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HARRY A. TAYLOR, JR.
WILLIAM J. WALSH

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by

Harry A. Taylor, Jr.
Laboratory for Planetary Atmospheres
Goddard Space Flight Center
Greenbelt, Maryland

and

William J. Walsh
Aero Geo Astro
Beltsville, Maryland

Goddard Space Flight Center
Greenbelt, Maryland

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ABSTRACT

Extensive observations of mid latitude depletions in electron and total ion density by both direct and indirect techniques, have prompted numerous studies of the possible association between these troughs, observed both in the F-region and in the topside ionosphere, and the plasmopause. Within this work, one basic problem arises in that while the plasmopause has been detected as a global phenomenon both by vlf and ion composition measurements, the electron and ion density troughs have been identified primarily as nightside features. This problem, as well as the difficulty in explaining various inconsistencies in relating the position of the plasmopause and the ionization trough, is explained by a close examination of the ion composition, generally unavailable in previous trough studies. In particular, ion composition results from the polar orbiting OGO satellites identify the persistence of a pronounced light ion trough in H^+ and He^+ , often identified by order of magnitude decreases in the light ion concentrations, occurring within a few degrees of latitude, reaching residual concentration levels of 10^2 to 10^3 ions/cm³ near 60° dipole latitude.

The light ion trough, observed both within the thermosphere and at high latitudes in the magnetosphere has been correlated directly with the vlf whistler identification of the plasmopause. On the nightside near 1000 km, a complex relationship is observed between the dominant ions O^+ and H^+ . The rapidly changing mean ion mass observed at the plasmopause typically produces a resultant total ion density distribution of complexity sufficient to confuse correlative studies with the plasmopause, even though the light ion trough is very sharply defined within the ion composition. On the dayside, where O^+ is typically the predominant ion near 1000 km., light ion trough structure is often hidden beneath the O^+ layer, which may exhibit little or no depletion even though H^+ and He^+ show trough structure at the plasmopause. This analysis of the mid latitude topside ion composition indicates the need for caution both in studies of the plasmopause per se, and in phenomenological studies such as the relationship between the sub auroral red arc and the plasmopause, which are most likely dependent upon the detailed information available within the ion composition.

THE LIGHT ION TROUGH, THE MAIN TROUGH, AND THE PLASMAPAUSE

INTRODUCTION

Since the early work of Muldrew [1965] there has been continuing interest in the phenomena of mid and high latitude charged particle depletions and the possible association of these events with mechanisms responsible for the plasmopause. In early phases of such studies, attention was focused upon F-layer effects, since both the work of Muldrew as well as the later results of Sharp [1966] described charged particle depletions or 'troughs' in the 300 to 400 km. region. Muldrew, observing a variety of trough-like features in the electron density, identified a persistent 'main trough' on the nightside, near 60° magnetic latitude. Sharp observed abrupt nightside depletions in total ion density in the same latitude range, identifying the result as the 'mid latitude trough'. Although these F-layer variations have not been substantiated to be of identical origin, their similar features have led some investigators to the assumption that such troughs may be the result of a similar or common mechanism.

One important feature observed in the lower ionospheric trough is the tendency for the depletion to dissipate and often become indistinguishable during dayside hours, including some evidence that the trough position may move to significantly higher latitudes as day approaches. This evidence is summarized in Figure 1, taken in part from Jelly and Petrie [1969], who illustrated the diurnal variation of the F-layer trough observed by Muldrew. As shown, the 'main trough' shifts sharply to higher latitudes between $70-80^\circ$ in the afternoon sector, and disappears altogether between about 0700 and 1400 LT. In contrast to this observed

behavior of the 'main trough', we have included in Figure 1 a plot of the average position of the plasmapause reconstructed from the earlier work of Carpenter [1966] as deduced for moderate magnetic conditions ($K_p=2-4$). The principal feature of the data comparison in Figure 1 is that while the F-layer 'main trough' is absent over much of the dayside, the vlf results identify the position of the plasmapause throughout this local time interval, with the average position remaining relatively close to the 60° dipole latitude position.

In addition to a variety of observations of F-layer troughs, there have been extensive observations of mid and high latitude electron density depletions in the topside ionosphere level, near 1000 kilometers, from both direct and indirect measurements. Direct measurement studies of the main electron trough at 1000 kilometers by Miller [1970] verify the persistence of a generally well defined electron density depletion near 60° dipole latitude on the nightside, while dayside results by contrast exhibit considerable variability, making a regular dayside trough again difficult to distinguish. Similarly, as shown in Figure 2, a summary of the topside sounder results from Alouette I [Thomas et al., 1966] reveals that at the 1000 kilometer level, the nightside ionization minimum observed near 60° shifts in position with local time, essentially disappearing during dayside hours.

The electron density trough characteristics described above, as well as the results of studies by Rycroft and Thomas [1970], Liszka [1967], the others, have supplied considerable evidence of both mid and high latitude ionization decreases, leading to a tendency on the part of some workers to categorize such results as evidence of a 'main trough', or,

simply, 'the trough', and to associate this phenomenon with the plasma-pause. Unfortunately, however, due to differences in both measurement types and times and locations of the orbits involved, there has been little or no simultaneous comparison of observed trough characteristics. Thus, there is insufficient evidence to identify whether or not the various forms of ionization depletion are indeed the result of a common geophysical mechanism, exerting its influence over a wide range of altitudes and local times.

Intuitively, since the ion composition is changing rapidly throughout the 300-1000 kilometer region, it should be anticipated that ionization trough behavior observed at widely different altitudes and local times may be best compared only after consideration of the behavior of the ion composition for these same conditions. Toward this end, in this paper we examine the characteristics of a related but unique phenomenon, the light ion trough, (hereafter LIT) which will be contrasted with simultaneous observations of the total ion density near the topside or 1000 kilometer level. These results will show that the light ion concentrations, particularly the distribution of H^+ , provide a most sensitive indicator of the behavior of the plasmasphere, even within topside ionosphere regions where O^+ continues to be the dominant ion. We show that the LIT is observable on the dayside, exhibiting, on the average, good agreement with the vlf deduced position of the plasmopause, and at local times for which a total ionization trough is not formed. Finally, we describe briefly a diurnal variation in the relationship between the LIT and total density distributions, indicative of the complexity of the plasmopause region, suggesting caution in the identification

of the plasmopause as well as in geophysical studies dependent upon knowing precisely the boundary of the thermal particle distribution.

RESULTS

A persistent feature of the ion composition results obtained from the OGO-2, 4, and 6 satellites, spanning the period 1965 through 1971, is the LIT, a feature which appears fundamental to the description of the behavior of the mid latitude ionosphere. In contrast to the concept of the 'main trough', we identify the LIT as a depletion observed specifically in the 'light ions' of hydrogen and helium. The equatorward edge of the LIT is often marked by an abrupt decrease in the local concentrations of both H^+ and He^+ , with the rate of variation exhibiting a complex relationship with respect to local time, season, and magnetic activity. Under the most pronounced conditions, the concentrations of H^+ and He^+ may decrease by at least an order of magnitude within a degree of latitude, as the satellite moves poleward across the plasmopause [Taylor et al., 1968a]. In earlier case studies, we have found that the LIT is closely associated with the plasmopause, as determined independently both from satellite and ground based whistler results [Carpenter et al., 1969] [Taylor et al., 1969] [Grebowsky et al., 1970]. An example of the ion-vlf correlation performed earlier is shown in Figure 3. Near 60° dipole latitude, the decrease in H^+ accompanied by the termination in whistler occurrence rate and onset of vlf noise activity combine to identify the location of the plasmopause. A most important feature of this event is exhibited in the relationship between the latitudinal distributions of

O^+ and H^+ observed as the satellite moves across the plasmapause boundary. In this topside altitude range, near 1000 km., O^+ is the dominant ion exhibiting no trace of the discontinuity seen in the distribution of H^+ . Thus, even within the upper thermosphere, direct measurements of H^+ provide unique information relevant to the behavior of the plasmasphere and the plasmapause. It should be noted, also, that the distribution of He^+ follows a similar trough pattern to that of H^+ , although at a reduced concentration level, thus completing the evidence for the LIT in the absence of a total ionization trough.

Nightside LIT Characteristics

Typically, the LIT is sharply defined at night, where the equatorward edge of the trough is usually steepest, for average conditions of geomagnetic activity and moderate season. A representative profile of the dominant ions O^+ and H^+ is shown in Figure 4, observed from OGO-6 near midnight local time. The satellite pass selected for this figure was deliberately chosen to provide a wide range of altitude variation between the northern and southern hemisphere light ion trough zones, near 60° dipole latitude. As shown, H^+ exhibits a steep, well defined trough between 55 and 60° in both the southern and northern hemispheres, near 600 and 1000 km., respectively. The residual proton concentration levels observed poleward of the trough vary between about 10^2 and 10^3 ions/cm³, and are a function of altitude, season, local time, and auroral activity. These results follow a period of relatively quiet magnetic conditions $K_p(-6) = 1_+$, (where $K_p(-6)$ is defined as the maximum value of K_p

recorded in the six hour interval preceeding the time of the measurements) and exhibit the typical undisturbed boundary of the plasmasphere to be located near 60° dipole latitude. In marked contrast, we observe that the distribution of O^+ exhibits significantly different behavior in the plasmopause zone, and, in itself, provides no indication of the plasmasphere boundary. Indeed, in the very region where the H^+ distributions are falling most rapidly, the O^+ concentration is observed to be persistently increasing. As a result, the total ion density, N_i (composed primarily of O^+ and H^+ in this altitude range) provides only an indirect suggestion of trough structure, different both in degree and character from that exhibited in H^+ .

It is significant that the equatorward edge of the resultant N_i trough in both hemispheres is formed primarily by the distribution of the dominant low and mid latitude ion H^+ , and not by O^+ . Thus, both near 600 kilometers in the southern hemisphere and near 1000 kilometers in the northern hemisphere, the nightside distributions of the light ions provide a much clearer and more fundamental identification of the plasmasphere boundary than would be derived from the total density distribution alone. It is interesting to note, that at still higher latitudes, particularly in the southern hemisphere, O^+ reveals noticeable irregularity beyond the 60° latitude position, indicative of possible auroral ionization activity in the same region.

Dayside Light Ion Trough Characteristics

In contrast to the observed behavior in N_i , the light ion trough is also observed as a persistent feature of the dayside ionosphere, although the equatorward boundary of the trough is generally less sharply defined than on the nightside. Thus, while the decrease in ambient concentrations of H^+ to the 10^2 - 10^3 level beyond about 60° dipole latitude is a regular feature, the mid latitude rate of decrease in the concentration of H^+ tends to be less pronounced than at night. This dayside rate of decrease in H^+ is observed to be strongly influenced by season and magnetic activity, with steeper trough boundaries occurring toward winter and following magnetic storms. An illustration of the seasonal variation in the dayside LIT is given in figure 5a, in which northern hemisphere winter and summer distributions of H^+ and N_i are compared.

As shown, the LIT is more clearly identified during local winter, with both a more rapid decrease in $n(H^+)$ with latitude, and a lower residual ion concentration level observed near 60° latitude.

Evidence of the effect of magnetic storms upon the LIT characteristic is given in Figure 5b, where we compare the H^+ and N_i distributions observed during moderate ($K_{p(-6)}=3^\circ$) vs. significantly disturbed ($K_{p(-6)}=5+$) magnetic conditions. In the event of August 14, near 1130 LT, the equatorward edge of the LIT is not as sharply defined, relative to the boundary exhibited in the profile of August 18, at essentially the same local time. Note that following a period of enhanced magnetic activity, the LIT boundary is not only much steeper, but also the trough minimum level has moved significantly equatorward, occurring near 40° dipole latitude ($L=2.0$)

for the disturbed period in contrast to the minimum beginning near 60° dipole latitude ($L=4.7$) following the period of relatively quiet magnetic conditions. Another significant feature of Figure 5 is the fact that the total ion density does not exhibit a well defined trough. Even for the disturbed case on August 18, in which the plasmasphere has contracted equatorward significantly, the N_1 distribution (composed predominantly of O^+) provides little or no evidence of the plasmopause position. In this way, the dayside distributions of O^+ at the topside level are seen to be in a sense 'floating' above the lesser distributions of H^+ , to a large extent masking the light ion evidence of plasmasphere-plasmopause behavior.

DISCUSSION

LIT-Plasmopause Relationships

A primary feature of the OGO ion composition results is that the LIT, in contrast to the total ionization density, may be detected at all local times, thus permitting a global investigation of plasmopause related phenomena. Although the modifying effects of seasonal and magnetic activity variations are neither thoroughly documented nor understood, the evidence is clear that the dayside plasmopause characteristics observed at very high altitudes in the magnetosphere by similar Bennett spectrometer experiments on OGO's 1 and 3 [Taylor et al. 1965] and [Brinton et al. 1968] extend from the magnetosphere down into the ionosphere, [Carpenter et al. 1969]. Within the topside region, the light ion distributions reflect similar features to those observed in the magnetosphere, such as the equatorward contraction of the plasmopause in response to

enhanced magnetic activity [Taylor et al. 1968b]. As suggested in Figure 3, there is also strong evidence for the association of the LIT and the vlf deduced evidence of the plasmopause. As added evidence of the link between the LIT and the plasmopause, in Figure 6 we compare dayside and nightside LIT positions relative to the average position of the plasmopause as obtained from vlf techniques during periods of relatively steady, moderate magnetic activity ($K_p=2-4$) [Carpenter, 1966]. Although this illustration is not intended to provide a basis for rigorous comparison of measured plasmopause positions (due to differences in time, position, and magnetic activity), it does nevertheless serve to emphasize the point that the LIT is indeed a global phenomenon, relevant for ionospheric investigations on the dayside, as well as at night.

Hidden Ionic Structure

We have seen that both during day and night the topside total ion distributions may provide a misleading indication of the complexity of the ionic structure which may be most important for various geophysical studies. On the nightside, where noticeable total ion concentration troughs do indeed occur near the plasmopause position, the very rapid change in mean ion mass observed near 1000 km is an important complicating factor, often undetected in total ion concentration measurements. This difficulty was identified earlier by Marubashi [1970] although he unfortunately did not have sufficient information available on the ion composition to fully demonstrate the point. In Figure 7, a comparison of electron density and scale height near the plasmopause,

performed by Marubashi using Alouette data from August 1963, illustrates the hidden mean ion mass feature. Note that near 55° , following a relatively gradual decrease in total electron density content, the scale height rapidly decreases for more than 2000 km to near 400 km, reflecting a rapid change in ion composition near the 55° position. This earlier result appears to be entirely consistent with our OGO nightside observations, in which the N_i trough is often poorly defined, resulting indirectly from a sharp decrease in H^+ with an attendant increase in O^+ , near the plasmopause boundary.

On the dayside, where O^+ is generally the dominant ion near 1000 kilometers, LIT structure is often masked by the distribution of N_i , which exhibits relatively little evidence of a depletion in the plasmopause zone. Since the dayside photoionization process is strong, it may be that proton losses associated with the plasmopause are not sufficient to tax the available source of O^+ . Thus, although near sonic upward proton velocities have been detected at the LIT [Brinton et al., 1971], the dayside ionization reserve is apparently such that the charge exchange depletion process does not seriously affect the concentration of O^+ . Accordingly, except in the cases of very severe storm-time depletion of H^+ , we may not expect to see significant dayside depressions in N_i associated with the LIT, although the search for such results is certainly not yet complete.

The Relevance of LIT for Geophysical Studies

The fact that under a variety of conditions the detail of the light ion structure may be hidden within the total ion concentration

appears to be particularly significant for a number of geophysical studies of current interest. First, considering just the plasmopause as an isolated phenomenon, detailed studies of the structure sometimes observed in the LIT have shown that the identification of the position of the plasmopause may be quite complex. Specifically, portions of the higher resolution ion composition data obtained from the OGO-4 Bennett spectrometer have revealed the presence of a 'plasmatail' or significant increase in proton concentration lying just poleward of the initial plasmopause, [Taylor et al., 1971]. Preliminary evidence of similar plasmatail-like structure in the proton distributions observed from OGO-6 show that this added LIT complexity may also be masked by the absence of similar structure in the distribution of O^+ , which tends to be dominant in the latitude region where the plasmatail has been observed. Thus, even for detailed studies of the plasmopause per se, the study of the ion composition is fundamental.

In addition to basic studies of the plasmopause, it is emphasized that the information available in the ion composition is most important for a number of interesting ionospheric studies in this complex region. It is increasingly clear that neither energetic sources, nor dynamic forces, may be independently sufficient to explain the variety of features observed near the plasmopause. From the foregoing results, it is evident that the chemistry relating the behavior of both the heavier (O^+) and the lighter (H^+) ions must be of basic importance. Clearly, for the rigorous study of observed features such as the sub auroral red arc, which according to Chandra et al., [1971] may be critically

dependent upon chemical processes in the lower thermosphere, the relative behavior of the ion constituents must be carefully examined. Also, for studies involving the interaction of the cool thermal plasma with the hot energetic plasma trapped in the radiation belts, information on the LIT structure and position should be of particular concern. Specifically, if as suggested by Brice [1971] the distribution of thermal plasma may serve as a catalyst for enhancing the precipitation of trapped particles, LIT structural information, such as the evidence of the plasmatail, may be of fundamental geophysical significance.

In summary, we have presented a brief description of the characteristics of the light ion trough observed in the topside ionosphere. We conclude that at the topside level, the LIT should not be confused with features such as the 'mid latitude trough' or the 'main trough', etc., which are descriptive of the total ion-electron concentration and not necessarily representative of the behavior of the light ion dominated plasmasphere.

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FIGURE CAPTIONS

- FIGURE 1: A comparison of the diurnal variation observed in the main trough at the F2 peak (dashed curve) and the average position of the plasmopause deduced from ground based vlf recordings (solid curve). The trough results are from Alouette I during the period November 1962 to March 1963, with magnetic conditions equivalent to a mean daily value of $K_p = 2$ (after Jelly and Petrie, 1969). The whistler-plasmopause results describe average conditions during July and August 1963, with $K_p = 2-4$ (after Carpenter, 1966).
- FIGURE 2: Average latitudinal variation of N_s , the electron density at the Alouette I orbit, during the summer of 1963 (after Thomas et al., 1966).
- FIGURE 3: A comparison of simultaneous ion composition and vlf whistler results observed from OGO-2, for a plasmopause crossing near 60° dipole latitude. Note that the last observable whistler occurs near 1128 UT, as the concentrations of H^+ and He^+ are falling to background levels. Note also that O^+ as well as the total ion density, N_i reflect no evidence of the light ion trough-plasmopause.
- FIGURE 4: An example of the light ion trough in H^+ observed near midnight local time, with trough boundaries occurring near $55-60^\circ$ in both the northern and southern hemispheres. The total ion density distribution, N_i , is derived as a

sum of all positive ions measured in the mass range 1-45 AMU, and reflects primarily the contribution of the two most dominant ions in this altitude range, O^+ and H^+ . Note that pronounced light ion troughs are observed both at lower altitudes near 600-700 kilometers as well as at the topside near 1000 km.

FIGURE 5: Examples of the effects of (a) seasonal and (b) magnetic variations upon the distributions of H^+ and N_1 in the plasmopause zone. In panel (a) the seasonal variation is observed for quiet magnetic conditions ($K_{p-6}=1-2$). The difference in magnetic activity for the events of panel (b) is $A:K_{p-6} = 3^{\circ}$ and $B:K_{p-6} = 5^+$. Although the range of altitude variation between the passes of panel (a) is an unavoidable result of the selection process, experience with similar results indicates that altitude variations are sufficiently small that the seasonal evidence is not compromised.

FIGURE 6: A comparison of plasmopause positions determined independently from ion composition and ground based vlf techniques. The dashed curve gives the average position of the plasmopause during July-August, 1963, with $K_p=2-4$. The dots give the position of the LIT-plasmopause obtained from OGO-6 during 1969-70, for the same range of K_p variation.

FIGURE 7: Variation in electron density at 950 km. altitude and scale height at 950 and 400 km. levels along the Alouette I

orbit, in the vicinity of the trough (after Marubashi, 1970).

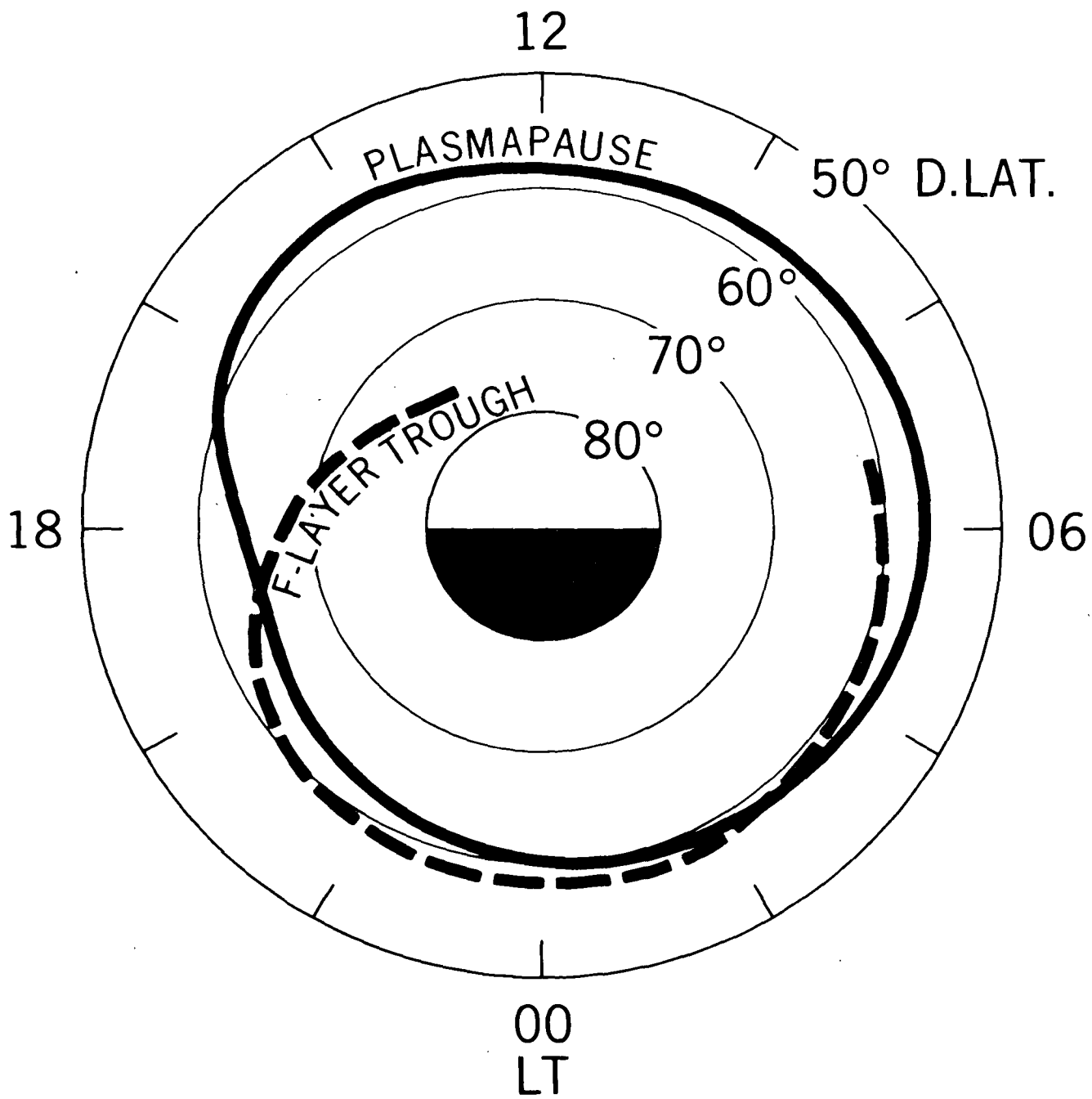


FIG.1

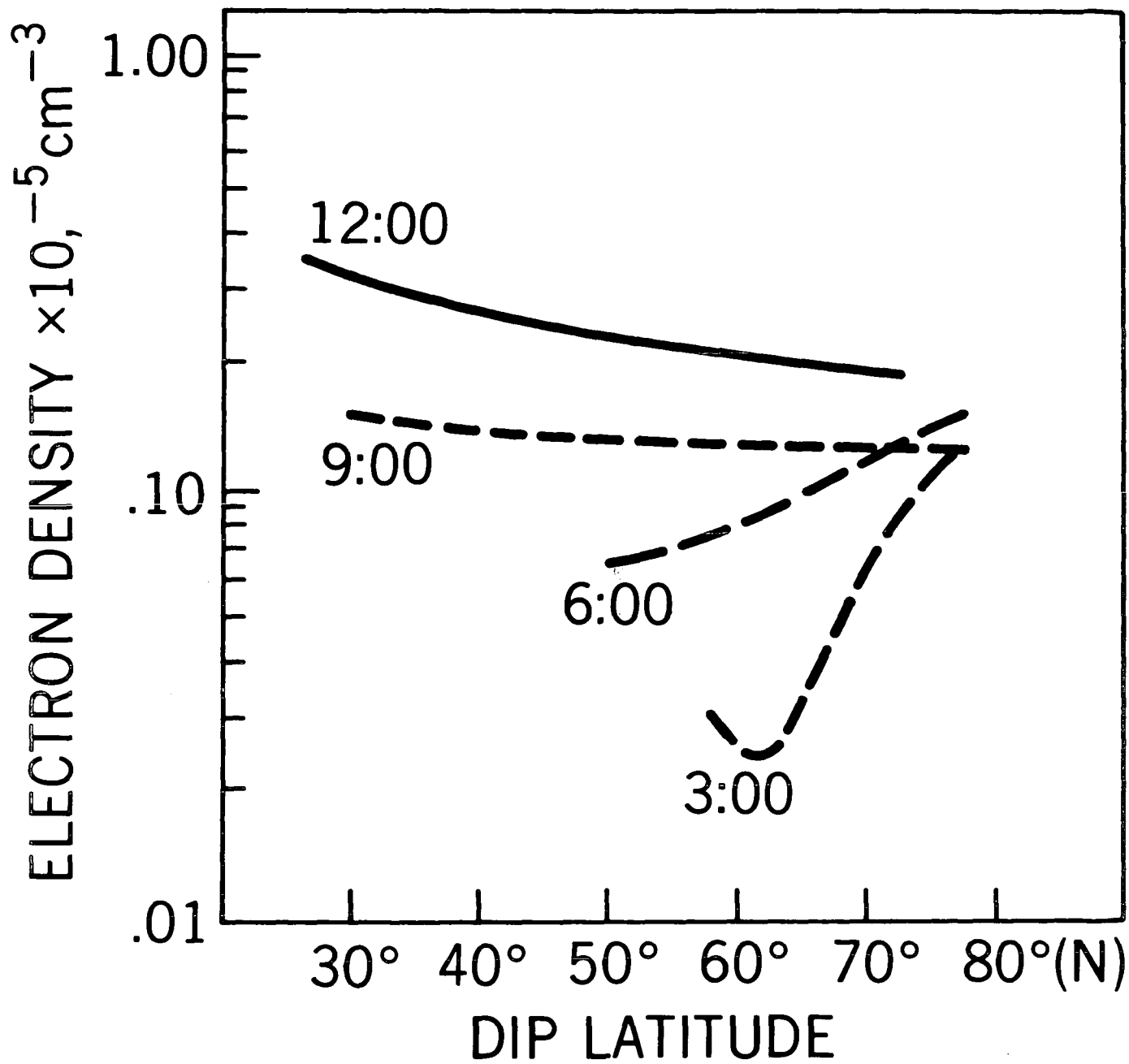


FIG. 2

OGO-2 OCTOBER 22, 1965
 UT 11:22 :25 :28 :31 :35
 D.LAT. (S) 40° 50° 60° 70° 80°

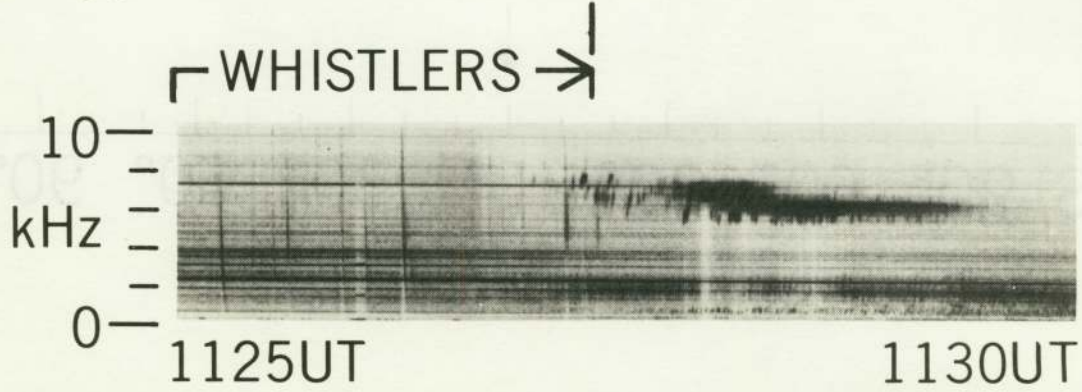
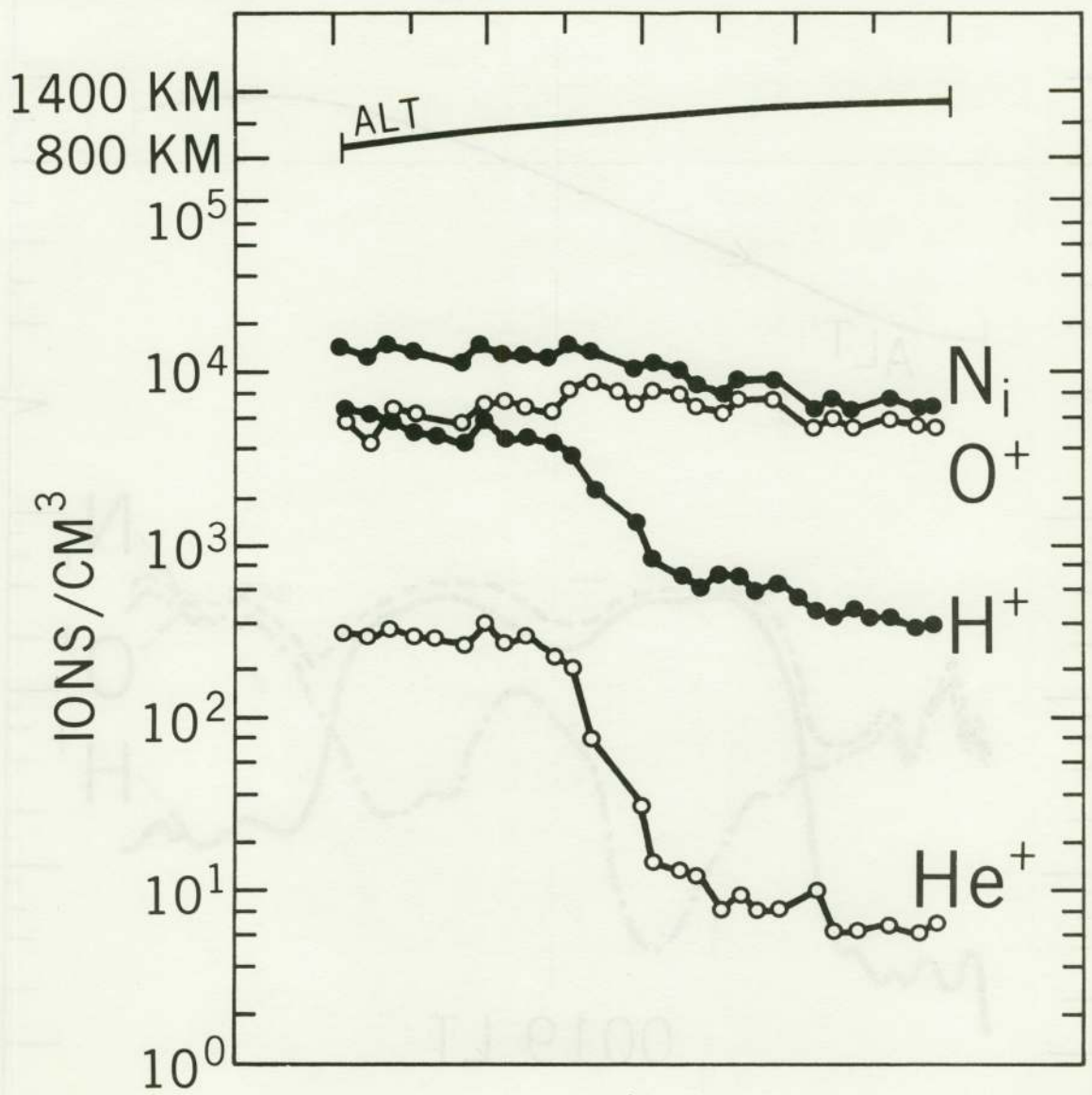


FIG. 3

OGO-6 AUG. 2, 1970 1917-2007UT $K_{P(-6)} = 1+$

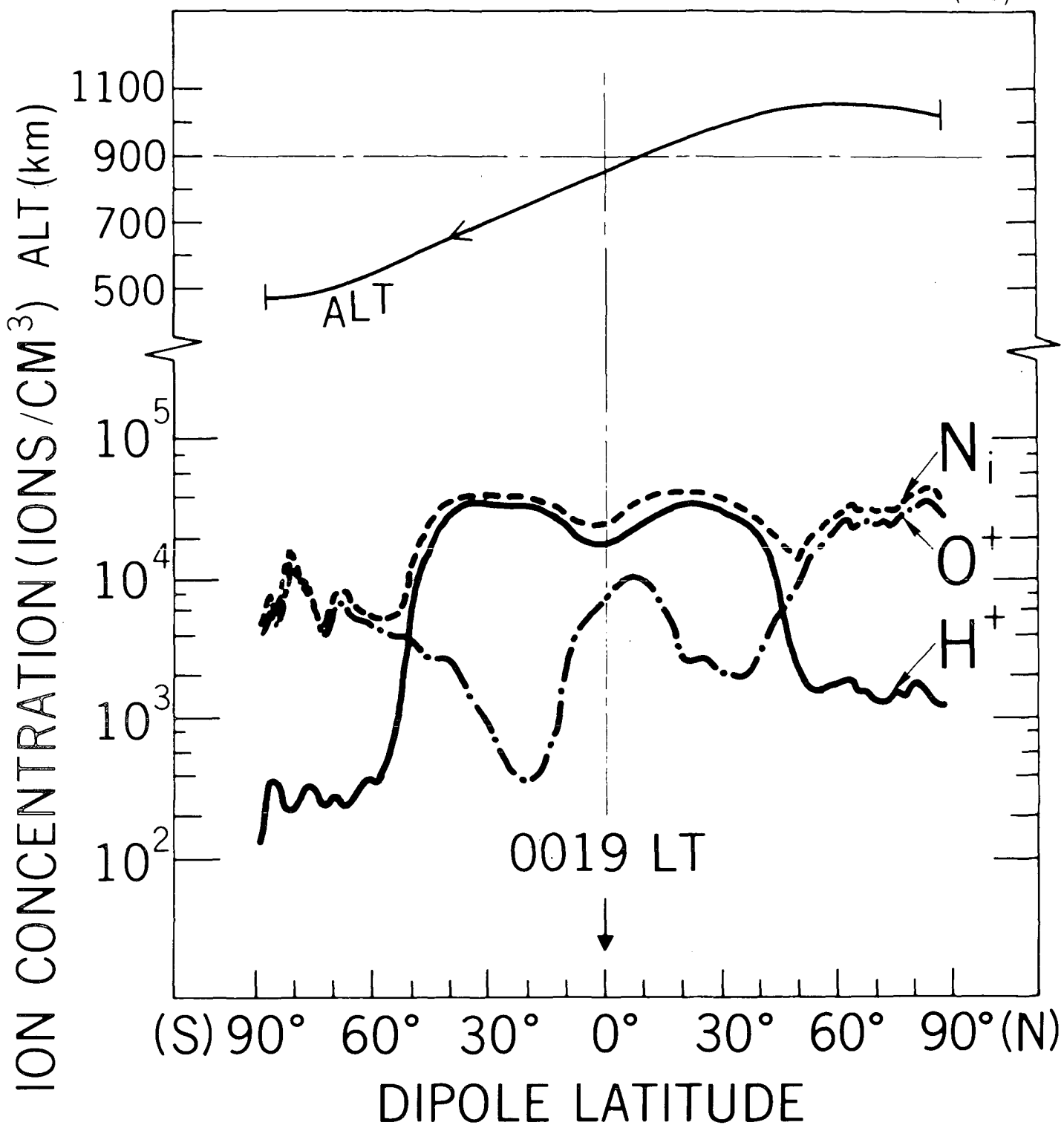


FIG. 4

OGO-6

1970

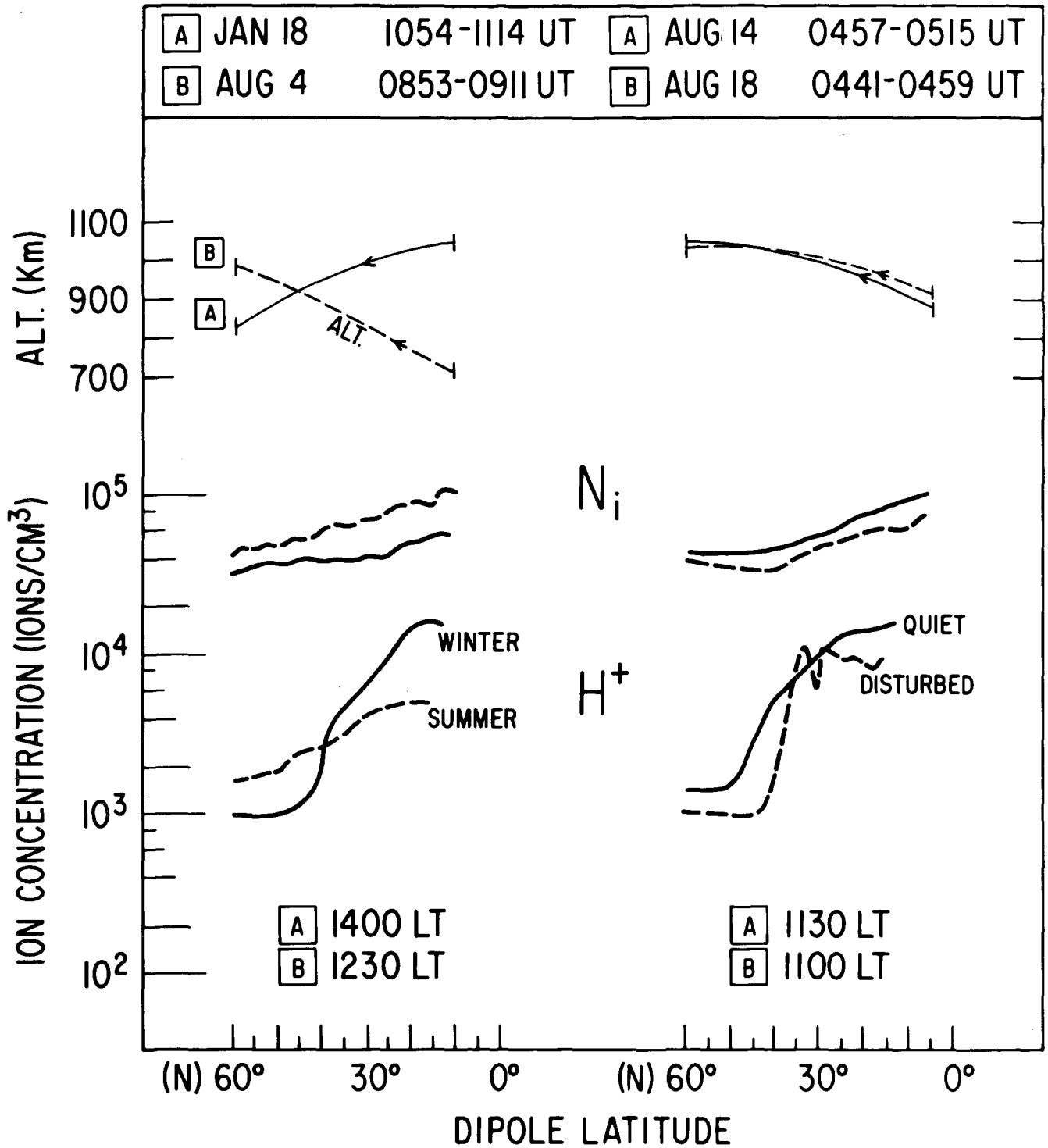


FIG.5

PLASMAPAUSE: • ION
— VLF

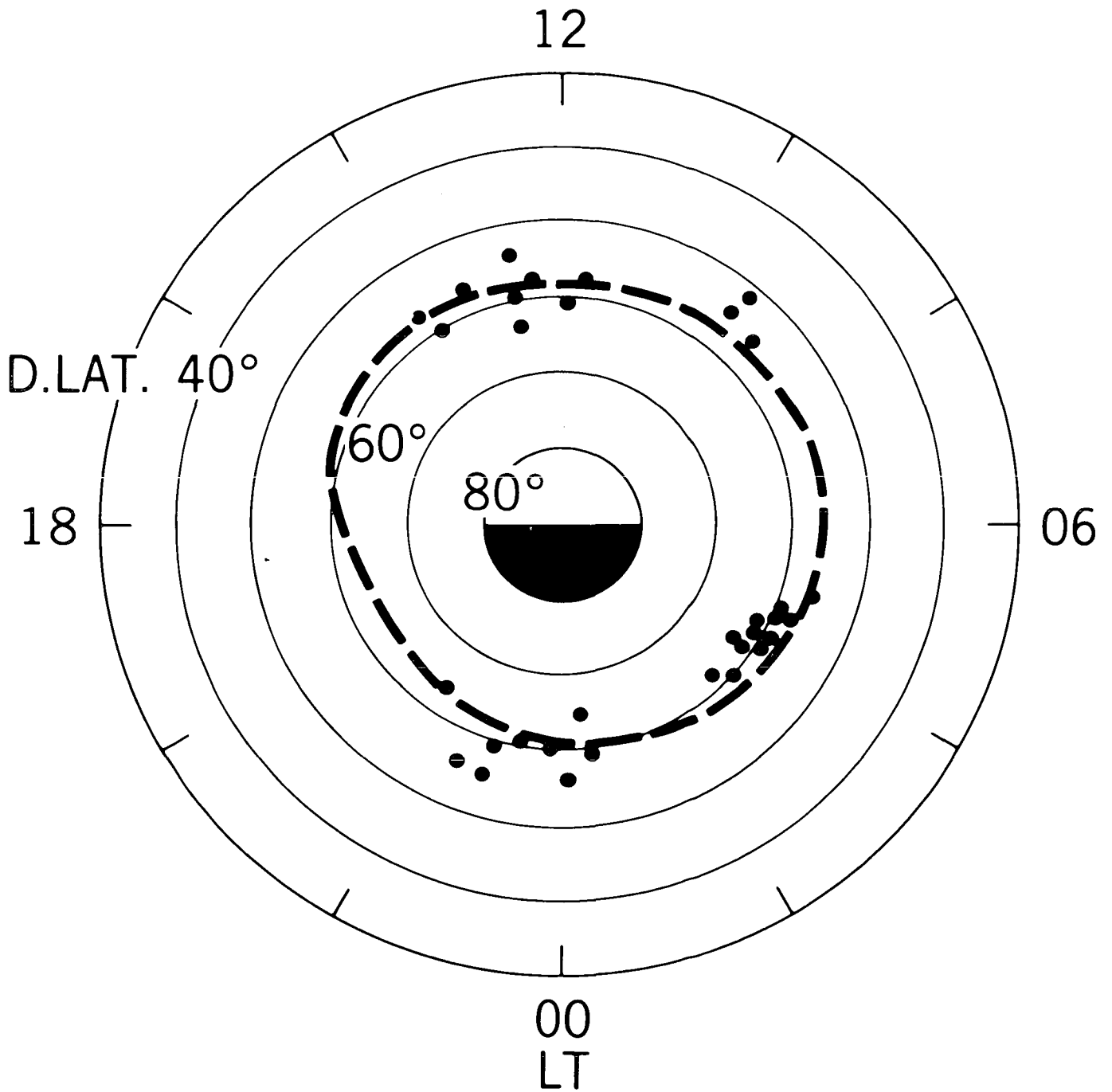


FIG. 6

1963 AUG 10

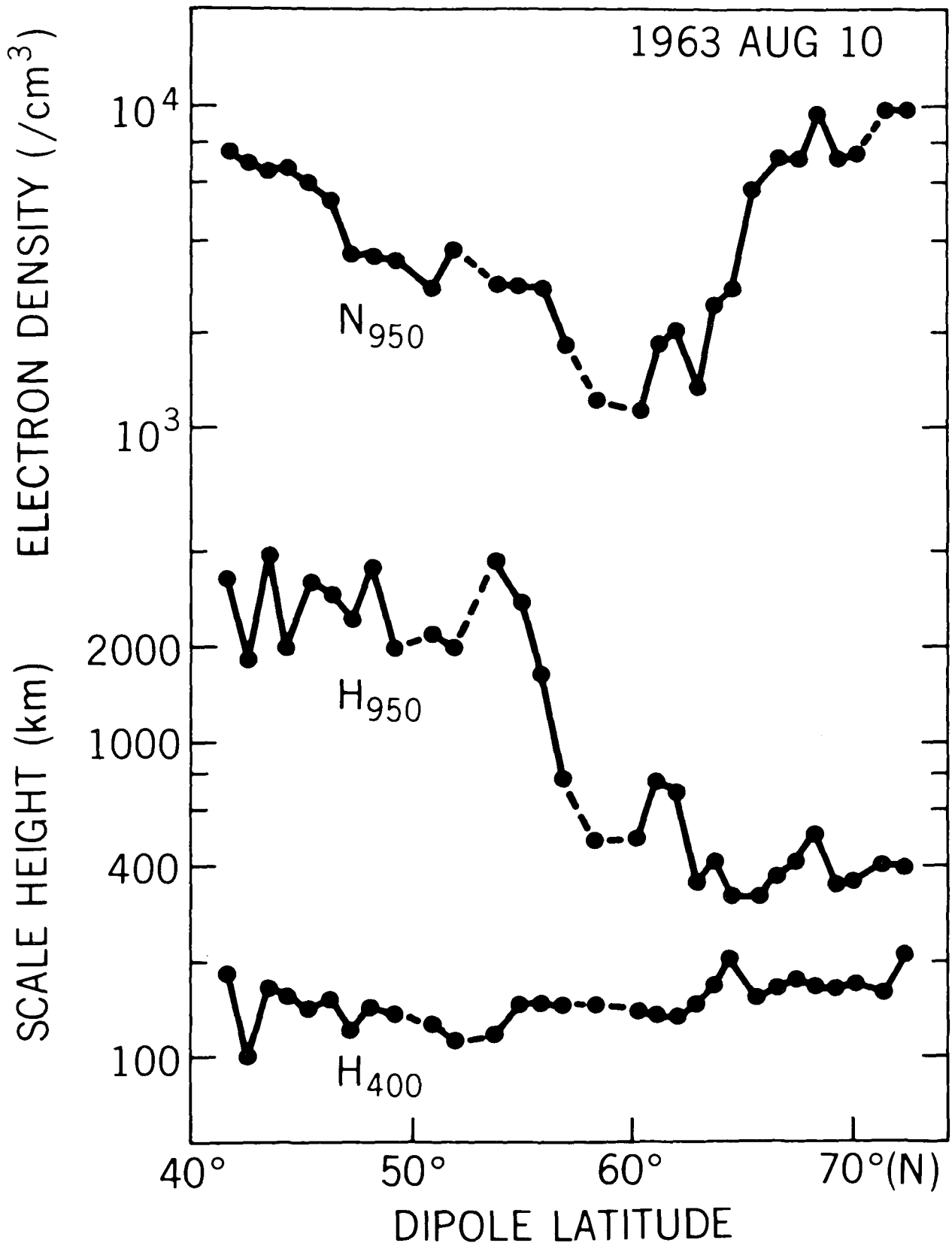


FIG. 7

c