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A DE-1\WHISTLER STUDY OF THERMAL PLASMA STRUCTURE AND DYNAMICS IN THE DUSK BULGE SECTOR OF THE MAGNETOSPHERE

Final Technical Report

D. L. Carpenter, Principal Investigator

Period covered: 01 August 1989-01 October 1992

Grant No: NAG 8-784

Stanford University
Stanford, CA 94305

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The objective of this research was to obtain new understanding of the thermal plasma structure and dynamics of the plasmasphere bulge region of the magnetosphere, with special emphasis on the erosion process that results in a reduction in plasmasphere size and on the manner in which erosion leads to the presence of patches of dense plasma in the middle and outer afternoon-dusk magnetosphere. The work was in part based upon case studies involving data from the DE 1, GEOS 2, and ISEE 1 satellites and from ground whistler stations Siple, Halley and Kerguelen.

The activities under the grant have been well summarized in previous semiannual reports. During the period since the most recent report, namely 30 April, 1992--01 October, 1992, substantial time was devoted to final preparations of a major paper and submission of that paper. Since the termination of the grant, the paper has been returned for revisions, and substantial additional time has been devoted to making those revisions and responding to the comments of the referees. Generally speaking, the reviews were quite favorable, in that the basic findings of the paper were not challenged and mostly peripheral issues were raised.

Because the work under the grant has been more or less completely represented in a paper published in February 1992 and in the major paper that should soon be in press, the remainder of this report will consist of i) a copy of the published paper entitled "A case study of

plasma structure in the dusk sector associated with enhanced magnetospheric convection," by D. L. Carpenter, A. J. Smith, B. L. Giles, C. R. Chappell, and P.M.E. Decreau, published in the *Journal of Geophysical Research, 97*, 1157, 1992; ii) a copy of the concluding remarks from the major paper "Plasmasphere dynamics in the duskside bulge region; a new look at an old topic," by D. L. Carpenter, B. L. Giles, C. R. Chappell, P.M.E. Decreau, R. R. Anderson, A. M. Persoon, A. J. Smith, Y. Corcuff, and P. Canu, anticipated to be in press in the *Journal of Geophysical Research* within a few weeks.

It is a pleasure to note that the results of the research reported in the above papers have been informally communicated to various research groups and have already been used in the work of several of those groups.

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380

A Case Study of Plasma Structure in the Dusk Sector Associated With Enhanced Magnetospheric Convection

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In a case study from June 8-9, 1982, data from ground whistler stations Siple and Halley, Antarctica, located at $L \sim 4.3$ and spaced by ~ 2 hours in MLT, and from satellites DE 1 and GEOS 2, have provided confirming evidence that the bulge region of the magnetosphere can exhibit an abrupt westward "edge," as reported earlier from whistlers. The present data and previous MHD modeling work suggest that this distinctive feature develops during periods of steady or declining substorm activity, when dense plasma previously carried sunward under the influence of enhanced convection activity begins to rotate with the Earth at angular velocities that decrease with increasing L value and becomes spirallike in form. For the first time, whistler data have been used to identify a narrow dense plasma feature, separated from the main plasmasphere and extending sunward into the late afternoon sector at L values near the outer observed limits of the main plasmasphere bulge. The westward edge of the main bulge, found by both whistler stations to be at $\sim$1800 MLT, appeared to be quasi-stationary in Sun-Earth coordinates during the prevailing conditions of gradually declining geomagnetic agitation. It is possible that outlying dense plasma features such as the one observed develop as part of the process leading to the occurrence of the more readily detectable abrupt westward edge of the bulge. It was not possible in this case to determine the extent to which the outlying feature was smoothly attached to or isolated from the main bulge region.

1. INTRODUCTION

Two phenomena of the Earth's plasmasphere have long been recognized: the existence of a duskside "bulge," or region of larger radius [*Carpenter*, 1966; *Chappell et al.*, 1970a], and a reduction in plasmasphere size during magnetic storms [*Carpenter*, 1963, 1966; *Chappell et al.*, 1970b]. However, surprisingly little detailed information has been presented on the distribution and flow of thermal plasma in the dusk sector during and following magnetically disturbed periods.

In regard to the storm time reduction in plasmasphere size, it is widely believed that an erosion process occurs in association with enhanced convection [e.g., *Nishida*, 1966; *Brice*, 1967], and numerical simulations of such a process [e.g., *Grebowsky*, 1970; *Chen and Wolf*, 1972; *Spiro et al.*, 1981; *Kurita and Hayakawa*, 1985] support the idea that portions of the outer plasmasphere are transported sunward toward the afternoon magnetopause, presumably entering the magnetosheath if the convection is sufficiently strong and/or persistent. Figures 1*a* and 1*b*, adapted from *Kurita and Hayakawa* [1985], show examples of this predicted effect. (Double probe electric field measurements made near the equator on ISEE 1 [e.g., *Maynard et al.*, 1983] as well as projections of incoherent scatter radar data from the ionosphere to the equator [e.g., *Fontaine et al.*, 1986] indicate the existence of strong sunward plasma flows in the dusk sector but do not provide much information about the manner in which the flow activity modifies the distribution of thermal plasma.) *Lemaire* [1974, 1975, 1985] and *Lemaire and Kowalkowski* [1981] have taken exception to the popular MHD model viewpoint, arguing that the loss process is dominated by the gravitational interchange instability, which should have a particularly strong effect in the postmidnight sector during periods of enhanced convection. Regions of locally depressed density move outward from lower L values or inward from higher ones. When they reach a certain track in L-MLT space, the location of which is determined by the configuration and intensity of the convection electric field, a deeper local depression is formed. Beyond this depression, which becomes the plasmapause, a plasma trough is then formed as locally dense regions drift outward due to the same instability, having become "detached" from the main plasmasphere by the formation of the longitudinally extended depression.

A major difficulty in studying thermal plasma dynamics in the dusk sector is the limited ability of individual satellites, ground stations, or instruments to probe a very large spatial region and to do so on the widely varying time scales on which significant changes occur. This difficulty can be at least partially overcome by using data from multiple platforms, as *Corcuff and Corcuff* [1982] have demonstrated. In the present research note we report on such a study and find new evidence about the bulge structure during periods of magnetic disturbance.

In earlier experimental work it was found that during multiday periods of moderate and relatively steady geomagnetic disturbance activity following the onset of weak magnetic storms, the plasmasphere radius (heavy curve in Figure 2*a*) did not increase steadily with increasing magnetic local time in the afternoon but instead tended to increase rapidly at some point, usually between $\sim$16 and 20 MLT, thus causing the bulge to appear to have an abrupt westward "edge" [*Carpenter*, 1966, 1970]. Because this particular feature often appeared to be quasi-stationary in Sun-Earth coordinates, it was well suited to being "scanned" by a ground whistler station. However, it was not positioned so as to be readily detected from the orbits of most single satellites, with the apparent exception of Explorer 45, which was in near-equatorial orbit with apogee at $L \sim 5$. With Explorer 45 statistical data derived from the density-sensitive response of a double-probe antenna, *Maynard and Grebowsky* [1977] found a bulge similar in form to that

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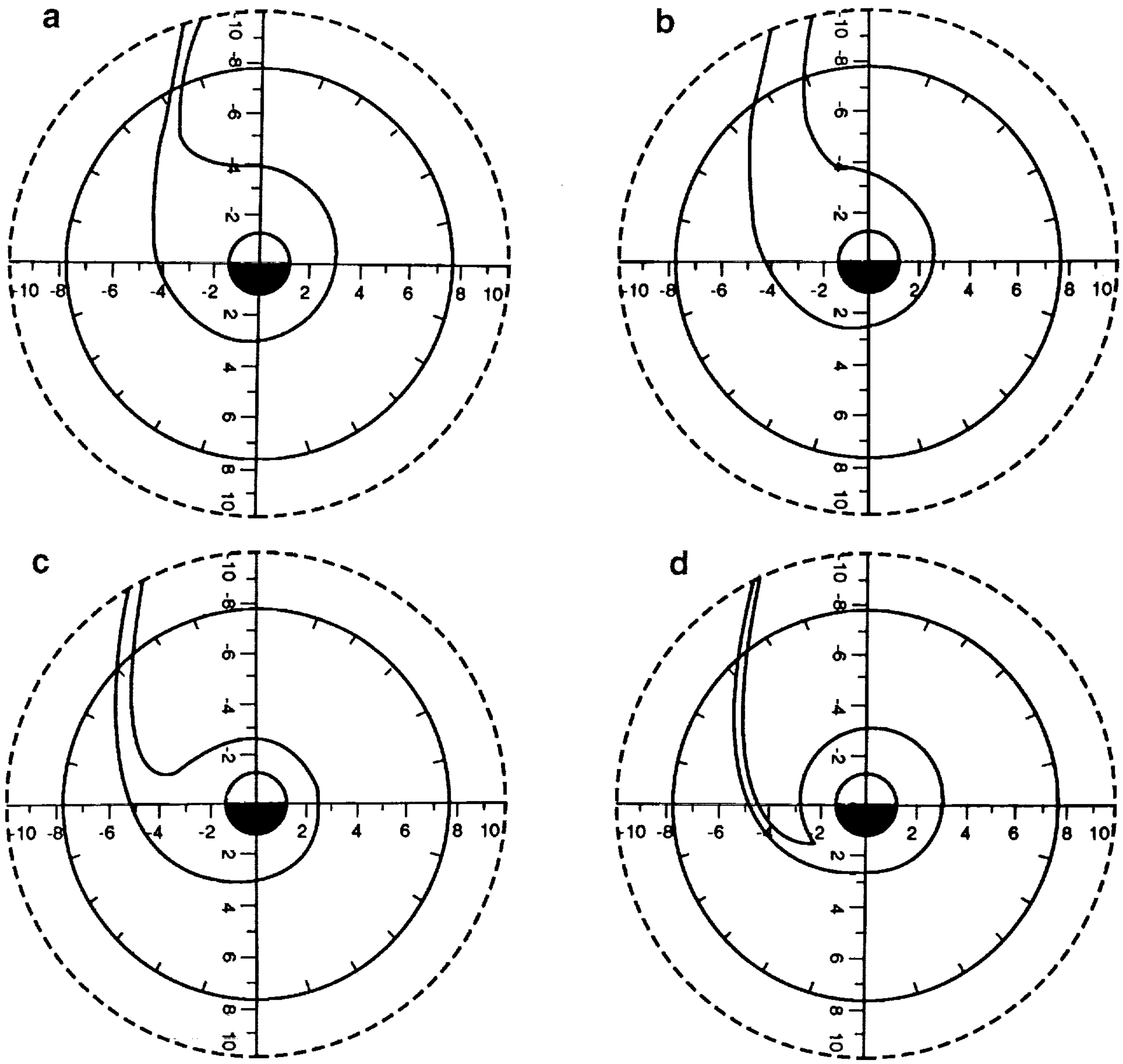

Fig. 1. Illustration of MHD model calculations by *Kurita and Hayakawa* [1985] of plasmasphere shape at 6-hour intervals during a disturbed period. (*a*) Conditions ~24 hours after the onset of moderate to severe substorm activity (1800 UT on December 17, 1971). (*b*) Effects of a further surge in convection activity. (*c*) and (*d*) Effects of a tendency to corotate with the Earth, at angular velocities decreasing with increasing L, during a period of reduced disturbance activity.

reported from whistlers, but with a westward edge located after dusk, typically near 20-21 MLT.

While Figure 2*a* represents an average of plasmasphere observations under conditions of moderate and relatively steady geomagnetic agitation, Figure 2*b* presents a sketch of additional features one might expect to observe in a "snapshot" of the large-scale structure of the plasmasphere during a period following the onset of enhanced substorm activity [*Carpenter*, 1983]. Irregularities in plasmasphere radius centered at various local times and with azimuthal scales of 10°-30° have been detected from whistlers [*Angerami and Carpenter*, 1966; *Smith et al.*, 1981] and from polar-orbiting satellites [*Carpenter and Chappell*, 1973; *Carpenter and Park*, 1973]. These have been partly attributed to the unsteady and spatially structured nature of substorm convection activity.

The existence of taillike extensions, or "extrusions," of the dense plasma, such as the one shown in Figure 2*b*, has been suggested by empirical data in several ways. Statistical studies of DE 1 ion density data by *Horwitz et al.* [1990] reveal the regular occurrence near dusk of a class of profiles with inner and outer high-density regions separated by a well-defined trough. Whistlers have shown strong evidence that the outer part of the plasmasphere, identified by the bulge westward edge, is displaced sunward during periods of substorm activity [*Carpenter*, 1970]. In such cases, assuming that the magnitude of the electric field in Sun-Earth coordinates is roughly constant with increasing L value [e.g., *Fontaine et al.*, 1986], one might expect the velocity of the sunward flow to increase with L value and thus lead to greater sunward extensions of the plasmasphere from the outer part of the bulge region than from the inner parts, as suggested in Figure 1 and in Figure 2*b*.

There is very little information regarding the connection of extended density features to the main plasmasphere. *Ho and Carpenter* [1976], using a fortuitous combination of data from two

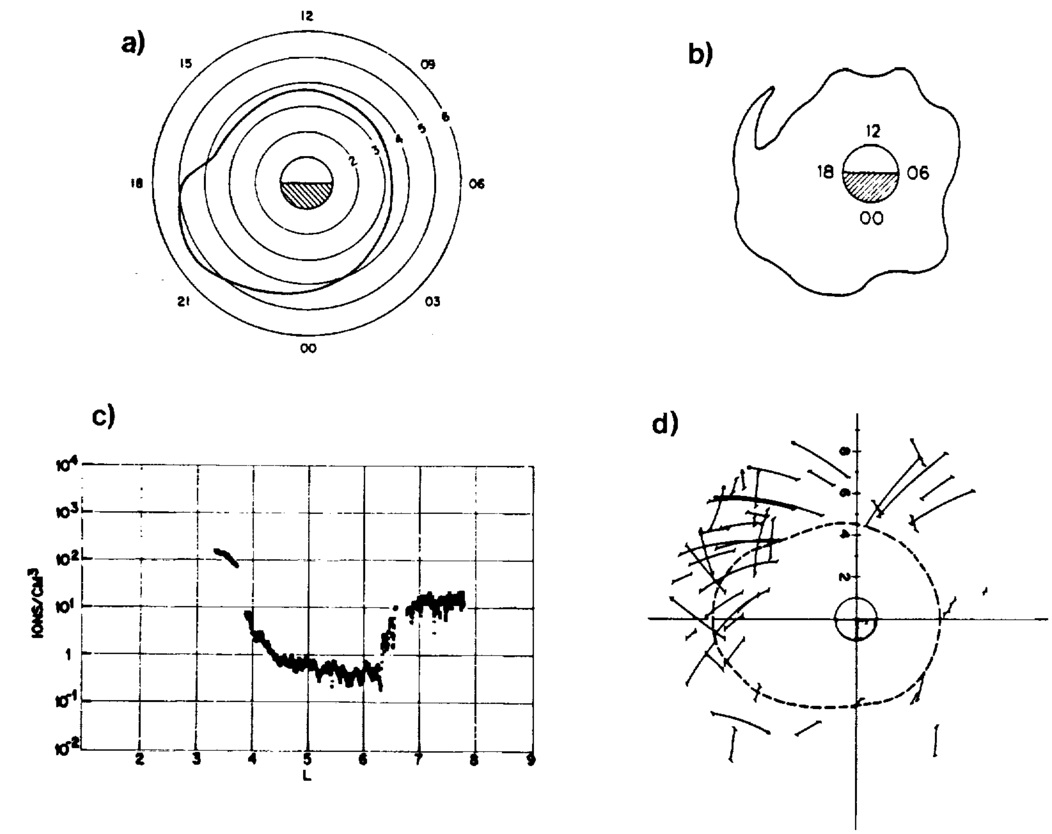

Fig. 2. (*a*) Equatorial radius of the plasmapause versus magnetic local time, showing the relatively abrupt westward edge of the bulge, or region of larger plasmasphere radius. The form indicated, deduced from whistlers acquired at Eights, Antarctica, was found to be typical for multiday periods of moderate, steady geomagnetic agitation (Kp=3-4) in the aftermath of weak geomagnetic storms [from *Carpenter*, 1966]. (*b*) Sketch showing how a "snapshot" of the plasmasphere might be expected to appear as a consequence of spatially and temporally structured convection activity that produces azimuthal variations in plasmapause radius as well as a sunward extending feature in the late afternoon sector [from *Carpenter*, 1983]. (*c*) Dusk region H^+ density profile obtained from the ion mass spectrometer on OGO 5, showing an outlying region of high density plasma [from *Chappell et al.*, 1971]. (*d*) Segments of OGO 5 orbits along which "detached" plasmas were observed, the criterion for identification being separation from the main plasmasphere and density >10 ions cm^{-3} [from *Chappell et al.*, 1971].

whistler stations spaced by ~1 hour in MLT, were able to "scan" an outlying feature that was approximately 0.5 R_E in radial extent at the equator and which appeared to be approximately rotating with the Earth during deep quieting. They concluded that such a feature had been formed near dusk and was connected to the main body of the plasmasphere. A case for a taillike feature was made by *Taylor et al.* [1971] from proton density measurements during a succession of polar satellite passes at ionospheric heights by OGO 4.

The features indicated schematically in Figure 2*b* do not reflect the existence of the dense plasma features at various outlying locations in the afternoon-evening magnetosphere reported from OGO 5 by *Chappell et al.* [1971] and *Chappell* [1974], and from OGO 3 by *Taylor et al.* [1970]. The distribution and extent of the regions along the OGO 5 orbit suggested to *Chappell* [1974] that they were "detached" from the main plasmasphere. Figure 2*c* shows a dusk region H^+ density profile from OGO 5, in which an outlying increase in density appeared, while Figure 2*d* shows the results of a survey of the locations of such regions that appeared to be separated from the main plasmasphere. With Explorer 45, *Maynard and Chen* [1975] noted the occasional appearance of outlying density increases in the afternoon sector near $L = 5$, and *Corcuff and Corcuff* [1982] reported from GEOS 1 on the apparent detection of outlying dense patches in the afternoon sector roughly 10 hours after an onset of substorm activity.

Are sunward extending features such as the one sketched in Figure 2*b* actually formed near dusk during periods of enhanced convection? Are such regions connected to the main plasmasphere, or are they already in the form of isolated irregularities at this stage? If connected, how are they related to what have been reported to be detached, or isolated, regions? By what means does cold plasma accumulate in the outer magnetosphere, and what is the geophysical significance of this plasma? These questions are being addressed in current studies, including one in which the present authors are comparing DE 1 and other satellite data to equatorial electron density profiles from whistlers. In the course of that work a particular data set was found that provides evidence of a narrow feature that was nearly stationary in Sun-Earth coordinates and appeared to extend into the afternoon sector. Its location suggested that it may have been connected to the main body of the plasmasphere, but the possibility that it was an isolated patch cannot be ruled out. We present that case study in the present note.

2. EXPERIMENTAL RESULTS

General Description

The observations were made on June 8-9, 1982, and include data from (1) two ground whistler stations located near L=4 and separated by ~2 hours in MLT, (2) DE 1, operating with apogee near the equator at L ~4.5, and (3) GEOS 2, at synchronous orbit. Figure 3 shows four plots of equatorial radius versus magnetic local time. Each contains a drawing of the approximate shape of the afternoon-dusk plasmasphere as that shape was suggested by the data to be described below. Dashed lines at one end of the sunward extending feature in Figure 3*d* are indicated in recognition of the possibility that this feature was in fact isolated from the nearby bulge region.

The whistler observations on June 8-9, made from Siple (SI, 76°S, 84°W, L ~4.3) and Halley (HB, 76°S, 27°W, L ~4.3), are summarized by radial lines showing the local time positions of the two stations at four successive universal times in the local afternoon and evening. Solid circles (Siple) and pluses (Halley) along the radial lines show the measured L values of whistler components that have been used to identify regions of high, plasmasphere-level densities and low, plasma trough concentrations.

Figure 3*a* represents 1845 UT, when the MLT at Siple was ~1400 hours and at Halley ~1600 hours. At this time both stations were observing plasma trough conditions. Just 36 min later, DE 1 crossed the magnetic equator along its nearly field-aligned orbit, close to the 1800 MLT meridian. The retarding ion mass spectrometer (RIMS) experiment on DE 1 [*Chappell et al.*, 1981] indicated predominantly high density cold plasma extending to nearly L=6. This was confirmed by the plasma wave instrument (PWI) on DE 1 [*Shawhan et al.*, 1981], which provided information on electron density.

The DE 1 data, presented in Figure 4, were taken June 8 from 1715 to 2200 UT. The satellite was moving from south to north, beginning at L=5.67 at 1738 UT. It crossed the magnetic equator

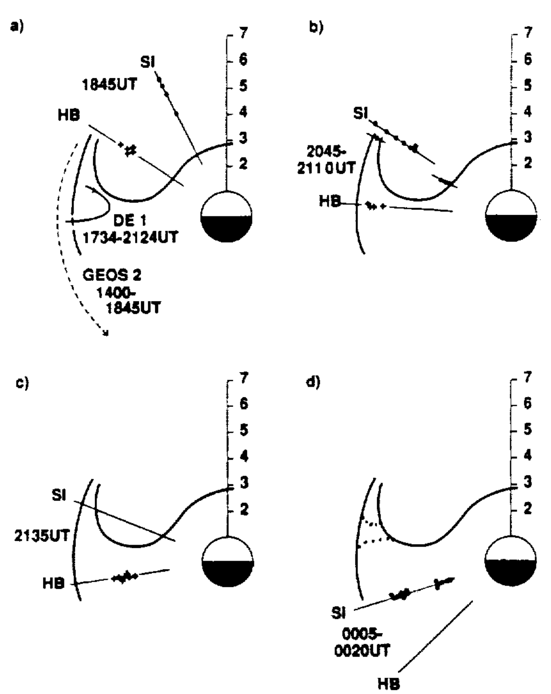

Fig. 3. (*a*)-(*d*) Plots of equatorial radius versus magnetic local time, showing by a bold line the inferred shape of the afternoon-dusk plasmasphere in four successive periods on June 8-9, 1982. Radial lines show the approximate meridians of Siple and Halley stations in the four periods of interest. Marks along the lines indicate the L values of observed whistler components; their actual longitudes could be within ~ ±1 hour in MLT of the radial lines. The positions of the June 8 GEOS 2 orbit and of an equatorial projection of the June 8 DE 1 orbit are indicated in Figure 3*a* with respect to the apparent outer limits of plasmasphere-level densities.

at 1921 UT at L=4.69 and reached an L of 8.78 at 2200 UT. A spin angle-versus-time spectrogram showing the RIMS 0-50 eV He^+ data from the radial detector is presented in Figure 4*a*. The satellite ram direction is along the center of the spectrogram. The maximum pitch angle direction is indicated by the dashed black line, which in this case nearly coincides with the ram direction. The short-dashed black line segments, one at the upper left and the other at the lower center and right, indicate the spin phase for minimum pitch angle. The counts per sample are coded in shades of gray, with white representing low counts (0 to 2 counts/sample) and black representing high counts (≥500 counts/sample). The gray shaded bar on the right-hand side of the figure shows this scale. The count rate per sample is approximately proportional to the integral ion flux. In the spectrogram shown, for L shells extending to just beyond 6, the plasma is essentially a "ram" plasma, distinguished by a broad symmetric band in particle count rate centered at the ram direction. This distribution is characteristic of the cold low-energy plasma (≤1 eV) typical of the plasmasphere region [*Chappell et al.*, 1982]. After ~2038 UT, in the outer part of the high-density region, the distribution as a whole became slightly skewed toward the field direction. However, between the full width at half maximum points there was no skew, and the centroid of the distribution remained within 10° of the ram, while the magnetic field direction was about 30° from the ram. After 2112 UT, faint traces of field-aligned ions became apparent, indicating that the satellite was leaving the plasmasphere near an L of 6.2. Figure 4*b* shows the total electron density versus time along the orbit, determined from measurements of the upper hybrid resonance on the PWI sweep frequency receiver (SFR) spectrograms. Figure 4*c* shows the electron density versus L value; plasmasphere levels appear to have extended to just beyond L=6.

Around 2100 UT, as shown in Figure 3*b*, Halley whistlers probed the dense bulge plasma, while Siple, 2 hours behind in MLT, continued to detect trough levels over a wide L range. However, at this time, Siple also observed an outlying region of dense plasma near L=6. Then at 2135 UT, Figure 3*c*, Halley showed clear evidence of being well inside the bulge at an MLT of ~1830 hours. When Siple reached that same MLT at ~0010 UT (Figure 3*d*), it also observed high densities at L values where trough densities had been detected a few hours earlier.

Our estimate of the outer limit of the plasma feature in Figure 3 is based in part on the DE 1 data of Figure 4, which showed L=6 to have been the approximate plasmasphere limit along the dusk meridian. Other supporting evidence is presented in Figure 5, which shows the AE index for June 7 and 8, 1982, and, in clock dial format, the plasma densities deduced from GEOS 2 records of the upper hybrid resonance during roughly 12-hour periods on the two days. On June 7, during a quiet period shortly following a several hour interval of AE levels near 1000 nT, plasmasphere-level densities (near and above 50 el cm^{-3}) were detected from the beginning of the data coverage at 16 MLT (~14 UT) until ~1800 MLT. The data for June 8 were recorded following nearly 24 hours of quiet but during a period of renewed and relatively steady substorm activity in which AE was mostly in the range 300-500 nT. The electron density levels remained near 10-15 el cm^{-3}, characteristic of the trough region in the late afternoon, from the beginning of the observations at 1600 MLT until ~2000 MLT, when there was an abrupt transition to levels characteristic of the nightside trough [*Higel and Wu*, 1984]. These observations of the 16-18 MLT sector preceded the whistler probing of that sector by several hours (see Figure 3*a*) but because of the relatively steady behavior of the AE index in this period suggest that synchronous orbit was just beyond the plasmasphere as the latter was observed by DE 1 and the whistler stations.

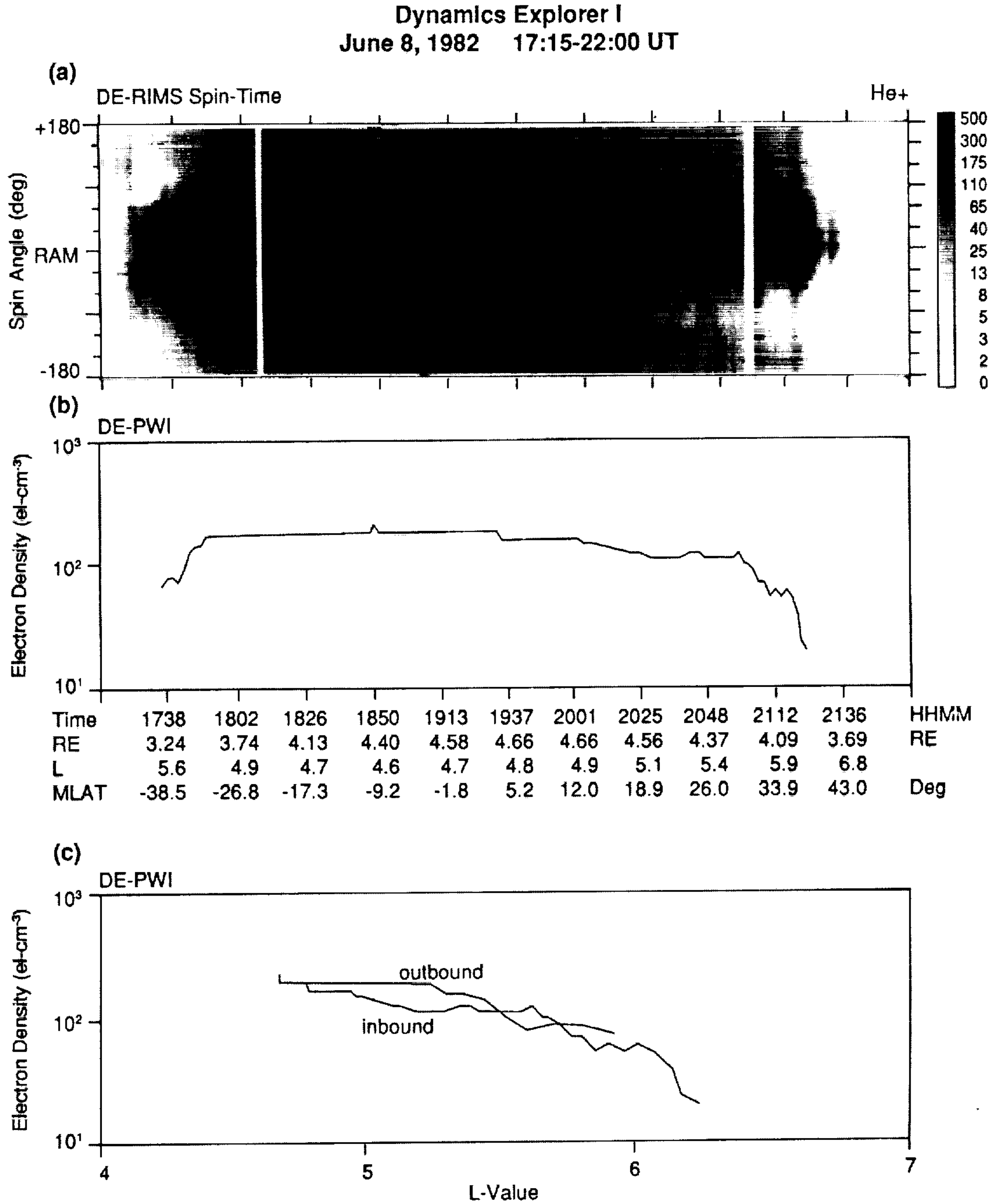

Fig. 4. DE 1 RIMS data showing penetration of the dense outer plasmasphere near 18 MLT on June 8, 1982. (*a*) Gray scale spin angle-versus-time record indicating the presence of a cold, rammed, isotropic distribution near apogee on June 8, at the approximate time that HB and SI whistler stations were detecting the plasma trough in the corresponding L range near midafternoon (Figure 3*a*). (*b*) Electron density versus time from the PWI instrument on DE 1, showing the increase in electron density associated with the change in He^{+} counts illustrated in Figure 4*a*. (*c*) Electron density versus L value, showing a dropoff in density at L ~6.1, the approximate outer limit of the plasmasphere as seen by DE 1.

Some Details of the Whistler Analysis

On the basis of existing empirical models of magnetospheric equatorial electron density [e.g., *Park et al.*, 1978; *Carpenter and Anderson*, this issue] and whistler propagation theory [e.g., *Helliwell*, 1965], it is possible to construct the diagram of Figure 6*a*, showing two domains in coordinates of whistler frequency versus travel time. One domain, at low travel times, corresponds to propagation through the plasma trough region, while the other corresponds to propagation within the plasmasphere. The dashed curve is intended to represent the approximate upper limit of observed plasma trough levels, and hence an early stage of recovery toward plasmasphere conditions. It corresponds to n_e =100 el cm^{-3} at L =4 and a profile with slope such that $d\log n_e/dL = -0.359$. Such a slope was found to be representative of typical, but not saturated, plasmasphere conditions by *Park et al.* [1978].

The approximate minimum gyrofrequency (and hence L shell) along a whistler propagation path can be estimated from the shape of the whistler curve [e.g., *Smith and Carpenter*, 1961; *Corcuff*, 1977; *Corcuff et al.*, 1977; *Tarcsai and Daniell*, 1979; *Daniell*,

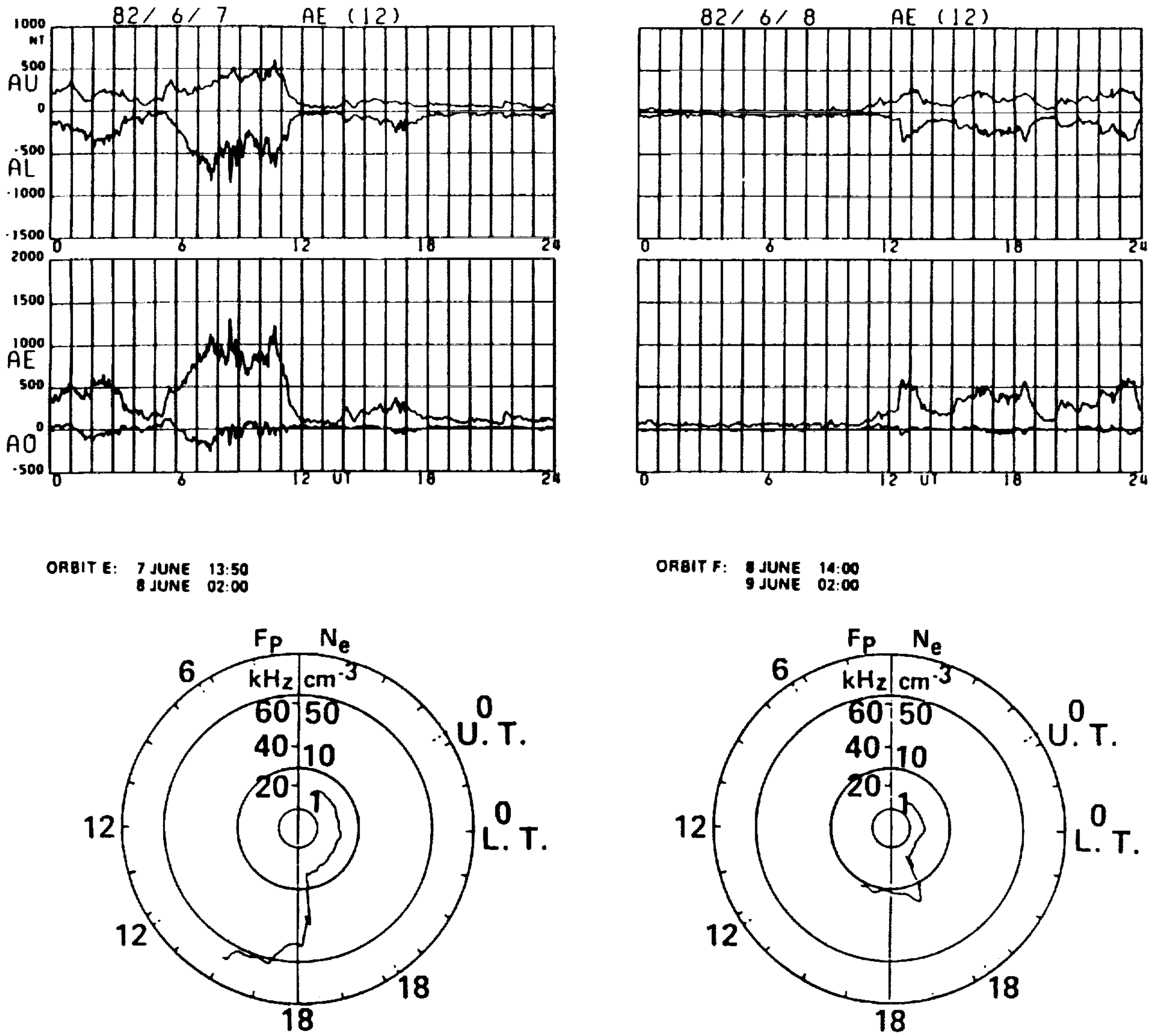

Fig. 5. (Top) The AE indices for June 7 and June 8, 1982, showing a 24-hour quiet interval prior to ~12 UT on June 8 and then moderate but relatively steady substorm activity during the ~18-24 UT period discussed here. (Bottom) GEOS 2 data from synchronous orbit on June 7 and June 8, showing in radially outward, clock dial format the densities inferred from the wave experiments package. On June 8 the densities were at afternoon plasma trough levels ($\lesssim$10-15 el cm^{-3}) throughout the 16-20 MLT period.

1986*a*, 1986*b*]. This shape is often studied in terms of the whistler nose frequency, or frequency of minimum travel time [e.g., *Park*, 1972]. The observed travel time from the lightning origin to the receiver at some higher whistler frequency is then used to estimate the electron density along the equatorial part of the propagation path. In Figure 6*a*, both the whistler components sketched correspond to propagation at L ~4.5, but they represent electron density levels that differ by a factor of roughly 10, or the square of the ratio of their travel times.

Figures 6*b* and 6*c* are sketches of whistler components that appear, respectively, in the spectrograms of Figure 7*a* and in the combined spectra of Figures 7*b* and 7*c*. Figure 6*b* summarizes the period when both Halley and Siple were observing the trough region (Figure 3*a*), while Figure 6*c* shows how both high- and low-density conditions were detected at the time represented in Figure 3*b*.

The equatorial electron densities inferred from Siple and Halley whistlers prior to, during, and after the bulge "encounter" are shown in Figure 8. The continuous curves in this figure are for reference; they represent results of recent empirical modeling of "saturation" plasmasphere levels and of trough levels, both appropriate to the afternoon sector [*Carpenter and Anderson*, this issue]. The profile of Figure 8*a* represents the data acquired in the trough region at ~1845 UT, as indicated in Figure 3*a*. Spectrograms of two closely spaced multicomponent whistlers from this period, separated by ~1 s in time, are shown in the Siple and Halley panels of Figure 7*a*. Similarities in the spectra recorded at the two stations indicate that the whistlers originated in the same two lightning flashes and that both stations were able to detect signals from some subset of the magnetospheric paths that were excited. This subset is indicated by traces 2, 3, and 4 of Figure 6*b*. There were clear differences between the Halley and Siple spectra, such as in some of the triggered VLF emissions. Furthermore, Siple, as the solid circles in Figures 3*b* and 8*a* indicate, detected components with paths at both lower and higher L than those observed at Halley (crosses). These Siple components are represented in Figure 6*b* by the traces numbered 1, 5, 6, and 7.

The actual displacements in longitude of the observed whistler

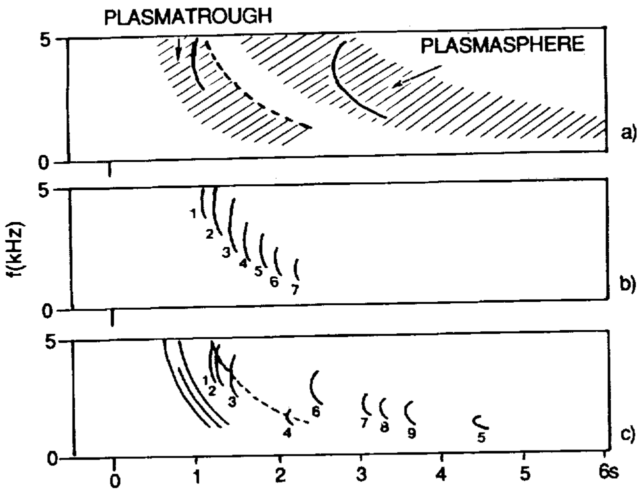

Fig. 6. (a) Diagram of domains in whistler frequency (0-5 kHz) versus time space corresponding to known plasma trough and plasmasphere electron density conditions. (b) Sketch, based on Figure 7, representing one of the whistlers recorded at Siple and Halley at 1845 UT. (c) Sketch, based on Figure 7, representing the distribution between Siple and Halley of the whistler components produced by a single lightning flash at 2045 UT. Component 5 was better defined in the Siple data of 2110 UT.

paths from the magnetic meridians of the two stations were not measured. Thus the azimuthal positions of the whistler paths indicated in Figure 3 should be understood to be only approximate. Comparisons of the intensity and dispersion properties of whistlers received at the two stations suggest that the whistler paths in this period were located closer to the Siple meridian than to that of Halley.

Figure 8b and corresponding Figures 6c, 7b, and 7c represent data acquired during the 2045-2110 UT period. The different Halley and Siple symbols in Figure 8b show that Siple continued to observe trough levels while Halley, as indicated in Figure 3b, began to sample the westward part of the bulge. However, within this period, Siple began to detect a single whistler component propagating in high-density plasma near L=6. In the sketch of Figure 6c, traces 1, 2, 3, and 4 represent Siple components that probed the trough region (as did all the Siple components detected at 1845 UT (Figures 6b and 7a)), while 6, 7, and 8 represent Halley traces from the same lightning flash, all of which probed the plasmasphere. Trace 5, indicated by arrows in Figures 7b and 7c but obscured by a noise band in these displays, represents the outlying high-density region detected from Siple. (The finding that these components were all from a single lightning flash was based not only upon their dispersion properties but also upon their identical frequency-time distributions in successive events.) In spectra recorded for 1 min every 5 min, the highest L trough data faded as the outlying high-density path made its first appearance, suggesting that Siple was "scanning" an outlier of limited westward extent at L=6 (see Figure 3b). For example, the "outlier" trace at 2110 UT (arrow in Figure 7c) was better defined than at 2045 UT, and the components seen at 2045:23 UT, with emission triggering near 1-2 kHz and propagation paths at trough levels near L=6, were no longer in evidence. (In Figure 7c, the traces corresponding to components 1, 2, and 3 of Figure 6c overlap several components from other whistlers.)

The lack of components observed at both Siple and Halley in the simultaneous records of Figure 7b suggests that propagation to the individual stations occurred on longitudinally well-separated paths in this period, in contrast to the at least limited longitudinal concentration implied by Figure 7a.

Figure 8c combines density data from Halley at 2130 UT with comparable data from Siple at ~0000-0020 UT. As implied in Figures 3c and 3d, measurable data were not obtained in the trough region by Siple at 2130 UT, and Halley data were not acquired at 0020 UT on June 9. The plot shows that both stations observed approximately the same density level upon encountering the main body of the bulge. As indicated, their results also agree with the level measured earlier from DE 1 at ~1920 UT, when it crossed the equator near the 1800 MLT meridian (see Figure 3a).

Spectrograms representing Halley whistlers at 2135 and Siple data at 0020 UT are shown in Figure 7d in the frequency band 0-10 kHz. The distributions of nose frequencies and travel times are similar; hence the similarity in the inferred profile levels.

The foregoing analysis of data in terms of "snapshots" at particular times was supported by the manner in which the activity changed with time in the records taken at 5 min intervals. During midafternoon, the two whistler stations detected what appeared to be the same whistlers. As the bulge encounter began, the stations began to observe separate and unique sets of whistler paths, but in each case the paths were still excited by a common lightning source. Later, both the whistlers and the whistler source activity became independent at the two stations.

3. DISCUSSION

Several of the phenomena discussed here seem to be at least partially understandable in terms of the types of MHD convection models that have been used to describe the erosion of the plasmasphere and the evolution of the plasmasphere shape during various stages of a disturbance. Figure 1, adapted from *Kurita and Hayakawa* [1985], shows the calculated plasmasphere shape at four successive times spaced at intervals of 6 hours. These four cases, part of a longer sequence, were obtained from a Volland-Stern convection field model with parameter γ=2 (allowing for partial screening of the convection field from the inner magnetosphere). The amplitude of the convection field was scaled according to Kp by a relation due to *Maynard and Chen* [1975]. Zero-energy electron trajectories were traced back in time from the universal times of interest, as in the earlier calculations by *Grebowsky* [1970] and *Chen and Wolf* [1972], and the plasmasphere limits were placed at the limiting positions of plasma elements that had experienced more than 5 days residence time in a closed field line configuration on the dayside of the Earth.

Figure 1a (representing 1800 UT on December 17, 1971) shows conditions ~24 hours after the onset of moderate to severe substorm activity, while Figure 1b shows the effects of a further surge in the convection field intensity. Distinctive features of Figure 1b, other than the diminution in plasmasphere radius in the night and dawn sectors, are the increase in plasmapause radius across the dayside and the broadening of the sunward extending tail or streamer that had developed earlier.

Quite different effects appear in Figures 1c and 1d, which represent a period of continuing but less intense disturbance activity. The tendency to corotate with the Earth became a progressively stronger effect with decreasing L, and the westward edge of the bulgelike region where the tail was "attached" became progressively better defined.

The scenario of Figure 1 appears to have counterparts in the present case as well as in previous whistler observations. In earlier work, *Carpenter and Seely* [1976] found evidence that when a substorm interrupts a quiet period, the cross-L drifts of whistler paths under observation in the afternoon sector reverse from their normal quiet day inward sense to outward. Such behavior is suggested by the topology of Figures 1a and 1b. On the other hand,

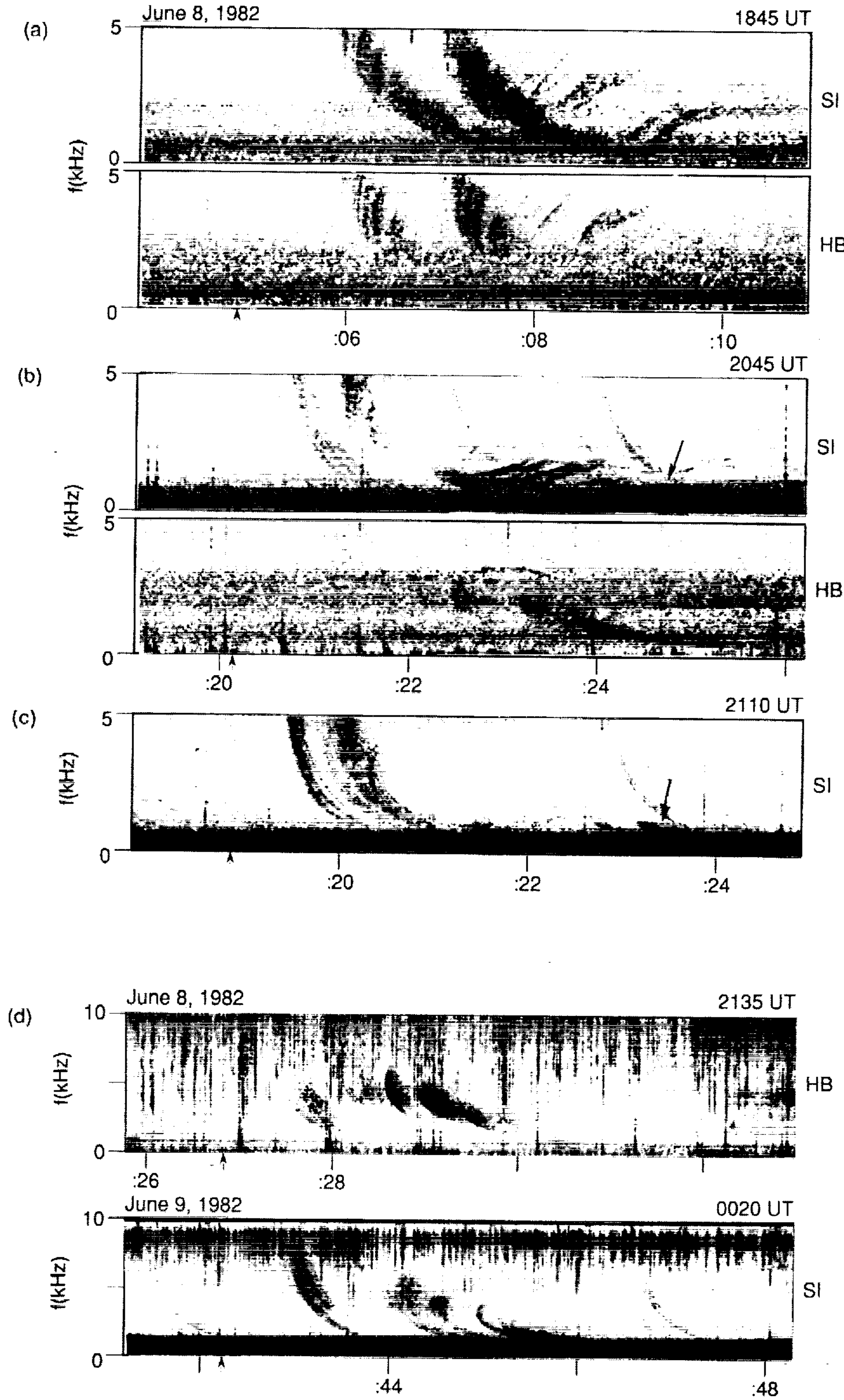

Fig. 7. (a) Spectrogram of two whistlers recorded simultaneously at Siple and Halley stations, Antarctica at 1845 UT on June 8, 1982. The whistlers originated in common lightning flashes and appear to have a number of common elements. An arrow below the time scales shows the time of origin of the first whistler (within $\pm$50 ms). (b) Spectrogram of a whistler recorded at both HB and SI at 2045 UT. In this case the dispersion properties of the whistler differ markedly from one station to the other, suggesting that the paths were well separated in longitude and that substantially different density regimes were probed, as outlined in Figures 3b and 6b. (c) Spectrogram of a Siple whistler from 2110 UT. The components near 2110:20 indicate the probing of the plasma trough, but the trace indicated by an arrow (as in the case of Figure 7b) indicates probing of a dense feature near L=6, again as indicated in Figures 3b and 6b. (d) Spectrograms of a Halley whistler at 2135 UT and a Siple whistler at 0020 UT. Both show multiple whistler components with dispersion properties characteristic of plasmasphere-level densities. Times indicated at the upper right of the records refer to the current minute.

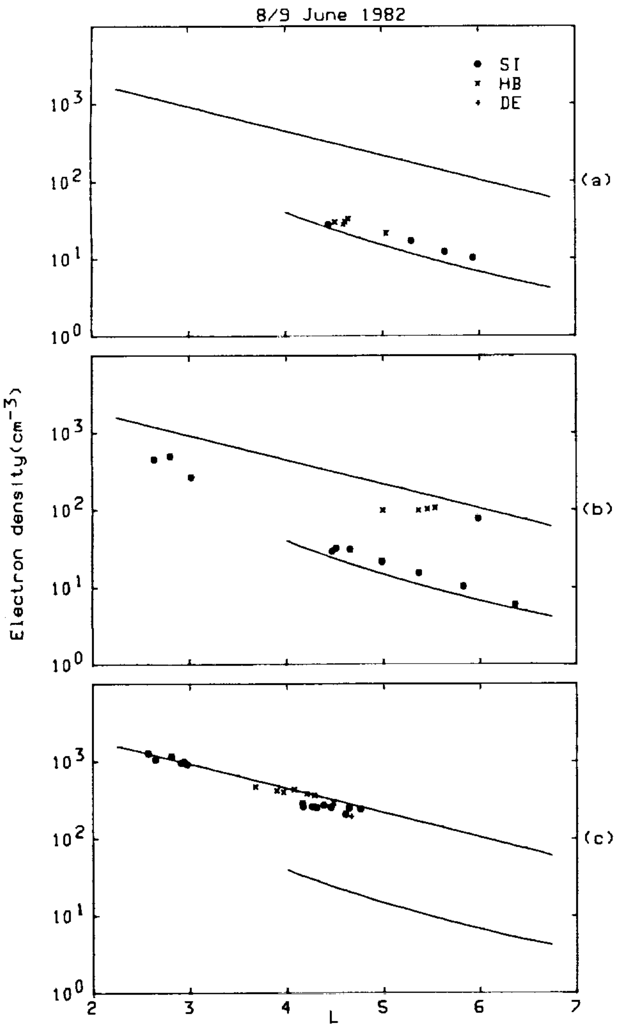

Fig. 8. (a) Values of electron density versus L value deduced from whistlers recorded at SI and HB stations near 1845 UT on June 8, corresponding to the situation of Figure 3a. (b) Same for the period 2045-2110 UT, corresponding to the situation of Figure 3b. (c) Same for HB at 2135 UT and Siple at ~0005-0020 UT, corresponding to the situations of Figures 3c and 3d. Also indicated is a DE 1 equatorial measurement at L ~4.7, made earlier at ~1920 UT along the orbit shown in Figure 3a.

during either a quieting period or one of relatively steady disturbance activity levels, the plasmasphere radius has been observed to be relatively constant with local time during afternoon hours until the westward edge of the bulge is encountered [*Carpenter*, 1970], as suggested by Figure 1c. The fact that in past whistler observations, evidence of this latter configuration has been detected more commonly than has evidence of the outward drifts is believed to be due to the fact that episodes of quieting and quasi-steady activity tend to be longer enduring than periods of increasing activity. The relatively large angular displacement of the westward edge of the bulge, suggested by the difference between Figures 1c and 1d, does not seem to be consistent with the quasi-stationary aspect that the bulge often presents in the frame of a ground whistler station. This may be due to the tendency for convection electric fields and associated flow opposing corotation to be particularly strong in the postdusk sector, even during periods of relatively low magnetic activity [e.g., *Maynard et al.* 1983].

In the present case, the observation of an apparently narrow outlying feature by a ground station prior to a well-defined bulge encounter and at an L value close to the outer limits of the main bulge region suggests the possibility that some type of sunward extending feature had developed when convection activity increased ~8 hours earlier and that it had relaxed into a quasi-steady position near dusk at the time of the reported measurements. While the sketches of Figure 3, as well as limited evidence from the earlier studies of *Ho and Carpenter* [1976] and *Taylor et al.* [1971], suggest that the feature was connected relatively smoothly in terms of density to the main plasmasphere, in fact this cannot be established in the present case. The process of its formation may have led to its development as an isolated irregularity, as suggested by the dashed lines in Figure 3d.

It is possible that an outlying plasma density feature such as the one reported here is characteristically present in the dusk sector when a well-defined bulge westward edge exists and that the lack of previous detection of such features by whistlers is simply a reflection of the problems in probing high-latitude structure noted above.

The qualitative agreement between MHD models such as the one discussed here and the reported data can be deceptive. As suggested by the GEOS 2 data of Figure 5, significant changes in plasma distribution, more complex than those described here, can take place very rapidly and over a wide spatial region in the afternoon-dusk sector (see, for example, *Corcuff and Corcuff* [1982] and *Higel and Wu* [1984]). In our larger study we are noting the occurrence of irregularities near and beyond the evening plasmapause, in a region where some of the strongest, generally sunward plasma flows have been found to exist [e.g., *Maynard et al.*, 1983], as well as outlying regions that persist in the dusk sector for days after the occurrence of a weak magnetic storm. Our impression is that only with significant further modeling efforts, as well as empirical studies, will a realistic picture of plasmasphere erosion begin to become available.

4. CONCLUSIONS

A case study based on a combination of ground whistler and satellite measurements of thermal plasma density has provided additional evidence that the abrupt westward edge of the bulge, reported earlier from whistlers, is a real phenomenon. This abrupt edge appears to be a characteristic feature of the relatively long periods of steady or declining activity that follow comparatively brief intervals of increasing convection electric fields. During steady or declining substorm activity, the interplay of the Earth's corotation electric field and the now less intense (and/or reduced by shielding) convection electric field is such that the dayside plasmapause becomes more nearly constant in radius, while portions of dense plasma previously carried sunward begin to rotate with the Earth in spiral fashion.

For the first time, whistlers have been used to detect a narrow dense feature extending sunward into the afternoon sector at L values near the observed outer limits of the main dusk bulge region. It is possible that such observationally elusive features regularly develop sunward of the main bulge in the aftermath of surges in convection activity. It was not possible to determine whether the observed outlying feature was connected smoothly to the main plasmasphere or was detached from it. There is earlier experimental evidence that both relationships may occur in the dusk sector.

While not contradicting the suggestion of *Lemaire* [1975] that a process of erosion of the plasmasphere takes place in the post midnight sector during periods of enhanced convection, the present observations appear to be most understandable in terms of processes occurring in the afternoon-evening sector.

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5. CONCLUDING REMARKS

The bulge region of the plasmasphere is a most difficult region to describe and interpret, in large part because of its dynamic nature and huge size, and because of the limited perspectives obtainable even from the present multi-platform approach. However, a number of generalizations appear to be warranted, based upon a combination of the present and previous research.

Patches of dense plasma, separated from the main plasmasphere by regions of plasmatrough-level densities, are regularly observed along high altitude satellite orbits that penetrate or traverse the afternoon- evening magnetosphere. Although often highly irregular in their profiles of $\log n_e$ versus L, the patches exhibit peak values consistent with an origin in the plasmasphere, and in some cases exhibit sharp density boundaries that resemble the gradients associated with the plasmapause.

The distribution of patches as a function of time during periods of plasmasphere erosion and recovery is not yet known, but it appears that the erosion process by which the mean plasmasphere radius is diminished is a primary contributor to the outlying patch distribution. Some patches, varying from a few tenths of an R_E to several R_E in extent along near equatorial orbits, appear to be present at all times, with the possible exception of periods when Kp approaches zero. On the basis of the case studies described above, coupled with our reading of other work, we offer the following descriptive model of thermal plasma behavior in the dusk sector. While elements of our model are variously speculative in nature, we believe that a model is needed as a point of departure for further investigations.

1. The plasmasphere rarely, if ever, assumes a teardrop shape, with a duskside radius of order 50% greater than the radius near dawn. An MHD teardrop model based upon calculations of a last closed equipotential may be useful in predicting the instantaneous flow patterns of low energy plasma and the approximate radius of the main plasmasphere in the dawn sector, but such models are not useful in describing the duskside plasma structures which are found to develop as a consequence of that flow.

2. The plasmasphere appears to be divided into two regions, the bulge region and the main plasmasphere. The separate identities of the two regions become clearest after an erosion event has occurred and a quieting trend has begun. The bulge is essentially the plasma that has originally been entrained by penetrating convection electric fields and displaced sunward and outward from the duskside plasmasphere, while the main plasmasphere is the bulk of the remaining dense plasma which, through approximate rotation with the earth during quieting, assumes a quasi-circular shape, with a duskside radius only $\sim 0.5 R_E$ greater than the radius at dawn, and thus a mean radius close to the radius established on the nightside during the main erosion period.

3. In the aftermath of an erosion event, the bulge and the main plasmasphere appear to be decoupled in the sense that the latter appears to be dominated by the Earth's corotation electric field, while the former appears to be strongly influenced by the convection electric fields that continue to be present.

4. During an erosion event, dense plasma flows sunward and outward from the late afternoon-dusk sector of the plasmasphere. The faster flows may at times exhibit a relatively sharp low-L limit. Within several hours, dense patches may be detected in the middle magnetosphere, at distances inside of and near synchronous orbit. As an additional consequence of the enhanced flow, patches of dense plasma, often several R_E in extent along satellite orbits, appear near the afternoon magnetopause.

5. In the aftermath of an erosion event, as the intensity of substorm activity subsides and/or as shielding of the inner magnetosphere by the ring current becomes important, extensive dense plasma patches may exist near the afternoon magnetopause for several days, being efficiently "trapped" in that region by high latitude fields, but unable to escape the magnetosphere for reasons that are not presently well understood. Such patches may at times cover a significant fraction of the outer afternoon-dusk magnetosphere, and are estimated to represent from ~10 to 30% of the outer plasmaspheric plasma entrained by the convection electric field during a weak magnetic storm. Meanwhile, the Earth's corotation becomes relatively more important at the middle magnetospheric radii previously penetrated by the erosion- period substorm fields, and any outward extending dense plasma features that had been entrained during the erosion phase but which had not been carried to the near vicinity of the magnetopause begin to move in the direction of the Earth's rotation. Their forms become spiral-like, due to the continuing influence of convection electric fields present along the outer magnetospheric field lines.

6. As the result of the decrease with distance in the angular velocity of the bulge plasma (the spiralling effect), the sunward flank of any outward-extending plasma streamer tends to become more sharply curved, leading to the formation of what a whistler station probing at radii near the afternoon plasmapause detects as an abrupt westward edge of the bulge region. The outer, streamer-like portions of the bulge plasma may appear as narrow features detected near to or sunward of the bulge westward edge, and may also appear along nearly radial satellite orbits as outlying dense plasma patches separated from the main plasmasphere by a trough region of order one R_E in width. These patches are usually narrower in their extent along satellite orbits than are the patches observed beyond synchronous orbit.

7. During continuing substorm activity after an erosion event, density irregularities with peak to minima ratios ranging from ~ 2 to 10 develop or appear near the plasmapause in the dusk-post dusk sector. These may represent the action of instabilities operating in the region of fast subauroral ion drifts, or SAIDs, and if displaced sunward during periods of enhanced convection, may contribute to the distribution of patchy irregular dense plasmas in the outer magnetosphere. The irregularities may be related to the wave-like features observed at the low latitude edge of the diffuse aurora.

8. If quieting is extremely deep, most outlying dense plasma patches move in the direction of the Earth's rotation and leave the afternoon magnetosphere devoid of major plasma irregularities. However, in most extended calm periods, dense plasmas become trapped in the afternoon-dusk sector, circulating there in response to the continuing, if

low level, substorm convection fields.

9. The properties of outliers observed near the plasmapause and out to synchronous orbit suggest that many of these are rooted in or attached to the main body of the plasmasphere. On the other hand, the distribution and occurrence of dense plasmas observed at $L \sim 6$ and beyond, and in particular their observation several days or more after an erosion event, suggest that many of those regions are effectively isolated from or detached from the main plasmasphere. While detachment may also develop in the aftermath of entrainment and outflow, velocity shear effects observed in the duskside ionosphere as well as various properties of pre-dusk substorm- associated convection surges detected by auroral radar [e.g. *Freeman et al.*, 1992] suggest that detachment may occur to some extent when the plasma first becomes entrained.

10. As quieting begins, a multiday process of plasmatrough filling begins within a belt extending from the main plasmasphere to those higher L values at which a plasma trough continues to form (under the quieter magnetic conditions now prevailing). Near dusk at $L = 4.5$ the apparent filling rate is roughly 4 ions-cm^{-3}-hr^{-1}. During the early stages of refilling, the light ions H^+ and He^+ tend to exhibit a bidirectional pitch angle distribution, as well as a trapped distribution within a few degrees of the equator. When the plasma density reaches a certain level, ~ 100 el-cm^{-3} at $L \sim 4.5$, still a factor of ~ 2-3 below the eventual saturation level, the observed distribution tends to become isotropic.

11. During the course of an erosion event, outer plasmasphere regions interior to the newly established plasmapause are disturbed, often becoming irregular and reduced in density by a factor of ~ 2-3 below saturation levels. These regions, which may have sharply defined inner limits, also undergo refilling toward saturation during the recovery period. Their loss of plasma occurs at a time when the underlying ionosphere is found to be depleted, supposedly by the perturbing effects of electric fields and associated Joule heating [e.g. *Aarons and Rodger*, 1991]. In the aftermath of a an increase in disturbance levels, warm light ions (~ 5 eV) can be observed in bulge regions close to the main plasmasphere (see also *Reasoner et al.* [1983]).

12. When depleted (trough) flux tubes exposed to dayside refilling reach the late-afternoon-dusk sector for the first time, their density levels are a factor of ~ 3-5 above those typically observed under nightside trough conditions.

13. Due to convection, there appears to be a separatrix between flow trajectories that come more or less directly sunward from the nightside and ones that cross the dayside. When this separatrix is outside the plasmapause, it may appear in satellite data (as in the case of GEOS 2) as an abrupt drop in density from typical dayside trough levels to typical nightside ones.

14. Relatively simple dynamic MHD models can be useful in predicting certain qualitative effects on a quiet plasmasphere of enhanced convection, such as the initial sunward entrainment of the outer regions and the effects of quieting on sunward extending features. However, as *Lemaire* [1985;1986] has pointed out, such models treat the

plasmapause as a mathematical concept, rather than a physical phenomenon. They do not address the question of the formation of the steep plasmapause profile, nor do they consider the possible role in that formation of instabilities due to such effects as subauroral ion drifts (SAIDs) or the generally enhanced eastward flows in the post- midnight sector during substorms . We find that the thermal plasma structure of the bulge sector is more complex than has been realized, and that success in attempts to model its behavior will depend upon improved models of the penetrating electric fields, of hot/cold (ring current/plasmasphere) plasma interactions, of plasmasphere boundary layer physics, of processes governing and inhibiting the flow of dense plasmas into and within the magnetosphere boundary layers, and of the physics of ionosphere-magnetosphere interchange flows. There is an obvious need for study of the plasma structure of the middle and outer magnetosphere, both in existing data sets and through the development and application of imaging techniques such as those envisaged by *Williams et al.* [1992] and *Roelof et al.*, [1992].

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