EROSION AND RECOVERY OF THE PLASMASPHERE IN THE PLASMAPAUSE REGION

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Abstract. Understanding the basic plasmasphere erosion/recovery cycle remains a major, as yet largely unmet, challenge to the space science community. We do not yet have a description of the formation of a new plasmapause boundary, nor have we been able to map the evidently complex electric fields that develop at subauroral latitudes during the process of plasmasphere erosion. Density structure regularly observed in the plasmapause region suggests that instabilities play an as yet unassessed role in the erosion/recovery cycle. Electron density interior to a newly formed plasmapause boundary tends to be reduced by factors of up to 3 in association with the erosion process, so that refilling during recovery occurs there as well as in the more deeply depleted plasmatrough region beyond. The number of electrons lost from this interior region, apparently through interchange with the ionosphere, can be of order 50% of the number lost from beyond the new boundary through flow perpendicular to **B**. Evidence has been found that of order 20% of the plasma removed from the main plasmasphere during an erosion event remains in the outer afternoon-dusk magnetosphere for extended periods. It is not yet known whether eroded plasmas entering the Earth's boundary layers make a geophysically important contribution to the plasma sheet. New insights into these and other important questions await both future photon and radio imaging of the plasmasphere from high altitude as well as continued work with certain excellent, as yet only partially exploited, satellite data sets.

1. Introduction

This paper concerns sources and losses of plasma in the Earth's plasmapause region. For decades, conventional wisdom on this subject has been that plasma exterior to a newly established plasmapause is lost from a larger plasmasphere by magnetospheric convection (e.g., Nishida, 1966; Brice, 1967); global-scale flow perpendicular to **B** carries the "removed" plasma generally sunward into the magnetospheric boundary layers. Density recovery in a region thus eroded occurs through refilling from the underlying ionosphere, or flow parallel to **B**.

A familiar form of evidence of loss and recovery is shown in Figure 1, which contains four electron density profiles obtained in 1983 using the sweep frequency receiver (SFR) technique on ISEE (Gurnett and Shaw, 1973). These were near-equatorial passes in the period August 3-12; a typical case spanned

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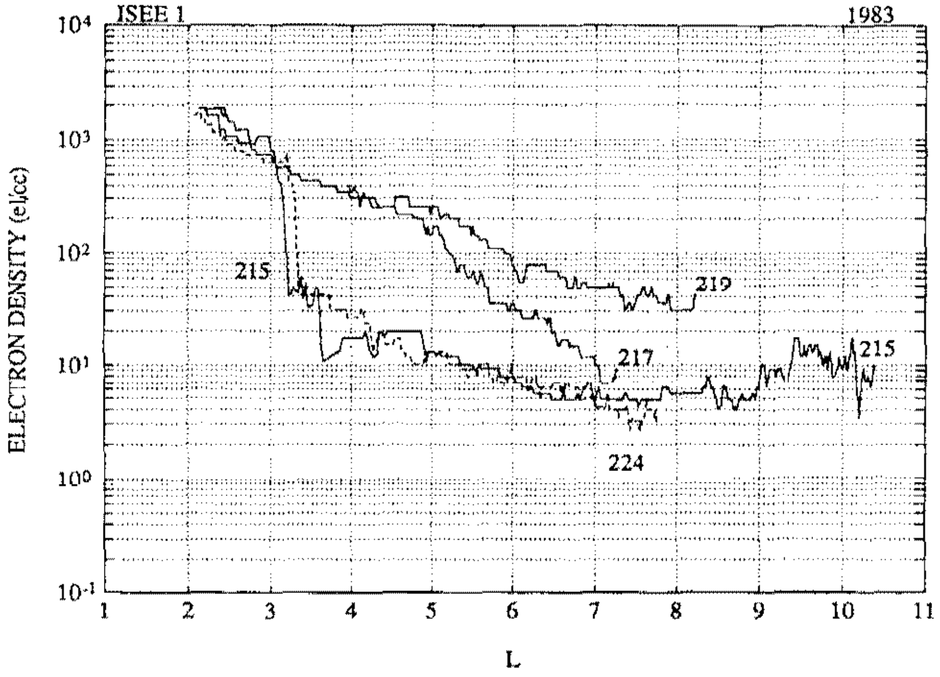

Figure 1. Post-noon electron density profiles obtained from ISEE 1 in 1983 illustrating the effects of plasmapause formation near L=3 (data from days 215 and 224) as well as states of recovery (data from intermediate days). Adapted from Carpenter and Anderson (1992).

several hours from post dawn to post noon. On day 215 a well defined plasmapause was crossed at L~3.2, and the density beyond that point was at typical dayside plasmatrough levels to at least L=8. On the next orbit, ~2 1/2 days later (day 217) the density had reached plasmasphere levels out to at least L=5, and on the following orbit (day 219) the plasmasphere appeared to extend to at least L=8. That such recovery is attributable primarily to refilling from the ionosphere is indicated by Figure 2, which shows profiles of flux tube electron content N_T and equatorial electron density vs L on successive nights in June, 1965. These are smoothed curves based on whistler measurements during an exceptionally long 8-day recovery period following a major magnetic storm on June 15-17 (Park, 1974).

The "conventional wisdom" noted above is at best only a starting point for study of plasma source and loss processes near the plasmapause. In order to understand plasmasphere erosion, we need to know what actually happens in subauroral regions, that is, in the immediate vicinity of the outer plasmasphere, during periods of enhanced convection activity. Our limited experimental evidence indicates that convection activity there is not describable by simple

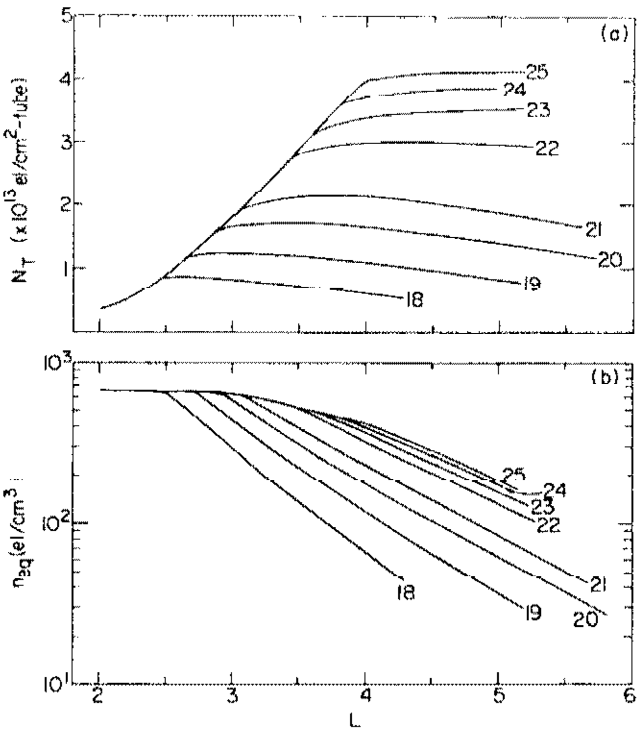

Figure 2. (a) Flux tube electron content profiles illustrating day to day refilling of the plasmasphere during an extended quiet period following a magnetic storm. The profiles were obtained by drawing smooth curves through data points from whistlers. The numbers indicate Universal Time days in June, 1965. (b) Equatorial electron concentration profiles corresponding to the tube content data. After Park (1974).

global-scale convection models. Furthermore, the plasmapause region is characterized by the development of irregular density structure, which points to the existence of both MHD turbulence and instabilities (e.g., Lemaire, 1974; Richmond, 1973; Roth, 1975; Huang et al., 1990, LeDocq et al., 1994; Moldwin et al., 1995). There is evidence of significant plasma loss through flow from the plasmasphere into the underlying ionosphere during substorm activity. To further complicate matters, there is evidence that the process of cold plasma transport into the boundary layers is inefficient, and that significant amounts of plasma eroded from the main plasmasphere remain "trapped" for extended periods in the outer afternoon-dusk magnetosphere (Carpenter et al., 1993).

We will now discuss processes involved in plasmasphere erosion/recovery cycles. Emphasis will be upon the erosion phase, rather than the recovery/refilling process.

2. Evidence for Processes Involved in Plasmasphere Erosion

2.1. GLOBAL SCALE CONVECTION

The evidence suggests that while global-scale convection originating in the solar wind dynamo acts as the driver of the loss process in the plasmasphere erosion phase, the pattern of erosion activity that actually results depends upon the cooperation of several processes that are active in the subauroral region.

The evidence for global scale convection includes: 1) data showing an inverse relation between plasmapause radius and measures of magneto-spheric disturbance (e.g., Carpenter, 1967; Chappell et al., 1970a; Carpenter and Anderson, 1992), 2) evidence of an outer region (density trough) in which density levels are substantially below expectations based upon outward density extrapolations from inner regions (Gringauz et al., 1960; Gringauz, 1963; Carpenter, 1963; Angerami and Carpenter, 1966; Carpenter and Anderson, 1992), 3) near-equatorial satellite detection of disturbance-associated sunward plasma flows (e.g., Lennartsson and Reasoner, 1978), including the almost immediate appearance of plasmasphere ions at synchronous orbit (and in earlier than usual local time sectors) following certain SSCs (Elphic et al., 1997; Weiss et al., 1997), 4) appearance of cold He$^+$, presumably of plasmaspheric origin, within the LLBL or adjacent dayside magnetosphere (Peterson et al., 1982; Fuselier, 1989).

The evidence of global scale convection also includes indications of interplay between the electric field associated with the Earth's rotation and solar-wind induced sunward convection, such as 1) observations of a duskside bulge of the plasmasphere that tends to be detected at earlier local times during periods of increased disturbance and at later times (or not at all) during quieting periods (Carpenter, 1966, 1970; Ho and Carpenter, 1976; Higel and Wu, 1984; Moldwin et al., 1994), and 2) observations suggesting transport by quiet-time corotation into the premidnight sector of narrow plasmasphere extensions or "plumes" created during earlier convection episodes (Ho and Carpenter, 1976; Ober et al., 1997a).

Additional evidence for a combination of sunward and corotational flow is a "day-night" boundary in the plasma trough region (exterior to the plasmasphere) in the dusk sector. At this boundary, reported from GEOS 2 synchronous orbit data by Carpenter et al. (1993), the electron density drops from ~ 10 to ~ 1 electron per cm^3. This change was interpreted as evidence of a separatrix in the combined flow: plasma elements on the westward side of the separatrix had recently been exposed to prolonged dayside upflows, while elements on the eastward side had experienced only nightside conditions of nearly zero or negative upflow. Figure 3 shows an example of GEOS 2

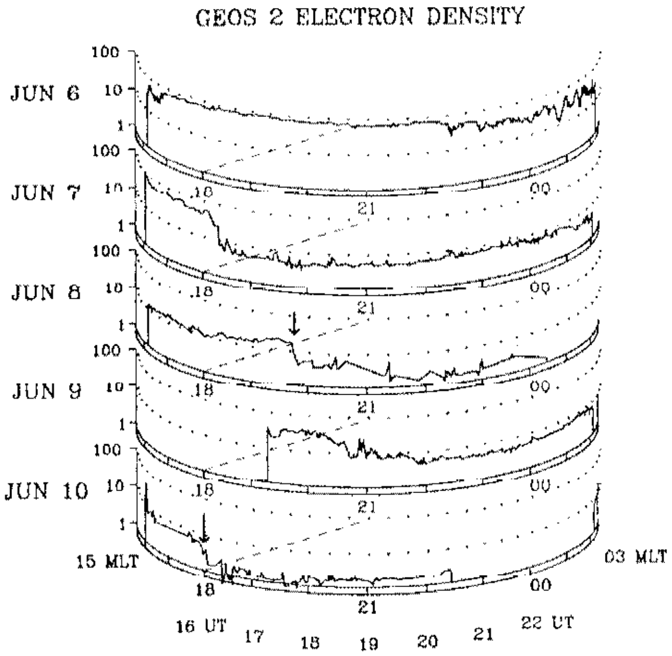

Figure 3. GEOS 2 electron density data for June 6-10, 1982, acquired by radio sounding at synchronous orbit. Log n_e is plotted versus MLT and UT for the ~1600-0200 MLT period. The dotted curves on the stacked perspective plots indicate, respectively, the typical late-dayside plasmatrough electron density level of ~8 per cm^3 and the corresponding saturated or quiet-time plasmasphere level of ~70 electrons per cm^3 at synchronous orbit. From Carpenter et al. (1993).

electron density data near dusk on six successive days in June, 1982. Density levels characteristic of the plasmasphere and of the afternoon plasmatrough are shown dotted. Transitions from daytrough to nighttrough conditions occurred on June 8 and 10, as indicated by arrows. A familiar type of density transition, from plasmasphere bulge region to dayside trough, occurred on June 7 and 9.

The importance of corotation in the combined flow is suggested by two phenomena: 1) delays in the detection of plasmasphere erosion effects on the dayside with respect to their observation on the nightside (Chappell et al., 1971; Décréau et al., 1982) and 2) the tendency of the "main plasmasphere", or innermost observed plasmapause radius at a given longitude, to be nearly circular, with only a slight bulge at dusk (Carpenter et al., 1993). The idea here is that from an observational standpoint there is a main plasmasphere that evolves toward a roughly circular form as nightside erosion effects are transmitted through corotation to the dayside. Meanwhile, the bulge region exists as one or more outlying features either connected to or effectively

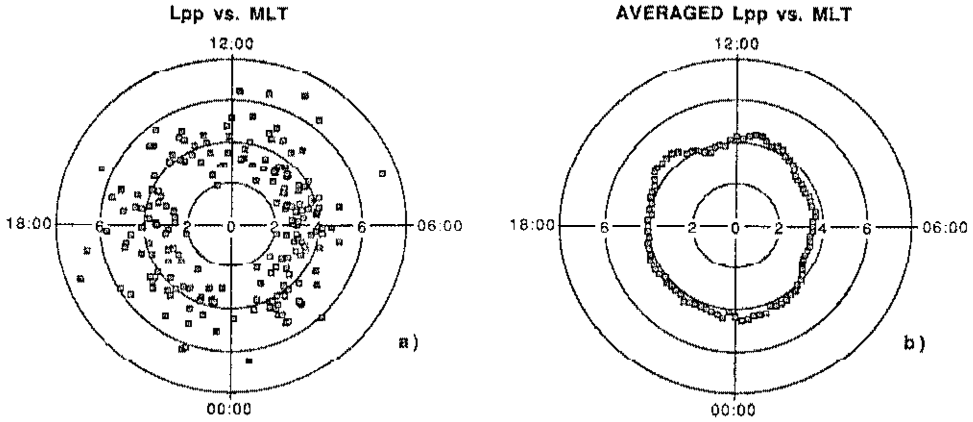

Figure 4. Plots of plasmapause L value versus MLT, illustrating the tendency of the main plasmasphere to become roughly circular in the aftermath of plasmasphere erosion events. (a) Scatter plot of 208 plasmapause crossings identified in ISEE 1 SFR data. (b) Two hour running average of the data of (a). After Carpenter and Anderson (1992).

detached from the main plasmasphere. Figure 4a shows innermost plasmapause crossing locations vs magnetic local time from approximately two years of ISEE sweep frequency receiver (SFR) data taken along either inbound or outbound near-equatorial passes (Carpenter and Anderson, 1992). These data were limited to cases in which there was a density jump by a factor of 5 or more within $0.5R_E$; hence they tended to represent periods either concurrent with or within tens of hours following multihour episodes of enhanced magnetospheric convection. In Figure 4b, a two hour running mean of the data shows a difference of only about $0.5R_E$ in the dawn and dusk plasmasphere radii.

Figure 5a shows an example of an ISEE profile in the afternoon/dusk sector in which evidence of both the main plasmasphere and the bulge appears (Carpenter et al., 1993). A projection of the orbit is shown by the inset in coordinates of geocentric distance versus MLT. An inner plasmapause appeared at $L\sim3$. From $L\sim2.9$ to 3.5 there was a trough, at dayside density levels, while an outlying plasmasphere-level feature with plasmapause-like boundaries appeared between $L\sim3.5$ and $L\sim4.2$. Beyond $L=4.2$ the density was at nightside trough levels. In this case the authors interpreted the main plasmasphere as being limited to within $L=2.9$ and suggested that the dense outlying feature was part of the bulge region. That feature may have been connected to the main body of the plasmasphere, but the morphology of the connection was not known.

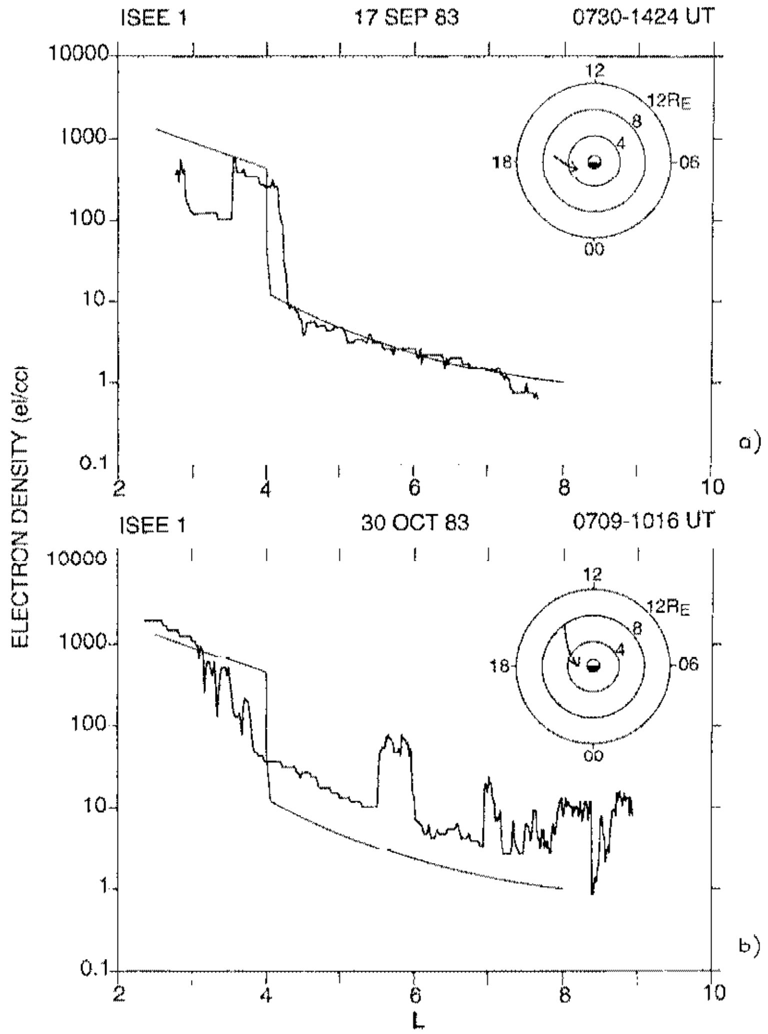

Figure 5. ISEE near-equatorial electron density profiles acquired along orbits in the afternoon-dusk sector. Insets show the geocentric distance of the satellite versus MLT. The accompanying curves are reference profiles from the empirical modeling work of Carpenter and Anderson (1992). The trough levels they show represent nighttime conditions in the aftermath of disturbance. (a) Profile showing evidence of an inner plasmapause, an inner trough inside a high-density feature, and an outer, lower-density trough. (b) Profile showing density structure in the plasmapause region near dusk and in the middle and outer afternoon magnetosphere. From Carpenter et al. (1993).

We now consider processes that appear to act in response to the imposition of high latitude convection electric fields.

2.2. SHIELDING OF THE INNER PLASMASPHERE BY THE ALFVEN LAYER

Shielding of the inner plasmasphere from a global scale dawn-dusk electric field is proposed to occur because of a charge separation electric field that develops at the inner edge of the plasma sheet or Alfven layer as the latter is displaced Earthward (e.g., Block, 1966; Karlson, 1971; Jaggi and Wolf, 1973; Wolf, 1983). For many years shielding has been included in an *ad hoc* manner in global scale electric field models used to study the evolving plasmasphere shape (e.g., Volland, 1973; Stern, 1974). It has appeared in calculations of the response of the coupled magnetosphere-ionosphere system to the imposition of a high latitude electric potential distribution (e.g., Spiro et al., 1981) and in cases in which statistical data on the location of the Alfven layer are employed along with assumptions about the role of that layer in the shielding process (Galperin et al., 1997).

There is evidence for shielding effects; low altitude polar orbiting satellite drift meter and *E* field measurements suggest that the transition from a low/middle latitude region of corotation to a high latitude convection regime is often relatively abrupt (e.g., Cauffman and Gurnett, 1972; Heppner and Maynard, 1987). Two case studies from the Millstone Hill incoherent scatter radar during disturbed periods showed fast westward flows in the premidnight sector with relatively sharp low latitude limits (Yeh et al., 1991). Similar findings were obtained from AKEBONO at ~10,000 km altitude along subauroral field lines by Okada et al. (1993). However, the connections between shielding and the erosion process are not clear. Prior to midnight, erosion would appear to occur (leaving aside questions of local processes, instabilities, etc.) through predominantly westward flow that erodes the plasmasphere as the Earthward "edge" of the flow, presumably the Alfven layer, is displaced progressively inward to some stormtime limiting configuration, meanwhile leaving the plasmaspheric region interior to the flow essentially free of cross-L inward drifts (e.g., Park, 1978). The apparent ionospheric effects of such a process, albeit observed in the predawn sector, were reported from COSMOS 900, in polar orbit at 480 km, by Afonin et al. (1997), who tracked the stormtime equatorward displacements of a sharp latitudinal front between a subauroral electron temperature enhancement, assumed to mark the ionospheric projection of the plasmapause, and enhanced auroral ionization.

In the postmidnight sector, shielding action appears to be less effective; whistler studies have shown evidence that although high latitude east-west electric fields do not penetrate the plasmasphere efficiently prior to the expansion phase of subsorms, cross-*L* inward drifts of whistler paths in the outer postmidnight plasmasphere become sharply enhanced as the expansion phase of a substorm begins (Carpenter et al., 1972: Carpenter and Akasofu, 1972).

2.3. DEVELOPMENT OF NONGLOBAL (MESOSCALE) STRUCTURE IN SUBAURORAL CONVECTION

2.3.1. *The Subauroral Ion Drift (SAID) Phenomenon*

A remarkable feature of plasma flow in the premidnight sector during substorms is the subauroral ion drift, or SAID. At ionospheric heights, SAIDs are observed as fast westward plasma flows at speeds of ~1-4 km-s^{-1}, which usually develop within a narrow, ~1° latitude range near 60° invariant (e.g. Galperin et al., 1974; Smiddy et al., 1977; Anderson et al., 1991, 1993). It has been suggested that these fast drifts are a consequence of field aligned currents established at the inner edge of the intruding plasmasheet (e.g., Anderson et al., 1993). The associated large electric fields develop because of the low Pedersen conductivity in the subauroral region just equatorward of the belt of auroral electron precipitation.

The SAID phenomenon, as well as latitudinally somewhat broader westward surges observed near dusk (e.g., Freeman et al., 1992), occur in the invariant latitude range where new plasmapause boundaries are most frequently created, i.e., L~3.5-4 (Carpenter and Park, 1973). A related phenomenon has been observed near 50° invariant during a great magnetic storm (Yeh et al., 1991) forming a peak at the equatorward edge of a latitudinally broad (~15°) region of westward flow observed over a ~6 h period near dusk by the Millstone Hill radar. It seems clear that such flow effects must be included in dynamic models if we are to understand the plasmasphere erosion process. The flow speed observations imply that a plasma element could be displaced by ~2000 km within a period of 20 min, or several hours in local time. Velocity shear effects could become important; dense regions poleward of the SAID channel might be effectively "detached" from the main plasmasphere. "Biteouts," variously narrow density depressions, have been observed interior to the plasmasphere during recovery periods (Ho and Carpenter, 1976; Horwitz et al., 1990). Recent modeling work by Ober et al. (1997b) suggests that some of these effects may be the result of SAID activity.

2.3.2. *Mesoscale Variations in Plasmasphere Radius*

Although the details of erosion patterns on the nightside are not known, it appears that their effects are detected at other local times through rotation of the distorted plasmasphere with the Earth. Studies from a single station (Angerami and Carpenter, 1966) and longitudinally spaced stations (Smith et al., 1981) have shown evidence of variations in plasmasphere radius of a few tenths of an Earth radius with spatial scales of ~15-30° longitude. It was suggested that these longitudinal ripples were imposed on the nightside by temporally and spatially structured convection activity and then appeared with rotational delays at the local times of observation.

2.3.3. *Differing Effects of Temporally Isolated and Prolonged Disturbances*

Whistler studies have shown that during temporally isolated substorms, the plasmasphere undergoes distortion by penetrating electric fields but not a significant change in global average radius (Carpenter et al., 1972, 1979). Evidence for the distortion effect comes from observations of compensating outward cross-*L* drifts immediately following the cross-*L* inward drifts observed in the postmidnight sector during temporally isolated substorms (Carpenter et al., 1972, 1979; Carpenter and Akasofu, 1972). In contrast, when substorm activity is prolonged, a significant reduction in global average plasmasphere radius occurs. At such times postmidnight cross-*L* inward drifts observed from whistlers are not followed by compensating outward flows (Carpenter et al., 1972, 1979). The outward flow effect remains to be explained.

2.4. INSTABILITIES AND TURBULENCE

The plasmapause appears to be a "source" region for density structure (e.g., Carpenter et al., 1993). Structure is reported to occur in conjunction with increases in magnetic disturbance activity (Moldwin et al., 1995), and the spatially structured and time varying nightside electric field during substorms may be imagined to support a number of processes, including the development of turbulence in dense plasma regions subject to enhanced flow speeds, shear flow instability in regions of subauroral ion drifts (SAID), gradient drift instability in the region of steep plasmapause density gradients, and gravitational interchange instability in regions where fast eastward drifts occur (Lemaire, 1974, 1975; Lemaire and Gringauz, 1997). However, the role of density irregularities in the loss process is not clear. The presence of irregularities with large peak to valley density ratios interior to, within, and just beyond the region of steep density gradients (e.g., Park and Carpenter, 1970; Oya and Ono, 1987; Koons, 1989; Horwitz et al., 1990; Carpenter et al., 1993; LeDocq and Gurnett, 1994) suggests that dense plasma elements can be detached from or shed by the plasmasphere, perhaps by analogy to the manner in which icebergs are "calved" from a glacier.

Substantial sources of data on irregular structure are now available. Electron density profiles taken along CRRES near-equatorial orbits using the sweep frequency receiver (SFR) radio technique provide a unique source of data on irregularities. LeDocq and Gurnett (1994) found indications of MHD

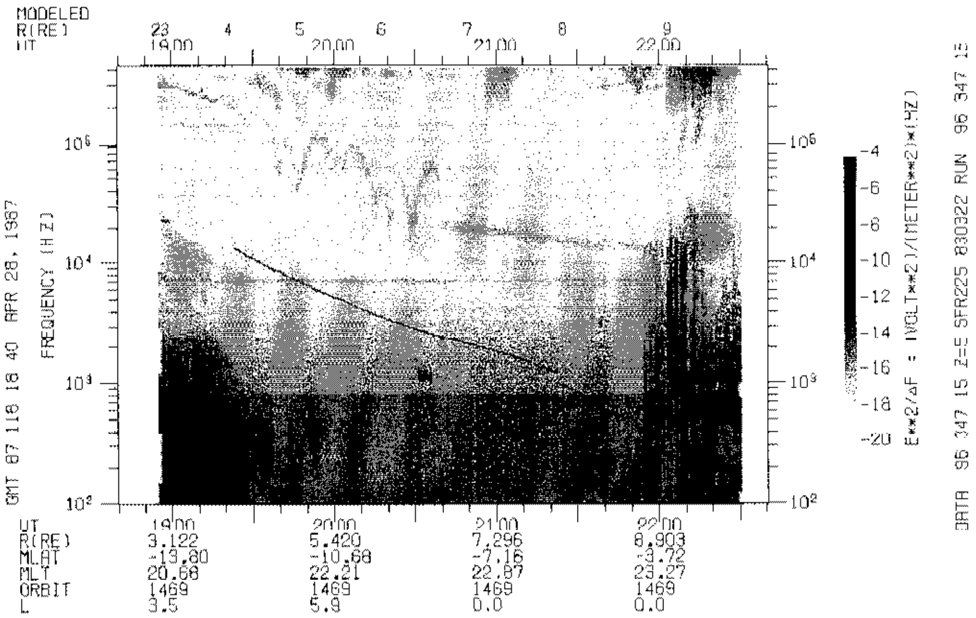

Figure 6. Sweep Frequency Record from ISEE illustrating irregular density structure in the nightside outer plasmasphere and in the plasmapause region. The density structure is revealed in the upper hybrid resonance (UHR) trace which falls at first smoothly from the upper left and then exhibits density variations with peak to valley ratios of ~4 in frequency and hence ~16 in total electron density. The thin dark curve below represents the total magnetic field (electron gyrofrequency) determined from the onboard magnetometer. Courtesy of R. R. Anderson.

turbulence near the plasmapause through Fourier analysis of CRRES time series of electron density data. They also reported evidence of spatially quasiperiodic structures near the plasmapause. From whistlers and ISEE records, Carpenter et al. (1993) reported irregularities inside the recovering, post-erosion-phase plasmasphere within a belt extending inward from the plasmapause. At a given longitude this belt was found to be of order ΔL=1 in width. On occasion it exhibited an abrupt inner limit inside which the profile remained relatively smooth, a limit that may be a measure of the limits of penetration of the stronger components of the nightside subauroral electric field. The major irregular features were often a few tenths of an Earth radius along an ISEE orbit.

The SFR record of Figure 6 shows an example of outer plasmasphere structure observed along an ISEE pass near 23 MLT (courtesy of R. R. Anderson). The density structure is revealed by the upper hybrid resonance (UHR) trace, which falls, at first smoothly, from the upper left and then exhibits variations with peak to valley ratios of ~4 in frequency and hence ~16 in total plasma density. The data were acquired during a very quiet period following a day of mild substorm activity. A single plasmapause location is not defined, but a nightside trough region is clearly present beyond ~6 R_E, as revealed by the dark trace (the plasma frequency) just below a band of diffuse continuum radiation. The thin dark curve superimposed on the lower part of the record represents the total magnetic field (electron gyrofrequency) determined from the onboard magnetometer.

Carpenter et al. (1993) found that in the aftermath of weak magnetic storms, irregular structure appeared in the premidnight sector just beyond and within the region of steep density gradients. A possibly related phenomenon, the occurrence of irregularities in auroral activity at the low-latitude edge of the diffuse aurora, has been discussed by Kelley (1986) as evidence of a shear flow instabilitiy associated with SAIDs.

Instabilities along field lines in the outer afternoon magnetosphere may cause a disconnection between the convection activity at ionospheric heights and that at greater altitudes. Dense plasmas, apparently of plasmaspheric origin, have been observed beyond synchronous orbit, mostly in the afternoon-dusk sector (Chappell et al., 1970b, 1971; Chappell, 1974). Carpenter et al. (1993) found examples whose extent and regularity of occurrence suggested that in the aftermath of a period of enhanced convection they formed a belt of dense plasma several Earth radii across interior to the magnetopause in the afternoon-dusk region. An example of such a case, from ISEE on July 9, 1982, is shown in Figure 5b. It thus appeared that erosion of the plasmasphere is not an efficient process, insofar as the expulsion of eroded plasma from the dayside outer magnetosphere is concerned.

2.5. PLASMA FLOW INTO THE IONOSPHERE

2.5.1. *Dumping of Plasma during Periods of Enhanced Convection*

Whistler data have shown that in addition to reductions in main plasmasphere size during periods of disturbance, there are reductions in electron density by factors ranging from ~1.2 to 3 in the outer part of the newly eroded plasmasphere (e.g., Park and Carpenter, 1970; Carpenter et al., 1993). These reductions tend to occur within a belt that often has a well defined inner limit, coincident with the belt of irregularities noted above. The density decreases in the outer plasmasphere, while not uniform in longitude, appear to involve amounts of plasma comparable to the amounts eroded from the plasmasphere through transport perpendicular to **B**.

The mechanism of this plasma loss was discussed by Park (1973) in terms of the combined action of a downward component of cross-L flow (inward component of flow at the equator) and draining of plasma along **B**. Park proposed that the downward component of cross-L drift reduces the O^+ concentration at a given altitude. In the altitude range below the critical level, where H^+ is in chemical equilibrium with O^+, this reduction in O^+ must be accompanied by a corresponding reduction in H^+. The H^+ reduction induces the draining along **B** of H^+ from the protonosphere.

A downward component of cross-L drifts may explain some fraction of the loss of plasma beyond a new plasmapause, since inward motions may occur on the nightside both for flux tubes that later remain within the eroded plasmasphere and for some that remain outside the main plasmasphere.

2.5.2. *Dumping of Plasma within and beyond the Plasmapause Region*

Limited evidence points to the possibility that new plasmapause formation is in part a local process involving dumping of plasma into the ionosphere. In their study of well defined plasmapause density profiles, Carpenter and Anderson (1992) found that the scale width of the boundary, or equatorial distance within which the density changed by an order of magnitude, was not a strong function of L value. The scale width would be expected to decrease with decreasing L if the plasmapause were formed strictly as the result of the inward entrainment and consequent steepening of a preexisting boundary region.

There are indications that flux tube electron content may not be preserved during inward convection from the tail region on the nightside, at least in the premidnight sector. Density data reported from GEOS 2 at synchronous orbit by Higel and Wu (1984) indicated that the lowest densities observed, in the ~0.1-1 electrons per cm^3 range, were in the premidnight sector, often following passage through an outlying bulge feature near dusk. Even at ~1 electron per cm^3, such densities would be difficult to explain as the result of electron-content preserving convection of plasma from greater nightside distances. Total densities in the near tail region are probably not below 0.1-1 electrons per cm^3. Assuming inward displacement at the equator from 12 to $6R_E$, we would expect a density increase by roughly the fourth power of tube radius, or a factor of 16, putting the trough level at L~6 above 1 electron per cm^3 and thus above the range in which it is believed to be near the time of plasmapause formation. A possible explanation of the situation is that during inward drift some type of dumping process occurred (in addition to the loss associated with an increase in size of the loss cone as a field tube convects inward). The quantity of electrons dumped would not have to be large, since the inward convecting flux tubes involved are already low in tube electron content.

3. Evidence for Processes Involved in Plasmasphere Recovery

3.1. PLASMASPHERE REFILLING THROUGH INTERCHANGE FLUXES FROM THE IONOSPHERE

Statistical as well as case study data on plasmasphere refilling provide clear evidence of post-disturbance recovery through refilling from the ionosphere. As suggested by Figure 2, this process is distinguished by its slowness, requiring of order days, and by its roughly uniform distribution throughout regions of depleted density, indicated by the changes in the tube content curves of Figure 2a.

Data on changes in plasma density in the trough region provide strong evidence of refilling flows from the ionosphere (e.g., Song et al., 1988). In the immediate aftermath of erosion events a given upward flux can produce very large relative changes in concentration (e.g., Angerami and Carpenter, 1966; Higel and Wu, 1984; Carpenter and Anderson, 1992). From a study of GEOS relaxation sounder data, Song et al. (1988) found that at synchronous orbit the refilling rate varies inversely with the absolute value of the *Dst* index. This dependence was interpreted as being due to changes in the ion composition in the topside ionosphere during disturbed conditions.

There exist a number of in situ measurements of refilling fluxes as well as modeling studies of the effects of "polar wind" flows into closed field line regions of the magnetosphere. These are beyond the scope of the present report.

3.2. CROSS-*L* DIFFUSION

Statistical data suggest that the mean density gradient in the plasmapause region is on average steeper on the nightside than on the dayside (e.g., Chappell, 1972; Nagai et al., 1985; Oya and Ono, 1987; Carpenter and Anderson, 1992). Cross-*L* diffusion, perhaps in association with instabilities, is probably responsible for this difference, in combination with the effects of rotation of plasma regions with the Earth away from nightside locations of plasmapause formation. Horwitz (1983) suggested that cross-*L* diffusion should not be important for "large scale considerations of the plasmasphere density profile." This may partially account for the fact that even during the most extended periods of quiet, the radial plasma density profile at the equator does not approach a hydrostatic equilibrium distribution, but instead appears dominated by boundary conditions at the ionospheric endpoints of flux tubes and by plasma interchange along **B**.

3.3. GLOBAL SCALE CONVECTION DURING RECOVERY

Some accretion of plasma may occur during periods of quieting when plasma in the bulge region begins to rotate with the Earth. In cases of tail-like features, simulations predict an inward spiralling effect, such that the plasma involved "wraps around" the main plasmasphere (e.g., Chen and Wolf, 1972; Kurita and Hayakawa, 1985). Evidence of the tendency of tail-like bulge features to rotate with the Earth has been found from whistlers (Carpenter, 1970; Ho and Carpenter, 1976) and in the results from syn-chronous orbit reported by Higel and Wu (1984) and Moldwin et al. (1994).

4. Numerical Estimates of Losses and Recovery Rates

4.1. LOSSES FROM OUTSIDE A NEW PLASMAPAUSE

The number of electrons lost from outside a newly established plasmapause boundary is of order 1×10^{31}. This estimate is based upon removal of essentially all plasma in a belt extending globally from L=3.5 to L=5 and upon the assumption that inside L=5 the pre-disturbance plasmasphere flux tube electron content between 1000 km altitude and the equator is $\sim 5 \times 10^{13}$ electrons in a field tube of 1 cm^2 cross section at 1000 km (e.g. Park, 1974). Elphic et al. (1997) have obtained a similar estimate based upon encounters with dense plasma at synchronous orbit during periods of enhanced convection activity.

It seems likely that most of this loss occurs through transport perpendicular to **B** by convection (however structured that convection may be). Some of the strongest evidence for this comes from observations, noted above, of sunward and outward displacements of dense plasma. The loss through transport perpendicular to **B** may be enhanced by instabilities to an extent that is not yet known. As noted above, a fraction of the overall loss beyond a newly formed plasmapause may be due to the downward flow of plasma into the ionosphere under conditions of inward cross-L motion.

To a limited extent, the losses from beyond a new plasmapause involve a redistribution within the magnetosphere. Based upon ISEE data, Carpenter et al. (1993) estimated that roughly 20% of the plasma convected away from the main plasmasphere during a weak magnetic storm remained trapped within the outer afternoon-dusk magnetosphere. Elphic et al. (1997) suggest that such long residence times might be explained by an outer afternoon region of relatively low electric potential gradient.

4.2. LOSSES FROM INSIDE A NEW PLASMAPAUSE

The number of electrons lost from within a newly eroded plasmasphere is substantial, in the neighborhood of 50% of the amount lost from outside. Some loss tends to occur at all longitudes, but the amounts of loss are not uniform. In some regions there may be a reduction by only of order 30%, while in others the density may be reduced from quiet time levels by a factor of 2 or in the most severe cases, 3.

These losses from within an eroded plasmasphere are believed to involve transport downward into the ionosphere. In one documented case, noted earlier, the inferred downward electron flux was ~1×10^9 per cm^2 per second during a several hour period (Park, 1973). This was believed to occur, as noted above, by a combination of flow transverse and parallel to **B**.

4.3. GAINS DUE TO REFILLING FROM THE IONOSPHERE

Here we emphasize day-to-day changes in total density or tube electron content in the magnetosphere. A pioneering whistler case study by Park (1974), summarized in Figure 2, shows how the plasmatrough region recovered from the magnetic storm of June 15-17, 1965 over a multiday interval of quieting. Details near the plasmapause, which was originally near L=2.5, are not shown, nor are what were probably the earliest stages of recovery. The data of Figure 2a represent total electron content between ~1000 km and the equator in a flux tube with ~1 cm^2 cross section at 1000 km . They show a net daily gain of 5×10^{12} electrons until the plasmasphere appeared to reach equilibrium with the underlying ionosphere. From earlier work on this case, Park (1970) had inferred daytime upward electron fluxes of ~3×10^8 per cm^2 per second and nighttime downward fluxes of ~1.5×10^8 in the refilling region. As illustrated in Figure 2a, the recovery time varied with L value, ranging from ~1 day at L=2.5 to ~8 days at L=4. Thus there tended to be two distinct regions, with a time variable boundary between an inner "saturated" plasmasphere and an outer "unsaturated" one.

Day to day changes in equatorial density have been measured that are consistent with these numbers. Carpenter et al. (1993), from a combination of satellite and ground whistler data, observed average increases of ~80 electrons per cm^3 per day at L~4.5 near the equator during a several day recovery period following a weak magnetic storm.

Song et al. (1988), as noted above, found evidence that at synchronous orbit the refilling rate varies inversely with the absolute value of the *Dst* index. Electron density was found to increase within the range ~10 to 25 per cm^3 per day. The corresponding refilling time constant (to a saturation electron density level of 70.5 per cm^3) ranged from ~3 days to more than 7 days, depending on the *Dst* index.

The depleted outer plasmasphere has been found to recover at rates that are roughly comparable to those in the refilling plasmatrough region (e.g., Tarcsai, 1985; Saxton and Smith, 1989). The reported persistence of such flows well into quiet periods, coupled with evidence that the quiet time equatorial radial profile falls off more steeply than would a hydrostatic distribution, led to a suggestion by Lemaire and Schunk (1992, 1994) that there is a slow plasmaspheric wind transporting plasma by interchange motion from the inner toward the outer plasmasphere.

4.4. GAINS DUE TO CROSS-*L* OUTWARD MOTIONS

In the early stages of a convection episode, cross-*L* outward moving plasma on the dayside should move some ionospheric plasma upward, effectively increasing the plasmasphere electron content. The magnitude of this effect is not known.

5. Balance Between Source and Loss Processes

It seems clear that in terms of erosion/recovery cycles, losses predominate during the erosion phase, which is of order a few hours to tens of hours in duration. Replenishment processes dominate during the middle and later parts of the recovery phase, which is typically several days in duration. To go beyond this simple picture, with questions pertinent to the comparative effects of specific loss and replenishment processes, requires a level of understanding that has yet to be reached. For example, what is the interplay between processes of loss and recovery during a "noisy" recovery cycle, when significant erosion effects have already occurred but substorm activity continues at reduced levels, often for days? This is a highly probable state of the magnetosphere, but we know little of such interplay observationally or from theory.

6. Gaps in Knowledge and Understanding

6.1. BACKGROUND

Gaps in knowledge about the plasmapause/plasmasphere are in part a consequence of rapid progress in that subject area in the 1960 discovery era. By 1967, a year when the plasmasphere had only begun to be explored by spacecraft, understanding of the processes giving rise to the plasmapause phenomenon appeared to be substantially complete. Some 30 years later, in 1997, many in the community remain with that impression and are largely unaware of the accumulated evidence and arguments to the contrary that have been offered over the years (e.g., Dungey, 1967; Carpenter, 1970; Chen and Wolf, 1972; Lemaire, 1975, 1985; Morfill, 1978; Carpenter et al., 1993; Moldwin et al., 1994; Carpenter, 1995).

Gaps are also attributable to limitations in the number and nature of pertinent investigations in the years since the discovery phase. Observational work has not been matched to the huge size and dynamic nature of the plasmasphere. The available measurements permit us a number of inferences about plasmapause/plasmasphere dynamics but are largely anecdotal, non-uniformly distributed in local time, and unrepresentative of conditions during erosion activity. Thus they have not provided direct information about the process of plasmasphere erosion and new plasmapause formation. Since the outer plasmasphere is located at subauroral latitudes, its modification must occur near the inner limits of penetration of hot plasma sheet plasmas. Changes in the plasmasphere by processes associated with the hot/cold plasma interface probably take place on substorm time scales and for this reason alone would be expected to be observationally elusive.

6.2. PLASMASPHERE EROSION AND PLASMAPAUSE FORMATION

6.2.1. *Plasmapause Formation*

Lacking direct observations of the plasmapause formation process, we do not know how that process is distributed in space or over what time scales a new profile develops. We wish to know how the density profile evolves with time during plasmapause formation, and whether the process includes local dumping of plasma into the ionosphere as well as motion perpendicular to **B**. We wish to know what aspects of the hot/cold plasma interface may be involved and how formation may depend upon the properties of the underlying ionosphere. We do not know to what extent the physics of the process depend upon the intensity of the high latitude convection field. Is plasmapause formation always underway at some location? How do its physics depend upon the starting conditions on the density profile? In particular, what happens to the process during periods of quieting? We need to place plasmapause formation within the context of substorm activity and hence within the full range of high-to-middle latitude disturbance phenomena of which it is a part.

6.2.2. *Plasmasphere Erosion*

As in the case of plasmapause formation, we see various effects of plasmasphere erosion through anecdotal data, without having direct global scale or mesoscale observations of the erosion process itself. Thus we often see the density profile of an eroded plasmasphere as well as outlying dense features in data taken along individual satellite orbits, but do not know how some original plasmasphere configuration evolved so as to appear this way. We do not know in what geophysically important ways the ionosphere and overlying regions may be coupled during the erosion process. Thermal coupling appears to be particularly important, as emphasized by Afonin et al. (1997), who showed how the subauroral ionospheric electron temperature enhancement, traditionally associated with the plasmapause (e.g., Brace and Theis, 1974), can exhibit a surprisingy steep falloff (~0.1°) on its poleward side and be displaced progressively equatorward during a magnetically disturbed period.

What kind of temporal and spatial structure develops in the subauroral electric field during periods of enhanced high latitude convection? How does a process of plasmapause formation interplay with corotation or instabilities to produce a plasmasphere boundary on a global scale? What aspects of the formation process explain longitudinal variations in plasmasphere radius? In what sense is the process of plasmasphere erosion different from that of plasmapause formation?

Numerical modeling of plasmasphere dynamics using global scale electric field models has been successful in simulating certain statistical aspects of plasmasphere observations (e.g., Gallagher et al., 1995). Recently, stormtime changes in dense plasma encounters at synchronous orbit by multiple satellites have been successfully simulated using models that increasingly employ observed or derived geophysical quantities as inputs (e.g., Weiss et al., 1997). Furthermore, Ober et al. (1997b) have shown how density troughs in the duskside bulge region can develop as a consequence of SAID-like flows. Serious efforts to understand plasmasphere erosion are clearly being made, although we are still in the early stages of this effort.

6.2.3. *Instabilities and Turbulence*

Available data on instabilities show us various types of plasma structure but do not tell us much about the conditions under which the structure develops. We don't know when, where, and under what geophysical conditions instabilities occur and what role they may play in the shedding of plasma by the plasmasphere. Where and when does MHD turbulence develop? We wish to know the extent of the affected regions in longitude. We need to know how instabilities may be driven, whether by velocity shear flow or by other gradients in the plasma parameters. How does the structure that appears in the outer plasmasphere differ in origin from the structure that is seen in the region of steep density gradients? We wish to know how the development of irregular structure in the outer plasmasphere interplays with processes involved in plasma dumping into the ionosphere and with the penetration of the plasmasphere by perturbing convection electric fields. What accounts for the sharp inner limit on irregular structure observed in the outer plasmasphere?

6.2.4. *Density Loss through Plasma Flow into the Ionosphere*

We do not know where and when plasma is dumped into the ionosphere during periods of erosion activity. What are the geophysical consequences for the ionosphere of any such dumping? To what extent are changes in ionospheric boundary conditions involved, as well as electric fields parallel to **B** and increases in the size of the loss cone during cross-L inward drifts? How extensive in longitude are the affected regions? Is the loss process ongoing during the early stages of recovery, or is it primarily a phenomenon of the principal erosion phase?

6.2.5. *Fate of Entrained Dense Plasmas*

What happens to plasmasphere plasma carried sunward and outward from the main plasmasphere? Under what conditions are such plasmas detached from or continuous with the main plasmasphere? What fraction of the plasma eroded from the main plasmasphere enters the magnetosphere boundary layers? It was proposed as early as 1962 (Carpenter, 1962), and later in more detail (Nishida, 1966; Brice, 1967) that plasma in the region beyond the plasmapause circulates along non dipole-enclosing paths (e.g., Axford and Hines, 1961) that extend into the geotail region or into regions of tailward flow near the magnetopause. The idea that recently eroded plasmasphere plasma could circulate into the geotail region has been discussed by Freeman et al. (1977), and recently Elphic et al. (1997) and Ober et al. (1997c) have suggested that such plasma, following entry into the LLBL and energization to ~1-2 keV, may contribute substantially to the population of the stormtime plasma sheet. Further study of this issue is clearly needed, as is study of the heating to suprathermal (~5-50 eV) energies of plasma in the vicinity of the plasmapause (e.g., Gurnett, 1976; Horwitz et al., 1981; Olsen et al., 1987).

What is the geophysical significance of regions of dense plasma that remain near the outer dayside magnetopause in the aftermath of erosion activity? What effects, if any, do they have on particle scattering and precipitation due to resonant wave-particle interactions? Is there a disconnection at high invariant latitudes on the dayside between the low altitude convection system and plasma flow at high altitudes? Or can such long residence times be well explained in terms of regions of small total electric field, as suggested by Elphic et al. (1997)?

6.2.6. *Plasmasphere Refilling*

What are the starting conditions for upflows of plasma from the ionosphere into the trough region beyond a newly formed plasmasphere? What processes govern the interchange flows of plasma throughout the period from plasmapause formation into extended quiet? To what extent is the refilling rate dependent upon the disturbance level? What are the principal factors governing the observed quiet time equatorial density profile and its failure to approach a hydrostatic distribution? What role does dayside refilling play in the distribution and density profiles of outlying dense plasmas in the afternoon-dusk sector?

7. Ways to Fill Gaps in Knowledge and Understanding

7.1. GLOBAL AND MESOSCALE PROBLEMS

Only with global scale imaging on multihour time scales will we be able to address major questions posed above about the conditions of plasmapause formation and the evolving structure of the main plasmasphere during the erosion process. Photon imaging (e.g., Frank et al., 1994) from the outer magnetosphere would be particularly helpful in obtaining global views of the evolving plasmasphere shape and in placing changes in plasmasphere morphology within the context of auroral activity and hot plasma dynamics. Photon imaging may also supply at least coarse infomation on the spatial and temporal conditions of plasmapause formation.

Radio sounding (e.g., Calvert et al., 1995) from high altitude would permit remote studies of plasmapause formation and plasmasphere evolution within the changing radio view of the sounder, and also supplement them with detailed measurements along the satellite orbit as the sounder penetrates the boundaries it has recently sounded or will subsequently probe. Radio sounding offers the possibility of comparing plasmapause dynamics with information on magnetopause location and structure.

Radio tomography, using multiple satellites, is attractive as a way of studying the development of irregular plasma structure and obtaining information on mesoscale features such as regions of dense plasma trapped in the outer dayside magnetosphere.

Modelers can contribute toward understanding of the physics of the erosion process by continuing to develop and apply more realistic models of the subauroral electric field.

7.2. MICROSCALE PROCESSES

For study of the physics of plasmapause formation and associated plasmasphere erosion effects, multiinstrument methods such as those currently employed for study of the auroral region need to be exploited. By use of such methods with existing or future data sets, it should be possible to investigate small scale relationships among hot plasmas, electric fields, field aligned currents, local plasma density, and plasma bulk flows, and to make rendezvous comparisons between satellites at different altitudes. Those cases representative of the elusive plasmapause formation process may be few in number and should be patiently sought. Multiinstrument data from satellites should be used to study the physical processes at the hot/cold plasma interface. The knowledge thus gained can be used to interpret data on erosion activity and plasmapause formation obtained by the global and mesoscale imaging techniques. Much variability in erosion phenomena may be expected; the complexity in this area should reflect that already found from imaging of substorm activity.

Instruments designed to study the auroral regions often are not sensitive to or designed for conditions in the subauroral region in the immediate vicinity of the plasmapause. Future satellite missions should be designed with attention to this problem.

Incoherent scatter measurements from the ground near L=3 as well as bottomside sounding experiments in the L=3-4 range should be conducted with a view to describing low altitude changes that occur during plasmapause formation.

8. Differences in Views

Major differences in perspective on plasma sources and losses in the plasmapause region exist between those who actively study the properties of the region and those who do not. The latter are inclined to dismiss the region and its dynamics as being relatively well understood or perhaps of minor geophysical importance. Meanwhile the former find themselves in what might still be considered a discovery phase, constantly challenged by new findings that reveal how little is in fact known, particularly about the erosion of the plasmasphere and the fate of eroded plasmas.

As future satellite photon and radio imaging missions are developed, one of their principal targets will be the plasmasphere. In this new era we may expect discussion and interpretation of the region to become more widespread and to be based upon increased community awareness of the region's observed properties. Until that time much can be done to reduce the present differences in perspective through study and interpretation of existing data.

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