Ann. Géophys., t. 26, fasc. 2, 1970, p. 363 à 370.

Remarks on the ground-based whistler method of studying the magnetospheric thermal plasma

by D. L. CARPENTER,

Radioscience Laboratory,
Stanford University,
Stanford, California, U.S.A.

RÉSUMÉ. — *Un récepteur T.B.F. installé à Eights, en Antarctique, peut détecter des sifflements qui se propagent dans une région s'étendant de $L \sim 2{,}5$ à $L \sim 6$, et ± 15° en longitude autour la longitude de la station. Les sifflements à composantes multiples, et dont les chemins de propagation représentent une partie importante de la région d'observation, peuvent être employés pour étudier les irrégularités dans les gradients (radiaux et longitudinaux) d'ionization magnétosphériques, les mouvements convectifs de l'ionization, et la position et les déplacements de la plasmapause.*

ABSTRACT. — *A whistler receiver at Eights, Antarctica is capable of viewing a region of the magnetosphere extending from $L \sim 2.5$ to $L \sim 6$ and roughly ± 15° around the longitude of the station. Multi-component whistlers propagating on paths distributed over a significant fraction of this region may be used to identify radial and longitudinal irregularities in electron density, bulk motions of the plasma, and the position and displacements of the plasmapause.*

INTRODUCTION

This paper briefly outlines the whistler method of studying certain properties of the thermal plasma of the magnetosphere. A few examples of recent experimental results are presented.

For reference, Figure 1 shows an equatorial cross-section of the inner magnetosphere and an estimate of the average position of the plasmapause during July, 1963 periods of moderate, steady magnetic agitation ($K_p = 2\text{-}4$) (from [CARPENTER, 1966]). The plasmapause is indicated by a heavy line, and a dashed line shows the approximate equatorial 'viewing area' of the Eights, Antarctica whistler receiver. The area, shown for illustration at 04 LT, extends from roughly $L = 2.5$ to $L = 6$ and over a range of ±15° in longitude around the longitude of the station.

Some examples of applications of the whistler method within the plasmasphere are illustrated in Figure 2, which again shows equatorial viewing areas. Figure 2*a* presents a case in which the plasmapause is assumed to be at $L \geqq 6$, so that the entire viewing area is within the plasmasphere. Whistlers observed at the ground station are propagating along a set of whistler ducts whose equatorial intercepts are shown by ellipsoidal symbols. (Duct cross-sections elongated by $\sim 4{:}1$ in longitude were inferred by ANGERAMI [1970] from a study of Ogo-3 VLF data.)

---

*Paper presented at the Symposium on "Comparison of the magnetospheric behavior with ground observations and new indices of geophysical activities." I.A.G.A. General Assembly (Madrid, 1-12 September 1969).

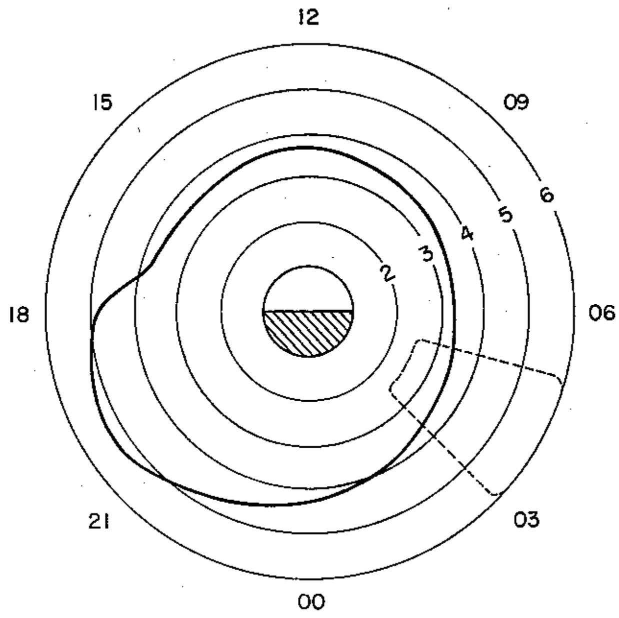

FIG. 1

Equatorial cross section of the inner magnetosphere showing (solid curve) an estimate of the average position of the plasmapause during periods of moderate steady magnetic agitation ($K_p = 2\text{-}4$) (from [CARPENTER, 1966]). The dashed line shows the approximate equatorial "viewing area" of the Eights, Antarctica whistler receiver at a local time of 04 *LT*. The estimates of plasmapause position were obtained from Eights whistler data for July 1963.

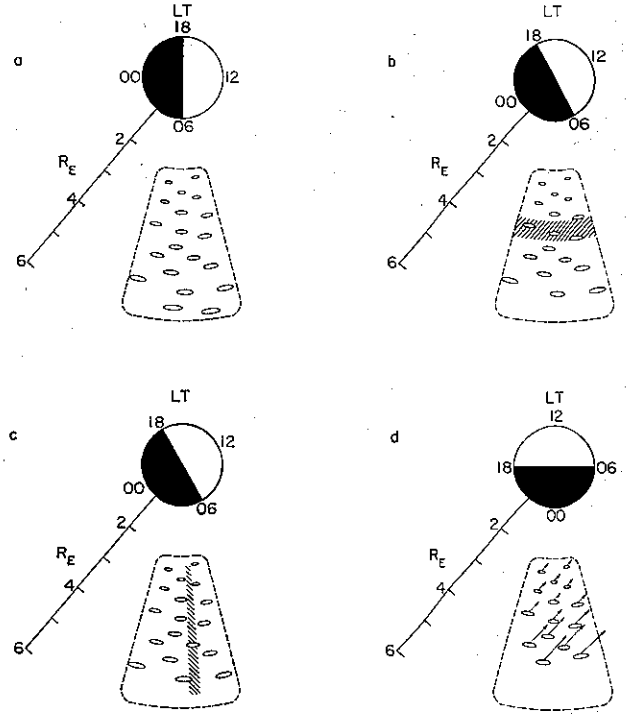

FIG. 2

Equatorial viewing areas showing examples of applications of the whistler method within the plasmasphere. Ellipsoidal symbols indicate the equatorial intercepts of whistler ducts: *a)* Illustration of quiet-time conditions and relatively small longitudinal electron-density gradients; *b)* Illustration of the presence of a region of irregular behaviour in radial electron-density gradients (shading near 4 R_E); *c)* Illustration of a region of large longitudinal gradients separating the viewing area into 2 density "sectors" with sensibly different scale values of electron density; *d)* Illustration of magnetospheric convection within the viewing area. As presently applied the whistler method detects the cross-*L* component of this convection.

Figures 2*b*, 2*c* and 2*d* represent relatively more active magnetic conditions than Figure 2*a*. Expected decreases in size of the plasmasphere are indicated schematically by a reduction in the number of ducts near $L = 5\text{-}6$. (Ducts are frequently observed outside the plasmapause, but this effect is not treated here in detail.)

The whistler method of determining magnetospheric electron density from multi-component whistlers provides information on path *L* value, but not on path longitude (see ANGERAMI [1966], or CARPENTER and SMITH [1964]). Some information on longitude may be obtained through comparisons of whistler intensity at spaced stations, or through evidence of the drift of whistler paths into or out of the viewing area of a station. These techniques are promising, but not yet well developed.

Suppose in the case of Figure 2*a* that longitudinal electron-density gradients are small compared to prevailing radial gradients, and that the radial gradients are themselves relatively well behaved. Then equatorial electron-density 'profiles,' determined from whistler signals propagating simultaneously along a number of paths, will have a form such as that shown in Figure 3 (adapted from [ANGERAMI and CARPENTER, 1966]). Such profiles are probably applicable more or less throughout the longitude range

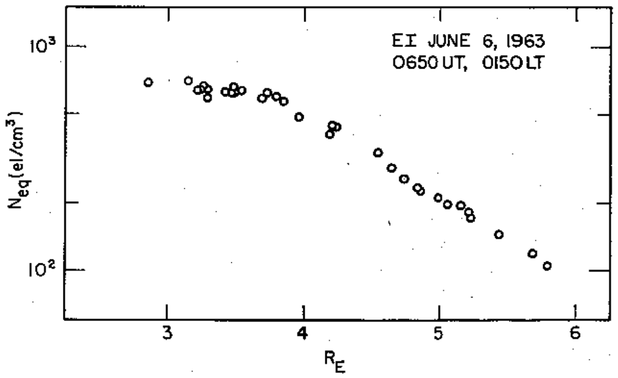

FIG. 3

Example of a quiet-day equatorial electron-density profile (adapted from [ANGERAMI and CARPENTER, 1966]). All of the measurements represent positions within the plasmasphere.

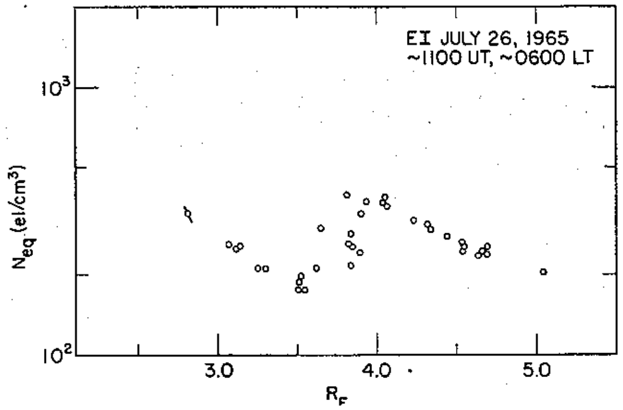

FIG. 4

Profile of equatorial electron density versus geocentric distance indicating an outlying peak in electron density.

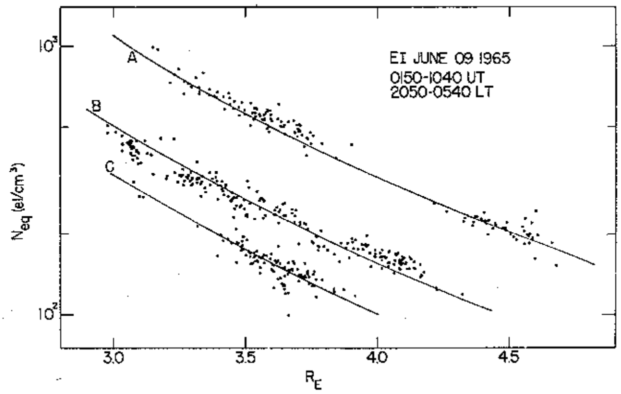

FIG. 5

Composite of a sequence of observations of equatorial electron density versus geocentric distance in the plasmasphere showing the existence of three distinct density levels within the longitudinal viewing range of the Eights, Antarctica whistler receiver. The individual observations were made several minutes apart and extended over a period of 9 hours. The curves A, B, and C were "fitted" on the assumption that for each distinct group of data points, electron content in a tube of ionization (above 1000 km) is constant with tube geocentric equatorial radius. (See the original reference [PARK and CARPENTER, 1970] for further details.)

of the station, in spite of the lack of information on longitude of the individual path intercepts.

Suppose now that longitudinal gradients continue to be small, but that within the L range of the receiver there is a region of irregular behaviour in the radial gradients. Such a region is shown schematically in Figure 2*b* by shading, and is illustrated by the data plotted in Figure 4 (from [PARK and CARPENTER, 1970]). The latter figure depicts an outlying peak in the equatorial distribution of ionization. The data points first show a decrease in density with distance between 2.8 R_E and 3.5 R_E, then an increase by a factor of ~ 2 to a peak near 4 R_E, and then a further decrease.

Consider now that radial gradients within the viewing range are relatively well behaved, but that there are one or more regions of large longitudinal gradients that divide the viewing area into density 'sectors,' with sensibly different scale values of electron density. This effect is indicated schematically in Figure 2*c* by shading. An example of this phenomenon is illustrated in Figure 5, which shows in composite form a series of equatorial electron-density measurements made over a period of several hours on June 9, 1965 (from [PARK and CARPENTER, 1970]). In this case the measurements cluster at three relatively distinct 'levels.' It is believed that irregular structures of the type suggested in this figure and in Figure 4 are attributable to the combined effects of protonosphere-*F* region coupling processes and perturbing convection electric fields in the magnetosphere [PARK and CARPENTER, 1970].

Consider what happens when there is a departure from simple co-rotation of the magnetospheric plasma, and in particular a cross-L drift. This effect is illustrated schematically in Figure 2*d* by arrows showing the convection velocity vectors of various whistler paths as viewed from the co-rotating ground station. The convection drift $\vec{v} = \vec{E} \times \vec{B}/B^2$ takes place in the inhomogeneous geomagnetic field, so that for a convection electric field $\vec{E}$ that is roughly homogeneous over a distance of one or two earth radii, the magnitude of equatorial drift velocity is proportional to R^3, and path displacements at the larger L values will be much larger than those at the earthward edge of the viewing area.

The whistler method depends upon the existence of a set of whistler ducts whose positions (and propagation characteristics) change slowly with respect to the rate of whistler occurrence. Gradual changes in the dispersion properties of the received whistlers are used to detect the corresponding changes in L parameter and electron density on the drifting paths. The method is illustrated in Figure 6, which shows a 3-hour-long, small-amplitude drift event that took place during a relatively calm period in the recovery phase of a weak magnetic storm (from [CARPENTER, 1966]). (This drift is possibly attributable to an enhanced large-scale convection field that underlies the larger perturbing substorm drift events.) The changes in whistler dispersion are summarized in the tracings at the lower right, which compare the frequency-time curves of a particular whistler component at the beginning and end of the 3-hour period. The actual spectra are illustrated at the top left by the spectrum (0-10 kHz vs. time) of a whistler recorded at 00 LT. This spectrum is followed by a series of spectral segments recorded roughly ten minutes apart over the 00-03 LT periods,

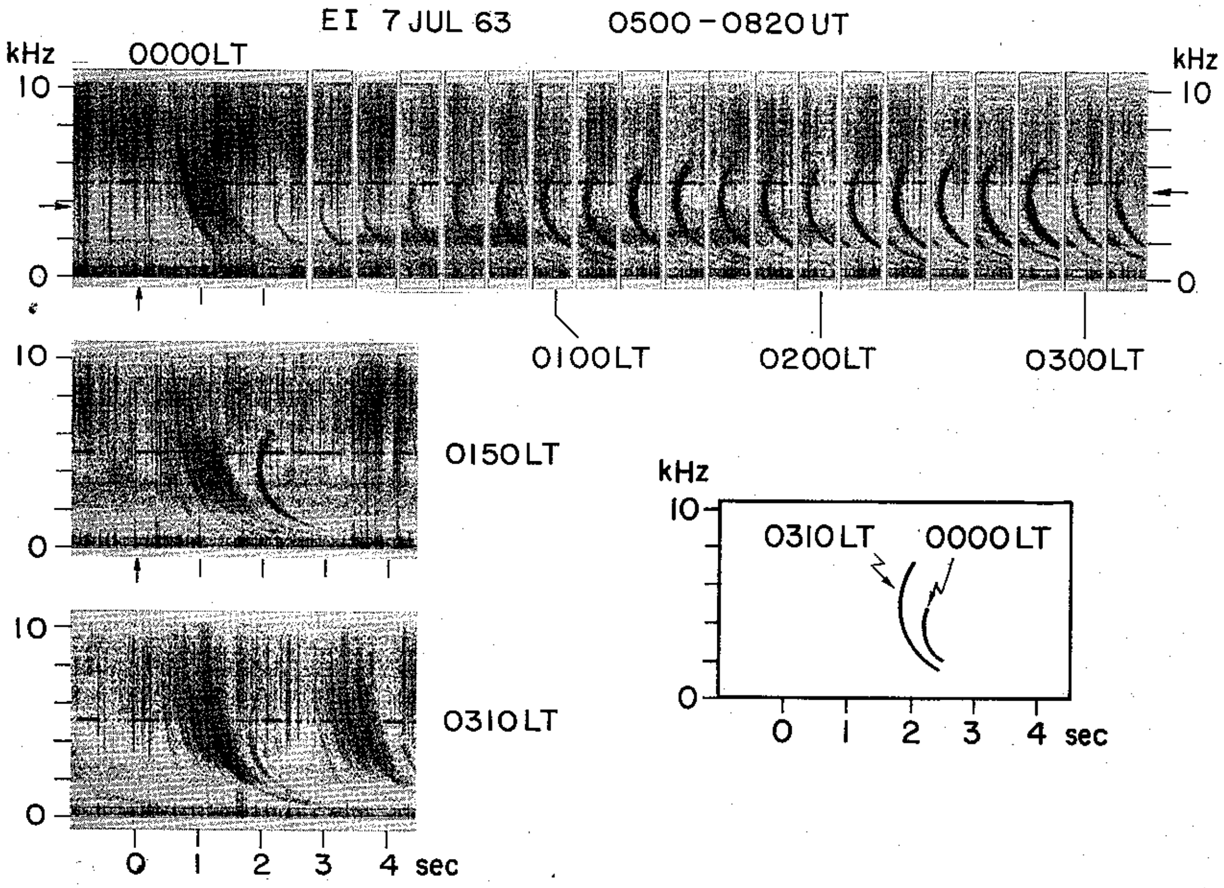

FIG. 6

Spectrograms illustrating the whistler method of detecting cross-L drifts of whistler paths in the magnetosphere (from CARPENTER, [1966]). See text for details.

but showing only the whistler component with initial nose frequency near 3.7 kHz (arrow at upper left). During the 3-hour period the nose frequency of this whistler component rises more or less steadily to a value of ~ 4.7 kHz (indicated at the right by an arrow). In a dipole field this corresponds to a displacement from $L \sim 4.6$ to $L \sim 4.2$. The reduction in whistler travel time associated with the drift is illustrated by the three whistlers aligned vertically at the left-hand side of the page. The travel time to the whistler nose at 00 LT (upper left) is ~ 2.2 sec, and in the later events of 0150 and 0310 LT (middle and lower left) decreases to a value of ~ 1.9 sec.

Simultaneous motion on paths distributed relatively widely in L space is illustrated in Figures 7 and 8, which show a cross-L drift event associated with a substorm (from [CARPENTER and STONE, 1967]). Figure 7 shows the measured variations in nose frequency (f_n) versus time on 15 paths labeled A through O. The length of time during which f_n for a path could be tracked varied widely, but it

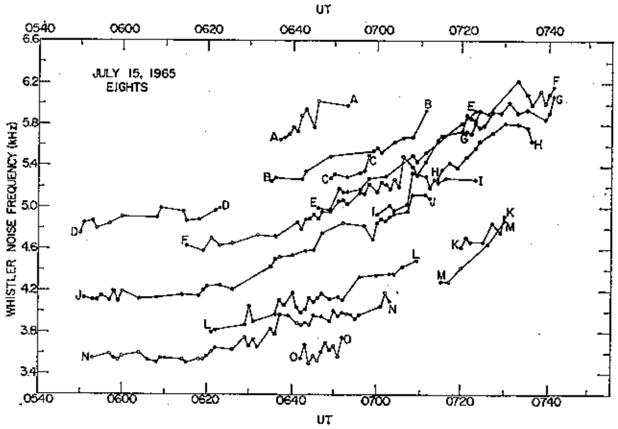

FIG. 7

Measured variations in whistler nose frequency during a cross-L drift event associated with a substorm. Letters indicate the time intervals in which various paths or ducts could be separately identified.

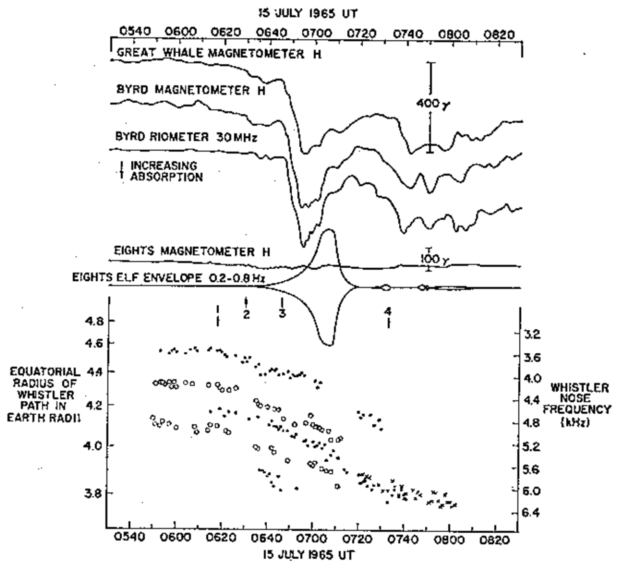

FIG. 8

Whistler path drifts during a substorm (bottom) and a variety of geomagnetic indices (above) indicating certain features of the substorm (from [CARPENTER and STONE, 1967]). The whistler data are replotted from the more complete data of Figure 7.

appears that all of the paths participated in a trend to increasing nose frequency that began at ~ 0620 UT. Data from paths *A*, *B*, *D*, *F*, *J*, *K*, *N* and another not shown in Figure 7 are replotted in Figure 8 (below) in coordinates of equatorial radius versus time (radius decreases as nose frequency increases). In the upper part of Figure 8 are transcriptions of certain information on magnetic activity, ionospheric absorption, and micropulsations recorded at the conjugate pair Great Whale and Byrd Stations ($L \sim 7$) and at Eights, Antarctica ($L \sim 4$, ~ 1 hour ahead of Byrd in magnetic local time). The displacement of whistler paths to smaller earth radii apparently begins some 10 to 30 minutes before the main substorm bay as indicated by the Byrd and Great Whale magnetometers. Details of this event are described in the original reference [CARPENTER and STONE, 1967].

Consider now that the plasmapause is well within the viewing area of the receiver, as indicated in Figure 1. Figures 9 and 10 show some results on the variation with L and dipole latitude, respectively, of equatorial electron density and tube electron content, (i.e., total electrons in a tube of magnetic flux with cross section 1 cm^2 at 1000 km and extending from 1000 km to the magnetic equator) [ANGERAMI and CARPENTER, 1966]. The figures are scatter plots of several days of measurements in the afternoon sector (open circles) and in the post midnight sector (filled circles) during conditions of moderate, steady magnetic activity (K_p = 2-4). The estimated uncertainty in

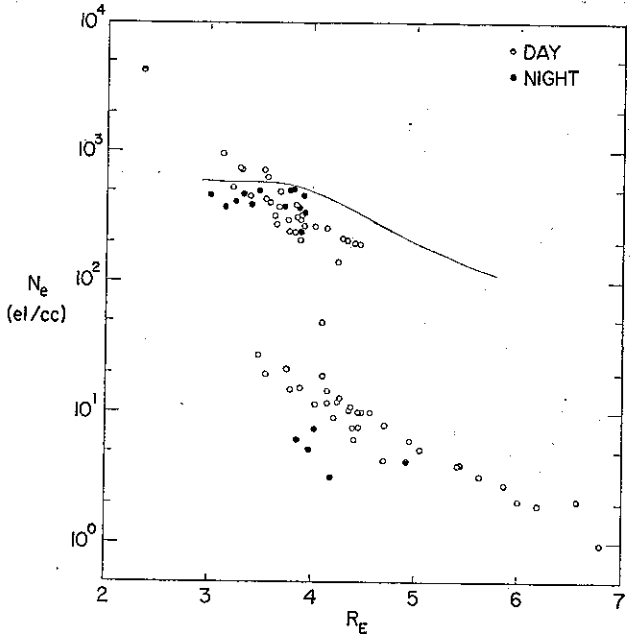

FIG. 9

Whistler measurements of equatorial electron density versus geocentric distance showing the presence of the plasmapause. This is a scatter plot of several days of measurements in the afternoon sector (open circles) and in the post midnight sector (filled circles) during conditions of moderate, steady magnetic activity (K_p = 2-4). The whistler measurements were made at Eights, Antarctica.

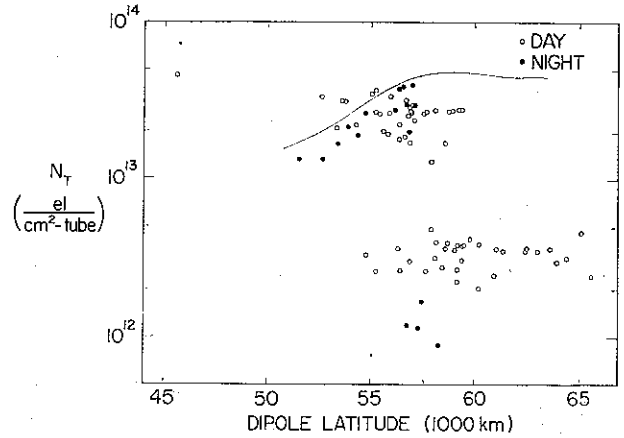

FIG. 10

Whistler measurements of total electron content in a tube of force (above 1 cm^2 at 1000 km and extending to the equator) versus dipole latitude at 1000 km. This is a scatter plot of several days of measurements in the afternoon sector (open circles) and in the post midnight sector (filled circles) during conditions of moderate, steady magnetic activity in 1963 (K_p = 2-4). The whistler observations were made at Eights, Antarctica.

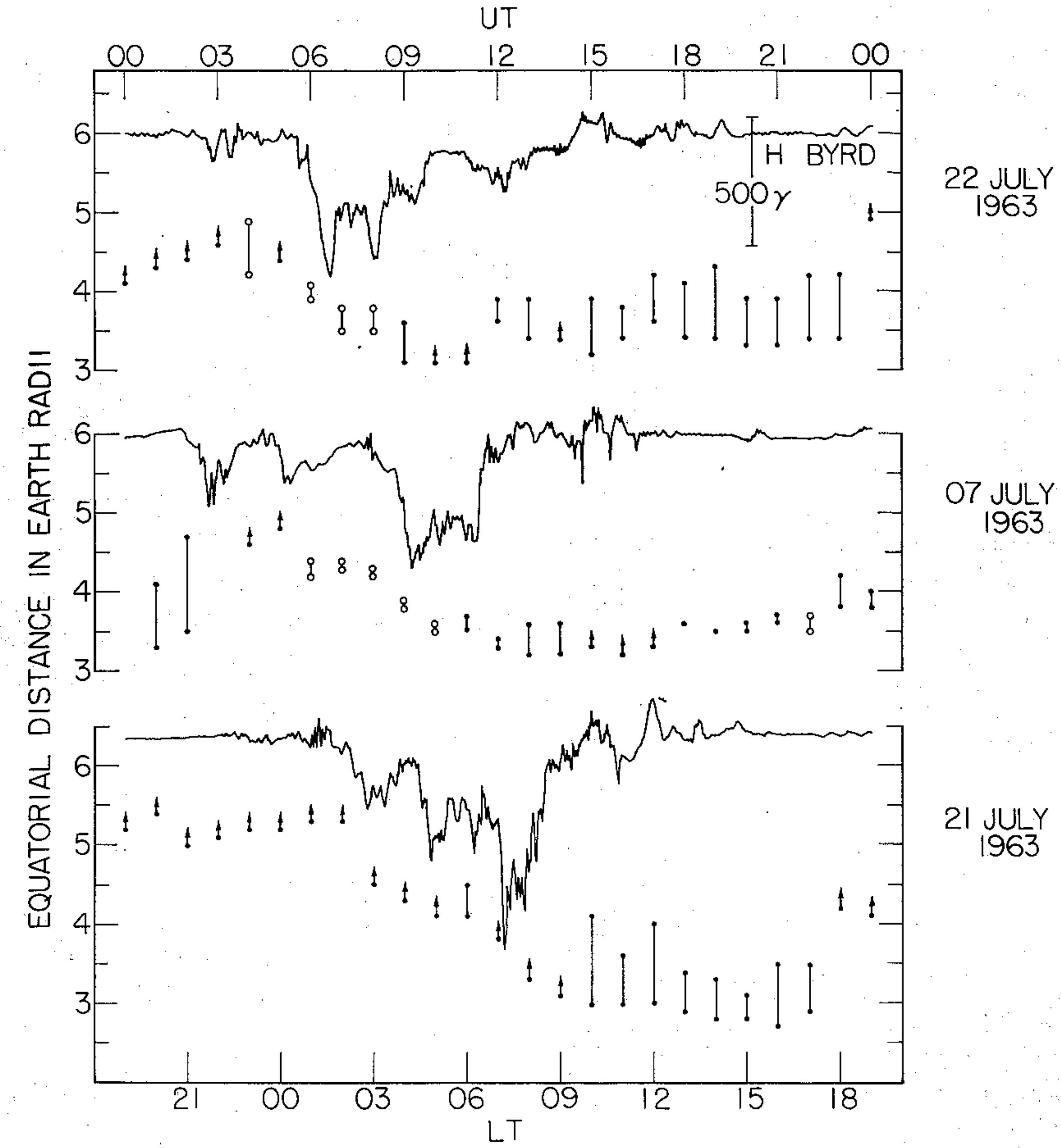

FIG. 11

Comparison of temporal variations in the position of the plasmapause and magnetic substorm activity during three 24-hour periods, illustrating the tendency for a minimum plasmapause radius to be achieved at roughly the time of termination of the main magnetic bay activity. The substorm index is the *H* component at Byrd Station (located roughly 1 hour from the Eights whistler station in magnetic local time).

absolute value of electron density is ±30 % in equatorial density and ±20 % in electron tube content [ANGERAMI, 1966]. (The continuous curve is taken from the quiet-day data of Fig. 3.)

The plasmapause profile appears to be steepened during brief, severely disturbed periods, and then to be in the process of 'relaxing' at all other times (see, for example [CHAPPELL et al., 1970]). The various processes tending to reduce the density gradients work relatively slowly, permitting continued identification of the plasmapause during many relatively quiet periods. During prolonged quieting there may be plasmapause 'effects' at several positions, the inner ones carrying the 'imprint' of previous storm-time conditions, while the outer ones reflect the presence of new, quiet-time conditions of plasmapause 'generation' at larger radii.

Efforts to track certain types of displacements of the plasmapause appear promising. For example, it appears that the plasmapause is displaced inward on the nightside of the earth in a manner roughly consistent with observed cross-L drifts of the plasma within the plasmasphere. Figure 11 shows three 24-hour periods during which the position of the plasmapause and magnetic substorm activity are compared. Approximate local time is indicated at the bottom of the figure. The substorm index is the H component at Byrd Station, located roughly 1 hour from the whistler station in magnetic local time. The whistler-based estimates of plasmapause radius involve a variety of symbols, either bracketing the position (2 symbols connected by a line) or indicating an inner limit (arrows). The figure shows pronounced substorm bay activity at local times varying from the immediate post-midnight period in the upper panel (22 July) to post dawn in the lower panel (21 July). The inward displacements of the plasmapause exhibit a similar variation, the main effect being the achievement of a minimum radius at roughly the time of termination of the main bay activity. Such displacements are consistent with the known features of cross-L convection within the plasmasphere [Carpenter and Stone, 1968]. When more is learned about the detailed relationship between plasmapause displacements and magnetospheric convection, it may be possible to use rather detailed boundary measurements for purposes of monitoring certain features of the convection.

Another application of plasmapause-position measurements is illustrated in Figure 12, which shows how the westward end of the dusk-side bulge in the plasmasphere is detected. It has been found that although the bulge is an essentially permanent feature of the plasmasphere, located in an average sense near the dusk meridian, it in fact moves back and forth in local time in synchronism with substorm activity, surging sunward during substorms and

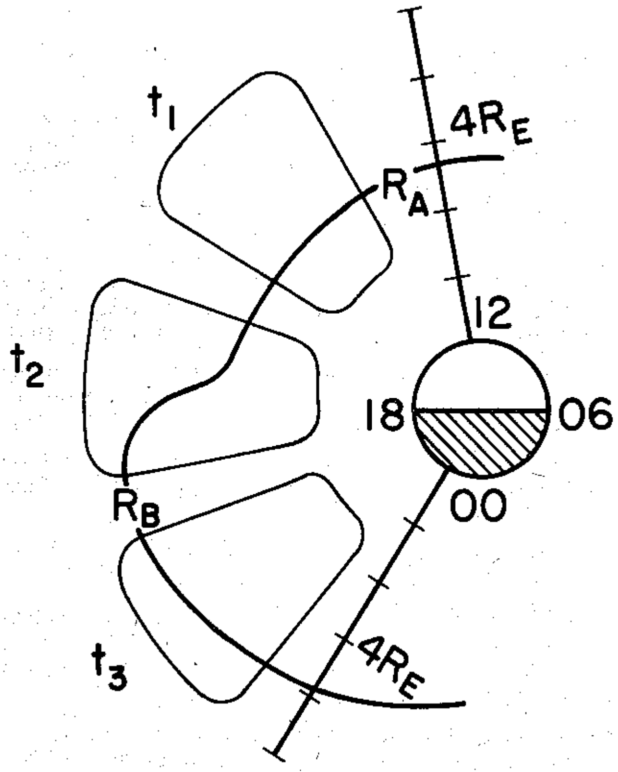

FIG. 12

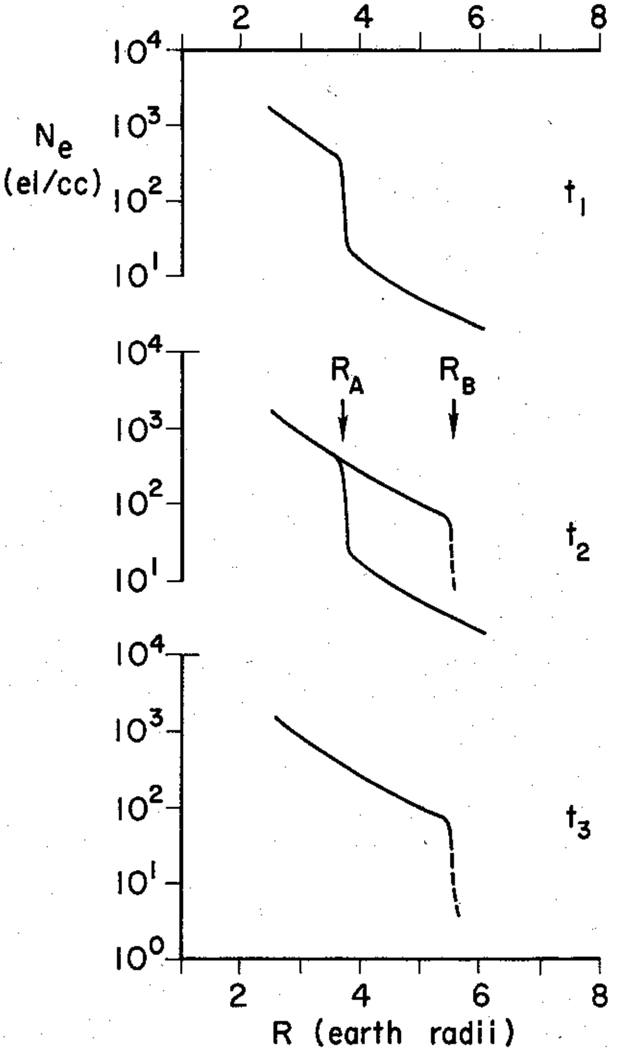

FIG. 12

Illustration of the whistler method of detecting the westward end of the dusk-side bulge in the plasmasphere (from [Carpenter, 1970]).

tending to move in the direction of the earth's rotation during quieting [CARPENTER, 1970]. It is inferred that the sunward surges of the bulge represent a sunward convection of the bulge plasma and hence a penetration of convection electric fields deep within the plasmasphere.

The method of detecting the local time of bulge encounter is illustrated in Figure 12 by a sketch of the Eights, Antarctica viewing area at three successive times, t_1, t_2, t_3. At the right of Figure 12 are sketches of equatorial electron-density profiles deduced from multipath whistlers recorded at times t_1, t_2, t_3. In mid-afternoon at t_1 the electron-density profile shows the plasmapause to be at an equatorial distance R_A. At time t_2 the viewing area embraces both the sunward edge or shoulder of the plasma bulge and nearby features of the plasma trough. Since the equatorial intercepts of whistler paths are distributed over a range of longitudes, the inferred electron-density profile is now double-valued, with a knee as before at R_A, but also a high density extension beyond R_A to some point R_B, where a knee may either be evident or where propagation showing high densities may simply terminate. The difference $R_B - R_A$ is usually in the range 0.5-2.5 R_E. The length of time during which overlapping or double profiles are observed varies from minutes to several hours, with most cases in the range 20-60 minutes. (Note that the distribution of ducts in Figure 2 is an idealization. The fraction of the viewing area occupied at any time by 'active' ducts varies in a complicated way with magnetic activity, local time, lightning-source activity, and season.)

At time t_3 the viewing area is well into the bulge region. High plasma densities are seen to well beyond R_A, although for various reasons the knee at R_B may not be well defined in the data.

This concludes a brief introduction to whistler methods of studying magnetospheric behaviour. There has been only brief mention of second generation studies, and no discussion of subjects such as the whistler amplitude spectrum and triggering of VLF emissions by whistlers. Some references to work in these areas are included in the bibliography.

ACKNOWLEDGMENTS

This research was supported in part by the Office of Antarctic Programs of the National Science Foundation under grants GA-1151 and GA-1485 and in part by the Atmospheric Sciences Section of the National Science Foundation under grants GA-775 and GA-10719.

Manuscrit reçu le 30 novembre 1969.

REFERENCES

ANGERAMI J. J., "A whistler study of the distribution of thermal electrons in the magnetosphere," PhD Thesis, Stanford University, Stanford, Calif., 1966.

ANGERAMI J. J., "Whistler duct properties deduced from VLF observations made with the OGO-3 satellite near the magnetic equator," (in press, *J. Geophys. Res.*, 1970).

ANGERAMI J. J. and CARPENTER D. L., "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**, 711-725, 1966.

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**, 693-709, 1966.

CARPENTER D. L., "Whistler evidence of the dynamic behavior of the dusk-side bulge in the plasmaphere," (in press, *J. Geophys. Res.*, July 1970).

CARPENTER D. L. and SMITH R. L., "Whistler measurements of electron density in the magnetosphere," *Rev. of Geophys.*, **2**, 415-441, 1964.

CARPENTER D. L. and STONE K., "Direct detection by a whistler method of the magnetospheric electric field associated with a polar substorm," *Planet. Space Sci.*, **15**, 395-397, 1967.

CARPENTER D. L. and STONE K., "Recent whistler research on hydromagnetic motions in the plasmasphere," Paper presented at International Symposium on the Physics of the Magnetosphere, Washington, D.C., September 1968.

CARPENTER D. L., "Ducted whistler-mode propagation in the magnetosphere; a half gyrofrequency upper intensity cutoff and some associated wave growth phenomena," *J. Geophys. Res.*, **73**, 2919-2927, 1968.

CHAPPELL R., HARRIS K. K. and SHARP G. W., "A study of the influence of magnetic activity on the location of the plasmapause," *J. Geophys. Res.*, **75**, 50-56, 1970.

HELLIWELL R. A., *Whistlers and Related Ionospheric Phenomena*, Stanford University Press, Stanford, California, 1965.

HELLIWELL R. A., "Low-frequency waves in the magnetosphere," *Rev. of Geophys.*, **7**, 281-303, 1969.

LIEMOHN H. B., "The cyclotron resonance amplification of whistlers in the magnetosphere," Rept. D1-82-0713, Boeing Scientific Research Labs., Geo-Astrophysics Lab., Seattle, Washington, April 1968.

PARK C. G. and CARPENTER D. L., "Whistler evidence of large scale electron density irregularities in the plasmasphere," (in press, *J. Geophys. Res.*, July 1970).