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PLASMAPAUSE SIGNATURES IN THE IONOSPHERE AND MAGNETOSPHERE

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Abstract. Isis 2 observations of a variety of topside ionospheric 'signatures' of the plasmapause are compared with simultaneously acquired equatorial electron density profiles obtained by the whistler technique. The satellite data were acquired at ∿1400-km altitude at dusk and dawn in the sunlit northern hemisphere summer ionosphere within ∿15° longitude of the VLF receiver. Results suggest that the dynamics of plasma coupling between the ionosphere and plasmasphere dominate the topside data and obscure the location of the equatorial plasmapause field line. The total density and light ion troughs begin 2°-10° equatorward of the field line through the equatorial plasmapause and are not clear plasmapause signatures. The invariant latitude of the region of steep spatial gradient in thermal plasma density, i.e., the plasmapause, appears to increase with altitude. Thus measurements of its position at different altitudes may give different results. Plasma sheet electrons, however, are observed on field lines just outside the equatorial plasmapause at both dawn and dusk. Their low-latitude extent at 1400-km altitude can be used as a signature of the equatorial plasmapause position.

Introduction

Upward diffusion of low-energy ionospheric particles maintains the plasmasphere. The flux tube content saturates when a state of diffusive equilibrium is attained, and a diurnal ebb and flow of thermal plasma between the plasmasphere and ionosphere results. The extent of the high-density plasmasphere is determined by the history of previous magnetic activity, which erodes the outer reaches of the plasmasphere, and by the refilling time of flux tubes, which is a strong function of latitude (tube volume). The more or less abrupt outer boundary of the plasmasphere, the plasmapause, plays a dominant role in the physics of the mid-latitude magnetosphere.

Near the equatorial plane, where the magnetic field strength is lowest along a field line, the sharp spatial gradient in thermal plasma density at the plasmapause creates a preferential environment for wave-particle interactions and other processes which result in particle precipitation into the lower ionosphere and atmosphere. Relativistic electrons are dumped from the radiation belts [Thorne and Kennel, 1971], the slot between the inner and outer belts is formed [Lyons et al., 1972], ring current protons are lost [Cornwall et al., 1970; Williams and Lyons, 1974], and substorm injected electrons are precipitated [Foster et al., 1976]. The enhancement of whistler ducting at the plasmapause [Inan and Bell, 1977] promotes cyclotron resonance interactions with energetic particles, and the characteristics of VLF emissions change abruptly across this region. The equatorial plasmapause was discovered as a knee in the altitude distribution of the charged particle density [Gringauz et al., 1960; Carpenter, 1963] and has been extensively surveyed by particle measurements at high altitude [e.g., Taylor et al., 1965; Gringauz, 1969; Chappell, 1972].

Many ionospheric signatures of the plasmapause have been proposed, but it is unclear how they relate to the field line through the equatorial plasmapause where dynamic magnetospheric processes occur. Statistical studies reveal that the afternoon bulge in the equatorial plasmapause is conspicuously absent in low-altitude satellite data [e.g., Brace and Theis, 1974] and that the sharpest features associated with the ionospheric troughs are considerably displaced from the plasmapause field line. These results suggest that the dynamics of plasma coupling between the ionosphere and the plasmasphere dominate the low-altitude data and obscure the location of the equatorial plasmapause field line. The purpose of this paper is to clarify this relationship by comparing a variety of topside signatures with simultaneously acquired equatorial electron density profiles obtained by the whistler technique. We find that although energetic particles map out a field line between high and low altitudes due to their guiding center motions, thermal particles do not. The invariant latitude at which a sharp spatial gradient in the thermal (diffusion-dominated) plasma density is observed increases with altitude. The low-altitude troughs are associated with flux tubes on which the equatorial density is less than its equilibrium value and which are refilling from below. H^+ outflow and the effects of horizontal electric fields combine to reduce topside light ion densities in this region. As a result of flow saturation effects and the considerable refilling times for mid-latitude flux tubes, the low-altitude total density and light ion troughs, as well as the region of enhanced polar wind outflow, begin significantly equatorward of the equatorial plasmapause field line.

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Plasmapause Signatures in the Ionosphere

A net outflow of thermal plasma is observed on flux tubes for which the equatorial plasma density is below the diffusive equilibrium level. A total electron density trough in the topside ionosphere is expected on field lines in this region, at least during conditions of local darkness in the F layer photo-ionization production region [Park and Banks, 1974, 1975]. Rycroft and Thomas [1970] and Rycroft and Burnell [1970] have reported that the minimum of the observed total density trough is associated with the statistical location of the whistler plasmapause, although their data are more consistent with the trough minimum being 2^o-3^o equatorward of the plasmapause field line. Using a more extensive data set, Kohnlein and Raitt [1977] find that this trough minimum is observed at the statistical plasmapause latitude for Kp $\simeq$ 0 but is seen at increasingly lower latitude than the plasmapause as Kp increases. Brace and Theis [1974] have observed latitude profiles of total electron density on Isis 1 and find that profiles across the plasmapause at different altitudes may be quite different. They note little diurnal variation of the plasmapause at altitudes less than 3000 km and conclude that the difference in equatorial and midaltitude plasmapause behavior may be caused either by diffusion-limited proton flow out of the ionosphere or by field line distortion caused by plasma convection. They suggest that the plasmapause may not coincide with a specific field line. Grebowski et al. [1976] compared the total density trough measured on Ariel 4 at ∿600 km with the high-altitude plasmapause determination of S^3 and found no consistent feature of the trough at the plasmapause latitude mapped down from S^3.

Taylor and Walsh [1972] note that the sharp latitude gradient in H^+ and He^+ density below ∿1000 km, the light ion trough (LIT), is a more consistently observable mid-latitude feature than the total density trough, and they propose the LIT as the low-altitude signature of the plasmapause. Direct intercomparison of the LIT with the high-altitude plasmapause determined by whistler [Taylor et al., 1969; Carpenter et al., 1969] and thermal particle [Grebowski et al., 1970] techniques revealed a general agreement in position but no one-to-one relationship. Morgan et al. [1977] compared whistler observations of equatorial electron density with ion density measurements at ∿800 km for two Ogo 6 passes during quiet conditions. They conclude that the H^+ trough is a manifestation in the topside ionosphere of the equatorial plasmapause but admit the possibility that the H^+ trough may lie at a somewhat lower L value. Park and Banks [1975] propose that the plasmapause should occur near the equatorward edge of the LIT, since H^+ outflow causes this edge of the LIT to form at the boundary between diffusive equilibrium flux tubes and those involved in the outflow [Banks et al., 1976]. Diurnal effects and the large refilling times of the plasmasphere tend to complicate this simple relationship. An O^+ or F layer total density trough is not expected to be associated with the plasmapause in the sunlit ionosphere, since there the O^+ density is very insensitive to H^+ flow [Park and Banks, 1975].

Brace and Theis [1974] noted a localized enhancement in the electron temperature within the region of N_e gradient on the low-latitude edge of the electron density trough. This temperature increase was found to be more pronounced at higher altitudes. Titheridge [1976] notes that the T_e peak occurs at the same latitude as that at which the H^+ outflow reaches its limiting value. This he defines as the plasmapause location. Serbu and Maier [1970] reported a sudden increase in ion temperature as Ogo 5 exited the plasmasphere during moderately disturbed conditions. They found that ion temperatures of $\gtrsim 10^5$ °K characterized the region outside the plasmapause.

Banks and Holzer [1968] proposed that the outflow of light ions from the ionosphere would attain supersonic velocities on open field lines, creating a polar wind. The refilling time for mid-latitude closed flux tubes, depleted during prior magnetic disturbance, has been measured to be of the order of days [Park, 1970], and the diurnal reversal of H^+ flow between plasmasphere and ionosphere does not begin until the equilibrium tube content has been reestablished [Banks et al., 1971]. Knudsen [1974] speculates that the ebb and flow boundary near the equatorward edge of the trough is at the approximate plasmapause latitude, but Park [1974] separates the plasmasphere itself into two regions, an inner region of H^+ ebb and flow on filled flux tubes and an outer region of refilling flux tubes within the plasmapause. Evidence for an extension of polar wind to mid-latitudes is found in altitude profiles of ion composition [Brinton et al., 1971] and topside electron density [Banks and Doupnik, 1974] which can be explained only if there is a rapid outflow of light ions along field lines in that region. Banks and Doupnik find the region of this outflow to extend to much lower latitude than the expected plasmapause position in the morning sector, giving evidence of strong light ion outflow within the outer zone of the plasmasphere. Raitt and Dorling [1976] interpret the global pattern of H^+ density in the topside ionosphere in terms of regions of light ion outflow or inflow from the plasmasphere. They find the region of continual daily outflow to be near the expected plasmapause position. Titheridge [1976] notes that a strong outflow can occur in the dusk sector on filled flux tubes as they rotate into the bulge region of the plasmasphere and their high-altitude volume increases. He postulates that the evening sector bulge in the equatorial plasmasphere actually drives the low-altitude signature of H^+ outflow, i.e., the LIT, to lower latitude. Thus the region of H^+ outflow is not a good signature of the plasmapause.

Simultaneous Observations of Ionospheric Signatures and the Whistler Plasmapause

In order to clarify the relationship between the equatorial plasmapause and features of the mid-latitude ionosphere we have examined data from a 6-day interval in June 1973 during which the Isis 2 satellite, in a circular polar orbit at ∿1400 km, overflew the Stanford University magnetically conjugate VLF receiver sites at

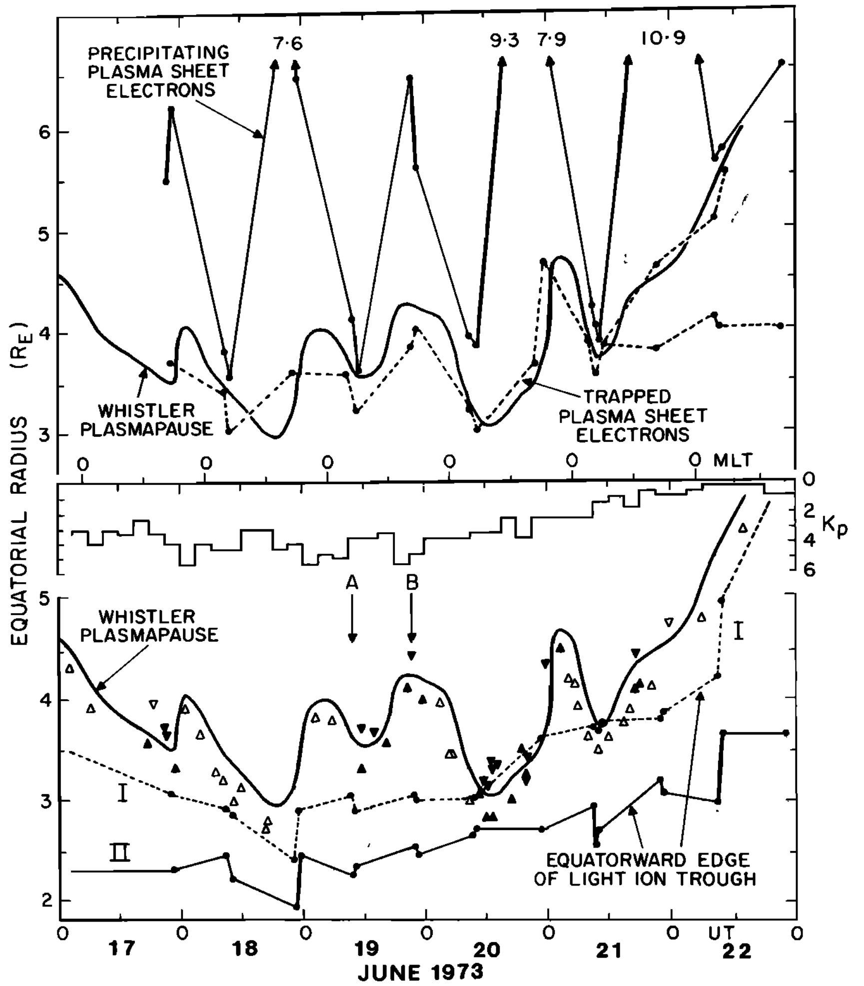

Fig. 1. Diurnal variation in the location of the whistler (equatorial) plasmapause: (top) the low-latitude extent of precipitating and trapped plasma sheet electrons and (bottom) the equatorward edge of the light ion trough observed by Isis 2 during a period of decreasing magnetic activity. See discussion in text. (Detailed observations at dawn and dusk, A and B, are presented in Figures 2 and 3.)

Siple Station, Antarctica (∿84°W, L ∿ 4), and Roberval, Quebec (∿76°W, L ∿ 4). Satellite data included in this study were acquired at dawn and dusk within 15° longitude of the Roberval VLF station. Magnetic conditions changed gradually from moderately disturbed to quiet during the interval of the study.

Whistler profiles of equatorial electron density versus equatorial distance were acquired essentially continuously (see Park and Seely [1976] for details of the whistler observations). These were used to determine the position of the equatorial plasmapause for comparison with the satellite data. A combination of the IGRF/65 internal reference field and an external field model due to Olson and Pfitzer [1974] was used in whistler analysis to insure meaningful comparison with the satellite results. The magnetic coordinates of satellite position were calculated by using the IGRF/65 model. Latitude profiles of ionospheric composition, density, temperature, and H^+ upward streaming velocity at 1400-km altitude were examined orbit by orbit and compared with nearly simultaneously acquired equatorial measurements. All ionospheric data were acquired in the sunlit summer (northern) hemisphere. F layer and topside electron density profiles were also examined, but the troughs were too shallow or ill-defined to offer a basis for comparison with the other data. A description of the Isis 2 experiments is found in work by Shepherd et al., [1973]. Additionally, Isis 2 energetic electron data were used to determine the low-latitude extent of trapped and precipitating plasma sheet electrons. The major results of this study are presented in Figure 1.

The lower section of the figure presents the equatorial radial distance of the whistler plasmapause and of the field line associated with the equatorward edge of the ionospheric light ion trough determined from the satellite data. Triangles denote individual measurements of the plasmapause position, and the solid curve is fitted to these data [Park and Seely, 1976]. In addition to a long-term incursion of the plasmapause to low latitudes during the period of enhanced magnetic activity (as seen in the Kp index) a distinct diurnal modulation of the equatorial plasmapause position is evident. The equatorward edge of the LIT has been identified in two ways for each dawn and dusk Isis 2 pass during this interval. Curve I denotes the field

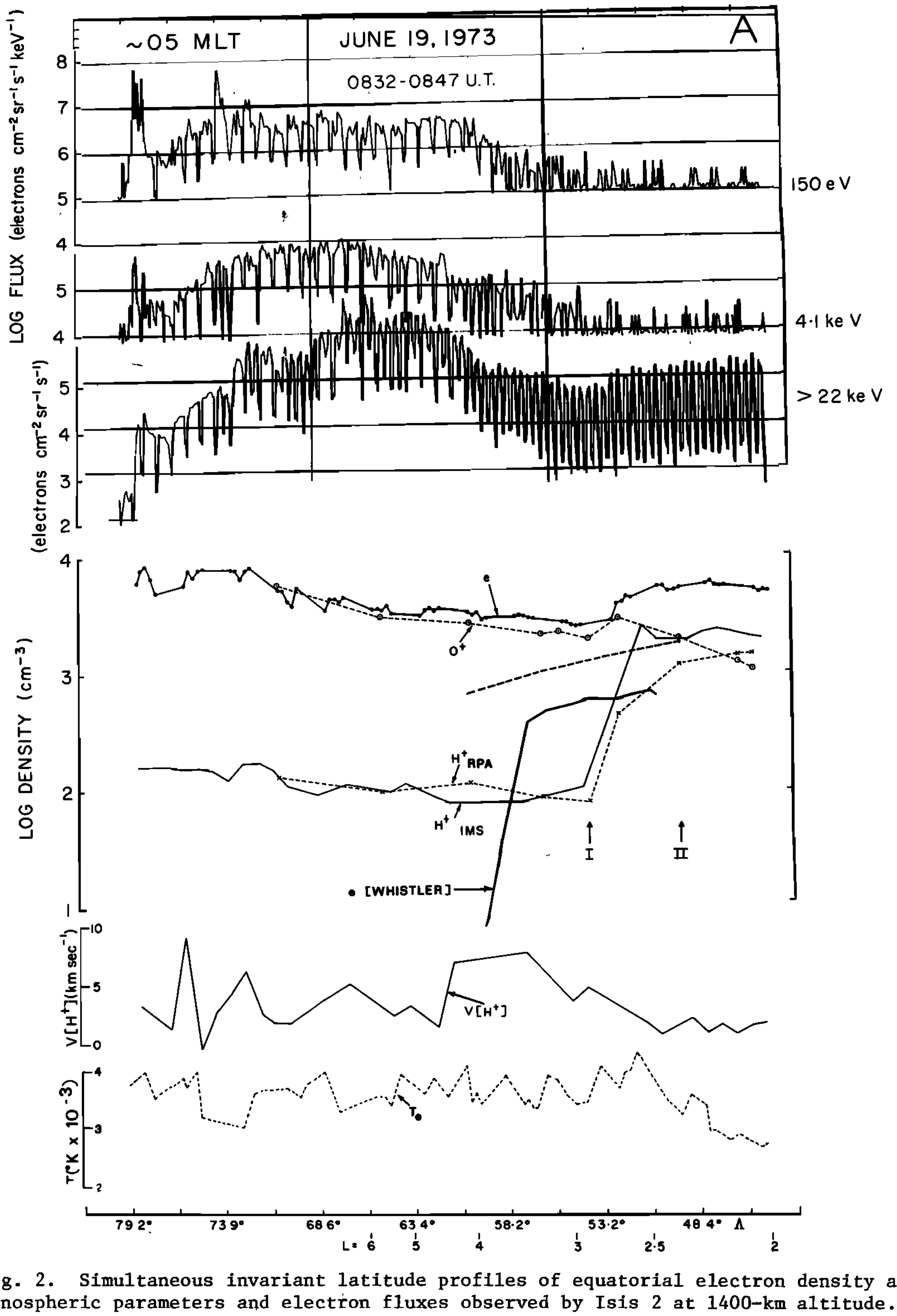

Fig. 2. Simultaneous invariant latitude profiles of equatorial electron density and ionospheric parameters and electron fluxes observed by Isis 2 at 1400-km altitude. These data are representative of conditions observed during dawn passes through the sunlit northern hemisphere ionosphere.

line on which H^+ and He^+ attain their trough minimum density at 1400-km altitude. Curve II denotes the position of the first decrease in light ion density associated with the trough. Both curves lie well equatorward of the equatorial plasmapause field line, observed at the same time and longitude. These measurements of the edge of the LIT at dawn and dusk do not exhibit the diurnal variation in position seen for the high-altitude plasmapause. However, long-term variations in the position of boundaries I and II are similar to those of the equatorial plasmapause. Both the plasmapause and the ionospheric trough low-latitude boundaries are seen to move to higher latitudes as the magnetic activity diminishes near the end of the study period.

Electrons in the near-earth plasma sheet have a characteristic energy of ∿5 keV. The low-latitude extent of trapped (anisotropic) and

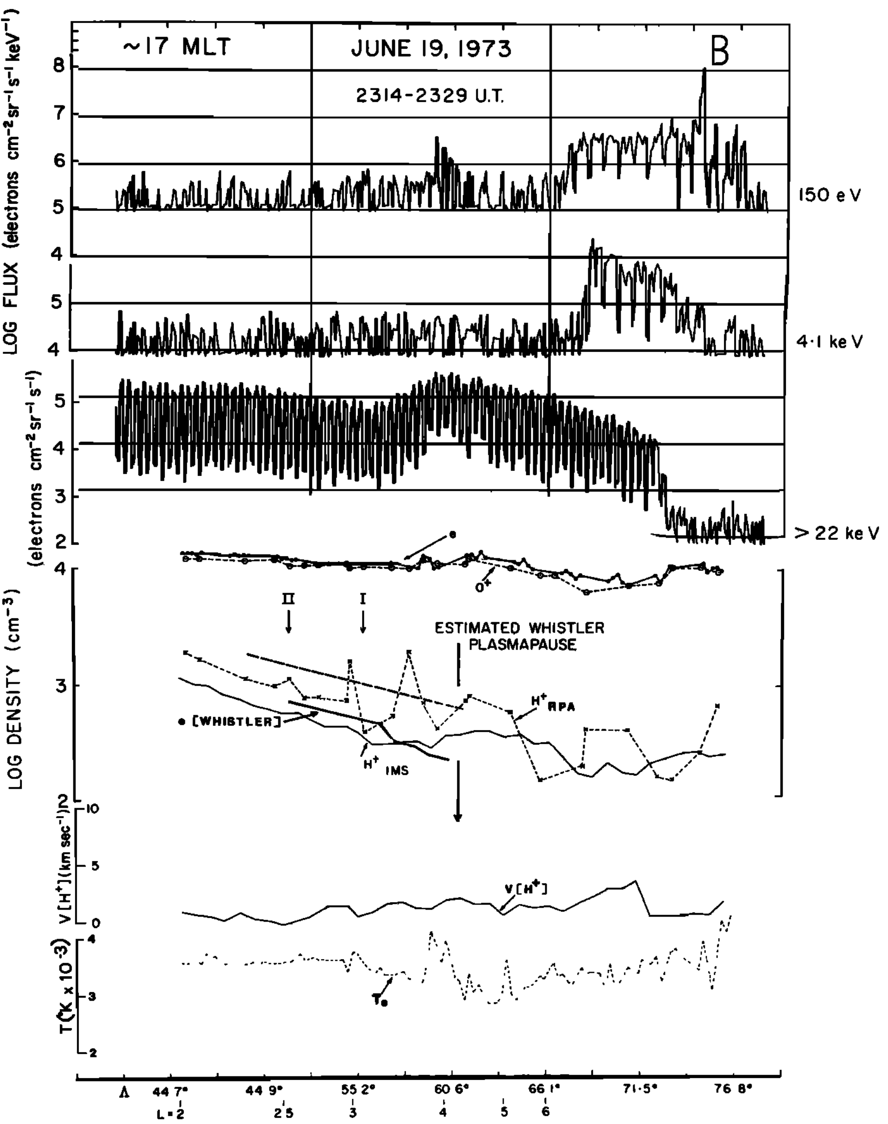

Fig. 3. Similar to Figure 2. Data presented are representative of dusk passes.

precipitating (isotropic) fluxes of plasma sheet electrons at 1400 km is shown in the upper section of Figure 1, along with the position of the equatorial plasmapause as described previously. Whereas the inner edge of the plasma sheet precipitation shows an extreme diurnal variation in latitude, approaching the plasmapause position at dawn and receding to high latitudes at dusk, trapped electrons of identifiable plasma sheet origin extend inward to the vicinity of the plasmapause at both dawn and dusk. Since trapped electrons mirroring above the satellite are not detected, this boundary depends on satellite altitude, instrumental sensitivity, and our determination of the noise threshold of the data. We have placed this boundary at the inner edge of the most equatorward region of the identifiable plasma sheet particles. The boundary of the trapped fluxes, defined in this way, provides a good indicator of the plasmapause position throughout the time interval of this study. The two positions of this boundary on June 21 and 22 (cf. Figure 1) correspond to two distinct regions of trapped electron mirror height lowering. Park and Seely [1976] have presented whistler evidence for a detached plasma (or plasma tail) outside L ∿ 4 at that time.

Data acquired during individual passes near dawn (∿05 MLT) and dusk (∿17 MLT) are presented in Figures 2 and 3. These data are representative of the observations made during the ∿20 passes through the sunlit northern hemisphere summer ionosphere which have been included in this study. Electron fluxes at three representative energies (energetic particle detector) are presented in the upper portion of the figures. A complete pitch angle scan, 180°-0°-180°, is obtained every 18 s. In regions of electron precipitation the downcoming loss cone, $\alpha \lesssim 45°$, is nearly filled, resulting in only one distinct flux minimum each spin period. Trapped fluxes, mirroring above the atmospheric loss region, exhibit flux minima at both 0° and 180°.

The lower portion of these figures presents ionospheric parameters at the 1400-km satellite altitude and the equatorial electron density profile e (whistler), obtained at the time and longitude of the satellite pass. The dashed curve above the whistler profile is the equilibrium (full flux tube) density profile determined during quiet days earlier in the month. Ionospheric parameters presented include the total electron density and electron temperature from a cylindrical electrostatic probe, O^+ and H^+ densities from a retarding potential analyzer, and H^+ density and upward streaming velocity from an ion mass spectrometer.

During dawn passes (cf. Figure 2), the H^+ density begins to decrease, and O^+ becomes the dominant ion at boundary II. H^+ density attains its trough value, $\sim 10^2$ cm^{-3}, and there is a minimum in total density at boundary I, some 5° equatorward of the field line through the equatorial plasmapause. The upstreaming H^+ velocity peaks equatorward of the equatorial plasmapause and somewhat poleward of boundary I. No abrupt change in light ion density or H^+ flow rate is apparent at the equatorial plasmapause latitude. T_e exhibits a broad maximum in the region of rapidly decreasing light ion density. Precipitating plasma sheet electron fluxes extend inward to the equatorial plasmapause field line (cf. cutoff of isotropic 150-eV electrons at $\Lambda \sim 58°$), while anisotropic fluxes are observed several degrees inside that position (4.1-keV electrons at $\Lambda \sim 53°$). The most clear-cut and repeatable ionospheric feature near the dawn plasmapause is the LIT equatorward boundary, and that lies some 2°-5° equatorward of the plasmapause (cf. Figure 1).

If the LIT is formed by upward plasma flow into unfilled flux tubes, one would expect the equatorial density to reach the saturation level (dashed curve) on the boundary II field line. The whistler data of Figure 2 do not show this, due to lack of data at low L values. This relationship needs to be further investigated in future studies.

At dusk (cf. Figure 3), O^+ is the dominant ion at 1400 km at all latitudes. There is little evidence of a total density mid-latitude trough, and the sharp decrease in H^+ density which marks the equatorward edge of the LIT at dawn is largely absent. Accordingly, determination of trough boundaries I and II is somewhat arbitrary. Their positions on the pass shown in Figure 3 are somewhat less well defined than on the majority of dusk passes included in this study. Upward H^+ flow is small and quite uniform over subauroral latitudes, with no discernible increase near the plasmapause or LIT equatorward edge. The dusk whistler plasmapause is at higher latitude than that seen at dawn and, in the case shown in Figure 3, has been estimated from incomplete whistler coverage. The low-latitude boundary of the LIT does not bulge poleward at dusk as does the plasmapause in the equatorial plane (cf. Figure 1) and is observed $\sim$ 5°-10° equatorward of the plasmapause field line. There is a distinct increase in T_e 1°-2° equatorward of the equatorial plasmapause field line. This is the most pronounced mid-latitude ionospheric feature observed near the dusk plasmapause during this study.

Precipitation of plasma sheet electrons is clearly confined to auroral latitudes ($\Lambda \gtrsim 65°$), well poleward of the plasmapause field line at dusk (cf. Figure 3). Figure 1 shows the large diurnal variation in the low-latitude extent of this precipitation which produces the visible diffuse aurora [Lui and Anger, 1973; Lui et al., 1977]. Equatorward of the region of auroral precipitation at dusk a background count rate is observed until the vicinity of the equatorial plasmapause is reached. Here fluxes of these particles are again observed (cf. Figure 3).

These data suggest that trapped plasma sheet electrons, with mirror heights normally above 1400 km, populate field lines outside the equatorial plasmapause at both dusk and dawn and that a lowering of their mirror heights (i.e., precipitation) occurs near the position of the equatorial plasmapause. Distinct auroral arcs, detached from the main auroral oval, are frequently observed at subauroral latitudes in the dusk sector by the auroral scanning photometer on Isis 2 (D. D. Wallis, unpublished data, 1976). These arcs are produced by electrons with plasma sheet characteristics and may be a signature of wave-particle interactions involving a trapped plasma sheet population near the plasmapause.

Discussion

This and previous studies reveal an array of mid-latitude ionospheric features in the vicinity of the equatorial plasmapause field line. In a general sense the latitude of these features responds to geomagnetic activity in a way similar to that of the equatorial plasmapause. Their precise locations, however, do not identify the plasmapause field line in a clear-cut fashion but appear to be determined by the dynamic processes of plasma exchange between the ionosphere and plasmasphere. In contrast, energetic particles, which are constrained to travel nearly along a magnetic field line, accurately delineate by their appearance at low altitude the field lines on which they are perturbed by processes in the equatorial plane.

Under moderately disturbed conditions, whistler analysis and satellite observations near the equatorial plane find a well-defined plasmapause whose position varies markedly with local time. In the topside ionosphere a region of spatial gradient in thermal plasma density can also be observed, but its position is influenced or even masked completely by the effects of local plasma composition and transport. Energetic particles, which accurately map field lines between high and low altitudes, indicate that the equatorial plasmapause often lies considerably poleward of the density gradients associated with the ionospheric troughs.

The light ion and electron density troughs are associated with flux tubes which are not in diffusive equilibrium. Banks et al., [1971], who have discussed flux tube refilling by supersonic and subsonic plasma flow, suggest that a shock front travels earthward from high altitudes during the refilling process. Due to a longer travel time at higher latitudes the shock front cuts across L shells as it descends. In the subsonic flow region behind the shock the density may be a factor of ~ 4 larger than that ahead of the shock. The density gradient at the shock front has the appearance of a plasmapause whose invariant latitude decreases with decreasing altitude [cf. Banks et al., 1971, Figure 7]. It has not been established that the equatorward edge of the low-altitude ionospheric troughs is smoothly connected to the equatorial plasmapause by a shock front or other feature which cuts across L shells, but observations of a distinct density gradient at altitudes above the O^+-H^+ transition altitude and at invariant latitudes less than the latitude of the equatorial plasmapause [e.g., Brace and Theis, 1974] strongly suggest that the outer surface of the more dense plasmasphere, the plasmapause, is not L shell aligned.

Conclusions

The specific results of this intercomparison of the location of the equatorial plasmapause with a variety of mid-latitude ionospheric features at dawn and dusk suggest the following conclusions.

1. The low-altitude total density and light ion troughs begin significantly equatorward of the equatorial plasmapause field line.
2. The ionospheric troughs are associated with flux tubes on which the equatorial density is below its equilibrium value and which are thus refilling from below. The troughs are not clear plasmapause signatures.
3. Plasma sheet electrons, with mirror heights as low as 1400 km, are observed on flux tubes outside the equatorial plasmapause at both dawn and dusk. Their low-latitude extent at this altitude can be used as a signature of plasmapause position.

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