Altitude variation of the plasmapause signature in the main ionospheric trough

Joseph M. Grebowsky [a,*], Robert F. Benson [b], Phillip A. Webb [c], Vladimir Truhlik [d], Dieter Bilitza [e]

[a] Planetary Magnetospheres Laboratory, Code 695, Solar System Exploration Division, Goddard Space Flight Center, Greenbelt, MD 20771, USA
[b] Geospace Physics Laboratory, Code 673, Heliophysics Science Division, Goddard Space Flight Center, Greenbelt, MD 20771, USA
[c] GEST/UMBC/Space Weather Laboratory, Code 674, Heliophysics Science Division, Goddard Space Flight Center, Greenbelt, MD 20771 USA
[d] Institute of Atmospheric Physics, Academy of Science Czech Republic, Praha, Czech Republic
[e] GMU/Heliospheric Physics Laboratory, Code 672, Heliophysics Science Division, Goddard Space Flight Center, Greenbelt, MD 20771, USA

ARTICLE INFO

ABSTRACT

The projection of the plasmapause magnetic-field lines to low altitudes, where the light-ion chemistry is dominated by O^+, tends to occur near the minimum electron density in the main (midlatitude) electron density trough at night. With increasing altitude in the trough, where H^+ emerges as the dominant ion on the low-latitude boundary, we have found cases where the plasmapause field lines are located on the sharp low-latitude side of the trough as expected if this topside ionosphere H^+ distribution varies in step with the plasmapause gradient in the distant plasmasphere. These conclusions are based on near-equatorial crossings of the plasmapause (corresponding to the steep gradient in the dominant species H^+) by the Explorer-45 satellite as determined from electric-field measurements by Maynard and Cauffman in the early 1970s and ISIS-2 ionospheric topside-sounder measurements. The former data have now been converted to digital form and made available at http://nssdcftp.gsfc.nasa.gov. The latter provide samples of nearly coincident observations of iono-spheric main trough crossings near the same magnetic-field lines of the Explorer 45-determined equatorial plasmapause. The ISIS-2 vertical electron density profiles are used to infer where the F-region transitions from an O^+ to a H^+ dominated plasma through the main trough boundaries.

Published by Elsevier Ltd.

1. Introduction

High-altitude, outer-plasmaspheric low-energy plasma structures, especially of the characteristically dominant H^+ ions, couple down magnetic-field lines into the ionosphere, and play a role in midlatitude ionospheric morphology. Conversely, the outer plasmaspheric structures, consisting of ions produced at low altitudes, respond to changes in the ionosphere. Knowledge of the relationships between the two regions is needed to understand how the ionosphere impacts the outer plasmasphere and visa versa. Understanding the topside ionospheric structural relationship to the location of the outer boundary of the plasmasphere, i.e., the plasmapause, near the equator would provide a tool for applying the more prevalent ionospheric measurements to (1) complement magnetospheric missions, (2) study the evolution of the plasmapause, and (3) investigate the ring current dynamics as well as the outer radiation belt processes, which depend on the location of the plasmapause. Understanding the large-scale electron density (N_e) gradients in the middle and low-latitude ionosphere is also important to technological systems because of the large impact they have on navigation, communication, and radar observations. In order to obtain such an understanding, it is important to characterize the latitude and altitude dependence of large midlatitude ionospheric electron and ion gradients associated with outer plasmaspheric structures.

Our approach here is to use data from older satellite missions to provide characteristic examples comparing middle latitude topside ionospheric N_e and ion-composition profiles to nearly coincident magnetospheric E-field determinations of the plasmapause near the same magnetic-field lines. The topside ionospheric vertical electron density profiles $N_e(h)$, which often correspond to magnetic-field-aligned profiles at mid-to-high latitudes, are used to determine O^+/H^+ transition heights and to relate ionospheric main trough structures at different altitudes and different ion composition to plasmapause locations measured by magnetospheric satellites. In the topside ionosphere when H^+ is detectable as a minor or major ion, it also exhibits trough like structure called the light-ion trough (Taylor, 1972). Since the equatorial plasmapause is dominated by H^+, it was expected to be closely coupled to the low-latitude wall of the middle latitude light-ion trough in the ionosphere. In the region of the topside F2 layer, where O^+ is dominant, the H^+ distribution is coupled chemically and

* Corresponding author. Tel.: +1 3012866853; fax: +1 3012861177.
E-mail address: joseph.m.grebowsky@nasa.gov (J.M. Grebowsky).

dynamically to O^+. Because there are ionospheric plasma temperature enhancements in the ionosphere on the magnetic-field lines threading the outer plasmasphere (Brace and Theis, 1974; Titheridge, 1976), and because the plasma convection pattern morphology that controls the F2 layer distribution (e.g., Knudsen, 1974; Mendillo and Chacko, 1977) also reflects the dynamics leading to the plasmapause (e.g., Nishida, 1966), the position of the main N_e trough where O^+ is dominant would be expected to correlate with the plasmapause field lines but the density gradient on the low-latitude side of the trough would not be expected to directly map along the magnetic field to the equatorial plasmapause.

Hence differences might be expected between the correlation of the low-latitude boundary of the N_e trough near the F2 peak and the N_e trough in the topside ionosphere at higher altitudes after the transition to an H^+ dominated plasma, (i.e., to the protonosphere). In this regard, it is important to recall the local time variation of the location of troughs in the F-region electron density distribution where O^+ is the dominant ion. Under sunlit dayside conditions the trough location moves to polar-cap latitudes that are poleward of the ionospheric projection of magnetic-field lines associated with the plasmapause. The midlatitude trough is primarily a nighttime phenomenon (e.g., see review by Moffett and Quegan, 1983). In the daytime, photoionization at middle latitudes and magnetic-field-aligned diffusion with time scales of the order of hours dominates the latitudinal distribution of the electron density in the F-region. A close magnetic-field-aligned coupling of the O^+ dominated F-region to the depleted region outside of the plasmapause near the equatorial plane is not anticipated under such conditions. In the absence of photoionization at night, however, ionospheric chemistry and horizontal plasma convection compete with the field-aligned ion dynamics associated with the transition from the dense equatorial plasmasphere to the depleted region outside in determining the relationship of ionospheric and high-altitude plasmapause density gradients. Nightside topside ionosphere observations therefore are more appropriate for investigating plasmapause signatures in the ionosphere. This is particularly true for studying the transition from an O^+ dominated plasma to light-ion domination. Since H^+ is strongly chemically coupled to O^+ at low altitudes, the light-ion trough boundary is anticipated to better relate to the plasmapause at higher altitudes (e.g., see theoretical modeling by Quegan et al., 1982) and the transition to an H^+ plasma can best be measured from topside-sounder satellites at night. The goal of this paper is to examine plasmapause—main N_e trough correlations at night with measurements of the ionospheric changes with increasing altitude from an O^+ dominated medium to one dominated by light ions (assumed to be H^+).

The ionospheric main trough low-latitude wall gradient has been previously shown to be related at times to nearly coincidently measured plasmapause magnetic-field lines (e.g., Grebowsky et al., 1976). Even at locations in the topside ionosphere where an electron density trough was not present, and O^+ was the dominant species, a light-ion trough was detectable in the minor species H^+ whose low-latitude wall was deduced to be a signature of the plasmapause (Taylor and Walsh, 1972). Although statistically the light-ion trough low-latitude boundary tracks the plasmapause field lines better than the main N_e boundary (e.g., see the review by Muldrew (1983)) there were differences observed between the boundary N_e gradient locations and the plasmapause magnetic-field line projections into the ionosphere (Foster et al., 1978; Grebowsky et al., 1978). These discrepancies may have been due, in small part, to magnetic field models that did not include the effects of magnetic-field inflation during active periods in the field-line tracing. In both

of these studies there was a consistent trend for the plasmapause L coordinate to be greater than the trough boundary L coordinate. A recent study by Anderson et al. (2008), comparing DMSP topside H^+ latitudinal profiles and IMAGE EUV plasmapause images, shows the same trend. The separation between the light-ion trough wall and the plasmapause field lines in the early papers described above was attributed to the refilling (e.g., Titheridge, 1976) of outer plasmaspheric flux tubes from below, depleting the ionospheric H^+ on these field lines.

The N_e trough boundary in the topside ionosphere, based on in-situ measurements, was found in case studies to be even further uncorrelated with the magnetic-field lines threading the light-ion gradient defining the plasmapause (Grebowsky et al., 1976). Yizengaw and Moldwin (2005) made a survey of coincident observations of midlatitude topside ionosphere $N_e(h)$ profiles, from a tomographical analysis of global positioning system (GPS) total electron content (TEC) data, and plasmapause field lines as determined from EUV He^+ plasmaspheric images from the IMAGE satellite. They found that the plasmapause field line consistently fell within the minimum region of the main N_e trough as Mendillo and Chacko (1977) deduced from an early study of ISIS 2 topside-sounder ionization altitude profiles. The relationship of the density gradient at the plasmapause to the ionospheric main trough structure, however, is not clear.

The above studies (with the exception of Mendillo and Chacko, 1977) treated the correlations between the plasmapause and ionospheric troughs independently of a measure of the low-altitude composition and its change with altitude. In many of the case studies, and even in the statistical cases, H^+ was often a minor species and was therefore chemically and dynamically under the control of the ionospheric O^+ distribution. The intent of the current paper is to present examples showing how the ion-composition change with altitude in the topside ionosphere can change the correlation between the main ionospheric N_e trough and the H^+ magnetospheric plasmapause. We place particular emphasis on ionospheric topside-sounder-derived $N_e(h)$ profiles because they are produced in a matter of seconds several times per minute along the satellite path. Thus the portion of the orbit-plane N_e contour through the trough region is produced in a few minutes enabling detailed investigations of dynamics and structures that tomographical techniques might miss.

2. Observations

The topside-sounder data used for this study were obtained from the nssdcftp.gsfc.nasa.gov online archive that is maintained by the Space Physics Data Facility (SPDF) and National Space Science Data Center (NSSDC). The topside sounding $N_e(h)$ profiles provide measurements of the middle latitude structures in the transition from a chemical to a diffusion-transport region. There are altitude variations in the ionospheric latitudinal N_e gradients and their relation to the plasmapause. This dependence was recently shown in a comparison of ionospheric tomographic imaging and IMAGE/EUV plasmapause determinations by Yizengaw and Moldwin (2005). The ionospheric topside $N_e(h)$ profiles deduced from Alouette-1 and -2 and ISIS-1 and -2 35-mm-film topside ionograms, and those automatically determined using the Topside Ionogram Scaler with True height (TOPIST) algorithm (Bilitza et al., 2004; Huang et al., 2002) from ISIS-2 digital topside ionograms, available from the NSSDC are shown in Fig. 1a. Digital Alouette/ISIS ionograms are being produced by an ongoing data restoration effort and the TOPIST ISIS-2 profiles were obtained from a subset of these digital Alouette-2, ISIS-1, and ISIS-2 topside ionograms (Benson, 1996; Benson and Bilitza, 2008; Bilitza et al., 2003) as indicated by
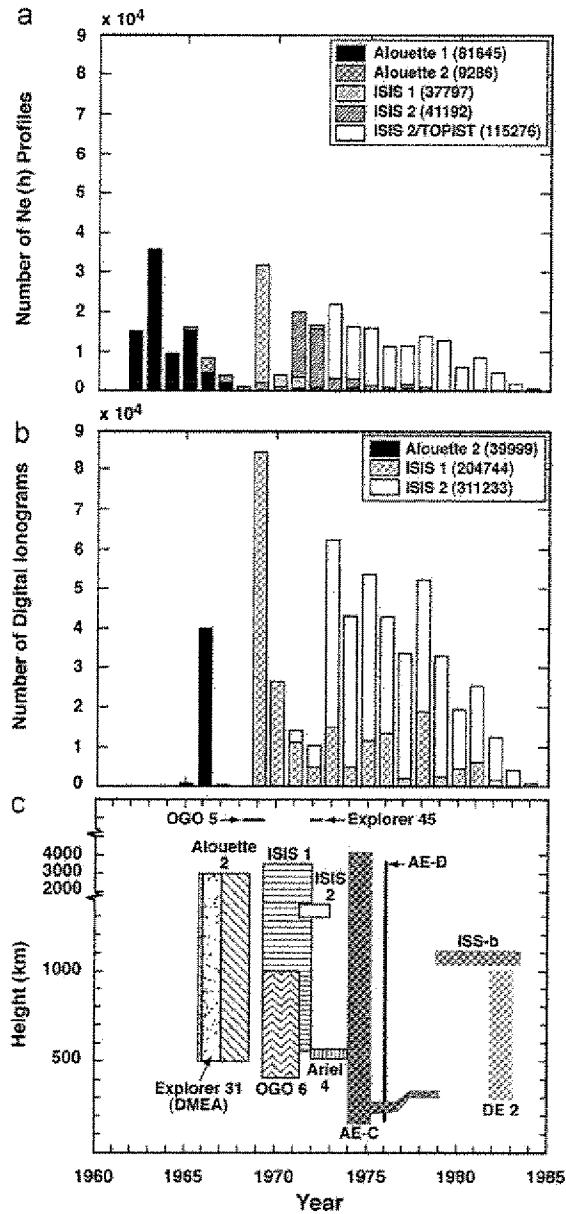
Fig. 1. Distribution of topside-sounder data sets and in-situ ionosphere measurements available online from NSSDC: (a) topside $N_e(h)$ profiles, (b) topside digital ionograms, (c) in-situ measurements. (Notes: an OGO-5 data gap from 4/24/68 to 6/12/68 is not shown; also, ISIS-2 often operated in a mode where active and passive ionograms were interleaved so it was not possible to obtain TOPIST $N_e(h)$ profiles from all of the digital ionograms).

Explorer-45 satellites are now available for conjunction studies on SSCweb.gsfc.nasa.gov making it possible to characterize the magnetic latitude and altitude dependence of large midlatitude ionospheric N_e and ion density (N_i) gradients associated with plasmapause magnetic flux tubes. Here we report the first results of comparing some of these data sets.

Since the equatorial plasmasphere and its structures are typically dominated by H^+ ions, whereas the topside ionosphere transitions from O^+ dominance near the F-region peak to light-ion dominance at higher altitudes, the relationship between the topside ionosphere latitudinal structures in the N_e and the outer plasmasphere radial structures are ion species dependent as shown by Foster et al. (1978), Grebowsky et al. (1978), and more recently by Anderson et al. (2008). Hence the ionospheric ion composition is valuable, if not necessary, for understanding the relationship between the ionospheric trough low-latitude density gradient and the plasmapause. The ionospheric composition can be estimated from a consideration of the N_e altitude variation from topside sounding $N_e(h)$ profiles, GPS derived profiles, and/or in-situ ion-composition measurements. In this paper we use topside-sounder measurements, which provided good spatial resolution and an ability to compare the observations with near-equatorial plane observations of the plasmapause transition in the total ion density corresponding to essentially H^+ ions.

Fig. 2 shows an example where topside ionospheric $N_e(h)$ profiles were used to produce constant-altitude orbit-plane contours and to determine O^+/H^+ transition heights. The main N_e trough structure variation with altitude along the magnetic field shown in Fig. 2 was derived from topside-sounder $N_e(h)$ profiles from the ISIS-2 satellite in a polar circular orbit at 1400 km. This example corresponds to one of the magnetic storm events originally investigated by the ISIS-2 experimenters (Murphree, 1980). Here the data are presented in the form of constant-altitude profiles (each simulating the results of an in-situ probe on a satellite in a circular polar orbit) with the approximate plasmapause location, based on the Carpenter and Anderson (1992) statistical model for the local time and magnetic activity conditions corresponding to the ISIS measurements, superimposed as a vertical dashed line labeled PP. One sees that the midlatitude N_e depression deepens with increasing altitude. The average modeled plasmapause location falls on the transition from the low-latitude high-density region into the trough. Although one cannot be certain that the modeled plasmapause location accurately represents conditions measured by ISIS, the ionosphere does have a plasmapause-like decrease at the modeled location. The low-latitude trough boundary slope becomes steeper, however, with increasing altitude (as it must if it is to approach the typical sharp plasmapause transition seen at large radial distances near the equator). At lower altitudes the trough N_e fills in, and the plasmapause field line begins to slide into the trough density minimum region. This behavior indicates that the plasmapause-ionospheric trough coupling weakens with decreasing altitude where the light ions become chemically depleted and local ionospheric chemistry and convection of plasma from other regions dominate over the dynamical coupling of the light ions along the magnetic-field lines to the inner magnetospheric thermal plasma population.

The topside-sounder $N_e(h)$ profiles, used to produce the constant-altitude profiles of Fig. 2, can also be used to produce vertical ion profiles. That there is a significant ion-composition change associated with the trough gradient region and the plasmapause region is readily seen by using such profiles at locations equatorward of the trough wall and in the trough minimum. Vertical H^+ and O^+ profiles were derived from the $N_e(h)$ profiles of Fig. 2 assuming diffusive equilibrium, using the
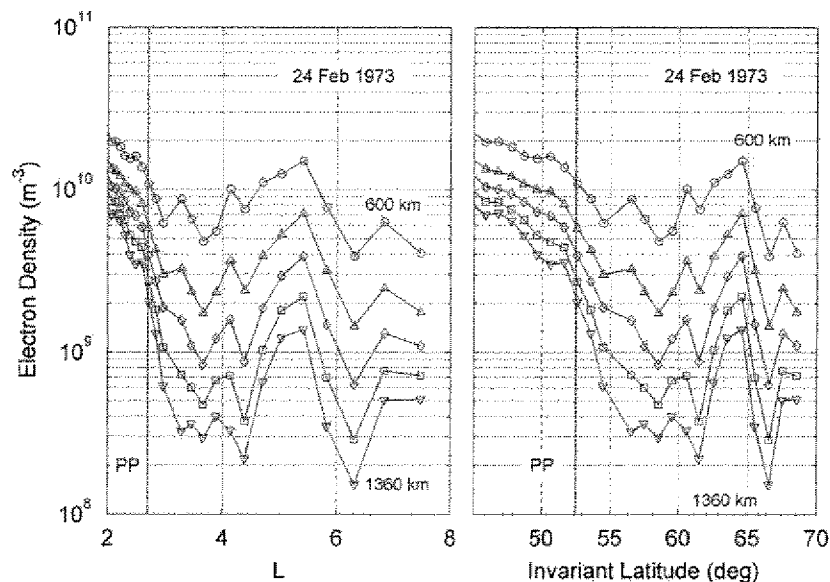
comparing Fig. 1a with Fig. 1b. (There are plans to apply the TOPIST software to the Alouette-2 and ISIS-1 digital topside ionograms.) Searching for ion-composition measurements and plasmapause crossing information during the Alouette/ISIS mission time period we have located older not yet archived ion mass spectrometer measurements from OGO-5 and Explorer-45 recordings of plasmapause crossings (see Fig. 1c).

Unfortunately, the Explore 45 data were never archived in the NSSDC. Fortunately, a browned hard copy (compiled by N. Maynard) of most of the plasmapause crossing locations was found. These old data sets were scanned, digitized and merged with satellite ephemeris data and are now available from nssdcftp.gsfc.nasa.gov. The orbital data for the Alouette, ISIS and

Fig. 2. Example of altitude changes in the midlatitude N_e trough structure determined from ISIS-2 topside-sounder data from 0744:11–0754:42 UT on 24 February 1973 during a pass near 0200 LMT as a function of the L coordinate (at the position of ISIS 2), typical of equatorial plasmasphere measurements, (left) and the usual latitude coordinate used for ionospheric measurements (right). PP denotes the statistical plasmapause location (Carpenter and Anderson, 1992) for the Kp~5 conditions of the ISIS-2 pass.

approach described by Titheridge (1976) and Webb and Essex (2001), and the results were presented by Webb et al. (2006). Within the trough minimum, the light-ion H^+ was found to be significant only within a few hundred km of the spacecraft altitude whereas it was observed to be the dominant species at low latitudes. Hence at high altitudes, above ~1000 km at night, the latitudinal profile of N_e through the trough wall reflects the light-ion H^+ behavior and is more strongly coupled to the equatorial plasmapause; this coupling decreases with decreasing altitude. Using the ISIS-2 topside-sounder $N_e(h)$ profiles, used to make orbit-plane contours such as those shown in Fig. 2, one can determine the latitudinal variation of the O^+/H^+ transition altitude, which corresponds to the transition from the protonosphere to the O^+ dominant ionosphere, as was done for the ISIS 2 example of Fig. 2 in Webb et al. (2006). This transition is seen in N_e altitude profiles as a rapid increase in scale height with increasing height.

3. Coincident sounder and plasmapause measurements

The example above shows the value of topside sounding data in providing a useful two-dimensional snapshot of how the ion composition in the midlatitude ionosphere tracks or does not track the outer plasmasphere variations in N_e (predominantly an H^+ ion population). That sample used a modeled average location of the plasmapause, however, which need not reflect the state at the time of the ISIS pass. Hence there is a need for data sets that contain nearly coincident passages of a topside sounding satellite through nearly the same magnetic flux tubes as a satellite passing through the plasmapause. Our approach is to locate outer plasmasphere measurements overlapping in time with topside-sounder measurements. For that purpose we looked at the availability of OGO-5 and Explorer-45 data that overlapped available topside-sounder data (see Fig. 1c). In this paper we emphasize data from Explorer 45.

Maynard and Cauffman (1973) and Maynard and Grebowsky (1977) discussed the use of the saturation to non-saturation of the

electric-field measurements on Explorer 45 (an eccentric, equatorial orbiting satellite with ~5.2 R_E apogee) as an indicator of plasmapause transitions. The crossings were determined when the electric-field detector went into saturation outbound or out of saturation inbound. The most probable N_e level corresponding to this saturation was determined to be $60\,cm^{-3}$ by Morgan and Maynard (1976). The database also records the sharpness of the transition into saturation, providing a measure of the plasmapause gradient. Although the measurements correspond to one density, it also reflects a typical density on the plasmapause density gradient. Hence it is considered to be a measure of the plasmapause gradient rather than the termination of the gradient.

Grebowsky et al. (1976) found near-coincident passes of ISIS 2 and Ariel 4 through the vicinity of Explorer-45-determined plasmapause magnetic-field line (Fig. 1c shows the overlap in these data sets). Using in-situ N_e measurements from the ionospheric satellites they could not find a location in the midlatitude N_e trough that appeared to consistently relate to the plasmapause. Fig. 3 presents an unpublished example from their database. It depicts the N_e measured during a near field-aligned conjunction of ISIS 2 (1400 km), Ariel 4 (550 km), and an Explorer-45-determined plasmapause near the same local time (within one hour of the low altitude measurements) at a slightly later universal time (two hours later than Ariel and within one hour of Isis 2). Although the N_e structures are similar at both altitudes there are differences in the L profiles at low latitudes and through the trough structure. The plasmapause seems to be associated with the boundary of the isolated N_e peaks observed by both ionospheric satellites. Perhaps these features are ionospheric signatures of a plasma plume in the plasmasphere, but it could also just be a disturbance in the trough that obscures the true outer plasmasphere behavior, e.g., a localized enhanced temperature producing a scale-height increase in the topside ionosphere. Knowledge of where H^+ or O^+ is dominant would enable this uncertainty to be resolved. Variations in the density of ionospheric light ions are expected to best parallel N_e variations in the equatorial plasmapause.
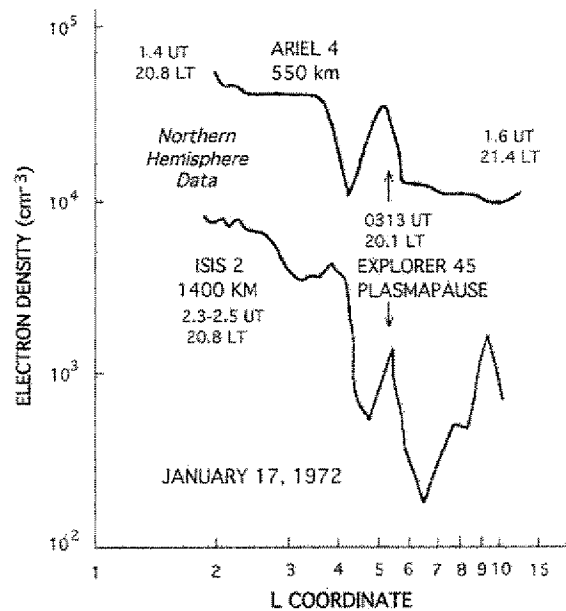
Fig. 3. In-situ N_e measurements from ISIS 2 and Ariel 4 during nearly coincident passes at two different altitudes through a midlatitude trough, with imbedded patches at each altitude, in the vicinity of an Explore 45 determined plasmapause field line based on a dipole magnetic field.

Since the plasmapause is a gradient in the light-ion density, one anticipates a light-ion gradient in the ionosphere across the same magnetic-field lines. Foster et al. (1978) and later Grebowsky et al. (1978), using near-coincident equatorial plasmapause and ionospheric ISIS-2 ion-composition measurements, showed that although the light-ion trough low-latitude boundary was more consistent with the plasmapause than the main trough O^+ boundary there was not always a one-to-one agreement observed in the magnetic-field lines on which each occurred. Recent results (Johnston et al., 2007), however, indicate that there is a good correlation at the DMSP 840-km-altitude measurement of the light-ion trough wall with the IMAGE/EUV deduced equatorial plasmapause field line. Thus there is still a need to further explore, from different perspectives, the relation of structures in the midlatitude ionosphere gradients and the plasmapause.

Topside-sounder profiles provide an ideal tool to determine how the trough and its composition vary with altitude and relate to the plasmapause field lines. Unfortunately there were no topside ionosonde $N_e(h)$ profiles available for the time shown in Fig. 3. Figs. 4 and 5, however, present examples where topside ISIS-2 hand-scaled $N_e(h)$ profiles were available from the nssdcftp site for orbits nearly coincident with Explorer-45 determined plasmapause magnetic-field lines. These topside ionospheric profiles are cataloged as vertical profiles, i.e., $N_e(h)$ profiles, but the alignment of the orbit-plane constant-altitude N_e contours in these figures (as a function of the L value corresponding to the satellite altitude using the IGRF model) suggest that they correspond to field-aligned contours. This situation is common at high latitudes where vertical and field-aligned propagation follows almost the same path (Hagg et al., 1969). The L values in the N. Maynard listing of Explorer-45 plasmapause crossings did not include corrections for magnetic activity. The PP values given in Figs. 4 and 5 were based on these values reduced by 0.25 L from calculations using the T96 model (Tsyganenko, 1995; Tsyganenko and Stern, 1996), appropriate for the disturbed conditions for these two events as indicated in Fig. 6. In each of the examples

presented in Figs. 4 and 5, the Explorer 45-determined plasmapause field line is on the midlatitude ionospheric N_e trough wall at high altitudes, where H^+ is more prevalent, but with decreasing altitude it is located in the midst of the trough depression. These observations suggest that O^+ and ionospheric trough chemistry coupled with the plasma convection pattern at high latitude (e.g., Knudsen, 1974) is dominating over a straight forward coupling of protonospheric plasma from high altitudes to the topside ionosphere. This suggestion is supported by the variations of the O^+/H^+ transition heights along the ISIS-2 orbital tracks shown in Fig. 7 (as determined using the procedure described at the end of Section 2).

The change of the plasmapause-trough relation with ion composition is apparent by comparing Figs. 4 and 5 to the O^+/H^+ transition altitudes in Fig. 7. When O^+ is dominant (altitudes below about 1000 km on 17 December 1971 in Fig. 4 and below about 800 km on 18 December in Fig. 5) the plasmapause magnetic-field line falls within the minimum region of the N_e trough. On the other hand, the plasmapause field line moves onto the sloping low-latitude side of the trough above the O^+/H^+ transition altitude. This is the expectation if the high-altitude plasmapause light-ion density gradient maps directly along the field lines to the topside ionospheric light-ion distribution. This transition takes place at higher altitudes with the December 17 ISIS measurements (Fig. 4) than for the December 18 measurements (Fig. 5), commensurate with the computed altitude differences of the transition heights in Fig. 7.

4. Discussion

The relationships between the main ionospheric N_e trough and the ionospheric light-ion trough to the plasmapause have been studied for several decades but uncertainties remain. As discussed in the text, the main N_e trough is composed of O^+ ions at the F-region peak, but with increasing altitude the light ions (particularly H^+) become more dominant and eventually become the major species and should reflect a direct coupling to the outer plasmasphere and plasmapause transition particle population. The minimum region of the main trough in the O^+ dominated region, as seen by ISIS 2 topside sounding measurements, encompasses plasmapause magnetic-field lines identified by Explorer 45 locations of the equatorial plasmapause. This relationship is most likely due to the nature of the plasma convection pattern that determines the plasmapause configuration and also controls the ionospheric transport into the nightside midlatitude chemical sink, of ionization produced in the dayside and in the auroral regions. The morphology of the ionospheric trough, driven by chemical processes, neutral-wind ion drag, etc., is more complex than the plasmasphere–plasmapause-trough configuration in the magnetosphere. Indeed, successful modeling of the ionosphere N_e distribution near and slightly above the F-region peak density does not even require consideration of the light ions, the species that comprise the high-altitude plasmapause, but simply reflects local chemical processes (e.g., see the review by Sojka, 1989). At these low altitudes H and H^+ are in chemical equilibrium with the O and O^+, and H^+ will track the O^+ distribution and will not be strongly coupled to the plasmapause transition at high altitudes. In these examples it is apparent that there was negligible impact of high speed flux tube refilling in the outer plasmasphere on the H^+ concentration profiles in the ionosphere as had been deduced in earlier light-ion trough-plasmapause correlations.

The current study has expanded the data sets publically accessible to be applied to obtain a better understanding of the plasmapause-ionospheric trough relationships. In particular,
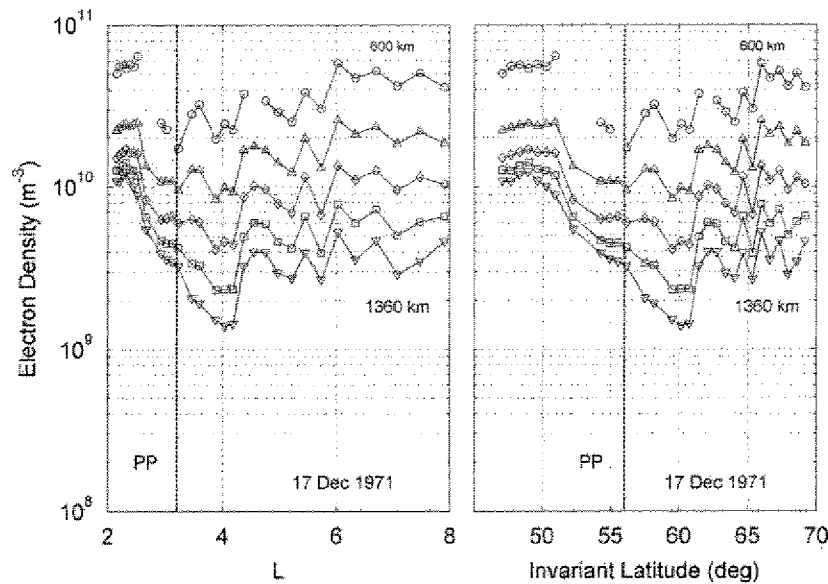
Fig. 4. Same as Fig. 2 except for 0531:31–0539:36 UT ISIS 2 data on 17 December 1971 (0535:05 UT; 2242 LMT near PP) and PP corresponds to the plasmapause field line as determined by Explorer-45 at 0613: 40 UT; 0012 LMT. The altitudes given on the contours are slightly low because the analysis assumed vertical propagation whereas the observations suggest that the propagation was along the magnetic-field direction. The corrections increase with decreasing altitudes (greater propagation distances). The corrections for the 600 km contour are about 3% and 10% at 70° and 55° invariant latitude, respectively.
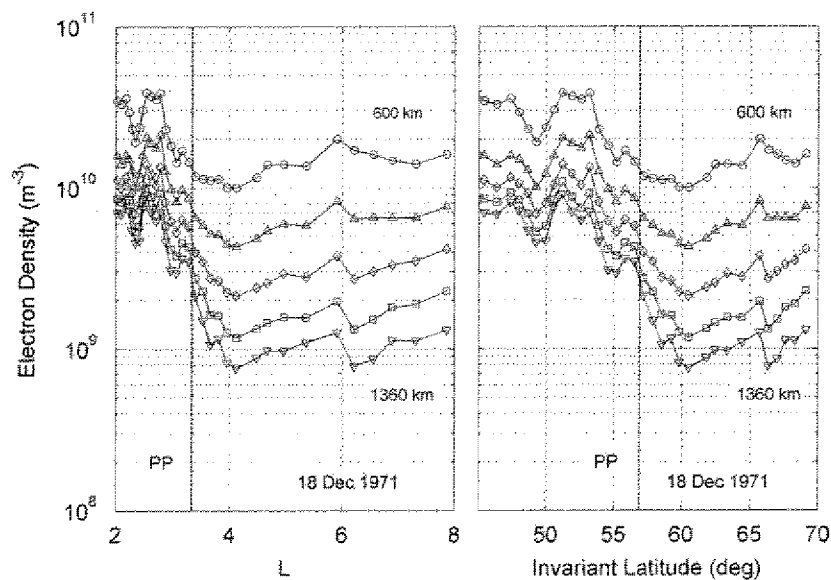

Fig. 5. Same as Fig. 4 except the ISIS 2 profiles correspond to 0608:44–0623:57 UT on 18 December 1971 (0612:07 UT; 2224 LMT near PP) and PP corresponds to the plasmapause field line crossed by Explorer-45 at 0526:20 UT; 0000 LMT.
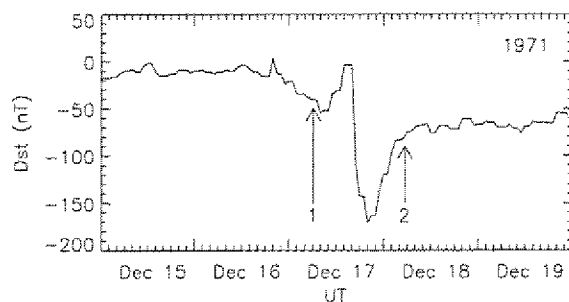

Fig. 6. Dst values for 15–19 December 1971. The PP times of Figs. 4 and 5 are identified by the arrows labeled 1 and 2, respectively.

equatorial plasmapause data have now been archived that overlap with ionospheric satellite measurements—including topside-sounder N_e(h) profiles. These data sets allow a comparison of trough boundaries with near-coincident plasmapause observations, a determination of how the trough wall location and gradient varies with altitude, and an understanding of the importance of H^+ relative to O^+ in the troughs. Thus they make it possible to determine the altitude at which the trough boundary mimics the magnetospheric plasmapause transition. As a first step in this direction ISIS 2 topside-sounder N_e(h) profiles were compared to near-time locations of plasmapause field lines as observed by Explorer 45 electric-field saturations. The two nighttime examples presented occurred during a period of magnetic disturbance and indicated that at low altitudes the
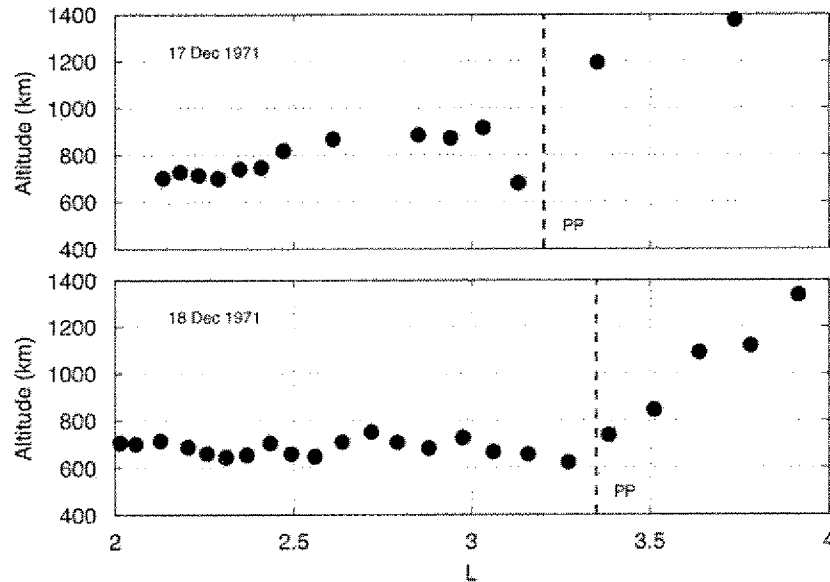
Fig. 7. O^+/H^+ transition heights along the ISIS-2 orbital tracks corresponding to the ISIS-2 topside-sounder data of Figs. 5 and 6, with the Explore 45 determined plasmapause field lines again designated by PP, in (a) and (b), respectively.

plasmapause field line falls within the minimum region of the electron density trough, whereas as the altitude increases, and H^+ becomes dominant, the plasmapause field line falls on the low-latitude trough wall.

Acknowledgment

This work is based on a NASA Living with A Star (LWS) supported research effort "Characterizing the composition of large midlatitude topside ionospheric and plasmaspheric gradients" led by R. Benson. It is part of a larger LWS Targeted Research and Technology (TR&T) research group effort focusing on "Global Distribution, Sources and Effects of Large Density Gradients" led by R. Heelis. V.T. was supported, in part, by grant A300420603 of the Grant Agency of the Academy of Sciences of the Czech Republic. We acknowledge the industrious work of Sahil S. Shah, a High School Senior supported by the National Space Club Scholars Program, for scanning and digitizing the Explorer 45 data. Helpful comments of the two referees are also acknowledged. The ISIS topside-sounder data were provided by NASA's Space Physics Data Facility and National Space Science Data Center.

References

Anderson, P.C., Johnston, W.R., Goldstein, J., 2008. Observations of the ionospheric projection of the plasmapause, paper presented at Space Weather Workshop, April 29–May 2, 2008, Boulder, Colorado.

Benson, R.F., 1996. Ionospheric investigations using digital Alouette/ISIS topside ionograms. In: Goodman, J.M. (Ed.), Ionospheric Effects Symposium, Technology for Communications International. BR Communications, Alexandria, Virginia, pp. 202–209.

Benson, R.F., Bilitza, D., 2008. New satellite mission with old data: The status of the ISIS data transformation and preservation project, paper presented at International Ionospheric Effects Symposium, Radio Propagation Services, Inc., Alexandria, Virginia.

Bilitza, D., Huang, X., Reinisch, B.W., Benson, R.F., Hills, H.K., Schar, W.B., 2004. Topside ionogram scaler with true height algorithm (TOPIST): automated processing of ISIS topside ionograms. Radio Sci. 39, RS1S27.

Bilitza, D., Reinisch, B., Benson, R., Grebowsky, J., Papitashvili, N., Huang, X., Schar, W., Hills, K., 2003. Online data base of satellite sounder and insitu measurements covering two solar cycles. Adv. Space Res. 31, 769–774.

Brace, L.H., Theis, R.F., 1974. The behavior of the plasmapause at midlatitudes: ISIS-1 Langmuir probe measurements. J. Geophys. Res. 79, 1871–1884.

Carpenter, D.L., Anderson, R.R., 1992. An ISEE/whistler model of equatorial electron density in the magnetosphere. J. Geophys. Res. 97, 1097–1108.

Foster, J.C., Park, C.G., Brace, L.H., Burrows, J.R., Hoffman, J.H., Maeir, E.J., Whitteker, J.H., 1978. Plasmapause signatures in the ionosphere and magnetosphere. J. Geophys. Res. 83, 1175–1182.

Grebowsky, J.M., Hoffman, J.H., Maynard, N.C., 1978. Ionospheric and magnetospheric "plasmapauses". Planet. Space Sci. 26, 651–660.

Grebowsky, J.M., Maynard, N.C., Tulunay, Y.K., Lanzerotti, L.J., 1976. Coincident observations of ionospheric troughs and the equatorial plasmapause. Planet. Space Sci. 24, 1177–1185.

Hagg, E.L., Hewens, E.J., Nelms, G.L., 1969. The interpretation of topside sounder ionograms. Proc. IEEE 57, 949–960.

Huang, X., Reinisch, B.W., Bilitza, D., Benson, R.F., 2002. Electron density profiles of the topside ionosphere. Ann. Geophys. 45, 125–130.

Johnston, W.R., Anderson, P.C., Goldstein, J., Kanekal, S.G., O'Brien, T.P., 2007. The role of the plasmasphere in radiation belt particle energization and loss, paper presented at AGU Joint Assembly, 22–25 May 2007, Acapulco, Mexico.

Knudsen, W.C., 1974. Magnetospheric convection and the high latitude F2 ionosphere. J. Geophys. Res. 79, 1046–1055.

Maynard, N.C., Cauffman, D.P., 1973. Double floating probe measurements on S3–A. J. Geophys. Res. 78, 4745–4750.

Maynard, N.C., Grebowsky, J.M., 1977. The plasmapause revisited. J. Geophys. Res. 82, 1591–1600.

Mendillo, M., Chacko, C.C., 1977. The baselevel ionospheric trough. J. Geophys. Res. 82, 5129–5137.

Moffett, R.J., Quegan, S., 1983. The mid-latitude trough in the electron concentration of the ionospheric F-layer: a review of observations and modeling. J. Atmos. Terr. Phys. 45, 315–343.

Morgan, M.G., Maynard, N.C., 1976. Evidence of dayside plasmaspheric structure through comparisons of ground-based whistler data and Explorer 45 plasmapause data. J. Geophys. Res. 81, 3992–3998.

Muldrew, D.B., 1983. Alouette-ISIS radio wave studies of the cleft, the auroral zone, and the main trough and of their associated irregularities. Radio Sci. 18, 1140–1150.

Murphree, J.S., 1980. Coordinated ionospheric and magnetospheric observations from the ISIS 2 satellite by the ISIS 2 experimenters: Volume 1: Optical auroral images and related direct measurements, National Space Science Data Center World Data Center A for Rockets and Satellites NSSDC/WDC-A-R&S Report no. 80-03, Greenbelt, Maryland.

Nishida, A., 1966. Formation of plasmapause, or magnetospheric plasma knee, by the combined action of magnetospheric convection and plasma escape from the tail. J. Geophys. Res. 71, 5669–5679.

Quegan, S., Bailey, G.J., Moffett, R.J., Heelis, R.A., Fuller-Rowell, T.J., Rees, D., Spiro, R.W., 1982. A theoretical study of the distribution of ionization in the high-latitude ionosphere and the plasmasphere: first results on the mid-latitude trough and the light-ion trough. J. Atmos. Terr. Phys. 44, 619–640.

Sojka, J.J., 1989. Global scale, physical models of the F-region ionosphere. Rev. Geophys. 27, 371–403.

Taylor Jr., H.A., 1972. The light ion trough. Planet. Space Sci. 20, 1593–1599.

Taylor Jr., H.A., Walsh, W.J., 1972. The light-ion trough, the main trough, and the plasmapause. J. Geophys. Res. 77, 6716–6723.

Titheridge, J.E., 1976. Ion transition heights from topside electron density profiles. Planet. Space Sci. 24, 229–245.

Tsyganenko, N.A., 1995. Modeling the Earth's magnetospheric magnetic field confined within a realistic magnetopause. J. Geophys. Res. 100, 5599–5612.

Tsyganenko, N.A., Stern, D.P., 1996. Modeling the global magnetic field of the large-scale Birkeland current systems. J. Geophys. Res. 101 (27), 127–187, (198).

Webb, P.A., Benson, R.F., Grebowsky, J., 2006. Technique for determining mid-latitude O^+/H^+ transition heights from topside ionograms. Radio Sci. 41, RS6S34.

Webb, P.A., Essex, E.A., 2001. A dynamic diffusive equilibrium model of the ion densities along plasmaspheric magnetic flux tubes. J. Atmos. Solar-Terr. Phys. 63, 1249–1260.

Yizengaw, E., Moldwin, M.B., 2005. The altitude extension of the mid-latitude trough and its correlation with plasmapause position. Geophys. Res. Lett. 32, L09105 (doi:09110.01029/20005GL022854).