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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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November 7, 1969

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ABSTRACT

Direct measurements of thermal ion distributions in the magnetosphere reveal a distinct variability in the position and structure of the plasmapause. The observed variability is generally pronounced in the afternoon-dusk local time sector, and is also observed at other locations during the recovery phase of a magnetic storm. Progressive passes of the OGO-3 satellite have verified an outward expansion or bulge in the dusk-side plasmasphere, accompanied by considerable fine structure, and similar fine structure near the plasmapause outside the dusk region during the recovery phase of a storm. In addition, a correlation with Pc-1 data further supports this evidence of plasma irregularities in the dusk and in the post-storm recovery regions. A limited Pc-1 data sample indicates that these geomagnetic micropulsations may be generated and propagated near the plasmapause. A correlation obtained in the dusk and midnight-to-dawn local time sectors under quiet to moderate magnetic conditions ($K_p \leq 3$) provides good agreement in the plasmapause and Pc-1 occurrence positions, and

in the proton concentrations near the boundary, including evidence of fine structure in the proton distribution just below the plasmapause. These preliminary results indicate that Pc-1 excitation is closely related to the irregular structure of the plasmapause and is particularly favorable in the diurnal 'plasma bulge' region of the equatorial plasmapause, or in a region in which the plasma is recovering from an earlier ion depletion. It is shown that the plasmapause and its relation to micropulsations may be examined in terms of the Alfvén velocity or index whose altitude profile is characterized in the form of a 'hump', accompanied in some cases by considerable fine structure, at the height of the plasmapause.

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INTRODUCTION

Background

Some earlier studies of the plasmapause have concentrated primarily on its large-scale structure as observed in the form of a field-aligned envelope of the thermal plasmasphere [Gringauz, 1963; Carpenter, 1963]. Many plasmapause crossings have been identified in satellite data, including results from ion mass spectrometers on OGO-1 and -3 [Taylor et al., 1965, 1968, 1970; Brinton et al., 1968], OGO-5 [Chappelle et al., 1970], plasma probes on IMP-2 [Binsack, 1967], traps on Electron-2 and -4 [Bezrukikh, 1968], VLF receivers on OGO-1, -3 [Carpenter et al., 1969], and -4 [Taylor et al., 1969]. While the reported plasmapause positions are in general agreement both among themselves and with ground-based whistler measurements of the plasmapause radius [Carpenter, 1966, 1967], some of the observations indicate complex irregularities of the plasmapause in its position and structure, although these irregularities have not yet been fully investigated.

Direct measurements of the thermal ion distributions throughout the plasmasphere obtained from OGO-1 and -3 have revealed a variety of plasmapause irregularities, particularly during the initial operation of OGO-3, when the attitude control system permitted orientation of the spectrometer axis to minimum angles relative to the spacecraft velocity vector. One feature of the observations is a pronounced local time asymmetry in the form of an elongation or bulge, comparable to that observed in earlier whistler experiments [Carpenter, 1966, 1970]. The dusk-side bulge is accompanied in some cases by regions of structured plasma recovery just above the plasmapause, a condition which is indicative of magnetospheric irregularities in the same region [Nishida, 1966]. Another feature of the OGO-3 data is a region of complex fine structure in the proton distributions located near the plasmapause, during the recovery phase of a magnetic storm, an observation which is indicative of the mechanism responsible for Pc-1 micropulsations, as suggested from ground-based Pc-1 measurements [Kenney et al., 1967, 1968; Liemohn, 1969].

This paper presents a preliminary result obtained from a correlation of closely spaced OGO-3 and Pc-1 data, suggesting that the irregular structure of thermal ion plasma near the plasmapause observed from OGO-3 is directly related to Pc-1 micropulsations observed simultaneously on the ground. This interpretation is supported by an analysis of the plasmasphere-plasmapause region in terms of the Alfvén velocity or index.

Coverage of correlation

High altitude positive ion composition results obtained from OGO-3 reveal a distinct variability in terms of the position and structure of the plasmapause. Such variability is observed to be pronounced in the afternoon-dusk local time sector and also during the recovery phase of a magnetic storm. A correlation of a limited sample of closely spaced ion and Pc-1 data has been performed, to examine these irregularities more closely. The number of events studied is limited primarily by the infrequency of satellite passes near the longitude of the ground station, and by the relative infrequency of sharply defined Pc-1 events. The data have been selected from the period June 1966 through February 1967 in view of availability and suitability for comparison. There are four sets of events, containing four inbound and three outbound OGO-3 passes and twelve Pc-1 events. During this period, the OGO-3 orbit was inclined at most between 31° and 49°, typically with a perigee of about 316 km and an apogee of about 122,120 km. The supporting ground Pc-1 data were obtained from Tulalip station (near Seattle, Washington, 53.6°N geomagnetic latitude) [Kenney et al., 1968].

RESULTS

Preliminary details

In Figures 1 to 4, which follow, the left half (a) of each figure displays the OGO-3 plasmapause crossings and the Pc-1 occurrence positions together with an observed average plasmapause boundary in a local time-L coordinate system, while the right half (b) illustrates a comparison of hydrogen ion concentrations measured by OGO-3, and derived independently from Pc-1 micropulsations recorded on the ground, for the events shown on the left half of each figure. The solid and dashed portions of the OGO passes represent the inside and outside of the plasmasphere, respectively, and the arrow along each pass indicates whether the pass is inbound or outbound. The open circle on each pass identifies a plasmapause crossing, while the solid circle represents a Pc-1 propagation path in L position.

The equatorial plasmapause radius represents an estimated average location, for magnetic conditions of moderate but steady agitation ($K_{p-24} = 2_0 \sim 4_0$) obtained from OGO-3 during the period June, 1966 through August, 1967. The notation K_{p-24} refers to the maximum value of the planetary magnetic activity index K_p recorded during the 24-hour interval before the time of event. This plasmapause boundary clearly exhibits a pronounced local time asymmetry in the form of an elongation or bulge located in the afternoon-dusk local time sector, accompanied in some cases by significant fine structure. Specifically, the plasmapause is observed at L positions as distant as $L = 7 \sim 9$ in the afternoon-dusk sector, in contrast to positions near $L = 5 \sim 6$ observed in other local time sectors in both the dayside and nightside magnetosphere. This local time variation of the plasmapause radius is similar to that deduced from whistler data during 1963 [Carpenter, 1966], although the later results locate the plasmapause at a position generally more distant, by about $1 \sim 2L$, than that deduced from the VLF data [Taylor et al., 1970].

The determination of proton concentrations from Pc-1 measurements depends on the plasma distribution model along the magnetic field line and the assumed field configuration. Among the plasma models $N \sim \exp(3R^{-1})$, and $R^{-\nu}$ $(3 \le \nu \le 8)$ (R = geocentric distance) considered, the exponential model based on a diffusive equilibrium theory [Johnson, 1962; Kenney et al., 1968] was found to provide a best fit with proton profiles from OGO-3 direct measurements within the plasmasphere ($L \leq 4 \sim 6$). In the immediate vicinity of the plasmapause, the inverse power model $R^{-\nu}$ ($5 \leq \nu \leq 8$) appears to provide a better fit with OGO profiles because of an abrupt decrease of proton concentrations at the plasmapause, while outside the plasmasphere, the decrease in thermal plasma concentrations with the altitude or L slows down, forming a density plateau with a background ion concentration of $1 \sim 50$ ions/cm^3, so that the exponential model was extrapolated tentatively to the plasma trough region, since this provides the least decrease in ion concentrations with increasing L among the above models. In regard to the magnetic field, a centered dipole and a distorted field model [Mead, 1964] were considered. The discrepancy between them is generally not appreciable within the plasmasphere ($L \lesssim 5$) but the effect of field line compression appears gradually with further increasing L. This reflects the Pc-1 propagation path which is assumed to propagate more closely along a distorted field line deformed inward, although the foot of its field line at the Earth's surface coincides with that of the dipole field line. Consequently, the exponential model $N \sim \exp(3R^{-1})$ in the distorted magnetic field was employed for deduction of the ion concentration from Pc-1 measurements.

Comparison of ion and Pc-1 data

Details of the June 27, 1966 event (Figure 1)

On the OGO-3 inbound pass of June 27, 1966, a plasmapause crossing was identified in the ion data at L = 5.9 and 0726 UT, at which time the satellite was near the midnight meridian at 0013 LT, a geomagnetic latitude $\lambda = 9.5°N$, and an altitude H = 30,086 km. At that time, the ground station was located at 2326 LT in a position very close to OGO-3. At 1021 ~ 1042 UT, about three hours later, the ground station corotated with the Earth to the 02-03 local time sector and observed three Pc-1 events at 0221, 0236, and 0242 LT. During this interval, the predicted L position of the plasmapause would decrease along the average plasmapause boundary from 5.9 to 5.2 ~ 5.5, which coincides with the L positions of Pc-1 events 5.14, 5.18, and 5.52. In other words, the positions of the plasmapause crossing and three Pc-1 events in the postmidnight-predawn local time sector are very close to the average plasmapause boundary as might be expected, since those data were obtained under nearly the same local time and magnetic conditions.

The H^+ profile from OGO-3 on June 27, 1966 is one of a series of measurements made during inbound and outbound passes on June 23, 25, and 27 (Figure 1-b) and is a nearly equatorial midnight profile, fairly typical of the recovery phase subsequent to a magnetic storm ($K_{p-24} = 3_-$). An inward displacement of the plasmapause was observed during a storm that occurred on June 25, 1966. The magnetic disturbance reached its peak at $K_p = 5_+$ in the interval 1800-2100 UT on June 24. On June 25, approximately 12 hours after the peak of the storm, the plasmapause was seen at L = 3.75. Later, the plasmapause was observed to have moved outward to a position at L = 5.9 on June 27, considerably recovering to its prestorm value (L = 5.9 on June 23), although the considerable fine structure observed indicates that the recovery is not yet compl... The equatorial H^+ concentrations obtained from Pc-1 data are $N_+ = 185$, 243, and 115 ions/cm^3 at L = 5.14, 5.18, and 5.52, respectively in excellent agreement with OGO data, and also exhibiting evidence of the fine structure of the recovery phase of the storm near the plasmapause. This agreement suggests that Pc-1 micropulsations are most favorable for excitation under these circumstances.

Details of the December 12, 1966 event (Figure 2)

In the December 12, 1966 event, two Pc-1 events were observed at 0151 UT in a dusk meridian plane (1751 LT) about four hours before the arrival of the inbound OGO-3 at the plasmapause (L = 6.84, λ = 25.7°S, H = 29,617 km) near the noon meridian (1300 LT) at 0604 UT. The plasmapause crossing is outward by as much as 1.2L from the average plasmapause boundary ($K_{p-24} = 2_0 \sim 4_0$), indicating an outward expansion of the plasmapause during very quiet magnetic conditions ($K_{p-24} = 1_0$).

The H^+ concentrations from OGO-3 represent a dusk profile up to L $\simeq$ 4.5, and a nearly postnoon profile for L $\gtrsim$ 5, as seen from the satellite orbit. Beyond the plasmapause, a number of patchy H^+ recoveries, with concentrations of about 50 ions/cm^3 are observed in the plasma trough up to L $\simeq$ 10, H $\simeq$ 53,000 km or higher, suggesting a continuing thermal component in the background population beyond the plasmapause. In contrast to Figure 1-b of the June 27 event, two data points of the H^+ concentration from Pc-1 micropulsations generated in the dusk meridian are lower by an order of magnitude than OGO data, representing

N_+ = 96.5 and 4.92 ions/cm^3 at L = 5.92 and 8.32, respectively. The apparent discrepancies indicated by these derived densities arise mainly from local time differences of both measurements relative to the local time asymmetry of the plasmasphere. This reflects expectations that the plasma distribution of the bulge may be noticeably different from that of other local time sectors and that the dusk-side plasmapause may have a complex structure as a result of its coupling to the magnetospheric tail through open field lines. Such complexities may in some cases produce discrepancies in ion concentrations deduced from Pc-1 measurements on the basis of a diffusive equilibrium and an existing field model which may not be feasible near and beyond the dusk-side plasmapause.

Although the local time asymmetry tends to be less pronounced under very quiet magnetic conditions [Carpenter, 1970], one of the L positions of dusk-side Pc-1 events (L = 8.32) is still greater than the position of the plasmapause crossing (L = 6.84) because of an ~1300-1751 LT separation, and is located close to the elongated average plasmapause boundary. The other Pc-1 event is located at L = 5.92 within the plasma bulge by about 2.7L from the plasmapause boundary, suggesting that the inner Pc-1 event in the dusk region is possibly associated with irregular fine structure near an inner plasmapause-like boundary (initial plasmapause), as indicated from the dusk-side profile shown later in Figure 5-b. The Pc-1 activity in the dusk region is thus closely related to magnetospheric irregularities which produce plasma turbulence at the interface of closed, corotating field lines which through convection are connected to the magnetospheric tail [Nishida, 1966].

Details of the January 17, 1967 event (Figure 3)

On the OGO-3 outbound pass of January 17, 1967, a plasmapause crossing was identified in the ion data nearly on the average plasmapause boundary at L = 5.02 and 1918 UT, at which time the satellite was in the predawn sector at 0348 LT. One Pc-1 event was observed at 1136 UT in the predawn sector at a position of 0336 LT and L = 4.48 that is just below the position of the plasmapause crossing, while another two Pc-1 events occurred in the predawn sector at 1248 UT, 0448 UT, L = 6.49 (outward by about 1.5L from the plasmapause boundary), and 1333 UT, 0533 LT, L = 5.34 (close to the plasmapause boundary), respectively, indicating irregular variabilities near the plasmapause during the recovery phase of a storm that reached its peak (K_p = 8_-) in the interval 0300-0600 UT on January 14. In the dusk-side Pc-1 events observed about 12 hours earlier, the dotted line indicates a temporal displacement of the Pc-1 propagation path, which is indicative of dusk-side plasmasphere anomalies. Details will be described later together with a sonagram in Figure 7.

Although the plasmapause was observed to have recovered to a position at L = 5.02, λ = 30.0°N and H = 17,239 km on January 17 during the recovery phase (K_{p-24} = 3_+), the outer plasmasphere reveals some irregular structure and appears to be still compressed over the range of L = 3 to 4, indicating that the recovery is not yet complete. Three Pc-1 data points, N_+ = 182.6, 31.1, and 6.3 ions/cm^3 represent equatorial H^+ concentrations in the predawn sector, while another two data points represent those in the dusk sector. Two of the predawn Pc-1 data points are in good agreement with OGO data just below and above the plasmapause as might be expected, since both data were obtained under nearly the same local time and magnetic conditions. In fact, the H^+ profile from OGO-3 was obtained in the midnight-dawn local time sector. Another predawn and two dusk Pc-1 data points appear in the plasma trough to be consistent with a normal background H^+ concentration $1 \sim 50$ ions/cm^3, although no OGO data point is available beyond L = 5.67 for this event.

Details of the February 13-14, 1967 event (Figure 4)

On the OGO-3 outbound pass of February 13, 1967, a plasmapause crossing was identified in the ion data just on the average plasmapause boundary at L = 5.74 and 0206 UT, at which time the satellite was near the midnight meridian at 0029 LT, λ = 49.0°N, and H = 10,534 km. One Pc-1 event was observed at 1042 UT, February 14 in the postmidnight sector at a position of 0242 LT and L = 5.16 just on the average plasmapause boundary. The other Pc-1 event occurred 1.5 hours later at 1215 UT in the predawn sector at a position of 0415 LT and L = 4.35 just below the plasmapause boundary ($L \simeq 5.0$), indicating a continuous decrease to a dawn minimum in the plasmapause radius. Therefore, the apparent small discrepancies in L value between the plasmapause crossing and the Pc-1 positions may be attributed to local time differences, since magnetic activity remained almost unchanged at $K_{p \cdot 24} = 2_0$, February 13 through 14.

The H^+ concentrations from Pc-1 micropulsations N_+ = 381, and 129 ions/cm^3 at L = 4.35, 0415 LT and at L = 5.16, 0242 LT, thus may be considered as those just below the equatorial plasmapause at 415 and 0242 LT, respectively, and appear to be somewhat lower than the midnight H^+ profile from OGO-3, because of local time differences. When Pc-1 data points are transformed to local midnight, near which time OGO-3 data were obtained, assuming that the H^+ concentration remains unchanged along the equatorial plasmapause boundary, the discrepancies of both data in the proton concentrations virtually disappear.

Typical L or altitude profiles of the Alfvén index

Since the plasmasphere and plasmapause are characterized by a geomagnetically controlled thermal plasma distribution, the relationship between the plasma structure and the generation and propagation of geomagnetic micropulsations may be examined in terms of the Alfvén index or velocity

$$V_A = \frac{c}{n_A} = \frac{B_0}{\sqrt{\mu_0 N_+ m_+}} \qquad (1)$$

where V_A and n_A are the Alfvén velocity and index, c the velocity of light, B_0 the Earth's magnetic field, N_+ and m_+ number and mass of ions, and μ_0 is the permeability of free space. Rationalized MKS units are employed.

Large scale irregularities of the solar wind arriving at the magnetosphere boundary produce irregularities of the convective flow in the magnetosphere which compresses the plasmasphere corotating with the Earth and these irregularities modulate the size of the plasmasphere. We thus can think of the plasmapause as a field-aligned layer 'breathing inward and outward' and generating magnetohydrodynamic waves in its vicinity, and with fine structure. This evidence is obtained from simultaneous observations of fluctuating proton distributions and Pc-1 micropulsations in the same L position (Figure 1: June 27, 1966 event), and may be explained in terms of irregularities of the Alfvén index or velocity which come from the fluctuations of the proton distribution and the magnetic field in general via Equation (1).

Figures 5 and 6 illustrate a series of profiles of the Alfvén index during the prestorm (5-a), (5-b), main phase (6-a), and recovery phase (6-b) periods of June 23, 25, and 27, 1966 (also refer to Figure 1). The plasmapause and fine structure in the form of sharp fluctuations in the recovery region (6-b) are observed in terms of the Alfvén index, corresponding to the ion profiles in Figure 1-b obtained from OGO-3 and Pc-1 data. The plasmapause is observed for both prestorm and recovery profiles near midnight as a sharply defined boundary inward of the trough zone and appears to be compressed during the main phase as near to the Earth as $L \simeq 3.5$. The fluctuations just below the plasmapause in the recovery profile are observed to exhibit a wave-like structure with periodic occurrence of $0.1 \sim 0.2L$ and relative fluctuations of $\Delta n_A/n_A \simeq 0.2 \sim 0.4$, while the prestorm midnight profile has no significant fine structure but forms an envelope of the recovery profile, possessing a minimum at the position of the plasmapause.

On the other hand, three closely spaced Pc-1 data points are located within the recovery region with fine structure (Figures 1-b and 6-b), giving the Alfvén indices n_A = 818, 958, and 799, i.e. the Alfvén velocity V_A = 367, 313, and 376 km/sec. for L = 5.14, 5.18, and 5.52, respectively. As the average frequencies for three Pc-1 events on June 27 are 0.425, 0.450, and 0.450 Hz, the Pc-1 wavelengths in the medium are 864, 696, and 836 km which are comparable to the size of irregularities, i.e. a peak-to-peak interval of the fluctuations of 640 ~ 1,280 km. In view of the fact that Pc-1 events appear to occur in a region characterized by rapid fluctuations, such irregular fine structure seems to form a world-wide L-shell structure extending to a high latitude trough and to persist as long as Pc-1 signal trains are observed. Thus it appears that Pc-1 events propagate along field-aligned fine structure ducts of a size comparable to the Pc-1 wavelength in the medium. This indicates that a formation of such specific fine structure is essential as a necessary condition for Pc-1 occurrence.

While the above discussion is concerned with midnight or postmidnight profiles obtained from the OGO inbound passes and Pc-1 micropulsations, Figure 5-b represents a prestorm dusk profile of the Alfvén index obtained from the outbound pass on June 23, 1966. The plasmapause is observed as distant as L = 7.25 in this dusk profile in contrast to L = 5.9 observed in the inbound pass on the same day, revealing an elongation in the dusk-side plasmasphere, characterized by double humps or troughs with considerable fine structure. The inner hump represents the initial plasmapause-like boundary at L = 5.49 followed by a region of significant plasma recovery which extends up to the main hump defining the final plasmapause. This suggests that the plasmapause-like boundary characterized by the inner hump is also favorable for excitation of Pc-1 micropulsations, as seen in the dusk Pc-1 events on December 12, 1966 and January 17, 1967, although no simultaneous Pc-1 events on June 23, 1966 are yet available.

It should be noted that irregularities of the Alfvén index presented herein are attributed primarily to the fluctuations of the plasma distribution rather than those of the magnetic field in this height range even during a magnetic storm or even in the dusk-side magnetosphere. This may be explained by recalling a pressure balance argument, from which we find that $\Delta B/B_0 \simeq -1/2\, \beta \Delta N_+/N_+$, β being the ratio between plasma and magnetic pressure at the location of excitation, with the magnitude of the order of 10^{-2} near the plasmapause. In addition, satellite data support that such significant magnetic field irregularities as observed at the magnetopause are not observed within the magnetosphere, including plasmapause crossings [Cahill and Amazeen, 1963; Heppner et al., 1963, 1967].

Evidence of the dusk-side plasma bulge in a Pc-1 sonagram

An example of dusk-side Pc-1 sonagrams taken on January 17, 1967 is given in Figure 7 (refer to Figure 3-a). One dominant event indicated by time interval M starts prior to dusk and lasts until 02:22 UT and 18:22 LT. This event maintains a nearly constant midfrequency of 0.72 ~ 0.70 Hz (precisely slowly decreasing) until 17:38 LT and then reveals an abrupt decrease in midfrequency down to 0.65 Hz at 17:43 LT, as indicated by a pair of connected arrows. After that, Pc-1 signal trains become intense and broad-band, keeping the midfrequency and bandwidth nearly constant (precisely slowly decreasing) until they disappear at 18:22 LT with midfrequency of 0.61 Hz. This decrease in average frequency indicates an increase in L-shell associated with the Pc-1 event from L = 6.47 to L = 8.36, which is consistent with the increase in average L position of the plasmapause in the dusk region. In fact, the outward displacement in L position of the Pc-1 propagation path is observed nearly along the plasmapause boundary as shown in Figure 3-a, and may be regarded as evidence of the dusk-side plasma bulge from Pc-1 measurements. The disappearance of Pc-1 trains at 18:22 LT arises possibly from large cyclotron damping due to the access of the Pc-1 frequency to the equatorial ion cyclotron frequency or from conversion of the oscillating processes to the plasma turbulence due to intersection of convective and co-rotational flows. This is consistent with the fact that dusk-side Pc-1 events are often observed in the earlier or later hours of the dusk local time sector, possibly near the periphery of the turbulent region, rather than its middle hours where the turbulence is most predominant. Another two less intense and less persistent Pc-1 events are observed during 17:00-17:25 LT (time interval S_1) and during 18:10-18:30 LT (time interval S_2), possessing the midfrequencies of 0.87 Hz and 1.02 Hz and the propagation paths of L = 6.28 and L = 6.6, respectively. The former event S_1 may be a higher frequency band of the main event M mentioned above and is possibly associated with rapid fluctuations in a region of transition from single to double 'hump' in the plasma bulge, while the latter event S_2 is possibly associated with irregular fine structure just below an inner plasmapause-like boundary (initial plasmapause) characterized by a second 'hump' in the dusk region.

DISCUSSION AND INTERPRETATION

Plasmapause with fine structure and Pc-1 propagation path

Through a limited sample of closely spaced OGO-3 ion composition and ground-based Pc-1 data, it is inferred that Pc-1 events at midlatitudes tend to be propagated on L-shells along which ionization exhibits specific fine structure near the plasmapause. Such fine structure responsible for Pc-1 events requires an L-shell containing ionization irregularities of size of $0.1 \sim 0.2L$ or less, and is formed most likely during the recovery subsequent to a magnetic storm, or in the dusk-side plasma bulge region even during less active magnetic conditions. This appears to be consistent with general observations that Pc-1 activity at midlatitudes rises in the nighttime, particularly in the afternoon-dusk and pre-dawn hours during several days subsequent to a storm [Campbell and Stiltner, 1965; Kenney and Knaflich, 1967].

As many existing theories of Pc-1 micropulsations do not assume the plasmapause and fine structure irregularities, difficulties exist in explaining why the Pc-1 events are restricted to specific time and space and appear in a narrow band of regular quasi-sinusoidal signals, although such theories attribute explanations for these problems wholly to energetic proton distributions (for example, see [Troitskaya and Gulélmi, 1967]). The present results suggest that a formation of discontinuous L-shell structure, characterized by rapid fluctuations, is essential in addition to the regular plasmapause as a necessary condition for Pc-1 events in order to account for their occurrence in time and space and their properties. An appropriate energetic proton distribution near the plasmapause may also be required as a sufficient condition for their long persistence. In fact, the low energy proton distributions in the 200 eV $\leq E_p \leq$ 50 keV range, observed from the same OGO-3 during June-July, 1966, indicate that the position of a maximum of the quiet time distribution at L = 6.8 on June 23 moved inward to L = 4.5 on June 25 and to L = 3.3 on July 9, accompanying the increase in intensity as much as an order of magnitude during the main phase of the storm and that the storm profiles went back to the prestorm condition with the decay of the distribution over a several day period [Frank, 1967]. This appears to coincide in L position with the movement of the plasmapause and Pc-1 occurrence locations in an inverse correlation with magnetic activity, suggesting a possibility of cyclotron instabilities for repetitive persistent Pc-1 micropulsation events (for instance, see [Cornwall, 1965]). Apart from the current model of the plasmasphere and plasmapause, it is of interest to note that a simple model of discontinuous L-shell structure of the magnetosphere was postulated in order to account for some European midlatitude observations of geomagnetic pulsations with latitude-dependent periods [Siebert, 1964].

Pc-1 propagation paths are observed to move inward and outward following the movement of the plasmapause in an inverse correlation with magnetic activity, and higher frequency Pc-1 events are more likely to occur during enhanced magnetic activity [Tepley, 1962; Heacock and Hessler, 1965]. In addition, indirect evidence of the temporal movement in Pc-1 propagation paths is reflected in local time variations in Pc-1 signal frequency, which appears to be highest just prior to dawn and lowest in the late afternoon at middle and high latitudes [Heacock and Hessler, 1962; Campbell and Stiltner, 1965; Kenney and Knaflich, 1967; Campbell, 1967; Fraser, 1968]. The decrease in Pc-1 midfrequency with time indicates an increase in L associated with its propagation. In general, Pc-1 propagation paths in L positions possess a maximum in the dusk-side region and a minimum in the predawn hours.

These factors indicate that the Pc-1 propagation path coincides nearly with the plasmapause or plasmapause-like boundary, accompanied by considerable fine structure.

Dusk-side plasma bulge and its significance in Pc-1 and Pi-1 (IPDP) events

Direct measurements of the thermal ion distributions throughout the plasmasphere obtained from OGO-3 revealed an outward expansion or bulge, accompanied by considerable fine structure in the dusk-side plasmasphere [Taylor et al., 1970], similar to that observed from extensive ground-based VLF studies [Carpenter, 1966]. The Pc-1 measurements made nearly simultaneously with OGO-3 ion experiments on January 17, 1967 also exhibit an outward displacement of the propagation path, following an elongation of the plasmapause boundary in the dusk region. This is verified by a sharp decrease in Pc-1 midfrequency with time on afternoon-dusk sonagrams as observed in Figure 7. In addition, two Pc-1 events associated with different L shells often coexist nearly simultaneously in the dusk region, as observed in the December 12, 1966 and January 17, 1967

Pc-1 events (Figures 2 and 3). The second Pc-1 event is most likely to occur near the inner plasmapause-like boundary followed by a recovery region whose formation can be maintained for some interval of time as a result of its coupling to the magnetospheric tail.

Evidence of the plasma bulge is further supported by a class of Pi-1 micropulsations, the so-called 'IPDP' (Irregular Pulsations of Diminishing Period) event which occurs in the dusk-side plasmasphere during the main phase of a storm. IPDP events do not display repetitive multihop pattern, but seem to appear more or less at random, superimposed on a broad-band noise source that gradually increases in average frequency over the lifetime of event [Troitskaya, 1961; Tepley, 1966; Heacock, 1967; Knaflich and Kenney, 1967]. This suggests that no amplification mechanisms are involved for IPDP events, but that the oscillation processes may be broken up in part because of dominant turbulences, in contrast to Pc-1 micropulsations which require nearly constant fluctuations in the plasma concentrations or in the Alfvén index in an L-shell region. Specifically, the propagation region for IPDP events is located at $L = 6 \sim 13$, having a strong maximum occurrence rate around 21:00 LT [Tepley, 1966; Troitskaya and Schepetnov, 1967; Heacock, 1967; Knaflich and Kenney, 1967]. This indicates that IPDP events are a manifestation of elevated turbulent interactions in the plasma bulge of corotational and convective streams in the magnetosphere during the main phase of a storm.

Alfvén index profiles and their significance in the plasmapause and micropulsation events

The generation and propagation of magnetohydrodynamic waves associated with irregular thermal and magnetic structure in the magnetosphere is basically reduced to investigations of the Alfvén index or velocity irregularities where these waves can be generated or propagated. While it is well-known that the Alfvén index (or velocity) profile with the equatorial altitude possesses a minimum (or maximum) at a height of 2,000 ~ 3,000 km, forming a hydromagnetic waveguide between this height and a base of the F_2-region, another minimum (or maximum) defined fairly sharply in the form of a 'hump' at the plasmapause has recently been pointed out with an indication of the generation and propagation of geomagnetic pulsations at the location of this anomaly [Van'yan et al., 1967; Kikuchi, 1968, 1970].

Although the prestorm midnight profile of the Alfvén index in Figure 5-a is fairly typical of undisturbed profiles, a variety of its modifications occurs under different conditions of magnetic activity and local time (Figures 5-b, 6-a, -b). In the dusk-side region, the Alfvén index profile will reveal complex structure near the plasmapause in general even during less active magnetic conditions as a result of magnetospheric irregularities primarily in the plasma concentrations. In some cases the dusk-side Alfvén profile will exhibit another 'hump' within the outer plasmasphere in addition to a main 'hump' at the plasmapause, both being accompanied by significant fine structure. Outside the dusk region, similar fine structure with rapid fluctuations may be formed just below the plasmapause during the recovery phase of a storm. Such irregularities, somehow, may form a favorable region for micropulsation excitation and also may produce plasma heating in the plasmapause or trough region, depending upon critical conditions for instabilities and turbulences.

Effects of ionospheric ducting for Pc-1 micropulsations

The Alfvén velocity profile with the altitude suggests the possibility of a hydromagnetic waveguide between the height of a maximum Alfvén velocity, i.e. the height of 2,000 ~ 3,000 km and a base of the F_2-region (for instance, see [Kikuchi, 1968]). In order to explain Pc-1 observations at middle and low latitudes, occasionally with falling tones superimposed on repetitive rising tones, it is natural to assume ionospheric ducting along such a hydromagnetic waveguide, since Pc-1 events are associated originally with a higher L-shell region near the plasmapause or high latitude plasma trough. The transition from field line guiding to ionospheric ducting at the foot of a field line is facilitated by a mode conversion from anisotropic slow to isotropic fast Alfvén waves. The duct attenuation rate is small during the nighttime and has a minimum in the predawn hours, leading to an apparent predawn enhancement of the Pc-1 occurrence rate at middle and low latitudes [Tepley and Landshoff, 1966; Manchester, 1966]. This, however, does not mean necessarily that predawn Pc-1 events are more active than dusk-side Pc-1 events, since larger duct attenuation in the latter events may reduce the observation rate of dusk Pc-1 events at middle and low latitudes.

CONCLUSION

Examination of a limited sample of nearly simultaneous OGO-3 and Pc-1 data reveals that:

1. A correlation study obtained in the dusk and midnight to dawn local time sectors under quiet to moderate magnetic activity ($K_p \lesssim 3$) provides good agreement in the proton concentrations near the plasmapause boundary, including evidence of fine structure in the proton distribution just below the plasmapause during the recovery phase of a magnetic storm.
2. Substantial agreement of the plasmapause crossings identified on the satellite with the Pc-1 occurrence positions observed on the ground indicates that these Pc-1 events were generated near the plasmapause and propagated along a plasmapause-associated duct which forms a natural Pc-1 waveguide.
3. The dusk-side plasmasphere exhibits an elongation or bulge, as distant as $L = 7 \sim 9$, often accompanied by irregular fine structure responsible for Pc-1 events even during less active magnetic conditions. Evidence from Pc-1 sonagrams is identified by a decrease in midfrequency during early dusk local time and by an increase in midfrequency during pre/post midnight.
4. Outside the dusk region, such significant fine structure may not exist during steadily quiet activity, but during the recovery subsequent to a magnetic storm, similar fine structure responsible for Pc-1 events

whose size of irregularities is $0.1 \sim 0.2L$ or less is formed just below the plasmapause.

5. In terms of the Alfvén velocity or index with the altitude or L, the plasmapause is characterized in the form of a 'hump', accompanied during the recovery of a storm by considerable fine structure responsible for Pc-1 micropulsations.
6. In some cases, the dusk-side Alfvén profile exhibits 'another hump' within the outer plasmasphere in addition to a 'main hump' at the plasmapause, both being accompanied by significant fine structure responsible for Pc-1 or Pi-1 (IPDP) micropulsations.
7. Pc-1 propagation paths move inward and outward in an inverse correlation with magnetic activity, following the movement of the plasmapause, and their L positions appear to possess a maximum in the dusk-side region and a minimum in the predawn hours, consistent with the local time variation of the plasmapause radius.
8. An apparent predawn enhancement of the Pc-1 occurrence rate at middle and low latitudes may be due to a minimum ionospheric duct attenuation in the predawn hours. This, however, does not mean necessarily that predawn Pc-1 events are more active than dusk-side Pc-1 events, since larger duct attenuation in the latter events may reduce the observation rate of dusk Pc-1 events at middle and low latitudes.

Clearly, the present study does not provide a statistical correlation based on a large collection of ion and Pc-1 data, but rather reflects a detailed analysis of selected individual events involving rather distinct irregular features of the plasmasphere and plasmapause. Consequently, selected OGO-3 and Pc-1 events are interpreted self-consistently in relation to the irregular structure of the plasmasphere and suggest a unified picture of the structure of the plasmasphere and plasmapause, related to the overall magnetosphere.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Figure 1: Comparison of simultaneous OGO-3 and Pc-1 events on June 27, 1966.

(a): The OGO-3 passes and Pc-1 events together with an average plasmapause boundary in a local time-L coordinate system. In addition to the June 27 OGO-3 inbound pass during the recovery, the June 23 inbound and outbound and 25 inbound passes are provided for comparison with the prestorm and main phase events. Note that two plasmapause crossings (open circles) near midnight and three Pc-1 occurrence positions (solid circles) during postmidnight coincide very well with the average plasmapause boundary ($K_{p-24} = 2_0 \sim 4_0$), while a plasmapause crossing during the main phase ($K_{p-24} = 5_+$) is well below the average boundary. Another plasmapause crossing at dusk is somewhat inward of the average boundary because of elevated magnetic activity ($K_{p-24} = 4_-$). The notation K_{p-24} refers to the maximum value of the planetary magnetic activity index K_p recorded during the 24-hour interval before the time of event.

(b): Comparison of hydrogen ion profiles from simultaneous OGO-3 and Pc-1 measurements on June 27, 1966 during the recovery phase of a storm that reached its peak at $K_p = 5_+$ on June 24. Both data are in excellent agreement, exhibiting evidence of the fine structure just below the plasmapause.

Figure 2: Comparison of simultaneous OGO-3 and Pc-1 events on December 12, 1966.

(a): The OGO-3 pass and dusk Pc-1 events together with an average plasmapause boundary in a local time-L coordinate system. Note that the plasmapause crossing is outward by as much as 1.2L from the average boundary ($K_{p-24} = 2_0 \sim 4_0$), indicating an outward expansion of the plasmapause during very quiet magnetic conditions ($K_{p-24} = 1_0$). Two associated Pc-1 events are near the dusk meridian, one being located close to the elongated plasmapause boundary, and the other being at the L position of an initial plasmapause (outside the dusk region).

(b): Comparison of hydrogen ion profiles from OGO-3 and Pc-1 measurements on December 12, 1966. The apparent discrepancies of both data may be due to local time separation, indicating complex variability of the dusk-side plasmasphere in the proton distribution. Observe a number of patchy H^+ recoveries, with concentrations of about 50 ions/cm^3 in the plasma trough.

Figure 3: Comparison of simultaneous OGO-3 and Pc-1 events on January 17, 1967.

(a): The OGO-3 pass and Pc-1 events together with an average plasmapause boundary in a local time-L coordinate system. The plasmapause crossing coincides with the average boundary, and two predawn Pc-1 events are close to the boundary. In the dusk Pc-1 events, two dotted lines represent the temporal displacements of Pc-1 propagation paths in L position obtained from a dusk-side sonagram, one exhibiting a sharp increase consistent with an elongation of the dusk plasmapause boundary, and the other disappearing and appearing at the L position of an initial plasmapause.

(b): Comparison of hydrogen ion profiles from simultaneous OGO-3 and Pc-1 measurements on January 17, 1967 during the recovery phase of a storm that reached its peak at $K_p = 8_-$ on January 14. Both data are in excellent agreement just below and beyond the plasmapause. A data point just above the 10 ions/cm^3 scale represents an average ion concentration of the dusk Pc-1 events at an initial plasmapause boundary located near L = 6 (left-hand panel). Another data point just above the 2 ions/cm^3 scale is an average concentration of the dusk Pc-1 event indicated by the outward dotted line near the elongated plasmapause boundary (left-hand panel).

Figure 4: Comparison of nearly simultaneous OGO-3 and Pc-1 events on February 13 and 14, 1967, respectively during moderately quiet magnetic activity ($K_{p-24} = 2_0$).

(a): The OGO-3 pass and Pc-1 events together with an average plasmapause boundary in a local time-L coordinate system. Note that the plasmapause crossing coincides with the average boundary and that Pc-1 occurrence positions are just below the plasmapause boundary.

(b): Comparison of hydrogen ion profiles from nearly simultaneous OGO-3 and Pc-1 measurements on February 13, and 14, 1967, respectively. The apparent discrepancies between both data may be attributed to local time differences, since magnetic activity remained almost unchanged February 13 through 14.

Figure 5: Prestorm profiles of the Alfvén index from OGO-3 data, showing in general a 'hump' at the plasmapause, and in some cases 'another hump' at an inner plasmapause-like boundary (initial plasmapause). A dashed curve represents a profile of the Alfvén index in the plasma trough which is assumed to possess a uniform background ion concentration of 5 ions/cm^3 in a centered dipole magnetic field. When the magnetic field distortion is appreciable, the dashed curve is still retained if the background ion concentration is replaced by a concentration more than 5 ions/cm^3, depending upon local time.

(a): A prestorm midnight (undisturbed) profile of the Alfvén index from OGO-3 inbound on June 23, 1966. Observe a sharply defined boundary inward of a 'hump' at the plasmapause. Compared to the disturbed (dusk, main phase, and recovery) profiles, there is no significant fine structure in the undisturbed profile.

(b): A prestorm dusk profile of the Alfvén index from OGO-3 outbound on June 23, 1966. Note that the Alfvén index possesses two minima in the form of 'double hump' at an elongated plasmapause boundary and at an initial plasmapause boundary, followed by a limited region of significant plasma recovery, both humps being accompanied by considerable fine structure.

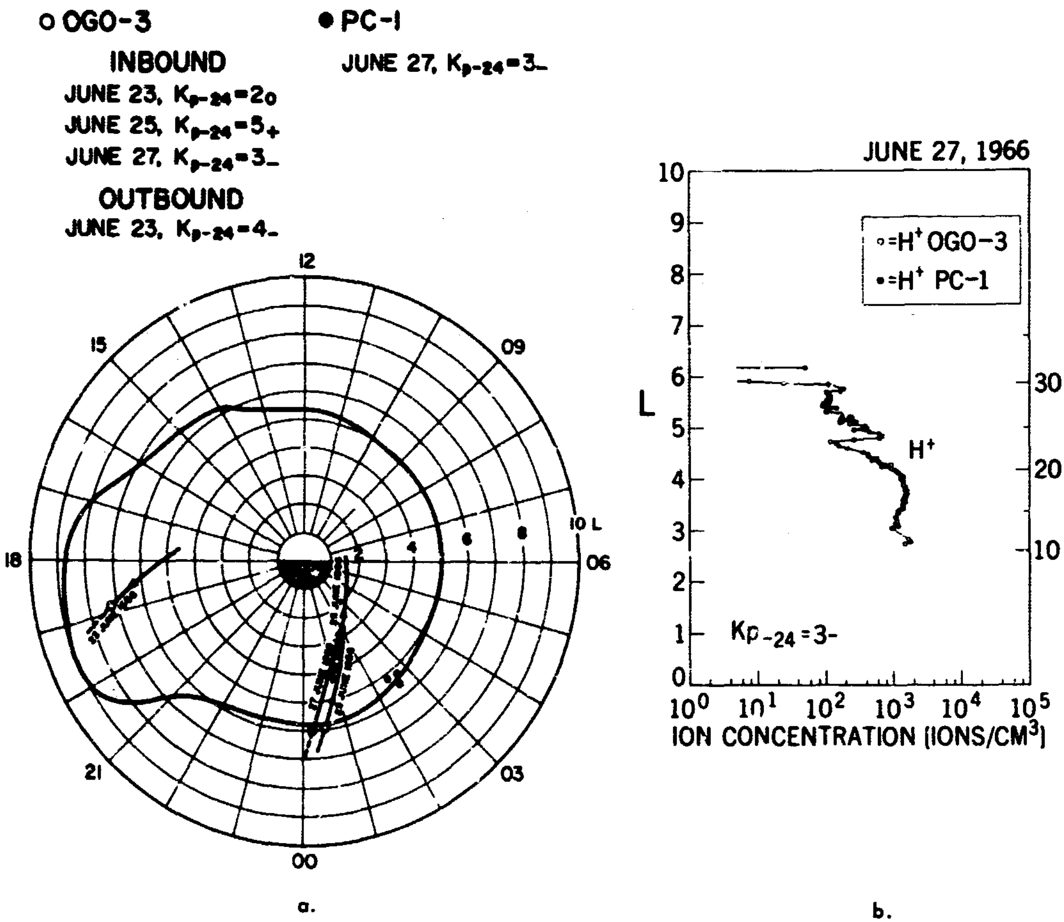
Figure 6: Disturbed profiles of the Alfvén index from OGO-3 and Pc-1 data. A dashed curve represents a profile of the Alfvén index in the plasma trough which is assumed to possess a uniform background ion concentration of 5 ions/cm^3 in a centered dipole magnetic field.

(a): A main phase, postmidnight profile of the Alfvén index from OGO-3 inbound on June 25, 1966. Significant is the inward displacement of the plasmapause or 'hump' during the main phase of a storm ($K_{p-24} = 5_+$).

(b): A recovery (post) midnight profile of the Alfvén index from OGO-3 inbound and Pc-1 events on June 27, 1966. Observe significant fine structure with rapid fluctuations just below the plasmapause where three Pc-1 events were generated and propagated possibly along a field-aligned fine structure duct whose meridional size is comparable to the Pc-1 wavelength in the medium.

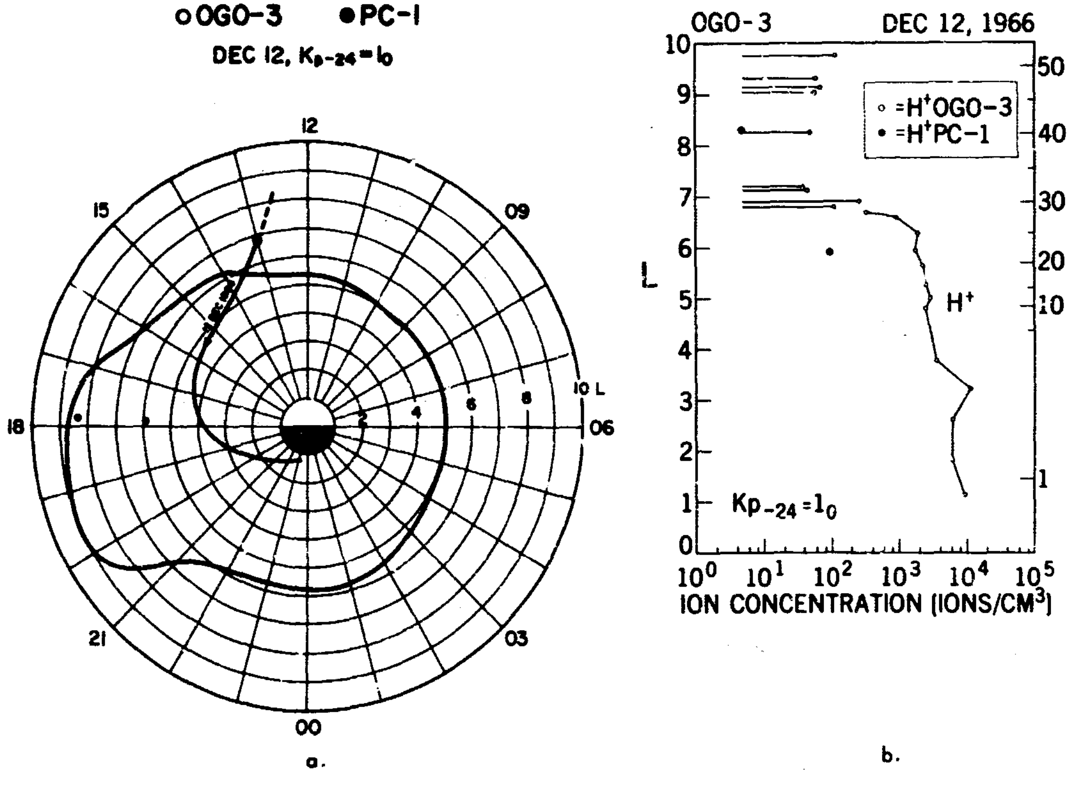
Figure 7: An example of dusk-side Pc-1 sonagrams recorded on January 17, 1967 at Tulalip station (near Seattle, Washington, 53.6°N geomagnetic latitude). An abrupt decrease in midfrequency (a pair of connected arrows) of the main event (M) indicates an outward displacement in L position of the Pc-1 propagation path, showing evidence of the dusk-side plasma bulge. Another two less intense and less persistent Pc-1

events are indicated by the time intervals, S_1 and S_2. The event S_1 may be a higher frequency branch of the main event M, while the event S_2 is possibly associated with fine structure near an inner plasmapause-like boundary (initial plasmapause).



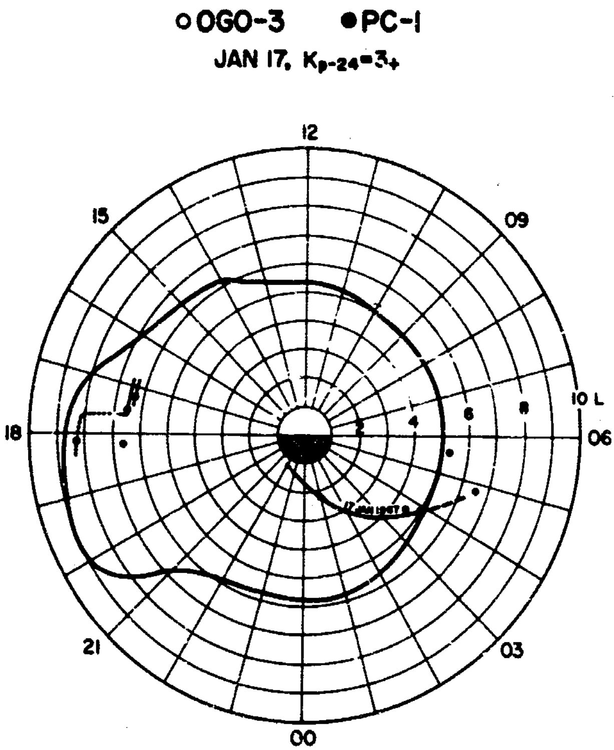
o OGO-3
● PC-I
INBOUND
JUNE 23, Kp-24=2o
JUNE 25, Kp-24=5+
JUNE 27, Kp-24=3-
OUTBOUND
JUNE 23, Kp-24=4-
JUNE 27, Kp-24=3-
12
15
09
18
06
21
03
00
10 L
a.
JUNE 27, 1966
o=H+ OGO-3
•=H+ PC-1
L
H+
ALTITUDE (1000 Km)
Kp-24=3-
ION CONCENTRATION (IONS/CM3)
b.

Figure 1.



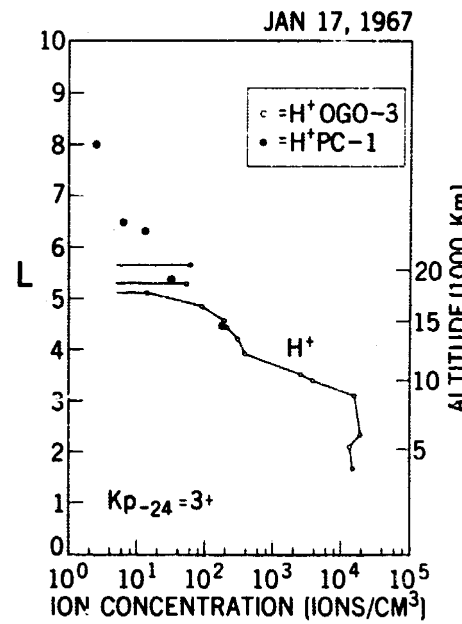
○OGO-3 ●PC-1
DEC 12, Kp-24=1o
12
15
09
18
06
21
03
00
2
4
6
8
10 L
a.
OGO-3
DEC 12, 1966
○ =H+OGO-3
• =H+PC-1
H+
Kp-24=1o
L
ALTITUDE (1000 Km)
ION CONCENTRATION (IONS/CM3)
b.

Figure 2.



○OGO-3 ●PC-1
JAN 17, Kp-24=3+
12
15
09
18
06
21
03
00
2
4
6
8
10 L

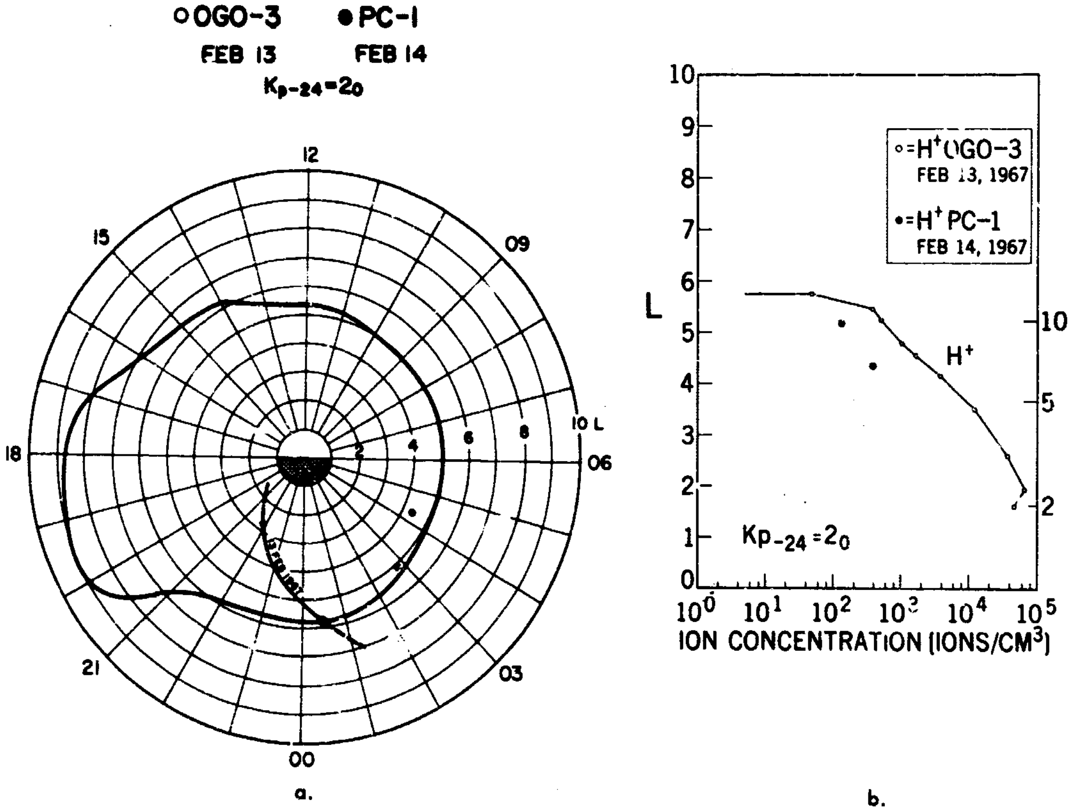
a.



JAN 17, 1967
○ =H+ OGO-3
• =H+ PC-1
L
ALTITUDE (1000 Km)
H+
Kp-24 =3+
ION CONCENTRATION (IONS/CM3)

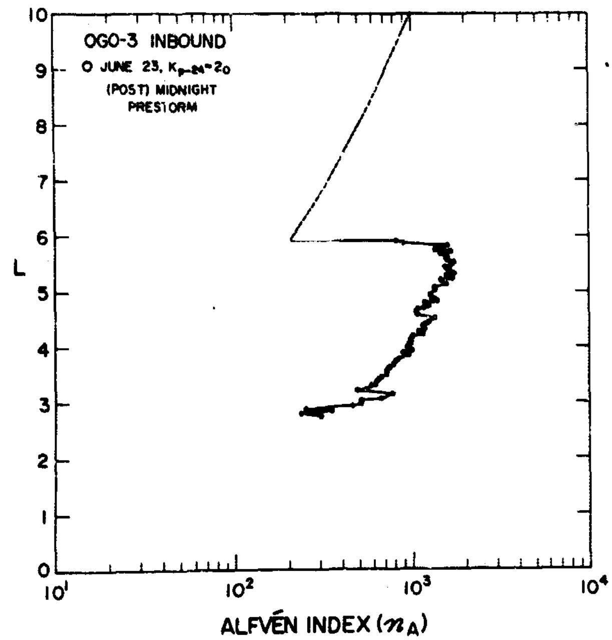
b.

Figure 3.

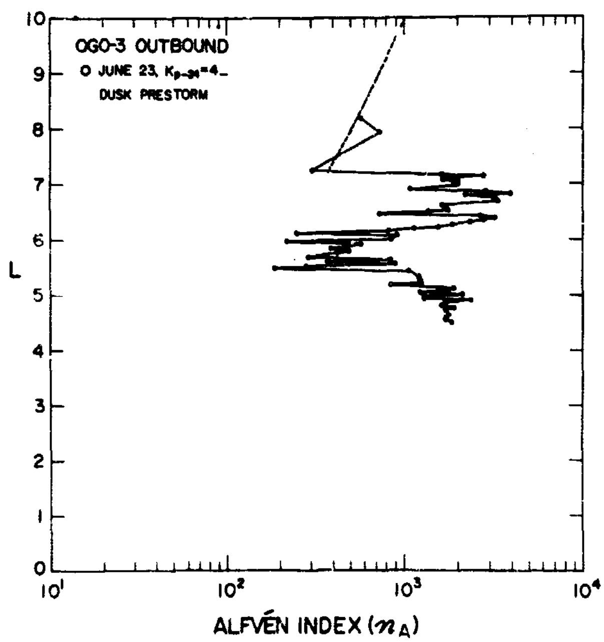


OGO-3
PC-1
FEB 13
FEB 14
Kp-24=2o
12
15
09
18
06
21
03
00
2
4
6
8
10 L
a.
10
9
8
7
6
5
4
3
2
1
0
L
=H+ OGO-3
FEB 13, 1967
=H+ PC-1
FEB 14, 1967
H+
Kp-24=2o
10
5
2
ALTITUDE (1000 Km)
ION CONCENTRATION (IONS/CM3)
b.

Figure 4.

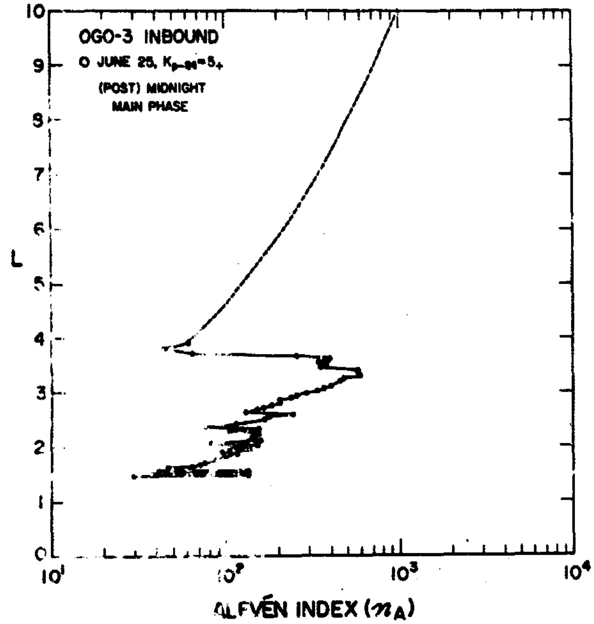

OGO-3 INBOUND
(POST) MIDNIGHT
PRESTORM
L
ALFVÉN INDEX (n_A)

a.


OGO-3 OUTBOUND
DUSK PRESTORM
L
ALFVÉN INDEX (n_A)

b.

Figure 5.


OGO-3 INBOUND
O JUNE 25, $K_{p-24}=5_+$
(POST) MIDNIGHT
MAIN PHASE
L
ALFVÉN INDEX (n_A)

a.

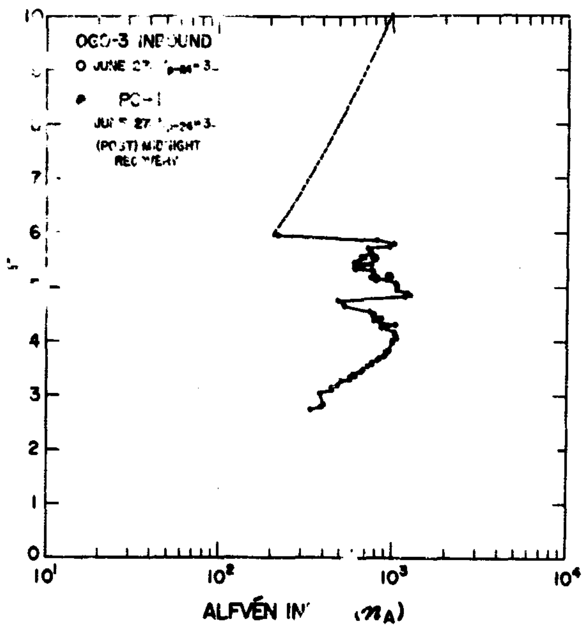

PC-1
(POST) MIDNIGHT

Figure 6.

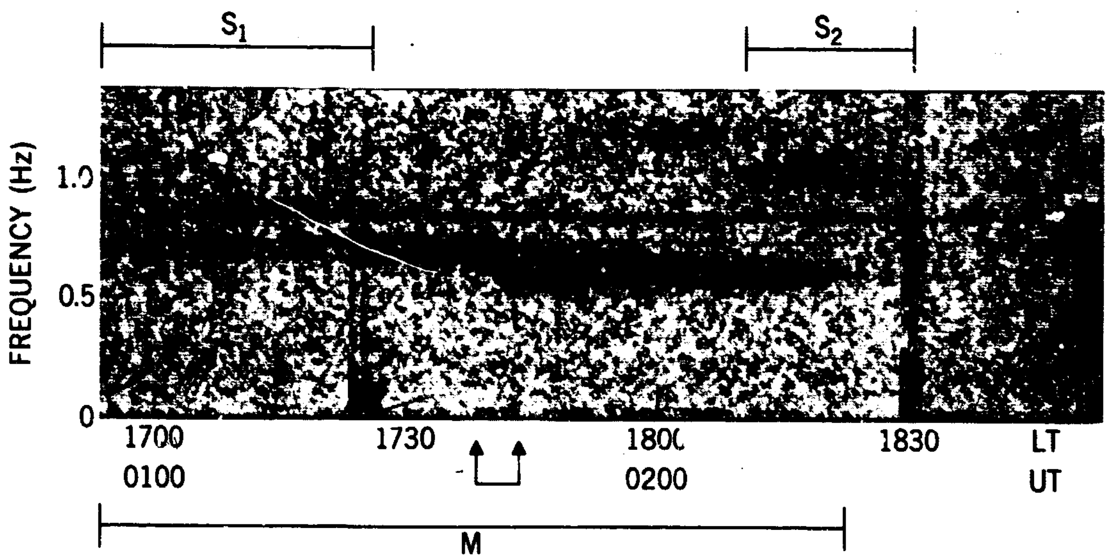


Figure 7