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Ducted Whistler Propagation Outside the Plasmapause

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A study has been made of the conditions under which lightning whistlers are observed after propagating along geomagnetic field aligned paths or "ducts" located outside the plasmapause. The study was based in part upon results previously obtained from Antarctic whistler recordings in 1963 and in part upon new data from 45 days of observations at Siple Station, Antarctica ($L \simeq 4.3$) in 1977 and in 1982. Propagation beyond the plasmapause was found, as expected, to be rare in comparison to propagation within the nearby outer plasmasphere. However, detectable propagation beyond the plasmapause near dawn was found to occur on at least one path on roughly one half of the days studied. The path equatorial radii of propagation tended to cluster in two locations, one at the plasmapause outer edge, and the other in a belt separated from the plasmapause by a region of low activity of order 0.5 R_E in extent. The outer edge of the belt was at $L \simeq 5.5$–6. The probability of whistler detection at any L value outside the plasmapause up to $\simeq 6$–7 was found to increase with local time across the dayside of the Earth; maximum activity was observed after noon. Whistler activity beyond the plasmapause was least common in the 1800–2400 MLT sector. Spatial variations in lightning source activity may be responsible for large variations with longitude in whistler activity outside the plasmapause and for the many cases in which only a small fraction of whistlers within a given period exhibit evidence of plasmatrough propagation. Ionospheric processes, such as wave damping, defocusing in the mid-latitude trough, scattering by 10 to 100-m irregularities, and focusing within 50 to 100-km blobs, can explain many features of the observed spatial distribution of whistler paths beyond the plasmapause and also the relatively low amplitude of the associated whistlers as compared to plasmasphere events. The large differences in whistler activity between afternoon and premidnight appear to be due to spatial differences in perturbing magnetospheric electric field activity and in electron density in the plasma trough region. The experimental findings serve to make a relatively sharp distinction between the plasmasphere and the region beyond from both the propagation and wave-particle-interaction points of view.

1. INTRODUCTION

The propagation of a whistler from a lightning source to a ground receiver in the geomagnetically conjugate region is sufficiently well understood to permit use of the observed frequency-time curve for diagnostics of magnetospheric cold plasma density, electron tube content, and cross-L plasma drift motions [e.g., *Park*, 1972; *Corcuff*, 1975; *Park and Carpenter*, 1978]. However, much remains to be learned about important aspects of this interhemispheric propagation, such as the excitation of field-aligned paths or ducts, wave growth and damping, triggering of emissions by whistlers, and accessibility of whistlers to various magnetospheric regions. A key problem is explaining the limited occurrence of ground-observed, or ducted, whistler activity in the region beyond the plasmapause. Given recordings of sufficient duration at a favorable location, the absolute numbers of such events can actually be large, as reported by *Carpenter* [1966]. However, the numbers are at most of order 10% of corresponding values for the nearby plasmasphere, when averages are taken over time at an observing station located near the mean position of the plasmapause. In order to evaluate these differences, one needs a first order description of whistlers and associated wave-particle interaction phenomena observed outside the plasmapause. The purpose of this note is to contribute to such a description and to discuss briefly physical mechanisms that may affect the observations. We emphasize ducted propagation to ground stations but include some information on propagation in nonducted modes to satellites.

The subject of whistler propagation outside the plasmapause is of interest for several reasons. Ground-to-ground propagation is usually interpreted as evidence of guiding by density irregularities or "ducts" that extend without interruption over most of the length of field-aligned paths [*Smith*, 1961; *Bernhardt*, 1979]. Thus whistlers observed at ground stations may provide information on the conditions under which such plasma structures exist above medium-to high-latitude regions. Whistlers propagating outside the plasmapause provide a means to study nonlinear wave-particle interactions such as the triggering of intense, often relatively long enduring, noise bursts by comparatively weak, quasi-coherent input signals. Such effects are relevant to the development of wave injection experiments and to the futher study of unintentional modification of the medium through radiation from power distribution systems.

The question of whistler propagation beyond the plasmapause has been raised by *Koons* [1985], who used statistics of whistler observations near the equator on the SCATHA satellite as a measure of the probability of the propagation of line radiation from power systems on Earth to high mag-

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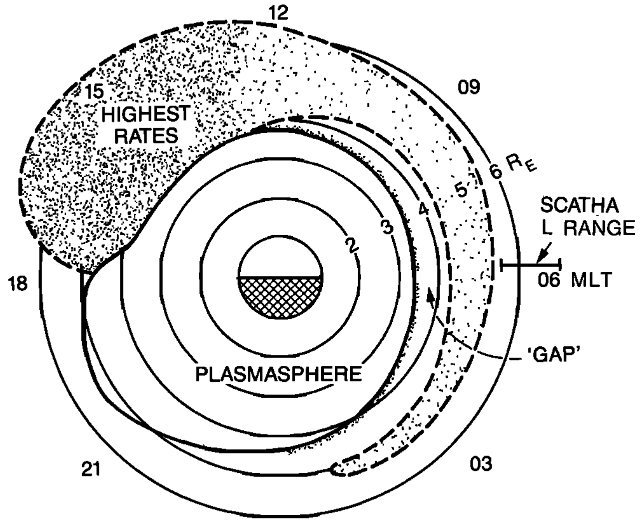

Fig. 1. Equatorial cross section of the magnetosphere providing a crude measure of the probability of observing ducted whistler activity outside the plasmapause as a function of magnetic local time and equatorial distance from the boundary. The conditions represented are those of moderate, steady agitation ($Kp \simeq 3$), typical of the multiday recovery phase of a moderate magnetic storm (maximum Kp = 6–7). The results are based upon observations near the 75°W meridian in Antarctica.

netospheric altitudes at $L \simeq 6$. Very few whistlers were found in the SCATHA L range of 5.5–7.6 and, in particular, no events were observed in the dawn sector. This was interpreted as evidence that whistler mode waves originating on the ground, and in particular low level signals from power lines, do not regularly have access to equatorial regions beyond the plasmapause, especially near local dawn.

At first glance, ground-based whistler observations would seem to contradict the SCATHA results. For example, in studies of burst electron precipitation near local dawn by means of various ionospheric probing techniques, whistlers and/or their triggered emissions have been identified as one of the major wave types driving the precipitation [*Rosenberg et al.*, 1971; *Helliwell et al.*, 1980; *Dingle and Carpenter*, 1981; *Doolittle and Carpenter*, 1983; *Hurren et al.*, 1986]. However, as discussed below, the SCATHA and ground-based whistler results appear to be mutually consistent, in that the L values covered by SCATHA were outside the equatorial region typically crossed by the observed whistlers.

In the following, we provide a brief summary of earlier results on ducted whistler propagation outside the plasmapause and then present the results of a recent study. We also describe satellite observations of signals injected into the magnetosphere poleward of the plasmapause.

2. EARLIER RESULTS FROM GROUND-BASED WHISTLER OBSERVATIONS

In an extensive study of the plasmapause phenomenon based upon 1963 data from Eights, Antarctica ($L \simeq 4.1$, near the present Siple Station), ground-to-ground propagation outside the plasmapause was observed under specific magnetic and local time conditions and at certain positions with respect to the plasmapause [*Carpenter*, 1966, 1968]. Figure 1 is an illustrative figure, adapted from those findings, which shows in equatorial cross section the plasmasphere and region immediately beyond. The conditions represented are those of moderate, steady agitation ($Kp \simeq 3$), typical of the multiday recovery phase of a moderate magnetic storm of the period (maximum Kp=6–7). As expected, highest rates were observed within the plasmasphere. Outside the plasmapause, the probability of observing whistler propagation through the corresponding equatorial region (under the stated magnetic conditions) is crudely indicated by the density of the dot pattern. The following observations were made about the outer region:

1. Just beyond the region of steep plasmapause density gradients, or at the plasmapause outer "edge," propagation was observed during the local time interval ≃ 0000–1800 hours.

2. In the premidnight sector, little or no ground-to-ground propagation was observed beyond the plasmasphere.

3. A "gap," or region of relatively infrequent activity, was found to separate the plasmapause outer edge from a "belt" of activity beyond. The gap, of order 0.5 R_E in width, began near local midnight and extended in local time to early afternoon. Within the gap the whistler activity rate increased with local time, beginning with a very low level near midnight.

4. The outer belt of activity in the plasma trough extended in local time from near midnight to late afternoon and increased in radial extent during that time. Within the belt the number of detected whistler paths within a given L range increased with local time, reaching a broad maximum in the local afternoon.

Table 1 provides a coarse measure of the distribution of activity among these several subregions on 15 days in July–August, 1963. Days were selected that were geomagnetically as active as those represented in Figure 1, and on which propagation outside the plasmapause was detected during one or more of the hourly 2-min recording periods [*Carpenter*, 1968]. Spectrograms from three successive periods near midnight, dawn, and midafternoon were examined. The tabulated values represent the number of days (of a possible 15) on which at least one whistler component was identified as propagating through the corresponding equatorial subregion.

The occurrence rates just beyond the plasmapause in Table 1 are high in part because of the criterion used in selecting the data. However, the results provided evidence for the existence of the various subregions indicated in Figure 1 and for the statements made above about variations with local time in activity within the subregions.

The occurrence of detectable ducted whistler activity out-

TABLE 1. Detection of Whistler Activity Outside the Plasmapause on 15 days in 1963: Number of cases

MLT	Plasmasphere	Plasmapause Outer Edge	GAP	Outer Belt
2300–0100	15	4	0	0
0500–0700	15	12	1	7
1400–1600	14	13	4	9

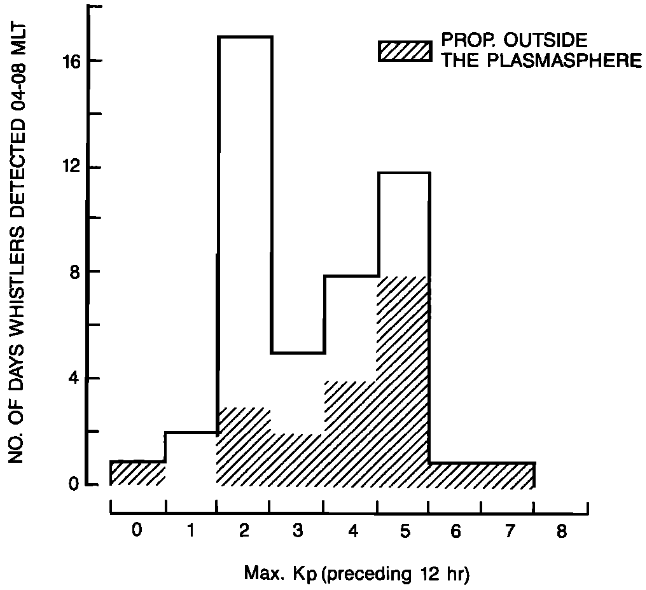

Fig. 2. Histogram of the number of days surveyed versus maximum Kp value in the 12 hours preceding local dawn, showing by shading those cases for which whistler propagation near dawn was detected in some subregion outside the plasmapause.

side the plasmasphere has been found to vary with observing longitude and between hemispheres. The activity represented in Figure 1 and Table 1 appears to be unique to the southern hemisphere, where it exhibits a longitudinal maximum near the 75°W meridian. For example, *Corcuff et al.* [1985] have been able to use whistlers recorded at Belgrano station, Antarctica ($L \simeq 4.1$), at $\simeq$ 55°W, for case studies of plasmapause dynamics, while farther east at SANAE, Antarctica ($L \simeq 4.2$), near the 0° meridian, whistler propagation outside the plasmapause has rarely been observed [*Woods et al.*, 1974]. However, as indicated in a current study by the Upper Atmosphere Physics Working Group of the Scientific Committee on Antarctic Research (SCAR) (A. J. Smith et al., manuscript in preparation, 1988), extraplasmapause activity levels may recover substantially still farther east, at the meridian of Kerguelen ($L \simeq 3.7$, 60°E). Among reasons for the higher levels of activity near Eights/Siple are the high rates of lightning activity in the conjugate region [e.g., *Turman and Edgar*, 1982; *Orville and Henderson*, 1986] and the $\simeq 10^\circ$ by which geomagnetic latitudes exceed geographic latitudes over much of that region.

3. Present Study of Ground-Based Whistler Observations

Propagation outside the plasmasphere to Siple ($L \simeq 4.3$), located within $\simeq$ 200 km of Eights and about 1° in magnetic latitude poleward, has appeared to differ from that observed at Eights in 1963, for example, in showing fewer examples of propagation at the plasmapause outer edge. It was therefore decided to make an occurrence study of Siple data, emphasizing the dawn sector. Characteristic features of the data, including triggering of VLF emissions bursts, were identified, and equatorial electron density profiles were estimated using the methods of *Park* [1972]. The dawn sector was selected, both because of the observations of wave-associated burst precipitation noted above and because of the desire to compare with the SCATHA data reported by *Koons* [1985].

The data set consisted of 35 mm spectrographic records which in most cases displayed broadband wave activity in the 0- to 10-kHz range on time scales ranging from 0.25 to 1.0 cm/s. The period 0900–1300 UT, corresponding to the local time range 0400–0600 hours, was emphasized. In most cases the records were available on a synoptic sampling basis, covering 1 min each 5 min or 1 min each 15 min. Data already available in spectrogram format were studied; these usually represented several days in succession. (The records had previously been prepared for other reasons, for example, to review data from an IMS campaign period in June 1977 or to provide a whistler/VLF emission activity survey during June 1982 periods of cooperative study by the Upper Atmosphere Physics Working Group of SCAR.) A total of 45 days were studied, 28 from 1977 and 17 from 1982.

The occurrence of propagation beyond the plasmasphere was in most cases detected from the dispersion properties of whistler traces that were directly observed on the records. In 5 of 20 cases, detection was indirect, being based upon emissions that were evidently triggered by a whistler component. The appearance of the records in cases of this kind has been discussed in several papers involving wave-associated burst precipitation outside the plasmapause [e.g., *Rosenberg et al.*, 1971; *Foster and Rosenberg*, 1976; *Carpenter*, 1978; *Helliwell et al.*, 1980].

3.1. *Occurrence Data on Propagation Beyond the Plasmapause*

Figure 2 shows a histogram of the days surveyed, binned according to the maximum Kp value in the 12 hours preceding local dawn. Shading indicates those cases for which whistler propagation in some subregion outside the plasmapause could be identified by visual inspection of the records. The large number of cases with maximum $Kp=2$ is associated with the relatively quiet conditions that prevailed in June, 1977. The figure shows that overall, propagation beyond the plasmasphere was detected on about 45% of the days, and that percentagewise, such propagation was more frequently observed as the maximum Kp value increased. These results are broadly consistent with the earlier findings from Eights, except for the apparent fact of more frequent detection at Eights of propagation at the plasmapause outer edge.

3.2. *Dynamic Spectra of Whistlers Propagating Outside the Plasmasphere*

Figures 3 and 4 show spectrograms of whistlers recorded on June 24, 1977, and July 2, 1982, respectively. Figures 3*a* and 4*a* represent the dawn sector, and Figures 3*b*, 3*c*, 4*b*, and 4*c* represent midafternoon local time. In Figure 3*a*, two events are shown. The one at the right, from 0950:50 UT, exhibits a strong component (marked A) propagating at the plasmapause outer edge (note that above $\simeq$ 3 kHz, this component exhibits essentially constant travel time). The noise onset (B) is evidence of triggering in an outer belt (see Figure 1) by a component that is not itself visible on the record. The other event in Figure 3*a*, from 0920:42 UT, does not show propagation just beyond the plasmapause but

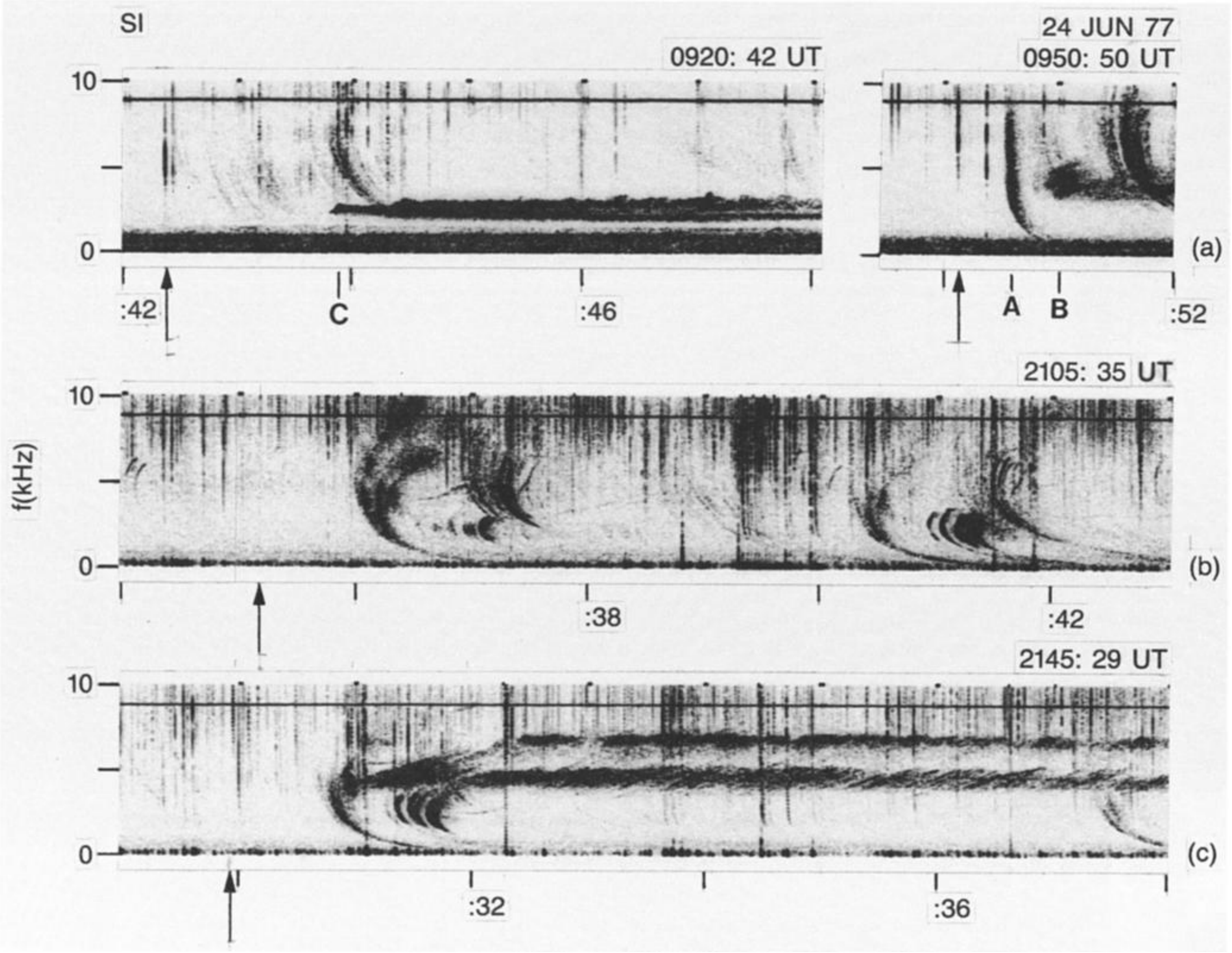

Fig. 3. Spectrograms of whistlers recorded at Siple Station, Antarctica on June 24, 1977, showing evidence of propagation outside the plasmasphere (*a*) in the dawn sector and (*b*) and (*c*) in the afternoon sector. The line at 9 kHz represents a time-coded reference frequency injected at the receiver.

does indicate triggering of a long enduring noise in the outer belt (onset at C). Figure 4*a*, from the dawn sector on July 2, shows another example of triggering of long enduring noises in the outer belt. Again the triggering whistler component is poorly defined. Preceding the noise onset is a component propagating closer to the plasmapause, without triggering. Two echoes of a component propagating within the plasmasphere appear at intervals of $\simeq$ 3 s.

Figures 3*b*, 3*c*, 4*b*, and 4*c*, representing times near 1500–1600 MLT, show whistlers with components that are distributed over a wide L range beyond the plasmasphere. Again there is triggering of long enduring emission bands (Figure 3*c*), but rising tones of duration $\simeq$ 1 s or less are also observed (e.g., Figure 4*b*). In Figure 3*b* the initial component, propagating at or near the plasmapause outer edge, exhibits a diffuse, noiselike extension well above the nose frequency, as described in an earlier report on whistler propagation at the plasmapause [*Carpenter*, 1978].

3.3. *Electron Density Profiles*

Electron density profiles deduced from the whistlers of Figures 3 and 4 are shown in the top and bottom panels of Figure 5, respectively. Figures 5*a* and 5*c*, at left, represent the dawn sector, and Figures 5*b* and 5*d* represent midafternoon. Variation in the symbols used represents a combination of results from whistlers recorded typically within 30 min of one another. The solid curve is a reference curve; it represents median density values in the plasmasphere observed from Siple Station in June 1973, with all local times considered [*Park et al.*, 1978]. The results are consistent with the data reported from 1963 recordings by *Angerami and Carpenter* [1966], in that they show levels within the plasmasphere at dawn (Figures 5*a* and 5*c*) that are comparable to those observed the following afternoon (Figures 5*b* and 5*d*), while densities outside the plasmapause are a factor of $\simeq$ 1.5–2.0 larger in the afternoon than at dawn (at the same L value). The profiles are consistent with Figure 1 in showing a smaller number of components (data points) outside the plasmapause in the dawn sector in comparison to midafternoon and extension of paths to higher L shells in the afternoon. Similar relations are implicit in profiles shown by Angerami and Carpenter, who superposed results from several afternoon and several postmidnight measurements.

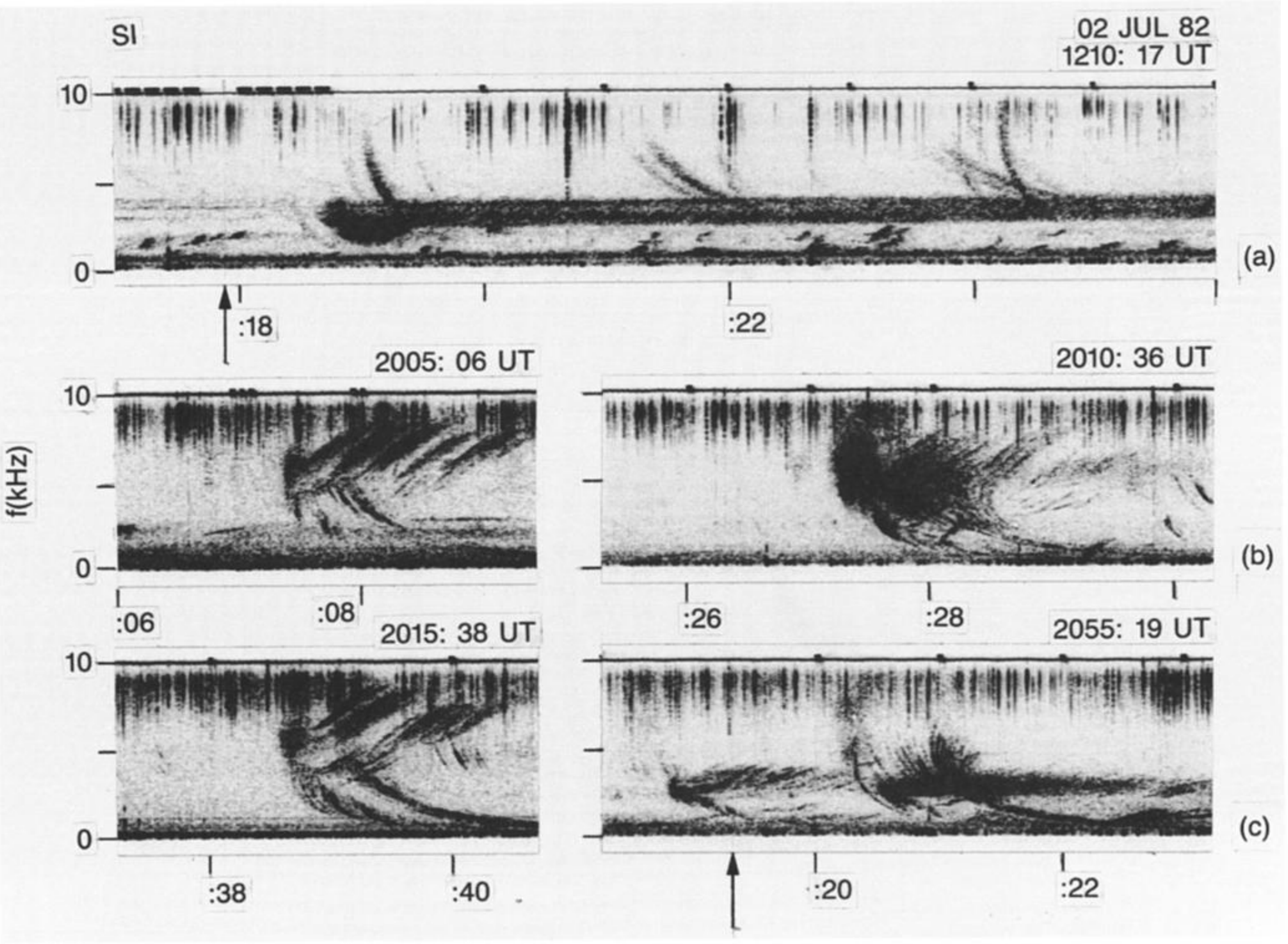

Fig. 4. Spectrograms of whistlers recorded at Siple Station, Antarctica on July 2, 1982, showing evidence of propagation outside the plasmasphere (*a*) in the dawn sector and (*b*) and (*c*) in the afternoon sector. Frequencies above 9 kHz were attenuated by 20 dB because of interference from the Argentina Omega VLF transmitter. The line at 10 kHz represents a time coded reference frequency injected at the receiver.

3.4. *Maximum Observed Whistler Path Radii Near Dawn*

From the new data set, measurements were made of the outermost L shell of propagation near dawn. The results for the scalable 15 of the 20 observed cases are plotted as a histogram in Figure 6, with the number of cases (days) binned in units of 0.5 in path equatorial radius or L value. In most cases the measurements were made on a whistler component (often weak) that triggered a noise in the outer belt of activity shown in Figure 1. Figure 6 shows that the outermost observed paths were concentrated inside $L \simeq 5.5$, and thus were below the $L = 5.5$–7.6 range covered during the search for whistler activity at SCATHA near the magnetic equator [*Koons*, 1985].

The single case of propagation near $L = 7$ indicated in Figure 6 is represented by the whistler spectra in Figure 7 and by the corresponding equatorial profile of Figure 8*a*. In this case of July 5, 1982, magnetic conditions were unusually quiet ($\Sigma Kp = 3$ in the preceding 24 hours). Propagation outside the plasmapause was indicated by a whistler component (slanting arrow in Figure 7) with nose frequency $\simeq 800$ Hz. Two examples are shown to illustrate the repeatability of the effect. The profile of Figure 8*a* shows the difference in density levels associated with the plasmapause but, as is often the case, does not provide information narrowly delimiting the boundary position.

3.5. *Observations During Partial Recovery Following Disturbance*

Because the plasma trough region is at most times in a state of recovery from depletion [*Corcuff et al.*, 1972; *Carpenter and Park*, 1973; *Chappell*, 1972], one might anticipate the occasional development of favorable propagation conditions, characteristic of the plasmasphere, at times when densities are still sufficiently low to permit wave-particle interactions of the enduring kind seen most often outside the plasmapause. Such conditions are in fact observed and are illustrated by the spectrograms of Figure 9 and the density profile of Figure 8*b*. In the spectrogram, relatively long enduring noise events are triggered directly by a strong whistler component. The associated density profile, deduced from a number of similar whistlers of the period, indicates a density level a factor of $\simeq 3$ below typical plasmasphere levels, with indication that a plasmapause had previously been established at $L \simeq 3$.

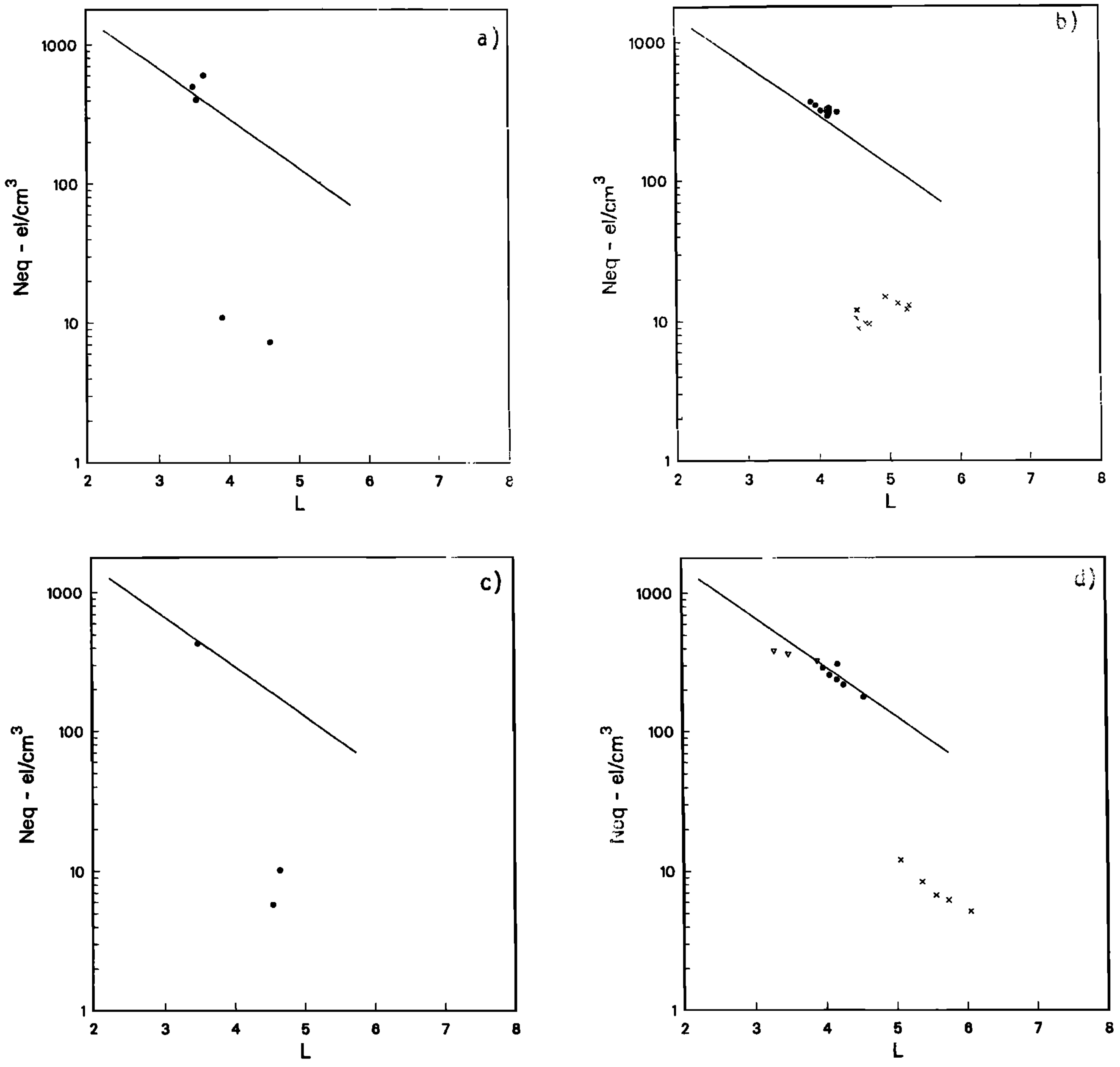

Fig. 5. Magnetospheric equatorial electron density values deduced from whistlers recorded at Siple Station during the time periods represented in Figures 3 and 4. Figures 5*a* and 5*b* represent dawn and midafternoon on June 24, 1977, and Figures 5*c* and 5*d* represent dawn and midafternoon on July 2, 1982. The solid curve is a reference profile representing median density values observed from Siple in June 1973 [from *Park et al.*, 1978]. Electron density values in the plasma trough region were determined using a hybrid field line plasma density model of the type employed in ground-satellite comparisons by *Corcuff and Corcuff* [1982] and discussed by *Park* [1972].

4. UPGOING SIGNAL EFFECTS DETECTED FROM SATELLITES

Results from satellites are pertinent to the question of ducted whistler propagation outside the plasmapause, in spite of the fact that satellite receptions do not distinguish in a straightforward way between signals that propagate in a ducted as opposed to a nonducted mode. One of the earlier findings in this area was that whistlers propagating from the opposite hemisphere to a satellite moving poleward in the topside ionosphere tend to be cut off at the plasmapause [*Carpenter et al.*, 1968]. The latitude variation of the amplitude of fractional hop whistlers, i.e, those propagating upward on a short ionospheric path to a satellite, has not to our knowledge been reported, but a number of reports have been made about upgoing signals from VLF transmitters. Using OGO 2 magnetic field data on signals from NAA at 17.8 kHz (Cutler, Maine) and NLK at 18.6 kHz (Jim Creek, Washington), *Heyborne et al.* [1969] found amplitude cutoffs of 10–40 dB at latitudes typical of the plasmapause. The cutoffs usually took the form of an initial abrupt drop, occasionally by as much as 15 dB in $\simeq$ 1

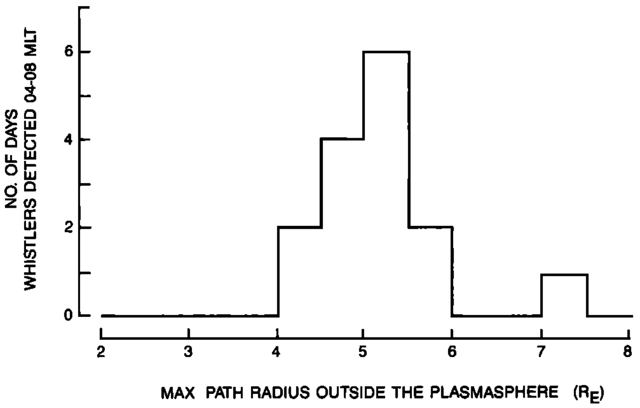

Fig. 6. Histogram showing the distribution of the outermost L shell of detected whistler propagation near dawn for the 1977 and 1982 data sets. A path L value could be estimated for 15 of the 20 cases represented by shading in Figure 2.

s, from a relatively steady level observed at lower latitudes. This was followed by a further decrease and signal disappearance. Strong auroral hiss was frequently observed in a belt poleward of the dropoff. In about half of the 17 cases studied, which represented the 0400 and 1600 MLT sectors, the upgoing VLF signals became detectable again poleward of the hiss activity. *Storey and Malingre* [1972] observed a similar phenomenon in the region of the mid-latitude ionospheric trough when studying FR-1 receptions of upgoing 16.8-kHz signals at 750 km.

Although Heyborne et al. could not confirm that the cutoff occurred at the plasmapause, one of us (D.C.) has examined a number of receptions of upgoing NAA signals observed at $\simeq$ 600 km altitude on OGO 4 in the southern hemisphere, $\simeq$ 10,000 km from the transmitter. It was found that rapid intensity changes can occur at the ionospheric projection of the plasmapause. On one northbound pass near 0000 MLT, a steady upgoing signal of $\simeq$ 0.1 pT, $\simeq$ 15 dB above the backround noise in the narrowband (500-Hz bandwidth) receiver, was initially detected in a region poleward of the plasmapause. The signal then gradually decreased in amplitude and was at or below the noise level over a distance of about 100 km prior to crossing the plasmapause at $L \simeq$ 4. That boundary was identified by the sudden appearance of a broad band of hiss above 4 kHz that was confined to the plasmasphere. At the boundary a nonducted, magnetospherically propagated signal from the north appeared for the first time. Its amplitude reached $\simeq$ 0.2–0.3 pT within a time interval of $\simeq$ 200 ms, or a distance of $\simeq$ 1–2 km along the satellite orbit.

On high-altitude satellites in the middle magnetosphere such as IMP 6 and ISEE 1, nonducted signals from the Siple, Antarctica, experimental VLF transmitter have been detected on both sides of the plasmapause. When absolute measurements of the signal electric field could be made in the 2- to 5-kHz range of frequencies commonly observed in whistlers, values outside the plasmapause have been found to be 10–20 dB lower than those inside [*Inan et al.*, 1977; T. F. Bell, personal communication, 1987]. Although the low- and high-altitude satellites do not separately measure the portion of injected wave energy that becomes ducted, we believe that in a statistical sense they provide a good measure of latitudinal variations in the wave levels available for excitation of ducted whistler paths.

In addition to these spatial variations in upgoing signal amplitude, evidence has been found of substantial spectral broadening of upgoing transmitter signals in the $\simeq$ 3- to 30-kHz range received on satellites with electric antennas. This effect, in which sideband components appear within ±5% of the injected carrier, occurs at frequencies above the local lower hybrid resonance (LHR) [*Bell et al.*, 1983; *Inan and Bell*, 1985] and has been observed over a wide range of latitudes. It is believed to be the result of conversion of some of the electromagnetic whistler mode wave energy to electrostatic waves in the presence of 10- to 100-m density irregularities associated with particle precipitation.

5. Discussion

The results confirm the fact that whistler rates outside the plasmapause are generally substantially lower than those inside and that whistler components detected in the outer region are often low in amplitude and may be identifiable only through the emissions that they initiate. However, the results also suggest that signals from lightning injected outside the plasmapause have exceptional "leverage" as far as wave-particle interactions are concerned. That is, thresholds for nonlinear wave growth appear to be generally lower than is the case within the plasmasphere, and comparatively large amounts of particle energy are evidently converted into wave activity as the result of interactions with individual whistlers. Given these conditions, it is not surprising that observations of ducted propagation beyond the plasmapause are more irregularly distributed both in space and time than is the case within the plasmasphere. In the following we offer some general remarks on these distributions.

5.1. *Ionospheric Processes Affecting Whistler Propagation Poleward of the Plasmapause*

The low intensities of upgoing signals observed just poleward of the plasmapause may be due to strong attenuation of injected VLF waves by collisional absorption, or by enhanced damping of the waves through currents driven by the wave electric field in the presence of irregularities that extend along the magnetic field direction [*Sayasov and Ritz*, 1983]. On the other hand, *Storey and Malingre* [1972] have used ray tracing to show that FR 1 observations of low upgoing signal intensities in the trough region could be explained as an effect of refraction of injected rays due to large horizontal gradients of density. Also, when 10- to 100-m irregularities are present, the upgoing waves may be subject to scattering of the type involved in the spectral broadening process.

Irregular ionospheric structure may also act to selectively enhance upgoing wave amplitudes. In particular, large irregularities or "blobs" of 50- to 100-km scale [*Vickrey et al.*, 1980; *Kelley et al.*, 1982; *Robinson et al.*, 1985] may have a focusing effect on upgoing signals and thus explain some of the sporadic higher-latitude recoveries of upgoing transmitter signals noted above, as well as the fact that whistler activity prior to local noon in the outer belt of Figure 1 is often limited to one or two prominent components. Ducts of the kind followed by injected whistler waves in the region poleward of the plasmapause appear to have been detected by *Beghin et al.*, [1985] using the AUREOL/ARCAD 3 satel-

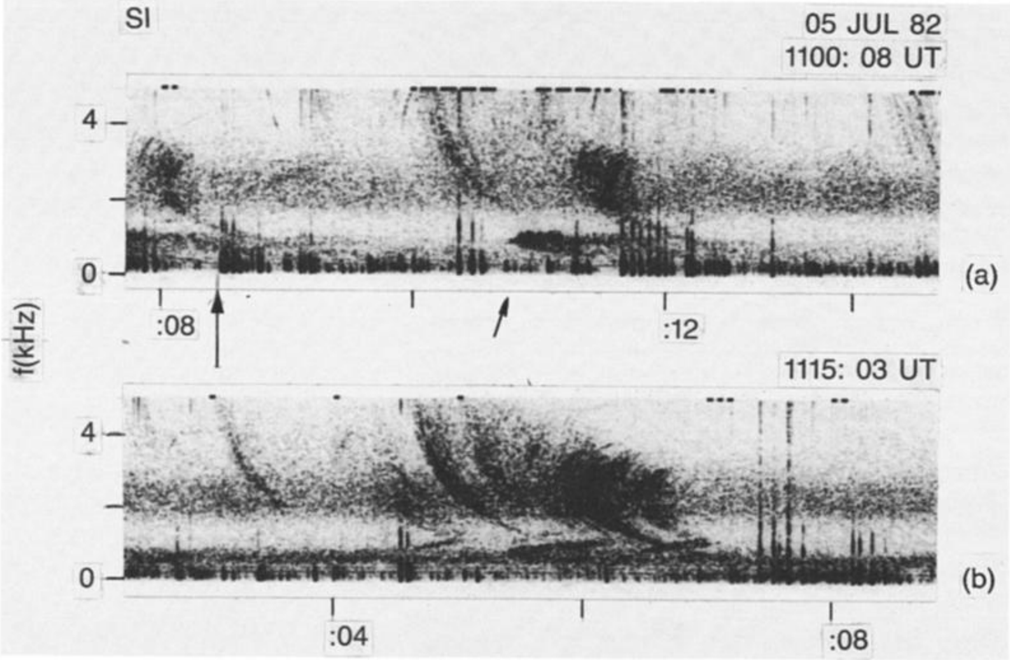

Fig. 7. Spectrograms showing an example of whistler propagation near $L = 7$ outside the plasmapause at local dawn. Two similar examples are illustrated; components that propagated within the plasmasphere are in and above the noise band near 2 kHz. A slanting arrow indicates the component that propagated in the outer region.

lite. Those authors found experimental evidence of ducting of downcoming 500- to 700-Hz hiss in the region poleward of the equatorial boundary of the mid-latitude trough.

Thus ionospheric processes in the hemisphere of whistler wave injection would seem to provide at least a partial basis for explaining Figure 1 and the associated results. However, magnetospheric processes as well as effects of lightning source distributions are clearly important as well. We now briefly consider the combinations of factors that appear to be most important in the various regions indicated in Figure 1.

5.2. *Magnetospheric Processes Affecting Propagation in the Afternoon and Night Sectors*

The premidnight sector, with its dearth of activity, contrasts sharply with the afternoon sector of highest rates and most widespread occurrence. We suggest that this difference is partially due to the occurrence in the premidnight sector of large perturbing convection electric fields and associated E field turbulence [e.g., *Maynard et al.*, 1982, 1983], including field-aligned electric fields that may inhibit the formation of continuous hemisphere-to-hemisphere field-aligned density irregularities that are needed to guide the waves [e.g., *Wescott*, 1981]. One of the most convincing indications of this, noted above, is that when there is sudden magnetic quieting, whistler paths observed in the late afternoon sector appear to move in the direction of the Earth's rotation and continue to be observed in premidnight hours. In such cases the convection pattern in the outer region is inferred to have changed rapidly to one of approximate corotation with the Earth [*Carpenter*, 1970]. The occurrence of stable ducts at relatively high L values in the afternoon sector is partly attributed to the opposing effects of sunward convection and the Earth's rotation, which cause the bulk velocities of the plasma in Sun-Earth coordinates to be comparatively low.

Another factor in the premidnight-afternoon contrast may be magnetospheric plasma density, which at synchronous orbit is reported to reach its lowest levels ($\leq$ 1 el/cm^3) in the premidnight sector [*Higel and Lei*, 1984]. As data from whistlers, GEOS 2, and OGO 5 [*Chappell et al.* [1971] have shown, plasma trough densities increase across the dayside, such that afternoon values may exceed nighttime concentrations by a factor of 5–10. Beyond the plasmasphere, the required electron parallel energies for gyroresonance at typical whistler frequencies are therefore a factor of 5–10 lower in the afternoon, and thus larger interacting particle fluxes should often be available at that time. (In contrast, statistical data from whistlers for 3-hour intervals in June 1973 did not reveal a significant diurnal variation in density at $L = 4$ within the plasmasphere, apparently because of the large tube electron contents involved and the obscuring effects of density perturbations associated with substorm and magnetic storm activity [*Park et al.*, 1978]).

The general tendency for path radii to remain within $\simeq$ 5.5 R_E over much of the nightside may be associated with a transition at that distance from a dipolelike to a taillike magnetic field configuration. Continuous ducts may not form beyond the transition due both to the dilated condition of the equatorial magnetic field and to the presence along the field lines of plasma sheet plasma, whose spatial distribution may be insensitive to any low-altitude process by which ducts are otherwise generated.

5.3. *Unusual Features of Propagation Just Outside the Plasmasphere*

Propagation between $\simeq$ 00 and 1800 MLT at the outer edge of the plasmapause density gradients often differs from the normal ducting process, in that detected whistler frequencies may extend above the usual half equatorial gyrofrequency duct cutoff, and there may even be echoing

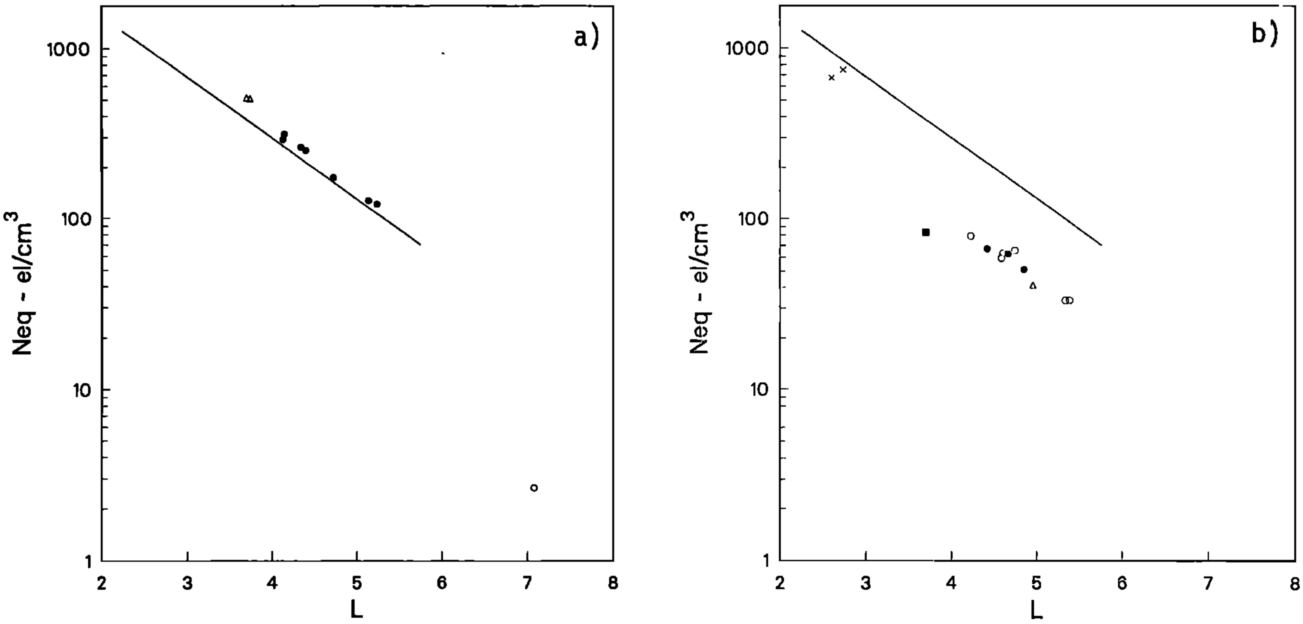

Fig. 8. (*a*) Equatorial electron density profile deduced from the whistlers illustrated in Figure 7. The reference profile from Figure 5 is repeated. (*b*) Profile deduced from whistlers represented in Figure 9, showing evidence of recovery of a depleted plasma trough region beyond $L \simeq 3$ to a level within a factor of $\simeq 3$ of typical plasmasphere levels.

back and forth in that frequency range [*Carpenter*, 1978]. This phenomenon is not understood. *Inan and Bell* [1977] have shown how rays could be guided along the low density edge of a smoothly varying plasmapause, but the associated wave normals must be at large angles with respect to B at low altitude (i.e., the Gendrin angle [*Gendrin*, 1961]), which presents problems in ionospheric penetration [*Helliwell*, 1963]. Horizontal ionospheric density gradients near the plasmapause projection could provide a mechanism for tilting the wave normal angle during ionospheric transit, as suggested by *Inan and Bell* [1977], but such gradients may be insufficient as an explanation for the regular occurrence of this type of whistler during daytime conditions near the lightning source. (However, propagation at the Gendrin angle may explain the lack of dispersion over several kilohertz of component A in Figure 3*a*, an effect also noted in satellite and ground records by *Carpenter* [1978]. R.A. Helliwell (personal communication, 1987) points out that at the Gendrin angle, the group velocity becomes independent of frequency. In any case, the possibility of ducting or guiding at high ratios of wave frequency to equatorial gyrofrequency provides a basis for strong gyroresonant interactions with lower energy electrons which, in nearby regions farther beyond the plasmapause, would be stable to interactions at most ducted whistler frequencies.

5.4. *Other Aspects of Magnetospheric Propagation in Regions Beyond the Plasmapause*

The gap, a "narrow" region of reduced activity beyond the plasmapause (Figure 1), appears to be at least in part attributable to the ionospheric processes noted above. The outer propagation belt in the dawn and near-dawn sector probably maps to the high-latitude edge of the plasma trough, which may serve as an ionospheric source of increased magnetospheric plasma density. This belt is often dominated by VLF chorus, and there is usually strong triggering of the chorus by whistlers and echoes of whistler-triggered emission bursts. As illustrated in Figures 3*a* and 4*a*, the triggering whistler component in the belt is usually poorly defined. When there is fast temporal wave growth and triggering of emissions, the triggered noise activity tends to dominate the frequency-time record. Thus the triggered noise may at its leading edge conform to the whistler frequency-time curve, as in Figure 4*a* (and to a lesser extent, at the right in Figure 3*a*). Or, as in Figure 3*a* at left, it may originate within such a narrow frequency band that the whistler shape is not indicated. The data suggest that wave field strength required for fast temporal growth is relatively low in this region and that the triggered emissions reach near-peak amplitudes within less than 100 ms following the appearance of the whistler in the corresponding range of frequencies. This behavior is similar to that described for individual chorus elements observed on the OGO 1 and OGO 3 satellites by *Burtis and Helliwell* [1975]. The chorus elements exhibited a growth or rise time of 10–300 ms and growth rates ranging from 20 to 2000 dB/s.

The occurrence of propagation outside the plasmapause at $L \simeq 7$ during a quiet period (Figures 7 and 8*a*) suggests that the steepness of the dropoff at $L \simeq 5.5$ in Figure 6 is in part the result of limited high-latitude lightning source activity and not a lack of propagation paths during quiet times. Lightning location may also help to explain the small fraction of whistlers (say 1 in 10) that contain components propagating on paths outside the plasmapause, during periods when such components are detected. The flashes causing whistlers propagating in the outer plasmasphere are more likely to be located equatorward than poleward of the plasmapause projection [e.g., *Orville and Henderson*, 1986], and thus may be less effective in exciting the plasma trough paths.

In the afternoon sector, conditions for whistler propa-

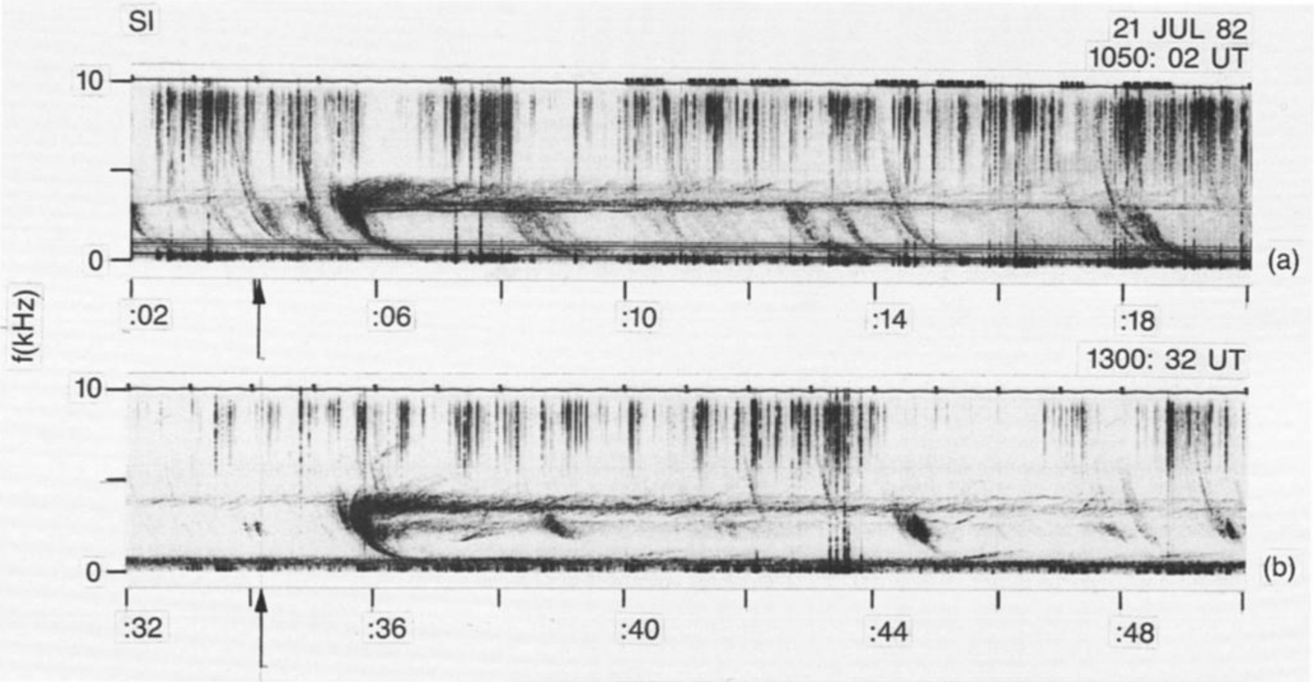

Fig. 9. Spectrograms of whistlers recorded at Siple Station during conditions of partial recovery following depletion of the region beyond $L \simeq 3$.

gation improve, both in terms of the number of observed components and the frequency range of their definition. As noted above, we associate this diurnal peak in whistler activity outside the plasmapause with an afternoon minimum in perturbing electric fields and hence with favorable conditions for the existence of continuous, field-aligned propagation paths. There is strong triggering of emissions by whistlers in the afternoon, as illustrated in Figures 3*b*, 3*c*, 4*b*, and 4*c*, but the triggering whistler is usually identifiable in the records, and the wave intensity threshold for triggering may on average be higher.

In general, whistler components outside the plasmapause show more direct evidence of frequency-dependent wave growth and damping than do whistlers inside. For example, it is common to observe an intensity maximum near the whistler nose frequency, as in Figure 3*b* near 37 s. In some cases only a limited segment near the whistler nose is detected, and the simultaneous occurrence of this effect on paths spaced in latitude is such that a multicomponent whistler exhibits only a single whistlerlike trace consisting of individual segments from the different paths.

6. Concluding Remarks

We have confirmed that ducted whistler propagation outside the plasmasphere occurs at comparatively low rates in comparison to activity within and that the activity outside tends to occur at certain distances from the plasmapause and within certain local time sectors. These spatial distributions and comparatively low rates can be understood as the result of a combination of effects involving the lightning sources, ionospheric effects, and magnetospheric processes.

The distribution of lightning sources appears to be an important factor in (1) the longitudinal peak in whistler propagation outside the plasmapause near the 75°W meridian, and (2) the sharpness in the cutoff at $L \simeq 5.5$ in observed whistler propagation beyond the plasmapause near dawn. Ionospheric processes of wave damping, scattering by 10- to 100-m irregularities, and defocusing in the midlatitude trough probably account for the low amplitude of many whistlers propagating outside the plasmapause. The frequent occurrence of propagation in an outer band, separated by 0.5–1 R_E from the plasmasphere, may be due in part to focusing of upgoing rays in large, 50- to 100-km, F region irregularities. The minimum of ducted whistler activity beyond the plasmapause in the premidnight sector and maximum in the afternoon appear to reflect a spatial differences in the concentration of perturbing electric field activity and in other factors such as electron density and geomagnetic field distortion.

Because the detection of whistlers outside the plasmasphere, particularly in the dawn sector, often depends upon the emissions that they trigger, we are led to emphasize the strong differences that can exist in ducted magnetospheric responses to injected whistler waves. In the outer region, injected wave amplitudes are on average lower than in the plasmasphere, but thresholds for fast temporal growth appear to be lower as well, so that triggering occurs as regularly, if not more regularly, than within the plasmasphere. Growth rates are higher in the outer region, leading to long enduring wave bursts and whistler forms shrouded in emissions, rather than to the individual, short-duration emission forms often triggered by whistlers propagating in the outer plasmasphere. In the outer region there is evidence of selective amplification near the whistler nose frequency, that is, in that leading part of the whistler wave packet in which the instantaneous fields may be largest. In contrast, plasmasphere interactions seem to depend upon wave coherence and the more dispersed, quasi-constant-frequency portions of the whistler.

The problem of identifying the presence, extent of, and role in wave-particle interactions of injected waves in the region outside the plasmapause is a difficult one that needs to be addressed both in theory and experiment. An indication of the difficulty is the fact that in the plasma trough region, injected waves are frequently near or below the noise background level in the recordings of ground stations, although they may have triggered intense and possibly long enduring bursts of wave emissions as well as bursts of detectable particle precipitation during their propagation through the magnetosphere.

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