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X-621-73-220
PREPRINT

NASA TM X- 70429

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(NASA-TM-X-70429) THE BEHAVIOR OF THE PLASMAPAUSE AT MID-LATITUDES: ISIS-1 LANGMUIR PROBE MEASUREMENTS (NASA) 48 p HC $4.50 CSCL 04A

N73-28442

Unclas
G3/13 10983

APRIL 1973

GSFC

GODDARD SPACE FLIGHT CENTER
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ABSTRACT

Observations of the electron concentration, N_e, and temperature, T_e, from the electrostatic probes on the ISIS-I satellite were used to examine the location and behavior of the plasmapause at about 3000 kilometers altitude in the vicinity of L=4. At these altitudes, the N_e measurements are equivalent to measurements of H^+ since the satellite is well into the protonosphere. The plasmapause is evident as a sharp drop in N_e by a factor of 10 to 100 as the satellite passes into the polar cap, and a corresponding increase is observed as it enters the plasmasphere on the opposite side of the Earth. An enhancement of T_e is also observed at the plasmapause, an effect that is most visible at night when the temperatures at latitudes above and below the plasmapause are usually very low. The position of the plasmapause, L_{pp}, decreases with magnetic activity but is found to be somewhat less sensitive to k_p than is the equatorial plasmapause. Also unlike its equatorial behavior, the mid-latitude plasmapause exhibits no detectable late afternoon bulge. These differences imply rather complex coupling of the thermal plasma along the field lines that link these two regions of the plasmasphere. An additional factor may be the recently observed axial asymmetry in the geomagnetic field at high altitudes.

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INTRODUCTION

The ISIS-I satellite was launched in January 1969 and continues to orbit the Earth in an eccentric orbit having apogee and perigee altitudes of 3600 and 600 km, respectively, and a near polar inclination of 88.2°. In addition to a topside sounder, the satellite carries a number of instruments that measure ionosphere and magnetosphere parameters (Florida, 1969) (Whitteker et al., 1972). The purpose of this paper is to report a study of the plasmapause that has been based upon the measurements of one of the ISIS-I instruments, the cylindrical Langmuir probe.

Most of what is known about the behavior of the plasmapause has been derived from equatorial measurements inferred from VLF whistler propagation (Carpenter, 1963) and by direct measurements from ion mass spectrometers in eccentric low inclination orbits (Taylor et al., 1965) (Harris et al., 1970) (Chappell et al., 1970). A comprehensive review of the morphology and dynamics of this region of the plasmasphere has been given by Chappell (1972).

On the other hand, knowledge of the behavior of the plasmapause at lower altitudes is rather incomplete and, to a certain extent, confusing. To some degree, this can be attributed to the low altitudes of the polar orbiters. Most of these satellites orbit entirely within the F-region and therefore cross the plasmapause where H^+ is a minor constituent. Thus the most commonly measured parameter, N_e, tends to reflect the ionospheric processes that control the major constituent, O^+. Unless the H^+ concentration is observed, it is questionable whether the behavior of the overlying plasmasphere can be deduced from within the F-region (Taylor and Walsh, 1972).

Muldrew (1965), Sharp (1966), Thomas and Andrews (1968), Rycroft and Thomas (1970), Rycroft and Burnell, (1970) and Tulunay and Sayers (1971) have found mid-latitude F-region troughs in N_e and attempted to relate them to the plasmapause as measured at the equator. Since the trough tends to be a nightside feature it has not been possible to compare the entire local time behavior of these regions. However, the correlation on the nightside has been reasonably good. To the extent that it has been possible to compare with the dayside plasmapause, the correlation has been poor. Unlike these F-region satellites, the ISIS-I satellite with its apogee above 3500 kilometers provides a particularly good platform for study of the mid-latitude plasmapause using N_e measurements alone. At this altitude we can follow the plasmapause through all times of day and with the high measurement frequency that is characteristic of low altitude satellites. The plasmapause is crossed at high altitudes about 24 times each day, and the satellite is in operation during about 6 or 7 of these crossings. Thus in the nearly two and one half years of data now reduced to N_e and T_e there are many thousands of plasmapause crossings available for analysis (Brace et al., 1973).

In this paper we present the results of an initial study of the plasmapause behavior at mid-latitudes and relate this to the behavior of the equatorial plasmapause.

THE METHOD

The ISIS-I Cylindrical probe instrument has been described elsewhere (Brace, Theis and Johnston, 1973) (Whitteker et al., 1972). The measurements are performed by either of two independent sensors located on the spacecraft as shown in Figure 1. One probe is mounted at the end of a 1.2 meter boom to extend it deeply into the ionospheric plasma, hopefully far enough from the spacecraft to eliminate its wake and sheath as an important source of measurement error. The second probe is mounted on the spin axis at the opposite end to obtain measurements when the spacecraft is travelling in that general direction, in the event that the boom probe measurements might be adversely affected by the wake of the vehicle. In fact, even when it trails the satellite, the boom probe appears to be free of wake effects throughout most of the spin period (20 seconds).

Each sensor consists of three cylindrical elements as shown in Figure 2; a wire collector, a driven guard and a floating guard, all made of stainless steel. The floating guard is not driven in potential but merely serves as an additional boom to separate the collector from whatever it is mounted on.

A single electronic unit services both sensors on a time-sharing basis, providing a sweep voltage and linear electrometer to resolve the currents collected from the plasma. Figure 3 is a functional block diagram of the electronics. The

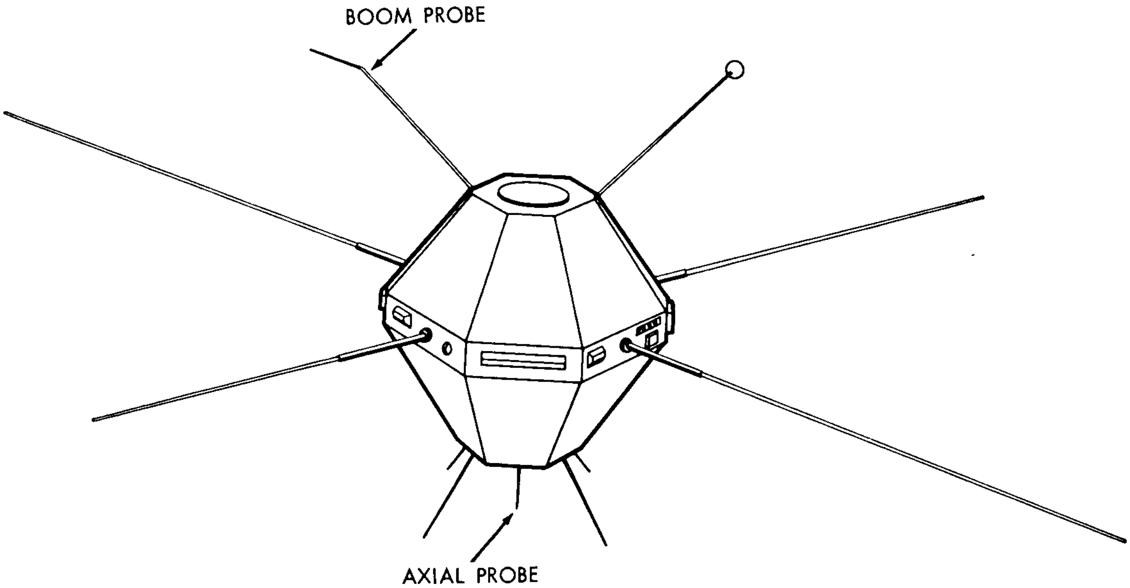

Figure 1. The ISIS-I spacecraft showing the location of the two cylindrical probes. The boom probe is mounted on a 1.2 meter boom and is perpendicular to the spin axis of the spacecraft. The axial probe is mounted on the spin axis at the opposite end of the satellite.

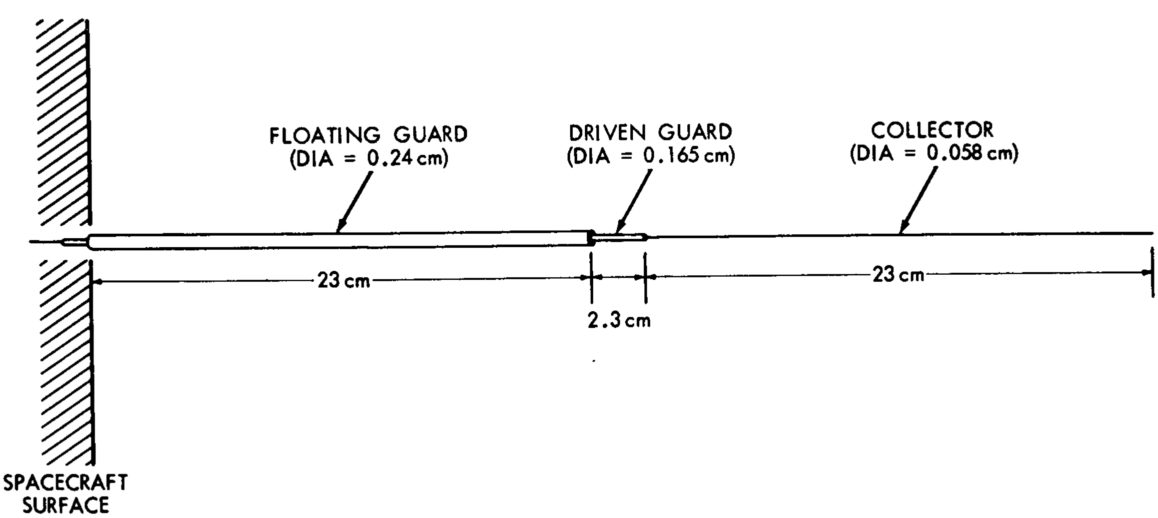

Figure 2. The configuration of the sensors.

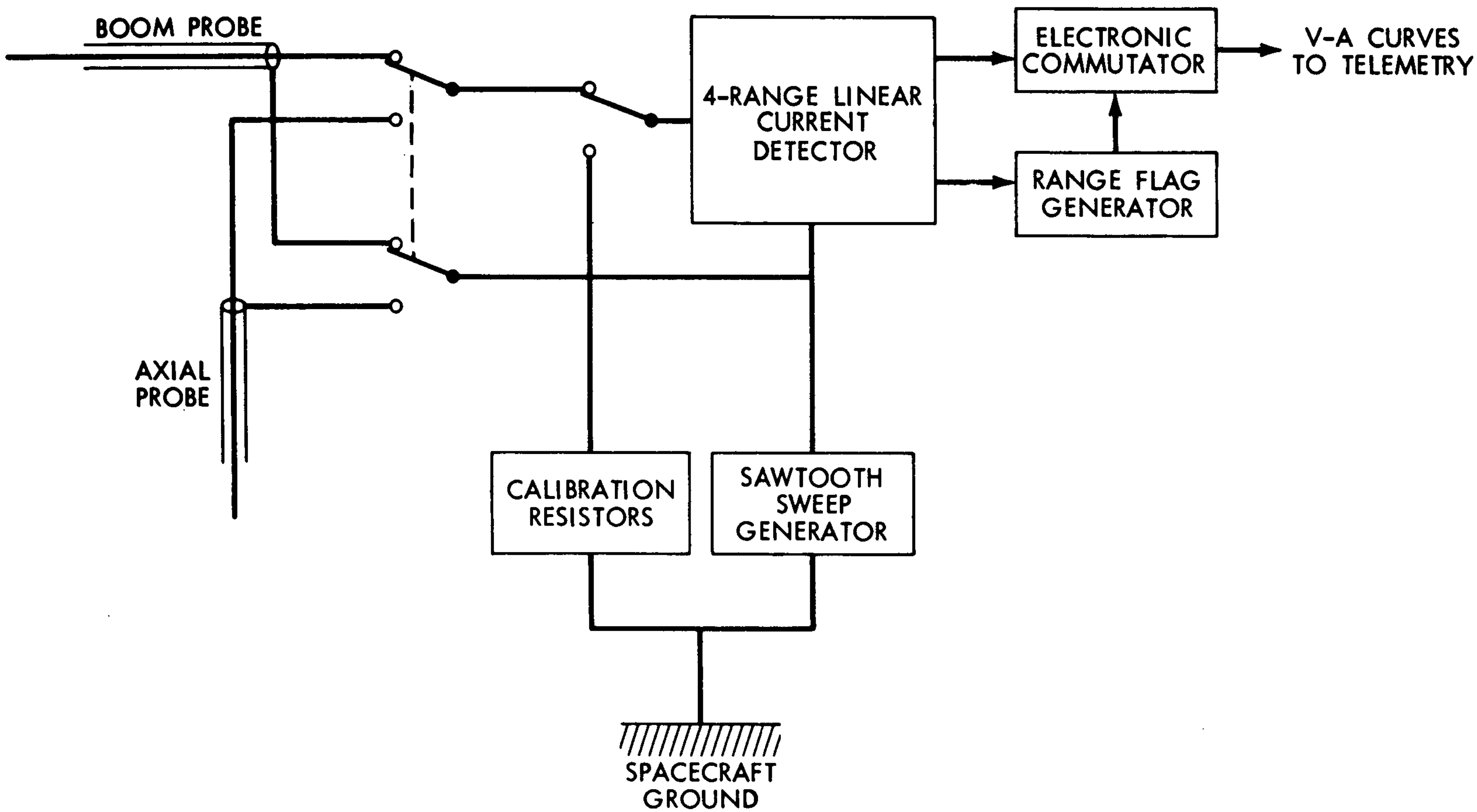

Figure 3. Block diagram of the electronics. The four linear current ranges are sequenced on consecutive satellite spin cycles. The probes are alternated at two-minute intervals.

sawtooth voltage (-2 to +10 volts) is repeated at 2 second intervals, as the electrometer sequences through its four ranges (20, 2, 0.2 and 0.02 μa) in a period of 120 seconds, holding each range for 30 seconds or approximately 1-1/2 satellite rotations. This arrangement permits any spin modulation in the volt-ampere characteristics to be resolved without interruption by range changes of the electrometer. The two redundant sensors time-share the electronic unit on alternate 2 minute sequences of the electrometer. For most purposes the two probes are equally useful, unless the axial probe happens to lie directly in the wake of the spacecraft. The electrometer sensitivities were selected to permit the measurement of N_e in the range 5×10^1 to 1×10^6/cc and T_e can be derived whenever N_e exceeds 3 or 4×10^2/cc.

Data Analysis

The reduction of the volt-ampere curves to values of N_e and T_e is achieved by computer routines that fit the curves with appropriate theoretical functions (Spencer et al., 1965) (Brace et al., 1973) (Theis, 1969). This provides a value of T_e and N_e at 2-second intervals whenever the electrometer is in the proper range to resolve the curves adequately. However, for most purposes high spatial resolution is not needed, therefore we derive an average value of T_e and N_e for each 30-second sequence of well resolved curves. This provides a value of T_e and N_e at 2-minute intervals along the orbit, corresponding to 6° of latitude. This is adequate to resolve the plasmapause location, except during magnetic disturbances when extremely sharp plasmapause crossings may be encountered. The latter can often be resolved by examining the data curve by curve, at 2-second intervals.

Accuracy

The relative accuracy of the N_e measurements is estimated to be within 10%. Comparisons with the local plasma frequency measured by the companion topside sounder indicate that the probe-derived values are systematically high by about 20%, an amount that probably reflects the inadequacy of the simple probe theory we employ to facilitate the processing of huge amounts of data inexpensively. Because of the straightforward nature of retarding potential theory, the T_e measurements are potentially more accurate than are the N_e measurements, although here too we have made some compromises in the fitting routines to keep the computer processing times as low as possible. In particular the values of T_e may be up to 10% too high, especially at the lowest temperatures ($<2000^\circ K$).

THE OBSERVATIONS

ISIS-I satellite data are acquired in the form of 15 to 20 minute passes at various places about the orbit where the satellite can be interrogated by one of the NASA-STADAN stations or one of the stations operated by countries participating in the ISIS program (Franklin, Bibby, Hitchcock, 1969). An onboard tape recorder provided additional geographic coverage during the first year in orbit. The most extensive latitudinal coverage is obtained at U.S. longitudes, although there is broad longitudinal coverage above 30° N because of the stations at Alaska, England and Norway. However, because of the limited number of stations at low latitudes, complete latitudinal coverage can be obtained only by combining the data from several days of operation. Since the orbital precession rate induces a local time drift of only one hour per week and an apsidal rotation of only 15°, one can obtain a fairly consistent global pattern from a weekly plot of the measurements. Figure 4 shows a computer plot of a typical week of measurements plotted versus magnetic dip latitude. Dip latitude is used because it includes the variation of the real field (based on the dip angle) without introducing discontinuities at the equator such as those experienced when plotting versus L or invariant latitude.

In addition to the values of T_e and N_e, Figure 4 shows the altitude and local times of the measurements. Consecutive measurements within a particular pass are connected by solid lines to distinguish the instantaneous structure from the variations that occur from one pass to another. The latter variations reflect real changes with UT as well as longitudinal structure in the ionosphere, although both are small compared to the altitudinal and latitudinal structure that dominate the patterns of T_e and N_e found along the orbit. During this particular period in northern winter, apogee was over the northern pole. Because of the very low polar values of N_e in winter ($\sim 10^2$/cc), the plasmapause is particularly well defined at both the day and nightside boundaries of the polar cap. Because of the upward escape of H^+ into the magnetospheric tail (Banks and Holtzer, 1969),

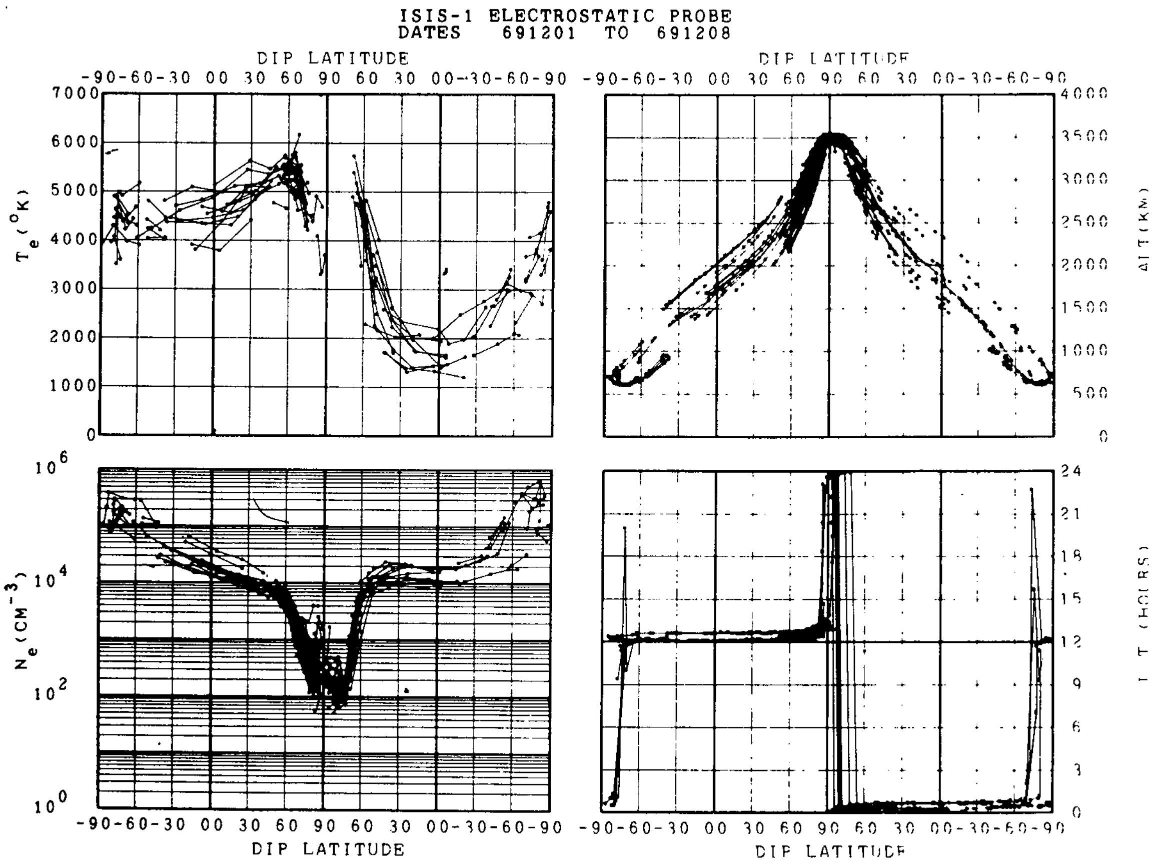

Figure 4. A typical week of measurements about the entire ISIS–I orbit, plotted versus dip latitude to order the geomagnetically controlled features. The local time and altitude corresponding to the measurements are shown at the right. All the measurements taken within a single 20 minute turn-on of the satellite are connected by lines. The "plasma-pause" can be seen at either side of the northern magnetic pole and is recognized as a two-order of magnitude decrease in N_e centered at about 70° dip latitude.

only a small residual population is present at these altitudes. This polar trough is a well known feature (c.f. Brace, 1969). Most of the polar trough ions at 3000 kilometers are O^+, but a residual of H^+ may also be present (Brinton et al., 1971). As ISIS-I crosses into the plasmasphere the H^+ concentration, and therefore N_e, suddenly rises by a factor 10 to 100 within a few degrees of dip latitude. On a global scale, this is perhaps the sharpest and most persistent feature that can be observed in N_e at these altitudes.

Incidentally, a peak of T_e is also observed at the plasmapause. This is not so evident in Figure 4 because N_e drops too low in the polar trough to permit T_e to be resolved. However, Figure 5 shows data from another week in which N_e remained high enough to resolve T_e throughout the plasmapause. Here T_e can be seen to peak at about the point where N_e falls below 1×10^3 /cc. Because of the correlation between the plasmapause and T_e, it may prove feasible to use the T_e peak to track the plasmapause when the satellite is at lower altitudes where N_e is no longer a good measure of H^+, but we will not attempt to do that in this paper.

Definition of the Plasmapause

As a prelude to our presentation of the ISIS-I measurements of the plasmapause, a definition of terms is perhaps in order. The plasmasphere is believed to be a more or less donut-shaped region such as shown in Figure 6. It is populated primarily by thermal electrons and protons having energies of the order

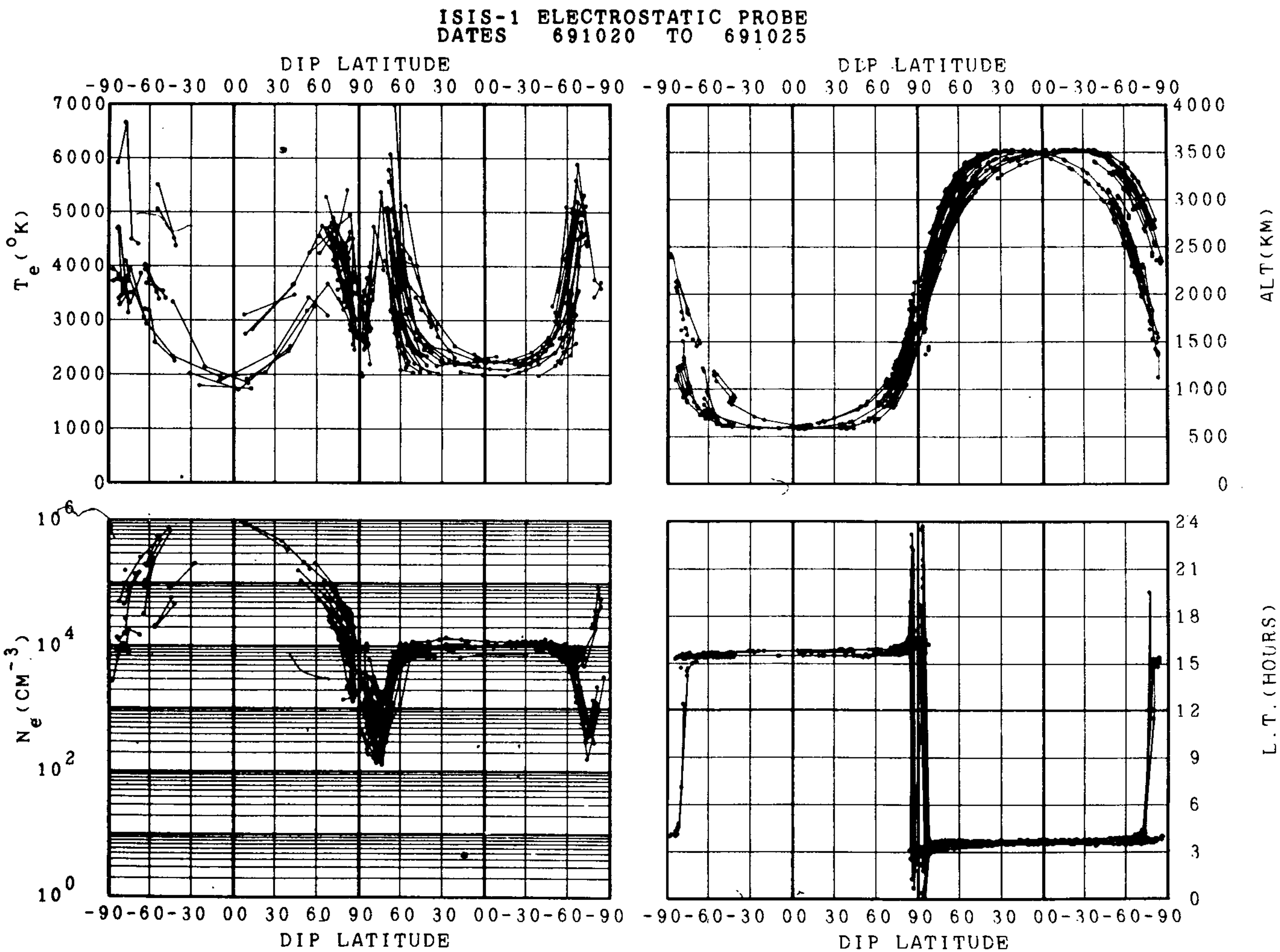

Figure 5. A week in which the plasmapause peak in T_e can be resolved.

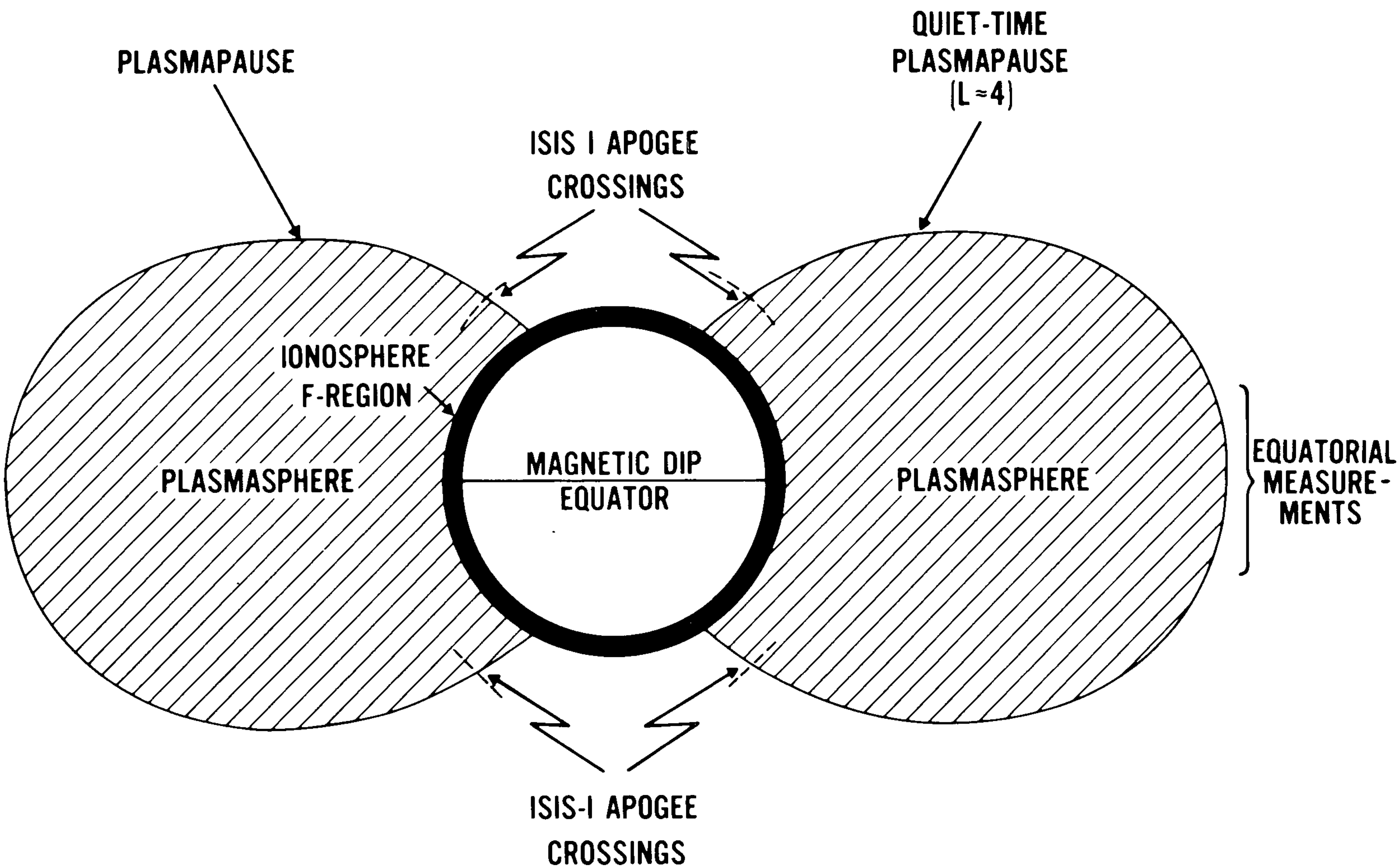

Figure 6. The locations where the ISIS-I apogee intersects the four plasmapause crossings. As apogee drifts in latitude the ISIS-I satellite has been able to look at each of these regions many times.

of an eV. The plasmasphere is bounded above by the plasmapause, a region of steep gradient in which the concentration falls by two or three orders of magnitude. It is bounded below by the F-region of the ionosphere, the transition lying between about 700 and 2000 kilometers depending upon the latitude and time of day. The ISIS-I measurements were taken in the regions shown by dashed lines when apogee of the satellite (3600 kilometers altitude) was near one of the four plasmapause crossings that are shown.

Although we have drawn the plasmapause coincident with an L=4 field shell, it is important to recognize that it is a complex and time varying surface whose configuration and temporal behavior have not been well resolved. It is known from equatorial measurements that there is a marked afternoon bulge at higher altitudes. The extent to which this feature extends to lower altitudes is one of the primary topics we deal with in this paper. However a major difficulty that we encounter in relating these two regions is our relatively poor knowledge of the geomagnetic field configuration at higher L values. We have employed a standard GSFC field model for assigning the L coordinates to ISIS data (Cain et al., 1967). However, models such as this one describe only the internal field of the Earth and do not reflect distortions caused by fields from magnetospheric sources. Sugiura (1973) has recently reported that such sources may introduce an appreciable axial asymmetry in the geomagnetic field at high altitudes. If so, the L values assigned to the ISIS data will be incorrect as they do not accurately describe the equatorial crossing height of the field line. Although this makes more difficult the comparison of high and low altitude plasmapause measurements, perhaps such comparisons will yield information on the field configuration itself.

Another problem encountered in making these comparisons is the quite different shapes of the plasmapause at the equator and at mid-latitudes when plotted against L. Although these features have similar linear dimensions ($\approx$1000 km), the mid-latitude plasmapause is usually much less abrupt when plotted versus L. This difference probably arises because of the complex coupling along field lines that connect these two regions. The thermal ions and electrons within the plasmasphere are believed to be approximately in diffusive equilibrium, except perhaps very near the plasmapause where proton removal processes at high altitudes induce upward flows from the ionosphere. However, even if diffusive equilibrium were maintained, a complex distribution of plasma would be found along any particular field tube because it depends upon poorly known variables like the electron and ion temperatures and their gradients. Since these parameters vary within the plasmasphere, profiles of N_e taken across the plasmapause at different altitudes may look quite different when plotted vs. L. Because of this it is difficult to find an unique definition of "the plasmapause" at ISIS-I altitudes that would be physically consistent with a corresponding definition of the plasmapause at the equator.

Recognizing these difficulties, we forge ahead and simply employ the same kind of experimental definition for the plasmapause that has been used at the equator; namely, we define L_{pp} as that location in L coordinate where the plasma concentration declines by about an order of magnitude from its value inside the plasmasphere (Chappell, Harris and Sharp, 1970). At ISIS-I altitudes this corresponds to an N_e value of 1×10^3/cc. This is an easily recognized point in our global plots because it falls about in the middle of the two order of magnitude decrease that is often encountered at the plasmapause.

In this paper we have tended to select L_{pp} using the crossings in the winter hemispheres to permit the proton region to be resolved down to the lowest concentrations. For example Figure 7 shows a weekly global plot in dip latitude taken in December 1970 when apogee was near the northern pole. The plasmapause can be seen both at the left of the pole (0800 hours) and at the right of the pole (2000 hours). The N_e plot is shown in expanded form in Figure 8. Here one can begin to see some of the detailed structure within the polar cap such as the polar cusp on the dayside of the pole and sporadic enhancements associated with the auroral oval on the nightside. These features are bounded on both sides by the plasmapause below about 75° dip latitude.

To show how we identify the plasmapause, Figure 9 shows data from the same week plotted versus L, eliminating the data above L=10 where precipitation effects confuse the picture. We have also included the N_e measurements from

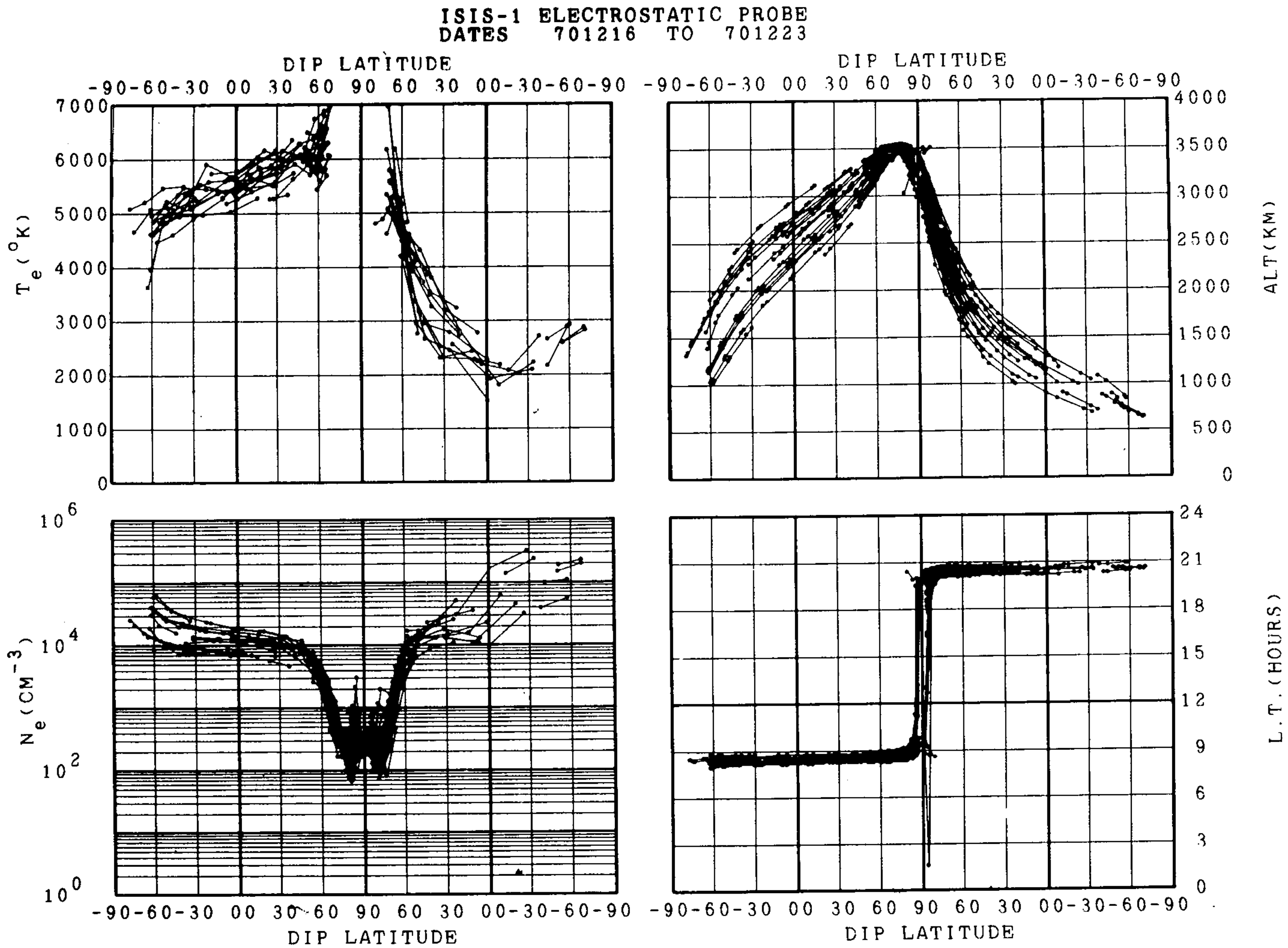

Figure 7. A weekly plot showing the deep winter polar trough with the plasmapause on either side. The dayside (0800) at the left and the nightside (2000 hours) is at the right.

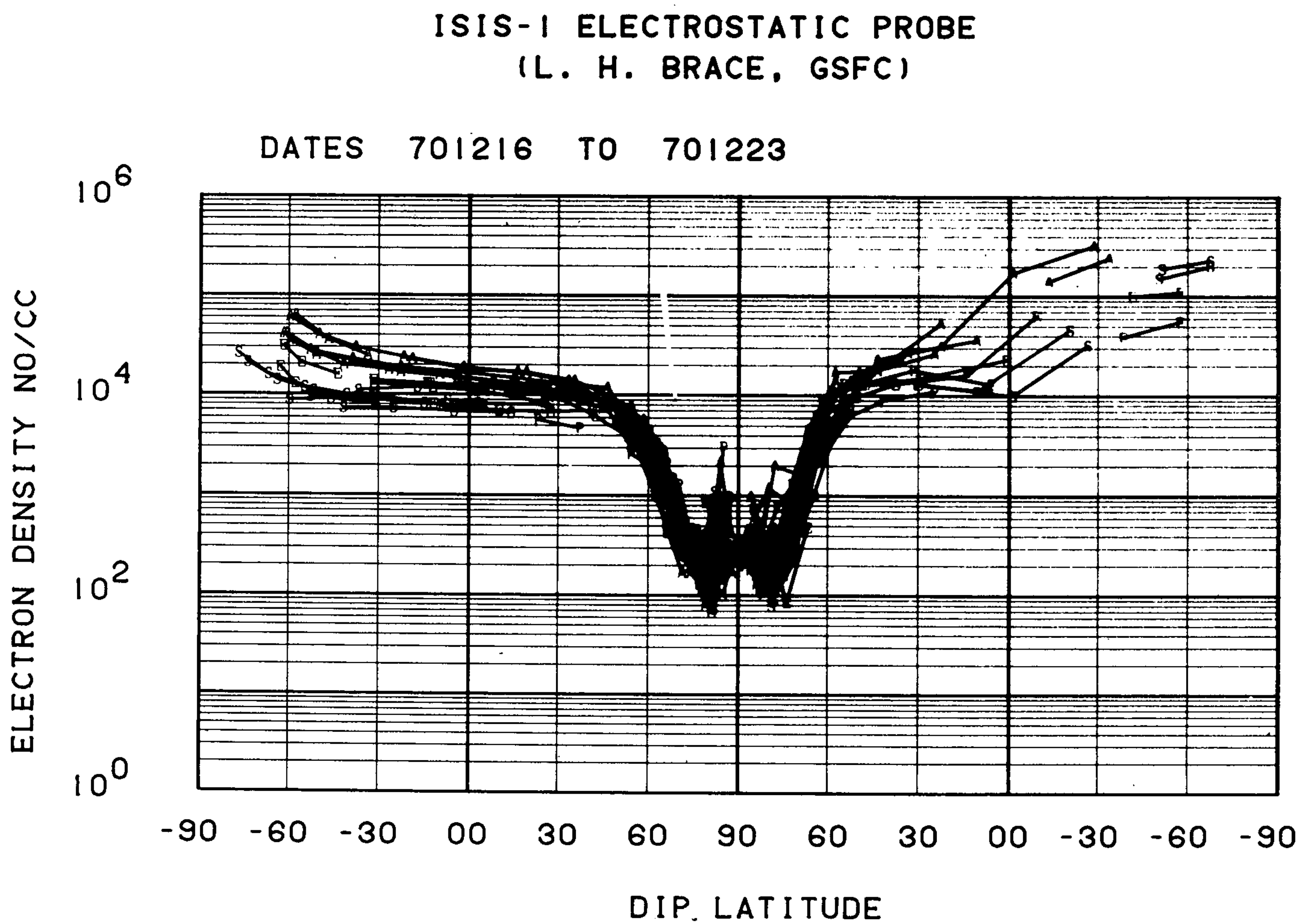

Figure 8. N_e vs. dip latitude expanded from Figure 7. Here the enhancement in the polar cusp on the dayside is seen at about 84° dip latitude and the nightside precipitation zone is the generally irregular region between 75° and 80°.

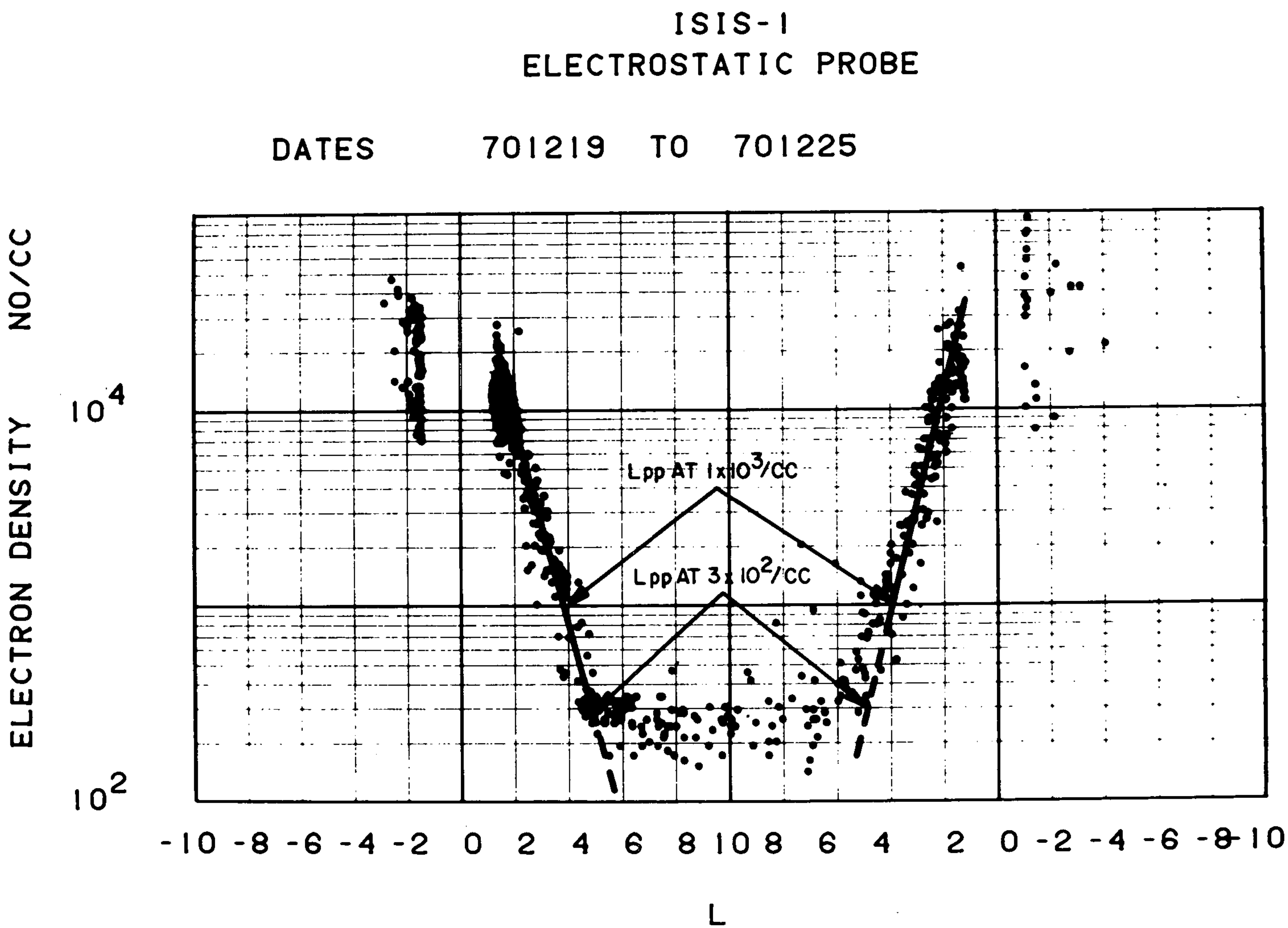

Figure 9. N_e vs. L for the same data as shown in Figure 8 showing the way in which L_{pp} is selected at N_e = 1×10^3/cc and 3×10^2/cc. This shows the high degree of symmetry across the dawn-dusk orbit.

both probes to enhance the spatial resolution and have eliminated the lines between consecutive points. Recalling that the left side is at a local time of 0800 hours and the right side at 2000 hours, a steep gradient of N_e is evident on both the dawn and dusk sides of the pole. This gradient is approximately linear above L=2, with N_e leveling off to a background of 2 to 3 x 10^2 /cc above L=5 or 6.

This background level probably represents the residual of O^+ which varies from pass to pass because of differences in altitude at the different longitudes of the measurements. Whatever its origin, the background ionization represents a lower limit on the N_e level at which the plasmapause can be resolved. The lines on Figure 9 are hand drawn fits to the data between L=2 and 4 and are extrapolated in dashed lines where N_e falls below the background. The plasmapause is defined somewhat arbitrarily as the point where N_e falls below 1 x 10^3/cc or 3 x 10^2/cc, respectively. In examining the magnetic storm response and the diurnal variation of L_{pp}, we looked at the behavior at both 1 x 10^3/cc and 3 x 10^2/cc, as will be seen later.

It should be noted that no sharp discontinuity in N_e is found in this region between 3 x 10^2 and 1 x 10^3/cc. It is simply about the "right" density range and at the "right" L position to be connected with the equatorial plasmapause. If a sharp discontinuity existed at higher L values ($L>5$), we would not be able to resolve it against the background of the high latitude ionosphere.

Plasmapause Variations with Magnetic Activity

During those weeks that were magnetically quiet the weekly global plots exhibit little spread in the plasmapause location. For example, Figure 10 shows the typical week of 2-8 October, 1969. The plasmapause is well resolved in both hemispheres on the nightside of the orbit (0500 LT). As in most weeks, a few passes exhibit some plasmapause compression, probably reflecting small k_p variations during the week or, as in this case, recovery from a storm during the previous week.

In contrast to the quiet or normal week behavior, Figure 11 shows the effects of plasmapause compressions in the previous week when k_p reached 8_o. At one point in this week, the plasmapause moved inward to a dip latitude of less than 50°, then slowly recovered toward its normal position near 70°. The net effect on the global plots was to cause an apparent spreading of the plasmapause location.

To illustrate the detailed response of the plasmapause to a storm, Figure 12 shows L_{pp} during a storm in early November, 1970. This storm is somewhat unique because a_p exhibited a relatively smooth rise and fall in an otherwise quiet period. L_{pp} begins near its quiet location at L=4.3 and decreases slightly as a_p increases. Early on November 7th a_p jumped rapidly to 111 (k_p=7_-) and L_{pp} responded almost immediately, falling to about L=2.9. This was followed by a slow recovery phase that extended over the next ten days. A slight increase

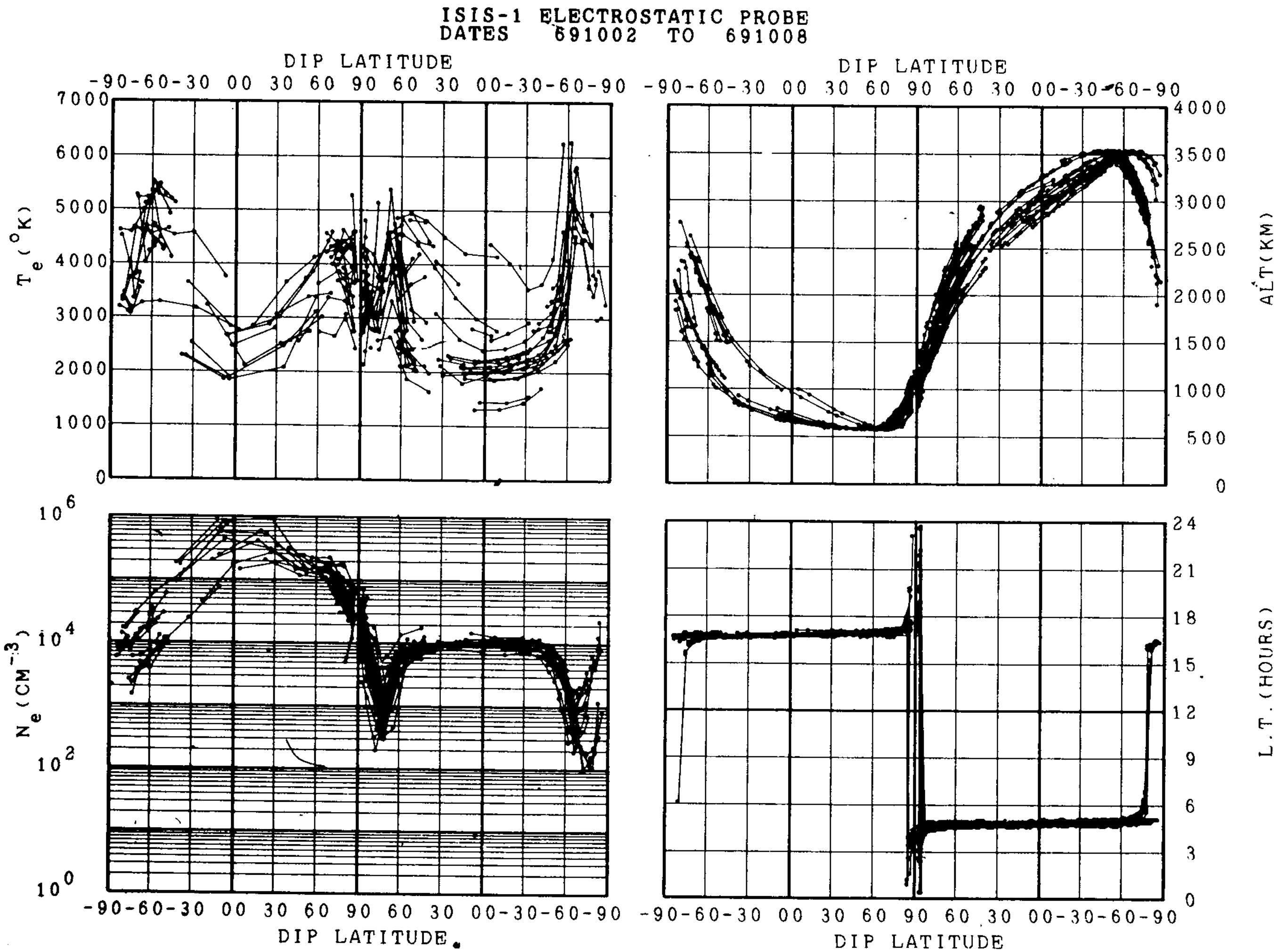

Figure 10. A weekly global plot near solstice showing the plasmapause in both hemispheres on the nightside during a typically quiet week.

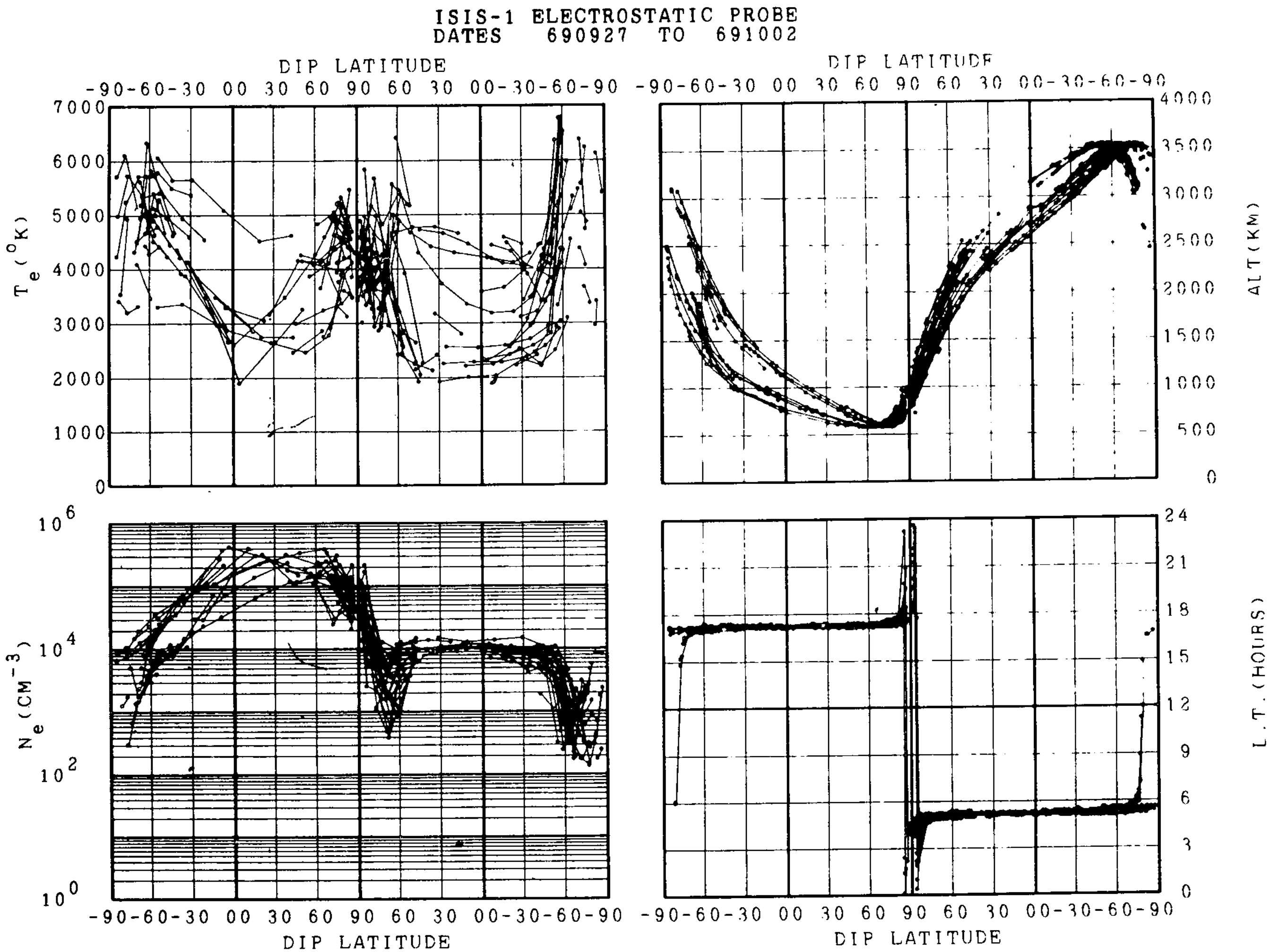

Figure 11. Global plot from the previous disturbed week in which large depressions of the plasmapause are evident in both hemispheres.

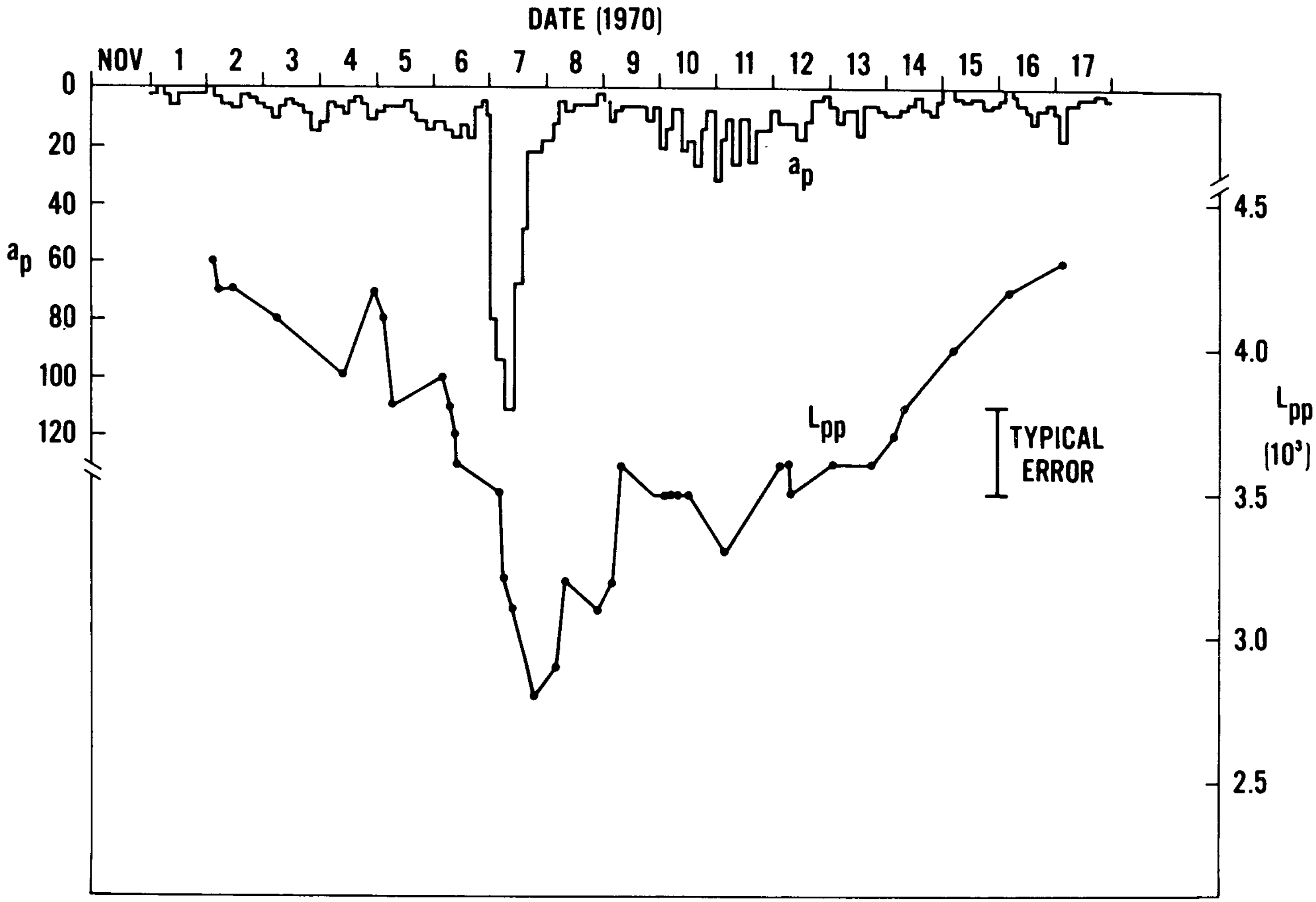

Figure 12. The detailed movements of L_{pp} in response to the early November storm of 1970. The plasmapause depresses in response to both large and small enhancements of the magnetic index a_p . The recovery time is of the order of a week and slows significantly as L_{pp} exceeds 4.

in a_p on the 10th appears to have interrupted the recovery for a day or two. This clearly inverse relationship between L_{pp} and a_p is an effect that is not surprising in view of the reported behavior of the equatorial plasmasphere during disturbed periods. We will compare the storm-time behavior of these two regions later in this paper.

To obtain a more statistical picture of the plasmapause movements during magnetically disturbed periods, we selected the two month period from November 1 through December 31, 1969 and followed the locations of the plasmapause on every available nightside crossings in the northern hemisphere. During this period, the local time was 24 ±3 hours and the crossing altitude was above 2500 kilometers. Figure 13 shows the L_{pp} (10^3/cc) derived from each ISIS-I crossing and the corresponding k_p values (3 hr.). Adopting the form of Carpenter and Park (1973), we find the statistical relationship,

$$L_{pp} = (4.47 - 0.18\, k_p) \quad \pm 0.27\, L, \; k_p \geqslant 0$$

where k_p is the largest 3 hr. k_p of the previous 12 hour interval. Thus the weekly average quiet position of the nighttime mid-latitude plasmapause is at L=4.47, and it exhibits an inward movement of 0.18L for each unit of k_p.

The Diurnal Variation of L_{pp}

The local time variation of L_{pp} was derived from the weekly global plots of N_e vs. L (such as the one shown in Figure 9) from the period of January 1969 through June 1971.

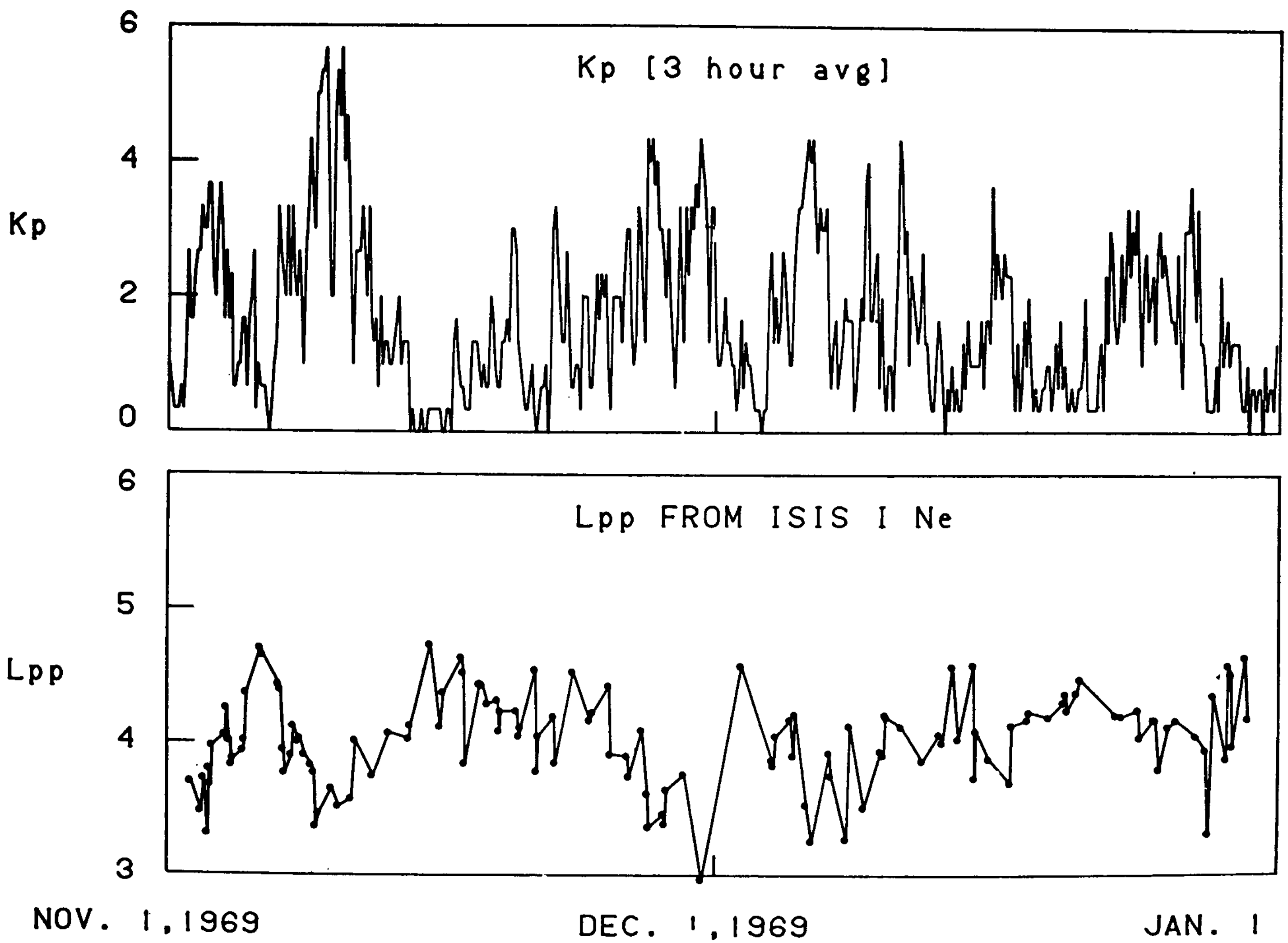

Figure 13. Plot of L_{pp} (10^3/cc) versus k_p for all ISIS-I plasmapause crossings in November and December, 1969.

Since the plasmapause can be defined only where H^+ predominates, only the high alti- altitude crossings were used. Given the orbital precession and apsidal rotation rates of the ISIS-I orbit, it happens that about 6 hours of local time could be observed above 2000 kilometers each time apogee drifted through one of the four plasmapause crossing regions. This permitted ample diurnal coverage of L_{pp} over this 2-1/2 year period. Figure 14 shows this in the form of an altitude and local time plot of the ISIS-I orbit for all L=4 encounters during this period. Each loop represents the altitude and local of the orbit at the point where it crosses L=4, each entire loop representing a 3-month period.

Figure 15 shows the resulting behavior of L_{pp} using both 1×10^3/cc and 3×10^2/cc as criteria for L_{pp}. Each point represents the average L_{pp} from between 10 and 20 plasmapause crossings in a particular week. In an effort to reduce the ambiguity introduced by storm induced motions of the plasmapause, we restricted the data to weeks in which k_p was less than 4. The residual spreading that could be observed in these quiet weeks was typically ±0.4L at 1×10^3/cc, a figure that ultimately limited the determination of L_{pp} to about ±0.2L.

Clearly the plasmapause at mid-latitudes exhibits very little diurnal variation at quiet times. Its mean position at $N_e = 1 \times 10^3$/cc varies from 3.7 in the early morning hours to 4.0 in the afternoon. The $N_e = 3 \times 10^2$/cc crossing level lies between 4.5 and 5.0 throughout the day, showing perhaps only a slight bulge

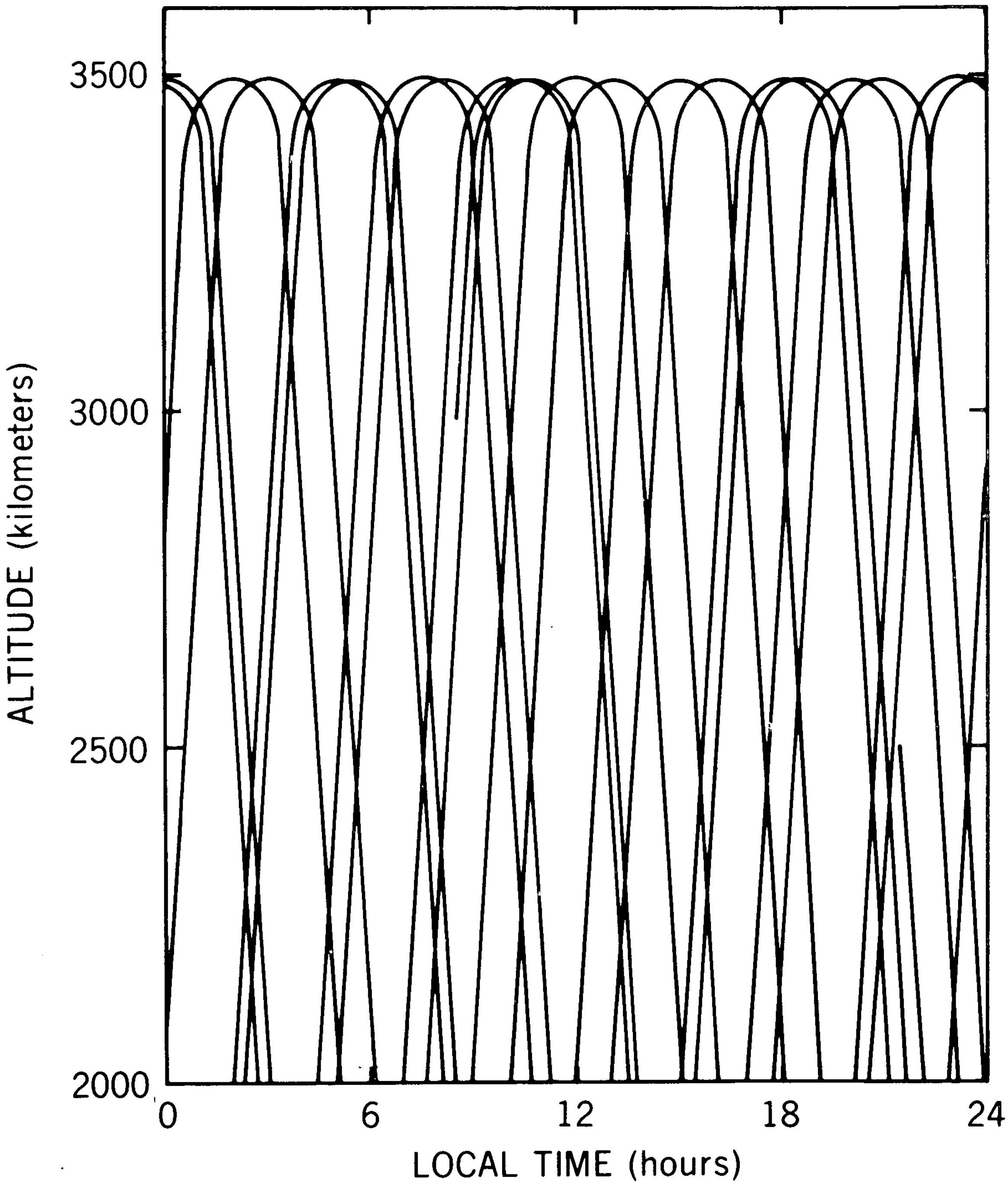

Figure 14. Altitude and local time of the ISIS-I passages at all L=4 crossings in the period of January 1969 through June 1971. Each Loop represents the crossing of one of the four L=r locations during the approach and recession of apogee from that point.

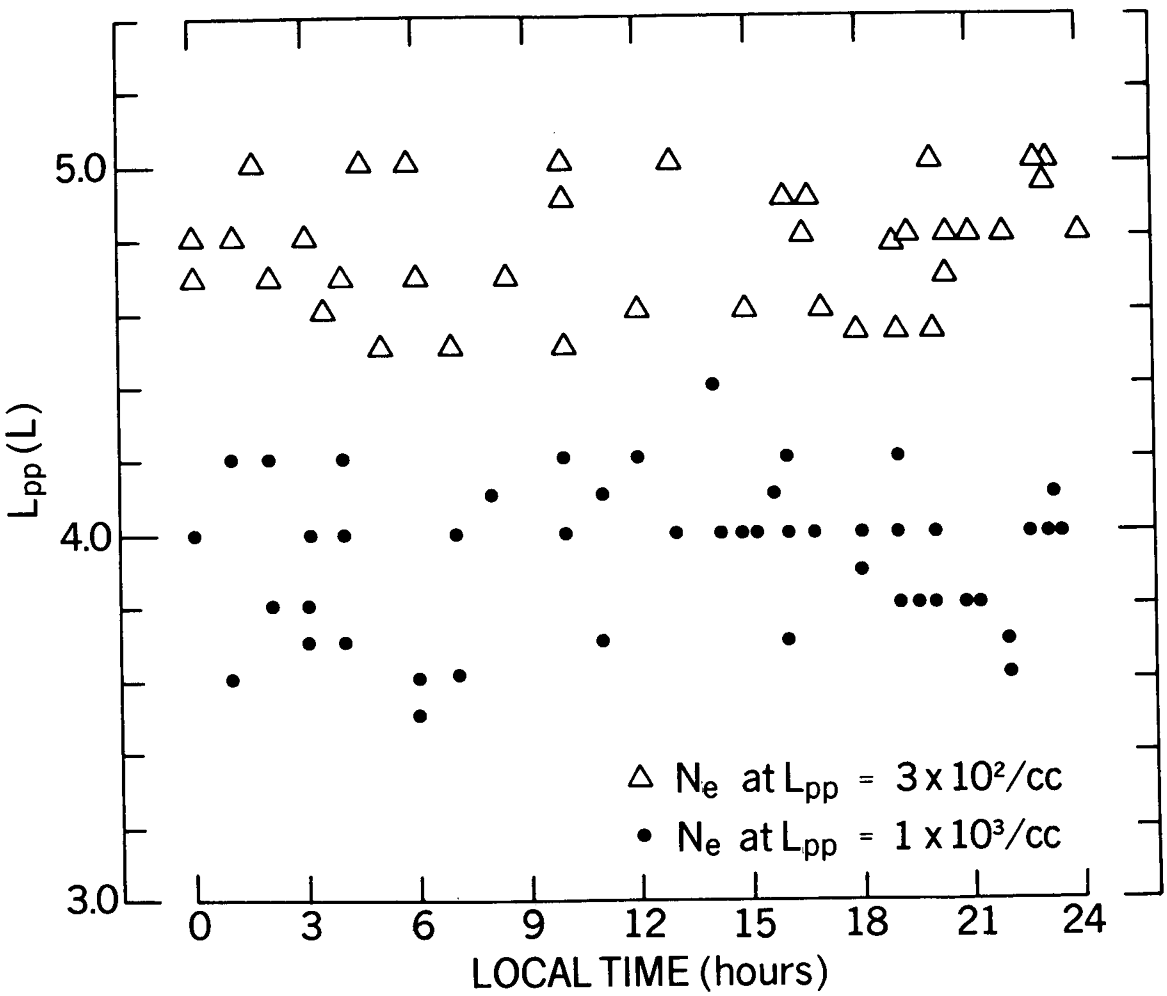

Figure 15. The variation of the plasmapause with local time, assuming it occurs at $N_e = 3 \times 10^2$ /cc and 1×10^3 /cc. Each measurement represents the average L_{pp} for a quiet week ($k_p<4$). The accuracy of the points is ± 0.2L.

on the evening side. It is quite possible that the scatter in L_{pp} could be reduced by further limiting the analysis to only the quietest periods, or perhaps by more detailed analysis and removal of the storm-induced movements. Although, these are topics for further study, the resolution available in Figure 15 is adequate to show that there is little diurnal variation in the mid-latitude plasmapause.

T_e Peak in the Plasmapause

As noted earlier, a peak of T_e is normally observed within the plasmapause gradient (see Figure 5). This peak provides an alternate means by which the motions of the plasmapause can be followed. It has the additional advantage that the peak can be followed at somewhat lower altitudes where L_{pp} cannot be uniquely identified in the N_e measurements because O^+ is no longer negligible at these altitudes.

The T_e peak at the plasmapause is evident at all times of day but is most obvious on the nightside where the background T_e is generally lower. There appears to be a strong positive vertical gradient in T_e within the peak, as it is seen as a weaker feature during lower altitude passes of the plasmapause. The value of T_e and its height gradient (typically $1°$/km) suggests that heat is being introduced at some altitude above the satellite and is being conducted downward at the rate of about 3×10^9 eVcm^{-2} sec^{-1}.

The mid-latitude peak in T_e is not a new feature. Brace and Reddy (1965) reported it as a nighttime phenomenon at 1000 kilometers altitude and attributed it to the large heat capacity of the field tubes above L=2, the daytime heating by photoelectrons being too great to be conducted away during the night. This was confirmed by Mahajan and Brace (1969) who showed that the cooling time constant at L=4 was more than a day. However, from the ISIS-I data we find that the T_e peak follows the plasmapause during magnetic disturbances and becomes enhanced in amplitude. This suggests that a magnetospheric heat source may also contribute to the enhanced T_e. Cornwall et al., (1971) have suggested that heating of the thermal plasma by ring current particles may be the source of mid-latitude red arcs, and it is conceivable that a similar process may occur normally at the quiet-time location of the plasmapause.

DISCUSSION

As noted earlier, the inverse relationship between plasmapause movement and k_p was to be expected in view of the many reports of this type of behavior in the equatorial region (Binsack, 1967) (Taylor et al., 1968) (Chappell et al., 1970). In a recent paper, Carpenter and Park (1973) characterized the location of the nighttime equatorial plasmapause by the empirical relationship,

$$L_{pp} = 5.7 - 0.47\, k_p \text{ (12 hr. max)},\ k_p > 3.$$

where k_p is the maximum magnetic index during the previous 12 hour interval.

If we adopt a form similar to that of Carpenter and Park, and limit the ISIS-I data to those periods in November-December, 1969, when $k_p > 3$ the midlatitude plasmapause location is given by

$$L_{pp} = 4.65 - 0.23\ k_p\ (12\ \text{hr. max}),\ k_p > 3.$$

It appears that the equatorial and mid-latitude plasmapause exhibit slight differences, at least at night where these relationships are believed to apply, if only crudely. The mid-latitude plasmapause exists at lower L values and is a factor of two less sensitive to k_p.

Perhaps the difference in quiet-time location is not of great significance because of our arbitrary definition of its location at $N_e = 10^3$/cc. If instead, L_{pp} had been defined at a lower value of N_e, its location would have been on a higher L shell. We estimate that an L_{pp} at 3 or 4 x 10^2/cc would be necessary to match the quiet-time Carpenter and Park Location of L=5.7. Adopting the observed slope throughout the plasmapause, and recognizing the non-linear increase in L with dip latitude, we find that the amplitude of the storm time variation of L_{pp} is increased at this newly defined level of N_e. This increases the k_p sensitivity from 0.23 to 0.29 k_p as compared with Carpenter and Park's location of 0.48 k_p for the equatorial plasmapause. Thus we conclude that our definition of L_{pp} could be made at a lower N_e level that would match the mid-latitude and equatorial quiet positions, but the mid-latitude L_{pp} would remain less sensitive to k_p variations.

Incidentally, it may be instructive to note that a diffusive equilibrium calculation predicts about a factor of 2 or 3 decrease in N_e along the L=4 field tube that connects the mid-latitude and equatorial portions of the plasmasphere. Since the equatorial plasmapause is found at a concentration of about 1×10^2/cc (Chappell et al., 1971), a value of about 3×10^2/cc might be expected at 3000 kilometers. However, these calculations are not to be relied upon too heavily because the plasma scale height depends upon temperatures and temperature gradients along the field tube, and neither are well known. In addition, Mayr et al., (1970) have commented that the high speed upward flux of H^+ in the vicinity of the plasmapause may cause significant departures from diffusive equilibrium that tend to decrease the electron scale height, a factor that would increase the density gradient between the two plasmapause regions. Thus even our arbitrarily chosen location of the plasmapause at $N_e = 1 \times 10^3 \text{cm}^{-3}$ at mid-latitudes could be consistent with an equatorial value of $1 \times 10^2 \text{cm}^{-3}$, if a sufficiently large convective flow were present.

The Local Time Behavior of the Plasmapause

In view of the rather similar storm-time behaviors of the mid-latitude and equatorial plasmapauses, one might also look for their diurnal variations to be similar. This does not seem to be true, however, at least in the late afternoon sector. The equatorial measurements show a pronounced afternoon bulge (Carpenter, 1966, 1970) (Taylor et al., 1970) (Chappell, et al., 1971) while the ISIS-I measurements reveal little or no diurnal variation of the plasmapause just above the ionosphere. Figure 16 compares the equatorial data with the ISIS data. We recognize that it may not be realistic to compare data from different eras too rigorously, but the persistence of the afternoon bulge in these and other reported equatorial data suggests that something physically significant may be emerging here. It would appear that either the surface we call the plasmapause does not coincide with the geomagnetic field configuration in the afternoon sector, or the field itself exhibits an afternoon bulge. Perhaps both are true.

Nishida (1966) and Brice (1967) described a process by which the afternoon bulge could be formed by the convection of plasma by magnetospheric electric fields. Although this process could create an equatorial bulge of low concentration, it is unlikely that enough plasma could be transported to fully populate a field tube in the bulge region (L=5 or 6). Park (1970) has shown that field tubes above L=4 require more than 5 days to be filled by upward proton fluxes from the ionosphere, a process that is likely to be more effective in filling the plasmasphere than is convection. This slow filling time in the vicinity of L=4 is also evident in November storm data of Figure 12, where it appeared to take about 5 days to fill the region between L=3.5 and 4.3. Thus those field tubes above

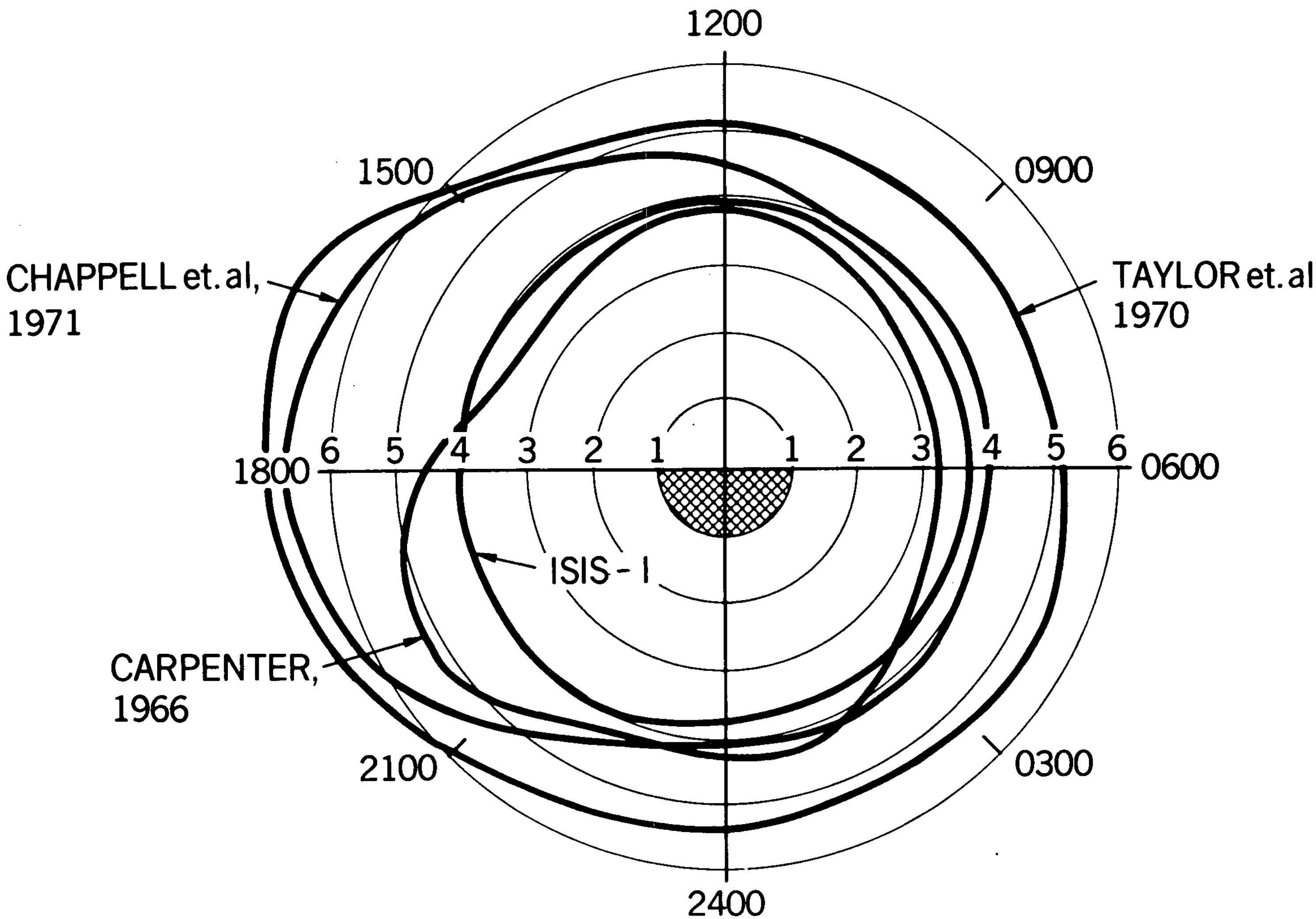

Figure 16. Comparison of the diurnal variation of the equatorial plasmapause by Taylor et al., Carpenter, and Chappell et al., with the behavior of the mid-latitude plasmapause (L_{pp} at 10^3/cc).

L=4, that are subject to daily depletion of charge on the nightside (Chappell, 1972), cannot conceivably be filled by upward proton fluxes even if the flow was continuously at the diffusion limit of several times $10^8 cm^{-2} sec^{-1}$ (Hanson and Ortenberger, 1962) (Parks 1970). These tubes may in fact undergo significant diurnal variation in total content because of their daily depletion, but their electron content must remain rather low at all times of day. Thus perhaps the absence of a diurnal variation in L_{pp} at mid-latitudes should be viewed as confirming the expected behavior of the ionosphere rather than as conflicting with the behavior of a very remote region of the plasmasphere, a region that is controlled by quite different physical processes.

One effect that has not been evaluated in comparisons of low and high altitude data is the configuration of the geomagnetic field itself. As noted earlier, recent ATS-5 magnetometer measurements have revealed an axial asymmetry in the field at about L=6 (Sugiura, 1973), an effect that must also be reflected in the configuration of the plasmasphere itself at high altitudes. The measurements suggest a deficiency of magnetic field strength in the afternoon sector, an effect that is consistent with an afternoon bulge in the field. Although the magnetospheric processes responsible for the field asymmetry have not been identified, it is likely to be caused in part by the plasma convection process itself and ultimately by the electric fields that drive it.

Relationship of the Plasmapause to Ionosphere Troughs

The absence of a large diurnal variation in the plasmapause just above the ionosphere (alt=3000 ±500 km) would appear to be in conflict with the F-region trough observations of Rycroft and Thomas (1970) and Rycroft and Burnell (1970). These authors found that the location of the trough exhibited the same kind of diurnal variation as the location of Carpenter's whistler knee and concluded that the trough and the knee were on the same field lines. Unfortunately, their trough could be observed only on the nightside from about 2100 hours to about 0600 hours, a period that misses the afternoon bulge substantially (Chappell et. al., 1971). In the same local time interval, the ISIS-I measurements of L_{pp} are in similarly good agreement with the equatorial plasmapause location.

Rycroft and Thomas also pointed out correctly that the trough-like structure is evident because of auroral ionization that forms its poleward boundary. This implies that the location of the trough should exhibit a component of diurnal variation similar to that of the auroral oval.

Muldrew (1965) has reported a similar narrow trough in the F_2 peak concentration that could be observed through the afternoon and night sectors from about 1400 to 0600 hours. Its position rose from a midnight minimum at L=4 to a midday maximum about L=10. This behavior is in contrast to Carpenter's bulge at 2000 hours and midday plasmapause at about L=4, as shown in Figure 16. It seems likely that Muldrew's trough was related in part to the movements of the auroral oval, particularly on the dayside where the cusp is found at about L=15-20 at midday and drifts equatorward at both dawn and dusk (Winningham 1972).

Similar F-region troughs found by Sharp (1966) and Tulunay and Sayers (1971) also tend to show little similarity with the diurnal behavior of the equatorial plasmapause. Tulunay and Sayers found their trough at L=5 at 1400 hours, decreasing smoothly through the night to L=3.5 at 0700 hours. Thus it is not established that the F-region troughs depict the equatorial plasmapause location, except perhaps on the nightside where all troughs, and the ISIS-I data, agree in the location of L_{pp} in the vicinity of L=4.

CONCLUSIONS

Measurements of the nighttime plasmapause location at mid-latitudes are found to exhibit variations with k_p that are similar to those found for the equatorial plasmapause, although the amplitude of the movement at mid-latitudes is slightly smaller. In contrast, the afternoon bulge of the equatorial plasmapause is not found to be a significant feature at the plasmasphere boundary just above the ionosphere. Although there are a number of difficulties in relating measurements from these two regions of the plasmasphere, this difference appears inescapable. The equatorial bulge, undoubtedly a real feature of the plasmasphere, has been explained in terms of plasma convection driven by electric fields in the magnetosphere. Recent magnetic field measurements suggest that an afternoon expansion of the field may also occur, perhaps induced by the convection process itself. The net effect would be to produce an even more enhanced afternoon bulge in the plasmasphere at very high altitudes. The fact that such field distortions would be greatly attenuated at ISIS-I altitudes may account for the supression of the afternoon bulge there. In any case, it can be shown from an ionospheric point of view that a plasmapause will be formed wherever the plasma pressure is low enough in the magnetosphere to draw a diffusion limited proton flux out of the ionosphere. During quiet times this appears to occur continuously above L=4, the location of the ISIS-I plasmapause.

ACKNOWLEDGEMENT

We thank Mr. Tuck Bin Lee, formerly of the University of Michigan, Space Research Laboratory, for his design and fabrication of the instrument, and to J. A. Findlay and E. Busboso of GSFC for their efforts in the integration of the experiment into the ISIS-I spacecraft. We are also indebted to J. Johnson and E. Gregg for their aid in the data processing and to Joseph Grebowsky for extensive discussions of its interpretation.

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