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Plasmasphere Dynamics in the Duskside Bulge Region: A New Look at an Old Topic

D. L. Carpenter,[1] B. L. Giles,[2] C. R. Chappell,[3] P. M. E. Décréau,[4] R. R. Anderson,[5] A. M. Persoon,[5] A. J. Smith,[6] Y. Corcuff,[7] and P. Canu[8]

Data acquired during several multiday periods in 1982 at ground stations Siple, Halley, and Kerguelen and on satellites DE 1, ISEE 1, and GEOS 2 have been used to investigate thermal plasma structure and dynamics in the duskside plasmasphere bulge region of the Earth. The distribution of thermal plasma in the dusk bulge sector is difficult to describe realistically, in part because of the time integral manner in which the thermal plasma distribution depends upon the effects of bulk cross-**B** flow and interchange plasma flows along **B**. While relatively simple MHD models can be useful for qualitatively predicting certain effects of enhanced convection on a quiet plasmasphere, such as an initial sunward entrainment of the outer regions, they are of limited value in predicting the duskside thermal plasma structures that are observed. Furthermore, use of such models can be misleading if one fails to realize that they do not address the question of the formation of the steep plasmapause profile or provide for a possible role of instabilities or other irreversible processes in plasmapause formation. Our specific findings, which are based both upon the present case studies and upon earlier work, include the following: (1) during active periods the plasmasphere appears to become divided into two entities, a main plasmasphere and a duskside bulge region. The latter consists of outlying or outward extending plasmas that are the products of erosion of the main plasmasphere; (2) in the aftermath of an increase in convection activity, the main plasmasphere tends (from a statistical point of view) to become roughly circular in equatorial cross section, with only a slight bulge at dusk; (3) the abrupt westward edge of the duskside bulge observed from whistlers represents a state in the evolution of sunward extending streamers; (4) in the aftermath of a weak magnetic storm, 10 to 30% of the plasma "removed" from the outer plasmasphere appears to remain in the afternoon-dusk sector beyond the main plasmasphere. This suggests that plasma flow from the afternoon-dusk magnetosphere into the boundary layers is to some extent impeded, possibly through a mechanism that partially decouples the high altitude and ionospheric-level flow regimes; (5) outlying dense plasma structures may circulate in the outer duskside magnetosphere for many days following an increase in convection, unless there is extremely deep quieting; (6) a day-night plasmatrough boundary may be identified in equatorial satellite data; (7) factor-of-2-to-10 density irregularities appear near the plasmapause in the postdusk sector in the aftermath of weak magnetic storms; (8) during the refilling of the plasmatrough from the ionosphere at $L = 4.6$, predominantly bidirectional field aligned and equatorially trapped light ion pitch angle distributions give way to a predominantly isotropic distribution (as seen by DE 1) when the plasma density reaches a level a factor of about 3 below the saturated plasmasphere level; (9) some outlying dense plasma structures are effectively detached from the main plasmasphere, while others appear to be connected to that body.

1. Introduction

Purpose of this Paper

The thermal plasma of the magnetosphere is a system that has memory, just as does the ionosphere [e.g., *Quegan*, 1989; *Rodger et al.*, 1992]. The distribution of magnetospheric plasmas at any time is dependent upon the convection activity, the instabilities, and the magnetosphere-ionosphere interchange fluxes to which the individual plasma packets have previously been exposed. This perspective seems of particular importance in studies of the duskside bulge region of the plasmasphere, a region that today remains poorly known and understood. Like the mid-latitude ionospheric trough near dusk [e.g. *Rodger et al.*, 1992], the duskside bulge plasma exhibits the effects of a strong interaction between convection and corotation electric fields, such that there is often a type of reversal with increasing latitude (or L value) from predominantly eastward flow (in a stationary frame) to predominantly westward flow. And by analogy to the midlatitude trough, the bulge may contain adjacent plasma regions whose preceding flow histories differ widely. The duskside bulge region is considered to be geophysically important because of its apparent involvement in the erosion of the plasmasphere by the action of enhanced convection electric fields [e.g., *Chappell*, 1972] and because of interactions between substorm-associated hot plasmas and the cool plasmasphere [e.g., *Barfield et al.*, 1975; *Kelley*, 1986; *LaBelle et al.*, 1988; *Yeh et al.*, 1991; *Freeman et al.*, 1992]. The region is important for the flow of dense plasma, entrained by convection electric fields, into the magnetosphere boundary layers (or, from a low-altitude perspective, onto the polar cap or into regions immediately equatorward of the polar cap). It is important for the flow and distribution of dense plasmas that are effectively removed from the main plasmasphere but do not escape from the outer magnetosphere [e.g., *Chappell*, 1974]. And it is important for the processes by which the electron content of depleted flux tubes is replenished in the aftermath of magnetospheric disturbances.

Along auroral and polar field lines in the duskside bulge sector, electric fields and associated plasma flows have been investigated in some detail, in most cases from measurements at ionospheric heights [e.g., *Heelis et al.*, 1982; *Foster et al.*, 1986; *Heppner*

[1]STAR Laboratory, Stanford University, Stanford, California.
[2]Space Sciences Laboratory, NASA Marshall Space Flight Center, Alabama.
[3]NASA Marshall Space Flight Center, Alabama.
[4]Laboratoire de Physique et Chimie de l'Environnement, Centre National de la Recherche Scientifique, Orléans, France.
[5]Department of Physics and Astronomy, University of Iowa, Iowa City.
[6]British Antarctic Survey, Natural Environment Research Council, Cambridge, United Kingdom.
[7]Laboratoire de Signaux et Communication, Université de Poitiers, Mignaloux-Beauvoir, France.
[8]Centre de Recherches en Physique de l'Environnement, Centre National d'Etudes des Télécommunications, Issy les Moulineaux, France.

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and Maynard, 1987; *Williams et al.*, 1990; *Anderson et al.*, 1991; *Yeh et al.*, 1991; *Freeman et al.*, 1992]. However, the large-scale distribution and circulation of thermal plasma that develops as a consequence of these fields and flows is not well known. Its description is complicated by the fact that much of the important "action" is expected to take place in subauroral regions, where the convection and corotation fields are of comparable magnitude, by the fact that the convection electric fields penetrating to middle latitudes appear to be unsteady in nature, and also because the properties of the high-altitude plasma cannot be readily inferred from the data of low-altitude satellites or ground-based ionospheric probing devices. This last difficulty is attributed in part to the compressed manner in which the outer magnetosphere maps to low altitudes and to the transition at low altitudes from an essentially magnetospheric plasma to the regular ionosphere. Furthermore, satellites operating at high altitudes have relatively long orbital periods, thus limiting the possibility for sampling of dynamic effects. There is also the problem of complacency, a tendency to believe that most of what there is to know about the duskside bulge was learned 20 years ago.

It is our purpose in this paper to provide an updated view of the properties of the duskside bulge region, with emphasis upon its structural complexity and the main features of its dynamic behavior. We will discuss the distribution of dense plasma in the aftermath of erosion events and several aspects of the interplay between convection and magnetosphere- ionosphere interchange fluxes during recovery periods. This broad approach is made possible by the availability of measurements from satellites DE 1, ISEE 1, and GEOS 2, each in a unique orbit, and from the longitudinally spaced ground whistler stations Siple, Halley, and Kerguelen.

Note that while commenting upon the issue of plasmapause formation and upon the general shape of the plasmasphere in the aftermath of disturbance, we are not attempting to investigate or review topics such as plasmaspheric ion composition [e.g., *Geiss et al.*, 1978; *Gallagher and Craven*, 1988], ion and electron temperature at various stages of disturbance and recovery [e.g., *Bezrukikh and Gringauz*, 1976; *Gringauz*, 1983; *Comfort et al.*, 1985], and a noon-midnight asymmetry in plasmasphere radius that is apparently characteristic of prolonged calm or quiet periods and has been reported from PROGNOZ satellite data by *Gringauz and Bezrukikh* [1976].

Background

Early interpretations of the duskside bulge. Current views about dusk sector thermal plasmas have been strongly influenced by empirical and interpretive work carried out twenty or more years ago. The initial whistler study of the plasmasphere as a worldwide phenomenon [*Carpenter*, 1966] included evidence of a diminution in its equatorial radius during periods of increased substorm activity as well as a duskside bulge. The average position of the plasmapause versus MLT that was estimated from whistler measurements is shown in Figure 1*a*. The conditions were ones of moderate, relatively steady geomagnetic agitation ($Kp = 2 - 4$). *Nishida* [1966], *Brice* [1967], and *Dungey* [1967] interpreted these phenomena in terms of the interplay between the large-scale, solar-wind-induced, convection electric field and the electric field associated with the Earth's rotation. (The classic discussion of such an interplay by *Axford and Hines* [1961] had earlier prompted *Carpenter* [1962*a*] to suggest that the dichotomy of an inner, Earth-dominated flow regime and an outer, convection-dominated one might explain the order-of-magnitude difference in density levels between the regions inside and outside the "knee" in the equatorial density profile.) The resulting plasma flow was divided into two regimes, an inner one that enclosed the Earth and an outer one that did not. The larger plasmapause radius near dusk was a consequence of the opposing nature of the convection and corotation electric fields in that local time sector. Erosion of the plasmasphere during a disturbed period occurred as the result of entrainment of the plasma in the outer plasmasphere and escape of some it from the magnetosphere along newly configured, non-dipole-enclosing streamlines of the combined flow.

Since these early works by Nishida, Brice, and Dungey, it has been common to assume that under "steady" magnetic conditions, the plasmapause tends to become coincident with the last closed equipotential of the flow regime. That idea has been used in several studies of magnetospheric thermal plasma structure and dynamics [e.g., *Chappell et al.*, 1971; *Higel and Wu*, 1984; *Doe et al.*, 1992], and has also provided the basis for estimates of the intensity of the large scale convection electric field [*Vasyliunas*, 1968; *Kivelson*, 1976*a*; *Berchem and Etcheto*, 1981]. Calculations of zero energy magnetospheric flow regimes that employ a uniform cross-tail electric field or a Volland-Stern [*Volland*, 1973; *Stern*, 1974] model predict a stagnation point in the dusk sector, the distance to which is a measure of the intensity of the solar wind-induced electric field (see discussion by *Morfill* [1978]). The magnitude of that field and its variations with magnetic activity have then been estimated from statistical data on plasmapause position.

Physics of the plasmapause as a boundary. The apparent success of the relatively simple MHD interpretation of the early plasmasphere observations probably served to deflect attention from questions about the physics of the plasmapause as a boundary. This was unfortunate; authors have become accustomed to discussing the plasmapause as a mathematical concept, one that emerges from the idea of a separatrix between two flow regimes, and as *Gringauz and Bassolo* [1990] have pointed out, little attention has been paid to the physical processes that should be at work as the boundary is being formed at a new location, and which should affect the boundary's subsequent stability, location, and density profile. An important but quite overlooked remark about the boundary question was made by *Dungey* [1967], who noted that the plasmapause profile was sharper than one might have expected from simple considerations of the effects of enhanced large-scale convection. Later papers have addressed questions of the thickness and stability of the boundary [e.g., *Richmond*, 1973; *Roth*, 1976; *Huang et al.*, 1990] but have relied on assumptions about the shape of the boundary profile after its initial formation. The formation problem has been discussed by *Lemaire* [1975, 1986] in terms of the coalescence along a certain trajectory of plasma "holes" or depleted regions that drift radially under the influence of the gravitational interchange instability.

Differences between the bulge sector plasmas and the "main plasmasphere." Other basic aspects of the plasmapause-plasmasphere system, such as the fundamentally unsteady nature of penetrating substorm-associated electric fields and certain observed complexities in thermal plasma structure, have received somewhat greater attention in the literature. For example, the earliest data on the distribution and variations with time of whistler paths indicated that when a ground-based observing station moved past the westward or sunward edge of the bulge, the plasma did not usually appear to flow outward to higher L values [*Carpenter*, 1966]. Instead, the bulge appeared to be a separate entity, with an origin essentially different from that of the main plasmasphere. Several near-equatorial crossings of the bulge region near dusk by the AMPTE IRM were studied by *LaBelle et al.* [1988], who described an outer plasmasphere region of order 1 R_E in extent that

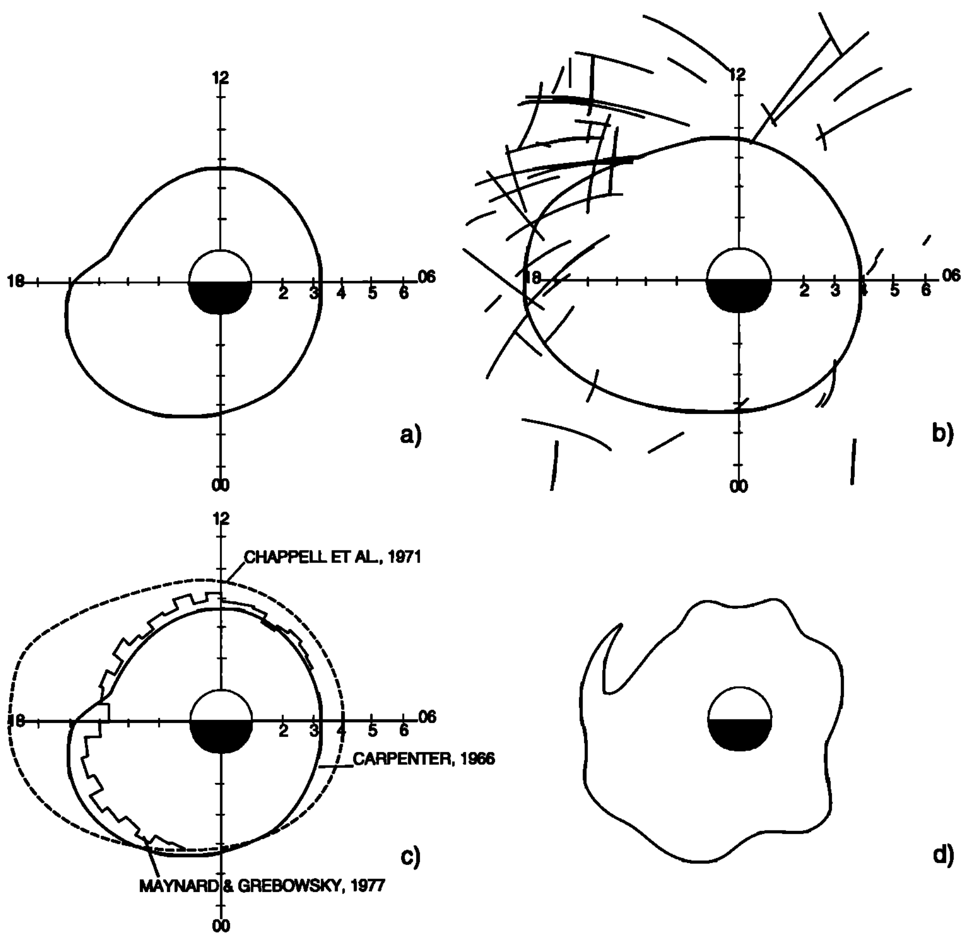


Fig. 1. (*a*) Equatorial radius of the plasmapause versus magnetic local time, showing the relatively abrupt westward edge of the bulge, or region of larger plasmasphere radius. The form indicated, deduced from whistlers acquired at Eights, Antarctica, was found typical for multiday periods of moderate, steady geomagnetic agitation ($Kp = 3 - 4$) in the aftermath of weak geomagnetic storms [from *Carpenter,* 1966]. (*b*) Segments of OGO 5 orbits along which "detached" plasmas were observed, the criterion for identification being separation from the main plasmasphere and density reaching a peak greater than $100(4/L^{-4})$ ions-cm^{-3} (to account for volumetric expansion of plasma tubes orginally at relatively low plasmasphere levels) [from *Chappell,* 1974]. (*c*) Comparison of estimates of average plasmasphere equatorial radius versus MLT from whistlers [*Carpenter,* 1966], from an ion mass spectrometer on OGO 5 [*Chappell et al.,* 1971], and from a double probe on Explorer 45 [*Maynard and Grebowsky,* 1977]. (*d*) Sketch showing how a "snapshot" of the plasmasphere might be expected to appear (exclusive of outlying features) 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].

was penetrated by ring current ions. The region of penetration or overlap was marked, even under relatively calm conditions, by evidence of sunward convection and by a plateaulike formation in the total density profile.

In discussing early work on magnetospheric convection, *Axford* [1969] considered the possibility that the bulge represents an eddy outside a roughly circular corotating region, while some of the potential patterns calculated in a paper by *Wolf* [1974] show a loop in the outer dusk sector that does not enclose the Earth. When equipotentials derived from EISCAT radar statistics were mapped to the equatorial plane by *Senior et al.* [1990], those representative of $4 \leq Kp \leq 6$ exhibited a tendency to form loops in the outer dusk sector. These particular lines of investigation, while promising, have not been actively pursued.

Additional evidence of the "decoupling" of the main plasmasphere and the dense plasmas of the bulge sector appeared in the form of outlying dense structures, intercepted over a wide range of distances beyond the main plasmasphere and predominantly in the afternoon or evening sectors. These were reported by *Chappell et al.* [1970, 1971] from OGO 5, by *Taylor et al.* [1970] from OGO 3, and later, from Explorer 45 near L =5, by *Maynard and Chen* [1975]. Figure 1*b* is a plot of the orbital segments along which the outlying features were detected from OGO 5. The structures exhibited density levels that were characteristic of the main plasmasphere, with allowance for changes with equatorial radius in flux tube volume, but were interpreted as having become "detached" from that body during periods of enhanced convection [*Chappell et al.,* 1971; *Chappell,* 1974]. A number of mechanisms for the detachment process have been briefly discussed, including rapid reconfiguration of the magnetosphere during substorms [*Barfield et al.,* 1975] and effects of localized structure in the electric field [*Chappell,* 1974]. *Grebowsky and Chen* [1976] found that the addition of a random spatial component to a large scale convection electric field could result in spatial irregularities in the thermal plasma density distribution in the vicinity of the plasmapause near dusk, some of which were detached from the main body of the plasmasphere. *Lemaire* [1985, 1986] has proposed a detachment process involving the gravitational interchange instability (as further noted below). Otherwise, this subject has received little attention.

Problems in measurements of plasmasphere shape. Additional complexity in the picture was introduced by the fact that while estimates of the average plasmasphere shape on the dawn side of the earth from satellite data agreed with estimates from whistlers, there were significant differences in results for the duskside bulge region. As illustrated in Figure 1*c*, data from an ion mass spectrometer on OGO 5 [*Chappell et al.*, 1971] produced a curve of average plasmasphere radius that extended well beyond the whistler-based curve in the dusk sector. Furthermore, it did not exhibit a special feature of the bulge reported from whistlers, namely a relatively abrupt westward edge, indicated by an increase of ~0.5-2.5R_E in plasmasphere radius within ~0.5 to 2 hours of observing time [*Carpenter* 1966, 1970]. *Chappell et al.* [1971] noted that such a feature is not configured so as to be readily identified by individual high altitude satellites, which move nearly radially across the L shells of interest. On the other hand, detection of such an effect was much more likely from the near equatorial orbit of Explorer 45, with apogee at L ~5, and in fact *Maynard and Grebowsky* [1977] used statistical data derived from the density-sensitive response of a double probe antenna on Explorer 45 to identify a bulge similar in form to that reported from whistlers (Figure 1*c*), but with a westward edge typically located after dusk.

The smoothness of the curves in Figure 1*c* can be deceptive, since there has long been evidence that the plasmasphere not only undergoes dramatic changes in overall size during periods of increasing disturbance, but that its radius can vary irregularly with longitude [*Angerami and Carpenter*, 1966; *Carpenter and Chappell*, 1973; *Carpenter and Park*, 1973; *Smith et al.*, 1981]. These variations have been attributed in part to spatial and temporal structure in the perturbing magnetospheric convection electric fields [*Carpenter and Chappell*, 1973; *Carpenter and Park*, 1973; *Carpenter*, 1983]. Figure 1*d* shows an earlier sketch of some of the ways in which a snapshot of the "instantaneous" plasmasphere, exclusive of more distant outlying features, has been expected to depart from the "average" behavior indicated in Figure 1*a* [*Carpenter*, 1983].

Observations of dynamic thermal plasma effects in the dusk bulge sector. Dynamic plasma effects in the dusk bulge sector, manifested both by reconfiguration of the plasmasphere and by depletion and refilling of flux tubes, have been documented in several specific ways. Early whistler results acquired during years of low solar activity [*Carpenter*, 1970] indicated that the location in local time of the comparatively abrupt westward edge of the bulge (Figure 1*a*) was correlated with magnetic activity. The edge was encountered by the moving ground station prior to 1800 MLT during or following periods of increased substorm activity, and tended to be observed at later local times under quieter conditions. If sufficiently deep quieting immediately preceded the penetration of the late afternoon sector by the station's field of view, the bulge was not detected. In such cases, any preexisting bulge was inferred to have already begun rotating with the Earth, such that it could not be "overtaken" by the ground station. (*Nishida* [1971] pointed out that such effects were more closely correlated with measurements of auroral electrojet activity in the dusk sector than with global indices of electrojet activity, thus anticipating later and still growing recognition of the importance of spatial variations in subauroral electric fields.)

A useful view of bulge dynamics was obtained from synchronous orbit by *Higel and Wu* [1984], who studied data from the Relaxation Sounder experiment on GEOS 2 [*S-300 Experimenters*, 1979]. On some very quiet days, plasmasphere-level densities were encountered for 10 hours or more in succession, but in most cases, such densities were encountered only for periods of ~1 to 3 hours in the afternoon or evening sectors. The local time at the center of the intercepted dense region varied with magnetic activity, being on average earlier during periods of greater disturbance, as in the case of the westward edge of the bulge detected by whistlers. The authors interpreted those cases that were preceded for 24 hours by relatively steady geomagnetic conditions (as indicated by Kp) in terms of a teardrop-shaped plasmasphere that varied in size with magnetic activity. The teardrop shape appeared to account for variations in the extent of the bulge along the satellite orbit but did not explain observed magnetic-activity-dependent shifts of the bulge midpoint away from its expected location at 1800 MLT (during "steady" conditions).

Numerical modeling of plasmasphere erosion and recovery. Numerical models have been used by a number of workers to study the process of plasmasphere erosion and recovery. They typically begin with an assumed potential distribution, in which the effects of the solar wind dynamo and the Earth's rotation dynamo are combined. Then, taking account of the refilling of depleted flux tubes from the ionosphere and allowing the solar wind dynamo to vary in intensity according to some measure of magnetic activity, they trace the flow of individual plasma elements backward in time from various locations in order to determine the extent of their recent exposure to net upward fluxes from the ionosphere, and thus to decide in what density regime (i.e., plasmasphere, plasmatrough, or intermediate density state), they are currently located [e.g., *Chen and Wolf*, 1972; *Maynard and Chen*, 1975; *Kurita and Hayakawa*, 1985]. This work generally supports the idea that during periods of enhanced convection, portions of the outer plasmasphere are transported sunward toward the afternoon magnetopause, presumably entering the boundary layers if the convection is sufficiently strong and/or persistent. Figure 2, adapted from *Kurita and Hayakawa* [1985], shows examples of this predicted effect, spaced by intervals of six hours. Figures 2*a* and 2*b* represent the effects of two successive enhancements in convection, while Figures 2*c* and 2*d* represent subsequent quieting, during which the effects of corotation gave rise to a progressively more spirallike configuration of the previously sunward extending region.

Additional physics have been brought into the problem by *Spiro et al.* [1981], who used data from a substorm period on September 19, 1976 to define a time varying potential distribution along a high latitude boundary. They then calculated the time varying electric field in lower- and middle-latitude field line regions by means of a convection model that included the shielding effect of the magnetospheric ring current and the effects of the nonuniform ionosphere in a self consistent way. The evolution of the plasmasphere shape was studied by following the $\mathbf{E} \times \mathbf{B}$ drift trajectories of the plasma flux tubes that made up an assumed pre-substorm plasmasphere boundary. This model, while limited by the necessity to choose a pre-substorm plasmasphere configuration, had the merit of predicting E fields that were in better agreement with substorm-period data from whistlers and radar than were results from model calculations based on spatially invariant convection electric fields. The model also predicted the drawing out of long, narrow filamentary tails near dusk during a four-hour substorm period.

MHD models have been used to explain a number of dynamic features such as changes with time in plasmapause positions measured at widely spaced ground stations [*Corcuff and Corcuff*, 1982]. *Chen and Grebowsky* [1974] used an MHD model to argue

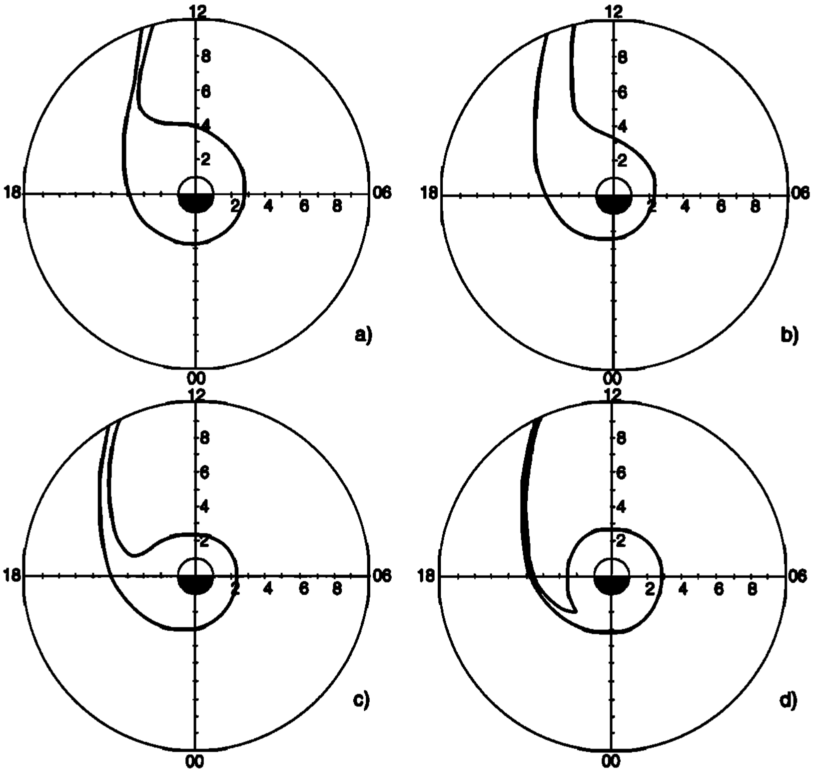


Fig. 2. Illustration of MHD model calculations by *Kurita and Hayakawa* [1985] of plasmasphere shape at 6-hour intervals during a disturbed period. Points within the plasmasphere were identified as those whose flow trajectories had remained inside L =10 for 5 or more days and thus had experienced five or more days of exposure to ionospheric plasma upflows on the dayside of the Earth. (*a*) Conditions ~ 24 hours after the onset of moderate to severe substorm activity at 1800 UT on December 16, 1971. (*b*) Effects of a further surge in convection activity. (*c*) and (*d*) Effects of a tendency of the thermal plasma to corotate with the Earth, at angular velocities that decrease with increasing L, during a period of reduced disturbance activity.

that certain of the outlying features reported from OGO 5 could be explained in terms of streamers of plasma extending sunward from the main plasmasphere. *Maynard and Chen* [1976] had some success modeling changes with time in the distribution of dense plasmas detected from Explorer 45, but experienced difficulties in modeling the configuration of outlying structures that appeared in the afternoon sector in the aftermath of increases in *Dst*.

Although much has been claimed for the MHD-type simulations, they have not gone unchallenged; *Lemaire* [1974, 1975, 1985] and *Lemaire and Kowalkowski* [1981] have pointed out that to the extent that the MHD interpretations of plasmasphere dynamics involve the assumption of infinite Pedersen conductivity in the ionosphere, local charge separation electric fields associated with instabilities are not being accounted for, and hence an important type of instability, namely the gravitational interchange instability, is being overlooked as a contributor to plasma erosion during substorms. Because of fast post-midnight eastward azimuthal drifts during substorms, this instability should have a particularly strong effect in the postmidnight sector during periods of enhanced convection. Regions of locally depressed density are expected to 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 formed as locally dense regions drift outward due to the same interchange instability, having become "detached" from the main plasmasphere by the formation of the longitudinally extended depression. The more remote outlying structures found on the dayside by *Chappell et al.* [1971] could be explained in terms of movement of dense regions from starting points in the postmidnight sector. Some success has been reported in using this model to interpret whistler data acquired during a several day period [*Corcuff et al.*, 1985].

A key point here is that Lemaire accepts the idea that the time varying, large-scale electric field modifies the plasmasphere shape during substorms, particularly in the dusk sector and in the early hours of the activity. However, he proposes that the interchange instability gives rise to a peeling effect that operates within the context of the existing electric field, and thus causes the plasmasphere configuration to differ from that which would be predicted from the action of the large-scale electric field alone.

Observations of flux tube depletion and recovery in the dusk sector. Empirical studies of the processes of flux-tube plasma depletion and recovery in the dusk sector have thus far been quite limited. There is essentially no observational work on flux tube depletion in the region that becomes the trough immediately exterior to the plasmapause. Such work might indicate whether the low equatorial electron densities, apparently <1 electron cm^{-3}, that occur on the nightside in the aftermath of substorms are attributable to an evacuation process that operates in particular middle-magnetospheric regions during an early substorm phase, or whether they are instead an inherent feature of the large-scale plasma circulation.

Recovery from depletion is more accessible to observation (with the possible exception of a very short and hence observationally elusive initial phase that immediately follows plasmapause formation [e.g., *Carpenter and Anderson*, 1992]); statistical data from whistlers [*Park*, 1974], from OGO 5 [*Chappell et al.*, 1971], and from GEOS 2 [*Higel and Wu*, 1984; *Song and Caudal*, 1987] have provided useful estimates of dayside density recovery rates, which are particularly pertinent to the dusk sector plasma trough regions. However, only with the DE 1 satellite, and during periods of operation along nearly field aligned orbits, has it become possible to investigate the thermal ion dynamics of the bulge region on a case study basis.

DE 1 studies of thermal ion dynamics. Among the accomplishments of the DE 1 program is the identification of thermal ion pitch angle distributions associated with particular ranges of invariant latitude and stages of recovery from disturbance. Three distributions commonly observed in the light ions H^+ and He^+ in the plasmasphere, plasmapause, and trough regions are (1) isotropic (usually rammed and thus peaked in the direction opposite to that of the spacecraft velocity vector), (2) bidirectional field aligned or BI (counter streaming field-aligned beams), and (3) equatorially trapped or TR (also called pancake). The isotropic distribution is associated with the inner plasmasphere and high total electron density [*Baugher et al.*, 1980; *Chappell et al.*, 1980,1982; B. L. Giles et al., A statistical survey of pitch angle distributions in core (0-50 eV) ions from Dynamics Explorer 1, submitted to *Journal of Geophysical Research*, 1993 (hereinafter referred to as Giles et al., submitted manuscript, 1993)]. In contrast, the BI has been found in regions of lower plasma density during periods of recovery from disturbance and corresponds to pitch angle distributions that have undergone one or more bounce periods [*Giles et al.*, 1988; also submitted manuscript, 1993]. The bouncing distributions are believed to be a manifestation of enhanced ionospheric heating associated with convection, such that enhanced upward flow occurs into closed, but depleted, field line regions [*Sojka et al.*, 1983]. The trapped distributions, involving warm light ions of a few electron volts to tens of electron volts at high pitch angles, have been observed within a few degrees of the magnetic equator [*Horwitz and Chappell*, 1979; *Horwitz et al.*, 1981; *Chappell*, 1982; *Chappell et al.*, 1982; *Gurgiolo and Burch*, 1982; *Olsen et al.*, 1987; Giles et al., submitted manuscript, 1993], and like the BI are associated with regions of low total density beyond the plasmasphere. The warm trapped ions are considered to be evidence of wave-particle interactions in the equatorial region where the counter streaming refilling plasma streams meet. In particular, they have been attributed to interactions between ULF waves and the thermal ions [*Olsen et al.*, 1987]. The occurrence of the TR and BI distributions, while apparently associated with the refilling toward saturation levels of recently depleted regions, has not yet been considered in terms of evolution with time and as a function of local plasma density. In the only previous study specific to the dusk region, *Décréau et al.*, [1986] found that the BI distribution tended to persist near the equator well into periods of quieting.

The Present Case Study Approach

Progress in the study of bulge sector plasmas has been hindered because of the limited ability of individual satellites, ground stations, or instruments to probe the very large spatial regions involved, 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 both ground stations and satellites, as *Corcuff and Corcuff* [1982] and *Fontaine et al.* [1986] have demonstrated. In the present paper we will use such an approach, employing data acquired during three case study periods by several satellites and by ground whistler stations in order to provide a more unified and comprehensive picture of bulge sector dynamics than has previously been available. The case studies are not presented in chronological order; instead the emphasis is upon particular physical phenomena and the evidence supporting them that can be drawn from any or all of the study periods.

2. SOURCES OF DATA

A longitudinal network of ground whistler stations near $L = 4$ provided whistler data on the equatorial electron density profile. The stations are: Siple (SI, 76°S, 84°W, L ~4.3), Halley (HB, 76°S, 27°W, L ~4.3), and Kerguelen (KE, 49°S, 69°E, L ~3.8). Kerguelen leads Siple by nine hours in MLT and Halley by ~7 hours. Applications of the whistler method, particularly in the case of the region near the plasmapause, have been discussed by *Corcuff* [1977], *Corcuff et al.* [1977], *Park and Carpenter* [1978], *Carpenter* [1988], and *Sazhin et al.* [1992], among others.

The DE 1 satellite provided data on thermal ions from the retarding ion mass spectrometer (RIMS) experiment [*Chappell et al.*, 1981] and on electron density from the plasma wave instrument (PWI). The density values were inferred from observations of the upper hybrid resonance (UHR) in the data of the sweep fre-

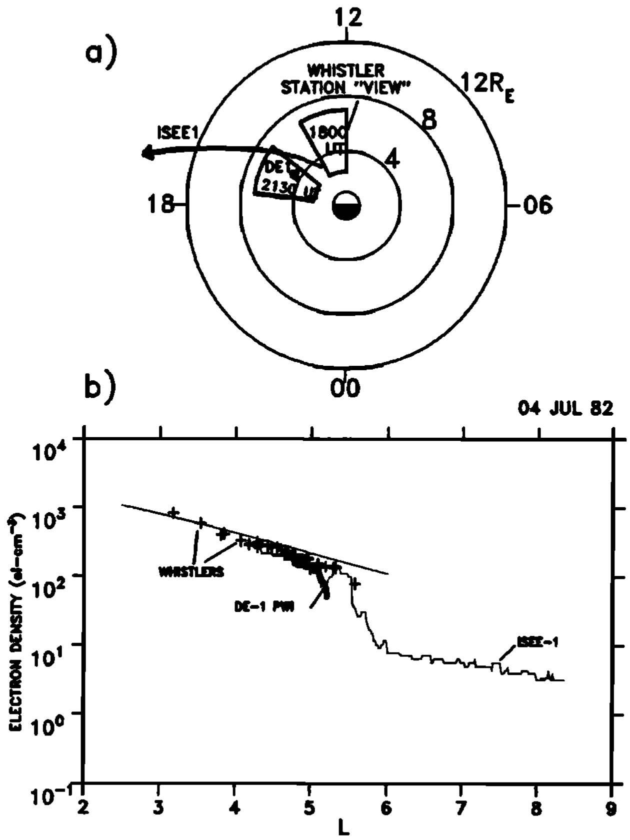


Fig. 3. Rendezvous situation on July 4, 1982, involving DE 1, ISEE 1, and the Siple, Antarctica, ground whistler station. (*a*) Plot of radial distance versus MLT, showing the estimated equatorial viewing area of the Siple whistler station at the beginning and end of a period of DE 1 observations near the equator. The position in L versus MLT of DE 1 as the satellite moved between -20° and +20° is shown by a heavy line segment. The ISEE orbit is plotted in terms of geocentric distance versus MLT; the time interval for the ISEE 1 profile in Figure 3*b* was 1805 to 2044 UT, overlapping the time of the DE and whistler observations. For most of the period, ISEE remained within ~ 20° of the magnetic equator. (*b*) Electron density profiles in coordinates of $\log n_e$ versus L, obtained during the rendezvous situation shown in Figure 3*a*.

quency receiver (SFR) [*Shawhan et al.*, 1981]. During the three case study periods the spacecraft followed an elliptical orbit with perigee of 6825 km geocentric distance, apogee of $4.67R_E$, and orbital period of approximately 7.5 hours. The orbit plane drifted westward at a rate of 1 hour MLT every 15.4 days (24 hours in 12 months); the orbit line of apsides drifted 0.328 deg in magnetic latitude each day (one pole to the other in 18 months). The spacecraft spun in a reverse cartwheel mode at 10 rpm with its spin axis perpendicular to the orbit plane. During the time period chosen for the study (May to July, 1982), the orbit was almost symmetric with respect to the magnetic equatorial plane, with some variation in the latitude of the apogee according to the universal time of the pass. Hence the L value near apogee was ~4.6 and roughly constant as the satellite moved between ~ ±30° latitude.

ISEE 1 provided data on electron densities derived from SFR observations of the UHR or of the plasma frequency [*Mosier et al.*, 1973; *Gurnett et al.*, 1979]. The ISEE 1 spacecraft was in a highly elliptical orbit with apogee at 23 R_E and perigee of a few hundred kilometers. The orbital period was approximately 2.5 days. The spacecraft's spin axis was oriented perpendicular to the ecliptic plane, and the spin period was 3 s. The orbital plane was inclined 30 deg with respect to the Earth's equatorial plane.

GEOS 2 provided data on electron densities derived from the plasma frequency, which was identified by the Relaxation Sounder experiment [*S-300 Experimenters*, 1979]. GEOS 2 was in synchronous orbit at 20°E and on the geomagnetic equator.

Figure 3*a* shows, in coordinates of radial distance versus MLT, a rendezvous situation involving ISEE 1, DE 1, and the Siple ground whistler station. The observations were made on July 4, 1982, near 16 MLT. The estimated location of the equatorial viewing area of Siple Station is shown at two universal times, 1800 and 2130 UT. The position in L versus MLT of DE 1 as the satellite moved between −20° and 20° is shown by a heavy line segment. Scalable PWI density data were available from 1800 to ~2020 UT, between ~−12° and 31° along the orbit. The ISEE orbit is plotted in terms of geocentric distance R versus MLT; the segment represented in the profile of Figure 3*b* covered the period 1805 to 2044 UT, overlapping the time of the DE and whistler observations. During most of this period ISEE remained within ~20° of the magnetic equator.

Good mutual agreement, within of order 30% between whistler and ISEE electron density data acquired in rendezvous situations, has earlier been demonstrated by *Carpenter et al.* [1981]. As an indication of this agreement in the present case, we compare in Figure 3*b* equatorial profile data from DE, ISEE, and Siple whistlers for the case of Figure 3*a*. The line is a reference for the quiet or "saturated" plasmasphere from recent empirical modeling work by *Carpenter and Anderson* [1992]. A plasmapause decrease is clearly shown in both the ISEE and DE data, although at slightly different L values. The whistler data show the beginning of a plasmapause effect where the steep falloff begins on the ISEE profile. All three experiments agree within their common L range near L = 5, and the whistler and ISEE data agree well on the average slope of the profile within the plasmasphere.

3. EXPERIMENTAL RESULTS

Introduction to the Case Studies

Multiday periods in May, June and July 1982 were selected so as to provide DE 1 and ISEE data from the dusk sector at 20, 18, and 16 MLT, respectively, and to take advantage of the austral winter peak in whistler activity at the stations Siple, Halley and Kerguelen. Figures 4*a*, 5*a*, and 6*a* provide introductory

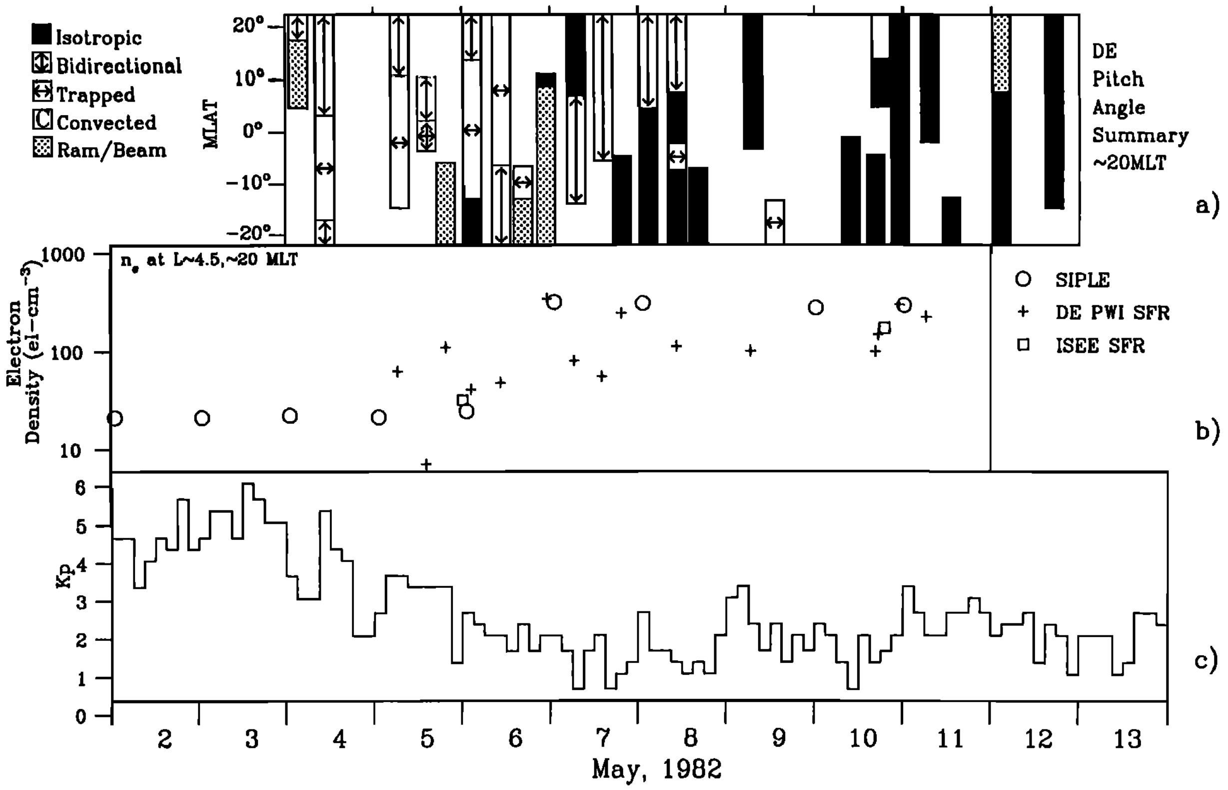


Fig. 4. Reference data versus UT for the May 1982 case study of events near 2000 MLT. (*a*) Predominant DE 1 thermal ion pitch angle characteristics recorded within ~ ±20° of the magnetic equator. (*b*) Equatorial electron density at L ~4.5 measured from the Siple, Antarctica whistler station and from the SFR data acquired on DE 1 and ISEE 1. (*c*) Three-hour Kp indices.

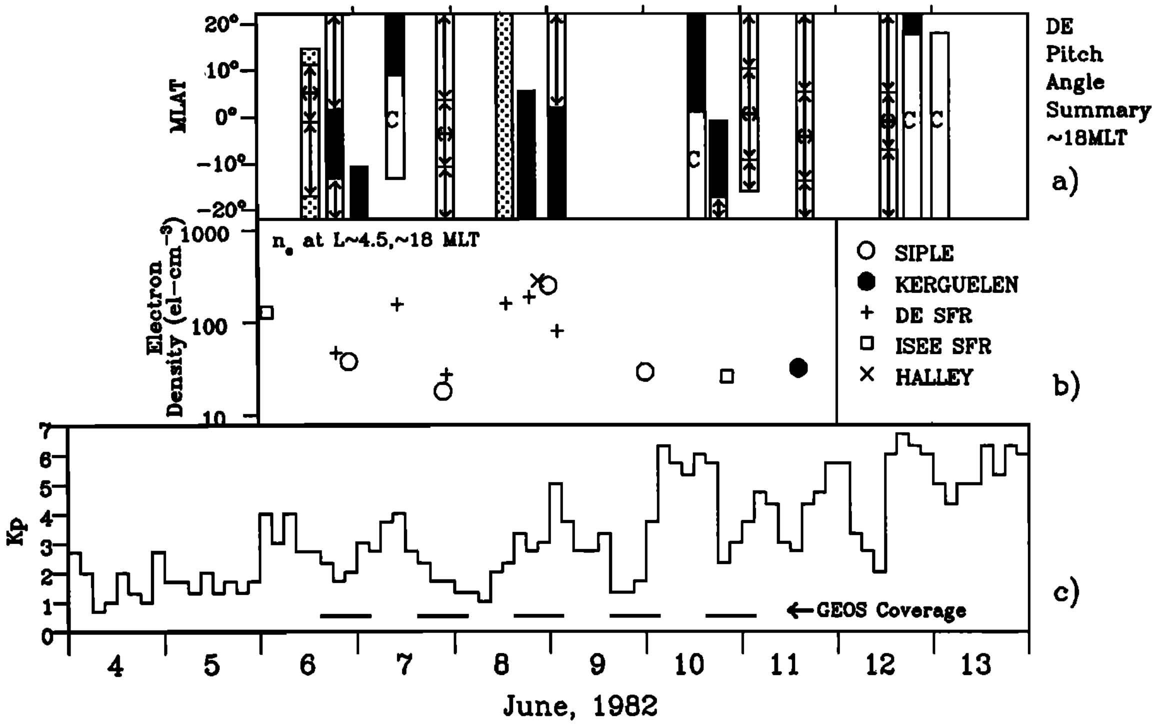


Fig. 5. Reference data versus UT for the June 1982 case study of events near 1800 MLT. (*a*) Predominant DE 1 thermal ion pitch angle characteristics recorded within ~ ±20° of the magnetic equator. (*b*) Equatorial electron density at L ~4.5 measured from the Siple and Halley, Antarctica, and Kerguelen whistler stations and from the SFR data acquired on DE 1 and ISEE 1. (*c*) Three-hour Kp indices.

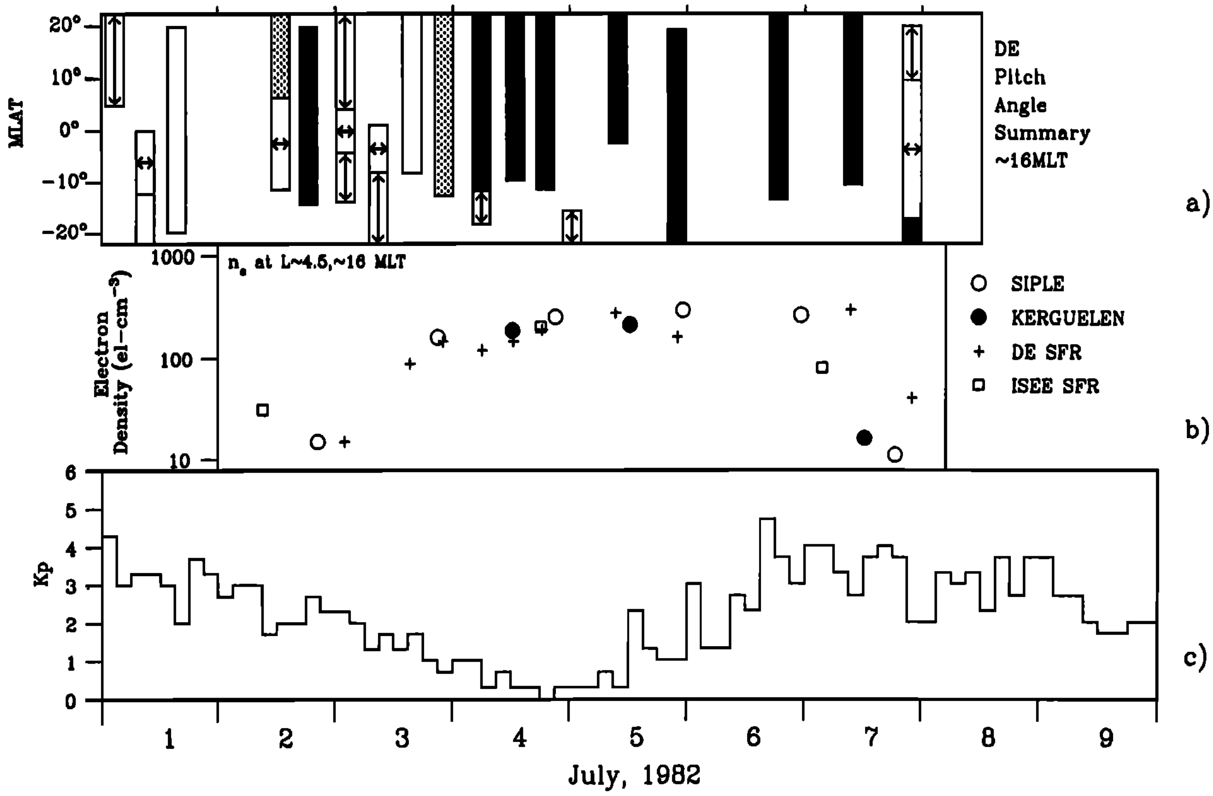


Fig. 6. Reference data versus UT for the July 1982 case study of events near 1600 MLT. (*a*) Predominant DE 1 thermal ion pitch angle characteristics recorded within ~ ±20° of the magnetic equator. (*b*) Equatorial electron density at L ~4.5 measured from the Siple, Antarctica and Kerguelen whistler stations and from the SFR data acquired on DE 1 and ISEE 1. (*c*) Three-hour Kp indices.

summaries of DE 1 thermal ion pitch angle data near the equator for the three periods, Figures 4*b*, 5*b*, and 6*b* equatorial electron density at $L \sim 4.5$, and Figures 4*c*, 5*c*, and 6*c* 3-hour Kp indices of magnetic activity. The "ram/beam" pitch angle category means that the ram direction was close to the magnetic field direction and that the pitch angle distribution was concentrated in the ram direction but was ambiguous, in that it could not be clearly classified as isotropic or as warm and beamed.

The cases represent a substantial variety of magnetospheric conditions. Both the May (Figure 4*c*) and July (Figure 6*c*) cases exhibited recovery from weak magnetic storms. In July (Figure 6*c*) there was relatively deep quieting, followed by renewed disturbance at moderate levels, while in May (Figure 4*c*) there was a prolonged postrecovery period of low level activity. Both the May and July cases illustrate a return to predominantly isotropic pitch angle distributions (solid black) as the plasmasphere refilling process proceeded. During the June period (Figure 5), there was a trend away from isotropic distributions as the mean level of disturbance activity increased. Surges of substorm activity were repeated at intervals of from ~24 to 36 hours, and on four orbits, marked by a "C," the RIMS data showed evidence of convection of dense plasma.

Daily Equatorial Profiles From Whistlers

Figures 7*a*–7*c* show the equatorial profiles deduced from whistlers recorded at Siple Station, Antarctica during major portions of the May, June, and July case study periods. Figure 7*a* represents daily recordings from May 2 to 11, 1982, at ~2000 MLT, while Figures 7*b* and 7*c* represent June 6–10 and July 2–7 at ~1800 and 1600 MLT, respectively. These local times correspond approximately to the MLTs of the DE 1 orbit plane during those periods. (For the May period (Figure 7*a*), only 4 of the 10 days are represented. The profiles for the missing intermediate days were found to be similar to the nearest preceding or following ones indicated.)

The smoothed profiles shown in Figure 7 were obtained by assuming certain functional forms of the radial density variation within the plasmasphere and plasmatrough (from statistical studies) and then in each case adjusting the scale factors of the plasmasphere and plasmatrough profile segments to fit the available measurements of equatorial electron density n_e versus L (see figure caption for further explanation). The solid lines show regions where the smoothed profiles were supported by measurements on well defined whistler components, while the dashed lines show regions of greater uncertainty, usually associated with the location and profile of the plasmapause (see, for example, the whistler data of Figure 3*b*). When a plasmapause effect is shown dashed, evidence of its location to within $\pm 0.3L$ was available in the data. We assumed a plasmapause scale width of $0.1L$, from the nighttime ISEE 1 based model of *Carpenter and Anderson* [1992], where scale width is defined as the distance in L over which the density changed by a factor of 10. (Whistlers provide good information on density levels on both sides of the plasmapause, but only limited information on the profile between levels.)

The profiles illustrate various stages in the well-known cycles of plasmapause formation during periods of increased disturbance [e.g., *Carpenter* 1966] and of density recovery both within and beyond the plasmapause during quieting periods [e.g., *Park* 1974]. Note that in all three case studies (and thus at all three MLTs), when a well-defined plasmapause was observed following an increase in magnetic activity, it appeared near $L = 4$, and not near $L = 5$ or 6 where one might have expected it to occur on the

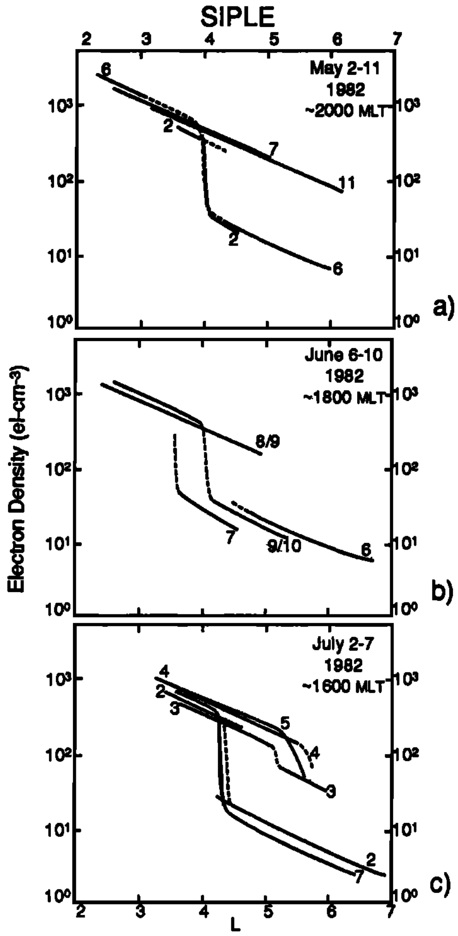


Fig. 7. Smoothed equatorial electron density profiles deduced from whistlers recorded at Siple, Antarctica, during the May, June, and July periods documented in Figures 4, 5, and 6, respectively. In the plasmasphere, curves with slope $d \log n_e / dL = -0.36$ were fitted to the observed data points (with the exception of the case of July 5, in which the saturation-condition value of -0.31 was used [*Carpenter and Anderson*, 1992]). This value, from *Park et al.* [1978], was chosen because it reflects typical conditions of recovery rather than saturation. Outside the plasmapause, curves corresponding to $n_e \propto L^{-4.5}$ [*Carpenter and Anderson*, 1992], were fitted to the data. (*a*) Daily profiles for May 2–11 at ~2000 MLT. Profiles for the missing intermediate days were found to be similar to the nearest preceding or following ones indicated. (*b*) Daily profiles for June 6–10 at ~1800 MLT. (*c*) Daily profiles for July 2–7 at ~1600 MLT.

basis of published evidence of a plasmasphere "bulge" near dusk [e.g., *Carpenter*, 1966, 1970; *Chappell et al.*, 1971; *Higel and Wu*, 1984]. We believe that the whistler data of Figure 7, as selected, emphasized the "main" plasmasphere, which tends to lie interior to the bulge region. This point will become clearer in later sections.

Dynamic Effects Associated With Surges in Convection

Observations of convection of dense plasma near dusk. During intervals of enhanced substorm activity in the June 6–13 period (Figure 5*c*), there were five occasions on which the RIMS experiment on DE 1 recorded evidence of dense plasma convection at ~1800 MLT. Four of these occasions are indicated by a "C" in the thermal ion pitch angle summary of Figure 5*a*. Plate 1*a* shows a spin- time RIMS He^+ record for 0930–1130 UT on June 7, during the latter part of a 4-hour (~0700–1100 UT) surge in the *AE* index to ~1000 nT. The satellite was moving from south

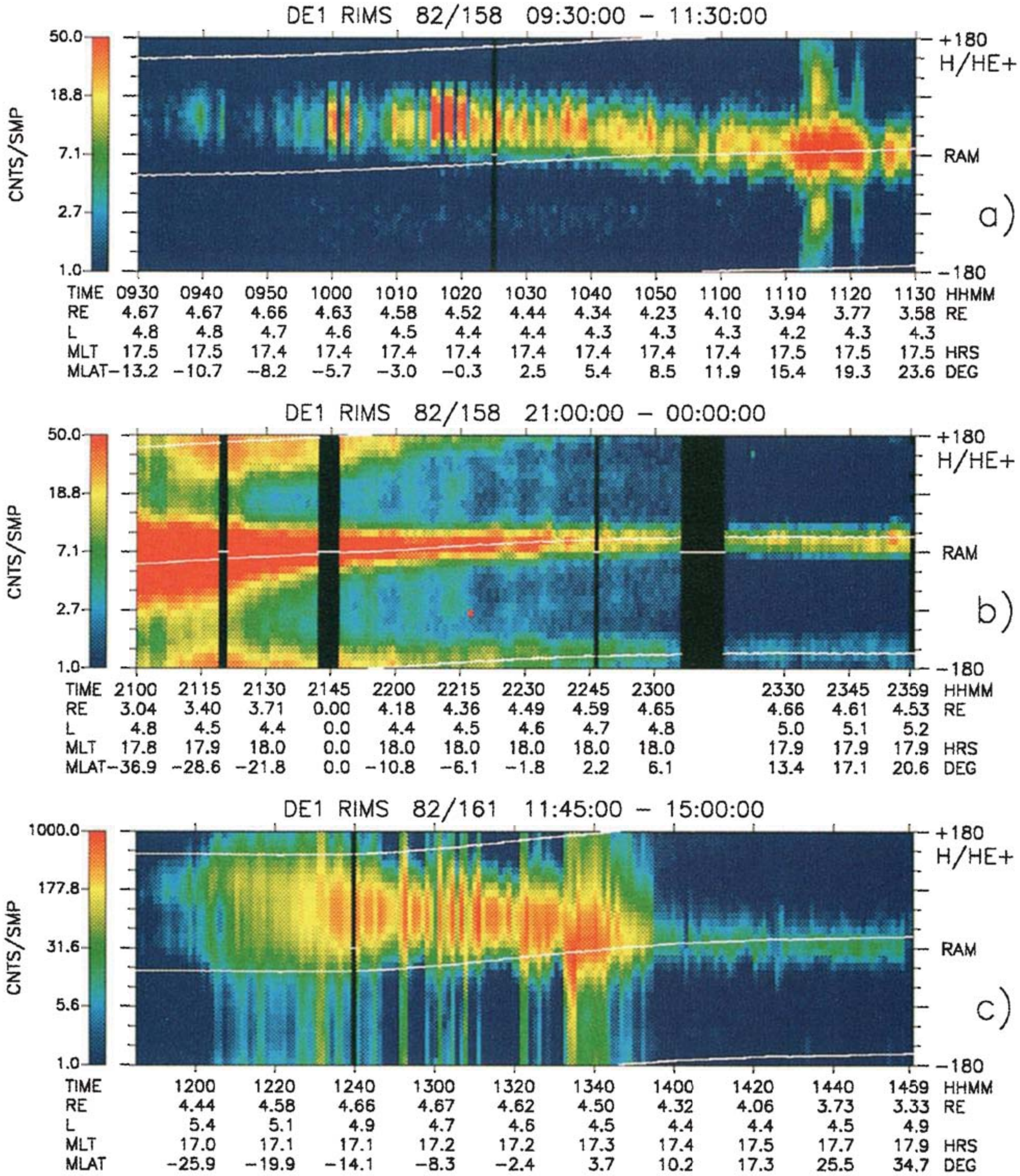


Plate 1. DE 1 records showing thermal He^+ counts per sample versus spin angle and time. White lines near the center and edges of the record indicate, respectively, the maximum and minimum magnetic pitch angles, corresponding to the closest aperture approach to the parallel and antiparallel directions of the Earth's magnetic field. (*a*) Record from June 7, 0930–1130 UT. The offset from the ram direction prior to ~1100 UT provides evidence of a convecting dense plasma (see text for details). b) Record from June 7, ~2100–2400 UT. A bidirectional field aligned distribution was detected (evidence of a trapped distribution at the equator was present on the H^+ record). (*c*) Record from June 10, 1145–1500 UT. The offset from the ram direction indicates convection, apparently in a spatially limited region of moderately dense, isotropic plasma.

to north, beginning at 0930 UT at L = 4.67, crossing the magnetic equator at 1021 UT at L = 4.51, and reaching an L of 4.31 at 1130 UT. The satellite ram direction is along the center of the spectrogram, meaning the point at which the radial detector was viewing into the direction of motion of the spacecraft. The maximum (180°) and minimum (0°) magnetic pitch angles are indicated by the white dashed and dotted lines, respectively, corresponding to closest aperture approach to the parallel and antiparallel directions of the Earth's magnetic field. In this case the ram and field-aligned directions nearly coincide. The counts-per-sample are color coded, with dark blue representing low counts (0 to 1 counts/sample) and red representing higher count rates (>50 counts/sample). The color bar on the left-hand side of each spectrogram shows this scale. One count per sample is roughly equivalent to $3.1 \times 10^4 cm^{-2}s^{-1}sr^{-1}$ for H^+ and $1.9 \times 10^4 cm^{-2}s^{-1}sr^{-1}$ for He^+. (Note that each of the spectrograms shown in Figure 8 has been scaled to emphasize a particular feature, so that the color count scale varies from panel to panel.) From 0940 to 1020 UT the record shows evidence of isotropic plasma, offset from the ram direction by around +60°, and in a direction suggesting essentially cross-L outward motion. This initial spin phase angle then began to close in toward the field-aligned direction (0°), indicating that through this period (1020 to 1110 UT), the ratio of the component of the cross-**B** bulk flow velocity to the spacecraft velocity was constantly decreasing. By 1115 UT the offset had disappeared, and trapped plasma was observed for a brief interval.

Cross-L outflow velocities in the range ~2–4 km/s are estimated for the period 1000–1300 UT on June 7, based on considerations of the spacecraft velocity, near 2.5 km/s, and the angle by which the spin-time data were offset from the ram direction. Such cross-L outflow velocities would correspond to an antisunward electric field component at L ~4.5 of ~1 mV/m, which is in the range of values reported for disturbed periods in that general part of the plasmasphere by *Maynard et al.* [1983].

The corresponding electron density at L ~4.5 indicated by the PWI instrument on DE was ~150 electrons-cm^{-3} (the measurement was actually made at L = 4.28, MLAT= 9.23°). This is indicated by a plus symbol in Figure 5*b*, which displays equatorial electron densities at L ~4.5 measured by both whistlers and satellites. This level corresponds to a partially refilled state of the plasmasphere, about a factor of 2 in density below the relevant saturated plasmasphere level of ~300 electrons-cm^{-3} [*Carpenter and Anderson*, 1992]. As noted in a later section, the disturbed outer plasmasphere is often structured; rapid fluctuations appeared in the ion count rate in Plate 1*a* and in the UHR (not shown), suggesting the presence of spatial structure in the convecting plasmas.

On the next recorded DE pass at 2100–2400 UT on June 7, midway through a ~24 hour lull in substorm activity, the electron density at apogee was low, ~30 el-cm^{-3} (Figure 5*b*). The He^+ pitch angle distributions observed (Figure 5*a*) were bidirectional field aligned (BI) and equatorially trapped (TR), characteristic of the low density environment beyond the main plasmasphere. Plate 1*b* shows RIMS spin-time records of the distributions on this later pass. The TR distribution was indicated only faintly; the BI distribution dominated the record.

On June 10, from ~1200 to 1400 UT, RIMS again exhibited an offset in an otherwise apparently isotropic plasma, as shown in the He^+ data of Plate 1*c*. Again the observations occurred during a period of a surge in *AE* to ~1000 nT. The temporal limitation on the period of higher counts suggests that a spatially limited structure was being observed. The variation in count rate on this pass was due to operation of a biasable voltage plate at the RIMS aperture, cycled over 0, −2, −4, and −8 V relative to the spacecraft potential.

Two additional cases of rammed but offset distributions are noted in Figure 5*a*. They were recorded on June 12 and 13, as substorm activity continued at relatively high levels (Figure 5*c*).

Corroborating evidence that the offsets of Plates 1*a* and 1*c* represented bulk flow, and of its generally sunward and outward direction, was obtained from a combination of RIMS and PWI static electric field data. During the periods of observed offsets from the ram direction, counts in the RIMS antisunward pointing −Z head were significantly larger than in the sunward oriented +Z head, reflecting the increased influence of sunward magnetospheric convection during these periods (possible effects of bias differences between the Z heads were taken into account). In each of the convection cases, the period of greatest offset occurred during the sampling of the outer L shells, while the component of the quasi-static electric field along the spacecraft Z axis was pointed antisunward, implying an outward component of low-energy plasma flow.

There was a complexity in the data that has not yet been resolved. In one of the convection cases, the O+ spin scans showed an offset from the ram, but in a direction opposite to that of the H+ and He+ ions. This feature is being investigated. Count rates for O+ in this case were low, and in the other convection cases were not sufficient for the identification of such an effect.

Whistler observations of the westward edge of the bulge. On July 7, from ~1030 UT to ~1330 UT, during a period of renewed and comparatively steady substorm activity (Figure 6*c*), whistler data from Kerguelen indicated that the station moved past an extension of the plasmasphere, with an abrupt westward edge in the ~1600 MLT sector. The equatorial path radii of whistler components used to identify the outer observable limits of the plasmasphere are shown in Figure 8*a*. This bulge encounter in the afternoon sector is typical of the manner in which whistler stations "see" or "scan" the bulge at times of increased disturbance activity [*Carpenter*, 1970]. When Siple station reached ~1600 MLT, 9 hours after the Kerguelen observations of Figure 8*a*, a well-defined plasma trough beyond L ~4.2 disappeared from its "whistler view." This is interpreted as a bulge encounter, although the extent in L of the bulge plasma beyond L ~4.2 was not defined in the data.

Detection of narrow outlying features near the plasmasphere. At ~2000 UT on July 7, during the time of the apparent Siple encounter with the bulge at ~1600 MLT just noted, DE 1 detected a region of high density plasma that appeared to lie beyond the main plasmasphere near 1600 MLT. Prior to this DE pass, from 1400 to 1900 UT, there was a surge in the *AE* index that reached ~1000 nT from 1600 to 1800 UT. Plate 2*a* shows a retarding potential analyzer (RPA)- time spectrogram for the +Z head (90° pitch angle) data and Plate 2*b* shows the corresponding spin angle-time spectrogram from the radial head at 0 V retarding potential. Between ~1955 and 2045 UT, DE encountered a region of dense but structured plasma as the satellite moved toward the equator and toward its minimum L value of ~ 4.7. Plate 2*c* presents the electron density profile from this region, derived from the SFR record shown as Plate 2*d*. From Plate 2*b*, the plasma of this region exhibited a generally rammed distribution (ordered by spin phase instead of the magnetic field direction), and was therefore primarily isotropic. However, as Plate 2*a* suggests, it varied widely in temperature. The pitch angle and RPA data exhibit more variation than is indicated by the n_e plot of Plate 2*c*; some of the colder ions in the outer structure may have been masked by the effects of positive spacecraft potential. Counts on the RPA scale during this time extended to 5 eV, somewhat above the 1-eV levels typically seen within the plasmasphere.

From ~2100 to 2215 UT, as DE reached $L \sim 4.7$, high counts were recorded, extending above 10 eV on the RPA scale, and a peak in the count rate at 90° in the spin-time plot identified warm anisotropic plasma trapped near the magnetic equator. The profile of log n_e versus L from the DE PWI for the latitude range −30° to +5° is presented in Figure 8*b*, along with a smoothed equatorial density profile from Siple station showing the plasmapause and an extended trough as they were observed during the afternoon prior to ~16 MLT. Interpretation of the outlying peak in Figure

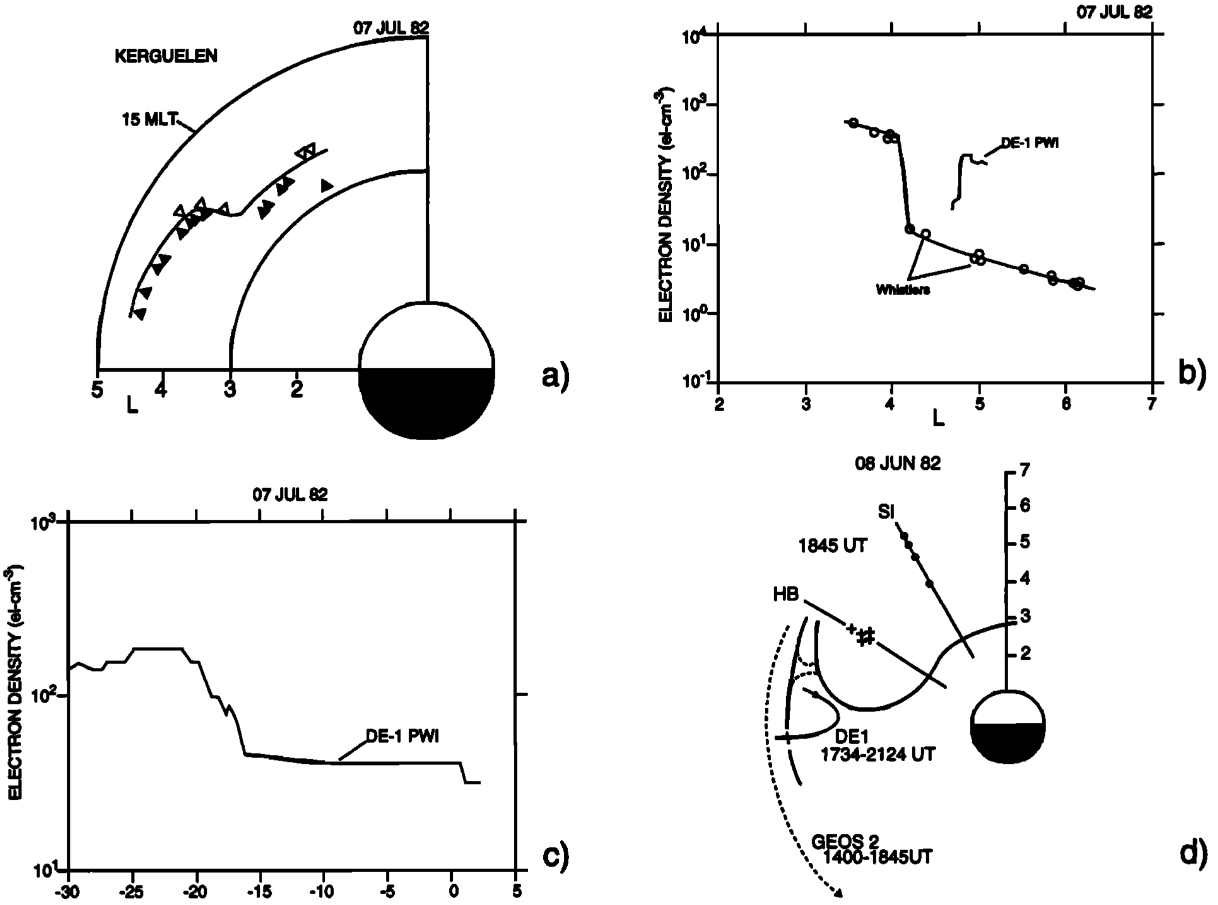


Fig. 8. (*a*) Plot of whistler path L value versus MLT, showing evidence of an encounter with the bulge region near 1530 MLT at the longitude of Kerguelen. The filled triangles represent whistler paths near the outer edge of the plasmasphere, while open triangles indicate propagation in the low density region just beyond the plasmapause. (*b*) Electron density versus L value from the PWI on DE 1, deduced from the July 7, 1982 SFR plot of Plate 2*d*. Also shown is a smoothed equatorial profile from Siple whistlers, acquired during the afternoon prior to detection of the westward edge of the bulge region. (*c*) Plot of the PWI densities for Figure 8*b* versus magnetic latitude. (*d*) Diagram of dense plasma structure indicated in the data of June 8, 1982, and discussed elsewhere by *Carpenter et al.* [1992].

8*b* is complicated by the fact that the PWI data were acquired over ~1.5 hours along an approximately field- aligned orbit (the DE 1 profile information of Figure 8*b* is plotted in Figure 8*c* in terms of $\log n_e$ versus magnetic latitude). Because of a quieting trend at the time of interest, the thermal plasma at the DE orbit was probably drifting eastward under the influence of the Earth's corotation electric field, but at a subcorotational angular velocity, evidenced by the apparent overtaking of the bulge westward edge by Siple Station. We infer that near 1600 UT there was either a real low-density gap betweeen the main plasmasphere and an outlying dense feature, or that, because of eastward rotation of the plasma, DE 1 first encountered a part of the bulge and then a wider (more inward extending) trough region. Both situations would be consistent with the formation of a sunward extending plasma feature during the preceding substorm activity.

The DE 1 sweep frequency receiver record for July 7 is shown in Plate 2*d*, in coordinates of frequency (1 Hz–400 kHz) versus time, with wave power spectral density color coded according to the scale at left. The electron gyrofrequency is indicated by the curved white line with minimum value at ~8 kHz. The record shows a band of intense VLF wave activity in the frequency range ~100 Hz–4 kHz in the region of the rammed plasma. Strong localized wave activity at such frequencies has been noted in previous studies of outlying high density regions [e.g., *Kivelson*, 1976*b*; *Chan and Holzer*, 1976]. As expected, there was a noise enhancement near 100 Hz during observation of the trapped distribution close to the magnetic equator [*Russell et al.*, 1970; *Gurnett*, 1976; *Olsen et al.*, 1987].

That density observations such as those just described may involve narrow dense features that extend generally sunward from the bulge region is suggested by observations on June 8, 1982, which followed a multihour period of increased but moderate substorm activity, with *AE* in the 300–500 nT range. Near 2200 UT, Siple and Halley whistler stations, 2 hours apart in MLT, successively encountered the westward edge of the bulge as each station approached 1800 MLT, much as in the case of Kerguelen and Siple on July 7 noted above. A separate research note on this case has been prepared by *Carpenter et al.* [1992].

The June 8 case was notable in that from the Siple whistler records it was possible to identify an outlying high density feature, apparently extending into the afternoon sector. Figure 8*d*, adapted from *Carpenter et al.* [1992], presents a diagram of the inferred plasmasphere shape, as well as the orbit of GEOS 2 and an equatorial projection of the DE 1 orbit. (The dotted curves at the base of the sunward extending feature indicate that its attachment to the main plasmasphere could not be confirmed). Evidence

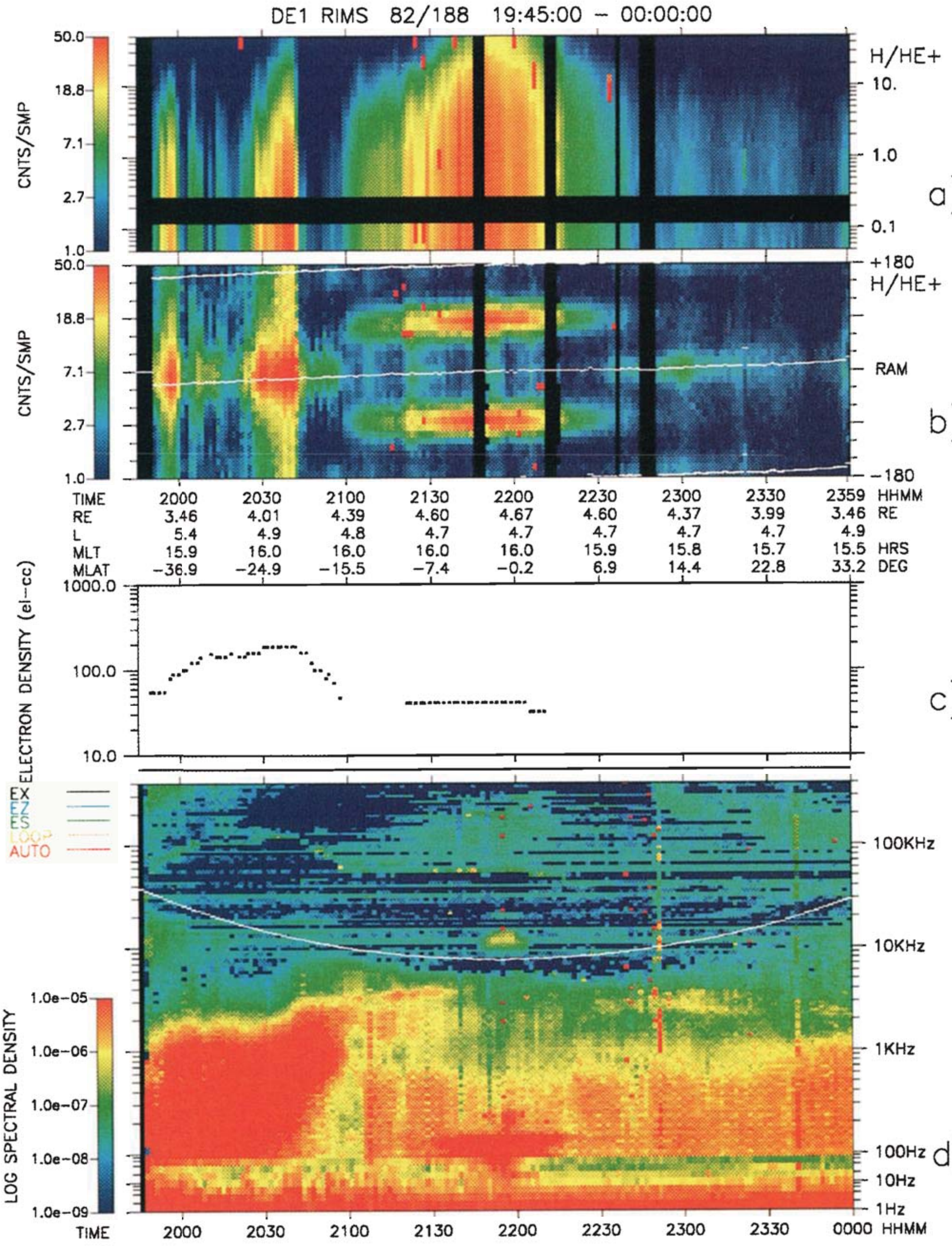


Plate 2. (*a*) RIMS data on He^+ energy (~ 0 – 50eV) versus time on the ~2000–2400 UT DE 1 orbit of July 7, 1982. (*b*) RIMS data on pitch angle versus time on the same orbit. (*c*) Plot of $\log n_e$ versus time for the same orbit, inferred from the UHR trace on the SFR record shown below. (*d*) Wave power spectral density, color coded in coordinates of frequency (1 Hz–400 kHz) versus time. The white line indicates the local electron gyrofrequency. The UHR trace can be seen on the left half of the record near 100 kHz.

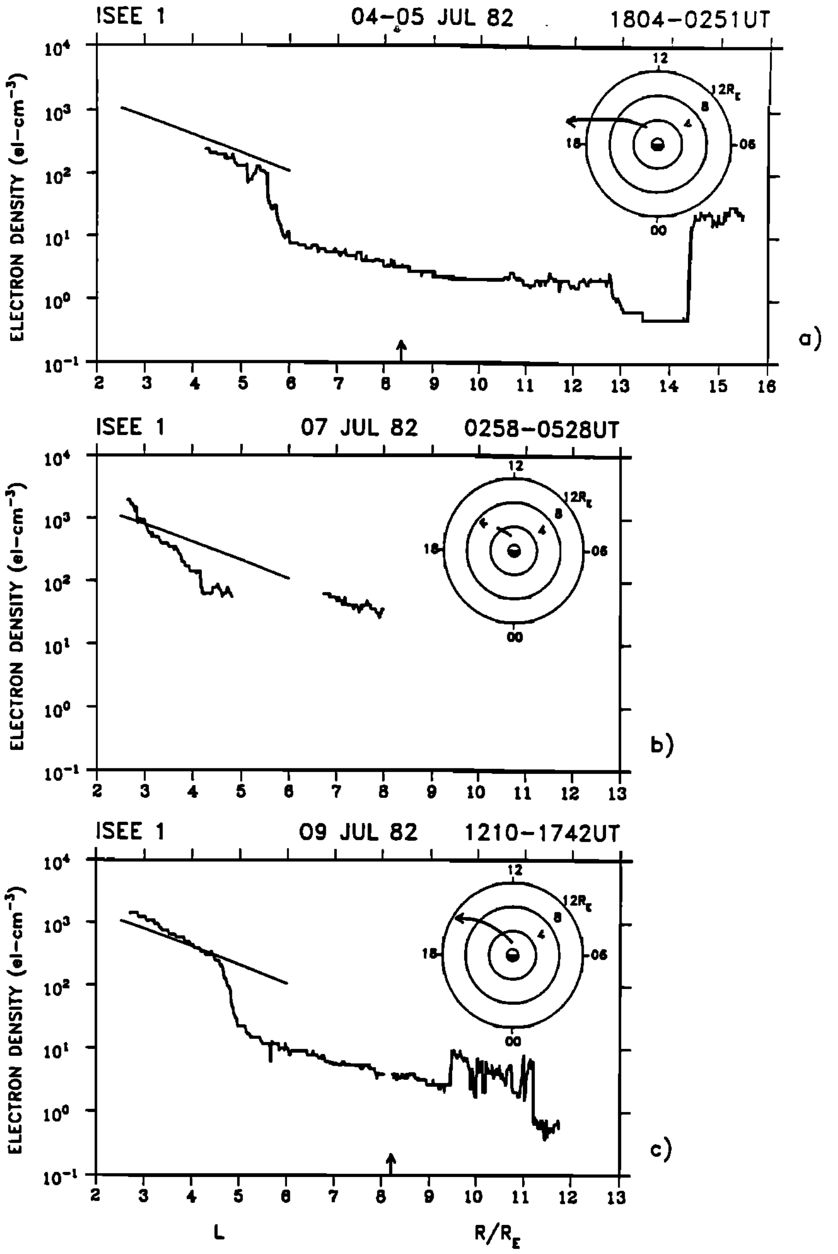


Fig. 9. Three successive ISEE electron density profiles from the afternoon sector. In each case the smooth curve is intended as a reference for the saturated plasmasphere; it is based upon an empirical model developed by *Carpenter and Anderson* [1992]. (*a*) Profile for July 4, 1982, during a period of deep quieting (see Figure 6c). Log n_e is plotted versus L at L <8.3 and versus R/R_E beyond that point (arrows). A plot of the orbit in coordinates of R/R_E versus MLT is shown as in inset. (*b*) Profile from July 7, 1982, following a period of renewed substorm activity. There was a data gap between L = 4.8 and 6.7. (*c*) Profile for July 9, 1982, following 3 days of moderate substorm activity.

that the feature was relatively narrow was obtained from GEOS 2, which failed to observe high densities at synchronous orbit, and from DE 1, which observed a plasmapauselike density drop near dusk at L ~6 at a time when the whistler stations were probing the afternoon trough region. Taken together, the whistler and DE data suggested that the outer plasmasphere near dusk had been roughly stationary during an approximately 5-hour period of observation. This is in agreement with previous reports (from 1963 and 1965, years of low solar activity) that during periods of moderate and regularly repeated substorm activity, the bulge plasma near L = 4-5 tends to appear fixed in space as observed by a ground station [*Carpenter*, 1966, 1970].

Detection of outlying dense plasma features in the middle magnetosphere. Figures 9*a* and 9*b* show equatorial n_e profiles from ISEE data on two consecutive outbound passes through the late afternoon magnetosphere, the first on July 4, a day of deep quieting (see Figure 6*c*), and the second about 12 hours after the surge of substorm activity that began on July 6. The quiet-day profile of Figure 9*a* is an extended version of the ISEE profile of Figure 3*b*. Along the horizontal scale to the left of the arrow, the data are plotted versus L, while beyond this point the values are shown versus geocentric distance in Earth radii. Inside L ~5.5 the profile exhibited an average slope characteristic of the plasmasphere. Some irregularities appeared in the vicinity

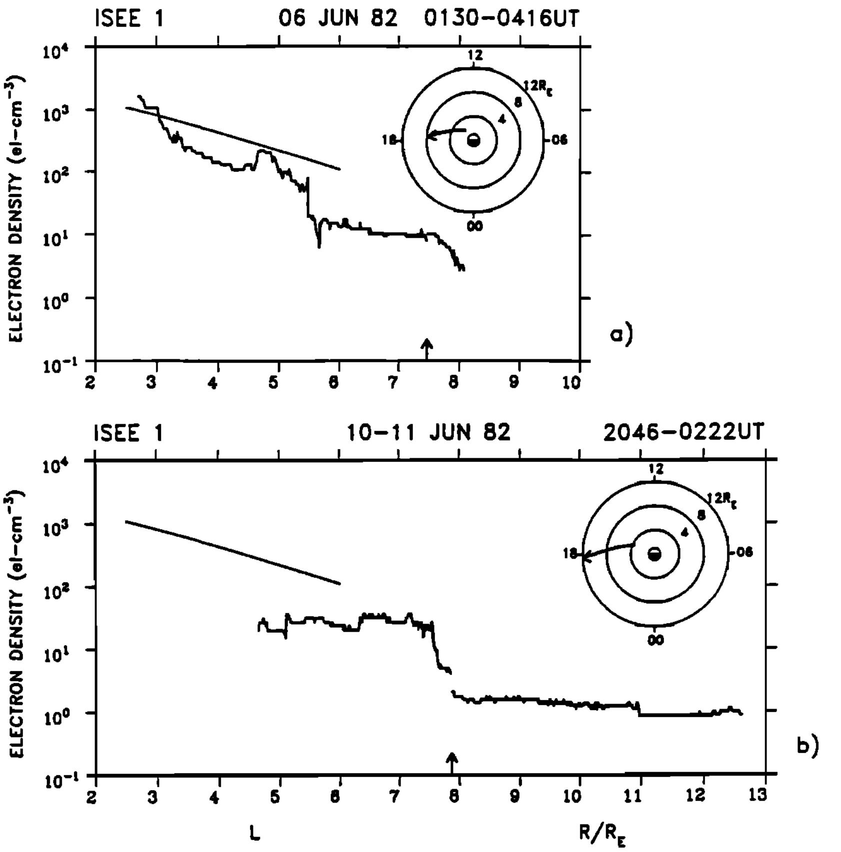


Fig. 10. Two ISEE electron density profiles from the June 6–11, 1982 period, in the format of Figure 9. (*a*) Profile from June 6, showing two regions of depressed density separated by a plasmasphere-level feature. (*b*) Profile from June 10–11, showing two extended regions of nearly constant density. Near L = 7 the density approached extrapolated plasmasphere levels.

of a well-defined plasmapause, and then a broad, relatively unstructured trough region was detected. The density leveled off near 3 electrons-cm^{-3} beyond $9R_E$, dropped below 1 electron-cm^{-3} near $13R_E$, and then at ~$14.4R_E$ jumped sharply to ~20 electrons-cm^{-3} as ISEE entered the magnetosheath.

The profile for July 7 at ~05 UT (Figure 9*b*) differs markedly from the "quiet" July 4 profile. Although there is an extensive data gap from L = 4.8 to ~6.7, it is clear that the slope of the falloff at $L < 4.7$ was much steeper than is normally observed in the plasmasphere, without constituting an obvious plasmapause effect, and that the density between L = 6.8 and 8 was at extrapolated plasmasphere levels, roughly an order of magnitude above corresponding values on July 4 (Figure 9*a*).

On June 6, during a surge in substorm activity (see Figure 5*c*), ISEE observed the profile shown in Figure 10*a*. There was an inner region of depressed density from L ~3.2 to L ~4.6, a localized region of higher density centered at L ~4.8, and then at L ~5.4 a steep drop to a plasmatrough level. The profile near the inner depression and the outlying high density feature are qualitatively similar in form to features of the July 7 ISEE profile in Figure 9*b*, which was also observed during a period of increased substorm activity that followed a relatively quiet period. A particularly clear example of this type of outlying plasmasphere-level density feature, recorded outside our case study periods but in the MLT sector of interest, is shown by the ISEE profile of Figure 11*a*, from September 17, 1983. Evidence of a plasmapause decrease appears at L ~ 2.9 and a high density feature is indicated between L ~3.5 and 4.2. (The accompanying reference profile is again from the modeling work of *Carpenter and Anderson* [1992]. In this case it includes a plasmapause arbitrarily placed at L ~4 and a trough region segment representative of nighttime density levels.) Profiles with form similar to those of Figures 10*a* and 11*a*, that is, with inner and outer regions of depressed density separated by a high-density feature, were reported to have occurred in about 10% of the cases in a statistical study of DE 1 RIMS data on light ion concentrations by *Horwitz et al.* [1990]. They were observed in all local time sectors but were most common on the nightside, with an occurrence peak near 2100 MLT.

At ~1600 UT on June 6, ~13 hours after ISEE detected the outlying high density feature shown in Figure 10*a*, and ~16 hours after the onset of renewed substorm activity, GEOS 2 crossed the 18 MLT meridian while observing electron densities at plasmasphere levels near 70 electrons-cm^{-3}. This is illustrated in Figure 12 where GEOS density observations for June 6–10 are shown in sequential perspective plots of $\log n_e$ versus MLT and UT. (The UT periods of the GEOS observations are also indicated by line segments at the bottom of Figure 5*c*.) In Figure 12, dots indicate the levels n_e = 8 electrons-cm^{-3} and n_e = 70 electrons-cm^{-3} that have been identified with late afternoon at synchronous orbit in the cases of the dayside plasmatrough and the saturated plasmasphere, respectively [e.g., *Higel and Wu*, 1984; *Carpenter and Anderson*, 1992].

The June 6 GEOS record shows essentially saturated plasmasphere levels from 1630 to 2230 MLT, followed by a period of somewhat lower, irregular concentrations. From the Kp record of Figure 5*c* and the stacked records of Figure 12, it appears that for the June 6–10 period, high-density plasma had its greatest extent along the GEOS orbit during the first afternoon-evening pass af-

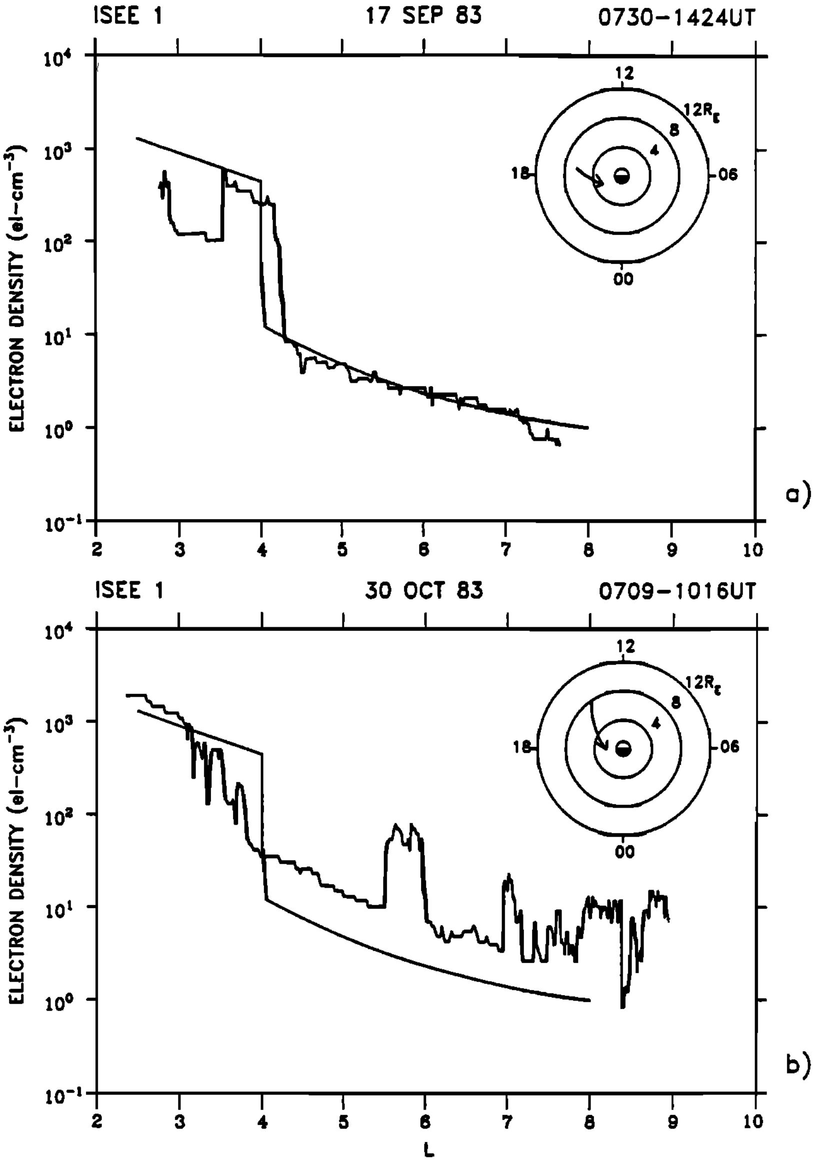


Fig. 11. Two ISEE profiles from outside the case study intervals. The accompanying curve is a reference profile from the empirical modeling work of *Carpenter and Anderson* [1992]. The trough density levels in this reference profile represent nighttime conditions in the aftermath of disturbance. (*a*) Profile from September 17, 1983, 0730–0926 UT, showing evidence of an inner plasmapause at L ~2.9, an outlying plasmasphere-level feature between L ~3.5 and L ~4.2, an inner trough inside the high density feature, and an outer, lower- density trough, all near the dusk meridian. (*b*) ISEE profile from October 30, 1983, 0709–1016 UT, showing density structure in the plasmapause region near dusk and in the middle and outer afternoon magnetosphere.

ter the beginning of increased activity on June 6. That the GEOS observations on June 6 were at least partly due to sunward and outward flow of dense plasma originally at lower L shells is suggested by the ISEE record of Figure 10*a*, which shows that trough levels were present at 18 MLT beyond L ~5.4 some 12-13 hours before GEOS reached the dusk meridian.

On June 7, GEOS 2 observed dense plasma prior to ~18 MLT, and then moved into a trough region. Four or five hours earlier, as noted in Plate 1*a*, DE 1 RIMS had detected evidence of sunward and outward convection in the outer plasmasphere during strong substorm activity.

One or both of the boundaries of dense plasma patches penetrated in the dusk sector by GEOS 2 may appear to be steep, an example being the dropoff at ~1800 MLT on June 7 in Figure 12. Such cases have generally been interpreted by *Higel and Wu* [1984] as indicative of plasmapause crossings. In our cases of ISEE data, the outlying feature at L ~5 in Figure 10*a* and the features at L = 3.5-4.2 and L = 5.5-6.0 in Figures 11*a* and 11*b* exhibit steep, plasmapauselike boundaries, which may be a clue to their origin in the outer main plasmasphere.

Figure 10*b* shows the ISEE equatorial profile near 18 MLT from June 10, following several days of surges in substorm activity. Beyond an inner data limit of L ~4.5, the density remained roughly constant to L ~7.7, and then dropped sharply to another nearly constant level. The region of nearly constant density in the range L ~4.5-7.7 was presumably exterior to a region of steep density gradients, possibly steeper than those near L = 3 in Figure 10*a*. The flattening effect may have been due to the presence of a patch

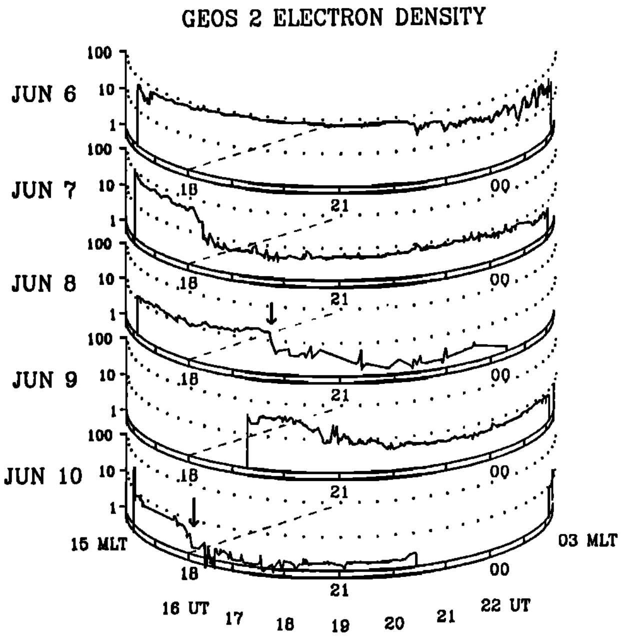


Fig. 12. GEOS 2 electron density data for June 6–10, 1982, acquired by radio sounding at synchronous orbit. Log n_e is plotted versus MLT and UT for the ~1600–0200 MLT period. The dotted curves on the stacked perspective plots indicate, respectively, the typical late-dayside plasmatrough level of ~8 electrons-cm^{-3} and the corresponding saturated or quiet-time plasmasphere level of ~ 70 electrons-cm^{-3} at synchronous orbit.

of near-plasmasphere level plasma at L ~7, much like the region shown in Figure 10*a* near L = 5 or the one at L ~7 in Figure 9*b*.

Evidence of a day/night trough boundary at synchronous orbit. When two regions of depressed density are observed in a radial profile near dusk, the outer one is frequently at levels lower than extrapolations of the inner one by a factor of order 5, as in Figures 10*a* and 11*a*, and in some of the data of *Horwitz et al.* [1990]. Such differences in level are made relatively easy to recognize when a high density intermediate region is present. The simultaneous presence of a dense feature and two different trough density levels suggests that the flow trajectories previously followed by the corresponding plasma elements, as well as the ionosphere/magnetosphere interchange fluxes that they experienced, fell into quite different categories. For example, the inner, higher density trough region may have been dominated by flow across the dayside and/or extended residence time on the dayside, while the outer one may have been exposed to refilling fluxes for comparatively brief periods, such as in the case of generally sunward flow from low-density nightside regions.

The GEOS 2 data of Figure 12 support the idea, already implicit in the work of *Décréau et al.* [1984] and *Higel and Wu* [1984], that near dusk there may on occasion be a relatively sharp boundary between two regions of low but substantially different density. In Figure 12, arrows above the June 8 and June 10 data indicate abrupt transitions near dusk from trough levels in the range 5-10 electrons-cm^{-3} to levels near 1 electron-cm^{-3}. The 5-10 electrons-cm^{-3} range is characteristic of the late afternoon trough on the dayside [*Higel and Wu*, 1984; *Carpenter and Anderson*, 1992], while the ~1 electron-cm^{-3} level is characteristic of recently formed or reformed plasmapause/plasmatrough profiles on the nightside [*Carpenter and Anderson*, 1992]. An equivalent density drop at ~ 9 R_E was reported in a case study by *LaBelle et al.* [1988] of an outbound AMPTE IRM pass near 19 MLT.

Note that on June 7 and June 9 there were also abrupt transitions, but in these cases the transition was from plasmasphere-range concentrations to levels characteristic of the dayside trough. The flow patterns during these two periods of quieting (Figure 5*c*) were evidently such that the plasma trough elements sampled had not recently been located in a newly formed nightside trough region.

Differences in the typical location of day and nighttime trough levels in the bulge sector are suggested in Figure 11. In the case of Figure 11*a*, the nightside level beyond L = 4.2 was observed just sunward of 1800 MLT, while in the case of Figure 11*b*, in which only dayside trough levels were observed, the outer magnetosphere was traversed much earlier, where dayside flow trajectories might be expected to be more common. Observations of the locations of orbital segments characterized by day or nighttime trough levels, as well as the locations of transitions between levels, would appear to provide the experimenter with information on the circulation of the thermal plasma, other than that provided by the observed boundaries of essentially plasmasphere-level regions.

Observations of dense plasma patches in the outer magnetosphere. Figure 9*c* shows the third in a sequence of ISEE passes through the outer mid-afternoon magnetosphere. In this case, from July 9, the period of moderate substorm activity that began late on July 6 had been underway for nearly 3 days (Figure 6*c*). A patch of dense plasma with sharp external boundaries and much internal structure was detected between ~9.3 and 11.2 R_E. This feature is comparable in terms of extent, location, peak density level, and density structure to a number of the outlying plasma regions reported from OGO 5 by *Chappell et al.* [1971] and *Chappell* [1974]. An additional example of dense plasma patches in the outer magnetosphere observed from ISEE is shown in Figure 11*b*. This profile, from October 30, 1983, shows a broad region of irregular dense plasma beyond L = 6.9, as well as a relatively smooth outlying feature in the range L = 5.5–6.0. The observations were made ~36 hours into a period of moderate substorm activity (*Kp*=3–5) that was preceded by 3 days of deep quieting.

The ISEE profiles of Figures 9*a*–9*c* suggest that the sunward surges of thermal plasma near the main plasmasphere indicated by DE 1 and by whistlers during and following the increase in substorm activity late on July 6 (Figure 8 and Plate 2) were associated with the appearance of extended patches of thermal plasma near and beyond synchronous orbit. The higher densities in the patches were consistent numerically with flow from dense inner regions; for example, the densities near $10R_E$ on July 9 were a factor of ~40 less than those typically observed in the outer plasmasphere at L ~4, which would be consistent with the expected roughly R^4 volumetric expansion of tubes of ionization that originate in the outer plasmasphere and retain the bulk of their electron content.

To what extent are the types of outlying features discussed in this paper confined to the ~12–20 MLT sector? Relatively large patches that exhibited densities at extrapolated plasmasphere levels and extended of order 1 R_E along equatorial satellite orbits were found by *Chappell et al.* [1971] and *Chappell* [1974] to be concentrated in the afternoon sector, as indicated in Figure 1*b*. A similar conclusion was reached by one of us (D.C.) on the basis of a visual survey of approximately three years of ISEE data on near-equatorial electron density. However, the classification and mapping of density irregularities in the middle and outer magnetosphere are far from being accomplished. For example, *Kowalkowski and Lemaire* [1979] reexamined the archived OGO 5 mass spectrometer data on ion density and found that when occurrence criteria less restrictive than those of *Chappell et al.* [1971] were used, a postmidnight maximum occurred in the local

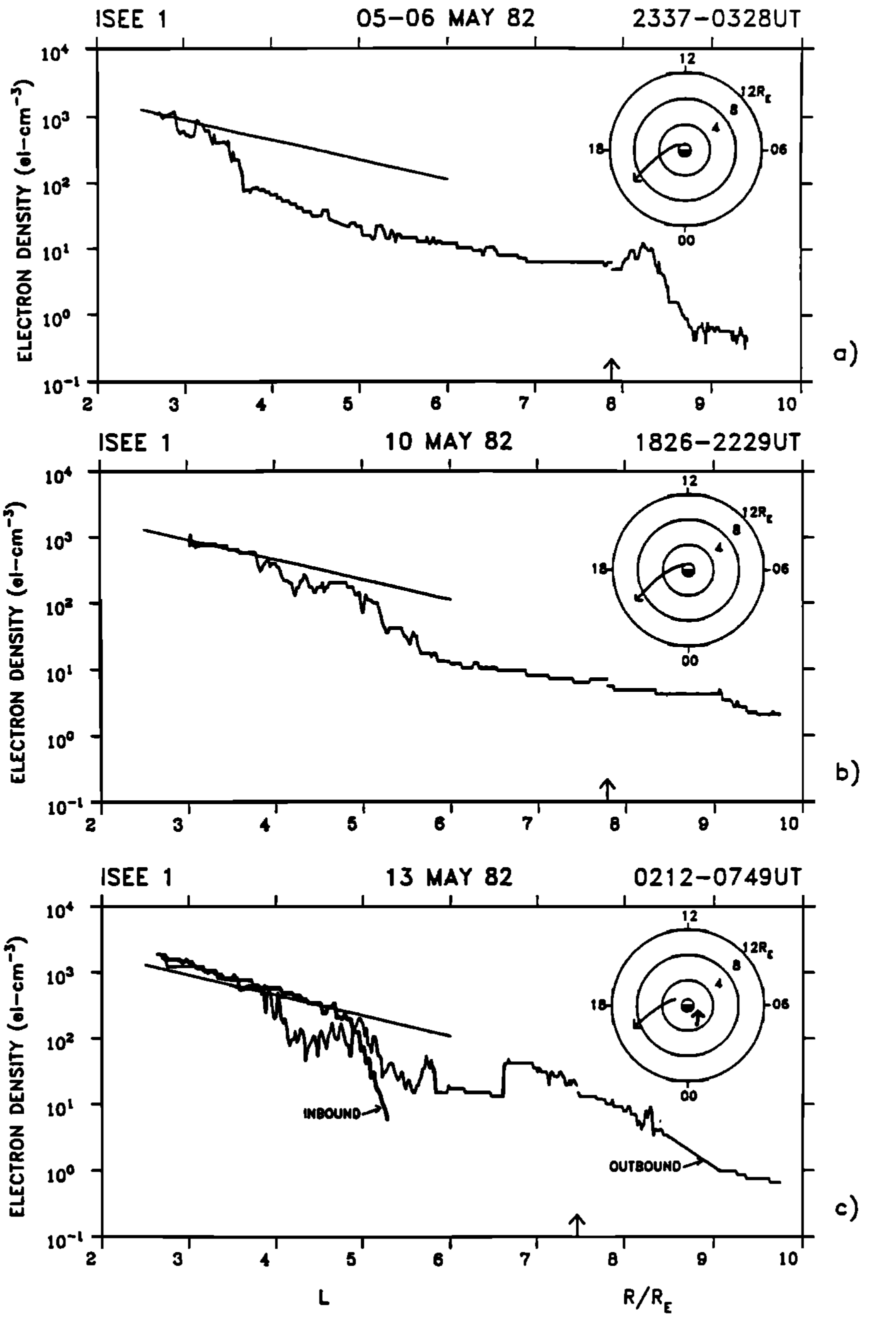


Fig. 13. ISEE profiles from the ~2000 MLT sector and in the format of Figure 9, showing the occurrence of density structure at various stages of a magnetically calm period. (*a*) Profile from May 5–6, 1982, showing some irregular structure in the outer plasmasphere. b) Profile from May 10, 1982, showing irregularities in the outer plasmasphere and plasmapause region. (*c*) Inbound (heavy line) and outbound profiles from May 13, 1982, showing on the outbound segment near 2000 MLT an extended region of irregularity near the plasmapause and an outlying high-density feature near $L = 7$.

time distribution of outlying density peaks. The postmidnight irregularities tended to be located just beyond the plasmapause and were interpreted as plasma elements in the process of detachment or removal from the plasmasphere.

Outlying Dense Features Observed Following a Prolonged Calm Period

Evidence that dense plasma can remain for extended periods in the dusk-evening sector is shown by the profiles of Figure 13*c*, recorded on an inbound post-midnight pass (thick line) and the immediately following outbound pass in the 18-19 MLT sector. This occurred on May 13, 7 days into a period of steady, low level, agitation that followed a weak magnetic storm (see Figure 4*c*). The presence of a relatively well defined plasmapause at L ~4.9 near 1 MLT is shown by the thick curve, while the profile near dusk exhibits a region of large, factor-of-3-to-5 fluctuations between L ~4 and L ~5.8, and near $L = 7$ contains an outlying feature with peak n_e in the extrapolated plasmasphere range. The difference in the lowest n_e levels reached on the inbound and outbound profiles suggests that the nightside plasma density just beyond the plasmapause was characteristic of the low density nightside trough, while the lowest levels near dusk represented dayside trough conditions.

Observations of Density Irregularities in the Plasmapause Region

A notable feature of the prolonged relatively calm period after May 4 (Figure 4*c*) was the detection of density irregularities in the plasmapause region. Plates 3*a* and 3*c* show the RIMS spin-time records from two successive orbits on May 9. The profile of electron density inferred from the SFR near ~0800 UT during the first orbit is shown in Plate 3*b*. In these two cases, RIMS encountered regions of dense plasma, separate from what appeared to be the main body of the plasmasphere, at ~0906 UT (Plate 3*a*) and about 3 1/2 hours later, near 1226 UT (Plate 3*c*). Similar evidence of density structure near the plasmapause was seen on May 11 by DE 1, as shown in Plate 3*d*. (In the case of Plate 3*a*, the outlying region showed limited evidence of field-aligned flow, while in the following case (Plate 3*c*) the distribution in the higher-L-shell region exhibited some angular structure within a generally isotropic overall pattern. In this case a bidirectional distribution was detected in the dense interior region encountered after ~1235 UT.)

Additional evidence of irregular structure near the plasmapause at ~20 MLT was provided by ISEE. Figures 13*a*, 13*b* and 13*c* present profiles from May 6, May 10, and May 13, respectively. The outer plasmasphere appeared to become progressively more structured as time passed within the period that included the days of the DE observations illustrated in Plate 3. On May 10, the profile was relatively smooth and near the saturation level out to a point near L = 4, after which the density dropped and became irregular. Then a plasmapause decrease, leading to an extended trough, occurred at L ~5. A similar but apparently more extreme case appears in Figure 13*c*, and another example is seen between L = 3 and 3.8 on the 1983 profile of Figure 11*b*. It is well known from whistler work [e.g., *Carpenter*, 1962*b*; *Park and Carpenter*, 1970] that the density in the outer plasmasphere can be depressed by a factor of up to ~3 in the aftermath of magnetic disturbances. ISEE profiles, such as those of Figures 11*b*, 13*b*, and possibly 13*c*, show that such outer plasmasphere regions may have well defined inner limits and may be substantially more structured than the immediately interior regions.

The mechanism for the development of irregularities along or near the plasmapause surface is not known but may be associated with persistent low-level substorm activity during a period when significant plasmasphere erosion is no longer occurring. The irregularities may be a counterpart of the perturbations in plasmasphere shape detected from whistlers during periods of temporally isolated substorms [*Carpenter and Seely*, 1976]. *Grebowsky and Chen* [1976] showed in an MHD modeling calculation that localized irregularities in plasmasphere radius in the dusk sector can occur if spatial noise is added to a large-scale convection electric field. The primary effect of temporal noise in the large-scale field tended to be confined to the topology of sunward extending taillike features.

Thermal Plasma Coupling of the Magnetosphere and Ionosphere

Plasmasphere refilling following disturbance. The panels of Figure 7 show the gross features of the equatorial electron density profile as determined each day near a specific MLT from a single whistler station. More detailed temporal records of equatorial electron density measured at specific MLTs and at L ~4.5, the approximate L shell on which DE 1 crossed the equator, are shown in Figures 4*b*, 5*b*, and 6*b*. These figures include results from whistlers (every 24 hours at a given station when data were scalable), all available samples from the DE 1 PWI (minimum interval between samples~7.5 hours), and all available samples from the ISEE 1 PWI (minimum interval between samples ~56 hours).

A major feature of the L ~4.5 density data for May (Figure 4*b*) and July (Figure 6*b*) is the recovery from trough to plasmasphere levels in the aftermath of a weak magnetic storm. This recovery was particularly well defined in the July data of Figure 6*b*. There was a relatively large fractional density increase in the period of deep magnetic quieting between July 2 and 3. This change was probably due to the effects of upward plasma flow from the ionosphere into magnetospheric flux tubes with initially very low electron content. The density recovered steadily and smoothly until an apparent saturation condition was reached on July 5, and then on July 7 dropped to low levels. The apparent filling rate toward saturation was ~80 electrons-cm^{-3}-d^{-1}, somewhat larger than but in general agreement with the ~ 30 – 40 electrons-cm^{-3}-d^{-1} indicated for L ~4.5 in the pioneering case study by *Park* [1974] and the estimate of ~50 electrons-cm^{-3}-d^{-1} at L =4 by *Chappell* [1974] from OGO 5 measurements. If we consider this to have occurred in a region where there was a net upward flux for ~20 hours per day, then the rate of density increase was on average ~4 electrons-cm^{-3}-h^{-1}. This compares well with the observed hourly increases of ~0.5 – 1 electrons-cm^{-3}-h^{-1} reported for synchronous orbit by the GEOS 2 experimenters [*Décréau*, 1983; *Décréau et al.*, 1984; *Higel and Wu*, 1984; *Song et al.*, 1988]. If comparable upward fluxes are present at L = 4.5 and L = 6.6, as discussed recently by *Moffett* [1990], the expected rate of density increase should vary inversely as flux tube volume, or approximately as L^4. This volumetric factor is ~ $(6.6/4.5)^4$ ~4.7.

The May-period data of Figure 4*b*, for ~20 MLT, show a well defined recovery toward saturated plasmasphere levels, as in the July period of Figure 6*b*, but in this case large temporal fluctuations by a factor of order 5 were indicated during the recovery, as well as continued variations by factors of 2 or 3 as the disturbance activity continued at a low but steady level. It is likely that these density fluctuations are related to the density irregularities near the plasmapause observed at various times during the period May 5–13 and illustrated in the ISEE and DE 1 data of Figure 13 and Plate 3.

The data of Figure 5*b* show that in the June period of enhanced and periodically surging convection activity, plasmasphere levels at L ~4.5 were observed along the ~18 MLT meridian at times on June 6 and 7 and late on June 8. The data discussed above suggest that the appearance at these times of densities within a factor of 3 of the saturated plasmasphere level was associated with enhanced convection and associated reconfiguration of the existing plasma distributions, such as through sunward and outward surges, rather than the refilling process.

Timing of a reduction from plasmasphere to plasmatrough levels. In the July case study there was an apparent ~20-hour delay between the onset of renewed substorm activity on July 6 (Figure 6*c*) and the detection from Kerguelen in the late afternoon sector of low trough levels on July 7 (Figure 6*b*). This delay is believed to be associated with the known time lag between the appearance of a newly formed plasmapause on the nightside and its detection at comparable L values on the dayside [*Chappell et al.*, 1971; *Décréau et al.*, 1982, 1984]. Evidence that a recently formed plasmapause inside L ~4.5 had already developed on the nightside by ~0600-0700 UT on July 7 was obtained from Siple whistlers. They showed a classic midnight-morningside plasmapause development, of the kind previously shown to be associated with increased or continuing substorm activity [*Carpenter*, 1966].

Evolution of the thermal ion pitch angle distribution. Figures

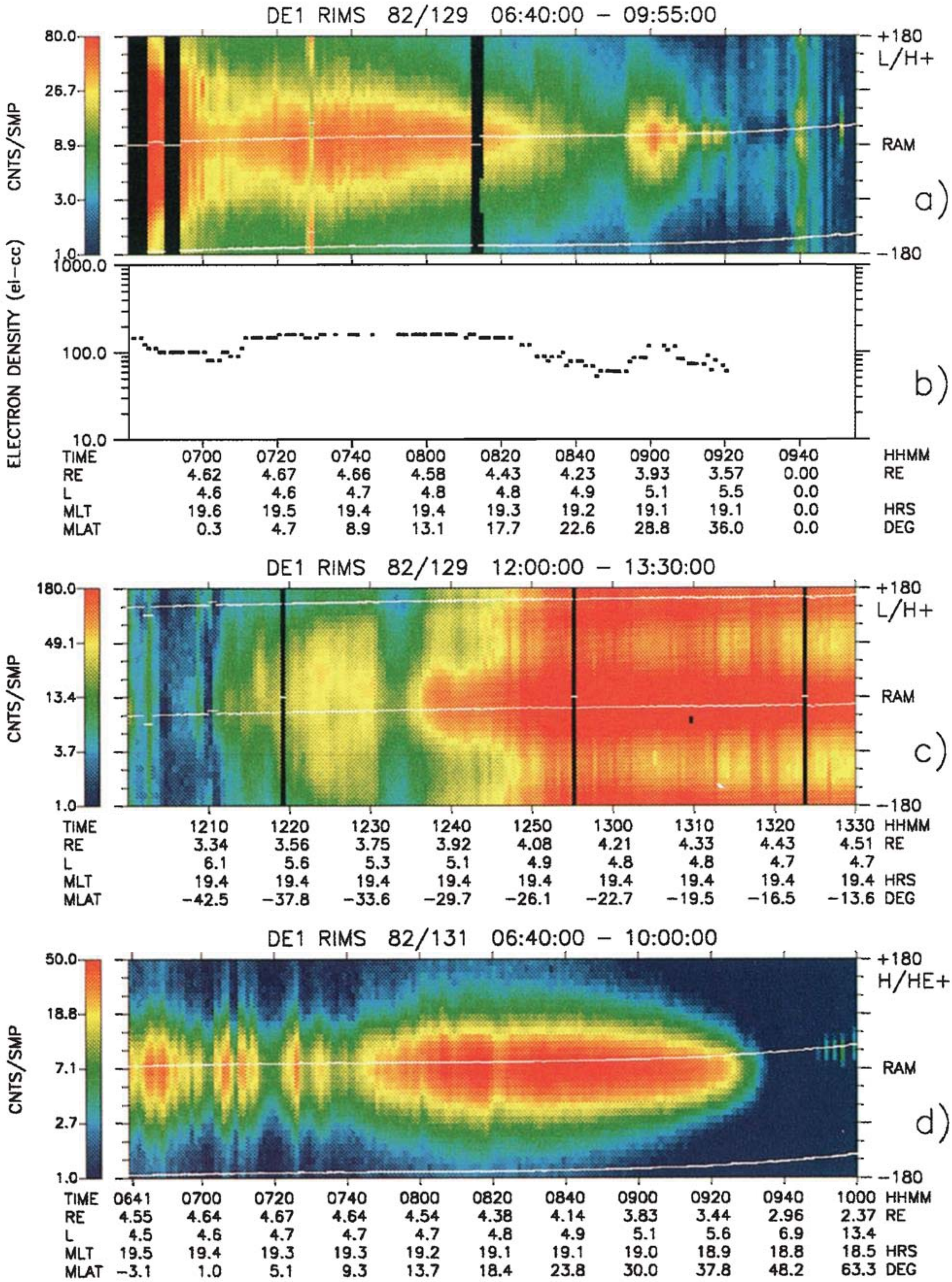


Plate 3. DE RIMS and PWI data indicating the presence of irregular localized dense plasma features near the plasmapause at ~2000 MLT. (*a*) RIMS spin-time record for 0640–0955 UT on May 9, 1982. (*b*) Plot of log n_e versus time from the PWI on DE 1. (*c*) RIMS spin-time record for 1200–1330 UT on May 9, 1982, showing density structure near the plasmapause roughly similar to that observed ~4 hours earlier (Plate 3*a*). (*d*) RIMS spin-time record for 0640–1000 UT on May 11, 1982, showing irregular structure in the outer plasmasphere.

4*a*, 5*a*, and 6*a* show the dominant characteristics of the DE 1 light ion pitch angle distributions as a function of time during the case studies and within $\sim \pm 20^\circ$ of the magnetic equator, while in Plates 4*a*–4*c* the dominant pitch angle characteristics are shown in meridian cross sections over the entire latitude range available in each case. The former clarify relations among near-equatorial pitch angle distributions, equatorial electron density, and Kp, while Plate 4 provides additional information on pitch angle variations with L and altitude. Some key features can be identified, in spite of variability in count rate and in pitch angle characteristics along orbits. In the cases from May and July (Figures 4*a* and 6*a*), in which the total density (Figures 4*b* and 6*b*) recovered from trough to plasmasphere levels during a multiday quiet period (apparently due, on average, to the refilling process), there was a corresponding transition from predominantly trapped and bidirectional field-aligned distributions to an isotropic one.

In the July case, for which the density recovery appeared to be particularly smooth, the RIMS data exhibited the distinct bidirectional and trapped refilling profiles for the first three days of the series. Also during this time there were several indeterminate data signatures (labeled "nothing" in Plate 4*c*) which are believed to be representative of a low-density isotropic background plasma having energy relative to the spacecraft so low that the ions were repelled by positive spacecraft potentials. Analysis of RIMS data by *Olsen* [1989] established a density-potential relationship such that the satellite accumulates positive charge on entering regions with density below 1000 cm^{-3}, rising slowly to about +1 V at 100 cm^{-3}, and about +5 V at 10 cm^{-3}. This potential, preventing measurements of the coldest plasma components, can mask out an isotropic background plasma when the density level is sufficiently low. However, the RIMS instrument aperture was biased by a steady -8 V during a number of the passes discussed here, and during conditions of total density $n_e \sim 20$ electrons-cm^{-3} on such passes, a significant isotropic component was not evident on the records.

The transition from bidirectional field aligned and trapped to isotropic occurred (July 3, 2115-0030 UT) as the equatorial electron density reached $\sim$100 electrons-cm^{-3} (Figure 6*b*). That level is a factor of $\sim$3 below the "saturation" level of $\sim$ 300 electrons-cm^{-3} for L = 4.5. (On DE 1 orbits with apogee at high latitude, the transition from RIMS data dominated by cold, isotropic ions to warm, field aligned ions has been found by *Horwitz et al.* [1990] to take place at electron density levels between 10 and 200 electrons-cm^{-3}, with an average value near 50–60 electrons-cm^{-3}.) The isotropic signature with relatively high density levels persisted through the period of increasing activity on July 5 and 6. On July 7 (Figure 6*a* and Plate 4*c*) the bidirectional and trapped distributions returned at $L \sim$4.5, once low densities had been reestablished there with the delay noted above.

The May data of Figures 4*a* and 4*b* suggest a similar transition as the density reached $\sim$100 electrons-cm^{-3}. In the May case (Figures 4*a* and 4*b* and Plate 4*a*), the BI and TR continued to be present, at least sporadically, during the early period of density recovery until May 9. During this period, substorm activity continued at a low level, and density at the DE 1 apogee varied from near the saturated plasmasphere level to near or below 100 electrons-cm^{-3}, as noted previously.

The bidirectional, and occasionally, the trapped distributions continued to be evident in the data for some time after the return of persistent cold isotropic distributions near the equator at $L \sim$4.5. In the July case (Figure 6*a* and Plate 4*c*), continued BI observations occurred at higher L, apparently beyond a plasmapause decrease in the L = 5–6 range (Figure 7*c*), even as Kp approached zero on July 4. On two occasions, May 6, 0810–1240, and May 8, 0815–1235 UT, isotropic and bidirectional and trapped distributions were observed at nearly the same L value along the DE orbit (Plate 4*a*). This is tentatively attributed to the development or occurrence of dense plasma structure in this region (as discussed above), and to its azimuthal motion past the orbital plane of DE 1.

The tendency of the bidirectional field aligned and trapped distributions to be detected preferentially under low density conditions is seen in the data of June 7 near 2300 UT (Figure 5*a* and Plate 4*b*). The bidirectional and trapped distributions were observed only 12 hours after the convection event discussed above (Plate 1), during which the density was high and an isotropic distribution off the ram direction was detected.

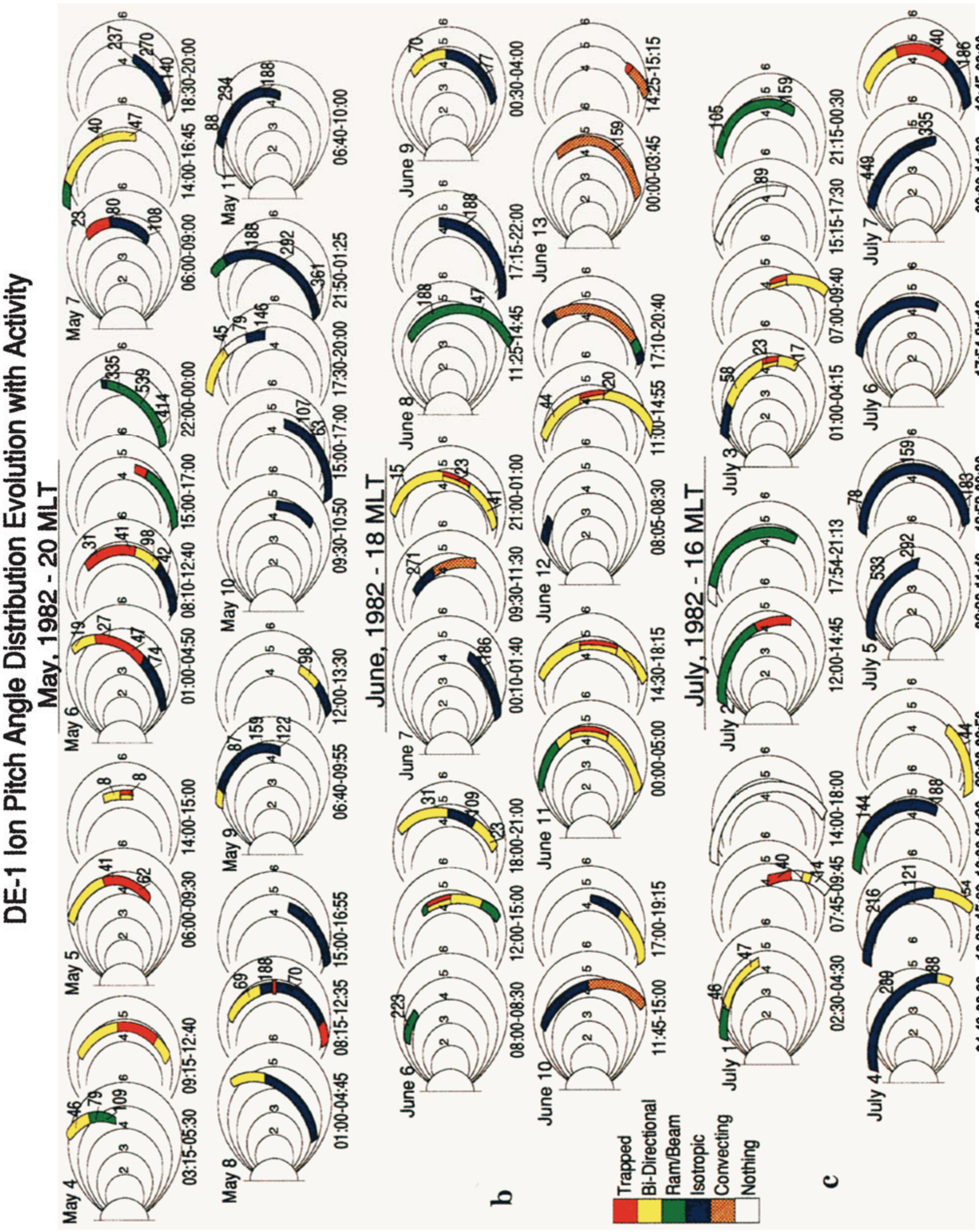
4. DISCUSSION

Erosion

During the process of erosion, from which local time sector(s) is the bulk of the plasma removed? Most MHD models of the erosion process [e.g., *Grebowsky*, 1970; *Maynard and Chen*, 1975] predict behavior of the kind illustrated in Figure 2, adapted from a case study by *Kurita and Hayakawa* [1985]. Figure 2*a* shows the eroded plasmasphere and an associated sunward extending streamer roughly 18 hours after an onset of enhanced convection, while Figure 2*b* shows conditions six hours later, after a further enhancement in the convection electric field intensity. One of the predicted effects is a broadening of the sunward extending flow region. A substantial contribution to this streamer is apparently provided by the outer plasmasphere in the late afternoon time sector.

As noted above, *Lemaire* [1975, 1985, 1986] has argued that this scenario is physically incomplete, that significant plasmasphere erosion should also occur in the post-midnight sector, such that an outer layer (or layers) of dense plasma is effectively detached from the main plasmasphere through the gravitational interchange instability. The layer drifts outward as it moves toward the dayside, where, due to the higher Pedersen conductivity of the ionosphere, it may approximately corotate with the Earth while also being carried sunward by the large-scale convection field. From a topological standpoint, this implies that outlying dense features observed during the course of an erosion episode should include the following: (1) plasmas that extend sunward from the late afternoon, duskside plasmasphere, and move under the influence of the convection electric field, particularly in the early stages of the disturbance, and (2) features that are separated from the main plasmasphere, and whose initial motions are dominated by a combination of the gravitational interchange instability and the convection electric field.

Previous work from high-altitude satellites [e.g., *Maynard et al.*, 1983; *Higel and Wu*, 1984; *LaBelle et al.*, 1988], from polar orbit [e.g., *Cauffman and Gurnett*, 1972; *Heelis et al.*, 1982; *Heppner and Maynard*, 1987], and from ground-based probing [e.g., *Foster et al.*, 1986; *Fontaine et al.*, 1986] provides clear evidence of disturbance-associated sunward plasma flows in the bulge sector at $L \geq 6$. *Yeh et al.* [1991] have used the Millstone Hill radar to show the occurrence near dusk of fast (order of 2 km-s^{-1}) westward ion flows extending to L values as low as $\sim$2.3 during a magnetic storm in which Kp reached 9. The DE data for the June period add to this picture by confirming the occurrence during moderately disturbed periods of sunward and outward flows in the high density outer plasmasphere near L = 4.5. Evidence of immediate outward cross-L flow in the afternoon sector during


DE-1 Ion Pitch Angle Distribution Evolution with Activity
May, 1982 - 20 MLT
June, 1982 - 18 MLT
July, 1982 - 16 MLT
b
c
Trapped
Bi-Directional
Ram/Beam
Isotropic
Convecting
Nothing

a

isolated substorms has been obtained from whistlers [*Carpenter and Seely*, 1976]. Thus it appears that there is efficient penetration of the outer plasmasphere in the afternoon-dusk sector by electric fields, and therefore strong support for the idea that this sector is significantly eroded during convection events. Instabilities such as the one proposed by *Lemaire* [1975, 1985] may also contribute to substorm-associated erosion of the plasmasphere, but the evidence of the present paper is not sufficient in scope to permit an evaluation of that contribution.

Cross Sections of Outlying Features

The data reported here and other data studied by the authors in preparing this paper suggest that dense plasma features observed in the magnetosphere beyond $L = 6$ are frequently large, ~2-$3R_E$ or more in cross section along a satellite orbit, while outlying features observed closer in, between L ~3 and 6, are often comparatively narrow, from $< 0.5R_E$ to $\sim 1R_E$ in extent, particularly when encountered beyond an inner density trough of order $1R_E$ in width. We suggest the following explanation for these observations.

Dense plasma regions observed in the outer magnetosphere, such as in the case of Figures 9*c* and 11*b*, are inferred to be either in a state of outflow toward the magnetopause or in a quasi-trapped state following a quieting trend in convection activity. If enhanced convection activity involving near-equatorial flow speeds of several km/s toward the magnetopause were to persist for extended periods, say for ten hours or more, one would expect most of the eroded plasma to escape into the magnetosphere boundary layers, so that observations of broad patches would be rare. Instead, possibly because magnetospheric convection electric fields tend to be unsteady and/or because intermediate-altitude electric field turbulence tends to decouple the high- and low-altitude flow regimes along field lines just equatorward of the dayside polar cap boundary, the evacuation process is inefficient, and regions of dense plasma regularly exist beyond synchronous orbit. The regularity with which such regions were observed in the present data and in other ISEE data studied by two of us (DLC and RRA) suggests that from ~10 to 30% of the plasma removed from the outer main plasmasphere during a weak magnetic storm does not "escape," but remains in the afternoon-dusk magnetosphere. This estimate is based upon assuming that all of the plasma in a belt extending $\sim \Delta L = 1$ inside an $L = 5$ plasmapause is removed from the plasmasphere, and that a fraction of this plasma, following flux-preserving sunward and outward bulk motion, is distributed within a belt $\sim 3R_E$ wide extending from noon to dusk beyond $L = 7$.

As intercepted by spacecraft, the regions in the outer magnetosphere should be of varying size, depending upon the distribution of dense plasma streams or sunward extending features at the time when the erosion process effectively terminates. Such streams or features could be several R_E across, in particular those that represent the erosion of a relatively large plasmasphere. Large size is also possible in the case of the instability mechanism of plasma detachment proposed by *Lemaire* [1985, 1986]

Outlying dense plasma features observed closer to the plasmasphere, at L ~3 to 6, should be more limited in extent, as suggested by Figures 10*a*, 11*a*, and 11*b*. This may be due in part to the thinning and inward spiralling of sunward extending features as quieting occurs and the Earth's corotation field becomes more important at a given L shell. As illustrated by Figure 2*a*, narrower features may also occur due to the fact that as erosion proceeds, a diminishing plasmasphere represents a progressively more limited source of plasma for sunward extending features. Furthermore, the fact that periods of quieting and of relatively steady activity are on average longer than intervals of increasing activity implies that data acquired at regular intervals in the vicinity of the main plasmasphere will be dominated statistically by evidence of narrower features.

The effects of inward spiralling and thinning may be such as to cause the density gradients at the edges of some outlying features to steepen, thus preserving plasmapauselike boundary profiles such as those illustrated near $L = 4$ and $L = 6$ in the ISEE cases of Figure 11*a* and 11*b*.

Relations Between the Duskside Bulge and the Main Plasmasphere

There is understandable confusion about the relation of the duskside bulge to the main body of the plasmasphere. It has been convenient for some modeling purposes to assume that the bulge is simply the elongated, duskside part of a teardrop-shaped plasmasphere [e.g., *Higel and Wu*, 1984]. However, the weight of the evidence presented both here and in other work suggests to us that while the teardrop model has been used with some success in dealing with statistics on plasmapause position in the dawn sector [e.g., *Berchem and Etcheto*, 1981], much of what is observed in the bulge region cannot be described in terms of such a model. From an observational point of view, the bulge and the main plasmasphere are essentially two separate entities. The bulge appears to consist of plasma that has been removed from the main plasmasphere by erosion processes, but which has not yet escaped from the magnetosphere. It only appears as an extension of the main plasmasphere when the "root" or point of attachment of an extending region is being observed, and even then may exhibit a density level sensibly different from that of the inner region. Such an effect has been reported by *LaBelle et al.* [1988], who studied the effects of the ring current overlapping the plasmasphere.

The distinction between the bulge and the main plasmasphere may develop in the following way. Whistler studies [*Carpenter et al.*, 1972, 1979] have demonstrated that erosion sufficient to make a significant change in overall plasmasphere size requires the occurrence of several substorms in close succession, or the equivalent of a weak magnetic storm (although significant local perturbations in the plasmasphere can occur during temporally isolated substorms). An analogous effect involving the relation between the depth of plasmasphere penetration by electric fields in the dusk sector and ring current development has been discussed by *Yeh et al.* [1991]. During the later phases of an erosion event, as the convection electric field intensity begins to decline

Plate 4. Meridian cross sections showing in color code the dominant pitch angle distributions observed by the DE 1 RIMS during the case studies. When the satellite ram direction and the magnetic field direction were close, field-aligned beams and isotropic distributions could not always be separately identified, so corresponding cases are identified as "ram/beam." Representative values of electron density determined from the PWI SFR are indicated along the orbital segments. (*a*) Data from ~2000 MLT for the May 4–11, 1982 period. (*b*) Data from ~1800 MLT for the June 6–13, 1982 period. (*c*) Data from ~1600 MLT for the July 1–7, 1982 period.

and/or shielding by the ring current to increase, the corotation field tends to become dominant within the region interior to sunward extending features, and the plasmasphere at all local times tends to become roughly circular, with a radius of only ~0.5–$1R_E$ greater at dusk than at dawn. This tendency toward circularity during quieting was nicely modeled in the work of *Chen and Wolf* [1972]. Meanwhile, the sunward extending features or other outlying dense regions that are usually present under recovery conditions will tend to remain within the magnetosphere and will appear as one or more aspects of the bulge region, as described in our case studies.

The distinction between the main plasmasphere and the bulge region is useful in explaining differences in results reported from various satellite and ground instruments. For example, in the case of the OGO 5 results summarized in Figure 1*c*, the plasmasphere limit on a given orbit was defined as that location where a steep ion density gradient occurred, and where a threshold density of 10 ions cm^{-3} was reached. This definition tended to emphasize the outer limits of any outlying features such as those indicated near $L = 4$ in Figure 11*a* and near $L = 6$ in Figure 11*b*, and led to an average plasmasphere with duskside radius several R_E beyond the dawnside values.

If, on the other hand, the plasmasphere limit is taken to be at the inner edge of the innermost observed region of steep density gradients, as in the case of recent work with ISEE SFR data by *Carpenter and Anderson* [1992], then plasmasphere limits at $L = 2.9$ and 3.1 would be identified in the cases of Figures 11*a* and 11*b*, respectively. *Carpenter and Anderson* [1992] studied 208 ISEE profiles with at least one identifiable plasmapause effect and found that typical values of plasmapause radius near dusk were only of order ~0.5 R_E greater than those at dawn. In their statistical study of DE 1 light ion profiles exhibiting an inner and outer region of steep density gradients, *Horwitz et al.* [1990] found that the MLT distribution of the innermost gradient was nearly circular at L=3–4. The existence of a more nearly circular main plasmasphere may explain why polar satellite measurements of a narrow peak in ionospheric electron temperature, believed to be associated with the plasmapause, do not exhibit a significant bulge effect (poleward excursion) in the dusk sector [*Brace et al.*, 1988].

Whistler data acquired near $L = 4$ show evidence of both the duskside bulge and the main plasmasphere. As the station advances in MLT, the bulge, when observed, usually appears in terms of a relatively abrupt increase in the outermost radius of whistler paths that show evidence of being within the plasmasphere [*Carpenter* 1966, 1970]. As noted above, this feature is now believed to represent the sunward flank of an outward extending streamer near the point where the streamer joins or nearly joins the main plasmsphere, the streamer being either quasi-trapped in the dusk sector or moving eastward at less than the angular velocity of the Earth [*Carpenter et al.*, 1992]. Although the westward edge of the bulge may be well defined in the whistler data, the data (with exceptions such as the case of Figure 8*d*) are usually not sufficient to define other aspects of the bulge configuration, including sunward extensions and outer radial limits.

During some periods, such as the ones illustrated in this paper, a bulge effect may be observed in whistler data on only a fraction of the days, say less than 20%, and the statistics on plasmasphere radius at dusk may not differ substantially from those for the dawn sector. In the quiet sun years 1963 and 1965, a well defined bulge was observed on a large fraction of the observing days, being particularly common in multiday periods of relatively steady substorm activity following weak magnetic storms. In other years, bulge observations have been less frequent (although a full statistical study has not been made), suggesting that the "trapping" of the bulge in a way that makes it clearly observable to a whistler station may be quite sensitive to secular variations in convection field intensity and/or the shielding process.

Outlying Regions; Attached or Detached?

There are indications that some outlying regions are fingerlike extensions of the main plasmasphere, as suggested in Figure 1*d*, and also indications that some are effectively isolated from the main plasmasphere.

In support of "connectivity," *Maynard and Chen* [1975] have argued that certain outlying features observed from Explorer 45 near $L = 5$ could be understood in terms of streamerlike outflow such as that suggested in Figures 2*a* and 2*b*. *Chen and Grebowsky* [1974] have argued that some of the outlying regions identified from OGO 5 by *Chappell et al.* [1971] can be explained in a similar way. Whistler [*Ho and Carpenter*, 1976] and polar satellite [*Taylor et al.*, 1971] data from quieting periods have been used as evidence that outlying dense structures, lying close to the plasmasphere during quieting periods and moving in the direction of the Earth's rotation, were in fact rooted in the main body of the plasmasphere.

In contrast, an absence of connection to the main plasmasphere is suggested by cases such as that of Figure 9*c*, in which a patch of dense plasma was crossed in the outer afternoon magnetosphere some 72 hours after an increase in substorm activity. Such regions might remain in the outer magnetosphere for extended periods under the influence of fluctuating high latitude electric fields that are not sufficiently intense or persistent to move them into the boundary layers. Meanwhile, the effects of partial shielding of the middle-inner magnetosphere and the increased importance of the corotation field may give rise to thinning of any dense streamers connecting the outlying features to the main plasmasphere, as illustrated in Figure 2*c*. Such streamers may also be subject to distortion and further thinning under the influence of unsteady convection electric field components, such that their identity as detectable dense plasma features is lost.

The possibility that the erosion process may be turbulent in nature has been suggested by *Reasoner et al.* [1983], based upon case studies of thermal light ions measured on the SCATHA satellite. Structure in the convection electric field that could involve velocity shear and hence possibly lead to detachment is suggested by the narrowness in latitude of the fast sub-auroral ion drifts (SAID) observed during substorms in the premidnight ionosphere [e.g. *Anderson et al.*, 1991, 1993] and by the relatively abrupt low-latitude limits of the inward extending sunward flows observed at dusk during a magnetic storm by *Yeh et al.* [1991]. From AKEBONO double-probe data recorded above ~4000 km altitude in the premidnight sector during the main phase of the great magnetic storm of March 13-14, 1989, *Okada et al.* [1993] showed evidence of a penetrating poleward directed electric field that rose abruptly, beginning at ~48.4° invariant latitude, and reached a peak with half width ~2° at ~50.5°. The inferred westward flow speed at the peak was ~5.7 km/s.

A new type of evidence of spatial and temporal structure in subauroral convection activity prior to dusk has been provided by *Freeman et al.* [1992], who report on substorm-associated radar auroral surges (SARAS) detected using the Sweden and Britain Radar-Auroral Experiment (SABRE). The authors describe events in which westward flow speed in the late afternoon E region increases from ~300 m/s to ~1 km/s for about 30 to 60 min, in association with substorm particle injections on the nightside. Wider in latitude than the postdusk SAID events (<2°), SARAS events were found to extend over at least 4° in latitude around the central observing geomagnetic latitude of ~ 66°N. The outlying irregular structure in the profile of Figure 11*b* was recorded near 0800 UT on 30 October, 1983, ~36 hours after the onset of a weak magnetic storm. It is noteworthy that a SARAS event was detected from SABRE ~7 hours later [*Freeman et al.*, 1992] as the moderate substorm activity of the storm recovery phase continued.

The irregular density profiles observed in the plasmapause region near 20 MLT during the May period suggest that large, factor-of- ~2- to-10 irregularities, often a few tenths of an R_E across, form in the dusk–postdusk sector. These may be related to the ripples found at the low-latitude edge of the diffuse aurora [e.g., *Kelley*, 1986] and to the auroral patches and detached arcs found equatorward of the diffuse auroral boundary in the evening sector by *Moshupi et al.* [1979]. Assuming that the irregularities are limited in longitudinal extent, we consider them to represent at least a class of isolated or detached features. Their relation to the larger patches observed in the outer afternoon magnetosphere during more disturbed periods is not known, although we note that within the patch illustrated in Figure 9*c* the profile was far from smooth, as was the profile beyond L ~7 in Figure 11*b*.

It might be expected that whistler measurements of cross-L motions in the vicinity of the plasmapause could be used to investigate the mechanism of plasma detachment proposed by *Lemaire* [1985, 1986] for the postmidnight sector. Available studies suggest that much of the observed diminution in plasmapause radius observed across the nightside after midnight can be attributed to the effects of convection, as indicated by simultaneous measurements of cross-L flows in the outer plasmasphere [e.g., *Carpenter et al.*, 1972; *Carpenter and Park*, 1973]. However, relatively few cases of prolonged whistler activity have been studied.

Eddy Flow in the Outer Plasmasphere in the Dusk Sector?

There is evidence that dense plasma may not only remain in the afternoon-dusk sector for several days following the beginning of a period of enhanced convection activity, but may also, in the aftermath of enhanced convection events, be observed in the post dusk sector many days after recovery begins, as illustrated in the case of Figure 13*c*. It appears that unless extremely deep quieting occurs, dense plasma regions that are present beyond some distance in the afternoon-dusk sector in the immediate aftermath of disturbance are unlikely to rotate past the midnight meridian, instead remaining "trapped" in the dusk sector and undergoing irregular, possibly eddylike motions under the influence of continuing low-level substorm convection fields, in the manner suggested by, for example, *Axford* [1969] and *Wolf* [1974]. When a new surge of convection activity occurs, the regions may be carried sunward toward the afternoon magnetopause, and thus contribute to the dense plasma distributions observed there for some time following the onset of higher levels of activity.

5. CONCLUDING REMARKS

The duskside bulge region of the plasmasphere is a most difficult region to describe and interpret, in large part because of its dynamic nature and great spatial extent, and because of the limited perspectives obtainable even from the present multiplatform 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. MHD models based upon combining an electric field associated with the Earth's rotation with a large-scale convection field may be useful in predicting the instantaneous flow patterns of low-energy plasma. Furthermore, such calculations (of a last closed equipotential) can under some limited conditions be useful in predicting the approximate radius of the main plasmasphere in the dawn sector. However, such models are not useful in describing the duskside plasma structures which are found to develop as a consequence of that flow.

2. During active periods, the plasmasphere appears to be divided into two principal 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. The latter, 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 one established on the nightside during the main erosion period.

3. In the aftermath of an erosion event, the duskside 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 effective, 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. The rea-

sons for this are not presently well understood, but may involve mechanisms that tend to decouple the high and low altitude flow regimes. The dense 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 field 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 spirallike, due to the continuing influence of convection electric fields present along the outer magnetospheric field lines.

6. As the result of the decrease with increasing 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, streamerlike 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 wavelike features that have been observed at the low latitude edge of the diffuse aurora or to detached auroral arcs and patches observed equatorward of the diffuse auroral region.

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 ~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 develop in the aftermath of entrainment and outflow, velocity shear effects observed in the duskside ionosphere as well as various properties of predusk 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 electrons-cm^{-3} at L ~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 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. Because of 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.

Relatively simple dynamic MHD models can be useful for certain qualitative predictions of the effects of enhanced convection on a quiet plasmasphere, 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 or the generally enhanced eastward flows in the postmidnight 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 penetrating electric fields, including the effects of high-amplitude localized field structures, 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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R. R. Anderson and A. M. Persoon, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 522442.

P. Canu, Centre de Recherches en Physique de l'Environnement, CNET, 92131, Issy les Moulineaux, France.

D. L. Carpenter, STAR Laboratory, Stanford University, Stanford, CA 94305.

C. R. Chappell, NASA Marshall Space Flight Center, AL 35812.

Y. Corcuff, Laboratoire de Signaux et Communication, Université de Poitiers, 86800 Mignaloux-Beauvoir, France.

P. M. E. Décréau, Laboratoire de Physique et Chimie de l'Environnement, CNRS, Orléans, France.

B. L. Giles, Space Sciences Laboratory, NASA Marshall Space Flight Center, AL 35812.

A. J. Smith, British Antarctic Survey, NERC, Cambridge CB30ET, U.K.

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