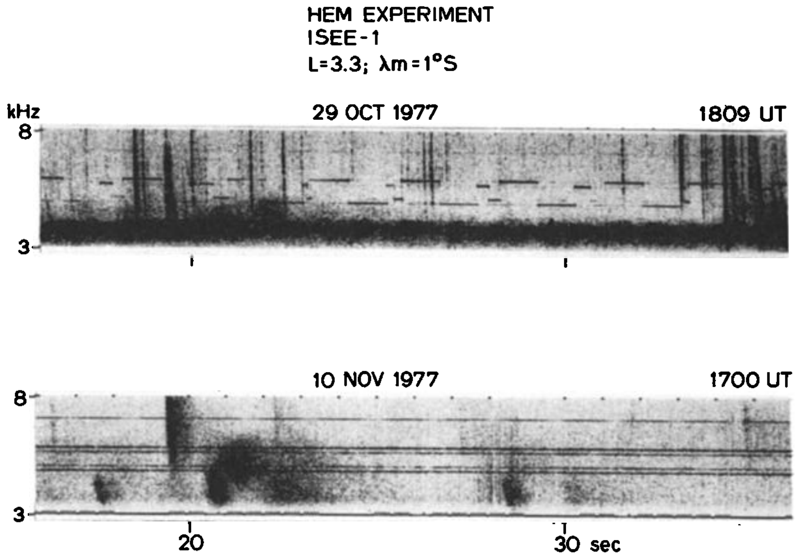

Fig. 3. Spectrograms of Siple Station transmitter signals observed on ISEE 1 on October 29 and November 10, 1977, at approximately the same magnetospheric location. The transmitted signal format is identical in both cases, but on November 10, echoing effects were so pronounced that individual transmitter pulses could not be readily resolved.

characterized as 'magnetospheric lines' [Helliwell et al., 1975]. For instance, the satellite line radiation occurs in the same frequency range as magnetospheric lines (2-5 kHz), exhibits similar drifts in frequency (0-50 Hz/min), and as in the case of magnetospheric lines, does not generally occur precisely at harmonics of 60 Hz (or 50 Hz).

As a result of these many similarities we conclude that the satellite detected line radiation shown in Figure 1 does in fact consist of a set of magnetospheric lines similar to those described in Helliwell et al. [1975].

The total data block in our survey between L = 4 and L = 8 consisted of approximately 100 hours of data, of which a total of 40 min showed the presence of line radiation. Thus the probability of directly detecting line radiation at any given time in this region of the magnetosphere was roughly 1% for the Stanford experiment. This result demonstrates that direct detection of VLF line radiation is improbably, a finding that is in good agreement with previous surveys of high-altitude satellite data, which found little or no direct evidence of the presence of line radiation [Luette et al., 1977; Koons et al., 1978; Tsurutani, 1979].

However, it is important to note that in our study the clearest example of line radiation was obtained when the satellite receiver was operating near its maximum sensitivity level. This circumstance and the general scarcity of satellite observations of line radiation may imply that the sensitivities of contemporary satellite VLF receivers are not sufficiently high to detect the generally low level of line radiation which may exist in the magnetosphere. In this case, routine detection of the radiation would require new experiments and new instrumentation.

One of the most intriguing features of line radiation is the fact that the center frequencies of the lines generally tend to increase with time. Possible explanations of this phenomenon, as observed in ground data, are discussed in Helliwell et al. [1975].

In the November 10 event, the center frequency of the lines of highest amplitude was found to a good approximation to increase linearly with time. For instance, during the period 1607-1615 UT the line of highest frequency in Figure 1 increased linearly in frequency by 5% from 3500 to 3670 Hz.

During the same interval, the local magnitude of the earth's magnetic field B_0, as measured by a magnetometer (C. Russell, Personal Communication, 1981) on the satellite increased by approximately 15% (245 γ to 280 γ). The much more rapid increase of B_0 suggests that the local value of the earth's magnetic field was not a controlling factor in the frequency increase of the line radiation.

It is perhaps worthy of note that the radial position of the satellite decreased linearly by 5% during the 1607-1615 UT interval, and thus to a good approximation the center frequencies of the prominent lines were inversely proportional to the radial position of the satellite. We are aware of no physical mechanism that could produce such a dependence and feel that this apparent correlation is coincidental. We mention it here solely for the sake of completeness.

Ground-based observations [Helliwell et al., 1975] suggest that the development of magnetospheric VLF line radiation depends upon the existence of good conditions for VLF wave echoing. Although wave echoing effects on November 10 were quite pronounced on magnetic shells below L = 4.4, there was no direct evidence of echoing on the magnetic shells where the line radiation was detected. One possible explanation is that the line radiation observed on ISEE 1 was actually a scattered component of line radiation echoing between hemispheres on a magnetic shell of lower L value.

This supposition is supported by two facts. First of all, ray tracing studies in a model magnetosphere (patterned after the density profile of Figure 2) have shown that the echoing of VLF wave energy would not occur beyond $L = 4.8$ for waves of frequency 3.1-3.7 kHz propagating in the nonducted mode. Second, at the beginning of the event of November 10, the local measured value of the electron gyrofrequency was approximately 6800 Hz and for the strongest lines the ratio of wave frequency to gyrofrequency exceeded 0.5. In this case according to theory, local ducting of wave energy could take place only in depletion ducts [Helliwell, 1965].

Although HF experiments have shown the existence of small diameter depletion ducts [Calvert and Warnock, 1969] there is no experimental evidence for the existence of the larger scale depletion ducts that would be necessary to guide VLF waves, or of VLF waves which have propagated in such ducts when the wave frequency exceeds half the gyrofrequency.

Therefore it seems possible that if echoing of the line radiation was taking place, it occurred in the region where echoing effects were prominent and reached the satellite only after scattering from a duct.

One possible model which fits the observations is depicted schematically in Figure 4. In this model, line radiation is assumed to be echoing between hemispheres in a whistler mode duct located near $L \sim 3.5$. It is assumed that ionospheric irregularities exist at the base of the duct in the northern hemisphere and that these irregularities scatter a small portion of the echoing line radiation so that the wave normal direction of the scattered waves differs significantly from the local direction of the earth's magnetic field. If the wave normals of the scattered waves possess a component lying in the direction of increasing latitude, then the scattered radiation can propagate to a higher L shell than that of the duct.

The ray path of the scattered radiation was determined by using the standard ray tracing program and magnetospheric model discussed in Inan and Bell [1977], with the important modification that the cold plasma density distribution was constrained to be identical to that of Figure 2 of the present paper.

In general, it was found that scattered radiation in the frequency range 3-3.7 kHz could reach the satellite position if the wave normal angles of the scattered waves was large enough.

Figure 4 shows the particular case in which line radiation of 3.6-kHz frequency is scattered at the base of the duct at $L \sim 3.5$ so that at 500-km altitude the wave normal angle of the upward propagating scattered component is 48° with respect to the local magnetic field (in the direction of increasing latitude). As the scattered component propagates upward it moves initially toward higher L shells and intersects the satellite track at 7°N latitude with $L \sim 5.2$.

The angle between the wave normal and the local direction of the earth's magnetic field is approximately 39° at the intersection point.

Using known relations for the polarization ellipse of whistler mode waves [Helliwell, 1965], the measured local values of cold plasma density and magnetic field, and the known direction of the satellite spin axis, it can be shown that a

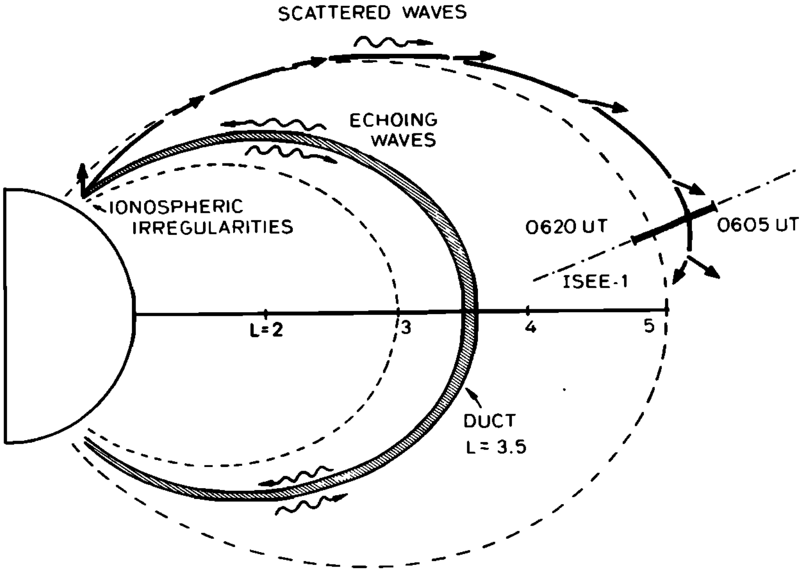

Fig. 4. Model depicting a possible propagation path for the magnetospheric line radiation. The line radiation is assumed to be initially echoing between hemispheres in a whistler mode duct located near $L \sim 3.5$, and ionospheric irregularities are assumed to exist near the base of the duct in the northern hemisphere. A small component of the echoing line radiation is scattered toward higher L shells by the irregularities and propagates upward to the satellite location near $L \sim 5$, $\lambda_m \sim 7°$N. The solid line which originates near the duct base in the northern hemisphere and which intersects the satellite track (dash-dot line) is the calculated raypath for a 3.6 kHz scattered wave component. The wave normal direction is shown by the arrows along the raypath.

wave normal angle of 39° should produce a fading ratio of approximately 7 dB. This value agrees reasonably well with the measured fading ratio of approximately 10 dB.

Thus we conclude that the model of Figure 4 appears to be consistent with our observations.

If the line radiation were in fact echoing in a duct below L = 4.4, it would be expected that this radiation would propagate to the ground near both endpoints of the duct. However, a study of the VLF wave data acquired on November 10 at the conjugate ground stations, Siple (Antarctica) and Roberval (Canada), shows no evidence of magnetospheric lines during the period when the satellite observations were carried out.

This lack of correlation between the ground and satellite observations may result from the fact that the satellite was located more than 15 degrees east of the Siple-Roberval meridian during the period of observation. Consequently, the wave spreading losses in the earth-ionospheric waveguide may have been sufficient to reduce the S/N ratio of the line radiation below detectable levels at the two ground stations.

On the basis of our ISEE 1 data it can be concluded that, in general, very little of the background VLF wave energy in the outer magnetosphere (L = 4-8) is contained directly in VLF line radiation. However, this circumstance does not necessarily imply that line radiation plays an insignificant role in VLF wave-particle interactions in this region since there is strong evidence that line radiation can act as a catalytic controlling agent in those interactions [Helliwell et al., 1975; Park, 1977; Park and Helliwell, 1977]. The assessment of the importance of the catalytic role of VLF line radiation in controlling VLF wave-particle interactions in the magnetosphere will be an important goal of future experiments.

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