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ABSTRACT

Direct measurements of the distributions of the thermal positive ions H^+ and He^+ in the magnetosphere reveal a distinct variability in the position and structure of the plasmapause. Such variability is observed to be most pronounced in the afternoon-dusk local time sector and is indicative of magnetospheric irregularities in the same region. As the OGO-3 satellite made progressive dusk-side (1500 - 1900 L.T.) and night-side (2200 - 0100 L.T.) passes during June-July 1966, the dusk-side plasmasphere was observed to exhibit an outward expansion or bulge, accompanied in some cases by considerable fine structure. In particular, the plasmapause was observed at L positions as distant as L = 7-8 in the afternoon-dusk sector, in contrast to positions near L = 5-6 observed near midnight on the same day and at comparable levels of moderate magnetic activity ($Kp \leq 3$). Within the bulge and just above the initial plasmapause structured plasma recoveries are observed, wherein $n(H^+)$ returns to concentrations of the order of 50-100 ions/cm^3 over intervals of 0.5 - 1.5L. Both the dusk-side

bulge and fine structure are observed to persist during periods of enhanced magnetic activity (Kp = 4-6). The above variability is superimposed on an average diurnal distribution of the plasmapause which is similar in shape to that deduced from whistler data during 1963, although the 1966-67 results indicate that the plasmapause may have expanded to a position generally more distant by about 1.5 - 2L. The evidence of the plasma bulge and the associated plasma fluctuations, is generally consistent with magnetospheric convection models proposed by Nishida and by Brice. These models predict both a similar local time asymmetry in the plasmapause radius, and a dusk-side region of plasma turbulence, generated at the interface of closed, co-rotating field lines and field lines which through convection are connected to the magnetotail, and thereby provide a plasma escape mechanism.

OBSERVATIONS OF IRREGULAR STRUCTURE IN THERMAL ION DISTRIBUTIONS IN THE DUSK-SIDE MAGNETOSPHERE

INTRODUCTION

Since the first evidence obtained by Gringauz [1963] and Carpenter [1963] that a distinct envelope of thermal plasma surrounds the earth in the form of the plasmasphere, considerable effort has been directed toward obtaining additional data sufficient to describe the global nature of this region. Extensive ground based whistler studies [Carpenter, 1966] have revealed a pronounced diurnal asymmetry in the radial extent of the plasmapause as observed in the equatorial plane. This asymmetry is in the form of an elongation or bulge located in the dusk sector of the plasmasphere as shown in Figure 1.

Direct measurements of the ion composition obtained from OGO 1 and 3 reported earlier have indicated that the plasmasphere is elongated in the dusk sector, relative to other local time positions in both the dayside and nightside magnetosphere [Taylor et al., 1965] [Brinton et al., 1968]. Plasma probe results from IMP-2 [Binsack, 1967] also suggest an increase in the average L position of the plasmapause toward the dusk meridian, although as was the case with the OGO-1 ion composition results, the data points available in the dusk region are limited.

In this paper, we present ion composition results obtained from

OGO-3 which reveal that the dusk-side plasmasphere is not only extended in L position relative to the plasmasphere in the midnight region, but is also frequently characterized by sharply structured concentrations of hydrogen ions. Some implications of these measurements, relative to other observations of thermal plasma in the magnetosphere and to existing magnetospheric models which predict dusk-side plasmasphere anomalies, are discussed. In addition, the long-term variation in the average position of the plasmapause, as observed during the decline of solar cycle 19 and the emergence of solar cycle 20, is examined.

Description of the Experiment

The ion composition experiment on OGO-3 consists of a Bennett radio frequency mass spectrometer which measures the ambient distributions of positive ions in the mass range 1-45 AMU. As operated, the Bennett spectrometer is strictly a thermal particle measurement device and does not provide composition data on charged particles with energies greater than a few electron volts.

The ion spectrum scan rate is 64 seconds, which provides a separation between successive samples of a given ion of about 250 km (or 0.1L) for satellite trajectories considered in this paper. The instrument sensitivity range extends from about 10^6 ions/cm^3 to a limiting sensitivity of approximately 1-5 ions/cm^3. Determination of the absolute value of the limiting sensitivity is in part dependent upon the type of processing techniques used for the reduction of the data. Since only part of the data used here has been processed to permit detection of particle concentrations below the 5 ions/cm^3 level, we have restricted the plots to this threshold level.

All of the data presented in the form of density profiles were obtained during the initial operation of OGO-3, (June-July, 1966) when the attitude control system provided orientation of the spectrometer axis to minimum angles relative to the spacecraft velocity vector. Accordingly, these data do not exhibit the ram-wake modulation associated with dynamic attitude-velocity changes, and thus the rapid fluctuations inherent in the distribution of the ambient plasma may be examined in detail. No attempt has been made to reconstruct possible fine structure detail in the spin mode ion distributions (obtained beyond July 1966), and these results are used only in describing the average position of the plasmapause. Further details of the ion composition experiment have been included in papers by Brinton et al. [1968] and Taylor et al. [1965].

EXPERIMENTAL RESULTS

Selection of Ion Profiles

The data to be discussed were obtained during the period June 1966 through August 1967. The detailed ion profiles presented are limited to the period June 17, 1966 through July 23, 1966 when OGO-3 was attitude controlled. An example of the H^+ and He^+ distributions observed in the plasmasphere under conditions for which the plasmapause is observed as a sharply defined boundary is given in Figure 2A. Within the plasmasphere, gradual decrease in the concentrations of both of the light ions with L and altitude is rather typical of the ion profiles obtained from OGO-3 during quiet to moderate magnetic activity ($Kp \leq 3$). The parallelism between the H^+ and He^+ distributions, with $n(H^+)/n(He^+) \approx 100$ is also typical of much of the data. The abrupt decrease in both $n(H^+)$ and $n(He^+)$ near $L = 6$ and about 30,000 km. is representative of other plasmapause crossings obtained under similar conditions of magnetic activity, local time, and trajectory-to-magnetic field orientation. As the above parameters change, conditions occur for which the observed H^+ and He^+ distributions at the plasmapause boundary are not as sharply defined. In Figure 2B a pair of H^+ and He^+ profiles obtained under different conditions of magnetic activity and local time reveal a noticeable difference in the general slope of the ion distributions relative to L and altitude, and in particular, a distinct difference in the plasma structure near the plasmapause. In Figure 2B the rapid fluctuations in $n(H^+)$ beginning near $L = 5$ show that the plasmapause may have a very complex structure, exhibiting wave-like irregularities near the boundary. In such a situation, the selection of the L position of the plasmapause is naturally somewhat arbitrary. For this study we have adopted the criterion that the plasmapause is identified by the occurrence of the first decrease in $n(H^+)$ of an order of a magnitude or more, the decrease being maintained during at least three consecutive samples of that ion. In the case of the attitude control mode data such as shown in Figure 2A and 2B, this criterion is usually rather easily identified. As a result of the modulation encountered in the spin mode data, however, the selection of the exact position of the plasmapause is sometimes more difficult, and for this reason we have selected from the total number of available satellite passes a sample of events for which the structure of the plasma distribution and the location of the plasmapause are clearly evident.

Diurnal Variation of Plasmapause Position

In Figure 3 the L positions of all identifiable plasmapause events yet available from OGO-3 are presented relative to their local time coordinate. Although no attempt has been made to remove the scatter produced by the effects of changes in magnetic activity and season, the dusk-side asymmetry, or bulge, in the distribution of the plasmasphere is apparent. The dashed lines near 1800 L.T. indicate regions of plasma recovery in which the initial (inner) plasmapause crossing is followed by periods of significant plasma recovery, wherein $n(H^+)$ may rise from the threshold concentration (5 ions/cm^3) to concentrations as large as 500 ions/cm^3. The characteristics of the plasma recovery region are discussed more fully in a later section.

Comparison of Midnight and Dusk Results

In order to examine the dusk-side plasmasphere bulge in more detail, and to contrast it with observations of the plasmasphere at another local time, we have selected a series of inbound and outbound passes which provide information on the position and character of the plasmapause as observed near midnight on inbound trajectories, and near dusk on outbound trajectories, obtained during the same day. Referring to Figure 4, the satellite trajectory typical for these selected passes is such that the L = 6 position on the inbound and outbound legs is traversed within a period of about 3.5 hours universal time. Thus it has been possible to select passes for which distinctly different local time regions of the plasmasphere may be examined within a comparatively short time interval, reducing the likelihood of structural changes caused by magnetic storm effects. In addition, the local time change in the position of the satellite in traversing the space between L = 4 and L = 8 on both the inbound and outbound trajectories is less than 2 hours local time, so that differences in the plasmapause structure observed from pass to pass may be interpreted primarily as evidence of irregularities in the azimuthal distribution of the plasma.

In Figure 5 a pair of H^+ distributions obtained on July 3, 1966, during low to moderate magnetic activity (Kp-24 = 2+), reveal a considerable difference in the position of the plasmapause observed in the dusk and midnight local time sectors. As OGO-3 moved inbound (5B) the plasmapause was observed at the position L = 6.5 (2336 L.T.; 34,400 km.). On the outbound pass (5A), the plasmapause was observed initially at about L = 6.5 (1750 L.T.; 28,500 km); followed by a fluctuating plasma recovery between about L = 7.5 and the final plasmapause observed at about L = 8.9 (1831 L.T.; 41,000 km.); thus, while the initial position of the plasmapause observed in the two different local time sectors is quite similar, the boundary in the dusk sector is followed by an anomalous bulge or recovery of plasma extending over the considerable distance of approximately 1.5L (7,500 km.). It is also interesting to note the pronounced structure in the H^+ distribution inside the plasmasphere in the dusk region, relative to the comparatively smooth distribution of H^+ within the plasmasphere in the midnight sector.

In Figure 6 a comparison of proton distributions obtained on July 21, 1966, shows that the dusk-side asymmetry in the plasmapause distribution is maintained during periods of more disturbed magnetic conditions (Kp-24 = 4-). The inbound profile (6B) shows a sharply defined plasmapause near L = 5.2 (2257 L.T.; 24,600 km.). The outbound profile (6A) reveals considerable fine structure in the plasma distribution within the plasmasphere, beginning just below L = 6 and extending outward to the location of the plasmapause at about L = 8.3 (1630 L.T.; 26,000 km.). In this case, while the altitude or radial distance of the plasmapause is not noticeably different between the midnight and dusk-afternoon regions, the L position of the plasmapause is considerably different, with the dusk plasmapause position being approximately 3L more distant than the boundary observed near midnight. In both local time sectors the plasmapause position observed on July 21 is closer to the earth than that observed on July 3 when the magnetic activity was comparatively reduced, which is consistent with the general observation that the plasmasphere contracts inward during periods of enhanced magnetic disturbance [Taylor et. al., 1968] [Binsack, 1967] [Chappell et al., 1969].

The afternoon-dusk asymmetry in the plasmapause position is maintained during periods of pronounced magnetic disturbance as shown in Figure 7. Both the inbound and outbound proton distributions reveal the effect of an extensive magnetic storm which began at 2103 UT on July 8. On the inbound pass (7B) the plasmapause is observed to be sharply defined and compressed to the very low position of L = 3.3 (0028 L.T.; 13,000 km.). The outbound profile (7A) exhibits very unusual characteristics including a sharply reduced proton distribution near L = 2.3 followed by a rapid falloff of H^+ up to the position near L = 4. The sharp recovery of plasma between L = 4 and L = 5 is characteristic of recoveries observed at high L positions during reduced magnetic activity. Once again the evidence of a pronounced compression of the plasmasphere during the magnetic storm is consistent with other OGO results.

Long Term Variation of the Average Plasmapause Position

In Figure 8 we examine possible evidence of long term variability in the average position of the plasmapause by comparing direct and indirect observations of the boundary obtained from (1) OGO-3 ion composition, (2) ground based vlf (Carpenter's data of Figure 1), and (3) Imp-2 Faraday cup results [Binsack 1968]. The similarity in the plasmapause asymmetry in the afternoon-dusk sector as observed by both the vlf and ion composition measurements is evident. Although Binsack's data is unfortunately quite limited in the afternoon-dusk sector, his results do provide a suggestion of the beginning of the plasmapause bulge near 2200 hours local time.

The average positions of the plasmapause observed by both IMP-2 and OGO-3 during 1965-66 and 1966-67, respectively, differ noticeably from the average boundary determined from the vlf results in July-August, 1963. In general, the OGO-3 and IMP-2 results show the boundary to be displaced outward from the earth. The IMP results give an average boundary position which lies between about 0.5 - 2L more distant than the vlf boundary, while the OGO boundary is consistently 1.5 - 2L more distant than the vlf boundary. The vlf data were obtained near the minimum of solar cycle 19, under conditions of moderate, steady magnetic agitation with Kp = 2-4. The IMP data were obtained during still lower solar activity, at solar minimum, while the OGO data were taken at higher solar activity, during the upswing of solar cycle 20. Both the OGO and IMP data have been sorted to provide a similar magnetic background, under the condition that Kp = 2-4, during the 6 hour period preceding the measurement. It was, of course, not possible to compare these data sets under identical magnetic conditions. These results indicate that while the general character of the diurnal distribution of the plasmapause may be maintained for a long term period, a significant variation of the average L position of the boundary may occur between contrasting periods of magnetic, and possibly solar activity.

DISCUSSION AND INTERPRETATION

The Dusk-Side Plasmasphere Bulge

The OGO-3 ion results are unfortunately of insufficient temporal and spatial resolution to completely identify the characteristics of what may be a rather permanent asymmetry in the average position of the plasmapause in the afternoon-dusk sector. The close comparison of results obtained within the spacing of but a few hours on the same day and under quiet magnetic conditions, however, shows that this anomalous region is indeed persistent in the form of a significant plasmasphere expansion accompanied by regions of structured plasma recovery. Both the position and magnitude of the observed asymmetry appear to agree favorably with magnetospheric models proposed by Nishida [1966] and by Brice [1967]. The thermal plasma distributions in the magnetosphere which are suggested from these models are shown in Figure 9A and 9B. In both models the combined effects of plasma convection induced within the magnetosphere by the interaction of the solar wind with the magnetic field that surrounds the earth and plasma co-rotation set up by the rotation of the earth's closed magnetic field system are examined. These mechanisms result in the formation of a plasma envelope which has the same general distribution in local time as we observe in the ion composition data. Both models predict a region of plasma turbulence to be created at the interface between the maximum opposing plasma flow regimes, and it is in this same region (between 1800 and 2400 hours L.T.) that we observe the anomalous bulge and associated fine structure irregularities in the proton distributions.

The contraction of the plasmasphere bulge during periods of enhanced magnetic activity is also consistent with the magnetospheric models decribed above. With increased magnetic agitation and an attendant increase in the solar wind induced convective flow, the equilibrium boundary between the convective and the co-rotational flow will be displaced inwards toward the earth, and as the models predict, the plasmapause will be observed at lower L positions. Whether the bulge envelope may change dimensions and move toward earlier or later local times under conditions of increased or reduced magnetic agitation cannot be deduced from our results. If, as suggested by Carpenter [1969] an intermittent or gusty tailwind results in a shifting bulge amplitude and position, such effects would be averaged out in our results. However, such fluctuations in the wind could enhance the turbulent region and explain the pronounced structure which we frequently observe in the dusk-side data.

An interesting geophysical question to which our results pertain is that of whether the plasma in the bulge region exhibits the same characteristics as that within the inner plasmasphere, or in contrast reflects characteristics of a different origin. If, as a result of the draining of high latitude field tubes by the action of mechanisms such as the polar wind [Banks, 1969], ionospheric plasma is transported to the magnetotail and then returns to the inner magnetosphere by means of large-scale magnetospheric plasma convection, then the thermal component of the plasma in the vicinity of the turbulent region, just above the plasmapause, might well resemble the ambient corotating plasma. If, on the other hand, the plasmapause represents a distinct interface between plasma of terrestrial and solar wind origin, we might expect to observe significantly different characteristics in the form of higher energy distribution of the plasma in the bulge region. The evidence from our data, however, suggests that the plasma observed just above the initial plasmapause, in the region of pronounced plasma fluctuations, is identical in nature (within the limits of our detection scheme) to the plasma measured within the plasmasphere itself. In particular, the spectral characteristics of the ion peaks of hydrogen observed within the closed plasmasphere and just beyond the plasmapause are essentially identical to the spectral patterns observed in the laboratory where thermal plasma is generated for calibration purposes. Thus our measurement provides no evidence of a sudden enhancement in the average temperature or energy of the thermal component of the plasma beyond the plasmasphere. Accordingly, our results appear to be consistent with Nishida's model which suggests that this region may be populated by thermal plasma being returned from the magnetotail.

Long Term Variability in the Plasmapause Location

The comparison of the average position of the plasmapause observed in 1963 by Carpenter with our results, for similar conditions of magnetic agitation (Kp = 2-4), indicates that in 1966-67 the plasmasphere may have expanded to an average position which is about 1.5-2L more distant than the average position measured earlier, nearer the minimum of solar cycle 19. According to Nishida's model, the expected dependence of the position of the plasmapause (at 1800 L.T.) upon the speed of the solar wind induced plasma convection velocity is such that for high velocities near 500 km./s. the plasmapause should move to low L positions, near $L \simeq 4$, while for lower velocities, near 100 km./s., the plasmasphere should expand to $L \simeq 6$. If we assume a higher average solar wind velocity during 1966-67 when the sunspot number level was about a factor of 2 higher than during the 1963 period, the model would predict a boundary position relatively <u>closer</u> to the earth. Such a predicted result is just the opposite of that which is observed, if we attribute the difference in boundary positions to be the result of long term (solar) rather than short term (magnetic) phenomena. The IMP results observed at the lowest solar activity levels, however, do show the boundary to be a higher L positions than the vlf results, for all local times observed.

Such interpretations of the apparent movement of the plasmapause are speculative, however, due to our limited knowledge of the solar and magnetic conditions surrounding the measurements. In the area of solar wind effects, since a direct relationship between solar wind velocity and Kp has been deduced by a number of workers [Axford, 1968] we might expect a similar convection velocity amplitude and therefore a similar plasmapause position for the three periods. In addition, all of the compared data were obtained during relatively low solar activity, when solar wind variations may not be pronounced. Since no distinct relationship between sunspot number and wind velocity has been deduced for this period, we have no direct basis for attributing the apparent boundary movement to solar wind effects.

With regard to magnetic activity effects, the interpretation is also uncertain. Although we have attempted to sort the data for similar magnetic conditions, too little is known about the significance of the timing and spatial extent of magnetic storms to permit a comparison of data taken under 'identical' conditions. Thus it is possible that the data sets have been averaged too coarsely and are perhaps biased toward either quiet or disturbed conditions. Clearly, the timing of a measurement during either the development or recovery phase of a substorm is significant in determining where the boundary will be observed, and we have not accounted for this variable in our analysis.

Another caution should be exercised in comparing the various plasmapause results, namely the consideration of coordinates. In the vlf results, as in many magnetospheric models, coordinates are specified within the equatorial plane, so that distance in earth radii is equivalent to L. In these and other satellite results, however, plasmapause coordinates are frequently specified in L, so that depending upon the latitude of the satellite, the distance (km) to the boundary may be quite different for two observations even though the L coordinates may be identical. Significantly, however, all of the OGO-3 data obtained on the June-July 1966 inbound passes occurred between $\pm 10°$ dipole latitude so that the differences between L and radial position for those plasmapause crossings are trivial. These data consistently show the boundary near midnight to be about 1.5L more distant than that observed during 1963. Furthermore, if as indicated by earlier results [Carpenter, 1966], [Brinton et al., 1968], the thermal plasma is constrained by the magnetic field lines and is distributed in a toroidal belt, the boundary of which is approximated by a field line, our general comparison of ground and satellite data in the L coordinate is rigorous. By comparing the results using an undistorted field model we may have overlooked L position differences due to solar wind induced compression and expansion of magnetic field lines. However, since most of the data are obtained within the L=6 region, we do not expect errors as large as 1.5 - 2L, will result from such effects.

Whether the above complications have limited the validity of the data comparison remains to be examined further. It is clear that the mechanisms controlling the distribution of the magnetospheric thermal plasma are complex and that while gross features seem to persist, caution should be exercised in describing either the 'average' profile, or position of the plasmapause. Clearly, more data, in the form of simultaneous high resolution observations at separate locations in the magnetosphere and from the ground are required to better describe the behavior of the plasmasphere.

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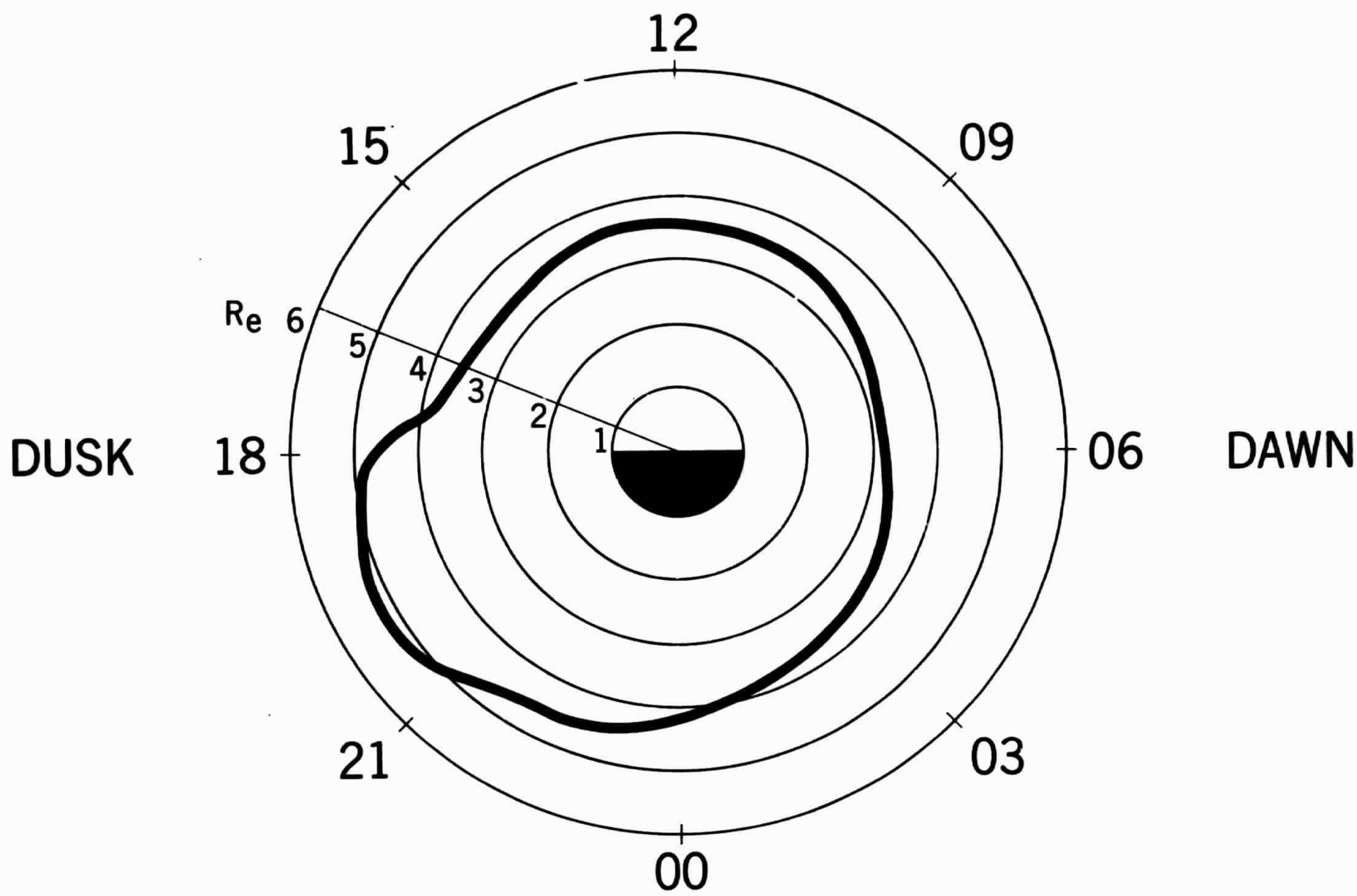


Figure 1–Average equatorial radius of the plasmapause or whistler knee versus local time during periods of moderate geomagnetic activity, in July and August, 1963. [after Carpenter, 1966.]

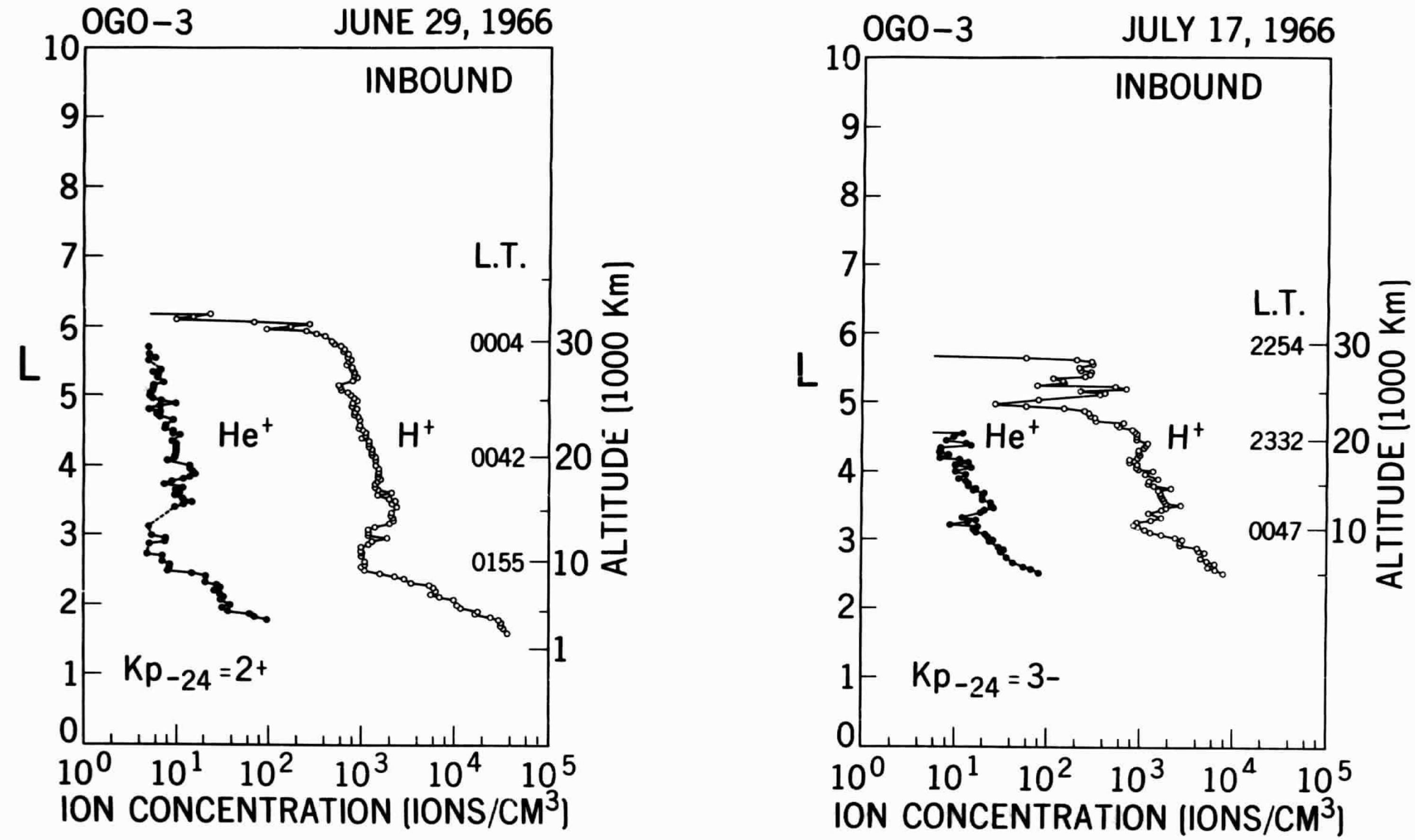


Figure 2–Examples of sharply defined and structured plasmapause boundaries observed on June 29 and July 17, 1966 respectively. In these and other examples not shown the He^+ distribution typically follows H^+ with a relative concentration of about 1%. The symbol Kp-24 indicates the maximum value of Kp in the 24 hour interval preceding the time of the plasmapause crossing.

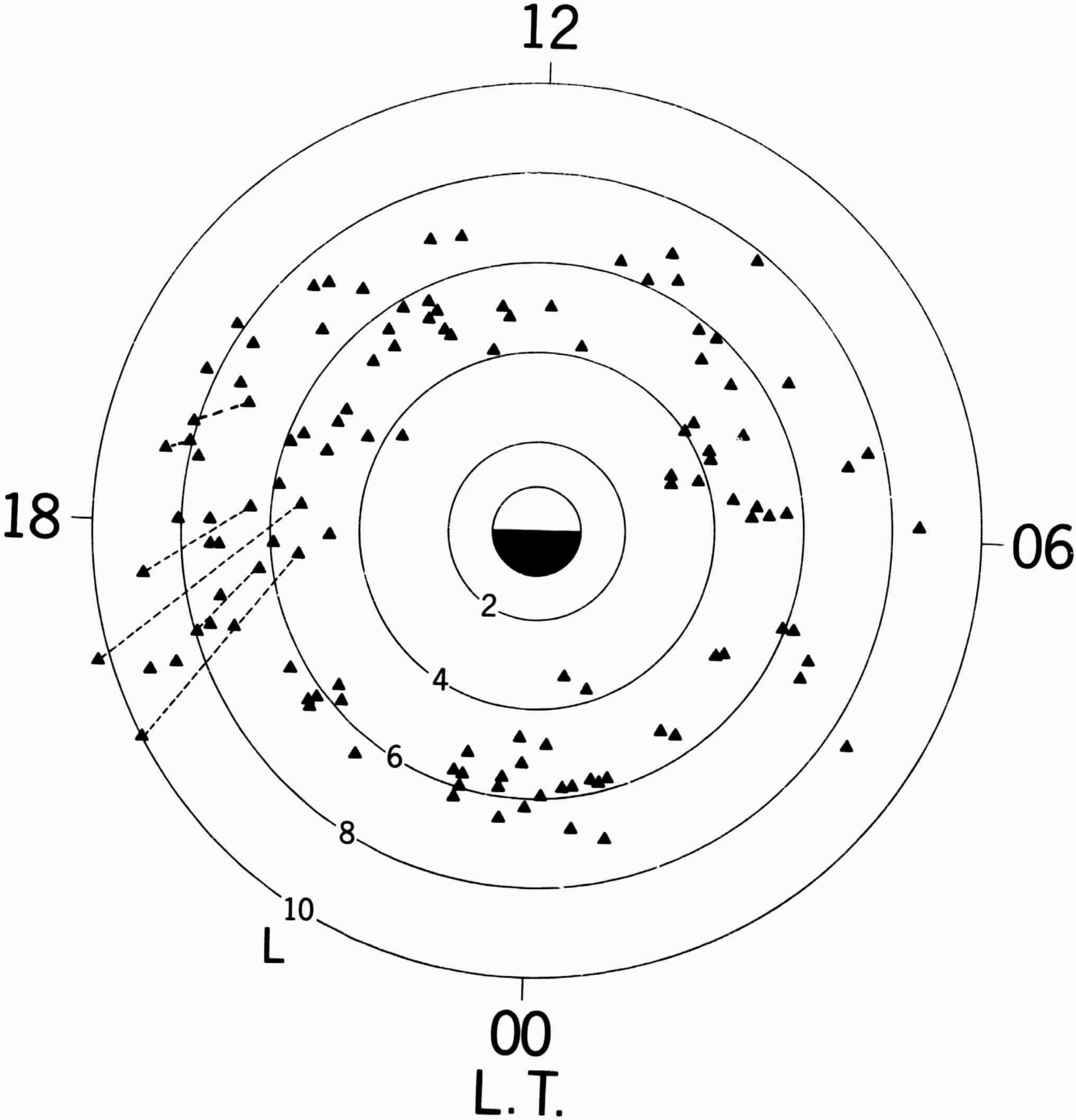


Figure 3–Locations of plasmapause crossings observed from OGO-3 during the interval June 1966 to August 1967. Dashed lines indicate regions of plasma recovery, where initial (inner) plasmapause is followed by fluctuating plasma recovery and a final (outer) depletion of plasma. Data are not sorted for Kp variation.

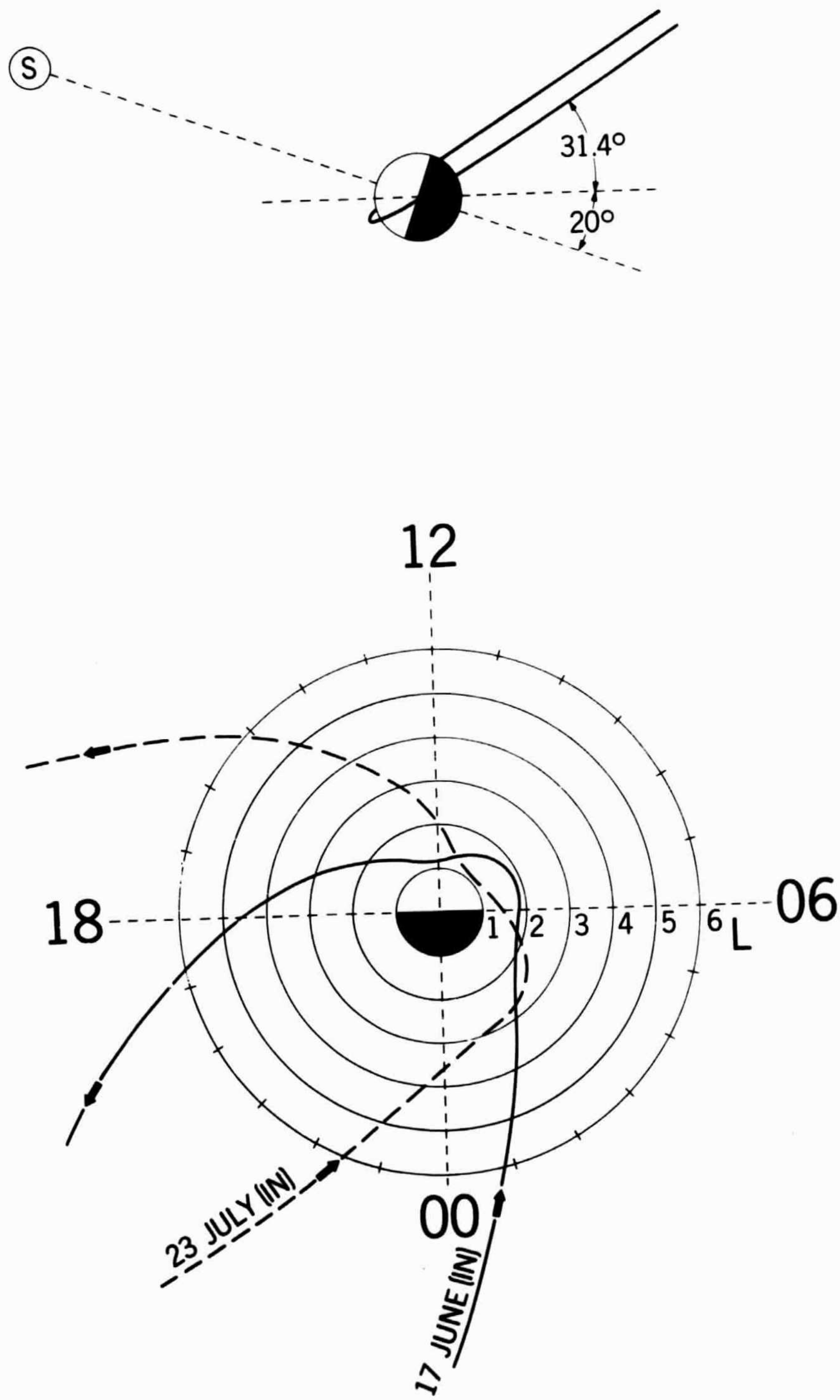


Figure 4–Characteristics of OGO-3 orbit during June-July 1966. Earth is viewed from above; and displacement between geographic and dipole equatorial planes is neglected. Solid and dashed curves are plots of satellite L and local time position for inbound and outbound arcs. Perigee, 316 km., inclination 31.4°, and period, 48 hr. 35 min.

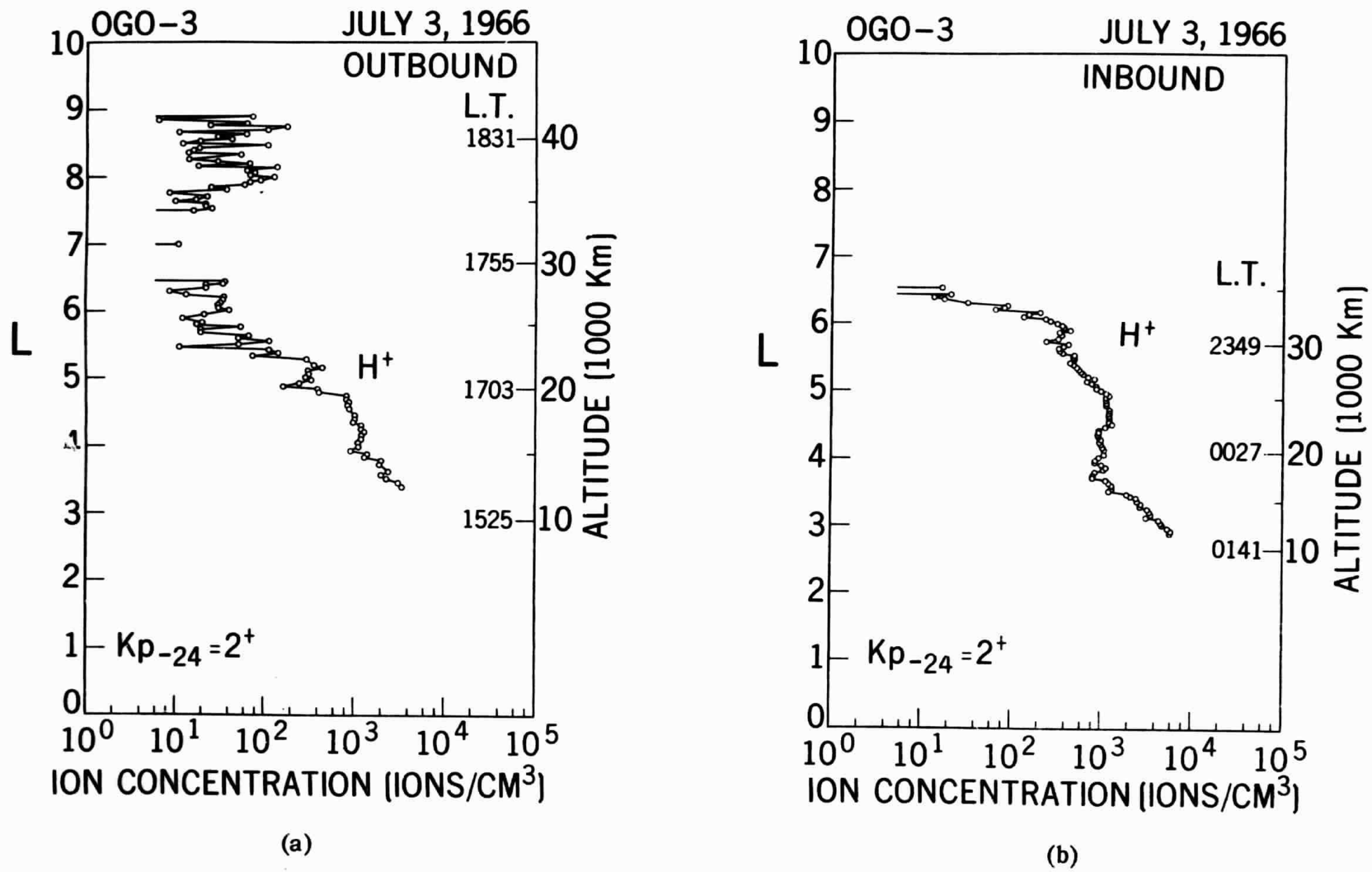


Figure 5–Inbound and outbound profiles of H^+ observed on July 3, 1966, during low to moderate magnetic activity.

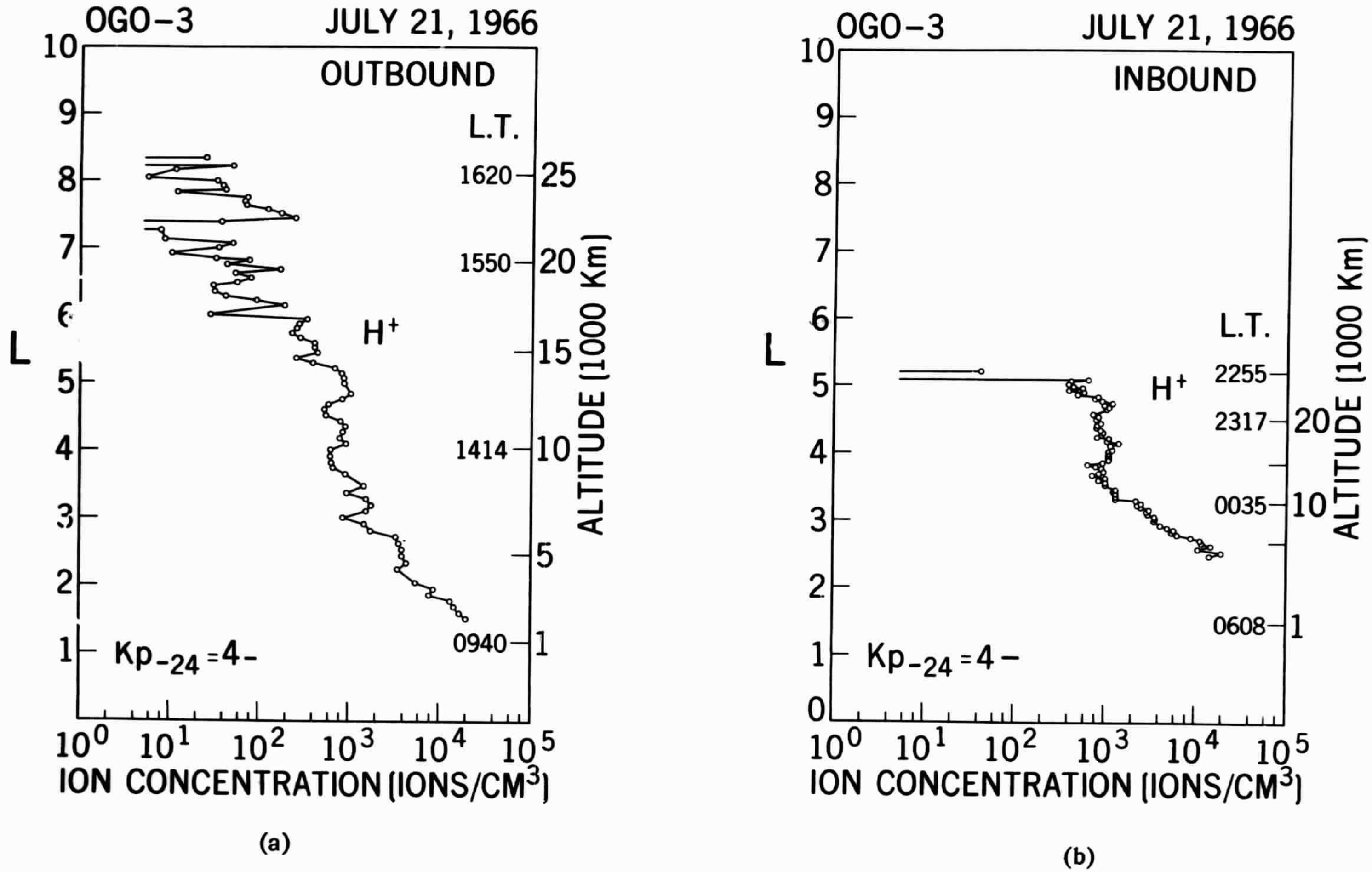
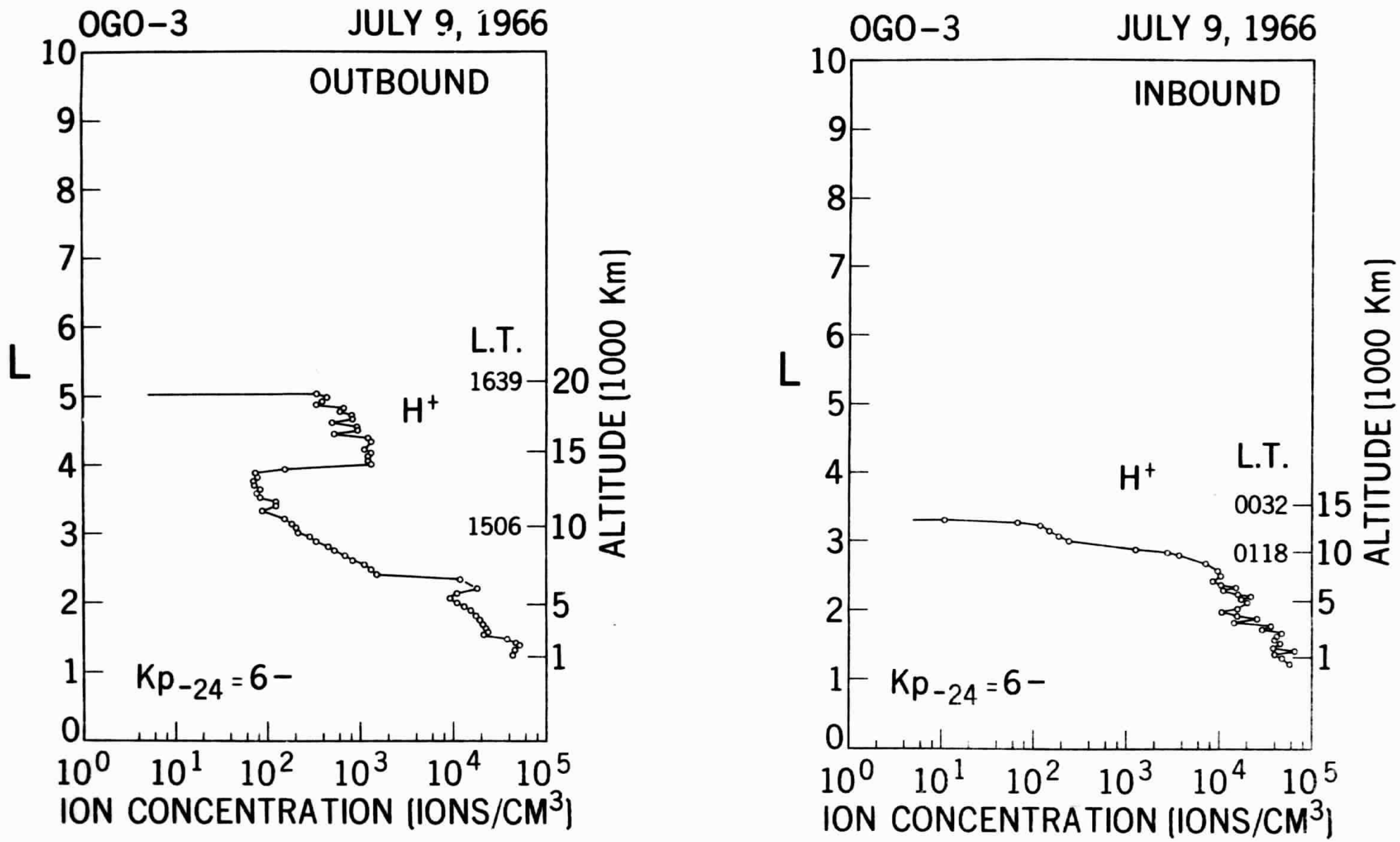


Figure 6–Inbound and outbound profiles of H^+ observed on July 21, 1966, during moderately disturbed magnetic activity.



(a) (b)

Figure 7–Inbound and outbound profiles of H^+ observed on July 9, 1966, during significantly disturbed magnetic conditions.

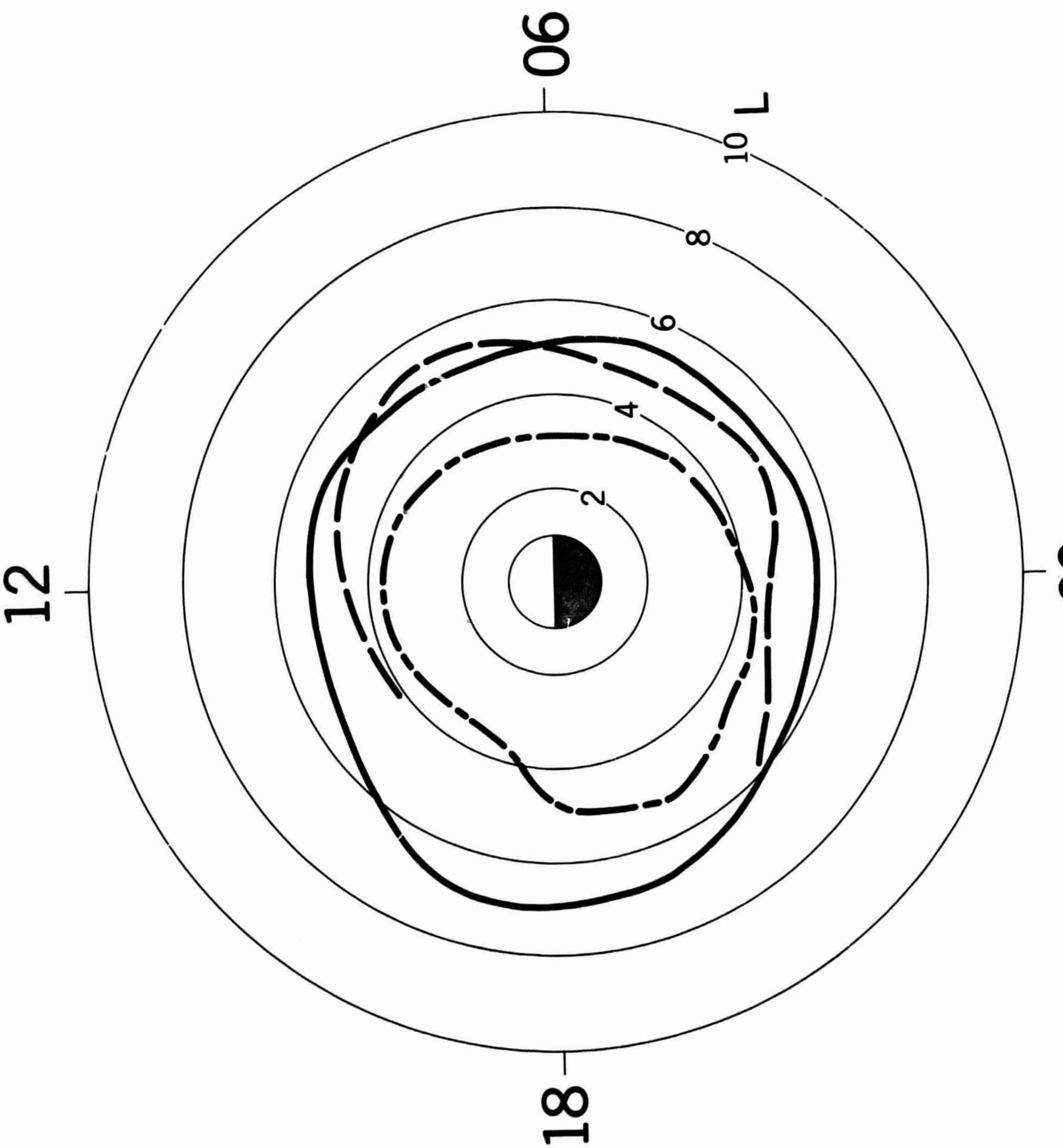
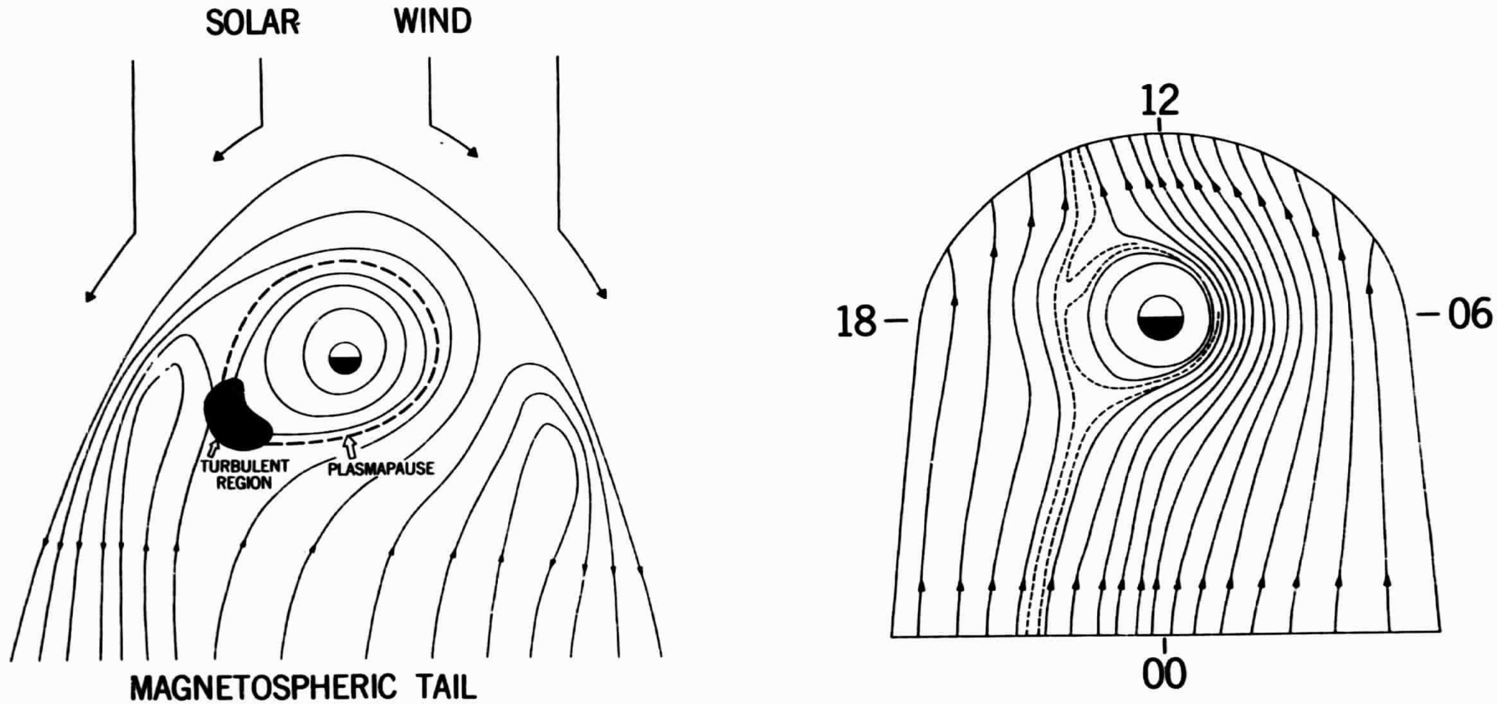


Figure 8–Comparison of average diurnal variation of plasmapause observed by vlf techniques in 1963 [Carpenter 1966 - dot dashed curve], by plasma probe in 1965-66 [Binsack, 1967-dashed curve, and by ion spectrometer in 1966-67 - solid curve. All data are sorted for Kp = 2-4. Binsack and OGO-3 data were observed at various L positions within the magnetosphere, while Carpenter data refers specifically to distance (or L) in the equatorial plane.



(a) (b)

Figure 9–Plasma convection models developed by (A) Nishida [1966] and (B) by Brice [1967]. Streamlines indicate direction of plasma flow induced by interaction of solar wind and earths magnetic field. Boundary between groups of flow lines indicates plasmapause, with diurnal asymmetry pronounced in the afternoon-dusk region.