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GSFC

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GREENBELT, MARYLAND

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ABSTRACT

Direct measurements of the pole-to-pole distributions of topside thermal protons obtained with the OGO-4 ion composition experiment, near local midnight, reveal sharply structured variations of the plasmasphere boundary. With increasing L values the proton density distributions may exhibit a pronounced inner trough, in which the ambient H^+ concentrations decrease by an order of magnitude near L=2, and subsequently recover to midlatitude concentration levels before a more pronounced and persistent trough is encountered at higher L positions. The time evolution of the trough boundaries observed during a sample of 5 consecutive satellite orbits following the peak of the magnetic storm on September 21, 1967 suggests that the observed structure results from a plasmatail or elongation of the plasmasphere which tends to co-rotate with the earth. The empirical model deduced indicates that, at the time of these observations, the plasmatail has a width of about 0.8L at the base, extending to an extremely thin region of 0.05L or less near

the tip, and with an azimuthal extent of approximately 85° of longitude. The general features of the observed plasmatail structure are in accord with the time evolution of the plasmapause predicted theoretically assuming the magnitude of the thermal plasma convective flow from the magnetosphere tail varies directly with the magnetic index, Kp.

INTRODUCTION

To date, much of our direct measurement evidence of structured variations of the distribution of thermal plasma within the plasmasphere has resulted from thermal proton observations from high altitude satellites such as the eccentric orbiting OGO [Taylor et al., 1965, 1968] [Brinton et al., 1968] [Harris et al., 1970]. Such results, combined with extensive ground-based whistler observations [Carpenter, 1966] have provided a generalized picture of the plasmasphere as an envelope of cool, dense plasma about the earth bounded by a rather sharply defined plasmapause. Also, it has been observed that the plasmasphere boundary is not always symmetrical in L-Local Time space and that under appropriate conditions may exhibit a significant bulge, typically in the dusk local time sector [Carpenter, 1970] [Taylor et al., 1970] [Chappell et al., 1970].

More recently, there has been increasing evidence of significant irregularities in the proton distributions near the plasmapause, which may be associated with non-uniform magnetospheric convection patterns [Park and Carpenter, 1970]. In addition, time dependent magnetospheric convection models [Grebowsky, 1970] predict deformations of the co-rotating plasma envelope, in the form of cusp-like elongations, referred to as the plasmatail in model studies by Chen [1970].

Together, the above observations and models indicate a dynamic pattern for the plasmapause configurations. With asymmetric features such as the dusk side bulge combining with irregular plasma depletion and accretion events, a very complex plasma distribution may result near the plasmasphere boundary. As a result, it is evident that high resolution in the observation of both temporal and spatial changes in the thermal plasma distribution may be required to understand the competing processes. An inherent advantage of using orbiting satellites such as OGO 4 and 6 for studies of storm induced plasmasphere phenomena lies in the increased resolution afforded by the relatively short orbital period and by the relative constancy of local time during the comparison of sequential orbits. Thus, compared with eccentric orbit studies, the POGO measurements permit a closer examination of the results of temporal changes in the magnetospheric convection processes.

From OGO-4 and OGO-6, the plasmapause has been studied in detail with directmeasurements from the Bennett RF Ion Composition Experiment. As shown in Figure 1, from OGO-6, the plasmapause is indicated by the formation of the light ion trough [Taylor et al., 1968] which is observed as a persistent feature of the nighttime topside ionosphere, near L=4. Correlative studies have shown that the light ion trough occurs simultaneously with the whistler cutoff at the plasmapause [Taylor et al., 1969] [Carpenter et al., 1969] and that the high altitude proton trough-plasmapause detected in the magnetosphere is directly linked with the topside light ion trough [Grebowsky et al., 1970] [Mayr et al., 1970]. Typically as shown, the topside distributions of both H^+ and He^+ indicate a sharply bounded plasmasphere followed at higher latitudes by regions of irregular plasma distributions which may be associated with particle events not necessarily related to the formation of the trough. The proton distribution in Figure 1 was obtained while the experiment was operated in the long sweep mode, and thus is constructed from sequential measurements made with a time spacing of approximately 37 seconds, corresponding to a latitudinal resolution of approximately 2.3° along the orbit. By operating the OGO-4 experiment in the short sweep mode, the time resolution may be increased to 3.2 seconds, providing a latitudinal resolution of approximately 0.2°.

In this paper, we examine a set of high resolution proton distributions obtained from OGO-4 during September 1967. These results, obtained during the declining phase of a magnetic storm which occurred on September 20-21 indicate that, under appropriate magnetic and electric field conditions, the plasmasphere may exhibit a tail-like structure which appears to co-rotate with the Earth, resulting in an unique pattern of depleted and non-depleted plasma regions which complicates the description of the main plasmapause. Subsequently, a time dependent analysis of the plasmapause motion using a simple plasma convection model will provide evidence that a plasmatail may be formed by the tendency of plasma associated with the storm distorted dusk-side plasmasphere bulge to co-rotate with the earth during a period of quieting magnetic activity.

RESULTS

In the results which follow, profiles of the plasmasphere distribution are examined for evidence of structured variations observed during the declining phase of a magnetic storm which was active during September 20-21, 1967. A histogram of the Kp activity characterizing the magnetic conditions during and subsequent to this storm period is given in Figure 2.

The relation between the phase of the storm and the universal times of the OGO-4 measurements to be considered can be seen in this figure.

An example of the contrast in plasmasphere structure which may be observed subsequent to different time histories of magnetic activity is shown in Figure 3. The H^+ profile observed on September 26, long after the storm, (B) is rather typical of the relatively smooth, undisturbed proton distributions frequently observed following periods of relatively quiet magnetic activity. In this case, although the proton trough is not sharply defined, we would identify the plasmapause by the first decrease of the proton concentrations with increasing L to the relative minimum observed near L=4 in both the northern and southern hemispheres. In contrast, the H^+ profile observed on September 21 near the main phase of the magnetic storm, position (A) of Figure 2, exhibits complex changes in the structure of the plasmasphere boundary. Overall, it is observed that the plasmasphere boundary steepened and contracted equatorward in both hemispheres, with the primary trough now near L=3. This observed inverse relationship between Kp activity and L position of the plasmapause is consistent with earlier thermal ion [Taylor et al., 1968a, 1968b] [Chappell et al., 1970] and whistler observations [Carpenter, 1966].

In addition to the observed inward contraction of the plasmasphere, the profile of September 21 exhibits a pronounced inner trough, beginning at about L=2, and followed by a sharp recovery of plasma with increasing L prior to the encounter of the primary trough of light ions near L=3. In view of such pronounced structure, the identification of the plasmapause becomes more arbitrary, and in the absence of higher latitude data one might identify the plasmapause by the initial sharp decrease in proton concentrations observed near L=2, where H^+ decreases by as much as an order of magnitude within 0.1L.

In the results shown in Figure 3, and in the data which follow, we will concentrate on examining conditions near the plasmasphere boundary where we have identified a patterned variation in the plasmasphere structure. At latitudes above the region of the main ion trough, located near L=3 for the data to be discussed, we observe additional pronounced features in the proton distributions, including examples of broad plasma recovery regions, as well as examples of extremely fine-structured plasma variations. It is very likely that these higher latitude regions, such as the interval between L=3 and L=8 in Figure 3 exhibit the combined effects of convection related plasma depletion and accretion, as well as irregular plasma formations associated with energetic particle activity. For simplicity, we deal only with plasma structure below L=3 in this paper and will treat such higher latitude complexities in subsequent papers.

Evidence for a Plasmatail

In Figures 4 and 5, we examine a sequence of five apogee-side H^+ profiles observed during September 21-22, in the recovery phase of the magnetic storm. These profiles were all measured near 0100 LT. Beginning with Profile (1) Figure 4 and proceeding through Profile (5) in

Figure 5 a distinct pattern is exhibited in the formation and displacement of the inner trough, which first appears on Profile (2), near L=2 in both the northern and southern hemispheres. Following the sequence, it is seen that the equatorward edge of this inner trough moves persistently higher in L, the trough depth increases, and the poleward peak or recovery which immediately follows this trough with increasing L moves to higher L positions and shrinks in prominence. By relating the structured behavior in both hemispheres, we see evidence that the inner trough and the bordering plasma recovery eventually disappear, with the last detectable evidence of this structure observed as a small peak in Profile (5) near the L=3 position in the southern hemisphere, where the detection of the peak becomes marginal. The progressing pattern in the distribution of the trough-peak structure is readily apparent, as well as the similarity in both the concentration and L position of these features in both the northern and southern hemispheres.

Although the same type of high resolution data has been examined throughout the periods September 22-23 and September 25-26, this observed structural variation in the region of the light ion trough was not encountered subsequent to the interval 0114-0159 UT on September 22. It is concluded from this that the extent of the pattern observed is relatively unique and is associated with a particular time history of geomagnetic disturbance events.

DISCUSSION AND INTERPRETATION

Deduced Features of the Plasmatail

Because of the unique characteristics of the observed plasmapause structure, we have assumed that the features detected result from the co-rotation of a spatial plasmasphere distortion feature with the earth, and have composed a schematic representation of a plasmapause configuration which would fit the observations. In Figure 6, the plasma distribution is constructed to show the relative presence or absence of protons along each of the longitudinal positions of the five sequential orbits described in Figures 4 and 5. In order to represent the observed light ion trough features, we have plotted each of the trough boundaries as if the light ions had co-rotated with the Earth through the relatively fixed local time position of the satellite. As indicated by the dashed line which is arbitrarily drawn to complete the plasmasphere envelope, the position and character of the plasmapause is not specified beyond the 97° arc of the observations, although as indicated previously, there is no evidence of similar plasmapause structure either before or after the period of these observations.

As shown in Figure 6, the structured proton profiles can be interpreted as evidence for a tail-like structure or cusp in the plasmasphere boundary which tends to co-rotate with the earth. At its base, the deduced tail exhibits a width of approximately 0.8L, which decreases to less than 0.1L at the position of our last observation of this characteristic. This suggests that the tip of the tail rapidly becomes too thin to detect, beyond the position corresponding to Profile (5) of Figure 5.

Although the schematic of Figure 6 represents the gross features of the observed plasma distribution, no attempt has been made to account for the small but detectable variations in structure observed both inside and outside the inner trough. For example, in Profile (3) of Figure 5 there is some evidence of further structure within the inner trough in the northern hemisphere, suggesting perhaps the presence of a secondary tail-like structure. In addition, just equatorward of the inner trough the profiles of Figure 5 show some evidence of possible second order trough structure in the inner plasmasphere, including a noticeable increase in the proton distributions toward the equator, a feature which we do not treat in this study but which may be associated with the effects of non-uniform magnetospheric convection as discussed by Park and Carpenter [1970].

Comparison of Empirical and Theoretical Plasmatail Features

In order to test the feasibility of the equatorial plasma distribution deduced from the observations, we have employed a relatively simple time dependent magnetospheric plasma convection model developed by Grebowsky [1970] in an effort to determine whether the magnetic storm events leading up to the period of our observations might result in a co-rotating plasmasphere distortion such as we have apparently observed. In this model the dayside magnetic field lines are assumed electrically shorted to one another in the rest frame of the rotating earth so that the component of the convective flow from the magnetosphere tail due to the solar wind-magnetosphere interaction does not penetrate onto dayside field lines. Using the statistical relationship between the plasmapause L position and the magnetic index Kp measured by Binsack [1967], the magnitude of this model convection tail wind can be related to Kp by assuming Binsack measured, on the average, steady state plasmapause locations.

For simplicity it is assumed that the plasmapause was in or near a steady state configuration at 0000 GMT on September 21, 1967 which was just before the peak of the storm. The time evolution of this boundary was then computed by changing the magnitude of the tail wind every three hours in step with the index Kp. The resulting computations in Figure 7 show that in a period of one day (at a time characteristic of when the measurements were made) a cusp forms with the same structure as deduced from the observed data--i.e., a tail-like structure which tends to co-rotate with the earth. The quantitative differences between the measured and computed variations of the plasmapause reflect the limitations of the assumed relationship between the convective flow and the magnetic activity but do not affect the qualitative conclusion reached.

As shown in Figure 7, it has been possible to derive a time dependent evolution of the plasmasphere boundary with general characteristics comparable to those deduced from the measurements. Thus, although from these measurements alone we cannot rule out the possibility that a unique sub-storm event may have produced the observed structure, the clear relationship between the deduced and predicted tail structures appears to be more than fortuitous.

Although a precise mapping of the detailed features of the plasmatail must await more complete observations, it is increasingly clear that the plasmapause may exhibit a wide variety of structural features. Consistent with the time dependent plasma convection models, the plasmapause is frequently found to be sharply defined during periods of pronounced magnetic activity when the convection boundary moves inward to low L positions, and field tubes above the new inner boundary are rapidly depleted of plasma, thus in a sense erasing complex structural patterns which may have evolved during previous depletion and accretion events. Conversely, at various stages of post-storm recovery, an infinite variety of structural features could be predicted as a result of the competing processes of plasma escape, diffusion, field induced drifts, and dynamic features such as deduced from these results. It is clear that dynamic effects could significantly confuse the identification of the plasmapause, and that plasma measurements from satellites must provide a high degree of resolution in both time and space, if a definitive treatment of structured variations of the plasmapause is to be performed.

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FIGURES

Figure 1 Pole to pole distributions of H^+ and He^+, identifying the light ion trough, with minima near L=4 in both the northern and southern hemispheres. Gaps in the ion distributions near the equator result from the relative geometry of the orbit and the L coordinate system. Data were obtained during relatively quiet magnetic conditions, with Kp less than 2 throughout the two day interval preceding the observations. The nominal local time of 0500 is determined as the orbit crosses the dipole equator.

Figure 2 A histogram of the Kp activity associated with the plasmasphere observations. Times designated (a) and (b) correspond to the contrasting H^+ profiles to be shown in Figure 3.

Figure 3 A comparison of H^+ profiles observed following periods of significantly different magnetic activity, related to times (a) and (b) identified in the Kp histogram of Figure 2. For clarity, Profile (b) has been shifted upward in amplitude throughout by a factor of 10, so that the profiles could be shown simultaneously without overlap. Note particularly both the inward contraction of Profile A relative to Profile B, as well as the appearance of an inner trough near L=2 in both the northern and southern hemispheres.

Figure 4 A series of three consecutive H^+ profiles observed near 0100 hours local time. Note the development and outward displacement of the inner trough observed first on Profile (2) near L=2.

Figure 5 A continuation of a sequence of H^+ profiles begun in Figure 4, with Profile 3 repeated as a reference. Note the continuing outward displacement of inner trough and the final evidence of this feature observed in Profile 3 near L=3, in the southern hemisphere.

Figure 6 A schematic representation of the plasmatail structure derived from the observations of Figures 4 and 5. Along the radial line corresponding to each of the five satellite passes, the presence or lack of plasma is indicated by the shaded and open regions, respectively. Although the nominal local time position of the satellite orbit remains essentially fixed during these passes, the data are illustrated in this fashion to suggest the form of the plasmatail structure which is believed to have co-rotated relative to the orbit. Because of incomplete data samples, the plasmapause position is not identified beyond the interval shown, and the dashed line simply suggests the undefined continuation of the plasmasphere. Additional plasma complexities observed beyond the primary trough near L=3 are not treated in this model.

Figure 7 Varying the magnitude of the tail wind in step with the Kp index and beginning with a computed steady state configuration near the peak of the storm, the time evaluation of the plasmapause was computed using the simple model described by Grebowsky (1971). In agreement with the measurements, a long plasmatail is generated which tends to co-rotate with the earth in the post storm period.

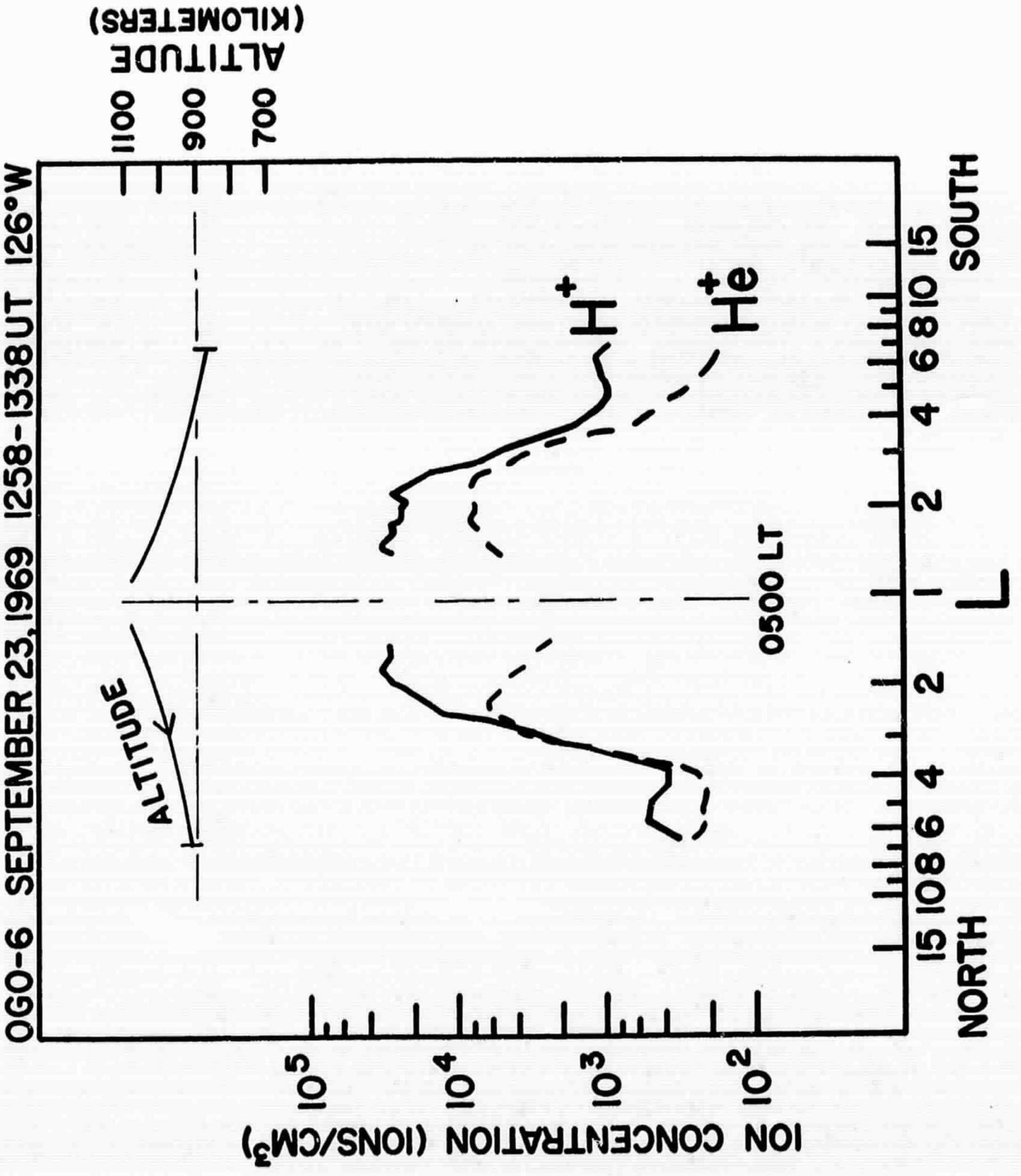

OGO-6 SEPTEMBER 23, 1969 1258-1338 UT 126°W
ALTITUDE (KILOMETERS)
1100
900
700
ALTITUDE
0500 LT
H+
He+
ION CONCENTRATION (IONS/CM3)
10^5
10^4
10^3
10^2
NORTH
15 10 8 6 4 2 1 2 4 6 8 10 15
L
SOUTH

Figure 1

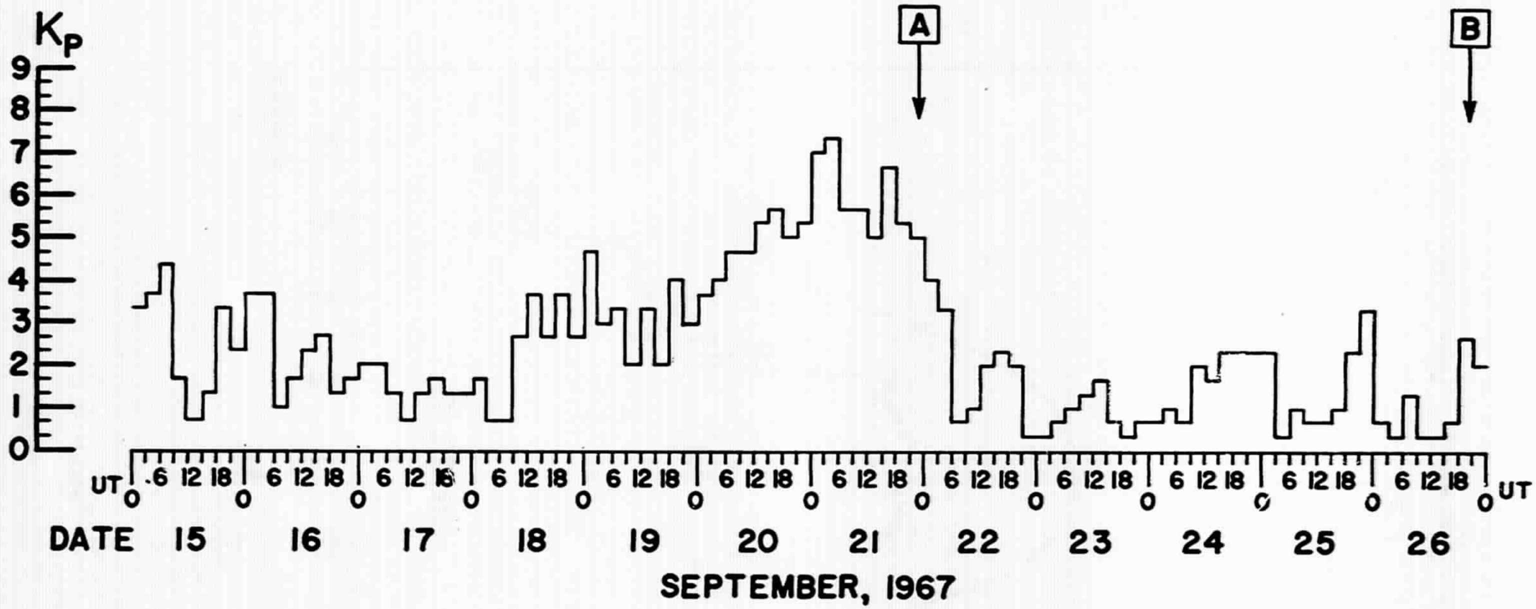
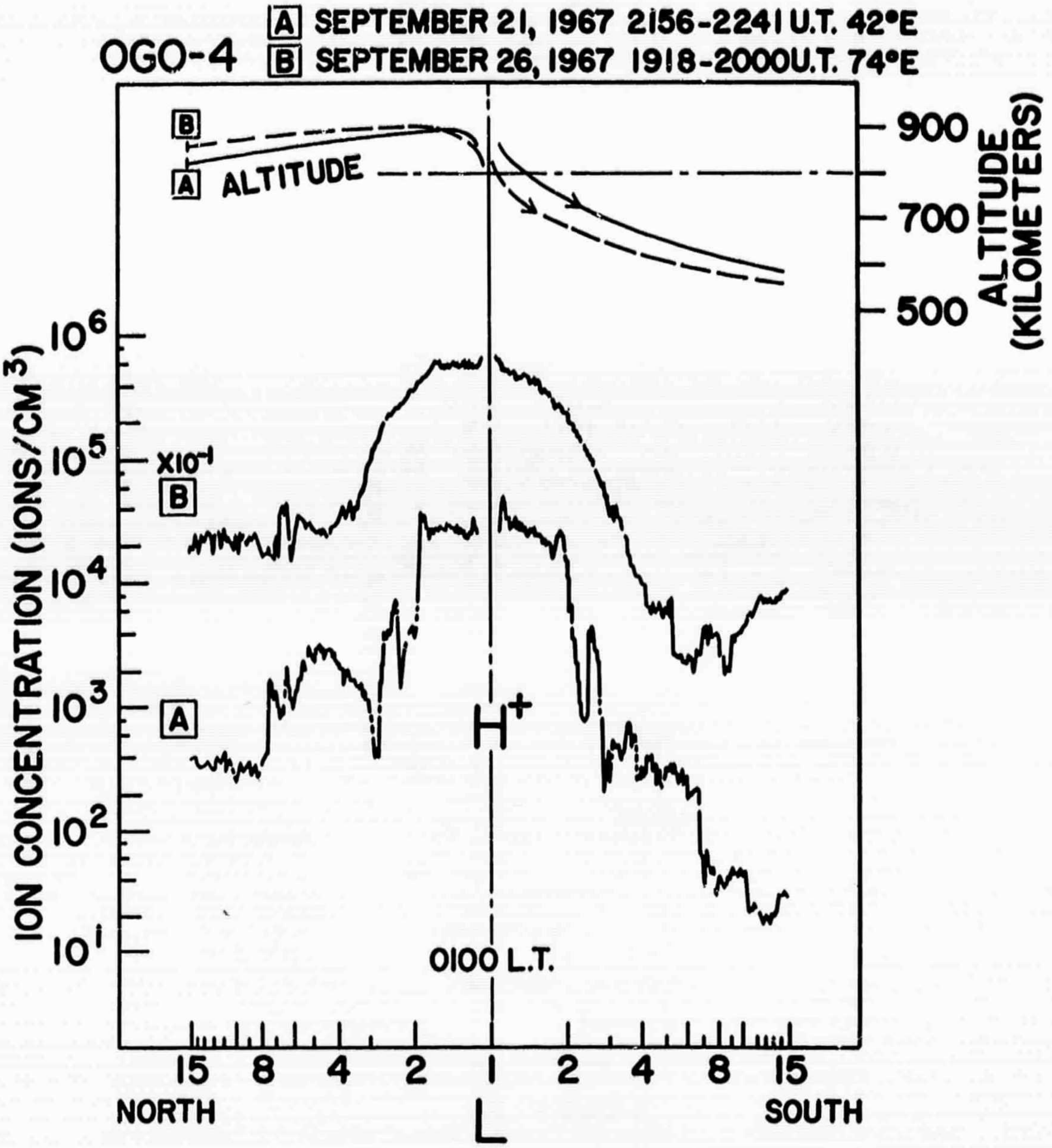
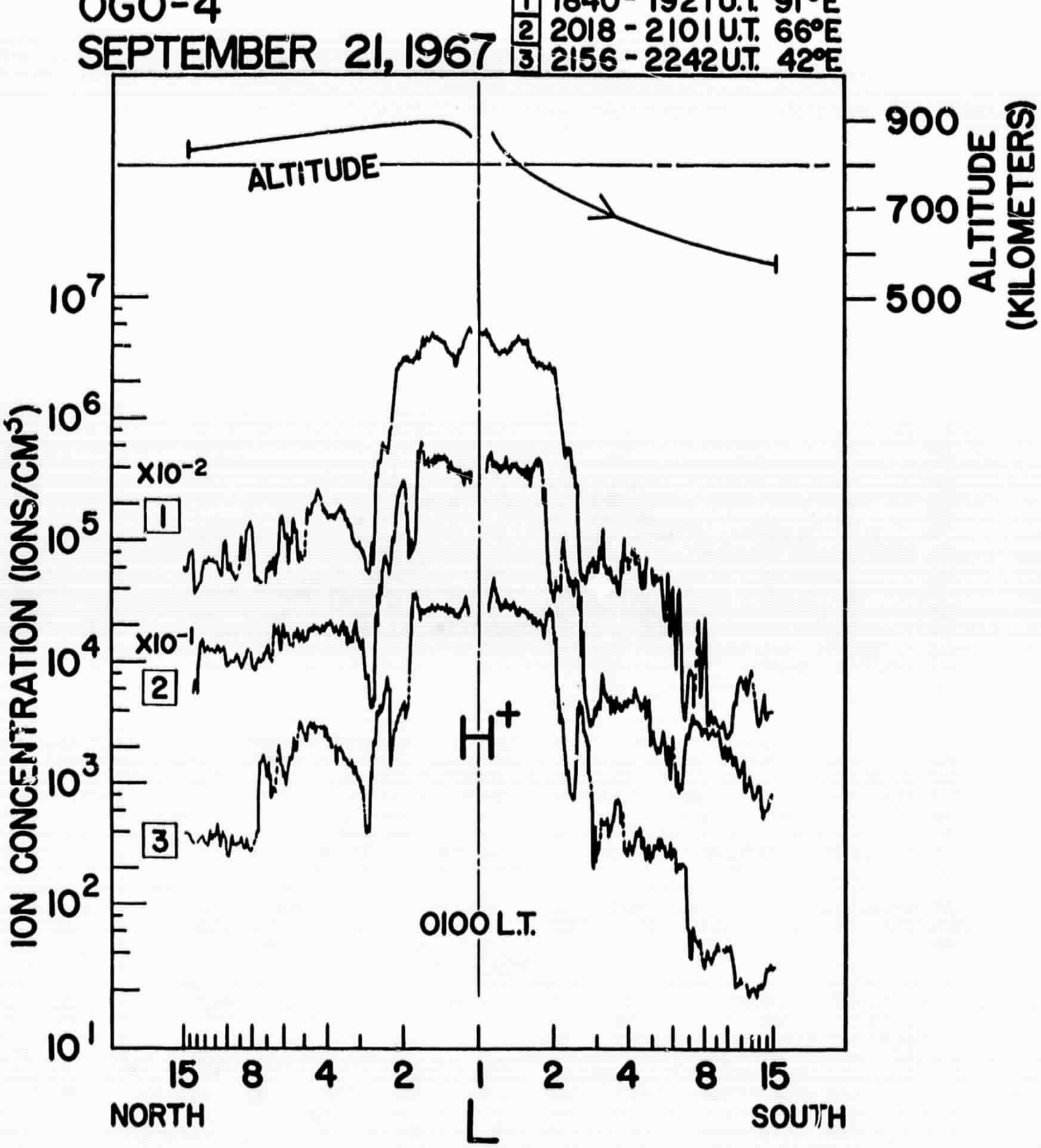


Figure 2



A SEPTEMBER 21, 1967 2156-2241 U.T. 42°E
OGO-4
B SEPTEMBER 26, 1967 1918-2000U.T. 74°E
B
A ALTITUDE
900
700
500
ALTITUDE (KILOMETERS)
ION CONCENTRATION (IONS/CM 3)
10^6
10^5
X10^-1
B
10^4
10^3
A
H+
10^2
10^1
0100 L.T.
15
8
4
2
1
1
2
4
8
15
NORTH
L
SOUTH

Figure 3



OGO-4
SEPTEMBER 21, 1967
1 1840 - 1921 U.T. 91°E
2 2018 - 2101 U.T. 66°E
3 2156 - 2242 U.T. 42°E
ALTITUDE
900
700
500
ALTITUDE (KILOMETERS)
ION CONCENTRATION (IONS/CM³)
10⁷
10⁶
X10⁻²
1
10⁵
X10⁻¹
10⁴
2
H⁺
10³
3
10²
0100 L.T.
10¹
15
8
4
2
1
2
4
8
15
NORTH
L
SOUTH

Figure 4

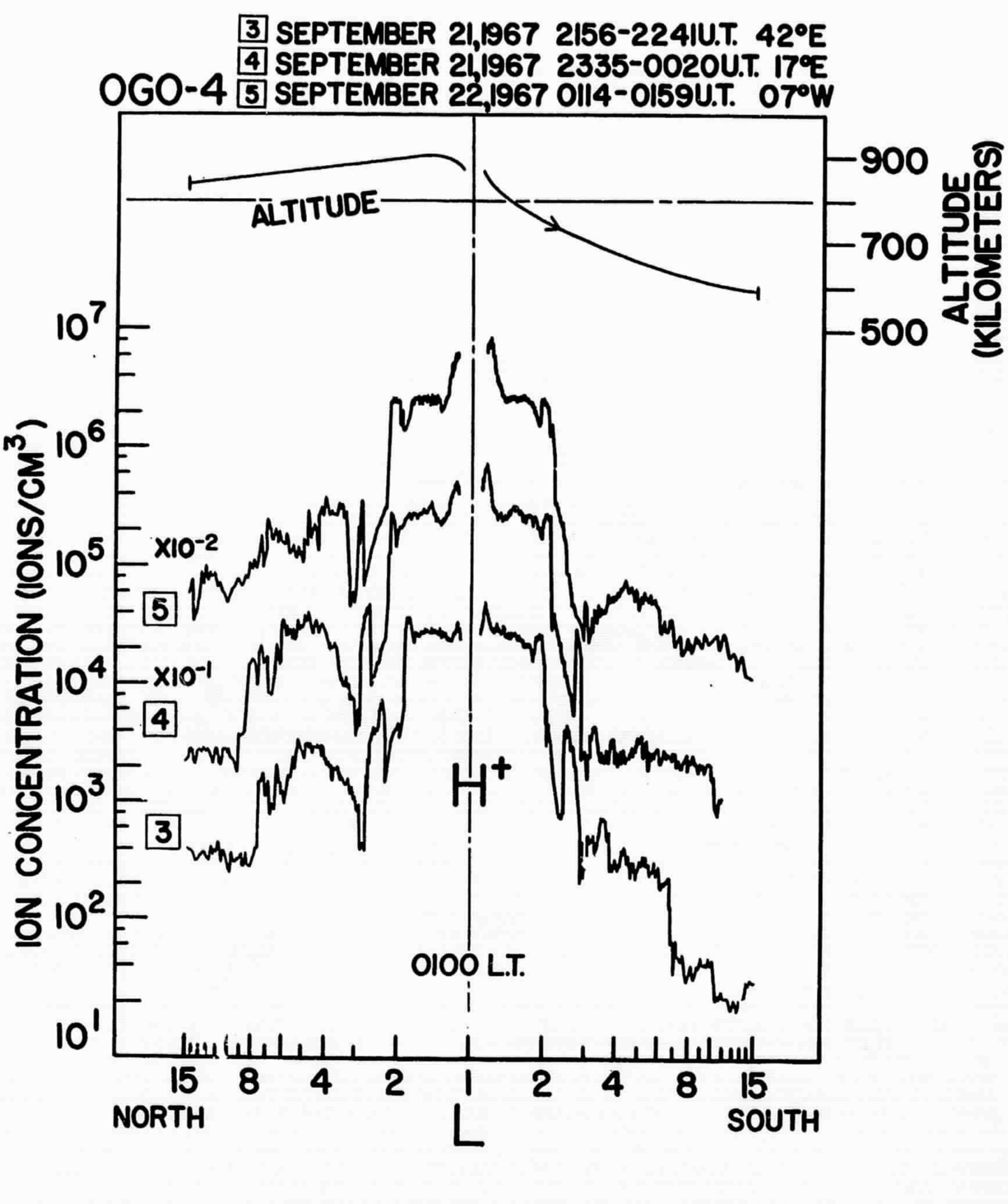

OGO-4
3 SEPTEMBER 21,1967 2156-2241U.T. 42°E
4 SEPTEMBER 21,1967 2335-0020U.T. 17°E
5 SEPTEMBER 22,1967 0114-0159U.T. 07°W
ALTITUDE
900
700
500
ALTITUDE (KILOMETERS)
ION CONCENTRATION (IONS/CM³)
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
X10⁻²
5
X10⁻¹
4
3
H⁺
0100 L.T.
15 8 4 2 1 1 2 4 8 15
NORTH
L
SOUTH

Figure 5

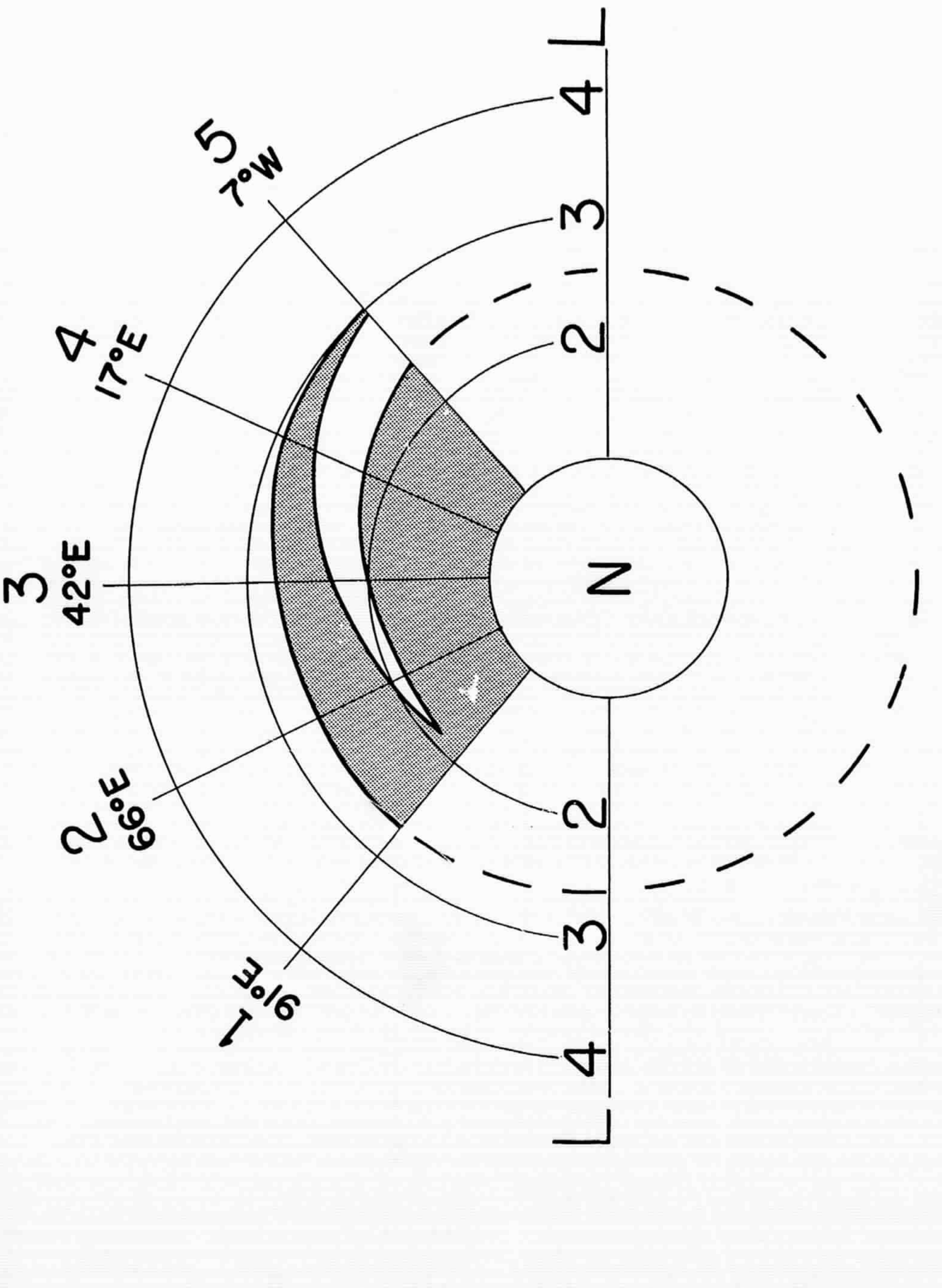


Figure 6

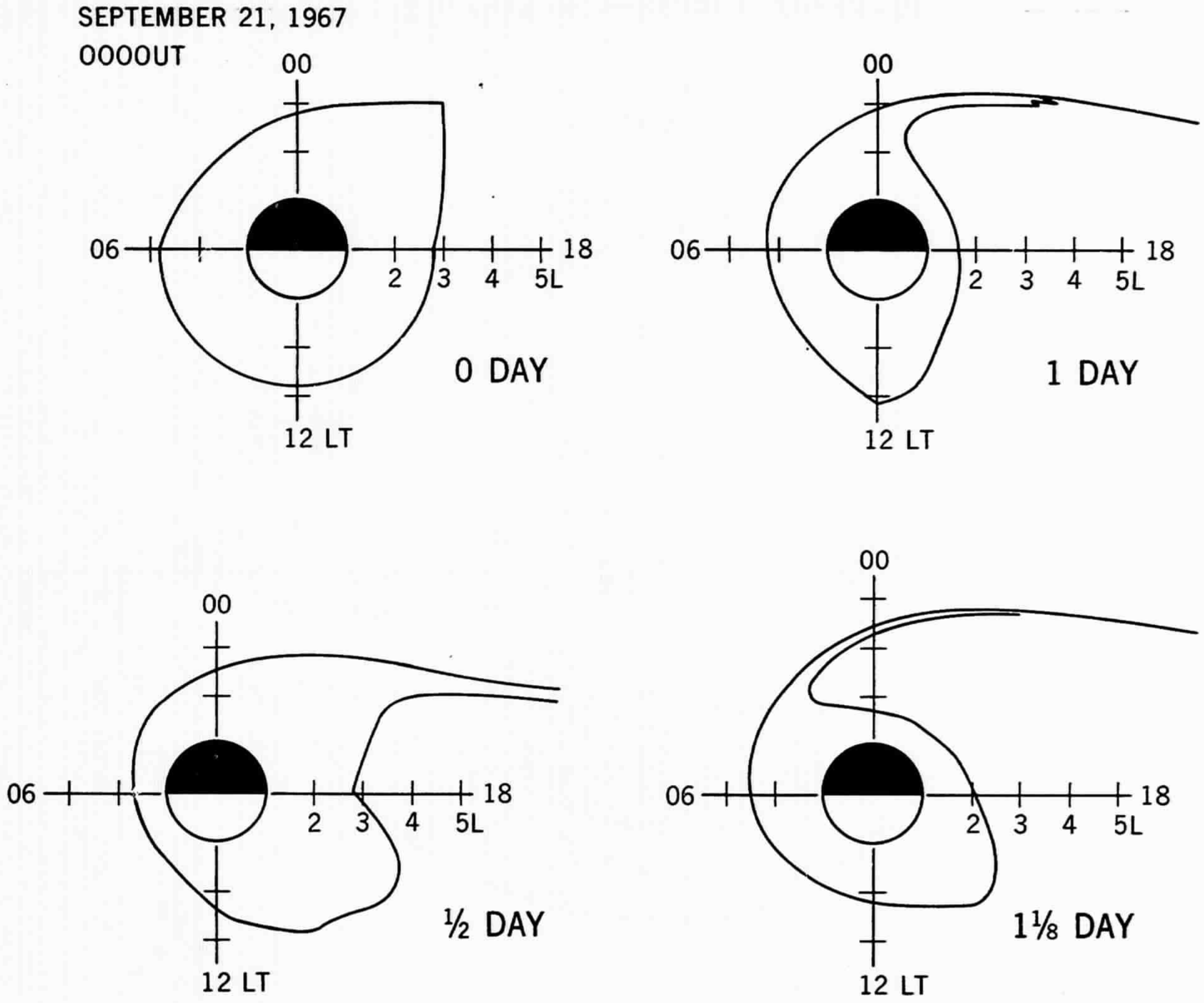

SEPTEMBER 21, 1967
0000UT
00
06
18
2
3
4
5L
12 LT
0 DAY
1 DAY
½ DAY
1⅛ DAY

Figure 7