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Some aspects of plasmapause probing by whistlers

D. L. Carpenter

Space, Telecommunications, and Radioscience Laboratory, Stanford University

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A guide to the whistler literature is presented, with emphasis on whistler probing of plasma structure and motions near the plasmapause. Whistler probing experiments have identified several types of variations in plasmasphere radius with local time, including (1) variations of a few tenths of an earth radius over ~20° longitude that appear to originate on the nightside of the earth during substorms; (2) a secondary maximum in plasmasphere radius near noon; (3) the duskside plasmasphere bulge. A variety of remarkable and as yet incompletely understood VLF propagation effects occur in the vicinity of the plasmapause, including a decrease in received whistler activity outside the boundary and unusual propagation features such as echoing above the half-equatorial gyrofrequency on paths just outside the plasmapause. Whistlers provide important information on magnetospheric conditions during wave-particle interaction periods, for example, on equatorial electron densities and path magnetic shell parameters needed in modeling studies of observed interactions.

INTRODUCTION

The purpose of this brief review is to provide some guidance to the literature as well as an updated point of view on a number of topics. The disproportionate number of references to the author's work is recognized, but will hopefully be interpreted to be the result of a personal concentration of activity in the general area reviewed, as well as a tendency, under conditions of limited time available, to focus upon more familiar subtopical areas.

The first section provides bibliography and comments on methods of plasmapause probing by whistlers. The second section briefly reviews whistler observational work on plasmasphere radius variations that have longitudinal scales of ~20° and larger. Next are notes on plasmapause-associated whistler propagation effects, with emphasis on the region just beyond the plasmapause. Last are a few comments on plasmapause probing in support of wave-particle interaction experiments.

THE WHISTLER METHOD: A GUIDE TO THE LITERATURE

The whistler method of measuring magnetospheric electron density has been described by a number of authors, including Smith [1961], Carpenter and Smith [1964], Helliwell [1965], Brice and Smith [1971], Roth [1975], and Y. Corcuff [1975]. A technical report by Park [1972] provides a valuable basis for numerical and graphical analysis work with whistlers.

Sagredo and Bullough [1972] discussed the effect of the ring current on whistler diagnostics, and Seely [1977] estimated the effects of using a realistic model of the quiet geomagnetic field in the analysis instead of a dipole. Corrections to account for the departures of the real field from a dipole are usually small and tend to be applied only in special cases. They typically involve a reduction of order 0.1 R_E in the estimated equatorial radius of a whistler path, coupled with an increase of order 10% in the estimated equatorial density. The result is that on a multipoint density profile, the mean density levels are essentially unaffected, while the radii of any irregular features delineated by the data undergo a slight shift inward.

The need to account for magnetic field distortions is reduced by the fact that at middle and higher latitudes, whistlers preferentially appear in regions that are not severely disturbed. Under very quiet conditions, whistlers have been observed out to radii of ~8 R_E in the afternoon sector [Carpenter, 1981]. On the other hand, during severe disturbances they may be observed to limiting distances of less than 3 R_E, and thus tend to be confined to that part of the geomagnetic field that is relatively undistorted.

A more serious problem in whistler analysis is that of the distribution of ionization along the geomagnetic field lines. In many studies, a function representing this distribution is assumed, and electron densities are inferred by using whistler measurements to evaluate the scale factor of the assumed distribution. Experimental work by Angerami [1966, 1970], Angerami and Carpenter [1966],

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and Smith and Angerami [1968] suggested use of a diffusive equilibrium (DE) model inside the plasmapause, and a "collisionless" model, behaving approximately as R^{-4}, outside. For the DE model, the inferred equatorial density level at a given radius is a factor of ~ 2 above that obtained using the R^{-4} model, and the inferred radii of individual whistler paths are ~ 0.1 to $0.3\ R_E$ smaller [Angerami, 1966; Roth, 1975].

Recent progress in evaluating field line density models comes from comparisons of whistler-based estimates of electron density at the magnetic equator with in situ measurements from high altitude spacecraft. In three cases of premidnight observations, whistler results on plasmasphere densities obtained using a DE model showed agreement within about 20% with values obtained from the sweep frequency receiver (SFR) experiment on ISEE 1 [Carpenter et al., 1981]. This provided new support for what had become standard practice, i.e., use of a DE model within the plasmasphere. A more difficult problem involves the choice of a model to apply in the highly variable region beyond the "quiet" plasmasphere [e.g., Rosenberg et al., 1981]. Again, ground-space comparisons have been of help; in two cases of dayside observations outside the plasmapause, whistler data were found to agree well with resonance and mutual impedance probe data from GEOS 1 [Corcuff and Corcuff, 1982]. The comparison provided support for use of a "hybrid" field line model of the type discussed by Park [1972]. This model leads to estimates of density and path radius intermediate between those from the DE and R^{-4} models.

The standard whistler method of detecting the plasmapause was discussed by Carpenter [1963, 1966] and Angerami and Carpenter [1966], while methods of detecting the duskside plasmasphere bulge or other regions of enlarged plasmasphere radius were discussed by Carpenter [1970] and Ho and Carpenter [1976]. Methods of tracking the cross-L bulk motions of the plasma near the plasmapause by means of slow changes in the dispersion properties of whistlers were described by Carpenter [1966], Carpenter and Stone [1967], Carpenter et al. [1972], and P. Corcuff [1978]. The effects on the whistler results due to electric fields induced by fluctuating plasma currents were discussed by Block and Carpenter [1974]. Recently, a multihour comparison was made between cross-L equatorial motions in the outer plasmasphere (or the equivalent east-west electric field component) estimated from whistlers, and the north-south component of plasma motion at ionospheric heights determined from incoherent scatter radar measurements [Gonzales et al., 1980]. When mapped along supposedly equipotential field lines, the results were in excellent agreement during an isolated substorm, suggesting that the associated electric fields were essentially curl-free.

Many papers have been written describing various features of the plasmapause as detected by whistlers. For lists of such papers, see Corcuff and Corcuff [1982], Y. Corcuff [1975], Carpenter and Park [1973], or Park and Carpenter [1978]. Studies of the plasmapause-plasmasphere system from spacecraft have tended to corroborate results from whistlers [e.g., Maynard and Grebowsky, 1977; Carpenter et al., 1968; Taylor et al., 1969; Morgan and Maynard, 1976], and have also presented quite new perspectives on phenomena such as outlying plasma regions [e.g., Chappell, 1972] and on the composition, pitch angle distributions and energy characteristics of thermal ions [Chappell, 1982; Chappell et al., 1982].

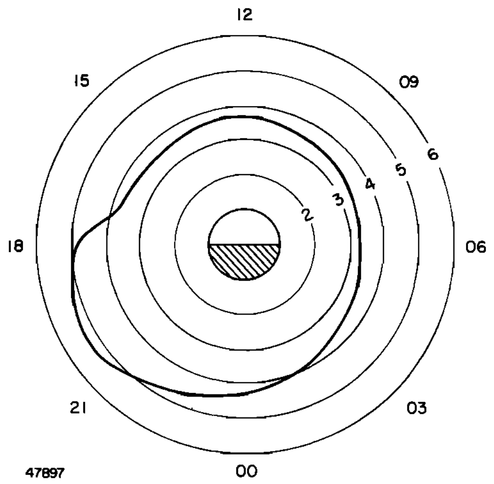

Fig. 1. Average plasmapause radius as a function of local time during the prolonged recovery phases (Kp ~ 3) of a series of weak to moderate magnetic storms [from Carpenter, 1966].

The foregoing discussion is but a limited guide to the whistler literature. As examples of informative papers on other topics, with helpful bibliographies, see P. Corcuff [1977] and Bernhardt [1979] on whistler curve fitting, and Walker [1976], Strangeways and Rycroft [1980], and Strangeways [1981] on problems in whistler propagation.

IRREGULARITIES IN THE PLASMAPAUSE

Progress in study of the plasmasphere-plasmapause system may well have been hindered by overacceptance of the relatively simple descriptive pitcures that emerged from the earliest research. However, these simple pictures are still useful for many purposes, and can serve as a starting point for more detailed investigation. Figure 1 shows the average plasmapause radius as a function of local time based on observations during the prolonged recovery phases (Kp ~ 3) of a series of weak to moderate magnetic storms [Carpenter, 1966]. The beginnings of complexity are illustrated in Figure 2, from Carpenter and Park [1973], which shows in idealized form the changes in the equatorial density in a given local-time sector that may occur as the plasmasphere undergoes storm time erosion, poststorm replenishment, and a later episode of moderate erosion.

The dynamics implied in Figure 2 are believed to involve two basic processes. One is essentially of magnetospheric origin; it gives rise to erosion of the outer plasmasphere and causes a steep plasmapause profile to be established during relatively brief periods of increasing disturbance (order of 10 hours). The other process is essentially of ionospheric origin, involving the slow (order of days) replenishment from below of both the plasmatrough and the plasmasphere itself [e.g., Park, 1970]. That the interplay of these processes in actual geophysical situations can lead to irregular density features has been discussed by Park and Carpenter [1970], P. Corcuff et al. [1972], Sagredo and Bullough [1973], and Corcuff and Corcuff [1982].

Figure 3 shows a sketch of how an irregular plasmasphere might be imagined to appear at a given time during a period of increasing disturbance. Arrows show regions where particularly strong modulation of the plasmapause radius is believed to occur.

The existence of variations in plasmasphere radius of a few tenths of an earth radius over ~20° in longitude were noticed by Angerami and Carpenter [1966], who used the fact that the multiple field-aligned paths or ducts followed by individual whistlers are distributed in both latitude and longitude. Dispersion analysis frequently showed an overlap of a few tenths of an earth radius in the radii of the outermost dense plasma region and the innermost plasmatrough region observed. The inference of an ~20° longitudinal extent of the variations was based on estimates of the longitudinal extent of the effective viewing area of the observing whistler station.

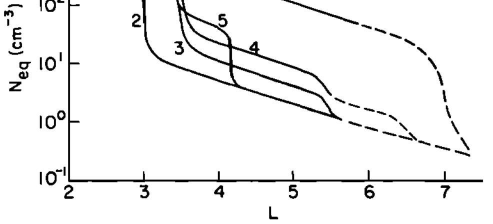

Fig. 2. Schematic illustration of changes in the equatorial profile of electron concentration in the magnetosphere during an ~10-day period that includes two magnetic storms. (Top) Indication of the Dst index of magnetic disturbance activity. (Bottom) Equatorial concentration profiles that correspond to the times marked along the Dst curve. These idealized profiles represent conditions near the ~0400 MLT meridian [from Carpenter and Park, 1973].

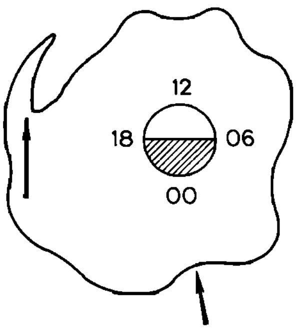

Fig. 3. Sketch of imagined equatorial cross section of the plasmasphere at a given time during a period of increasing disturbance.

A principal source of these irregularities appears to be structured convection electric fields that penetrate the plasmasphere during substorms. The fields are smaller than those reported at auroral latitudes, but at values of a few tenths of a millivolt to probably several millivolts per meter and periods of order 1 hour [Carpenter et al., 1972, 1979; P. Corcuff, 1978], they can be associated with significant displacements of the magnetospheric plasma (the corotation velocity at 4 R_E corresponds to a radially inward field of ~1.8 mV/m).

A major source of irregularity in plasmapause radius appears to be substorm-associated, spatially structured cross-L convection activity in the postmidnight sector. Because of the tendency of the plasmasphere to rotate with the earth, the structure imposed by this local convection activity is believed to result in an irregular, wavelike variation in plasmasphere radius that extends eastward onto the dayside [e.g., Chappell et al., 1971; Chappell, 1972; Carpenter and Chappell, 1973; Carpenter and Park, 1973].

A special feature of postmidnight cross-L convection detected by whistlers is a postsubstorm outflow. This effect was observed in the aftermath of temporally isolated substorms that followed relatively quiet periods [Carpenter et al., 1972; Carpenter and Akasofu, 1972; Carpenter and Seely, 1976]. From the perspective of a ground whistler station, ducts in the outer plasmasphere were observed to move inward during a substorm and then to drift outward at a roughly comparable speed and for a comparable period. This outflow effect has not been modeled or otherwise interpreted; its effect may be to enhance the devel-

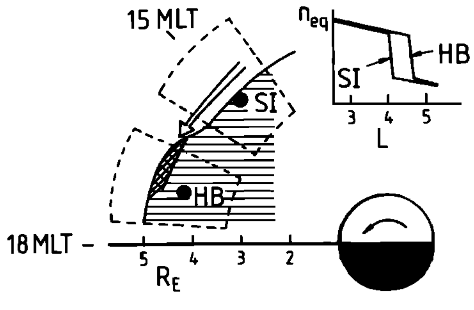

Fig. 4. Sketch of the plasmapause cross section in the equatorial plane (viewed from the north), as deduced from whistler observation at Halley Bay (HB) and Siple (SI) stations, Antarctica, at about 2000 UT on June 24, 1977. The plasmasphere is shown shaded. The dashed curves indicate the approximate "viewing windows" of the two stations. The plasmasphere extension near the Halley longitude is inferred from plasma density profiles shown schematically by the inset. The cross-hatched area is a region of intense VLF noise observed at Halley but not at Siple [from Smith et al., 1981].

opment of the variations in plasmapause radius with longitude noted above.

New evidence of irregular structure on the dayside was obtained during the 1976-1979 IMS period, when special multilongitude observing campaigns near L = 4 were conducted. In two studies of simultaneous data from Halley and Siple stations in Antarctica, which are spaced about 2 hours in MLT, a larger plasmapause radius near Halley was observed [Smith et al., 1981]. Figure 4 shows sketches of the magnetospheric equatorial plane, the viewing sectors in that plane of the two whistler stations, and an example of the differing equatorial density profiles at the stations' longitudes. During both multihour case studies, VLF noise activity appeared to concentrate in the region of extended plasmasphere radius near Halley. This effect is illustrated in Figure 5, which shows spectrograms of Halley (Figure 5b) and Siple (Figure 5c) records beneath a time-compressed, frequency-expanded record of the VLF noise at Halley. Events of this type were interpreted as evidence that irregular extensions in plasmasphere radius can be penetrated by drifting low energy electrons that become unstable to gyroresonant interactions, the consequences being enhanced wave activity, particle scattering, and precipitation of particles into the ionosphere.

Another irregular feature of the plasmasphere is a secondary maximum in radius near local noon that apparently develops as a result of quiet-time magnetospheric drift patterns. These latter are believed to be associated with the ionospheric dynamo process [Carpenter and Seely, 1976; Carpenter, 1978a]. Figure 6 shows examples of changes in whistler path equatorial radii, with time, during two quiet periods. The drifts are slow, in the range 0.1 to 0.2 R_E per hour, but are sufficiently long in period to give rise to a plasmapause radius of order 0.5 R_E larger at noon than at dawn. This noon bulge effect may be related to the noon-midnight plasmasphere asymmetry reported from spacecraft by Gringauz and Bezrukikh [1976]. As a consequence of the development of the noon bulge, the plasmapause radius tends to increase with local time in the morning sector. The mechanism noted above of boundary penetration by potentially gyroresonant electrons may then become important, particularly since the noon bulge tends to be approximately fixed in sun-earth coordinates.

The duskside of the plasmasphere appears to be very efficiently penetrated by substorm fields [e.g., Park, 1978]. This was earlier inferred from observations of the evening plasmasphere bulge, indicated in Figure 1. To a ground whistler station, the bulge appears to be displaced sunward during increasing disturbance, to be located near dusk when agitation is steady, and to begin rotating with the earth during quieting [Carpenter, 1970]. Although spacecraft data have shown substantial agreement with whistler results on the average behavior of the bulge in the 4-5 R_E range [Maynard and Grebowsky, 1977], the bulge phenomenon remains an elusive target for spacecraft and ground whistler studies alike. Some of its properties have been confirmed and their description extended by Corcuff and Corcuff [1982] in a recent multilongitude study of whistlers in combination with spacecraft data. Much remains to be done in this area, however. For example, the plasma flow pattern in the vicinity of the bulge needs to be tracked and variations in the phenomenon as a function of solar activity need to be investigated. The recent operations of DE 1 in the bulge region should provide an opportunity to merge the unique observing capabilities of spacecraft with the perspectives of ground techniques.

VLF PROPAGATION EFFECTS AT THE PLASMAPAUSE

A variety of remarkable and as yet incompletely understood VLF propagation effects occur in the vicinity of the plasmapause. One of these is a decrease in received whistler activity in the region outside the plasmasphere [Carpenter, 1968a; Woods et al., 1974]. Another is the fact that when propagation does occur just beyond the plasmapause, it exhibits a number of features unique to that field line location. The activity decrease is probably related to an observed cutoff or sharp reduction in the field strength of upgoing waves from fixed frequency transmitters as observed on polar orbiting spacecraft [Heyborne et al., 1969], as well as to a cutoff in whistlers propagating from the conjugate hemisphere to spacecraft in polar orbit [Carpenter et al., 1968]. Siple transmitter signals observed on the ground exhibit a corresponding effect; they propagate regularly in the outer plasmasphere and in that part of the region of steep plasmapause density gradients where the density levels are within a factor of ~ 2 of those

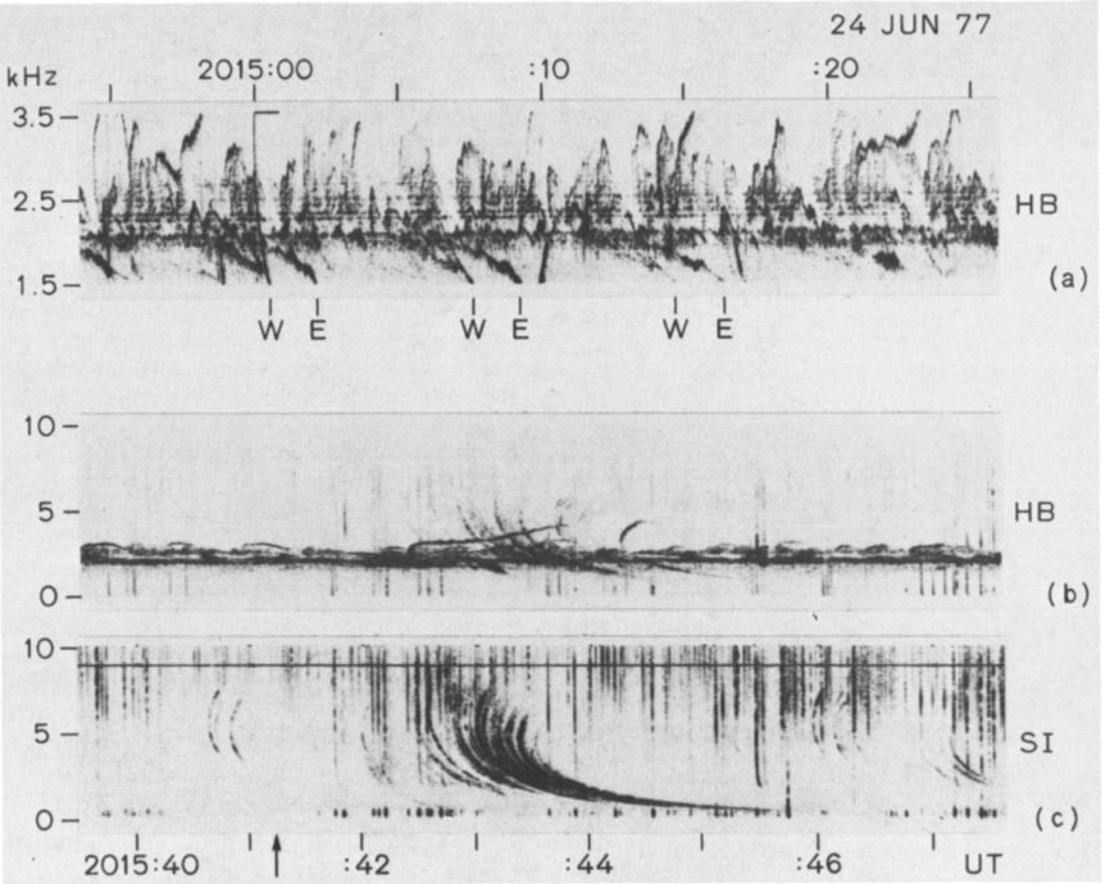

Fig. 5. Compared spectrograms from (b) Halley Bay and (c) Siple, showing a concentration of VLF noise activity near Halley. The top panel shows a time-compressed, frequency-expanded record of the Halley noise activity [from Smith et al., 1981].

in the nearby plasmasphere [Carpenter and Miller, 1976], but have been detected only rarely on paths in the plasmatrough (Carpenter and Miller, manuscript in preparation, 1982).

The decrease in activity apparently varies with longitude, becoming more pronounced eastward of the region of high whistler activity near the 75°W meridian [e.g., Woods et al., 1974]. At the more favorable longitudes for plasmatrough propagation, the latitudinal limits of propagation appear to be located at the plasmapause only in some average sense, tending to reach well beyond the boundary in quiet times and to fall within it during periods of increasing disturbance [Carpenter, 1981].

An explanation of the activity decrease is likely to involve a number of effects. Among processes that may contribute to a lack of efficient propagation outside the plasmapause are defocusing [e.g., Storey and Malingre, 1969] and enhanced absorption of the upgoing waves, scattering by irregularities, disruption of the ducting process by parallel electric fields, and conversion of upgoing waves into other modes. Such modes include the subprotonospheric whistler [Carpenter et al., 1964], explained by Smith [1964] as the result of tilting of upgoing wave normals away from the the vertical as they pass through the ionosphere.

Often observed in conjunction with an activity decrease at the plasmapause is a change in the form of discrete VLF emissions triggered by whistlers. Inside the plasmapause the triggered events are usually single elements lasting ~ 1 s or less. Just outside the boundary, the events often consist of multiple elements that overlap and endure for tens of seconds [Carpenter, 1978b]. The whistler involved in triggering these large releases of wave energy is often faint or unrecognizable on a frequency-time spectrogram. In such cases, recognition of triggering relationships is facilitated by the detection of components of the whistlers that propagated either within the plasmasphere or at larger radii in the plasmatrough. Also helpful is the fact

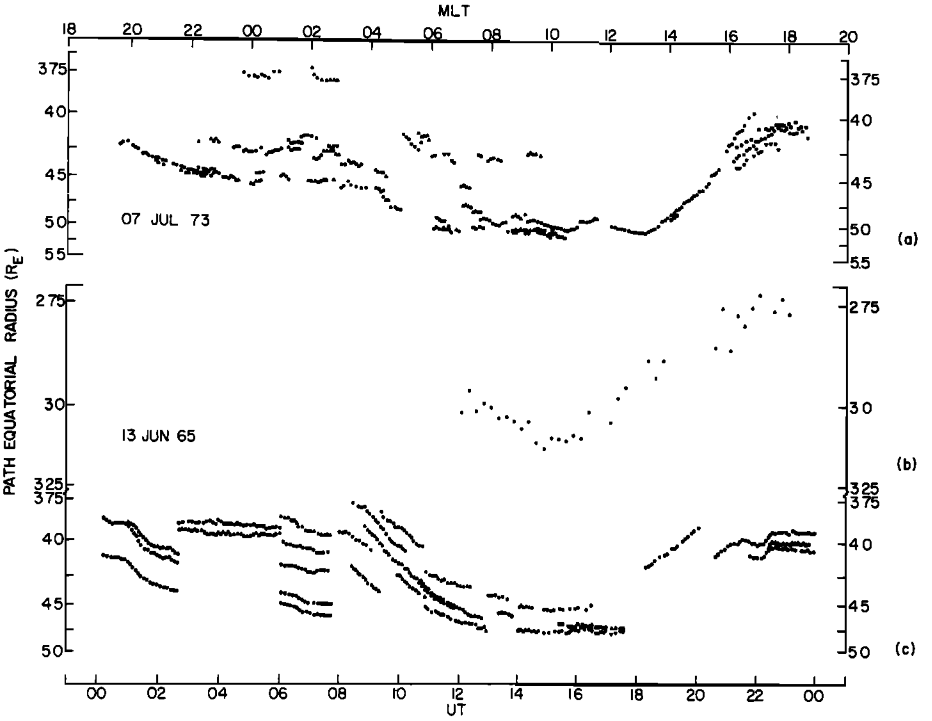

Fig. 6 Changes with time in measured whistler path equatorial radii on two quiet days. Magnetic local time is shown at top. See original reference for details [from Carpenter and Seely, 1976]

that whistler frequency-time signatures tend to be repeatable under similar magnetic and local time conditions; patterns established on days of relatively good definition can be used to interpret cases when the driving whistlers are poorly defined.

Whistler paths just outside the plasmapause support a type of propagation not observed on paths at greater or lesser radii [Carpenter, 1978b]. Whistler waves echoing back and forth just inside the plasmapause have been observed to couple to a path just outside at a time when waves could not efficiently penetrate the ionosphere and excite that path directly from below [Smith et al., 1982].

USE OF WHISTLERS TO STUDY WAVE-PARTICLE INTERACTIONS NEAR THE PLASMAPAUSE

In experiments involving wave growth and/or particle scattering by VLF waves, whistlers propagating along the magnetospheric paths of interest can provide information on the path radii and on electron density. This information, obtained in specific cases [e.g., Dowden et al., 1978] or from statistics [e.g., Helliwell and Inan, 1982], is then used in conjunction with observed waveform data to estimate quantities such as wave field strength in the interaction region and trap oscillation frequency. In scattering studies, the information provides a basis for comparing theoretical and observed time signatures of driving waves and the ionospheric perturbations that they induce [e.g., Rosenberg et al., 1971, 1982; Rycroft, 1973; Helliwell et al., 1980; Roeder, 1982].

In cases of middle-magnetospheric observations at ground stations instrumented for ionospheric probing, much can be learned about wave-particle interactions if it is known whether the overlying field lines are inside or outside the plasmapause, or are perhaps in some type of intermediate recovery state in terms of electron density. When the general spectral form of observed VLF activity indicates that either the quiet plasmasphere or a moderately to severely disturbed plasmatrough is overhead, the equatorial electron density levels on the corresponding paths are predictable from previous statistics within a factor or ~2 [e.g., Angerami and Carpenter, 1966; Park et al., 1978].

In some cases the plasmapause position needs to be known relatively accurately. In a recent study it was found that an ~600-km subionospheric VLF path fron Cutler, Maine, to Roberval, Quebec, had been perturbed. The precipitating particles involved had apparently been scattered by VLF noise bursts propagating along the outer "surface" of the plasmapause. Whistler analysis provided evidence that the plasmapause projection onto the ionosphere at 100 km altitude had indeed crossed the affected subionospheric path [Dingle and Carpenter, 1981].

CONCLUDING REMARKS

In order to further realize the potential of the whistler method of probing the plasmapause region, additional work is needed to clarify the nature of wave propagation in ducts and to investigate the processes by which ducted propagation is interrupted or obscured during periods of increasing magnetic disturbance and in particular regions of the plasmatrough. There is a need for continued studies of data acquired on a spaced-station basis during the IMS and a need for correlative studies, for example of the duskside bulge region, in cooperation with IMS and post-IMS satellite experimenters.

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D. L. Carpenter, Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford, CA 94305.