VOL. 83, NO. A1 JOURNAL OF GEOPHYSICAL RESEARCH JANUARY 1, 1978

WHISTLERS AND VLF NOISES PROPAGATING JUST OUTSIDE THE PLASMAPAUSE

D. L. Carpenter

Radioscience Laboratory, Stanford University, Stanford, California 94305

Abstract. Ground-based recordings of broadband whistler mode signals propagating along the outer 'surface' of the plasmasphere, just beyond the region of steep plasmapause density gradients, exhibit a number of features that have not been observed in other field line regions. The features include extension of signal frequencies into the range ≈0.5–0.8 f_{Heq}, where f_{Heq} is the equatorial electron gyrofrequency of the path, and echoing or repeated propagation over the path at frequencies above 0.5 f_{Heq}. The effects are frequently exhibited by the 'knee trace,' the whistler component propagating just beyond the plasmapause in the low-density or plasma trough region. The unusual features include VLF noise bands and bursts that are frequently triggered or 'activated' by knee whistler traces or echoes of knee traces. The noise bands and bursts tend to occur within the frequency range 0.4-0.8 f_{Heq} and near the frequency of an amplitude peak in knee whistler trace activity. The wave activity is documented in VLF data from Eights, Antarctica ($L \approx 4$), for 1963 and 1965 and from Siple, Antarctica ($L \approx 4.2$), for 1973 through 1975. Certain features of the whistler and noise activity and of equatorial electron densities deduced from whistlers support earlier findings that the plasmapause equatorial radius may on occasion be irregular, varying by up to 1 R_E within the longitudinal viewing range (≈30°) of a whistler receiver. Propagation effects such as guidance along the outer plasmapause surface and coupling of wave energy into and out of the ionosphere are not yet well understood. The VLF noise effects are of a kind recently found to be associated with detectable bursts of electron precipitation into the nighttime lower ionosphere. Because of the special propagation and warm plasma effects associated with the plasmapause, that region appears to offer advantages for experiments on magnetospheric wave injection both from the ground and from satellites.

Introduction

The VLF whistler technique has been used to study the plasmapause-plasmasphere system in terms of plasma density profiles and plasma motions [see Carpenter and Park, 1973]. However, relatively little attention has been paid to the subject of whistler mode wave phenomena in the region of steep plasmapause density gradients. These wave phenomena differ in a number of ways from effects observed both within and well beyond the plasmapause. They are of interest as propagation effects and also because of their possible role in plasmapause-associated wave-particle interactions [see Thorne, 1975]. An additional impetus to such study comes from the recent implementation of VLF transmitting experiments [e.g., Helliwell and Katsufrakis, 1974; McPherson et al., 1974]. It is important to describe the regimes of natural wave activity under which these controlled experiments take place. The natural activity tends to complicate the transmitting experiments but may also serve as a guide to new experimental opportunities.

Although a relatively large body of data on plasmapause-associated VLF activity has been accumulated, these data have been mentioned only briefly in the literature [e.g., Carpenter, 1968a]. It is the purpose of this paper to describe a number of features of this activity and thus provide a basis for further experimental and theoretical work. A brief review of whistler diagnostics of the plasmapause is presented first.

Figure 1 shows a simplified equatorial profile of magnetospheric electron density. Features of the profile that are associated with whistler mode propagation between hemispheres to ground stations are numbered 1, 2, 3, and 4. These features are located as follows.

1. Within the plasmasphere the propagation involves guiding within 'ducts' or field-aligned enhancements of ionization [e.g., Smith, 1961; Helliwell, 1965; Angerami, 1970]. The enhancements are believed to be of the order of 10% over the nearby background levels. There are as yet relatively few in situ measurements relating ducted whistler mode activity to density profiles across ducts, although promising starts in this direction have been made by Scarf and Chappell [1973] and by Cerisier [1974].

2. In the region of steep plasmapause density gradients propagation typically occurs at density levels that are a factor of 2-5 below an extrapolation of the nearby plasmasphere profile. The propagation is tentatively assumed to occur within field-aligned density enhancements, since the whistlers frequently exhibit the type of abrupt upper intensity cutoff that is found on whistlers propagating within the plasmasphere [Carpenter, 1968b]. (The cutoff is believed to be due to a frequency limit on the guiding properties of field-aligned enhancements of ionization [e.g., Smith, 1961].) In a ground-satellite study, Inan et al. [1977] show evidence of both ducted and nonducted propagation within a density enhancement at the plasmapause.

3. Immediately beyond the plasmapause propagation occurs at a density level characteristic of the plasma trough. The waves are assumed to be guided by some type of field-aligned structure, since, as reported below, they exhibit features such as repeated echoing back and forth between conjugate hemispheres. The form of structure is not known, but it may involve a localized depression of the kind indicated in Figure 1. Theory has shown that trapping and guiding may occur in density depressions under certain conditions, such as at frequencies above half the local electron gyrofrequency [e.g., Smith, 1961; Helliwell, 1965].

Paper number 7A0764.
0148-0227/78/027A-0764$03.00

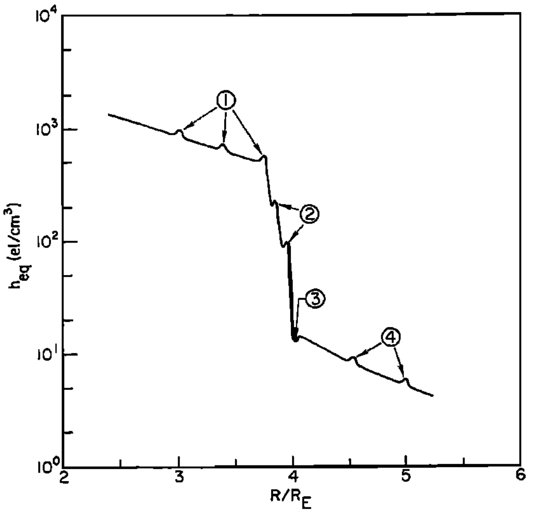

Fig. 1. Magnetospheric equatorial profile of electron concentration n_{eq} versus geocentric equatorial distance in earth radii. Numbers identify density irregularities within four propagation 'regions' that are variously situated with respect to the plasmapause.

4. Beyond the plasmapause, upper intensity cutoffs similar to those seen in the plasmasphere are frequently observed [Carpenter, 1968b]; hence the propagation is tentatively assumed to occur within density enhancements.

Figure 2a shows in meridional cross section the four regions of the equatorial magnetosphere that correspond to the density profile features indicated in Figure 1. The corresponding four categories of whistler components are shown schematically in the frequency-time diagram of Figure 2b. One advantage of the whistler method is that several members of a category, and frequently more than one category, may be excited by a single lightning flash.

Figure 3a shows in equatorial cross section the propagation regimes indicated in Figure 2a. The dashed enclosure represents an estimate of the equatorial viewing area of a ground whistler station in the Eights-Siple area of Antarctica; within this area are shown equatorial cross-sections of whistler ducts which may be active at a given time. In Figure 3a the plasmapause radius is approximately constant with longitude, and in the absence of steep longitudinal density gradients, information from the multiple whistler paths may be used to estimate a radial profile that is representative of the entire viewing area.

Figure 3b shows a situation in which the plasmapause radius varies by ΔR within the station's viewing range. This condition is of particular interest; it reflects the sensitivity of plasmapause topology to magnetospheric electric fields and the tendency of the plasmasphere to retain the imprint of convection activity after that activity terminates [e.g., Carpenter and Park, 1973; Chappell, 1972; Chen and Grebowsky, 1978; Ho and Carpenter, 1976]. Such 'tilts' of the plasmapause may also be indicative of the localized nature of some convection events. Irregularities in plasmapause radius present the possibility of plasmasphere penetration by drifting energetic particles, which may then lead to localized turbulence and precipitation [e.g., Thorne, 1975].

Under the conditions of Figure 3b, propagation at multiple points in regions 2 and 3 will give rise to whistler components with a range of nose frequencies (frequencies of minimum travel time). This effect may possibly be used to detect the presence and approximate scale (ΔR) of the variations in plasmapause radius.

The whistler component propagating in regime 3 of Figures 1-3 is often called a 'knee trace' or part of a 'knee whistler,' because of earlier references to the plasmapause density profile as a 'knee' [e.g., Carpenter, 1963]. Satellite data confirming the relation of this trace to the plasmapause are rare, probably due in part to the factors limiting the observation of such traces on the ground. Figure 4 shows such a case; it contains three samples of Alouette 1 VLF receptions at 1000 km telemetered to Byrd, Antarctica, on August 12, 1965. The satellite records (0-10 kHz versus time) are displayed above the data recorded simultaneously on the ground at Byrd (80°S, 120°W, L≈7). Universal time is indicated below each pair of panels; invariant latitude at the satellite (at roughly the middle of each record) is shown above. The period was one of low but relatively steady magnetic activity, with Kp in the range 1-2. The observations were near 0530 MLT at the Byrd meridian; the satellite, moving poleward with time, crossed the plasmapause at about Λ = 59.7° and about 20° east of Byrd's magnetic meridian. This crossing was reported in an earlier comparison of satellite and ground VLF measurements of the plasmapause [Carpenter et al., 1968].

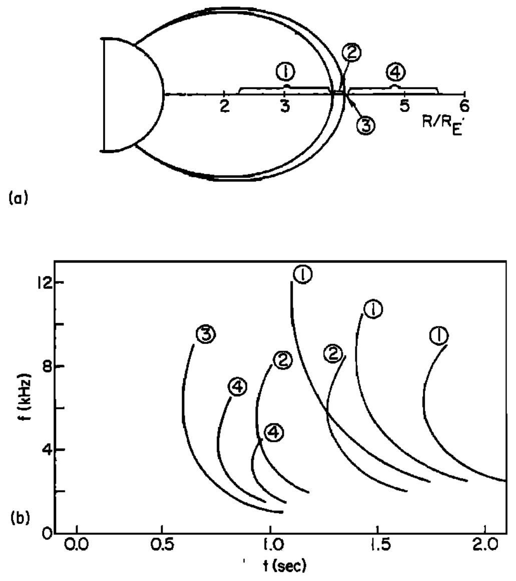

Fig. 2. (a) Meridional cross section of the magnetosphere showing the equatorial radii of whistler paths associated with the four propagation regions indicated in Figure 1. Region 2 is intended to show the region of steep plasmapause density gradients. (b) Sketch of whistler spectra corresponding to propagation in the four regions indicated in Figures 1 and 2a. Trace 3 is the so-called 'knee trace.'

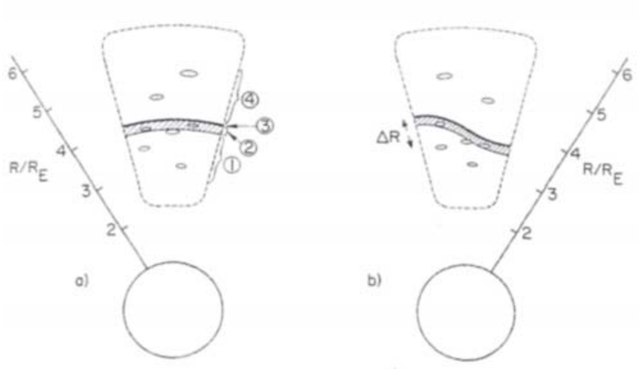

Fig. 3. (a) Equatorial cross section of the magnetosphere showing (dashed enclosure) the estimated viewing area in the magnetospheric equatorial plane of a ground whistler station such as Siple, Antarctica. The equatorial crossings of whistler paths active at a given time are indicated by ellipses. The four propagation regions identified in Figures 1 and 2 are indicated. (b) Modification of Figure 3a to include an irregular plasmasphere surface, such that the plasmapause radius varies by ΔR within the longitudinal viewing range of the whistler station (see text for details).

Figures 4a and 4b show multicomponent whistlers received as the satellite moved poleward within the plasmasphere. The initial components of the two ground events are knee traces. They are relatively intense and diffuse; furthermore, there is a flattening effect near the nose such that travel time is roughly constant with frequency over several kHz. In both cases, particularly Figure 4a, the satellite shows evidence of the traces propagating within the plasmasphere. These waves probably reached the satellite by upward propagation following reflection of ducted wave energy in the lower ionosphere, in the manner discussed by Thomson and Dowden [1977]. There is no evidence of the knee trace on the Alouette records.

The Alouette data of Figure 4c, received ≈1.5° beyond the plasmapause, include a series of wideband, burstlike events. The lower-hybrid resonance (LHR) frequency is intensified near 2.7 kHz following the bursts, in a manner characteristic of triggering by whistlers [Brice and Smith, 1965], but there is little evidence of whistler mode dispersion. However, the satellite events appear to involve knee traces; they coincide with knee traces observed on the ground. The latter precede the satellite bursts by 30-50 ms, probably due to satellite reception of the wave energy fol-

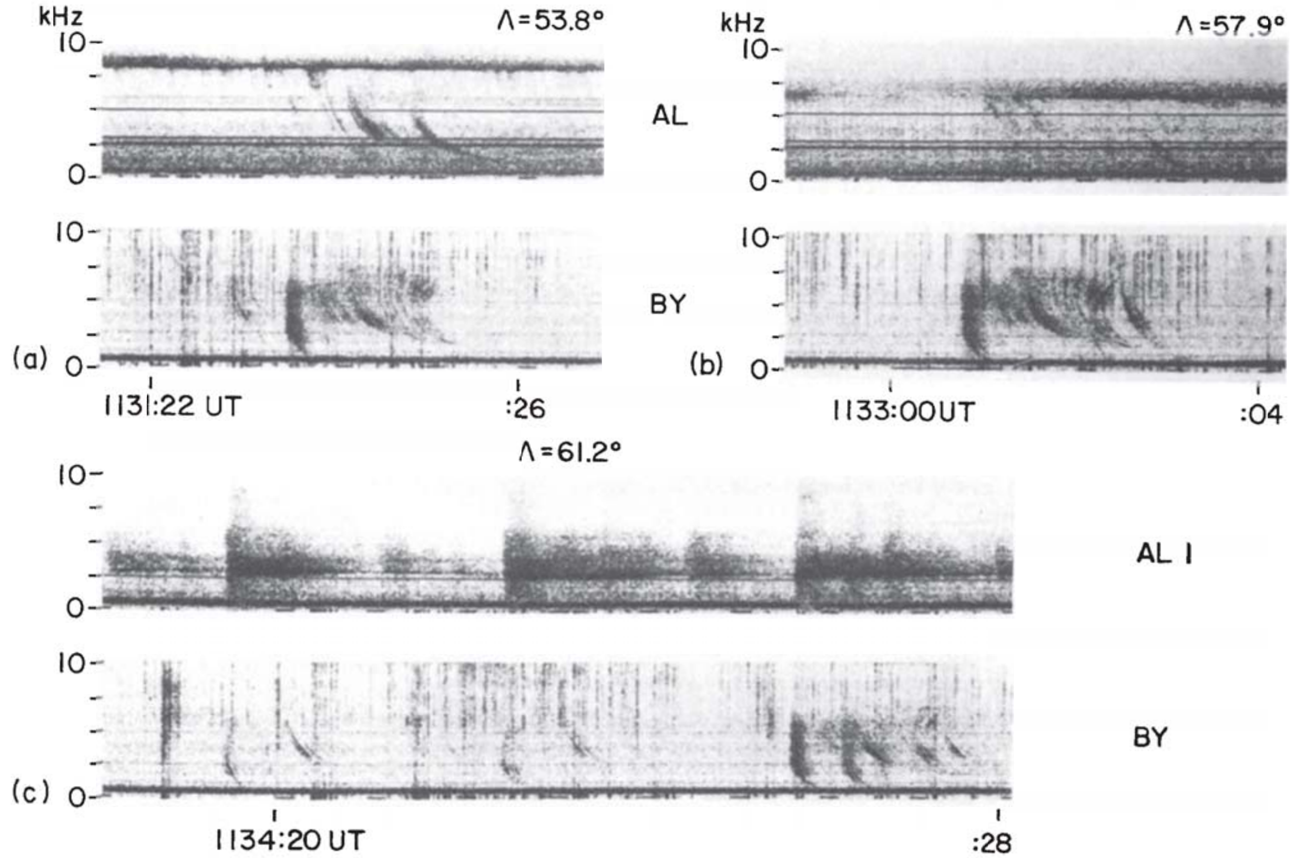

Fig. 4. Simultaneous Alouette 1 satellite and ground VLF spectra (0-10 kHz versus time) confirming the propagation of knee traces just outside the plasmapause. The ground recordings and telemetry station for Alouette were at Byrd, Antarctica (80°S, 120°W, L ≈ 7). Figures 4a and 4b represent satellite positions within the plasmasphere, while Figure 4c represents a position ≈1.5 invariant latitude poleward of the plasmapause. The horizontal lines on the satellite records near 2.5 and 5.0 kHz are of instrumental origin.

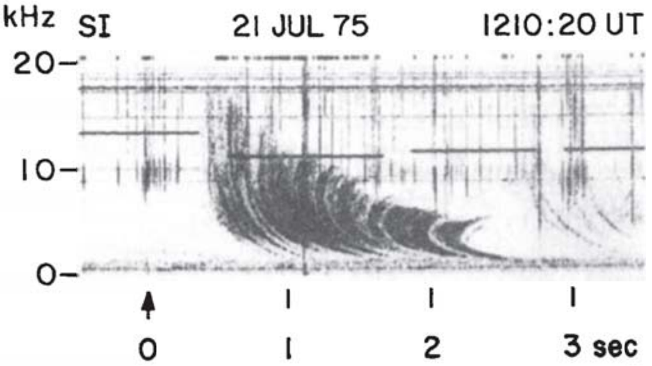

Fig. 5. Spectrogram illustrating the upper intensity cutoff effect in a multicomponent whistler propagating on paths within the plasmasphere. The event was recorded at Siple, Antarctica, on July 21, 1975. The equatorial radii of the observed paths ranged from ≈3 to ≈4.7 R_E.

lowing ionospheric reflection, in the manner noted above.

Features of VLF Propagation at the Plasmapause

Some special features of whistler propagation and associated noise phenomena in region 3 are described below. These subjects have been mentioned briefly in previous reports [e.g., Carpenter, 1968a], but few details have been given.

Propagation at Frequencies Between $0.5\ f_{Heq}$ and f_{Heq}

A characteristic feature of whistlers propagating in the plasmasphere is an abrupt ($\Delta f \approx 50$ Hz) intensity decrease and/or cutoff at approximately one-half the equatorial electron gyrofrequency f_{Heq} [Carpenter, 1968b]. This cutoff occurs at $f \approx 1.3\ f_n$, where f_n is the nose frequency; the multicomponent whistler spectra of Figure 5 show the effect on paths extending from <3 to ≈4.7 R_E geocentric equatorial distance. In our research a similar cutoff has been found on many whistlers propagating in region 4 of the plasma trough; Angerami and Carpenter [1966] showed spectrograms that illustrate the effect. Both within and beyond the plasmasphere there is a variety of other cutoff effects, but in general these involve the range $f < 0.5\ f_{Heq}$.

The upper intensity falloff of the knee trace is usually less abrupt than that found in the plasmasphere, and the upper limit of detection of the trace (or its emissionlike extension) may range both above and below $f_{Heq}/2$. Examples of extension to ≈0.8 f_{Heq} or to ≈2 f_n are illustrated in Figure 6, which shows knee whistlers recorded 1 hour apart on June 9, 1965, at Eights, Antarctica. Examples of cutoffs at ≈6-7 kHz, near the trace nose frequencies, are shown in the spectra of Figure 7. Three knee whistlers recorded within a period of 8 min at Byrd, Antarctica ($L \approx 7$), on July 12, 1967, are aligned with respect to their times of origin. The nose frequencies are near 5-6 kHz at travel times between 0.5 and 0.7 s.

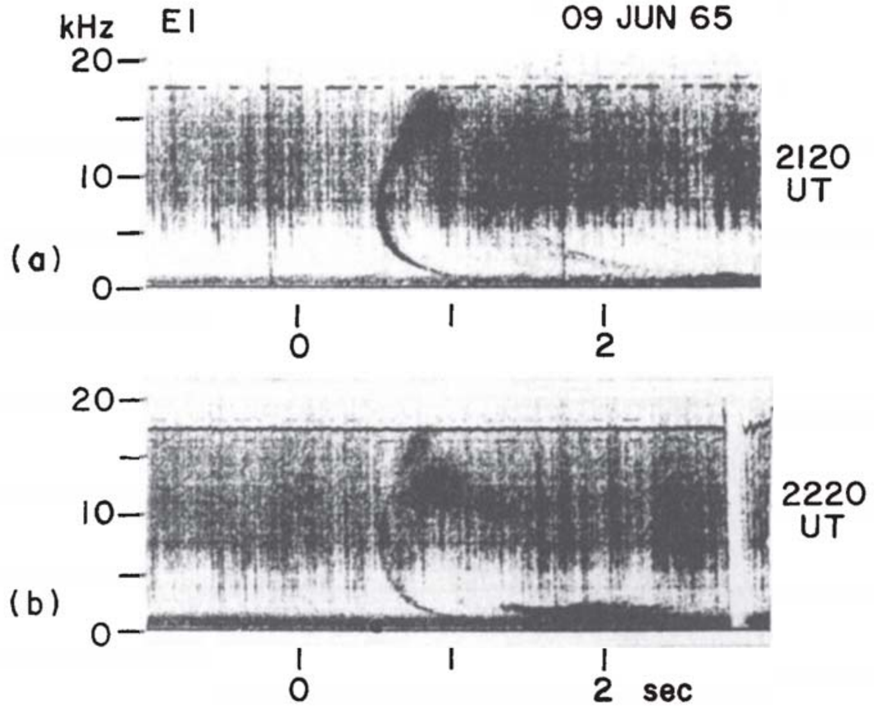

Fig. 6. Spectrograms of knee whistlers recorded on June 9, 1965, at Eights, Antarctica, during synoptic intervals separated by 1 hour. In both cases the whistler energy extends to approximately twice the nose frequency, well above the cutoff level shown in Figure 5.

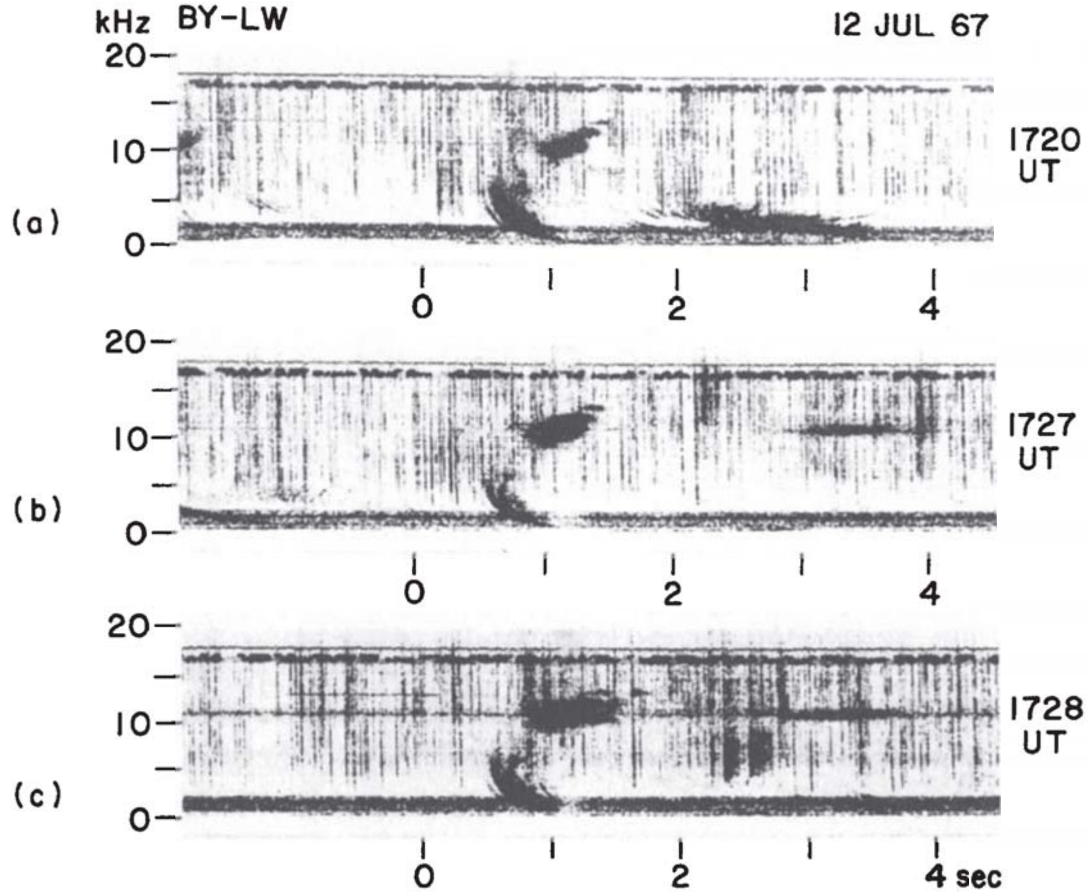

Fig. 7. Spectrograms of three knee whistlers recorded within an 8-min period at Byrd, Antarctica (long-wire antenna), on July 12, 1967. The spectra are aligned with respect to the time of occurrence of the causative atmospheric. Each event shows a group of knee traces with travel times at the whistler nose between ≈0.5 and 0.7 s and with a high-frequency continuation near 10-11 kHz. Echoing of the activity at 10-11 kHz is shown in Figures 7b and 7c.

Fine Structure of the Knee Trace and Associated Plasmapause Irregularities

Knee traces vary widely in appearance. At times they are diffuse, resembling relatively wideband noise bursts. Examples of this kind, in which travel time appears to be relatively constant with frequency over several kHz, are shown on the ground (BY) records of Figures 4a and 4b.

The knee trace frequently exhibits a relatively well defined leading edge, particularly below the nose frequency (as shown in Figure 6). The main body of the trace may contain poorly defined elementary traces. At times there may be closely spaced but apparently distinct knee traces, as illustrated by Figures 7b and 7c. Closer inspection of these traces and others recorded within 1 hour on the same date reveals a range of nose frequencies from ≈4 to 7 kHz.

When the plasmapause radius is roughly constant with longitude, as in Figure 3a, the diffuseness of the knee trace may be due to propagation in regions of slightly different density distributed along the plasmapause surface. When the fine structure of the knee trace or traces exhibits a range of nose frequencies, as in Figure 7, it is inferred that propagation occurs along a plasmapause 'surface' tilted across equi-B contours, as in Figure 3b. This interpretation is reinforced by the electron density 'profile' scaled from the whistler of Figure 7a and from several additional records recorded within several minutes of those illustrated. In Figure 7a the traces from region 1 (plasmasphere) appear at the right between $t = 2$ and $t = 4$ sec and at nose frequencies between 2 and 4 kHz. The corresponding equatorial electron density plot (Figure 8) shows that plasmasphere-level densities, near 200 el/cm^{-3}, extended to 5 R_E while plasma trough levels near 10 el/cm^{-3} were also present within a distance of less than 4 R_E.

Amplitude Peaks and Emissionlike Behavior Above the Nose Frequency

The upper part of the knee trace may be exceptionally intense and emissionlike. The lower part of the trace or a part near the nose frequency may be undetected. Figure 6 shows examples of diffuse noiselike behavior above 10 kHz. In the cases of Figure 7 the trace disappears in a range above the nose, while above this range there are intense

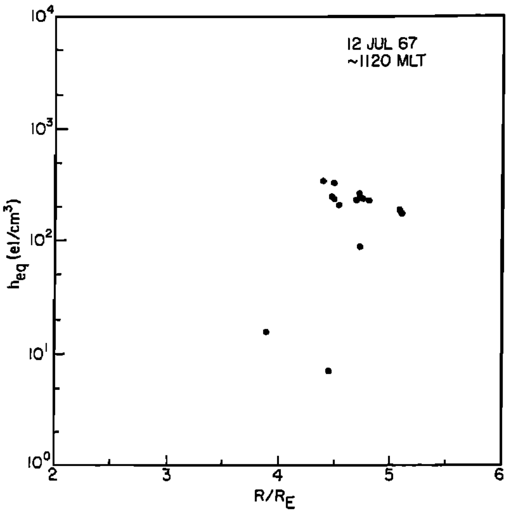

Fig. 8. Equatorial electron density data deduced from the whistler of Figure 7a. The profile shows evidence of an irregular plasmapause surface of the kind indicated schematically in Figure 3; plasmasphere-level densities extend to 5 R_E, while trough-level densities occur at less than 4 R_E geocentric distance.

noiselike forms. The noise forms frequently follow the expected dispersion curve of the associated whistler (as in Figure 7), but there are many variations. An example of this is the diffuse burst at about 12-13 kHz trailing the knee trace shown in Figure 6b.

Whistler Mode Echoing Above 0.5 f_{Heq}

Within regions 1, 2, and 4 of Figure 2a, observations of whistler mode echoing back and forth along field-aligned paths are confined to frequencies below 0.5 f_{Heq}. In region 3, however, echoing above 0.5 f_{Heq} is frequently observed; often this is the only range in which echoing occurs on such paths. The spectra of Figure 9 illustrate such an effect. At lower left (Figure 9c) is a knee whistler recorded at 1242 UT on July 24, 1963, at Eights, Antarctica. The knee trace, with nose frequency near 13 kHz and travel time near 0.3 s, is well defined below the nose. Immediately above this record (Figure 9b) is an event recorded about 3 hours earlier on the same day. In this case the knee trace is defined only over short ranges near 5 kHz and near 20 kHz. The portion of the trace at 20 kHz is followed by a series of echoes with separation of ≈0.75 s, or twice the apparent one-hop propagation delay of the knee trace at 20 kHz.

Narrowband Noises and Noise Bursts Propagating Along the Plasmapause Outer Surface

Noise bands and bursts at frequencies near an amplitude peak of a knee trace frequently share the knee trace path. The observed noises are typically within the ranges 4-20 kHz in frequency and 0.4-0.8 f_{Heq}. The collocation of whistler and noise propagation paths is often evidenced by enhancement or triggering of noises by individual knee whistler traces or their echoes. The noise bands and bursts usually involve much more wave energy than that present in individual whistler traces and are thus of particular interest in studies of wave-particle interactions and associated particle precipitation.

A close relationship between noise activity and a knee whistler trace is illustrated in Figures 9a and 9b, which represent recordings separated by ≈1 min. In Figure 9a a narrow noise band at ≈20 kHz appears at the left and increases in intensity with time. Its center frequency is approximately that of the whistler echoes in Figure 9b. Near $t = 4$ s the intensity of the band increases sharply, and rising tones appear. The noise then fades and disappears.

Figure 9d shows a knee whistler recorded on July 30, 1963. Several plasmasphere traces are well defined at 1.0-1.3 s, and the only evidence of the knee trace is a rising component extending from 14 to 19 kHz near $t = 0.7$ s. Other records show this component to be enhanced at about 15 kHz, which is the frequency of a faint noise band. The rising tones near 18 kHz at $t = 2$ s are believed to be associated with region 3 propagation, although the connection is not clear in this case.

Noise bands and their relations to the knee trace are further illustrated in Figure 7b, which shows near $t = 3.2$ s a whistler mode echo of an earlier noise form. The echo is relatively narrow in bandwidth in comparison with the initial noise near $t = 1$ s. The bottom panel shows a similar event 1 min later. The noise and 3rd-hop echo are in this case connected by a faint noise band.

The complexity and prolonged nature of noise band activity are illustrated in Figure 10, which shows data recorded at Eights, Antarctica, on July 6, 1965, following the onset of a weak magnetic storm. The spectrograms represent compressed 1-min samples of VLF activity recorded at 15-min intervals over roughly a 3-hour period from 1450 to 1736 UT. Below the broadband records is part of a continuous chart recording of wave field strength in microvolts per meter in the band 7-12 kHz. Data from 1400 to 1600 UT are shown. The five times at which synoptic recordings are available on the panels above are noted by arrows above the chart. The corresponding panels are marked by asterisks.

Banded noise activity is present during most of the approximately 3-hour period represented by the VLF spectra. The frequency, intensity, and bandwidth of the bands vary with time; occasionally there are two bands. On the 1720 record a new band develops as an existing one continues. Near 1520 and 1535 UT there appear to be quasi-periodic increases in band center frequency with time; the oscillations on the chart below suggest that new bands appeared at intervals of about 1-2 min at this time.

As in the case of multiple knee whistler traces, the noise features such as multiple bands may have been the result of irregularity in plasmapause radius. Propagation of the noises at the plasmapause is indicated by information (from records not shown) on approximate plasmapause radius (≈3.5 R_E), the high normalized frequencies of the bands, $0.5\ f_{Heq} < f_{noise} < 0.8\ f_{Heq}$ (assuming plasmapause propagation), and occasional interaction of knee traces with the bands. The 1520 record shows in its upper right half an example

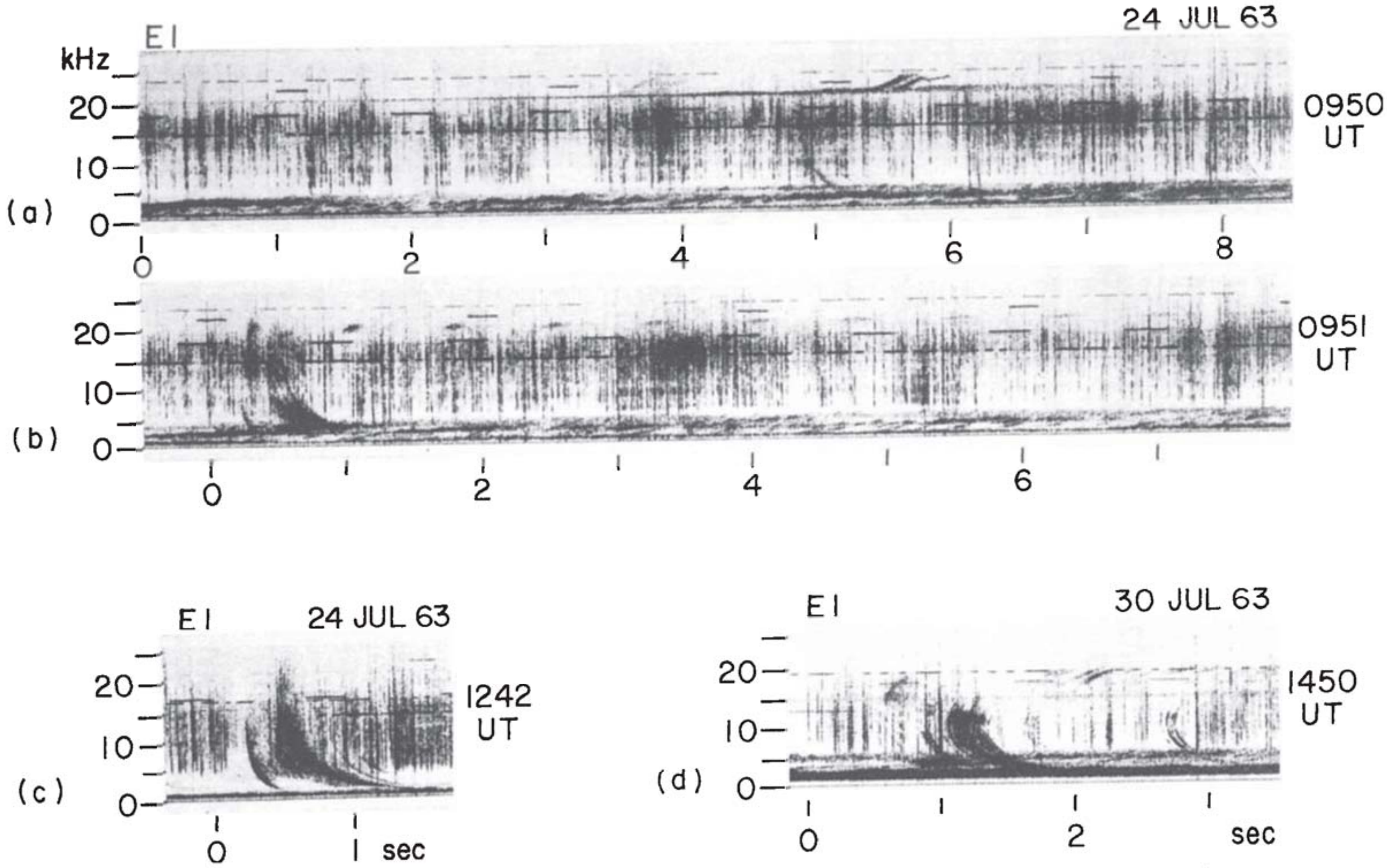

Fig. 9. Spectrograms of knee whistlers and associated noise activity recorded at Eights, Antarctica: (a) narrowband noise near 20 kHz, (b) knee whistler recorded within 1 min of the activity in Figure 9a, (c) well-defined knee whistler recorded within 3 hours of the activity in Figures 9a and 9b, and (d) knee whistler and associated noise band recorded on July 30, 1963.

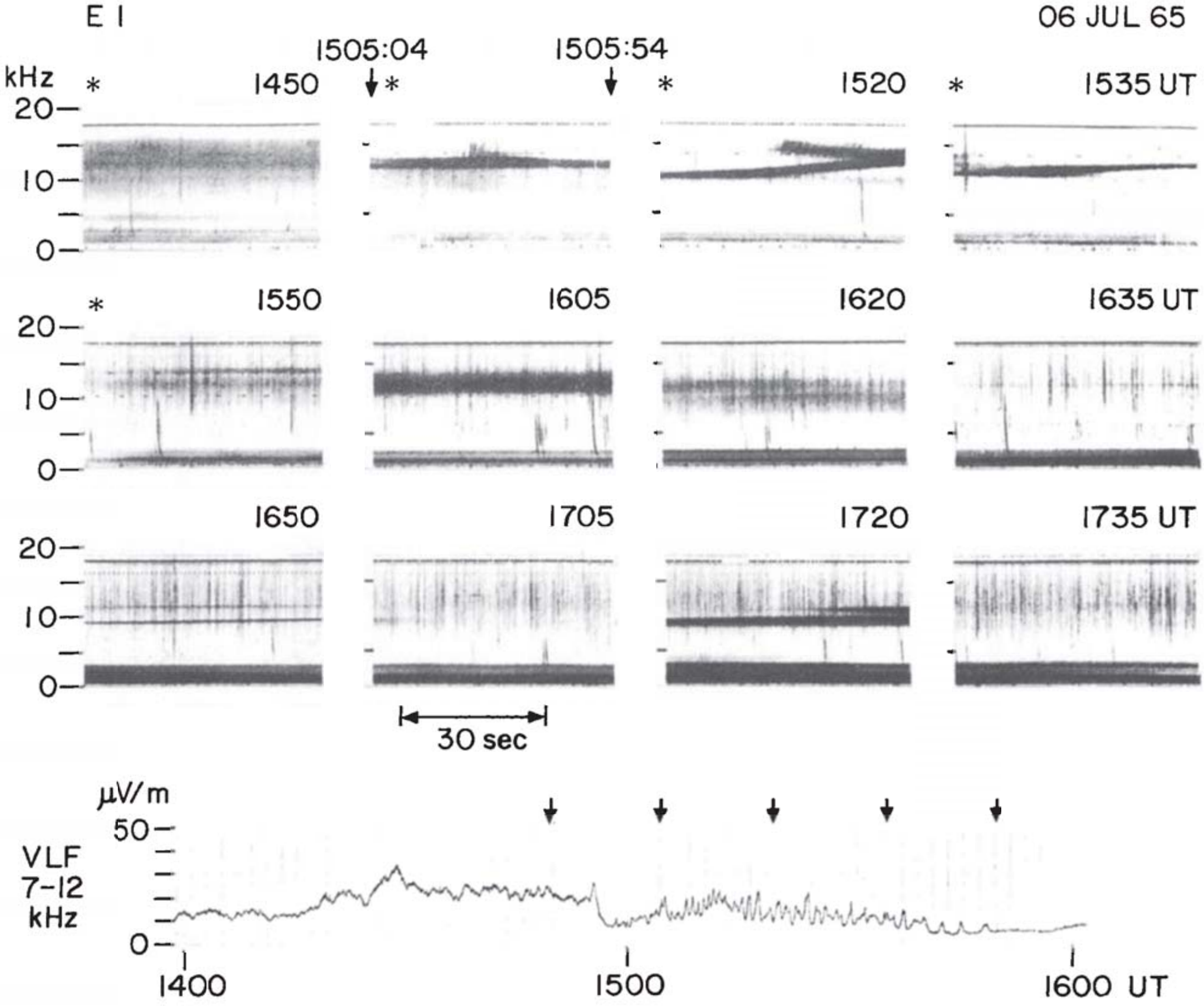

Fig. 10. Illustration of VLF noise bands propagating along the outer plasmasphere surface. The spectrograms represent synoptic recordings for 1 min every 15 min during an approximately 3-hour period on July 6, 1965. Details of the scheduling of the synoptic intervals are indicated above the record for 1505 UT. Below is a continuous chart record showing field strength in microvolts per meter in the 7- to 12-kHz band during the 2-hour period 1400-1600 UT. Arrows above the chart indicate times at which 1-min samples of the broadband spectrum are available.

of whistler mode echoing near 15 kHz. The echo train was apparently initiated by a knee trace in the manner of Figure 7c; roughly 20 echoes appear against a diffuse bandlike background.

Plasmapause-associated noise bursts, either isolated in time or observed as sudden enhancements of noise band activity, are of special interest because of their probable association with detectable particle precipitation into the ionosphere. Ionospheric effects of electron precipitation have already been detected in connection with whistlers propagating in the outer plasmasphere [Helliwell et al., 1973] and with chorus emissions triggered by whistlers outside the plasmapause [Rosenberg et al., 1971]. The special significance of the plasmapause-associated noise bursts lies in their duration of the order of 10 s and their separation from one another in time by from 1 to several minutes. The long duration provides for increased energy deposition in the lower ionosphere and thus for increased probability of detection by ground-based probing techniques. The temporal separation further favors the detection process; it exceeds the ≈30 s required for recovery of the perturbed ionosphere following a density perturbation at ≈90-km altitude [Helliwell et al., 1973].

Noise burst activity that has been clearly linked to precipitation events occurred on September 11, 1973. The evidence of precipitation, in the form of perturbations of the amplitude of subionospherically propagating VLF signals, is discussed elsewhere [Dingle and Carpenter, 1976]; here attention is restricted to the VLF spectra. The activity occurred during a several-hour period of deep quieting (Kp ≈ 1) following 2 days of moderately severe magnetic disturbance. Figure 11 shows representative spectra of the noise

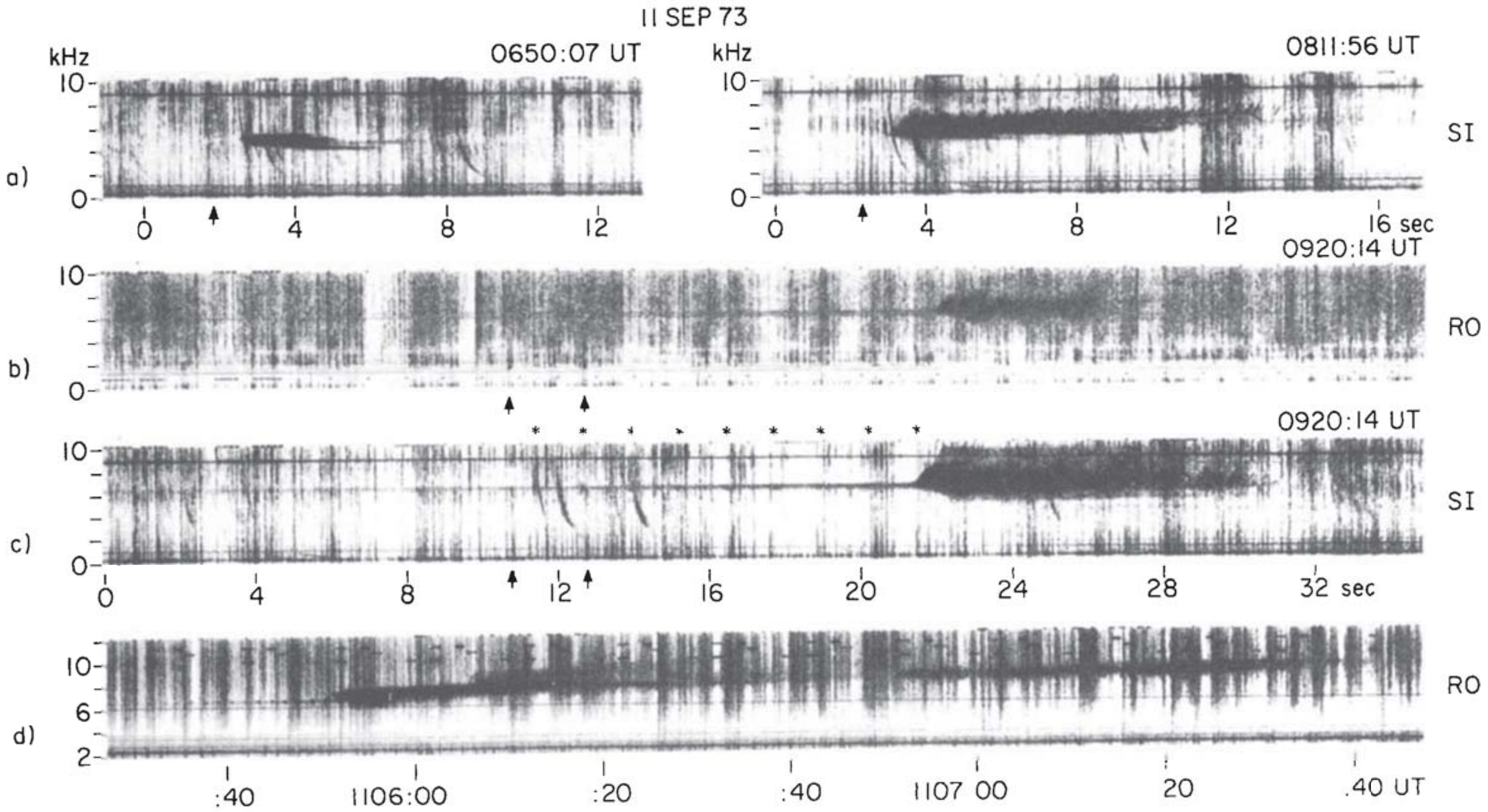

Fig. 11. Spectrographic records from September 11, 1973, showing noise burst activity known to be associated with precipitation of energetic electrons into the ionosphere. Figure 11a shows two examples of recordings at Siple, Antarctica, of noise bursts triggered by whistlers. Figures 11b and 11c show simultanoues recordings at Roberval and Siple, respectively, of noise burst activity near 0920 UT. Figure 11d shows a noise burst event recorded at Roberval near 1106 UT. The time scale is compressed in comparison with that of the panels above by a factor of 4.

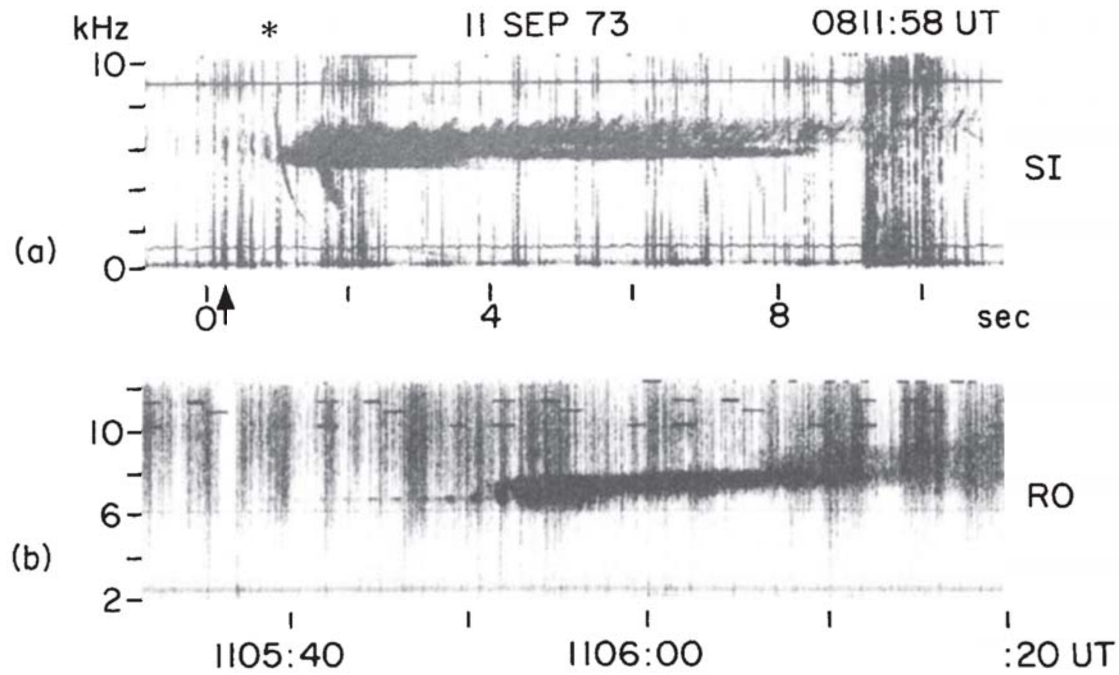

Fig. 12. (a) Enlarged spectrogram of the whistler-triggered noise burst at ≈0812 UT shown in Figure 11a. An asterisk marks the occurrence at 6 kHz of a segment of the triggering knee trace. (b) Enlarged spectrogram of the initial part of the noise event shown in Figure 11d.

activity observed during the period 0650-1105 UT (≈0150-0605 MLT). Throughout this period whistlers propagating within the plasmasphere (region 1) were observed at Siple several times per minute. Of these, 1-10% also contained traces propagating outside the boundary (in region 3), thus delimiting the plasmapause position. The noise bands or bursts occurred at intervals of several minutes to tens of minutes and appeared to be either triggered directly by knee whistler traces or 'activated' by a series of echoes of a knee trace.

Figure 11a shows noise bursts observed at Siple at 0650 and 0812 UT. The time origins of the whistlers that appear to have triggered the bursts are indicated by arrows below the records (an expanded view of the event at 0812 UT is shown in Figure 12a). The whistlers exhibit two main components propagating within the plasmasphere. The noise onsets precede these traces; this is characteristic of triggering by a knee trace. The knee trace at 0650 UT is not observed; at 0812 UT it appears as a blob of noise at 6 kHz (under the asterisk in Figure 12a) and is otherwise too faint for identification in the illustrations.

Figures 11b and 11c show simultaneous Roberval and Siple recordings of a noise event at approximately 0920 UT. On both records a flaring increase in noise intensity and bandwidth occurs at t ≈ 22 s. On the Siple record (Figure 11c) a faint narrowband noise is present at the left. At t ≈ 12 s the first of two whistlers is observed. The knee trace (first asterisk above Figure 11c) again appears as a noise blob near 6 kHz, but in this case there is echoing of the trace (further asterisks) in the manner of Figure 9b. On expanded versions of the record (not shown) the echoes appear as slight intensifications and broadenings of the band. The overall band intensity appears to increase with time, and the final flaring increase occurs near the time of an expected echo.

The noise event is similar on the Roberval record (Figure 11b), although it appears against an intense background of atmospherics. The flaring increase in noise intensity begins approximately 0.6 sec after the increase at Siple. This delay is roughly the one-hop propagation delay on the knee trace path, or half the echo period indicated by asterisks.

It is possible that power line radiation (PLR) Helliwell et al., 1975 affected the development of the noise event in Figures 11b and 11c. Examination of the Siple record on an expanded time scale showed the preburst noise to consist of two bands centered at 6540 ± 40 Hz and 6300 ± 40 Hz, or ≈240 Hz apart (B. Dingle, personal communication, 1977). These frequencies correspond to the 109th and 105th harmonics of 60 Hz.

Figure 11d shows an approximately 2-min-long noise event recorded at Roberval at ≈1106 UT (Siple recordings were not available due to transmitter operation). The time scale is compressed by a factor of 4 with respect to the other panels, and the frequency scale is changed to display 2-12 kHz. A faint noise band is present near the beginning of the record. Near 1105:45 the band exhibits periodic intensifications at the whistler mode echo period in the manner of the case in Figure 11c. (The intensifications were probably 'initiated' by a whistler, but Siple recordings are not available to confirm this.) At ≈1105:52 there is a sharp increase in noise intensity and bandwidth. Figure 12b shows an expanded view of this part of the record. The noise then continues for ≈2 min, exhibiting fading, a further recovery in intensity, and an increase in center frequency with time. Near t = 1106:10 there is another, higher-frequency band. The line near 6 kHz on this record is instrumental in origin.

Accessibility of Waves to the Outer Surface of the Plasmasphere

The immediate exterior of the plasmasphere tends to be shielded from both ducted [Carpenter et al., 1968] and nonducted signals [Scarabucci, 1969] propagating toward the boundary from within. This simplifies the conduct of natural and controlled experiments along or near the plasmapause outer surface. There are complications, however; the region is also shielded at certain times and locations from waves entering the ionosphere from below. This phenomenon was reported by Heyborne et al. [1969] in a study of upgoing fixed-frequency signals received on the Ogo 2 satellite. It is not yet known how and in what combination ionospheric density gradients and enhanced ionospheric absorption contribute to this effect. Storey and Malingre [1972] have discussed the defocusing of upgoing VLF waves in the ionospheric trough region.

Discussion and Concluding Remarks

The physical basis for the wave propagation phenomena described in this paper is not understood. Many ingredients of the problem are not present inside the plasmasphere in the normal ducted regime. Densities beyond the plasmapause may at times be so low that VLF group velocities approach c/2. When the plasmapause is near L = 3, the ratio of plasma to electron gyrofrequency near the equator may approach unity and may become less than unity over a significant portion of the path above the regular ionosphere. Under these conditions, calculations of group delay require use of an expression for the whistler mode refractive index that is more complete (but less tractable) than the one usually employed.

A good model of propagation at the plasmapause is not yet available. It is not clear what kind of field-aligned density structure may be required to guide plasmapause waves observed on the ground. A localized depression, as shown in Figure 1, would provide guidance above $f_H/2$ and at lower frequencies for waves with wave normals near the Gendrin angle [see Helliwell, 1965; Bernhardt, 1976]. (At the Gendrin angle the whistler mode ray direction is parallel to the static magnetic field.) Inan and Bell [1977] note that in ray tracing it is possible to obtain guidance along or near the plasmapause outer surface, but only for waves leaving the lower ionosphere with wave normals at the relatively large Gendrin angle. To explain knee whistler observations by this mechanism, they suggest that appropriate strong horizontal gradients in plasma density in the F region would be required at both the input and the output points of the rays. The presence of such special conditions during knee whistler observations has yet to be investigated, although Cairo and Cerisier [1976] have shown that significant departures of upgoing wave normals from the vertical are observed within the plasmasphere, apparently due to large-scale horizontal density gradients.

The efficiency of the guiding of waves along the outer plasmasphere surface is not clear; there may well be leakage or spreading of the signals away from the plasmapause surface toward higher-latitude field lines. However, the ground records in Figures 9b, 10, and 12b show long-enduring whistler mode echoing along the plasmapause, which implies efficient guiding over a major part of the path.

A theory of plasmapause propagation must explain the fact that when such propagation is detected, only ≈1-10% of the received whistlers may contain a knee trace. However, it must also explain the presence of a knee trace in nearly every whistler observed during some dayside periods and during some periods of quieting.

Whistler propagation outside the plasmapause to ground stations appears to occur most frequently near the meridian of Siple. In contrast, knee whistlers are reported to be a factor of 10-100 less common at SANAE, an Antarctic station at L ≈ 4, roughly 5 hours in magnetic time to the east of Siple [Woods et al., 1974]. While this difference is believed to be due in part to differences in the distribution of lightning sources in the conjugate regions, other factors may be at work, including longitudinal variations in energetic particle activity near the South Atlantic Magnetic Anomaly. Detailed information on the worldwide distribution of knee whistler activity is needed as part of further study of this question.

The special nature of plasmapause surface propagation is suggested by the fact that other active whistler paths beyond the plasmasphere are often separated from the plasmapause surface region by a gap that ranges from a fraction of an earth radius to an earth radius in width (at the equator) [Carpenter, 1966, 1968a]. The gap is most pronounced on the night and morning sides of the earth and may not be evident in the afternoon sector, where the largest number of active paths beyond the plasmasphere is usually observed.

The guiding of waves for significant distances along both 'sides' of the plasmapause, whatever the details of the mechanisms, should facilitate use of wave parameters measured at one point along a field line to infer properties of wave activity at other points along the same line. Because of its persistence in time, extent in longitude, and detectability by various means, the plasmapause may provide a reference frame within which physical processes involving magnetic conjugacy are studied at multiple points. A possible by-product of near-simultaneous multipoint measurements would be information about the shape of the field lines threading the plasmapause and hence about distortions of the subauroral magnetic field.

From an experimental point of view, the outer surface of the plasmasphere (regions 2 and 3 of Figures 1-3) would appear to offer special advantages in plasma-wave and wave-particle interaction experiments such as those planned for the ISEE and DE satellites. These advantages include (1) shielding from waves spreading toward the plasmasphere boundary from within, (2) guiding along or relatively near a field-aligned boundary that is detectable by various methods and at various altitudes, and (3) the possibility of investigating transequatorial propagation at relatively high ratios of wave frequency to equatorial gyrofrequency.

The natural noise phenomena described above afford special experimental opportunities. They may be used in real-time or retrospective studies of precipitation effects and may serve as a guide in real time to the programing of VLF wave injection experiments and satellite observations of wave-particle interactions.

There is a need to further investigate the conditions under which various types of noise develop or are triggered near the boundary. Wave activity near the plasmapause appears to be sensitive to the injection and subsequent drift of energetic particles [e.g., Carpenter et al., 1975; Foster and Rosenberg, 1976]. The development of this wave activity should be studied in conjunction with information on plasmasphere topology and on energetic particle activity.

Acknowledgements. I wish to thank R. A. Helliwell, C. G. Park and T. F. Bell for their valuable suggestions and assistance and J. P. Katusfrakis for his outstanding efforts in the management of the Stanford VLF field program in the Antarctic. I thank T. M. Wang and B. Dingle for help in data analysis and interpretation and am grateful to J. Yarbrough, who first recognized the VLF amplitude perturbations of September 11, 1973. This work was supported by the Atmospheric Sciences Section of the National Science Foundation under grant DES75-07707, in part by the Division of Polar Programs of the National Science Foundation under grant GV-41369X, and in part by the National Aeronautics and Space Administration under contract NGL-05-020-008.

The editor thanks H. G. James for his assistance in evaluating this paper.

References

Angerami, J. J., Whistler duct properties deduced from VLF observations made with the Ogo 3 satellite near the magnetic equator, J. Geophys. Res., 75, 6115, 1970.

Angerami, J. J., and D. L. Carpenter, Whistler studies of the plasmapause in the magnetosphere, 2, Equatorial density and total tube electron content near the knee in magnetospheric ionization, J. Geophys. Res., 71, 711, 1966.

Bernhardt, P. A., The response of the ionosphere to the injection of chemically reactive vapors, Tech. Rep. 17, Radiosci. Lab., Stanford Electronics Lab., Stanford Univ., Stanford, Calif., 1976.

Brice, N. M., and R. L. Smith, Lower hybrid resonance emissions, J. Geophys. Res., 70, 71, 1965.

Cairo, L., and J. C. Cerisier, Experimental study of ionospheric electron density gradients and their effect on VLF propagation, J. Atmos. Terr. Phys., 38, 27, 1976.

Carpenter, D. L., Whistler evidence of a 'knee' in the magnetospheric ionization density profile, J. Geophys. Res., 68, 1675, 1963.

Carpenter, D. L., Whistler studies of the plasmapause in the magnetosphere, 1, Temporal variations in the position of the knee and some evidence on plasma motions near the knee, J. Geophys. Res., 71, 693, 1966.

Carpenter, D. L., Recent research on the magnetospheric plasmapause, Radio Sci., 3, 719, 1968a.

Carpenter, D. L., Ducted whistler mode propagation in the magnetosphere; A half-gyrofrequency upper intensity cutoff and some associated wave growth phenomena, J. Geophys. Res., 73, 2919, 1968b.

Carpenter, D. L., and C. G. Park, On what ionospheric workers should know about the plasmapause-plasmasphere, Rev. Geophys. Space Phys., 11, 133, 1973.

Carpenter, D. L., F. Walter, R. E. Barrington, and D. J. McEwen, Alouette 1 and 2 observations of abrupt changes in whistler rate and of VLF noise variations at the plasmapause—A satellite-ground study, J. Geophys. Res. 73, 2929, 1968.

Carpenter, D. L., J. C. Foster, T. J. Rosenberg, and L. J. Lanzerotti, A subauroral and mid-latitude view of substorm activity, J. Geophys. Res., 80, 4279, 1975.

Cerisier, J. C., Ducted and partly ducted propagation of VLF waves through the magnetosphere, J. Atmos. Terr. Phys., 36, 1443, 1974.

Chappell, C. R., Recent satellite measurements of the morphology and dynamics of the plasmasphere, Rev. Geophys. Space Phys., 10, 51, 1972.

Chen, A. J., and J. M. Grebowsky, Dynamical interpretation of observed plasmasphere deformations, in press, Planet. Space Sci., 1978.

Dingle, B., and D. L. Carpenter, Electron precipitation associated with whistler-induced VLF noise bursts at the plasmapause, paper presented at 1976 Fall Meeting, AGU, San Francisco, December 1976.

Foster, J. C., and T. J. Rosenberg, Electron precipitation and VLF emissions associated with cyclotron resonance interactions near the plasmapause, J. Geophys. Res., 81, 2183, 1976.

Helliwell, R. A., Whistlers and Related Ionospheric Phenomena, Stanford University Press, Stanford, Calif., 1965.

Helliwell, R. A., and J. P. Katsufrakis, VLF wave injection into the magnetosphere from Siple Station, Antarctica, J. Geophys. Res., 79, 2511, 1974.

Helliwell, R. A., J. P. Katsufrakis, and M. L. Trimpi, Whistler-induced amplitude perturbation in VLF propagation, J. Geophys. Res., 78, 4679, 1973.

Helliwell, R. A., J. P. Katsufrakis, T. F. Bell, and R. Raghuram, VLF line radiation in the earth's magnetosphere and its association with power system radiation, J. Geophys. Res., 80, 4249, 1975.

Heyborne, R. L., R. L. Smith, and R. A. Helliwell, Latitudinal cutoff of VLF signals in the ionosphere, J. Geophys. Res., 74, 2393, 1969.

Ho, D., and D. L. Carpenter, Outlying plasmasphere structure detected by whistlers, Planet. Space Sci., 24, 987, 1976.

Inan, U. S., and T. F. Bell, The plasmapause as a VLF wave guide, J. Geophys. Res., 82, 2819, 1977.

Inan, U. S., T. F. Bell, and R. R. Anderson, Cold plasma diagnostics using satellite measurements of VLF signals from ground transmitters, submitted to J. Geophys. Res., 1977.

McPherson, D. A., H. C. Koons, M. H. Dazey, R. L. Dowden, L. E. S. Amon, and N. R. Thompson, Conjugate magnetospheric transmissions at VLF from Alaska to New Zealand, J. Geophys. Res., 79, 1555, 1974.

Rosenberg, T. J., R. A. Helliwell, and J. P. Katsufrakis, Electron precipitation associated with discrete very-low-frequency emissions, J. Geophys. Res., 76, 8445, 1971.

Scarabucci, R. R., Analytical and numerical treatment of wave-propagation in the lower ionosphere, Tech. Rep. 3412-11, Radiosci. Lab., Stanford Electronics Lab., Stanford Univ., Stanford, Calif., 1969.

Scarf, F. L., and C. R. Chappell, An association of magnetospheric whistler dispersion characteristics with changes in local plasma density, J. Geophys. Res., 78, 1597, 1973.

Smith, R. L., Propagation characteristics of whistlers trapped in field-aligned columns of enhanced ionization, J. Geophys. Res., 66, 3699, 1961.

Storey, L. R. O., and M. Malingre, The influence of horizontal electron density gradients associated with the mid-latitude trough on the propagation of VLF radio waves, C. R. Acad. Sci. Paris, 274, 97, 1972.

Thomson, R. J., and R. L. Dowden, Simultaneous ground and satellite reception of whistlers, I, Ducted whistlers, report, Phys. Dep., Otago Univ., Dunedin, N.Z., 1977.

Thorne, R. M., Wave-particle interactions in the magnetosphere and ionosphere, Rev. Geophys. Space Physics, 13, 291, 1975.

Woods, A. C., M. W. J. Scourfield, and N. D. Clarence, A whistler study of plasmapause motion in the vicinity of SANAE, Antarctica, Planet. Space Sci., 22, 1139, 1974.

(Received March 14, 1977;
accepted August 11, 1977.)