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WHISTLER STUDIES OF THE PLASMASPHERE SHAPE AND DYNAMICS

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ABSTRACT

Whistler studies of the plasmapause/plasmasphere are traced from their beginnings during the IGY through the early 1960's, when extensive data from Antarctica became available. Highlights of this period include discovery of the 'knee' in the equatorial electron density profile, initial comparisons with results from the Lunik probes, identification of magnetic storm effects, and discovery of the duskside bulge, or region of larger plasmasphere radius, as well as smaller-scale ($\Delta\phi \approx 20°$) variations in radius with longitude. In the mid-1960's, whistlers provided the first evidence of cross-L plasma drift patterns in the outer plasmasphere. From a present day perspective, the plasmasphere is seen as a region penetrated, perhaps most efficiently in the dusk sector, by the unsteady component of high latitude electric fields. In the pre-dawn sector, post substorm outward drifts may be an aftereffect of the shielding of the plasmasphere against the steadier components of the substorm electric fields. The available indirect whistler evidence of plasmasphere erosion during large disturbances suggests that erosion occurs primarily in the dusk-premidnight sector.

INTRODUCTION

This topical review is intended to provide both historical and present-day perspectives on whistler observations of the plasmapause/plasmasphere. An effort has been made to bring out historical facts that are not widely known, and to discuss a number of current scientific problems that are of significance to magnetospheric physics, but which have not been discussed in the recent scientific literature.

Notes on The Whistler Method of Measuring Magnetospheric Electron Density

The whistler method of investigating magnetospheric electron density is commonly used to provide estimates of electron density over a range of altitudes at the magnetospheric equator /1,2,3,4/. When this range of altitudes includes the region of plasmaspause density gradients, the position and electron density profile of the plasmapause may be studied /5/. Figure 1 shows a diagram of the method, comparing the idealized frequency-time spectra and analysis of a whistler propagating entirely within the plasmasphere (a, b, c) with corresponding results for a 'knee' whistler (d, e, f), which propagates on paths that thread the region of plasmapause density gradients. Figure 2 shows spectrograms of both types of whistler, recorded at Siple Station, Antarctica.

PLASMAPAUSE/PLASMASPHERE STUDIES; HISTORICAL PERSPECTIVES

Early Whistler Recording Programs

The detection of the plasmapause or 'knee' in the equatorial density profile was based upon complementary data from two sources, the Whistlers West IGY Network in the U.S./6/ and recordings at Byrd Station, Antarctica (maps of Figure 3). The IGY network (Figure 3*a*), which began operations in 1957, had the advantage of station locations in the $L = 2$ - 3.5 range, where later research /7/ found the plasmasphere to be frequently located under magnetic conditions typical of the highly disturbed IGY period. The whistler activity was sporadic, but a synoptic recording program of 2 min/hr at each station was pursued over

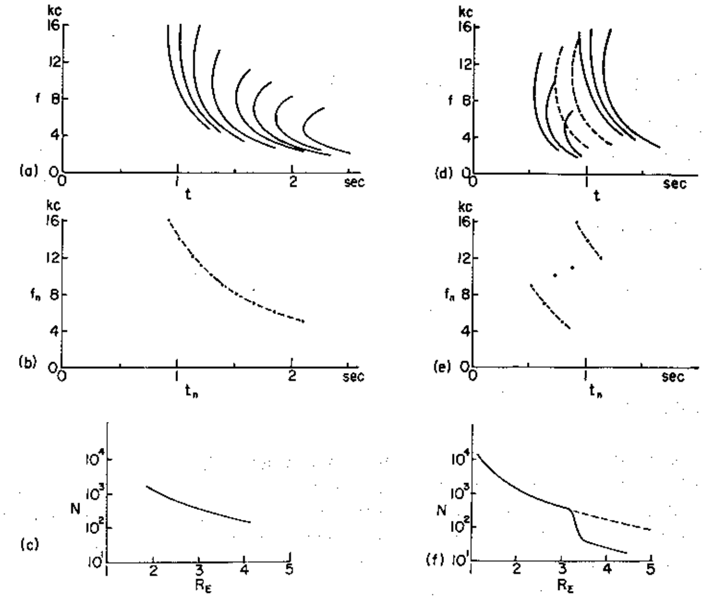

Fig. 1. Diagram of whistler spectra (top), loci in f - t space of the measured frequencies of minimum travel time ('nose' frequencies) (middle), and inferred magnetospheric equatorial profiles (bottom). At left is an example of propagation entirely within the plasmasphere, at right the condition of propagation on both sides of the plasmapause. Adapted from /5/.

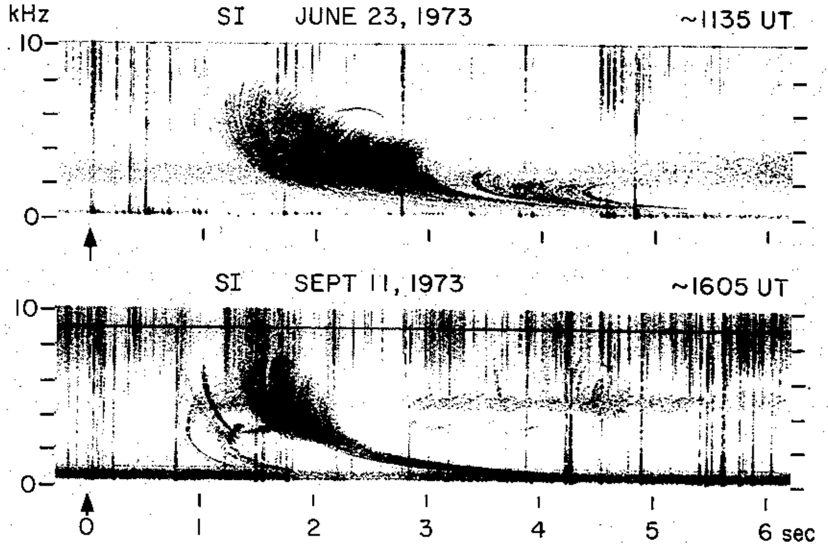

Fig. 2. Spectrograms from Siple Station, Antarctica, showing examples of the two kinds of whistlers diagrammed in Figure 1. Adapted from /4/.

extended periods, and sufficient resources were available to provide for aural monitoring of tapes and production of survey spectrograms.

At Byrd Station, where regular recording began in 1959, much higher whistler rates and more persistent activity were found, thanks in part to the high rates of lightning source activity in the eastern U.S. and Canada, and to the fact that the earth's dipole and spin axes are ~ 11 - 14° apart at the Byrd meridian, such that lightning in the north at a given geographic latitude illuminates paths whose entrance points are at significantly higher magnetic latitudes. The Antarctic work presented new problems in terms of field personnel requirements and station support; these in turn were solved through the efforts of many individuals and the support of the interested agencies, notably the National Science Foundation and the U.S. Navy.

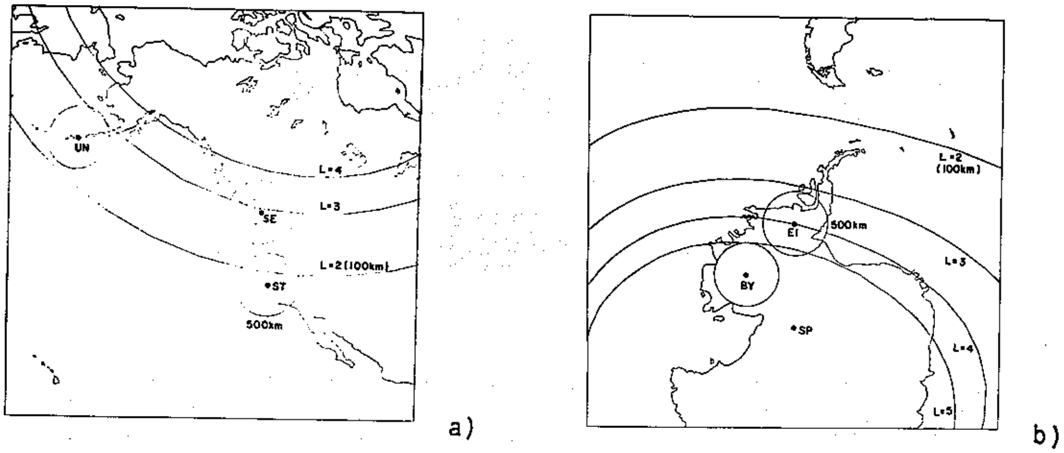

Fig. 3. (a) Map showing the Whistlers West IGY stations located at Stanford (ST), Seattle (SE), and Unalaska (UN). (b)Map showing the locations of Antarctic stations Byrd (BY) and Eights (EI). The circles of 500 km radius illustrate the effective area, or distance over which a whistler or VLF emission component of average strength would spread before disappearing into the backround noise.

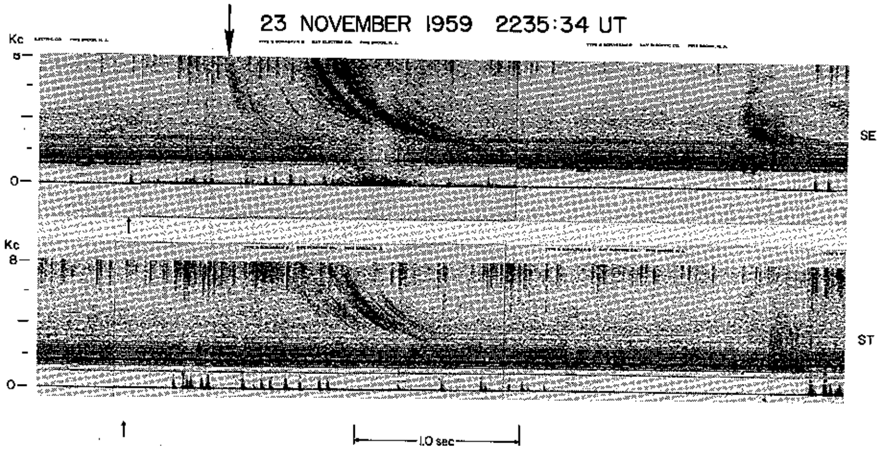

Fig. 4. Spectrograms of a multipath (multicomponent) whistler observed at Seattle (above) and Stanford, showing differences indicative of a plasmapause effect. The time of the causative atmospheric is indicated by arrows. Adapted from /5/.

Highlights of Whistler Results, 1958-1962

A common (but not routine) practice in the IGY period was the comparison of spectra of whistlers recorded simultaneously at spaced stations, such as Stanford and Seattle (Figure 3). In such cases, the whistler components with the lowest travel times were often observed at the lower latitude station only, having propagated on field-aligned paths with ionospheric endpoints relatively close to that station. However, in data from 14 January 1958, an apparent anomaly was observed, in which a whistler recorded at Seattle exhibited components with lower travel times than any recorded in a simultaneous event at Stanford. This raised the possibility that some type of highly irregular plasma density distribution existed at that time in the propagation medium. Figure 4 provides a clearer example of this type of comparison, recorded in 1959. The upper panel shows the Seattle (SE) record; some of the earlier arriving components are indicated by an arrow. Only the later arriving components are identifiable on the Stanford (ST) record below.

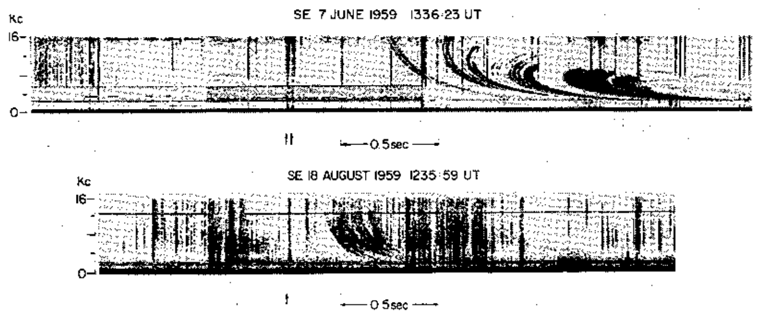

Fig. 5. Spectrograms from Seattle comparing an unusually well defined whistler propagating within the plasmasphere (above) to a whistler with much lower travel times observed during the magnetic storm of 18 August 1959. The times of the causative atmospherics are indicated by arrows. From /8/.

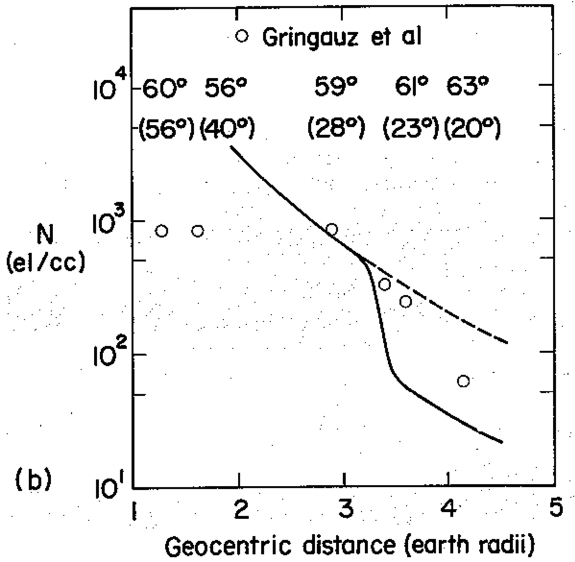

Fig. 6. Comparison of ion densities measured by the ion traps on Lunik 2 with an idealized equatorial electron density profile from whistlers showing a region of steep gradients near 3.5 earth radii.The numbers with and without parentheses represent, respectively, the approximate invariant latitudes and the latitudes associated with the ion measurements. From /11/.

This finding and other occasional observations of a similar type assumed additional importance when the 1959 Byrd, Antarctica (BY) data became available. These data, as noted, were characterized by high whistler rates. Furthermore, they contained many examples of events in which the individual whistler components were not mutually separated, as in Figure 1*a*, but tended to cross one another, as in Figure 1*d*. This again suggested density irregularity, but in a clearer way than before. Byrd (Figure 3*b*) could observe whistler components propagating poleward from a wide range of whistler path endpoint latitudes; components representing the higher latitude paths tended to be more completely defined on Byrd spectrograms than were the (lower-L-shell) components typically received at the Whistlers West stations, where only the the lower-frequency portions of the nose-like whistler form (as in Figure 4) were often observed.

The interpretation of the irregular whistlers in terms of a knee in the equatorial density profile developed quickly as the result of another finding from whistlers, namely evidence of deep, factor of ~ 10, depressions in electron density during magnetic storms of the IGY and post IGY period /8,9/. This effect was first identified, thanks to a suggestion by Alex Dessler, in data from a storm of 18 August 1959, and was subsequently found in data from a number of storms of the period, including the famous event of 11 February 1958. Figure 5, lower panel, shows a whistler recorded at Seattle during the 18 August 1959

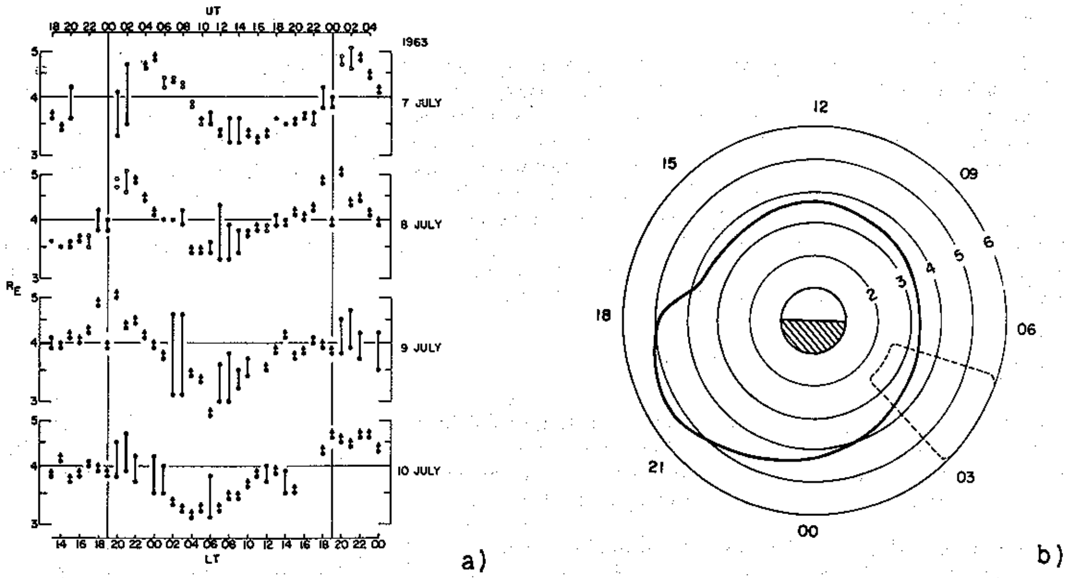

Fig. 7. (a) Diurnal variation of the geocentric distance to the plasmapause during a four day period in July, 1963. (b) Average equatorial position of the plasmapause versus magnetic local time during periods of moderate, steady agitation (Kp≈ 2 - 3) in 1963. The dashed curve shows the estimated limiting extent, at a given time, of the magnetospheric region within which whistler propagation was observable at Eights station /12/.

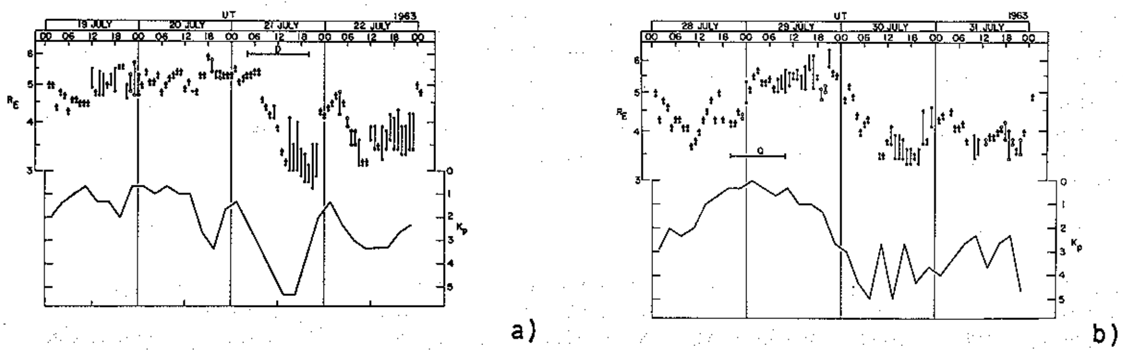

Fig. 8. Variation of the geocentric distance to the plasmapause during two four day periods in July, 1963, in each case showing a transition from quiet magnetic conditions to a weak magnetic storm. Kp is plotted below with values increasing downward. From /12/.

magnetic storm. The travel times of its various components are a factor of about 3 shorter than those of the exceptionally well defined multicomponent whistler shown above, which was also recorded at Seattle, but during a magnetically calm period.

It became clear during the course of 1960 that the deep density depressions occurred outside some dense inner region, and that the inner region was sometimes so reduced in size that propagation was being detected in the outer region only, as happened to be the case in the event of Figure 5, lower panel. In these terms the irregular whistlers with overlapping components were recognized as 'knee whistlers,' that is, as cases in which detectable propagation occurred on both sides of a knee in the electron density profile. It also became clear that the knee, as in the case of the aurora at higher invariant latitudes, was located deeper within the magnetosphere during the greater magnetic disturbances. This finding, as well as the increasing frequency with which knee whistlers were being recognized in the data, provided a basis for belief that the knee, like the aurora, was an essentially permanent feature of the magnetosphere /5/.

The Lunik Results

In 1962 we at Stanford became aware of the work of Gringauz and his colleagues /10/, whose ion traps on the 1959 Lunik 1 and 2 probes had detected a sharp decrease at several R_E in the concentration of thermal ions. Both the numerical values of ion concentrations reported and the location of the steep density gradient were consistent with the whistler results. Figure 6 shows a comparison between reported Lunik 2 data /10/ and a profile characteristic of the whistler data, published following a meeting of the author and K. Gringauz at the 1963 U.R.S.I. Assembly in Tokyo /11/. The Lunik data, *in situ* in nature, and containing information on ion temperature as well as concentration, understandably strengthened our confidence in the findings from whistlers. At that time, the whistler technique was not widely known, being practiced by a relatively small number of workers, and the capabilities of the method, based in part as they were on the existence of relatively stable, field-aligned paths, were only beginnning to be widely discussed.

Eights Station and the 'Plasmapause'

The next major advance in recording activity was the establishment of a Stanford University VLF program at Eights, Antarctica (Figure 3*b*). The Eights recordings, made during the years 1963 and 1965, exhibited the exceptionally high event rates already noted at Byrd, but in a latitude range substantially closer to the mean position of the knee, which was soon identified as $L \sim 4$.

The Eights austral winter data of 1963 provided much new information about the knee effect. Solar activity was low, and there occurred a series of weak ($\mathrm{Kp_{max}} \sim 5$ - 6) magnetic storms, each of which exhibited a multiday recovery phase during which magnetic agitation was moderate but relatively steady for several days in succession (Kp = 2 - 4). Whistler activity was present for most hours of the day, providing a previously unavailable opportunity to document the knee position versus time over periods of several days in succession. Figure 7*a* shows the results from the four day sequence 7-10 July 1963 /12/. The geocentric radius of the knee is indicated either by two bracketing points or by a limiting point with arrow. The results show both a distinctive diurnal pattern as well as remarkable day to day repeatability. Data from other recovery periods yielded similar results, making it possible to generate estimates of the average position of the plasmapause versus local time for conditions of moderate but steady agitation. The result is shown by the heavy curve in Figure 7b /12/. The most striking feature is the duskside bulge, which extends ~ 1 - 2 R_E or more beyond the minimum daily radius observed in the dawn sector.

In addition to this initial 'average' view, the new data also provided the first information on dynamic effects associated with quieting trends and intervals of rapidly increasing disturbance. Figure 8 shows two examples of changes in knee position during the onset of weak magnetic storms. Kp values are plotted increasing downward so as to show a parallelism with the knee effects. Again, as in the cases of steady agitation, there was a remarkable repeatability in the patterns. In both cases the knee was in the 5 - 6 R_E range during a deeply quiet period before the storm onset, but was rapidly displaced inward to the vicinity of $3.5R_E$ as the storm developed. The other storm events of 1963 studied also showed this general type of behavior.

The New Terminology

In 1963, the region of steep electron density gradients had been called the 'knee' /5/ because of the associated sharp change in slope of the electron density profile. However, as a picture of the worldwide morphology and dynamics of the knee began to develop, based on the new Eights data, it became clear that new terms were needed to express the idea of a large scale boundary effect. The term 'plasmapause' suggested itself, and was introduced, along with 'plasmasphere', 'plasma trough', and the somewhat unpleasant sounding word 'bulge', in the 1966 paper /12/ in which the new Eights data were first discussed. Figure 9*a* shows a figure used to summarize some of the results of that study. The terms plasmapause and plasmasphere quickly found their way into general use; they provided a terminological framework within which an increasing flow of data from high altitude spacecraft /13, 14/, as well as from measurements of apparently correlated 'trough' effects in the ionosphere /15, 16/, could be conveniently discussed.

Angerami's Studies of Electron Density and Tube Electron Content

Among highlights of the additional work on the Eights data in the 1965 - 1967 period were the radial profiles of electron density and latitudinal profiles of tube electron content obtained by J. J. Angerami as part of his thesis research at Stanford /17,18/. Figure 10*a* is a plot of equatorial electron density versus geocentric distance in earth radii, deduced from whistlers recorded during several of the 1963 periods when a well defined plasmapause was detected near L = 4 (adapted from /18/). The filled circles represent the post-midnight sector, while open circles represent afternoon. The solid curve is a smoothed version of a quiet-day profile measured during the same austral summer period. Of special interest, in addition to the factor of ~ 20 - 40 drop in density at the plasmapause, was the relatively large day-night difference in density level outside the plasmapause. This difference, percentagewise much larger than day-night

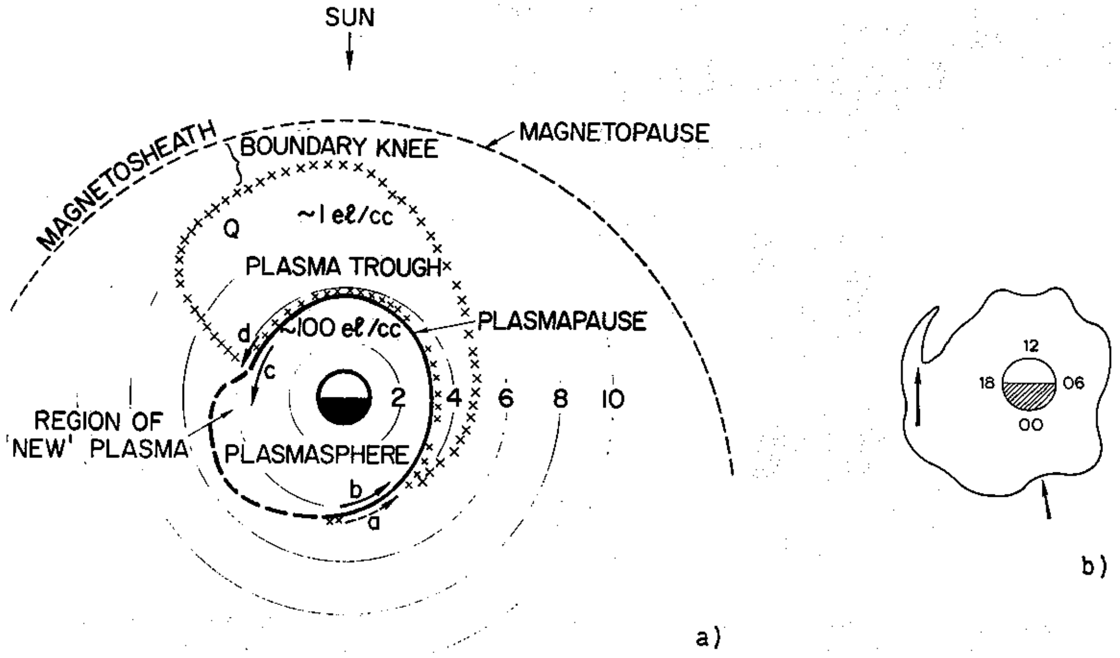

Fig. 9.(a) Diagram, published in 1966 /12/, showing the plasmapause/plasmasphere in equatorial cross section, as inferred from 1963 whistler data recorded during periods of moderate, steady agitation. (b) Sketch of the plasmapause equatorial radius, showing some irregular features believed to develop as the result of unsteady magnetospheric convection. From /55/.

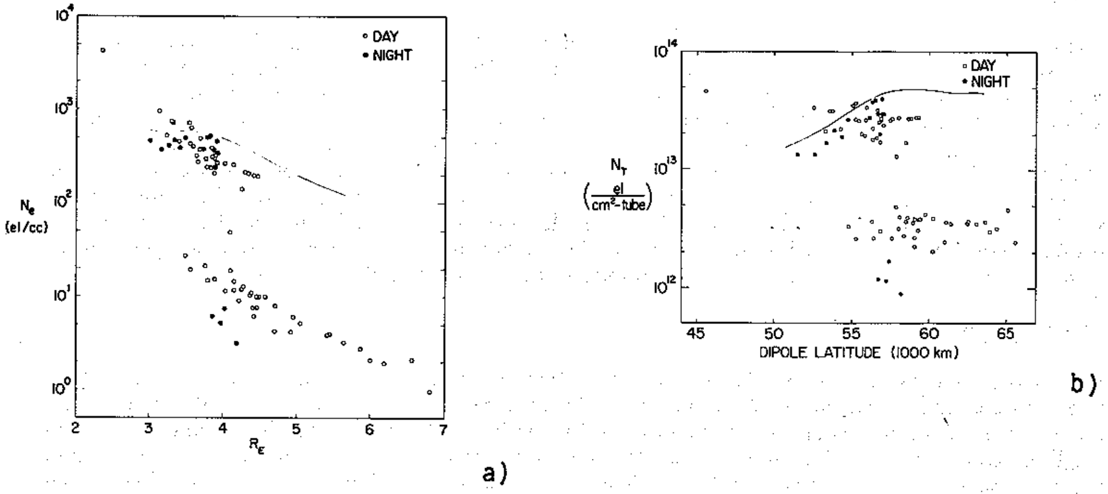

Fig. 10. (a) Equatorial electron density data from several days in 1963 /18/. Filled circles represent post midnight conditions, and open circles post noon hours. (b) Values of electron content in a tube of ionization extending above a square centimeter at 1000 km to the magnetic equator, corresponding to the data of (a).

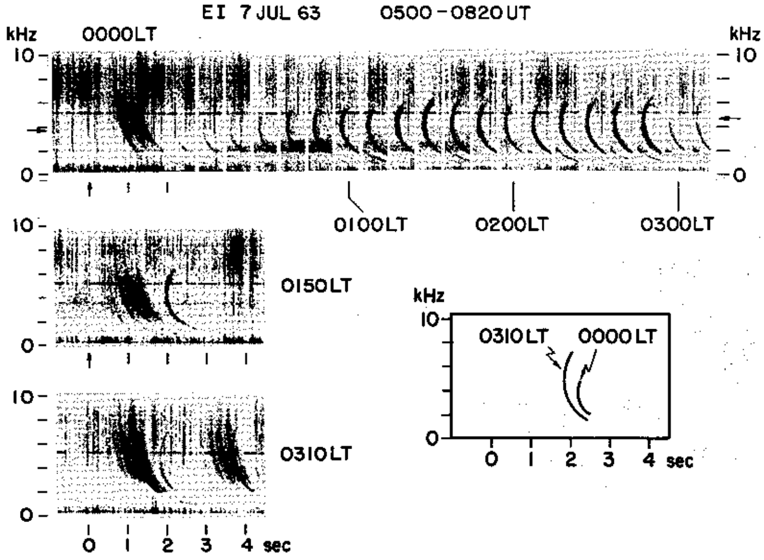

Fig. 11. Spectrograms illustrating use of temporal changes in the dispersion properties of whistler components to infer cross-L bulk motions of plasma in the outer plasmasphere. From /12/.

differences in the outer plasmasphere, could be understood in terms of plasma upflow from the ionosphere; Brice and Lucas /19/ were later to associate this recovering plasma density with the observed morningside buildup of VLF emission (chorus) activity and a morningside peak in ionospheric absorption.

Angerami compared equatorial data from whistlers with Alouette topside ionosphere data as well as existing theoretical ideas, and inferred that the distribution of ionization along the field lines within the plasmasphere could be approximated by a diffusive equilibrium model /20/, while a radially more rapidly varying distribution, such as a 'collisionless', or exospheric model /21/, was needed to describe the plasma trough region.

Angerami also presented and discussed his results in terms of tube electron content N_T, or the number of electrons within a tube of ionization extending from a cm^2 at 1000 km altitude to the magnetic equator. Figure 10*b* shows the content data corresponding to Figure 10*a*. As noted by Angerami, content estimates from whistlers are subject to less theoretical error than are equatorial density estimates, because of the inherently integral nature of the whistler measurement technique. Content measurements were later exploited by C. G. Park in pioneering studies of the interchange of plasma between the ionosphere and magnetosphere /22, 23/. In retrospect, one can interpret the leveling off of the quiet day tube content curve in Figure 10*b* as an indication of a transition from an inner 'low volume' region of the plasmasphere, where a day-night refilling - emptying equilibrium can be reached, and an outer, high volume region, where tube content tends to be independent of tube volume, and hence of endpoint latitude.

Irregularities in plasmapause radius

A major contribution by Angerami /17, 18/ was recognition of variations in plasmapause radius of several tenths of an earth radius within ~ 20° in longitude. These irregularities were frequently detected on the dayside of the earth by means of an observed overlap in the inferred L ranges of plasmasphere and plasmatrough electron densities. This overlap can occur because a ground whistler station in general receives whistler components distributed both in longitude and latitude (Figure 7*b* shows by the dotted curve the estimated equatorial limits of whistler paths detectable at Eights Station). Satellite measurements and later whistler studies suggest that the irregularities can have amplitudes of an earth radius or more /24, 25/. Figure 9*b* is a sketch, based upon Angerami's results and related measurements, showing how the 'real' plasmasphere radius might appear in equatorial cross section during a period of recurring substorm activity.

Irregularities with longitudinal scale of ~ 20° were later investigated using effects observed in VLF broadband data recorded on polar satellites and found to be associated with the plasmapause. These included a sudden (< 1 s) drop in frequency or 'breakup' with increasing latitude of a noise band associated with the local lower hybrid resonance (LHR) frequency, often accompanied by an abrupt disappearance of whistler activity originating in the opposite hemisphere/26/. Changes in plasmapause radius with time at a fixed magnetic local time in the post midnight sector were measured by this technique and interpreted as evi-

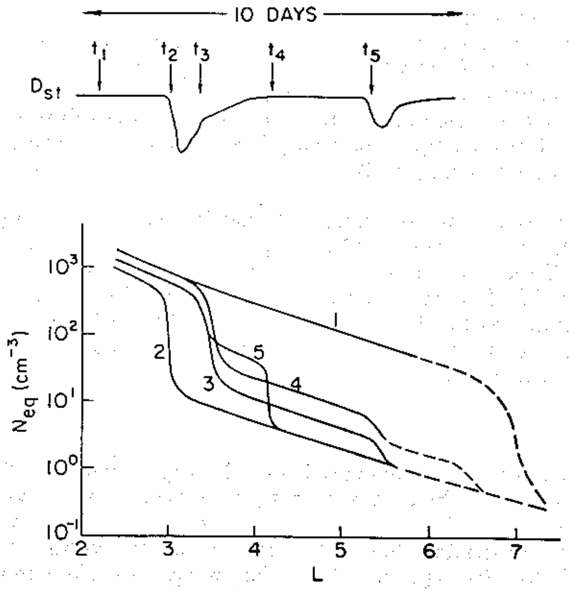

Fig. 12. Idealized magnetospheric equatorial electron density profiles showing dependence both upon the severity of a disturbance as well as the current state of recovery from preceding disturbances. From /35/.

dence that many of the observed irregular features had been imposed on the plasmasphere as the result of spatially structured convection activity near midnight, and were being sampled by the satellite as they moved eastward at approximately the angular velocity of the earth /27/. (In the late 1960's, but before the budget cutbacks that began in 1968, some thought was given by NASA to the idea of a plasmapause mission; in discussions of such a project at Stanford, the study of the irregular boundary was identified as a major objective.)

The Use of Whistlers to Study Magnetospheric Convection

In the early 1960's it became possible to use whistlers for tracking the bulk motions of the magnetospheric plasma, that is, to study magnetospheric convection /12/. This was found possible due to the fact that whistler ducts are discrete and tend to retain their identity for periods of minutes to hours /28/. Thus a whistler component provides a kind of tracer of the path along which it propagates, and as the plasma moves transverse to the magnetic field, it is possible to measure the corresponding changes in L value with time, and hence the cross-L component of plasma velocity.

Figure 11 illustrates a case in which the dispersion properties of a whistler changed over a ~ 3-hr period on the night side of the earth. Spectrograms of three representative events from the 3-hr period are shown one above another at the left, each aligned with the time of the causative atmospheric. To the right of the first whistler is a series of truncated records showing successive examples of a whistler component that propagated on a path near $L = 4$. As time passsed, the 'nose' frequency increased, indicating a drift to lower L shells. At lower right is a tracing of this component in frequency-time coordinates as it appeared at the beginning and end of the observing period.

In the early work on the Eights data, the new technique was applied to several aspects of convection. In the post-midnight sector, evidence was found that inward displacements of the plasmapause were accompanied by a corresponding inward drift of the plasma just inside the boundary /12/. This finding, represented in Figure 9*a* by arrow *b*, suggested that during the 1963 observing periods, convection was a dominant process in determining the morphology of the outer plasmasphere.

In the late afternoon sector, at the time of the bulge 'encounter', when the ground station appeared to move past the westward end of the bulge, evidence could not be found of a steady drift of plasma out into the region of larger radius. Instead, the whistlers that had been just inside the afternoon plasmapause appeared to propagate at nearly constant radius, and were supplemented by new components at higher L shells, as the bulge came into view. This finding, summarized in Figure 9*a* by arrow *c*, was interpreted as evidence that the bulge represented some kind of plasma accretion, with at that time unknown origin /12/.

The drift observations in the dusk sector were a precursor to use of whistlers in the late 1960's to obtain coarse information on the east-west component of motion in the outer plasmasphere near dusk. For example, the local time of observation of the westward end of the bulge, found to be earlier as magnetic activity in the preceding few hours increased, was used to infer that convection in the dusk sector was predominantly unsteady, and that in general the outward radial or dawn-dusk component of magnetospheric electric field near $L = 4$ at dusk was signficantly larger than the corresponding westward (again dawn-dusk) component of field near midnight/29/.

Another example was the 'untrapping' of the bulge, such that if deep quieting began while an observing station was in the afternoon sector, the profile and propagation conditions characteristic of the afternoon would continue past dusk, as if the entire system had begun to approximately rotate with the earth out to some distance well beyond the afternoon plasmapause. Some insight into this untrapping effect was obtained by comparing data from Byrd and Eights, stations spaced by ~ 1 hr in magnetic time. In a case study, rotation of the bulge in the direction of the earth's rotation, but at a lower angular velocity, was inferred to occur in the pre-midnight sector /29/.

Additional Activities

The period following description of the plasmapause involved many activities, including the gathering of statistical data showing the relation of the post-midnight plasmapause position to an integral measure of preceding magnetic activity /7/, comparisons of plasmapause position with data from high and low altitude spacecraft /13,16/, and the demonstration that SAR arcs were located within experimental accuracy at the ionospheric projection of the plasmapause /30/. This brings to a close this brief review of early whistler work on the plasmapause phenomenon. We now offer a few remarks about current problems of the plasmapause/plasmasphere and its dynamics, as seen in the light of earlier whistler measurements.

PLASMAPAUSE/PLASMASPHERE STUDIES; CURRENT PERSPECTIVES

In the study of complex geophysical phenomena, it is necessary to adopt simplified descriptive and interpretive models; the more widely accepted these models, the more difficult it may be to focus attention on their shortcomings. Perhaps because of the deceptively complete nature of the early plasmasphere descriptions from whistlers, and the well received interpretive articles by Brice /31/ and Nishida /32/, it has been difficult to gain attention for the view that the plasmapause, as originally described, in large part exists only because of the apparent slowness of recovery processes. The process of plasmapause formation, that is, the establishment of steep density gradients at a new geocentric distance, has yet to be directly observed, and has received only limited theoretical attention /33,34/). The process appears to be operative in some limited region located between late afternoon and midnight, and tends to produce detectable effects only during periods of generally increasing magnetic disturbance. During all other periods and in other local time sectors, which means most of the time and at most local times, recovery processses are probably dominant, as far as the density gradients are concerned /35,36/.

Figure 12 shows a figure prepared a number of years ago /35/ to illustrate (again in a simplified manner) the effect on the equatorial density profile of the interplay among short, localized disturbances and relatively long enduring, spatially extended conditions of recovery. The result, as modelers of plasmasphere dynamics have pointed out /37,38/, is that the profile is a function both of the initial conditions and of the spatial and temporal structure of convection activity. Disturbances occurring within a day or two after an earlier, much larger event may contribute to the development of an irregular profile which, over a limited L range, falls off more steeply and irregularly than that of a quiet plasmasphere, but does not exhibit the idealized knee associated with the erosion of a previously large and high density plasmasphere during a single multi-hour event /39/. The fact that the plasmapause seems to form within a limited region and then to be observed elsewhere, apparently through transport processes/24/, helps to explain why the dayside of the plasmasphere, as seen for example by the ISEE Sweep Frequency Receiver (SFR), frequently does not exhibit clear evidence of a plasmapause effect /40/.

Penetration of the Plasmasphere by Electric Fields of Solar Wind Origin

As noted above, whistler data suggest that disturbance-associated electric fields in the plasmasphere are predominantly unsteady, thus implying that the plasmasphere is indeed 'shielded' from the quasi-steady or multi-hour component of the high latitude field /41/. That in practice shielding is not a simple process is suggested by the fact that during the pre-expansion or 'growth' phase of a substorm, there is at most only a small enhancement of the westward electric field near midnight in the outer plasmasphere /42/. Only at the time of substorm expansion, as illustrated in Figure 13 /43/, does a rapid, easily identified increase in this field occur, as evidenced by the fast cross-L inward drift of whistler paths.

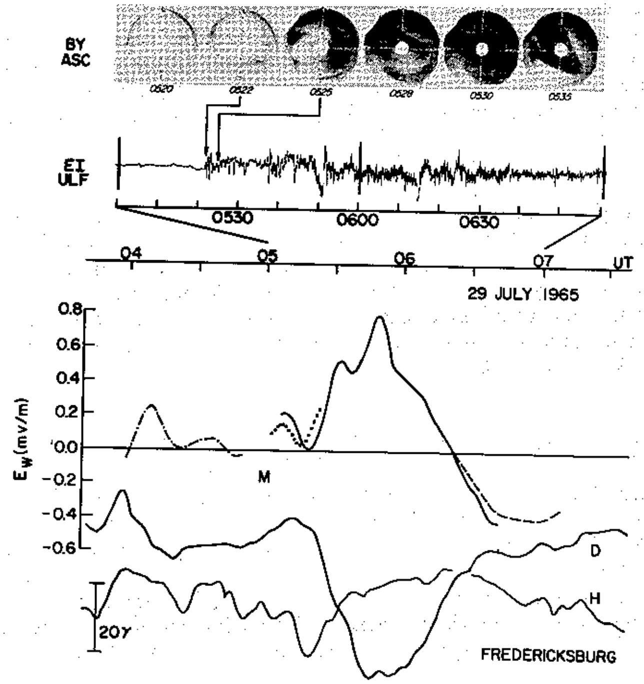

Fig. 13. The westward electric field (E_W) in the outer plasmasphere during an isolated substorm, inferred from drifting whistler paths /43/. The top panel shows all sky photographs from Byrd station (Figure 3*b*). The magnetogram records (below) are from Fredericksburg, near the longitude of the whistler observations.

Some of the most persuasive evidence of the efficiency of penetration of the unsteady component of solar wind-induced fields is the frequently abrupt, shoulder-like formation of the westward end of the bulge /12,29/ and the lack of evidence, noted above, that the bulge is dominated by plasma that drifts outward as it moves antisunward in the late afternoon. Neither of these features would appear compatible with an essentially steady state view of the flow pattern, and they are both among the better documented of whistler results.

Most of the whistler observations of penetrating fields have been made within ~ 0.5 - 1 R_E of the plasmapause, and the field components with periods 30 min to 1 hr have tended to exhibit little variation with L shell. In one case, with the plasmapause at $L \sim 4.5$, fields of comparable magnitude were observed over the range $L = 2.7$ to 4 /42/.

An interesting cross-L drift effect is detectable on the dayside. Whenever there is quieting in substorm activity, a steady pattern of drifts appears on the dayside, with outflow before noon and inflow afterward /44, 45/; the result is a secondary maximum in plasmapause radius near noon. The effect is apparently related to the noon-midnight asymmetry in plasmapause radius reported by Gringauz and Bezrukhikh /46/. The associated electric fields, which appear to be strongest at $L < 3$, are apparently of ionospheric dynamo origin /44/. When a substorm develops, the cross-L flow in the outer plasmasphere in the afternoon sector has been observed to temporarily reverse direction from the inward, quiet-time flow to outward /47/ (thus providing another indication of the efficiency of penetration of the duskside plasmasphere by substorm electric fields). However, within the dayside plasmasphere, the largest *steady* (multi-hour) component of electric field of external origin, other than that associated with the earth's rotation or unusually large magnetic storms, appears to originate in the ionosphere.

Erosion of the Plasmasphere During Substorms

We now comment briefly on the local time region in which an erosion process occurs in the outer plasmasphere during disturbed periods. Evidence from Ogo-5 of outlying density structure suggests that the process occurs in the late afternoon/dusk sector /36/. The evidence available from whistlers is either fragmentary or indirect, but suggests that erosion effects are concentrated in the pre-midnight sector and region of dusk and late afternoon. One clue is the well documented result that sunward (cross-L inward) drifts during substorms on the nightside are restricted to the local time sector following ~ 23 MLT /48/. Prior to midnight, during substorms, any detected cross-L motion is usually small and radially outward, or opposite to the post midnight direction /49/. Another clue comes from a case study /50/ in which the L values of a distribution of whistler components were observed over the course of an intense but temporally isolated substorm near 22 MLT. During the main part of the substorm, the ducts were found to remain at roughly constant L values, but the ones at highest L 'disappeared' or ceased to be detected, one by one, from outermost inward, until late in the substorm only some inner group remained. This 'interruption' of propagation is consistent with the fact that propagation outside the plasmapause is infrequently observed in the ~ 18 - 00 MLT sector, unless, as noted earlier, there is deep quieting and the afternoon plasma regime continues to be observed after dusk /12/. In Figure 9*a*, the x's outside the plasmapause give a crude idea of the region within which whistlers were detected at Eights during periods of moderate agitation.

While the above does not give information on the actual erosion process, it supports the idea that the major decreases in plasmasphere volume are effected in the region prior to local midnight. In the post midnight hours, the displacements of the boundary are initially inward, as noted above, but they appear to be part of cross-L flow activity in which the predominant effect is a steepening of the plasmapause density gradients rather than plasmasphere erosion. Erosion processes due to plasma interchange motion, such as proposed by Lemaire and colleagues both on theoretical grounds /34/ and from a case study of plasmapause positions /38/, would not, at least on this basis, appear to be a dominant process in the pre-dawn hours.

Anomalous Fast Nightside Outward Drifts in the Aftermath of Substorms

We now mention a feature of substorm electric fields that has gone unexplained for more than 10 years. This is a cross-L outward drift that develops in the post midnight sector in the aftermath of temporally isolated substorms /43,47/. Figure 13 shows an example in which the westward component of electric field (E_W) deduced from whistlers reversed direction (to outward drifts), with the result that the integrated cross-L displacement of a path following the reversal was comparable to integrated displacements observed during the preceding inward drift. When the outward drift velocity reached its peak, the substorm current system, as indicated by magnetometers, appeared to have already largely decayed.

This behavior gives the impression of being a kind of natural mode of the system, being most clearly defined when the magnetosphere is excited by a brief, temporally isolated substorm, as illustrated in Figure 13. The effect may be the result of what has been called 'overshielding'/51/, in that the inner edge of the plasma sheet is configured at the end of a substorm in a manner that continues to give rise to a dusk-to-dawn electric field. This field, which normally would be expected to perform a shielding function /41/, may then exist for some time after the main substorm electric field has decayed, and thus give rise to the outward drifts.

If shielding is sometimes really efficient on a time scale of an hour or so, how can those cases be explained in which substorm activity continues for several hours, outward drifts are not observed, and the plasmasphere undergoes significant reduction in worldwide average radius? We can suggest that while the fields are indeed more intense during larger storms, another important effect is a difference in the spatial distribution of the convection pattern. If for example the nightside inward drifts envelop a wider area, as they appear to do during larger storms /42, 52/, this may modify the shielding process and permit the fields to penetrate efficiently over a multi-hour period.

The Density Gradients at the Plasmapause

Little is known about the region of steep density gradients, since thermal plasma or total density measurements have been made on only a few satellites, and then with limited spatial resolution. A few comments on the width of the boundary can be made, based upon VLF studies. Along polar satellite orbits in the topside ionosphere in the post midnight sector, one can find cases in which a major change in the LHR noise band occurred within less than ~ 0.2 s, or within a distance of less than ~ 1.5 km /26/. Our impression is that in terms of electron density gradients, efficient mapping of the plasmapause to topside ionospheric altitudes tends to occur near or after midnight, and under the same somewhat restrictive conditions as those noted above under which the plasmapause is itself most sharply defined.

VLF Wave Propagation Near the Plasmapause

This is a substantial topic, beyond the scope of this brief review, and deserving of more attention than it has received in the literature. The propagation of whistlers near the plasmapause exhibits a number of as yet unexplained special features, and VLF emission activity outside the boundary generally differs from that observed inside /25,53/. There are important, unanswered, questions concerning accessibility of waves to various regions, as well as a need to extend recent evidence of coupling of ducted whistlers from one side of the plasmapause to the other /54/.

CONCLUDING REMARKS

The plasmasphere/plasmapause is a research area of great opportunity, but also a great challenge to experimenters. For instance, difficulties lie in the fact that study of the dynamical processes giving rise to the plasmapause may require observations at relatively high altitudes, and over times long compared to the times high altitude satellites normally spend within a fraction of an earth radius of a given field aligned feature. However, as noted above, there are conditions under which the high altitude plasmapause appears to be efficiently projected onto the ionosphere, and under such conditions a coordinated program of ground based probing and both low and high altitude satellite measurements could yield important new results.

A problem in all cases is the evidently unsteady nature of the convection activity that penetrates the plasmasphere and strongly affects its morphology. More ways must be found, both in experiment and in theoretical models, to account for this unsteady aspect of convection.

Much remains to be learned about many topics, such as the erosion of the plasmasphere during disturbances, the physics of the establishment of the steep plasmapause density gradients, the penetration of the plasmasphere by substorm electric fields and the consequent shape and dynamics of the duskside bulge region, wave-particle energy exchange at and near the plasmapause, and the coupling of energy from magnetosphere to ionosphere near the boundary. Existing data can help us in many of these areas, but I believe that development of new experimental methods, including special satellite missions, should also be emphasized.

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REFERENCES

1. D. L. Carpenter, and R. L. Smith, Whistler measurements of electron density in the magnetsophere, *Rev.of Geophys., 2(3)*, 415, 1964.
2. R. A. Helliwell, *Whistlers and Related Ionospheric Phenomena*, Stanford Univ. Press, Stanford, Ca., 1965.
3. Y. Corcuff, Probing the plasmapause by whistlers, *Ann. Geophys., 31*, 1, 1975.
4. C. G. Park, and D. L. Carpenter, Very low frequency radio waves in the magnetosphere, Pager 4 in *Upper Atmosphere Research in Antarctica, Antarctic Reserach Series Vol. 29*, L. J. Lanzerotti and C. G. Park (eds.), AGU, 1978.
5. D. L. Carpenter, Whistler evidence of a 'knee' in the magnetospheric ionization density profile, *J. Geophys. Res., 68*, 1675, 1963.
6. R. A. Helliwell, and D. L. Carpenter, *Whistlers - West IGY - IGC Synoptic Program*, Tech. Rept., Stanford University, 1961.
7. D. L. Carpenter, Relations between the dawn minimum in the equatorial radius of the plasmapause and Dst, Kp and local K at Byrd Station, *J. Geophys. Res., 72*, 2669, 1967.
8. D. L. Carpenter, New experimental evidence of the effect of magnetic storms on the magnetosphere, *J. Geophys. Res., 67*, 135, 1962.
9. Y. Corcuff, and M. Delaroche, Augmentation du gradient d'ionisation dans la proche magnéto sphère en périodes de forte activité magnétique, *Compt. Rend., 258*, 650, January 13, 1964.
10. K. I. Gringauz, V.G. Kurt, V.I. Moroz, and I.S. Shklovksii, Results of observations of charged particles observed out to R =100,000 km with the aid of charged particle traps on Soviet space rockets, *Astron. Zh., 37*, 716, 1960.
11. D. L. Carpenter, Whistler measurements of the equatorial profile of magnetospheric electron density, *Progress in Radio Science 1960-1963, Vol. III: Ionosphere*, Elsevier, Amsterdam, 1965.
12. D. L. Carpenter, Whistler studies of the plasmapause in the magnetosphere, 1: Temporal variation in the position of the knee and some evidence on plasma motions near the knee, *J. Geophys. Res., 71*, 693, 1966.
13. D. L. Carpenter, C. G. Park, H. A. Taylor, Jr., and H. C. Brinton, Multi-experiment detection of the plasmapause from EOGO satellites and Antarctic ground stations, *J.Geophys. Res., 74*, 1837, 1969.

14. J. H. Binsack, Plasmapause observations with the MIT experiment on Imp 2, *J. Geophys. Res., 72*, 5231, 1967.

15. D. B. Muldrew, F layer ionization troughs deduced from Alouette data, *J. Geophys. Res., 70*, 2635, 1965.

16. H. A. Taylor, Jr., H. C. Brinton, D. L. Carpenter, F. M. Bonner, and R. L. Heyborne, Ion depletion in the high-latitude exosphere: Simultaneous OGO-2 observations of the light ion trough and the VLF cutoff, *J. Geophys. Res., 74*, 3517, 1969.

17. J. J. Angerami, *A whistler study of the distribution of thermal electrons in the magnetosphere*, Ph. D. Thesis, Stanford University, 1966.

18. J. J. Angerami, 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.

19. N. Brice, and C. Lucas, Influences of magnetospheric convection and polar wind on loss of electrons from the outer radiation belt, *J. Geophys. Res., 76*, 900, 1971.

20. J. J. Angerami, and J.O. Thomas, Studies of planetary atmospheres, 1. The distribution of electrons and ions in the earth's exosphere, *J. Geophys. Res., 69*, 4537, 1964.

21. A. Eviatar, A. M. Lenchek, and S. F. Singer, Distribution of density in an ion-exosphere of a nonrotating planet, *Phys. Fluids, 7* , 1775, Nov. 1964.

22. C. G. Park, Whistler observations of the interchange of ionization between the ionosphere and the protonosphere, *J. Geophs. Res., 75*, 4249, 1970.

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

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

25. D. L. Carpenter, Whistlers and VLF noises propagating just outside the plasmapause, *J. Geophys. Res., 83*, 45, 1978.

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

27. D. L. Carpenter, and C. R. Chappell, Satellite studies of magnetospheric substorms on August 15, 1968. 3. Some features of magnetospheric convection, *J. Geophys. Res., 78*, 3062, 1973.

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

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

30. D. L. Carpenter, OGO-2 and 4 VLF observations of the asymmetric plasmapause near the time of SAR arc events, *J. Geophys. Res., 76*, 3644, 1971.

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

32. A. Nishida, 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.

33. J. Lemaire, The mechanisms of formation of the plasmapause, *Ann. Geophys., 31*, 175, 1975.

34. J. Lemaire, and L. Kowalkowski, The role of plasma interchange motion for the formation of a plasmapause, *Planet. Space Sci., 29*, 449, 1981.

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

36. C. R. Chappell, Recent satellite measurements of the morphology and dynamics of the plasmasphere, Rev. Geophys. Space Phys., 10, 951, 1972.

37. A. J. Chen, and R. A. Wolf, Effects on the plasmasphere of a time-varying convection electric field, *Planet. Space Sci., 20*, 483, 1972.

38. Y. Corcuff, Corcuff, P., and J. Lemaire, Dynamical plasmapause positions during the July 29 - 31, 1977 storm period: A comparison of observations and time dependent model calculations, *Ann. Geophysicae*, 1985.

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

40. R. R. Anderson, ISEE-1 wave measurements of the plasmasphere shape, this issue.

41. R. A. Wolf, Ionosphere-magnetosphere coupling, *Space Sci. Rev., 17*, 537, 1975.

42. D. L. Carpenter, K. Stone, J. C. Siren, and T. L. Crystal, Magnetospheric electric fields deduced from drifting whistler paths, *J. Geophys. Res., 77*, 2819, 1972.

43. D. L. Carpenter, and S. I. Akasofu, Two substorm studies of relations between westward electric fields in the outer plasmasphere, auroral activity, and geomagnetic perturbations, *J. Geophys. Res., 77*, 6854, 1972.

44. D. L. Carpenter, New whistler evidence of the dynamo origin of electric fields in the quiet plasmasphere, *J. Geophys. Res., 83*, 1558, 1978*b*.

45. W. Baumjohann, G. Haerendel, and F. Melzner, Magnetospheric convection observed between 0600 and 2100 LT; variations with Kp, *J. Geophys. Res., 90*, 393, 1985.

46. K. I. Gringauz, and V. B. Bezrukikh, Asymmetry of the earth's plasmasphere in the direction noon-midnight from Prognoz and Prognoz-2 data, *J. Atmos. Terr. Phys., 38*, 1-71, 1976.

47. D. L. Carpenter, and N. T. Seely, Cross-L plasma drifts in the outer plasmasphere: Quiet time patterns and some substorm effects, *J. Geophys. Res., 81*, 2728, 1976.

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

49. C.G. Park, Whistler observations of substorm electric fields in the nightside plasmasphere, *J. Geophys. Res., 83*, 5773, 1978.

50. D. L. Carpenter, Notes on broadband whistler measurements of electric fields and associated phenomena, reprint from *Memoirs of National Institute of Polar Research*, Tokyo, March, 1974.

51. R. W. Spiro, R. A. Wolf, and G. Mantjoukis, Application of the Rice convection model to a substorm period during the January, 1984, GISMOS campaign, *EOS, 66*, 994, 1985.

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

53. D. L. Carpenter, and T.R. Miller, Rare ground-based observations of Siple VLF transmitter signals outside the plasmapause, *J. Geophys. Res., 88*, 10227, 1983.

54. A. J. Smith, and D. L. Carpenter, Echoing mixed-path whistlers near the dawn plasmapause, observed by direction-finding receivers at two Antarctic stations, *J. Atmos. Terr. Phys., 44*, 973, 1982.

55. D. L. Carpenter, Some aspects of plasmapause probing by whistlers, *Radiosci.,18*, 917, 1983.