JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 86, NO. A2, PAGES 839-845, FEBRUARY 1, 1981

A STUDY OF THE OUTER LIMITS OF DUCTED WHISTLER PROPAGATION IN THE MAGNETOSPHERE

D. L. Carpenter

Radioscience Laboratory, Stanford University, Stanford, California 94305

Abstract. The outer limits of propagation of ducted magnetospheric whistlers have been estimated by analysis of whistlers recorded at Byrd (longwire) Station, Antarctica (L ~ 7) during two 3-day periods of magnetic calm (July 2-4 and July 8-10, 1967). Path radii in an IGRF/Olson-Pfitzer geomagnetic field model were determined from the nose frequencies of observed whistlers. On the nightside, the path radii typically extended to about 5 R_E geocentric distance. The dayside radii were generally larger; on 3 of the days they were observed in the 6-8 R_E range in the afternoon sector and during periods of 1 or more hours in duration. It was also found that on most hours in the 6 days, the outer propagation limits were located within $\Delta R < 0.3$ R_E of a plasmapause-type density falloff, usually on its inner side. From these results and earlier results on path radii, it is concluded that the distribution of ducted whistlers near 80°W longitude tends to reflect the instantaneous distribution of disturbance processes such as perturbing substorm electric fields. The path limits tend to fall well within the plasmapause following disturbance onset, but move beyond it during the early stages of recovery and then approach coincidence with the larger plasmasphere limits during prolonged quiet periods.

Introduction

There is strong evidence that the paths followed by VLF whistler-mode signals propagating in the magnetosphere between conjugate ground points are discrete in nature [e.g., Smith, 1961; Angerami, 1970], and it is believed that these discrete paths or ducts take the form of field-aligned enhancements of ionization. It is of interest to know under what conditions such ducts can exist, say, beyond L = 4, and in particular to determine to what geocentric distances in the magnetosphere they extend. It might be expected that beyond some equatorial radius, ducts are either prevented from forming as continuous field-aligned structures or are rendered ineffective as VLF waveguides by effects such as enhanced ionospheric absorption of the waves, unstable interchange motions, or disruption by parallel electric fields or plasma turbulence. If the nature of these inhibiting factors could be modeled, it might be possible to use ducted propagation as a means of identifying regions where certain conditions on duct continuity are met.

The object of this paper is two-fold: To summarize briefly previous reports on ducted propagation at relatively high L-values and to report on a recent study of the outer propagation limits observed under quiet magnetic conditions.

Paper number 80A1380.
0148-0227/81/080A1380$01.00

Previous research has revealed that (1) whistlers can propagate to equatorial distances 2-3 R_E beyond the plasmapause when the latter is observed near L = 4 [Angerami and Carpenter, 1966; Carpenter, 1966, 1968]; (2) ducted propagation to equatorial distances of 6-8 R_E regularly occurs in the equatorial sector.

Figure 1, from Angerami and Carpenter [1966], shows equatorial electron densities deduced from whistler components propagating on both sides of the plasmapause. The data were recorded during several observing days in 1963 at Eights, Antarctica, under conditions of moderate, steady geomagnetic agitation (K_p = 2-4). The filled circles represent postmidnight hours, the open circles afternoon observations. The plasmapause was near 4 R_E on most of the days represented. Data points extend to ~7 R_E on the dayside or to ~2-3 R_E beyond the plasmapause.

There is a well-defined diurnal pattern of propagation beyond the plasmapause under conditions of moderate, steady magnetic agitation [Carpenter, 1966, 1968]. Near midnight, propagation is usually restricted to the region just beyond the plasmapause, as indicated in Figure 1. With increasing local time, propagation near the plasmapause continues and also begins to appear in an outer belt separated by 0.5-1 R_E from the region of steep gradients. As this activity continues across the morning sector and into the afternoon, the number of observed ducts beyond the plasmapause tends to increase, and the distribution of duct radii tends to become more uniform. Near dusk, the bulge region of the plasmasphere appears, and propagation beyond the plasmapause is often not defined again until near local midnight.

Evidence of the frequency of propagation to ~6-8 R_E and its preference for the afternoon sector was provided in an earlier study of whistler data recorded at Byrd, Antarctica (L ~ 7) [Carpenter, 1963a]. From recordings of 2 min/h in 1961, it was found that propagation in the 6-8 R_E range occurred on at least 6 days in each of the months of June, July, and August. It was also found that the higher latitude whistlers tend to be observed on the dayside of the earth. From these results it was concluded that whistler propagation to 6-8 R_E is a regular phenomenon.

The evidence of optimum propagation conditions in the afternoon sector was reinforced by later findings that propagation well beyond the plasmapause also can be detected on the nightside before midnight, but only at times of sudden, deep quieting that begins as the observing ground station approaches the dusk meridian. Under such conditions the propagation regime being observed beyond the plasmapause in the afternoon sector appears to begin rotating with the earth. Ho and Carpenter [1976] showed examples of this behavior.

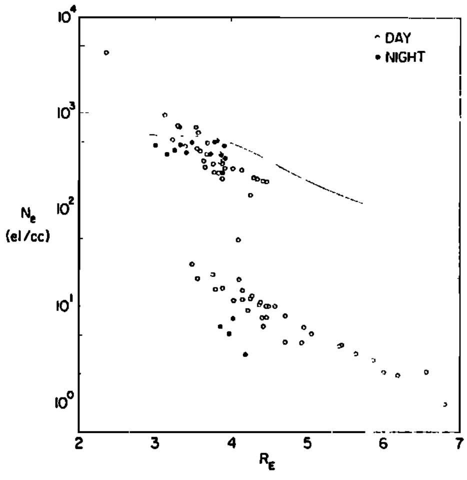

Fig. 1. Equatorial electron densities plotted versus geocentric distance in earth radii (adapted from Angerami and Carpenter [1966]). The data, determined from whistlers, illustrate cases of dayside propagation 2-3 R_E beyond the plasmapause under conditions of moderate, steady geomagnetic agitation (K_p = 2-4). The dayside data represent 7 different observing days; the nightside data (solid circles) represent 4 days. The solid curve is a reference profile from a day of K_p ~ 0.

It has been desired for some time to confirm and extend these earlier reports, particularly with respect to outer limits of propagation on quiet days. By analogy to the plasmasphere, which increases in size and in local time symmetry during quieting, it might be expected that the outer limits of ducted propagation would become larger and would exhibit greater local time symmetry during quiet conditions. This appears to be indeed the case, as indicated in past data sets and in the one reported here.

The data set used was acquired in June-July 1967 at Byrd Station (80°S, 120°W). It offered special advantages in terms of observing latitude (L ~ 7), conjugate lightning source activity, and temporal coverage. The whistler occurrence rates at the time were generally high, probably owing in part to high concentrations of lightning activity 500-2000 km southward of Byrd's conjugate point at Great Whale River, Canada [e.g., Turman and Edgar, 1980] and to the fact that lightning readily excites multicomponent whistlers with path entrance points 1000 to 2000 km from the flash (C. G. Park, private communication, 1980. See also Tixier and Charcosset [1978]). Furthermore, the records were nearly continuous in time; recordings were made at Byrd, using a 20-km dipole antenna for about 40 min/h in June and July 1967.

Two sets of magnetically quiet 3-day periods were selected for analysis, July 2-4 and July 8-10. ΣK_p values for the periods were 11, 7, 12, and 8, 6, and 6, respectively. On the 3 days prior to these periods, the ΣK_p values were 16, 23, 25, and 12, 24, and 14.

The analysis procedure was to survey visually 0-5 kHz spectrographic records of the 40 min of recorded data for each UT hour. The whistler component with the lowest observed nose frequency was then identified, and the value of the nose frequency measured (the nose frequency f_n, or frequency of minimum travel time of the whistler trace, is proportional to the equatorial electron gyrofrequency of the path [e.g., Park, 1972]). From these measurements, path equatorial radii were estimated from curves prepared by Seely [1977], who studied whistler diagnostics in a model geomagnetic field constructed from an IGRF field and the Olson-Pfitzer symmetric magnetospheric model.

Figure 2 shows frequency-time records of two whistlers recorded within a ~1 min period on July 3, 1967. Several whistler components exhibit well-defined nose frequencies; the lowest f_n, near t = 6 s is 670 Hz. This is the lowest nose frequency reported thus far; it corresponds to a path radius of ≈8.7 R_E.

To obtain information on the distribution of duct activity between L ~ 4 and the outer limit of observed propagation, the better-defined nose frequencies above the lowest value in each hour were also scaled. The number of separate whistler components scaled in each hour ranged from 1 to 6 or more; typical values were 2 or 3. An inner path radius bound of ~4 R_E was chosen because it corresponds approximately to the highest nose frequency observable on the 0-5 kHz records and because rates of observable noses at Byrd are highest for propagation at L > 4.

Figure 3 shows a scatter plot in coordinates of equatorial radius versus magnetic local time of all of the 6 days of data, including the outermost observed radii and the other radii beyond L ~ 4. Between ~4 R_E and ~5.5 R_E, the data points are relatively evenly distributed over the 24 hours, suggesting that for purposes of hourly sampling, the conjugate lightning source activity was relatively uniform in time during the periods of observation. There is a relative minimum in data coverage on the nightside prior to midnight, when auroral noise and associated particle precipitation are likely to affect whistler reception at the high latitude of Byrd Station (L ~ 7). However, the data from this period appeared to be consistent with data from nearby periods of higher activity. In Figure 3 the data points near and beyond 7 R_E were not associated with brief bursts of unusual activity, but instead represent periods of 1 or more hours duration and whistler rates of 10-100 per hour.

The spectrographic forms of the multicomponent whistlers were visually examined for information on the location of plasmapause-associated density gradients. Several types of departure from smoothness in the distribution of nose frequencies and nose travel times within whistlers can be identified with either localized depressions or holes in the density profile [e.g., Ho and Carpenter, 1976] or with a plasmapause-like decrease in density [Carpenter, 1963b]. In this study, attempts were not made to distinguish between these categories, since during recovery conditions any spatially isolated density falloff by a factor of 1.5 or more may be indicative of a plasmapause established during preceding disturbances [e.g., Corcuff et al., 1972].

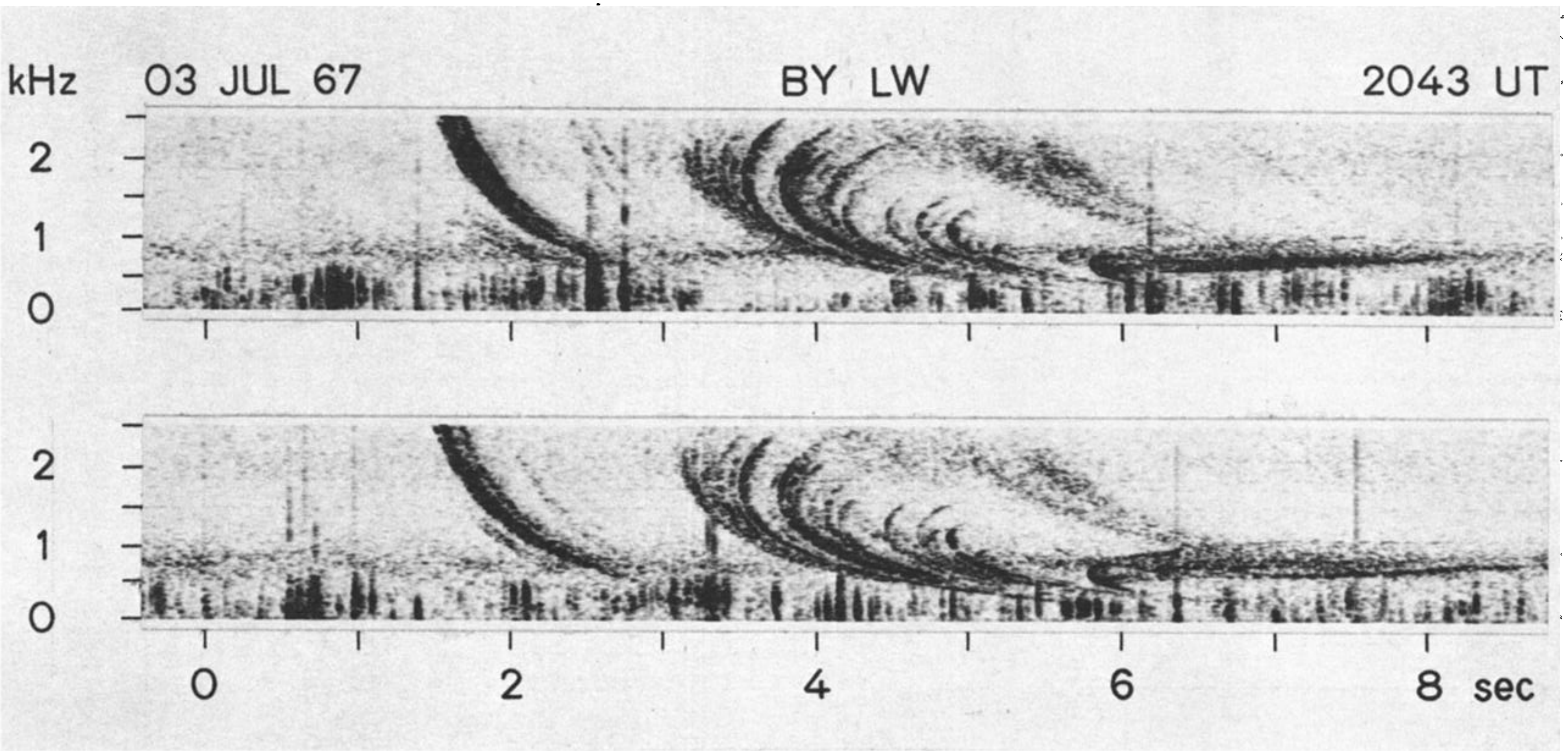

Fig. 2. Frequency-time records of two multicomponent whistlers exhibiting the lowest nose frequency thus far reported, ~670 Hz. This component, propagating to ≃8.7 R_E, has a travel time near 6 s and appears to trigger slowly rising emissions. Beginning at the top of the records near t = 5 s is a 3d-hop echo of the first prominent component. The two events, displayed to show the repeatability of the whistler structure, were recorded at Byrd longwire station within a ~1-min period near 2043 UT on July 3, 1967.

Figure 4 shows two examples of the types of electron density profiles that were encountered in this study. For purposes of clarity, all of the recognizable fine structure of the whistlers was scaled for density information, rather than the smaller number of more prominent traces that were measured for the information on path activity in Figure 3. The two cases represent times of propagation to 8.7 R_E on July 3 and to 7.3 R_E on July 10. The values of equatorial electron density and path radius were obtained from the calculations of Seely [1977], in which a diffusive equilibrium model of the field line distribution of ionization was employed. The profile for July 3 near 15 MLT shows a relatively smooth extension of plasmaspheric density levels out to the limits of observation. In contrast, the profile for July 10 near 17 MLT (Figure 3b) reveals a roughly 40% density increase near 4.5 R_E. This density decrease, although not large, was present over a period of many hours, and probably represented a plasmapause in an advanced state of recovery. In fact, the profile beyond 5 R_E on July 10 is close to the corresponding levels of July 3, except near 7 R_E, where on July 10 there was limited evidence of a localized density increase.

Experimental Results

The plot of the 6 days' data in Figure 3 provides a statistical view of the quiet-day propagation limits. There is a clear tendency for the paths of longer radii beyond 6 R_E to occur on the dayside and in the noon-dusk quadrant. On the nightside, there is a relatively well-defined limit near 5.5 R_E.

The Outer Propagation Limits of Whistlers

Figures 5 and 6 show the outer propagation limits for individual days in the 3-day sequences July 2-4 and 8-10, 1967, respectively. Each curve represents an eyeball fit to the measured hourly limits for the day in question. Gaps in the curves represent corresponding gaps in data coverage. A relatively repeatable nightside limit of $\sim$5 R_E is evident. There is much variation from day to day on the dayside, where path radii beyond 6 R_E were observed on the second and third days of the July 2-4 sequence and on the third day of the July 8-10 sequence. The three greatest maxima in daily path radius were 8.7 R_E, observed at $\sim$15 MLT on July 3, 7.3 R_E, observed at $\sim$12 MLT on July 4, and 7.4 R_E, observed at $\sim$1730 MLT on July 10.

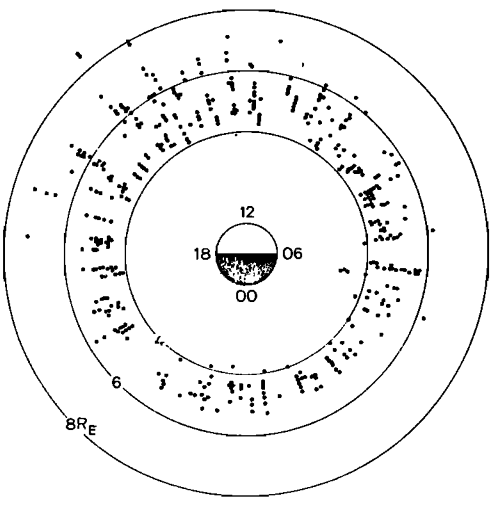

Fig. 3. Scatter plot of whistler path equatorial radii versus magnetic local time for the 6 quiet days July 2-4 and July 8-10, 1967. The plot includes hourly values of maximum path radius and other path radii observed beyond $\approx 4 R_E$. The whistlers were recorded at Byrd Station, Antarctica.

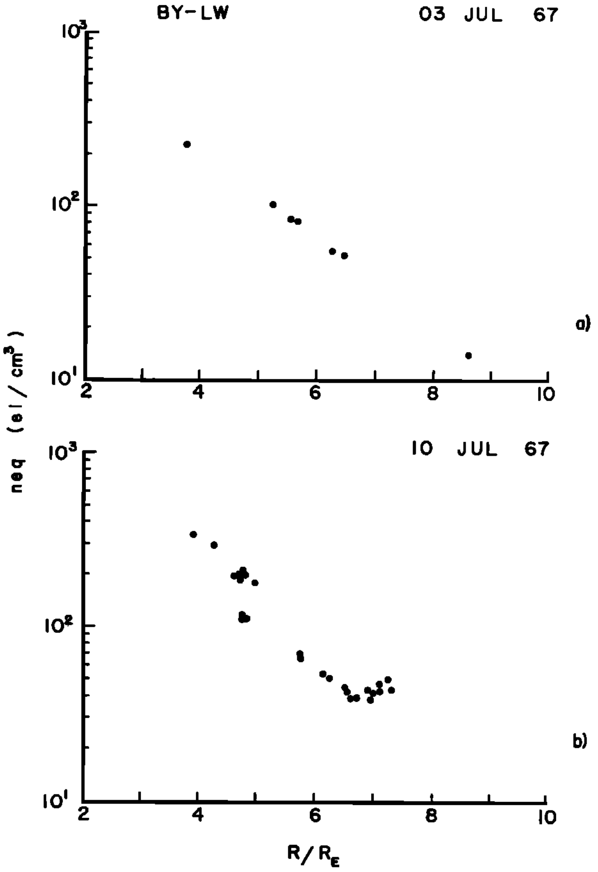

Fig. 4. Examples of equatorial electron density profiles during periods of propagation to relatively large radii. (a) Data from July 3, 1967, near 15 MLT; (b) data from July 10, 1967, near 17 MLT.

From the study of whistler trace structure noted above, it was found that the outer limits of propagation were at most hours on the 6 days located within $\Delta R < 0.3$ R_E of a density falloff, at which electron concentration decreased by a factor of $\sim$1.5 or more within a fraction of an earth radius. In the majority of cases the outermost path was found just inside the decrease. The density falloffs are interpreted as plasmapause boundaries in varying stages of development or recovery.

The finding of a plasmapause effect at $\sim$5.5 R_E on the nightside in quiet times is consistent with an earlier report on plasmapause position versus K_p by Carpenter and Park [1973], who

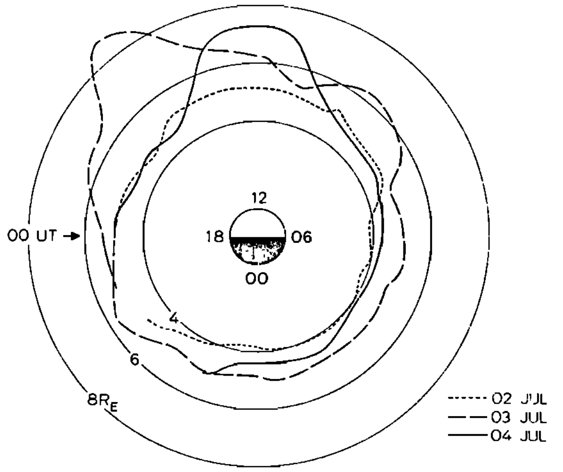

Fig. 5. The outer whistler propagation limits observed from Byrd Station, Antarctica, during the 3-day period July 2-4, 1967. The curves represent eyeball fits to the measured hourly values.

proposed the empirical formula $L = 5.7-0.47\ K_p$ for the postmidnight sector.

The Outermost Path and VLF Noise

Broadband ground records often exhibit evidence of VLF noise forms such as 'chorus' that propagate outside the plasmapause at times when whistlers propagating in such regions are not detected. The records of July 2-4 and 8-10 were studied for evidence of noise activity on paths beyond those observed to carry detectable whistlers. The paths of the noise were estimated by spectral comparisons with cases in which whistler triggering of noise had been observed. These cases occurred either within several hours, or on other UT days when similar magnetic conditions prevailed. The conclusion was that noise propagation beyond the whistler limits did occur, most frequently on the dayside of the earth, but probably within about 0.5-1 R_E of the limits shown in the figures.

Discussion and Concluding Remarks

The data reported here confirm earlier results on the regular existence of ducted whistler mode propagation to 6-8 R_E in the afternoon sector. Such propagation was observed on 3 of the 6 quiet days studied and during periods of 1 or more hours at a time. These findings, coupled with previous reports of such propagation during some moderately disturbed conditions, suggest that at ~80° west longitude, ducted whistler mode propagation in the afternoon sector is observable in the 6-8 R_E range on about 30-50% of all days.

The present study, coupled with previous reports, suggests the following simple comparison between the whistler path limits and the plasmapause. The worldwide form of the plasmapause during disturbed periods represents a kind of integral measure of preceding convection activity [e.g., Spiro et al., 1980; Grebowsky, 1971]. For example, inward displacements of the plasmapause from ~4 R_E to < 3 R_E near midnight may require several hours to complete [e.g., Carpenter and Park, 1973]. Portions of the plasmasphere that are on the dayside during the onset of a prolonged disturbance tend to experience penetrating electric fields that are weaker than those on the nightside, so that a corresponding ground station may not observe a substantial diminution in plasmasphere size until many hours have passed [e.g., Carpenter et al., 1971]. As perturbing electric fields subside, the plasmapause is again slow to respond as a defined density feature, this time in large part owing to the long times required for the higher L field tubes to be replenished by upfluxes of plasma from the underlying ionosphere [e.g., Park, 1974]. As time passes and densities increase, a new plasmapause may be detected at higher L-values, while evidence of steep gradients at lower L-shells may still remain (see Figure 4b).

In contrast to the electron density envelope, the distribution of ducted whistlers appears to reflect the instantaneous distribution of disturbance processes in the system. During moderate to severe disturbances, whistler propagation may disappear down to L-shells well within the plasmasphere as perturbing substorm electric fields penetrate that region. (Evidence of this effect was described by Carpenter [1974].) Then, as recovery begins, but while disturbance continues at a moderate level, ducted activity more or less immediately begins to appear at greater distances, usually to at least prevailing plasmapause limits and often well beyond, as noted earlier for the afternoon sector. As recovery proceeds further, the outer propagation limits tend to increase further and become more symmetrical and to be located near plasmapause-associated density gradients. Thus it appears that the propagation limits agree most closely with the detectable outer limits of the plasmasphere during extended quiet periods.

The physics by which ducting is inhibited are not yet known. The noted variations in path limits over cycles of disturbance and recovery suggest that processes associated with the for-

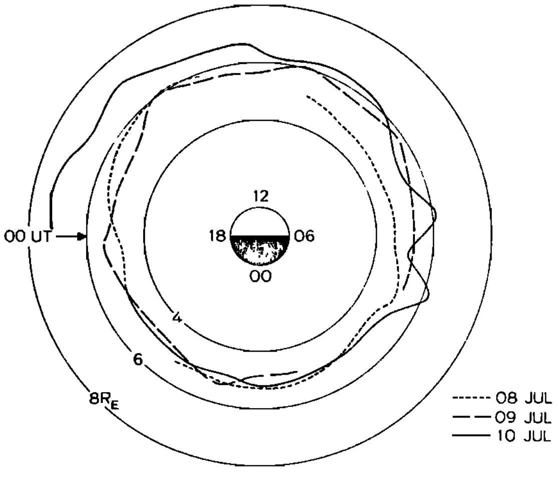

Fig. 6. The outer whistler propagation limits observed from Byrd Station, Antarctica, during the 3-day period July 8-10, 1967. The curves represent eyeball fits to the measured hourly values.

mation of the plasmapause and with its disturbed-time inward displacement are involved. The presence of parallel electric fields in regions of intense convection activity near or within the plasmapause may distort ducts to the point of interrupting ionosphere-to-ionosphere propagation. Furthermore, the eastward plasma flow speed in the postmidnight sector may be such that the centrifugal force becomes comparable to the gravitational force at some point along all field lines beyond a certain equatorial radius, that radius being dependent upon the level of convection activity [e.g., Lemaire, 1975]. Under such conditions, incipient enhancement ducts may become unstable to interchange motions and may fail to attain the stability and field alignment required for interhemispheric guiding of whistlers. The interruption of ducted propagation may thus become widespread during substorms, when electric fields penetrate the dayside and nightside plasmasphere [Carpenter et al., 1979].

On the dayside, ducting may be also sensitive to electric fields and to related convection activity. Substorm-associated electric fields penetrating the afternoon sector are inferred to oppose the rotation of the plasma with the earth [e.g., Nishida, 1966; Brice, 1967; Carpenter, 1970; McIlwain, 1972], thus giving rise over some large sectors to equatorial motions that are slow with respect to the local value of the rotation speed $\Omega_e R$. Under such conditions there is time for prolonged dayside replenishment of magnetospheric electron densities [Chen and Grebowsky, 1975; Chappell et al., 1971] and relatively high concentrations, as reported above, may be present at the higher path radii. Furthermore, slow drift speeds may tend to stabilize ducts against instabilities that would otherwise set in owing to centrifugal effects.

The data reported here indicate that field-aligned structures extending to 6-8 R_E can regularly exist. Such structures present an opportunity to study by in situ and remote techniques both the physics of duct interruption as well as the properties of relatively distant magnetospheric regions. Active VLF radio probing from the ground and from the Space Shuttle should provide basic tools for this work.

Acknowledgments. I thank R. A. Helliwell, T. F. Bell, and C. G. Park for discussions and acknowledge the efforts of J. Katsufrakis in supervising the data acquisition program in the field. I wish to thank J. Siren for his valuable work in acquiring the whistler data at Byrd Station, and S. Manning for his assistance in data reduction. I thank K. Dean and G. Daniels for their help in preparing the manuscript. This research was sponsored in part by the Division of Polar Programs of the National Science Foundation under grant DPP76-82646 and by the Atmospheric Sciences Section of the National Science Foundation under grant ATM78-05746.

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.

Brice, N. M., Bulk motion of the magnetosphere, J. Geophys. Res., 72, 5193, 1967.

Carpenter, D. L., Whistler measurements of electron density and magnetic field strength in the remote magnetosphere, J. Geophys. Res., 68, 3727, 1963a.

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

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, 1968.

Carpenter, D. L., Whistler evidence of the dynamic behavior of the duskside bulge in the plasmasphere, J. Geophys. Res., 75, 3837, 1970.

Carpenter, D. L., Notes on broadband whistler measurements of electric fields and associated phenomena, Mem. 3, Nat. Inst. of Polar Res., Tokyo, March 1974.

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., C. G. Park, J. F. Arens, and D. J. Williams, Position of the plasmapause during a storm time increase in trapped energetic (E > 280 keV) electrons, J. Geophys. Res., 76, 4669, 1971.

Carpenter, D. L., C. G. Park, and T. R. Miller, A model of substorm electric fields in the plasmapause based on whistler data, J. Geophys. Res., 84, 6559, 1979.

Chappell, C. R., K. K. Harris, and G. W. Sharp, The dayside of the plasmasphere, J. Geophys. Res., 76, 7632, 1971.

Chen, A. J., and J. M. Grebowsky, Plasmatail interpretations of pronounced detached plasma regions measured by OGO-2, J. Geophys. Res., 79, 3851, 1974.

Corcuff, P., Y. Corcuff, D. L. Carpenter, C. R. Chappell, J. Vigneron, and N. Kleimenova, La plasmasphere en periode recouvrement magnetique. Etude combinee des donnees des satellites OGO-4, OGO-5, et des sifflements recus au sol, Ann. Geophys., 28, 679, 1972.

Grebowsky, J. M., Time-dependent plasmapause motion, J. Geophys. Res., 76, 6193, 1971.

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

Lemaire, J., The mechanisms of formation of the plasmapause, Ann. Geophys., 31, 1975, 1975.

McIlwain, C., Substorm injection boundaries, in Proceedings of the Advanced Summer Institute held at Sheffield, U. K., D. Reidel, Hingham, Mass., 1973.

Nishida, A., Formation of plasmapause, or magnetospheric plasma knee by the combined action of magnetospheric convection and plasma escape from the tail, J. Geophys. Res., 71, 5669, 1966.

Park, C. G., and D. L. Carpenter, Whistler evidence of large-scale electron density irregularities in the plasmasphere, J. Geophys. Res., 75, 3825, 1970.

Park, C. G., Methods of determining electron concentrations in the magnetosphere from nose whistlers, Tech. Rep. 3454-1, Stanford Electron. Lab., Stanford Univ., Stanford, Calif., 1972.

Park, C. G., Some features of plasma distribution in the plasmasphere deduced from Antarctic whistlers, J. Geophys. Res., 79, 169, 1974.

Seely, N. T., Whistler propagation in a distorted quiet-time model magnetosphere, Tech. Rep. 3472-1, Stanford Electron. Lab., Stanford Univ., Stanford, Calif., 1977.

Smith, R. L., Electron densities in the outer ionosphere deduced from nose whistlers, J. Geophys. Res., 66, 2578, 1961.

Spiro, R. W., M. Harel, R. A. Wolf, and P. H. Reiff, Quantitative simulation of a magnetospheric substorm, 3, Plasmaspheric electric fields and evolution of the plasmapause, J. Geophys. Res., in press, 1980.

Tixier, M., and G. Charcosset, Partly ducted whistlers over Europe, J. Atmos. Terr. Phys., 40, 601, 1978.

Turman, B. N., and B. C. Edgar, Global lightning distributions at dawn and dusk, submitted to J. Geophys. Res., 1980.

(Received January 28, 1980;
revised September 29, 1980;
accepted September 30, 1980.)