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ABSTRACT

The existence of field-aligned currents in the polar cap boundary layer as a permanent feature of the magnetosphere is shown on the basis of the magnetic field observations from Triad at 800 km altitude and from Ogo 5 in the high-altitude magnetosphere. The results from these satellites indicate that in the morning half of the boundary layer, currents flow into the ionosphere, and that the current direction is reversed, i.e. away from the ionosphere, in the afternoon half of the layer. These currents constitute a net current flowing into, or away from, the ionosphere, as the Triad results clearly demonstrate. The Triad data further indicate that the net current is a maximum near 1500 MLT and that there may be a secondary maximum during early morning hours. According to the Isis 2 electron observations, the locations of these maximums of field-aligned net current roughly match those of two maximums in the isointensity contours for 150 ev electrons. It is proposed that the polar cap boundary current is driven by a current generator in the magnetotail, or ultimately in the solar wind. Examining the existing particle observations, in particular, those from ESRO 1A and 1B, it is suggested that the large scale field-aligned currents in the polar cap boundary layer are associated with the dominance of protons on the morning side and of electrons on the afternoon side near the poleward edge of the precipitation zone along the auroral oval. Based on the ESRO 1A, 1B and Isis 2 observations, it is further suggested that protons with energy $\sim$ 1 kev and electrons with energy of the order of 100 ev, and possibly up to about 1 kev, comprise the main carriers of the field-aligned currents flowing in the polar cap boundary layer.

INTRODUCTION

The existence of a field-aligned current region along the auroral oval was demonstrated by the magnetic field observations from satellite 1963-83C by Zmuda et al. (1966, 1967), from Explorer 22 by Zmuda et al. (1970), and from AZUR by Theile and Praetorius (1973). These three satellites were magnetically stabilized and the first two carried a single-axis magnetometer and the third, a two-axis magnetometer. In all cases the magnetometer measured transverse field perturbations which were interpreted as being caused by field-aligned currents, following the initial interpretation by Cummings and Dessler (1967). These observations did not provide the current directions because spacecraft attitude was not determined. Only for one pass of satellite 1963-83C over the auroral zone during a highly disturbed period, Armstrong and Zmuda (1970) determined spacecraft attitude and discussed the current direction.

The Navy/APL satellite Triad is the first spacecraft that provided vector magnetic field data from which field-aligned currents can be studied in detail. The initial Triad results were reported by Armstrong and Zmuda (1973) and Armstrong (1974). Subsequently, Zmuda and Armstrong (1974a) gave statistical results showing the location of the field-aligned current region along the auroral oval as a function of magnetic local time for two Kp levels. Zmuda and Armstrong (1974b) further showed that the field-aligned current region usually consists of two current sheets with oppositely directed currents. On the morning side, the current flow is downward in the higher-latitude sheet and upward in the lower-latitude sheet, and these directions are reversed on the afternoon side. Zmuda and Armstrong (1974b) held the view that the amounts of the oppositely directed currents in these two sheets are usually equal, implying a current continuity between the adjacent current sheets. The Triad observations were made at about 800 km altitude.

At much higher altitudes, transverse field perturbations have also been interpreted as indicating field-aligned currents. Examples of satellite observations of isolated events at high altitudes include those from ATS 1 by Coleman and McPherron (1970), from Heos 1 by Haerendel et al. (1971), from Explorer 12 by Kaufman et al. (1972), and from Imp 5 by Fairfield and Ness (1972). Aubry et al. (1972) and Fairfield (1973) showed the existence of field-aligned currents on the high-latitude boundary of the plasma sheet using data from Ogo 5 and Imps 4 and 5, respectively. In particular, Fairfield (1973) interpreted the signature of field-aligned current as indicating the encounter of the spacecraft with the boundary of an expanding plasma sheet at the time of a substorm. He showed that these field-aligned currents flow toward the ionosphere in the post-midnight quadrant and away from the ionosphere in the pre-midnight quadrant.

The effort to establish the basic pattern of magnetospheric field-aligned current system has been continued by Sugiura (1975), Sugiura and Potemra (1975), and Iijima and Potemra (1975), using Ogo 5 and Triad observations. This paper describes the basic features of the field-aligned currents near the polar cap boundary that have been investigated by these authors, and discusses the possible carrier of these currents on the basis of the published results of electron and proton observations.

OGO 5 OBSERVATIONS AT HIGH ALTITUDES

Polar Cap Boundary Layer

Whether the transition from the 'closed' dipolar field to the 'open' polar cap field is continuous or relatively abrupt with a boundary layer in between is an interesting question. If such a boundary layer exists, there will be a shear in the field across the boundary layer. All the existing magnetospheric field models have a continuous transition from the low latitude field to the polar cap field. Sugiura (1975) has shown that on many orbits the Ogo 5 satellite observed a field shear confined in a relatively thin layer that can be interpreted as being the polar cap boundary layer. In Figure 1, which gives an example of a crossing of such a boundary layer, observed inclination, I, declination, D, and the field magnitude, B, are plotted on an outbound pass of Ogo 5 on August 25, 1969; the smooth solid lines are the respective quantities calculated from the earth's main field model of Cain et al.(1967). The plot for D shows that the field configuration is essentially dipolar to about 0340 UT, marked b in Figure 1. After this time the field starts to deviate westward from the direction of the reference field. At 0340 UT the spacecraft was at a geocentric distance of 7.1 R_E and at about 47°N dipole latitude. The invariant latitude of this position was approximately 75°N, and the magnetic dipole local time (MLT) was near 16 hours. The relatively sudden westward deflection of the field at this location implies the presence of a well-defined boundary between the dipolar field and a tail-like polar cap field. The confinement of the change in D in a limited region and the absence of any notable changes in I and B corresponding to the change in D indicate the existence of a field-aligned current (upward in the case shown in Figure 1) in the boundary layer. In Figure 1 the location of the current layer is shown by the hatched band.

The question of how often Ogo 5 crossed the polar cap boundary layer carrying field-aligned currents is a complicated problem. The inclination of the Ogo 5 orbit at launch was 31.3°. Consequently, whether or not a polar cap boundary can be recognized in the Ogo 5 data from any given orbit is dependent predominantly on the geometry of the orbit relative to the boundary and not necessarily on the presence or absence of field-aligned current in the boundary layer. This situation is entirely different from the case of a polar orbiting satellite like Triad, where the traversals of the relevant regions on each orbit are guaranteed. Additional factors that must be considered include (a) that the orbit is sometimes nearly parallel to the magnetic field in the region of the crossing of the boundary layer, and (b) that because of the spreading of the magnetic flux tubes with increasing altitude the field-aligned current density decreases. These factors contribute greatly to the difficulty in detecting the field-aligned current layer from Ogo 5. It was found that during certain periods of the Ogo 5 lifetime the field-aligned current layer was detected quite frequently, while there were long stretches of period when a well-defined current layer was not detected. For instance, during the month of August 1970 the polar cap boundary layer carrying field-aligned currents was detected with certainty on approximately 78% of the orbits. More detailed discussions of this question are given in Sugiura (1975).

Based on the study of approximately 80 well-defined crossings of the polar cap boundary, Sugiura (1975) found that the direction of the field-aligned current in the boundary layer has a striking regularity. The current flows into the ionosphere on the morning side and flows away from the ionosphere on the afternoon side both in the northern and southern hemispheres.

Auroral Belt

In the example shown in Figure 1, irregular field fluctuations are seen in D on the earthward side of the polar cap boundary. This is a commonly observed feature and can be considered as a characteristic of the auroral belt magnetic flux. A more important characteristic of the auroral belt that was often observed by Ogo 5 is demonstrated in Figure 2. On this outbound pass on August 13, 1970, declination underwent an eastward change on the low-latitude side of the polar cap boundary at which the westward field deflection began. This indicates that there was another field-aligned current layer adjacent to, and equatorward of, the current layer at the polar cap boundary. The direction of the current flow in this second field-aligned current layer is opposite to that in the polar cap boundary layer. Namely, in the example shown in Figure 2, the current flows away from the ionosphere in the polar cap boundary layer and flows into the ionosphere in the lower-latitude current layer. These are the current directions in the double layer system observed on the afternoon side of the magnetosphere. On the morning side the current directions are reversed, that is, the flow is into the ionosphere in the polar cap boundary layer and away from the ionosphere in the lower-latitude layer.

The signatures of the lower-latitude current layer are generally less distinct than those of the higher-latitude current layer. Because of the limitations in the Ogo 5 spacecraft attitude accuracy at close geocentric distances $\lesssim 3\ R_E$, it is not possible to establish quantitatively that the amount of current flowing in the higher-latitude current layer is greater than that flowing in the lower-latitude layer. However, the analysis so far made seems to support such a relation at least qualitatively.

The lower-latitude current layer was identified by Sugiura (1975) as the auroral belt for several reasons. For instance, (a) during intense magnetic disturbances the invariant latitudes of this current region decrease; (b) the width of the current region expands under disturbed conditions, and (c) the current direction in the layer is the same as that in the lower-latitude current layer observed by Zmuda and Armstrong (1974b) from Triad at 800 km altitude in the northern hemisphere. The features described under (a) and (b) are in agreement with the well-known behavior of the auroral oval.

During magnetic disturbances the currents flowing in the field-aligned current layers become intense and often multiple current layers are observed. Figure 3 shows an example of such a multiple structure. It is interesting that although there is a series of double layers, the basic pattern is the same as in the simple structure seen in Figure 2.

<u>Continuity of the Polar Cap Boundary to the High-Latitude Boundary of the Plasma Sheet</u>

During the periods when Ogo 5 apogee is in the tail region the spacecraft, after passing the auroral belt and the polar cap boundary on its outbound orbit, stays in the polar cap magnetic flux for many hours. The observed field is usually steady and uneventful while the spacecraft is in this region. This quiet condition is abruptly interrupted when the spacecraft enters the diamagnetic region, i.e. the plasma sheet, in the north to south direction. At the time of the entrance into the plasma sheet a distinct field deflection as represented by a change in D is observed. This signature indicates the presence of a field-aligned current in the plasma sheet boundary layer. The current direction is away from the earth in the pre-midnight region and is toward the earth in the post-midnight region. These directions are the same as those deduced by Fairfield (1973) from the Imp results as has already been mentioned.

Based on the current continuity Sugiura (1975) concluded that on the night side the polar cap boundary current continues on to the surface current on the high-latitude boundary of the plasma sheet. The dayside field-aligned currents in the polar cap boundary layer that are not connected to the plasma sheet boundary must flow on the magnetopause surface in the antisolar direction. Where this division takes place, on each side of noon, is not as yet known.

TRIAD OBSERVATIONS AT 800 KM ALTITUDE

Polar Cap Boundary Current

Recently Sugiura and Potemra (1975) showed that the existence of a net current flowing into, or away from, the ionosphere is a basic feature of the field-aligned current system as observed by the Triad satellite at 800 km altitude. This deduction is based on frequent observations of a step-like level shift in the east-west component of the magnetic field. Figure 4 shows an example of such a level shift. In the figure the A and B sensors are approximately in the east-west and north-south directions, respectively, and the Z sensor axis is vertical; more detailed information on the sensor axes is found in Armstrong and Zmuda (1973). The uncertainties in spacecraft attitude and the magnetic field contaminations from the spacecraft make it impossible to accuratley determine the reference level for the magnetometer measurements. In Figure 4 the components of the difference field (i.e. the observed field minus the IGRF) are plotted relative to the level for the first data point.

To conduct a statistical analysis of such level shifts the following set of selection rules was applied: (a) that the duration of time in which the main part of the change in the east-west component takes place is short compared with the time scales of characteristic smooth variations that we ascribe to spacecraft attitude changes and (b) that the amplitude of the level shift is so large that the ambiguity in the reference level is no problem in determining whether or not there is a level shift. Figure 5 shows the frequency of occurrence of level shifts as a function of magnetic local time. There is a distinct maximum in the frequency of occurrence near 1500-1600 MLT. There is an indication of a secondary maximum in the early morning hours.

The three-hourly average magnitudes of level shifts are plotted in Figure 6 for two Kp groups, $Kp \le 2$ and $KP > 2$. For both Kp groups there is a maximum in the amplitude of level shift in the 1500-1800 MLT region. For the $Kp > 2$ group the amplitude has a broad maximum during the morning hours, but for the lower Kp group there are not enough cases to determine whether or not there is such a secondary maximum. Assuming an infinite current sheet model, the current density integrated over the thickness of the current layer, J, is equal to $\Delta B/\mu_o$, where ΔB is the magnitude of the level shift in the east-west component. Figure 6 thus shows that the net current flowing in the current layer has a maximum near 1500-1800 MLT.

In Figure 7 the magnitude of ΔB is plotted against Kp. The average ΔB for each Kp value is indicated by open circles together with the standard deviation marked by a vertical bar. There is a tendency that ΔB increases with increasing Kp. An interesting point is that ΔB does not tend to zero as Kp tends to zero. This is consistent with the view that the existence of a net current flowing into or away from the ionosphere is a permanent feature of the magnetosphere. Figure 8 shows the average invariant latitudes of the poleward and equatorward boundaries of the current layer and the average thickness of the layer, both as functions of MLT and for the two Kp group.

Comparing these Triad results with the Ogo 5 results there is no question in that the field-aligned current layer discussed above is the current layer observed by Ogo 5 and identified as the polar cap boundary layer. This current layer also is the same as the poleward current layer in the double layer model of Zmuda and Armstrong (1974b).

COMPARISON WITH A MODEL CURRENT SYSTEM

As has already been mentioned, the Triad observations do not provide the zero levels for the three components. Also, the spacecraft attitude is not accurately known. In other words, the base-lines, which are not necessarily straight lines in the data plots such as is shown in Figure 4 above, are not known. It is of interest, therefore, to compare the observed results with a theoretical model. Preliminary results of such a comparison are given below.

As a first step a field-aligned current sheet in a dipole field configuration was used as a model. The sheet current is represented by densely spaced line currents along the dipole field lines. The current flows from the equator to the ionosphere (to 100 km altitude) in the morning hemisphere and from the ionosphere to the equatorial plane in the afternoon hemisphere. In this preliminary report we discuss the fields produced by these field-aligned portions of the current system. Strictly speaking, the integral of the current must be made over an entire closed circuit. However, what is discussed here is the contribution to the field from the field-aligned portions of a current system. This step is considered to be important because the field distribution in some regions greatly depend on the pattern of closure currents.

Figure 9 shows the field distribution from the model field-aligned currents along a circular pass at a constant altitude of 800 km in four meridian half-planes simulating Triad orbits. The meridian half-planes are specified by the azimuthal angle Φ, measured eastward from midnight; that is, Φ is dipole local time in angular measure. Thus $\Phi = 90^\circ$, 60°, 30°, and 5° correspond to 0600, 0400, 0200, and 0020 dipole local time respectively. The field distribution in other quadrants can be obtained from the first quadrant by a set of symmetry relations. The current intensity is normalized so that the level shift is roughly 120γ, a very small size, representing an extremely quiet condition. Rather unexpected results were obtained. First, a steep slope is found in B_ϕ on the equator side of the current sheet, and this slope steepens as midnight is approached. Secondly, while B_ϕ in the polar cap is nearly flat at $\Phi = 90^\circ$, a gradient in B_ϕ develops as Φ decreases, and near midnight ($\Phi = 5^\circ$) the gradient in B_ϕ becomes steep and almost antisymmetric with respect to the current sheet. Thirdly, the B_θ component, which is zero at $\Phi = 90^\circ$, increases as Φ deviates from this meridian, reaching a maximum at midnight (and noon). Without true baselines it is difficult to compare the Triad observations with this behavior of B_θ in the model. However, it is clear that an arbitrarily selected smoothed background curve would not provide a reliable base-line for the Triad data.

It is of interest to see how the B_ϕ profile changes with altitude. The results, shown in Figure 10, indicate that with increasing altitude, the gradient in B_ϕ decreases, and that the profile approaches that expected from an infinite current sheet. This shows the significance of the effects of the curvature in the current sheet.

Figure 11 presents the diurnal variations in the magnetic field at the ground expected from the field-aligned currents of the present model. The results show that the effects on the ground are appreciable. The field in the polar cap is roughly uniform and is directed toward the sun. However, as has been pointed out, the ionospheric closure current will generally modify this field pattern. For instance, if the closure current is a Pedersen current over the polar cap, the field leakage below the ionosphere is expected to be small.

It is emphasized that these results are preliminary and are presented here only to indicate several factors that have to be taken into account in interpreting satellite observations of field-aligned currents and in interpreting magnetic field variations in the polar cap. Comparison of the model with the Triad observation and improvements and modifications of the model are still left for future work. A study with a more realistic field model than a dipole field for the geometrical configuration of the field-aligned current sheet is also being made.

DISCUSSIONS

Current Carriers

An extensive search in the literature for possible candidates for the current carriers has not produced any conclusive results. However, the results from Isis 2 discussed by McDiarmid et al. (1975) and those from ESRO 1A presented by Hultqvist et al. (1974) provide promising clues to the question of what the current carriers might be for the field-aligned currents flowing in the polar cap boundary region. The paper by McDiarmid et al. (1975) has been discussed by Sugiura and Potemra (1975) relative to their study of Triad results.

McDiarmid et al. (1975) gave average isointensity contours for electrons of various energies: 0.15, 1.3, 9.6, and > 22 kev. Of particular interest is the contour map for 150 ev electrons (their Figure 4), which shows intensity maximums near 1500 and 0300 MLT. The afternoon maximum is at roughly the same local time and invariant latitude as the maximum field-aligned current region determined from the Triad results. Thus, so far as the location of this maximum electron intensity is concerned, we may favorably view the interpretation that low energy (~ 150 ev) electrons precipitated in this region contribute to the field-aligned current. According to McDiarmid et al.(1975), the location of the afternoon maximum electron intensity shifts toward midnight with increasing energy. For 1.3 kev electrons, there are two afternoon maximums, one centered near 1600-1700 and the other about 2100 MLT. The contours for 9.6 kev electrons show a single afternoon maximum near 2300 MLT. Thus electrons with energies from about 150 ev to 1 kev may be regarded as being a candidate for the current carrier for the upward field-aligned current in the afternoon sector. The 150 ev energy is the lowest energy that McDiarmid et al. measured, and is not necessarily the lowest energy of the electrons precipitated in the relevant region.

It should be kept in mind that the isointensity contours represent an average pattern, and that on individual passes, profiles have a great variability. Large variabilities are common to all particle data (e.g., Frank and Ackerson, 1972; Gurnett and Frank, 1973; Hoffman, 1972; Hultqvist et al., 1974), and indeed, such large variabilities in particle fluxes and the relatively small variability in the field-aligned currents makes it doubtful if particle intensities correlate with field-aligned currents of the type discussed here. Indeed, on the basis of the existing data on precipitated electrons and protons and on field-aligned currents it can be stated that in general, there is no simple one-to-one correspondence between particle precipitation regions and field-aligned current regions. It seems certain to the present author that any attempts to directly correlate large scale field-aligned currents such as those treated in this paper with either precipitated electrons or protons separately will be futile. Currents carried by precipitated particles with charges of one sign appear to be compensated to a large extent either by precipitated particles of opposite charge or by particles of the same charge flowing outward from the ionosphere, or in some cases, by both. It is the difference between the opposing currents that results in the large scale field-aligned currents. Nevertheless, it is meaningful to investigate particle precipitation patterns because it is more likely than not that large differences between opposing currents occur in, or in the vicinity of, regions of high particle intensity. It is in this sense that the region of maximum (150 ev) electron intensity in the afternoon observed by McDiarmid et al. (1975) was discussed above. The maximum electron intensity near 0300 may or may not be related to the morning maximum in the net field-aligned current. If they are correlated, this must mean either that the intensity of precipitated protons exceeds that of electrons or that the thermal electrons are streaming upward in greater intensity than the precipitated electrons.

The view that the difference between precipitated electrons and protons is important is supported by the study made by Hultqvist et al. (1974). These authors summarized their observations of protons and electrons in the kev energy range on ESRO 1A and 1B. They note that by and large the protons and electron profiles coincide fairly well in all local time sectors. Therefore, at least in the kev energy range, it is unlikely that any isolated population of electrons or protons constitutes a current carrier; it is the difference between the electron and proton intensities that forms the current.

An examination of the electron and proton intensities presented by Hultqvist et al. (1974) for the dayside indicates that there are a number of cases which show protons extending more poleward than electrons on the morning side and electrons dominating over protons near the poleward edge of the particle zone on the afternoon side. Examples of such cases are shown in Figures 12 and 13, for the pre-noon and post-noon situations, respectively. In each of these figures the location of the trapping boundary for electrons with energy > 40 kev determined on the same satellite is indicated by a vertical line. It is interesting to note that in both cases the proton or electron dominance is observed at invariant latitudes immediately above the invariant latitude of the 40 kev electron trapping boundary.

Hultqvist et al. (1974) state that the kev protons seem to be a more permanent feature of the upper atmosphere in the auroral oval than the kev electrons are. This feature, combined with the tendency that on the morning side, protons extend further toward the pole than electrons do, would be consistent with the view that protons in the kev energy might be a current carrier in this time sector. The observations by McDiarmid et al. (1975) and Hultqvist et al. (1974) are consistent with the idea that precipitated electrons with energy from 100 ev to a few kilo electron volts contribute appreciably to the field-aligned currents in the afternoon. However, these considerations are still speculative in nature and should not be regarded as presenting evidence for the carriers of the field-aligned currents discussed in this paper.

Rocket observations of field-aligned currents and precipitated particles associated with auroral arcs have been reviewed by Arnoldy (1974). These observations are concerned with detailed structures in the field-aligned current system, and as such they cannot be directly incorporated into the gross picture of the large scale field-aligned current system dealt with in the present paper in this phase of the study. As the relations between the particle precipitation and visual auroras and between the particle precipitation and field-aligned currents are not as yet clear, it is not expected to find a clear-cut correlation between the auroras and the large scale field-aligned currents. However, from a comparison of Triad data on three passes with ground-based auroral and magnetic observations Armstrong et al. (1975) have found that the poleward arc coincided with the northernmost boundary of the field-aligned current region and that all the visual auroral arcs lay within the field-aligned current region. As these authors point out, more comprehensive analysis is required to establish such features.

Current System

In the study by Iijima and Potemra (1975) the field-aligned current layer discussed above is called current region 1, and the current region adjacent to, and equatorward of, region 1 is called current region 2. The current direction in region 2 is opposite to that in region 1, namely, the current flow is upward and away from the ionosphere on the morning side and downward and into the ionosphere on the afternoon side, in agreement with the current pattern derived from the Triad data by Zmuda and Armstrong (1974b) and from the Ogo 5 data by Sugiura (1975).

A field-aligned current system consistent with these observations is shown in Figure 14. On the night side of the magnetosphere the current flows from the tail into the ionosphere in the post-midnight sector and flows from the ionosphere to the tail in the pre-midnight sector. These currents, indicated by C_{fa}-1 in Figure 14, flow on the surface of the high-latitude boundary of the plasma sheet; this boundary becomes the polar cap boundary near the earth. The current in the lower-latitude layer flows from the ionosphere to the equatorial region on the morning side and flows from the equatorial region to the ionosphere on the afternoon side as indicated by C_{fa}-2 in Figure 14. The currents in these two sections are connected by the equatorial current.

As has already been mentioned, the polar cap boundary current near noon is likely to flow on the magnetopause in the antisolar direction. The currents in the lower-latitude layer flow to the equatorial region everywhere because the magnetic field along which these currents flow is essentially dipolar, according to the Ogo 5 observations. The polar cap boundary currents (C_{fa}-1) represent a more permanent feature than do the currents in the lower-latitude layer (C_{fa}-2). As Iijima and Potemra (1975) have shown, the latter currents are directly associated with substorm activity.

Sugiura (1975) proposed that the polar cap boundary currents are driven by a current generator in the tail, or ultimately in the solar wind. These field-aligned currents can thus be thought of as being a boundary phenomenon taking place in the boundary region between two distinctly different plasma regimes. The existence of the auroral oval itself is a boundary phenomenon and the auroral arcs and other visual features of the aurora themselves may be regarded as being boundary phenomena occurring on finer scales, all taking place in the large scale, broad boundary region.

CONCLUSION

The Triad and Ogo 5 observations have shown the existence of a field-aligned current system consisting of currents flowing in the polar cap boundary layer and those flowing in another layer situated equatorward of the boundary layer. In the polar cap boundary layer, which is identified as the high-latitude boundary of the plasma sheet in the nightside magnetosphere, the current flows into the ionosphere from the tail on the morning side and flows away from the ionosphere into the tail on the afternoon side. It is proposed that this current system is driven by a current generator in the tail.

In the lower latitude current layer which lies in the dipolar field region of the magnetosphere, the current direction is from the ionosphere toward the equator on the morning side and is reversed on the afternoon side. According to Iijima and Potemra (1975) the currents in this layer are more directly associated with substorm activity. The closure of this field-aligned current system is likely to be via the magnetospheric equatorial current system.

No particle data available at present provide a definitive answer to the question of what the carriers of the field-aligned currents are. A statistical analysis of the Isis 2 electron results by McDiarmid et al. (1975) suggests that precipitated electrons with energy 150 ev to about 1 kev are good candidates for the carrier of the net current flowing in the afternoon portion of the polar cap boundary current layer. On the basis of the analysis of ESRO 1A and 1B particle observations by Hultqvist et al. (1974) it is suggested that protons in the kev energy range may be the carrier of the net current flowing into the ionosphere in the polar cap boundary layer on the morning side.

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FIGURES

Figure 8. The average position and the thickness of the field-aligned current layer carrying net current, observed by Triad, as functions of magnetic local time (after Sugiura and Potemra, 1975).

Figure 9. The magnetic field profile calculated from a field-aligned current model at a constant altitude of 800 km; Φ represents local time in angular measure.

Figure 10. The magnetic field profile calculated from a field-aligned current model for different altitudes.

Figure 11. The magnetic field distribution in the polar cap region on the ground calculated from a field-aligned current model.

Figure 12. ESRO 1A observations of electrons and protons. An example showing protons extending more poleward than electrons in the pre-noon region. The vertical line indicates the location of the 40 kev electron trapping boundary. See Figure 13 for symbols used for different energies. (After Hultqvist et al., 1974).

Figure 13. ESRO 1A observations of electrons and protons. An example showing electrons dominating over protons near the poleward edge of the particle zone in the post-noon region. The verticle line indicates the location of the 40 kev electron trapping boundary. (After Hultqvist et al., 1974).

Figure 14. A model for the magnetospheric field-aligned current system. System C_{fa}-1 flows in the polar cap boundary layer which becomes the high latitude boundary of the plasma sheet on the night side. System C_{fa}-2 involves the equatorial current for closure. (After Sugiura, 1975).

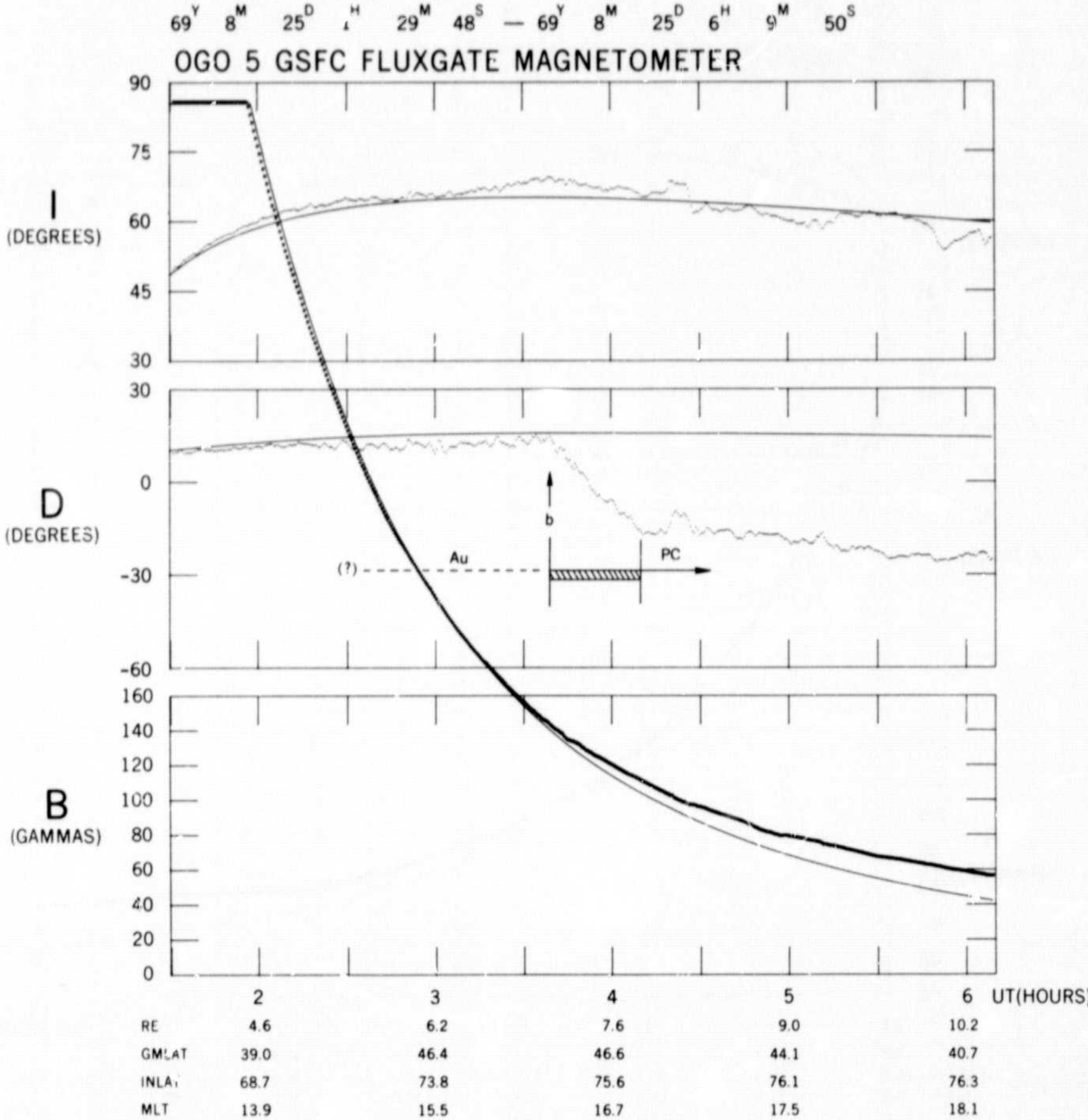

Figure 1

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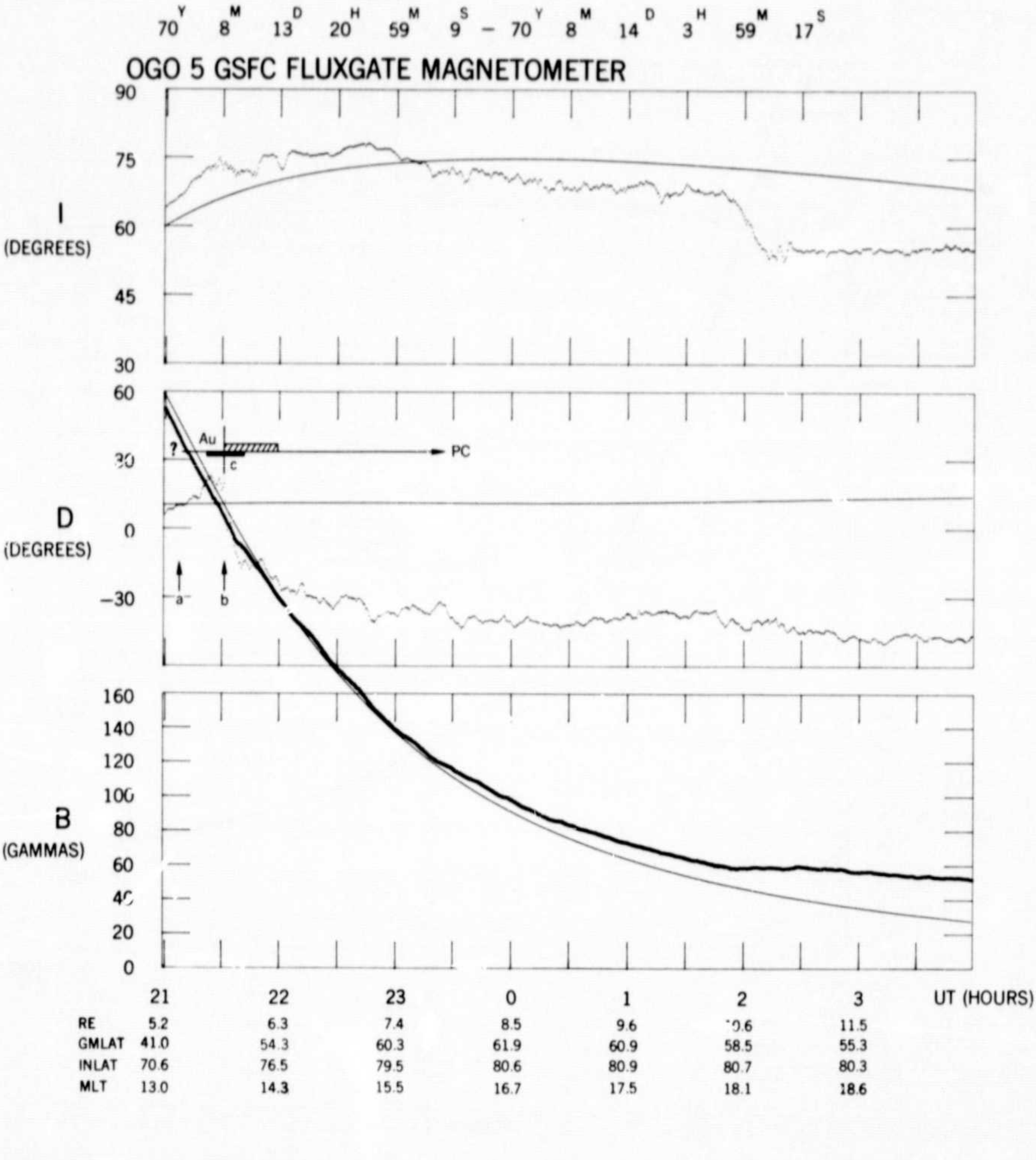

70Y 8M 13D 20H 59M 9S – 70Y 8M 14D 3H 59M 17S
OGO 5 GSFC FLUXGATE MAGNETOMETER
I (DEGREES)
D (DEGREES)
B (GAMMAS)
Au
PC
UT (HOURS)
RE 5.2 6.3 7.4 8.5 9.6 10.6 11.5
GMLAT 41.0 54.3 60.3 61.9 60.9 58.5 55.3
INLAT 70.6 76.5 79.5 80.6 80.9 80.7 80.3
MLT 13.0 14.3 15.5 16.7 17.5 18.1 18.6

Figure 2

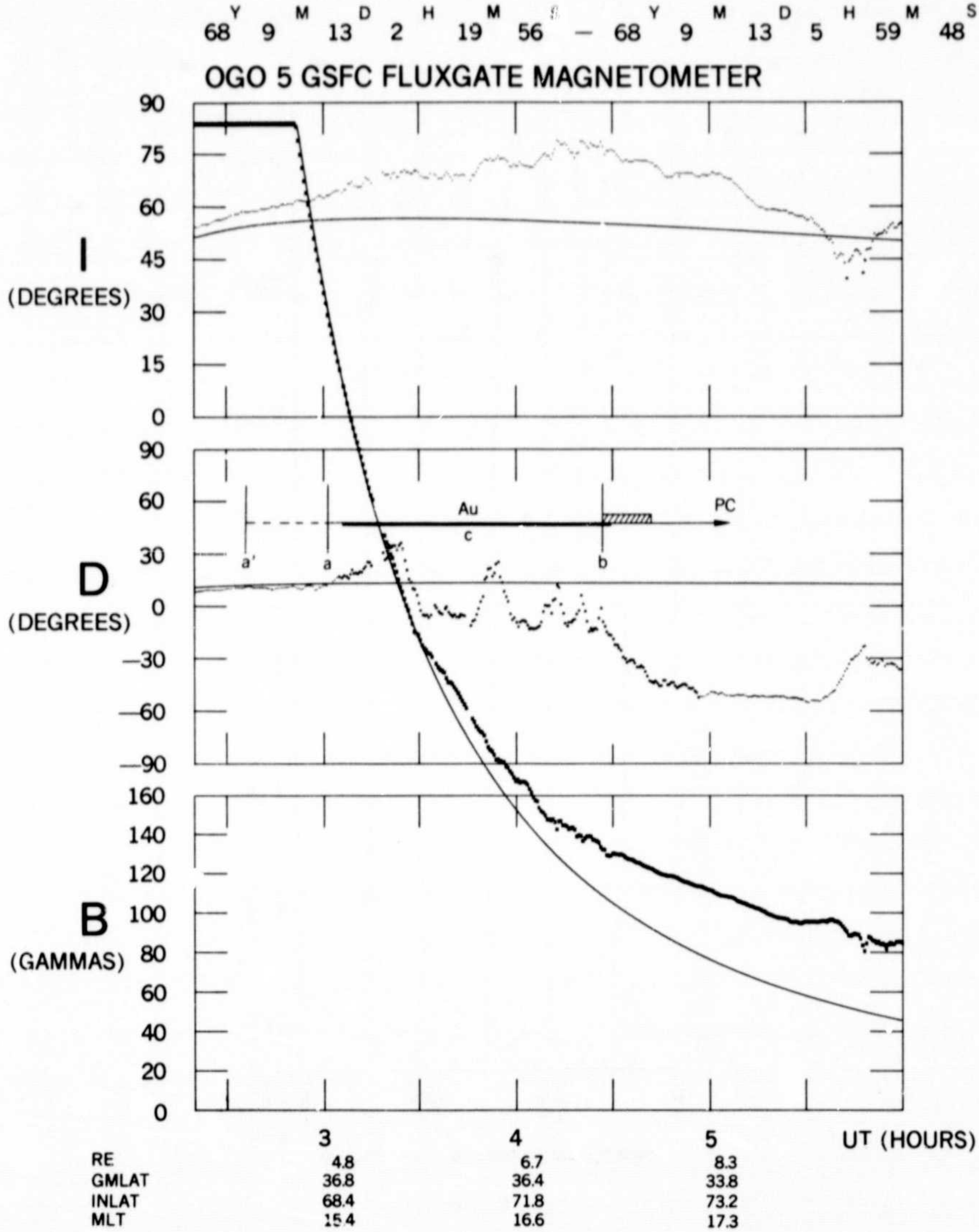
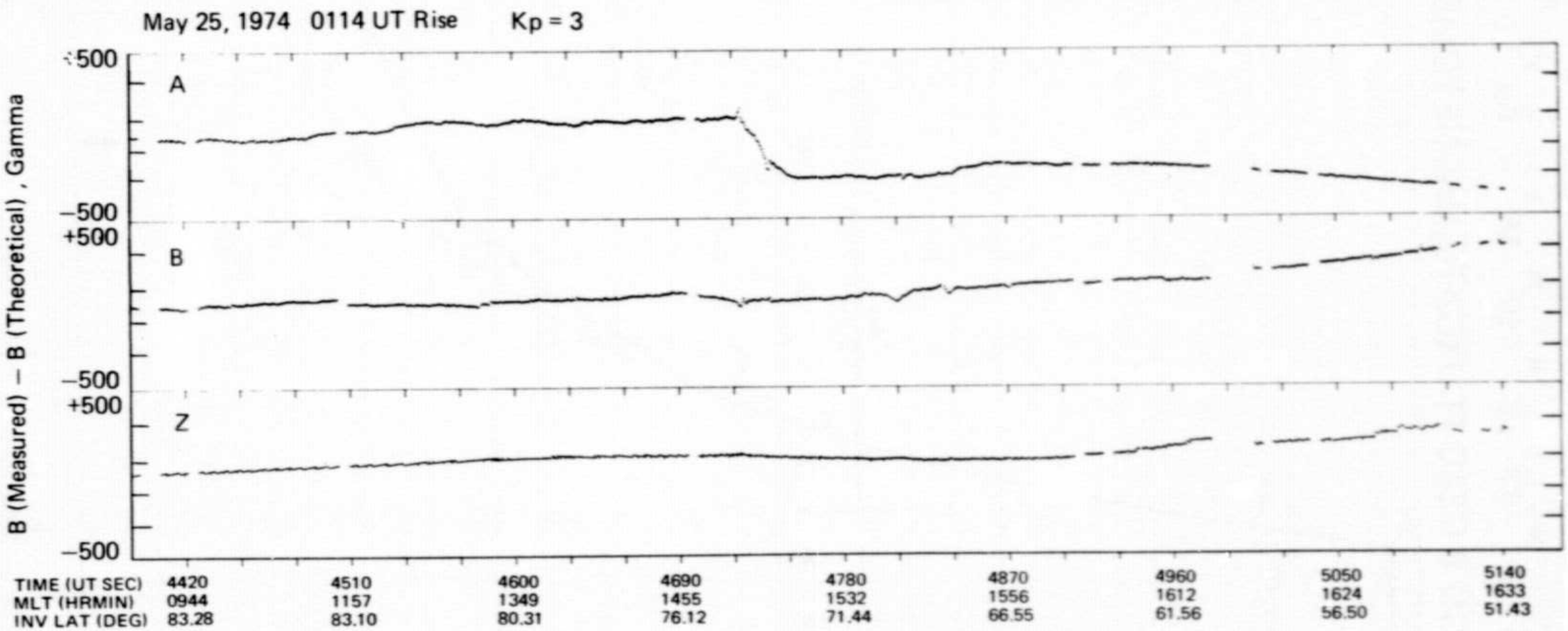

68 Y 9 M 13 D 2 H 19 M 56 S — 68 Y 9 M 13 D 5 H 59 M 48 S
OGO 5 GSFC FLUXGATE MAGNETOMETER
I
(DEGREES)
90
75
60
45
30
15
0
D
(DEGREES)
90
60
30
0
−30
−60
−90
Au
PC
c
a'
a
b
B
(GAMMAS)
160
140
120
100
80
60
40
20
0
3
4
5
UT (HOURS)
RE 4.8 6.7 8.3
GMLAT 36.8 36.4 33.8
INLAT 68.4 71.8 73.2
MLT 15.4 16.6 17.3

Figure 3



May 25, 1974 0114 UT Rise Kp = 3
B (Measured) − B (Theoretical), Gamma
A
B
Z
+500
−500
+500
−500
+500
−500
TIME (UT SEC) 4420 4510 4600 4690 4780 4870 4960 5050 5140
MLT (HRMIN) 0944 1157 1349 1455 1532 1556 1612 1624 1633
INV LAT (DEG) 83.28 83.10 80.31 76.12 71.44 66.55 61.56 56.50 51.43

Figure 4

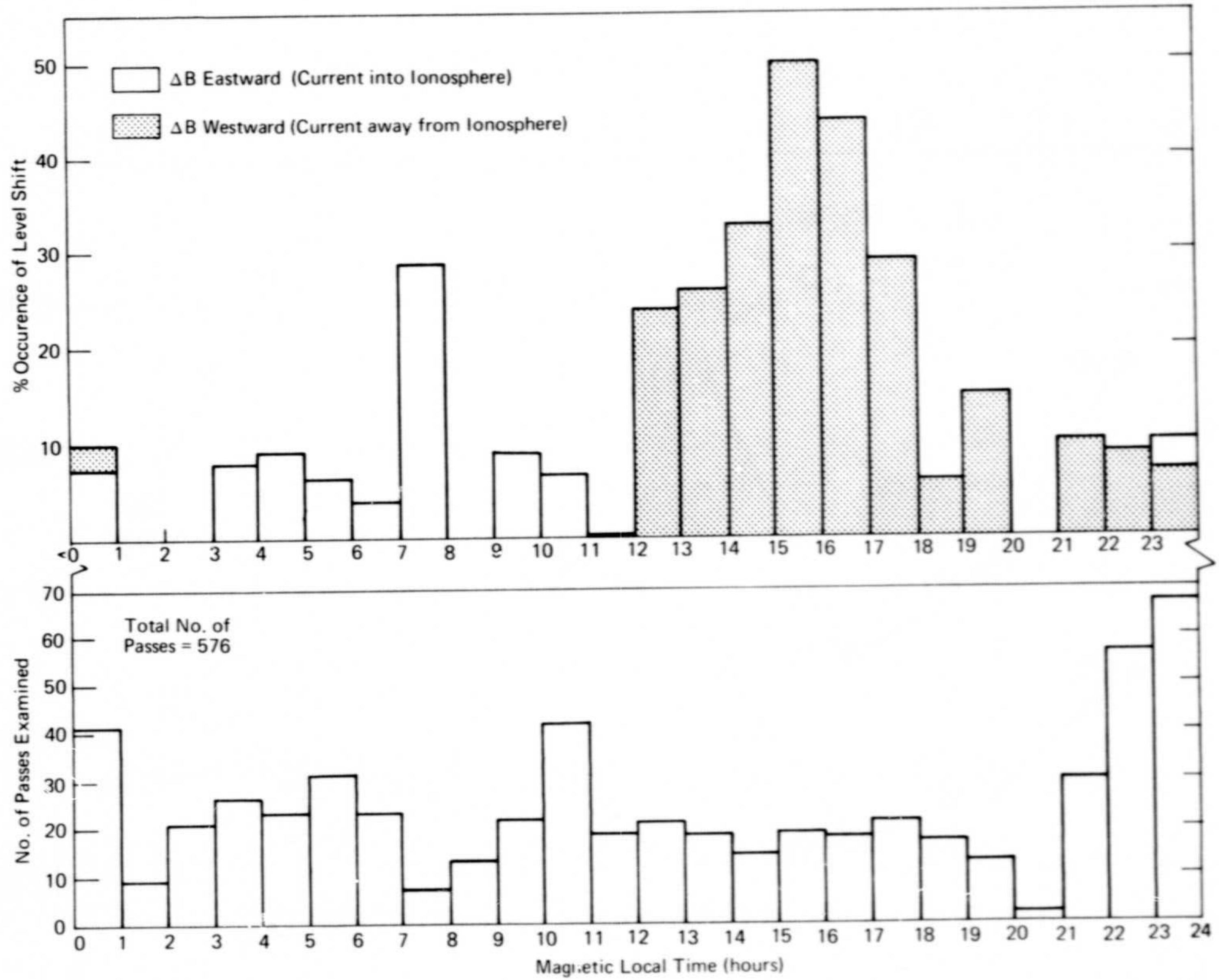

ΔB Eastward (Current into Ionosphere)
ΔB Westward (Current away from Ionosphere)
% Occurence of Level Shift
Total No. of
Passes = 576
No. of Passes Examined
Magnetic Local Time (hours)

Figure 5

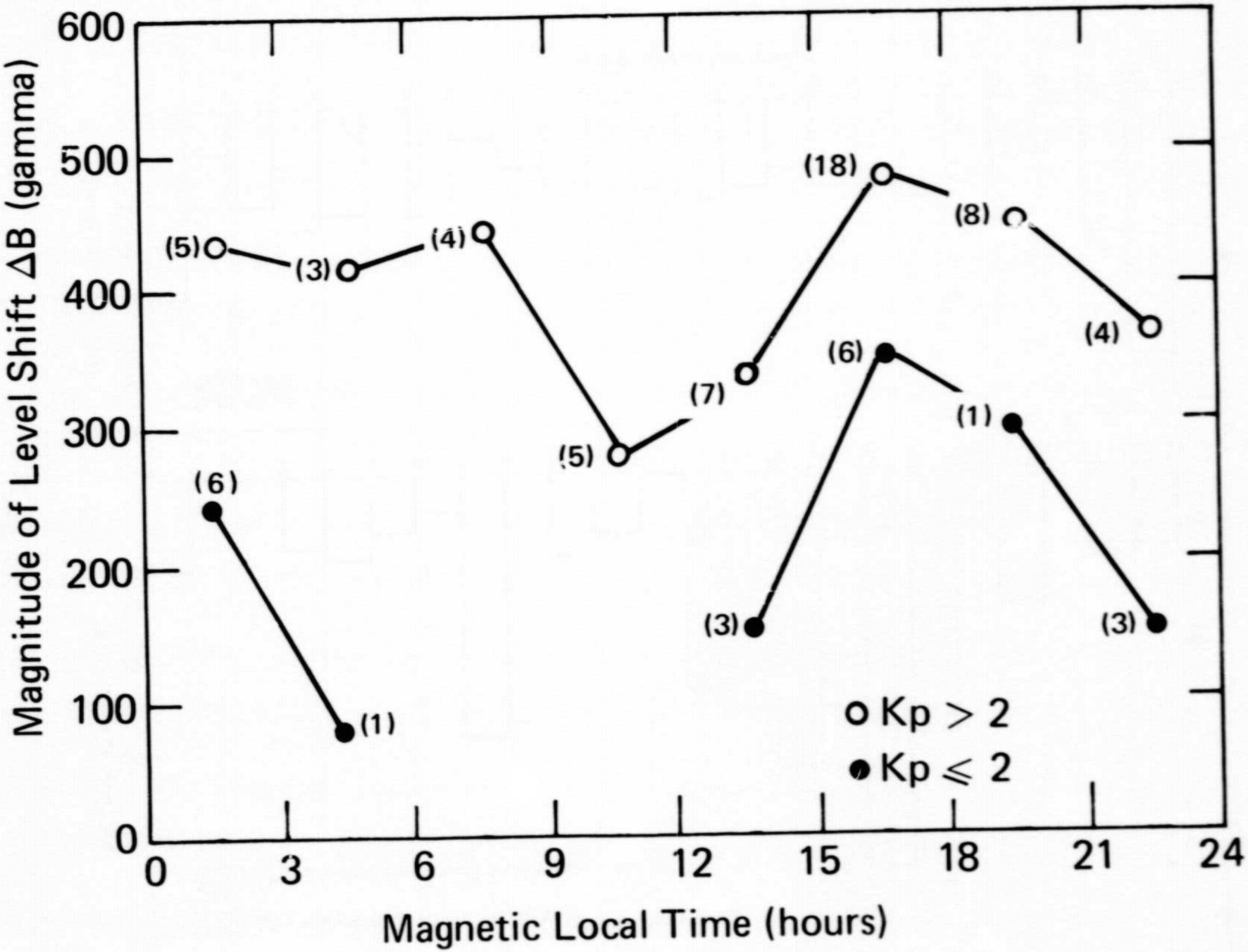

600
500
400
300
200
100
0
Magnitude of Level Shift ΔB (gamma)
0
3
6
9
12
15
18
21
24
Magnetic Local Time (hours)
(5)
(3)
(4)
(5)
(7)
(18)
(8)
(4)
(6)
(1)
(3)
(6)
(1)
(3)
○ Kp > 2
● Kp ≤ 2

Figure 6

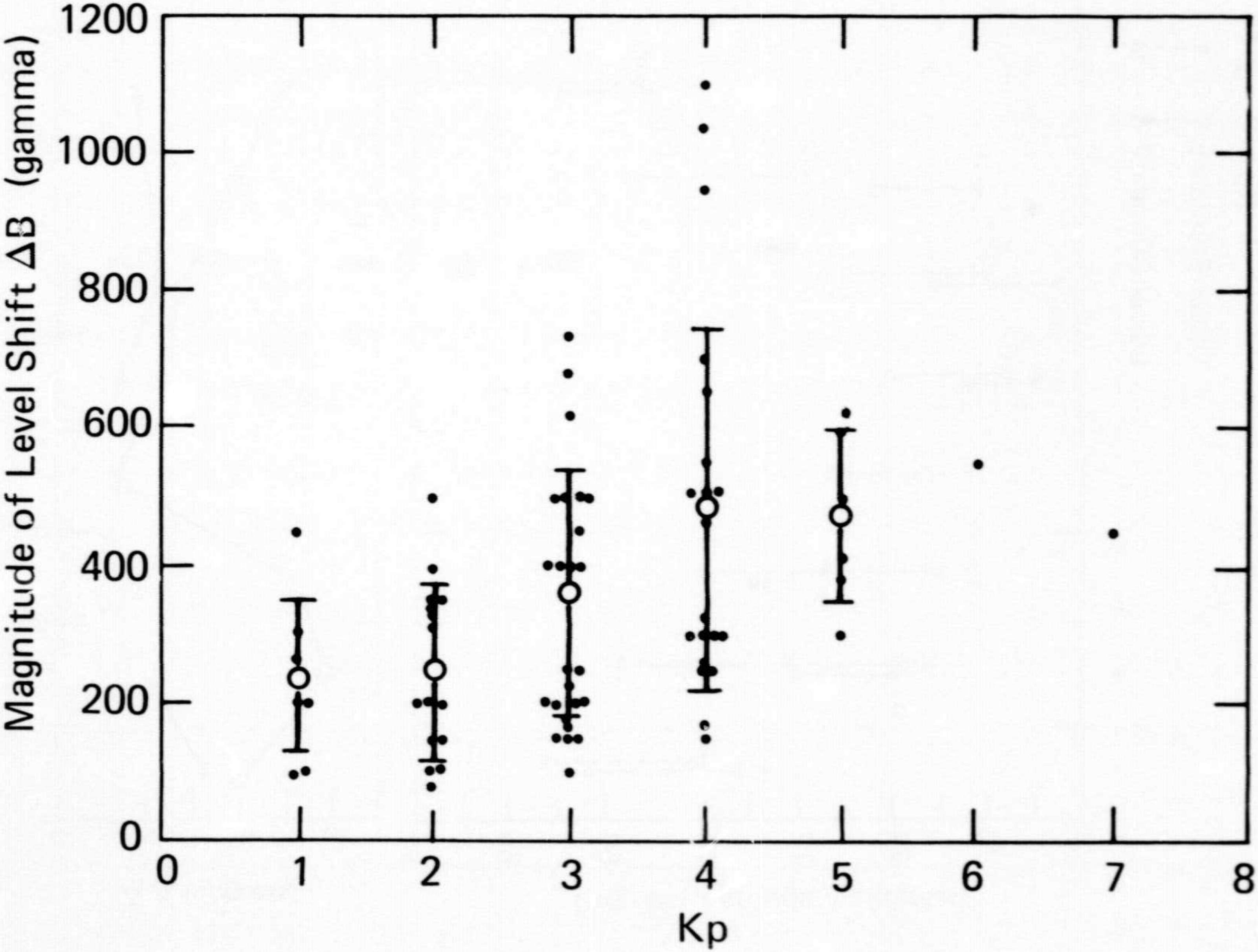

Magnitude of Level Shift ΔB (gamma)
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
Kp

Figure 7

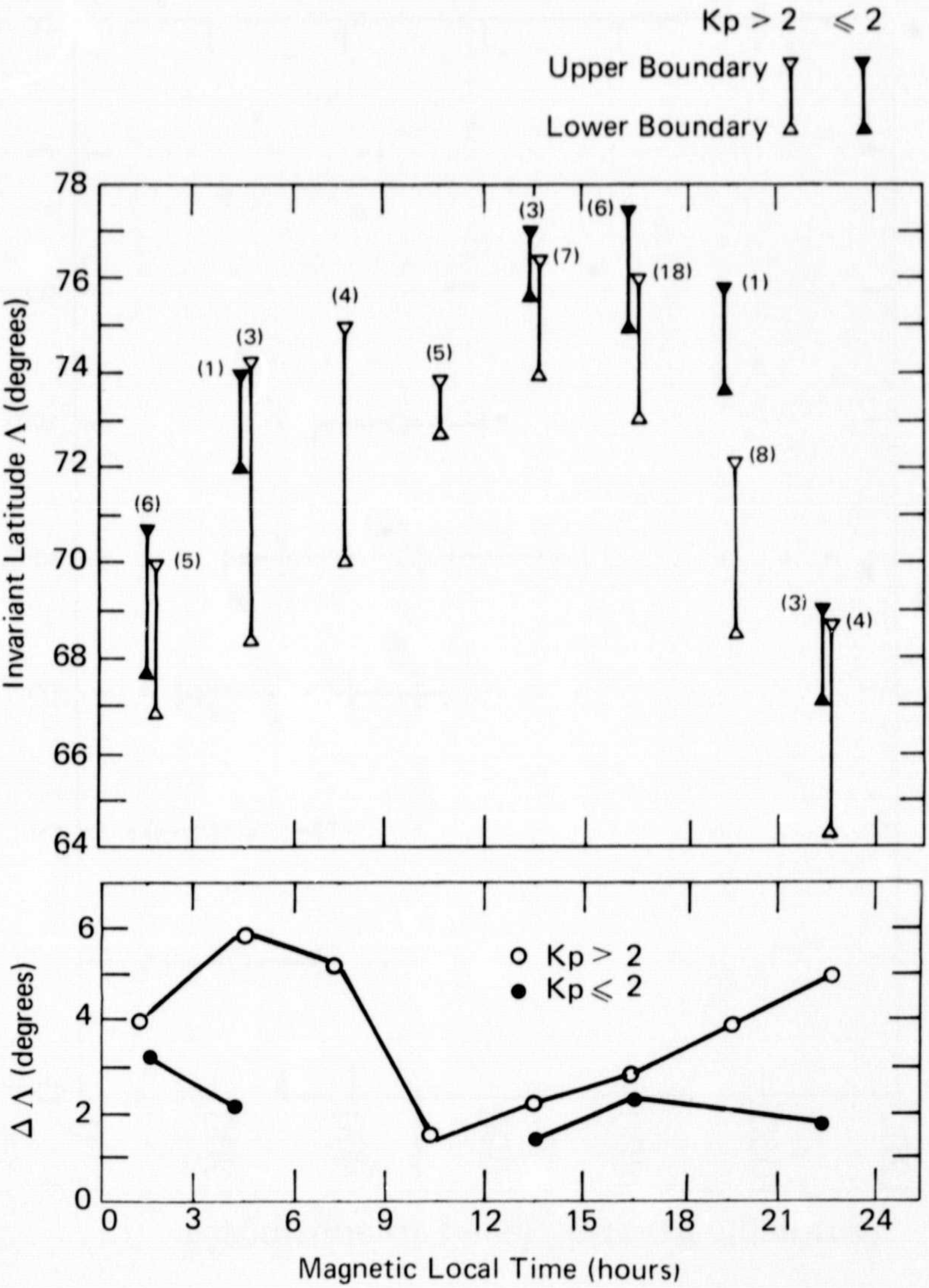

Kp > 2 ⩽ 2
Upper Boundary
Lower Boundary
Invariant Latitude Λ (degrees)
78
76
74
72
70
68
66
64
(6)
(5)
(1)
(3)
(4)
(5)
(3)
(7)
(6)
(18)
(1)
(8)
(3)
(4)
Δ Λ (degrees)
6
4
2
0
○ Kp > 2
● Kp ⩽ 2
0
3
6
9
12
15
18
21
24
Magnetic Local Time (hours)

Figure 8

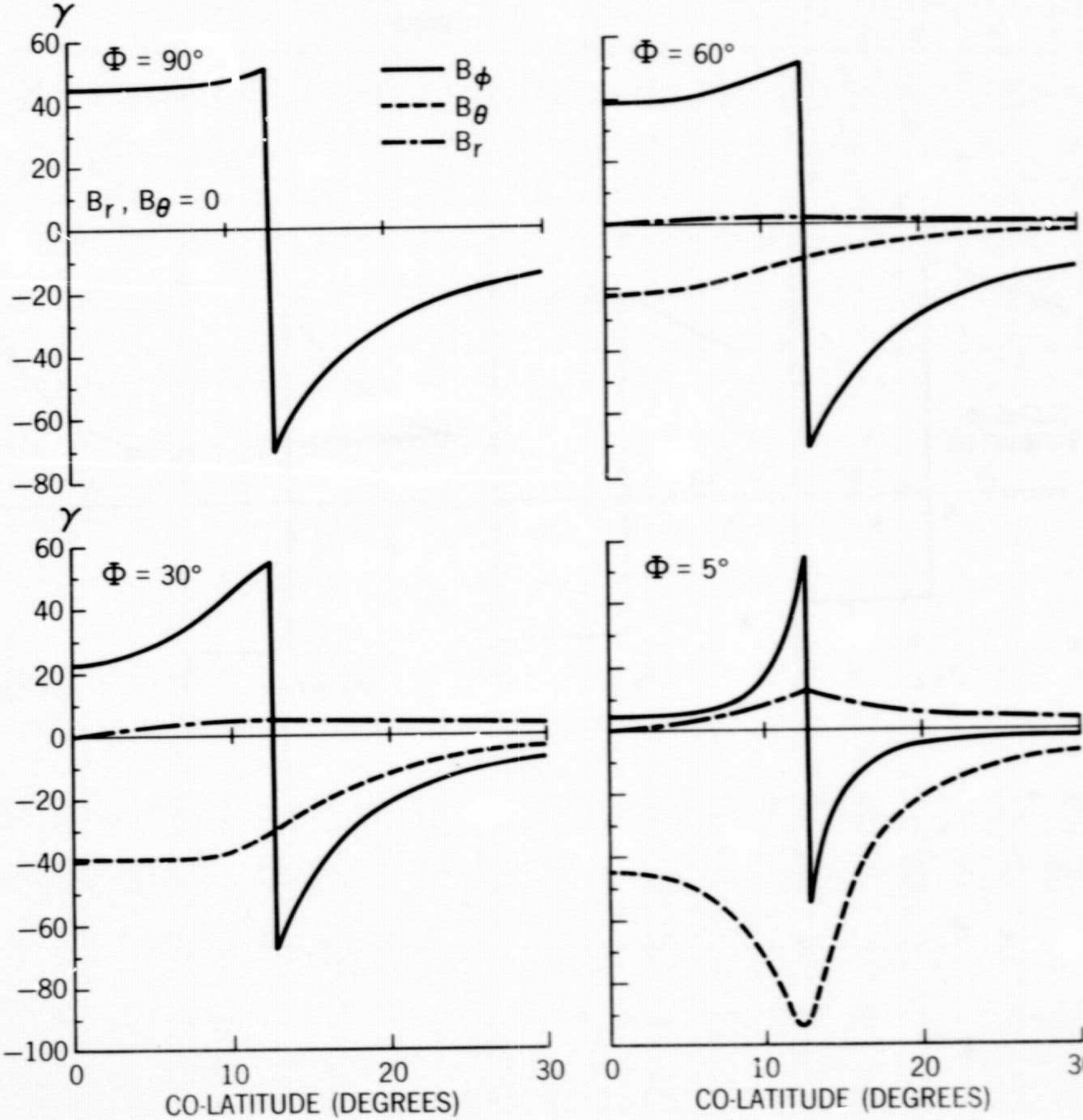
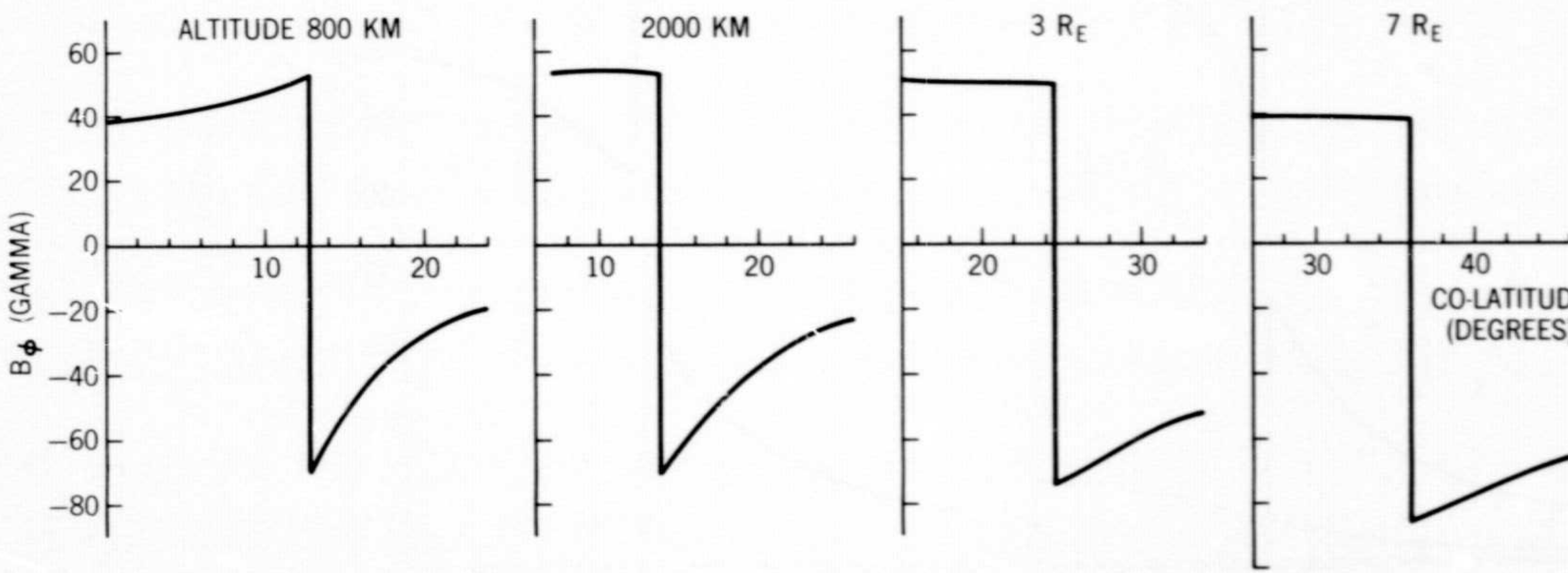

γ
Φ = 90°
B_φ
B_θ
B_r
B_r , B_θ = 0
Φ = 60°
Φ = 30°
Φ = 5°
60
40
20
0
−20
−40
−60
−80
−100
10
20
30
CO-LATITUDE (DEGREES)

Figure 9



ALTITUDE 800 KM
2000 KM
3 R_E
7 R_E
B_ϕ (GAMMA)
60
40
20
0
−20
−40
−60
−80
10
20
30
40
CO-LATITUDE
(DEGREES)

Figure 10

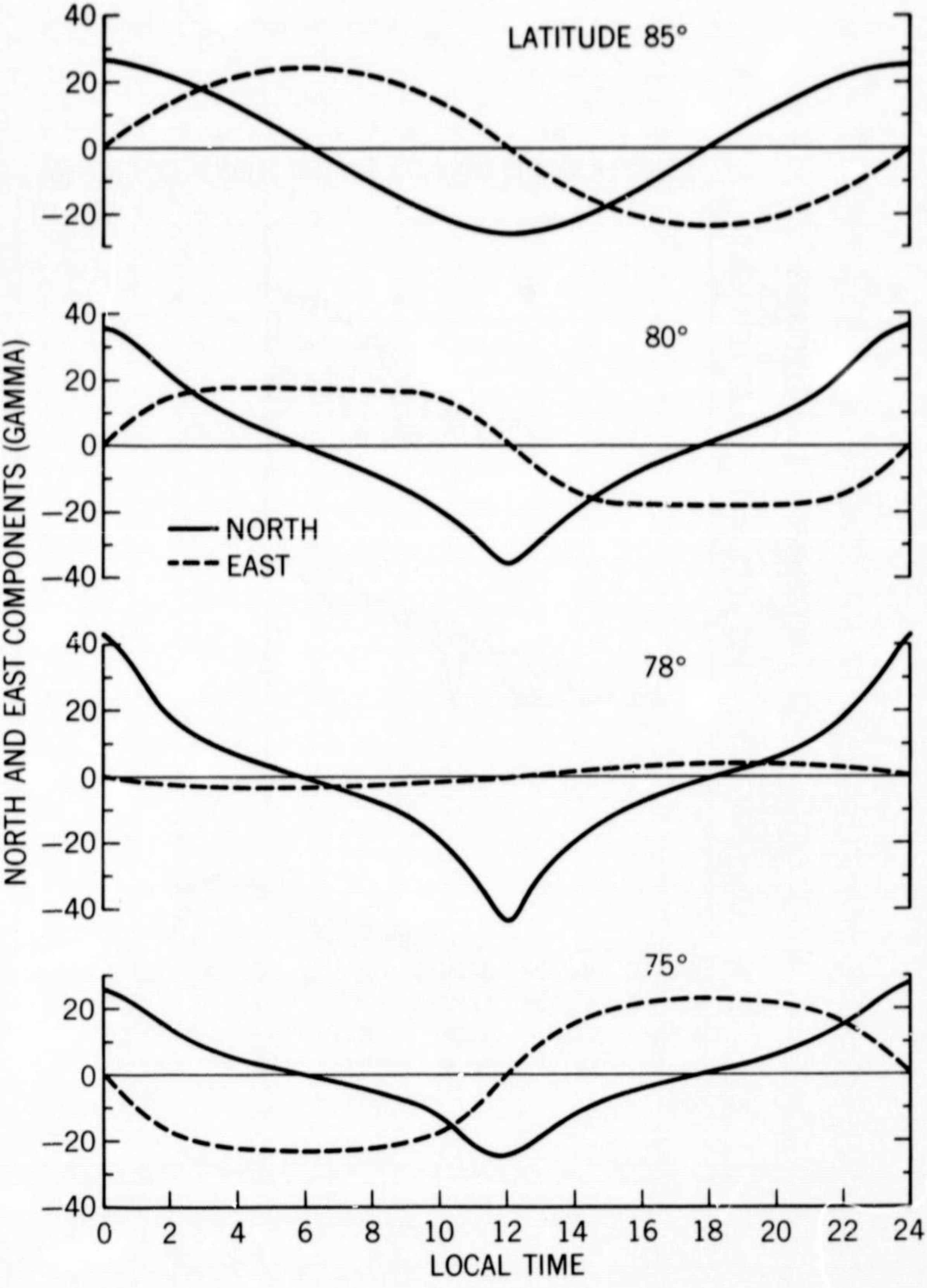

LATITUDE 85°
80°
78°
75°
NORTH
EAST
NORTH AND EAST COMPONENTS (GAMMA)
LOCAL TIME
40
20
0
−20
−40
0
2
4
6
8
10
12
14
16
18
20
22
24

Figure 11

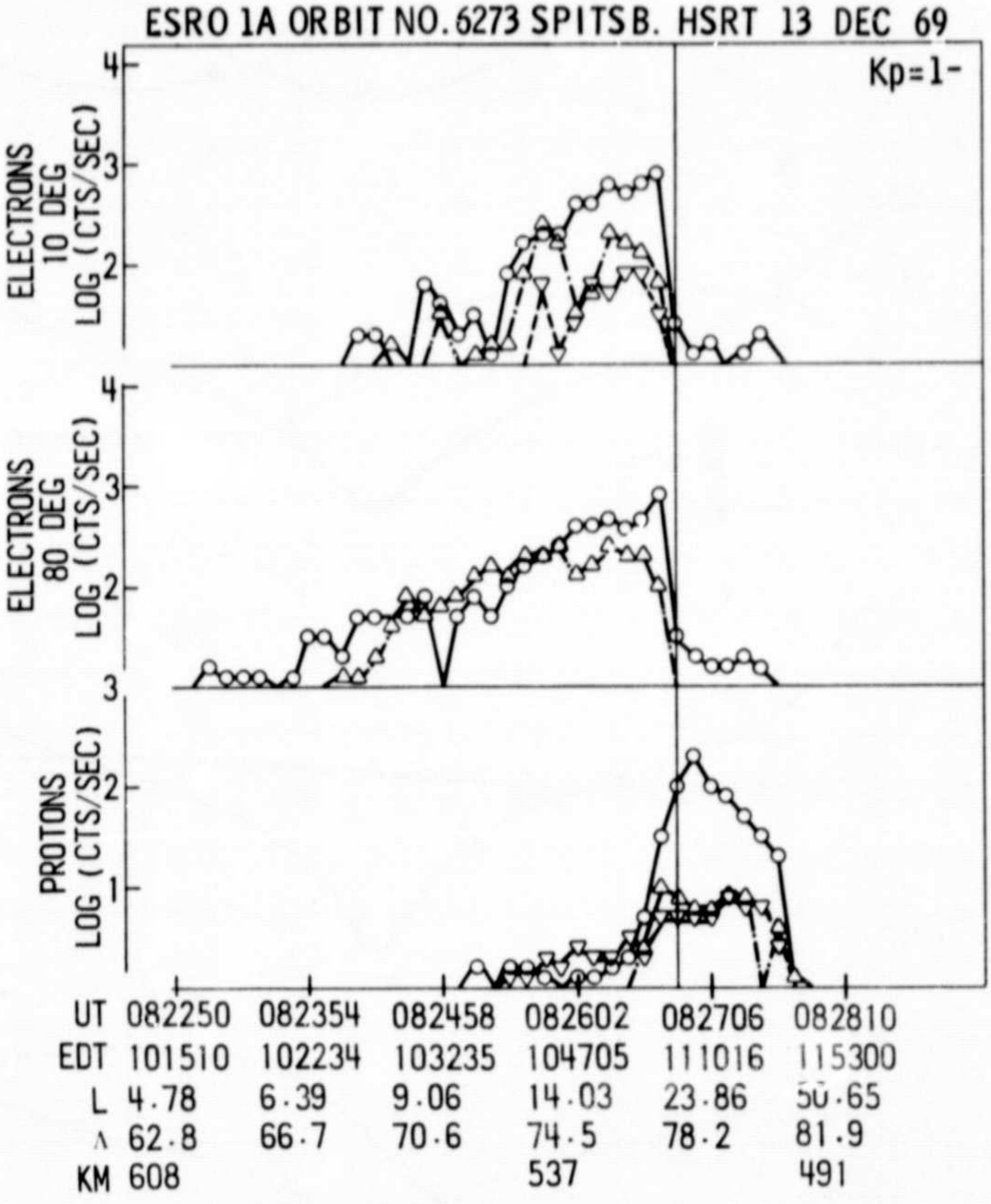
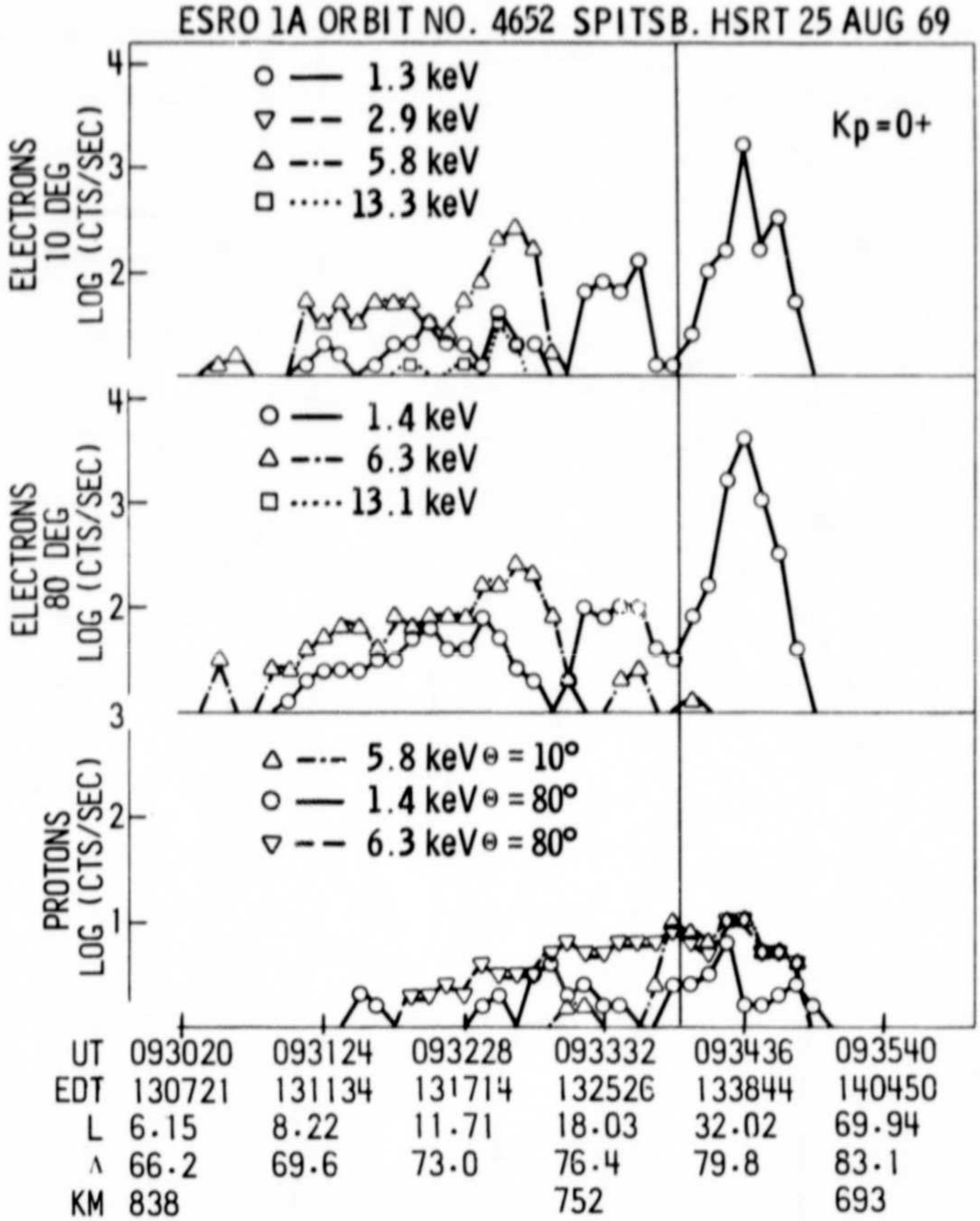

ESRO 1A ORBIT NO. 6273 SPITSB. HSRT 13 DEC 69
Kp=1-
ELECTRONS 10 DEG LOG (CTS/SEC)
ELECTRONS 80 DEG LOG (CTS/SEC)
PROTONS LOG (CTS/SEC)
UT 082250 082354 082458 082602 082706 082810
EDT 101510 102234 103235 104705 111016 115300
L 4.78 6.39 9.06 14.03 23.86 50.65
Λ 62.8 66.7 70.6 74.5 78.2 81.9
KM 608 537 491

Figure 12



ESRO 1A ORBIT NO. 4652 SPITSB. HSRT 25 AUG 69
ELECTRONS 10 DEG LOG (CTS/SEC)
1.3 keV
2.9 keV
5.8 keV
13.3 keV
Kp = 0+
ELECTRONS 80 DEG LOG (CTS/SEC)
1.4 keV
6.3 keV
13.1 keV
PROTONS LOG (CTS/SEC)
5.8 keV Θ = 10°
1.4 keV Θ = 80°
6.3 keV Θ = 80°
UT 093020 093124 093228 093332 093436 093540
EDT 130721 131134 131714 132526 133844 140450
L 6.15 8.22 11.71 18.03 32.02 69.94
Λ 66.2 69.6 73.0 76.4 79.8 83.1
KM 838 752 693

Figure 13

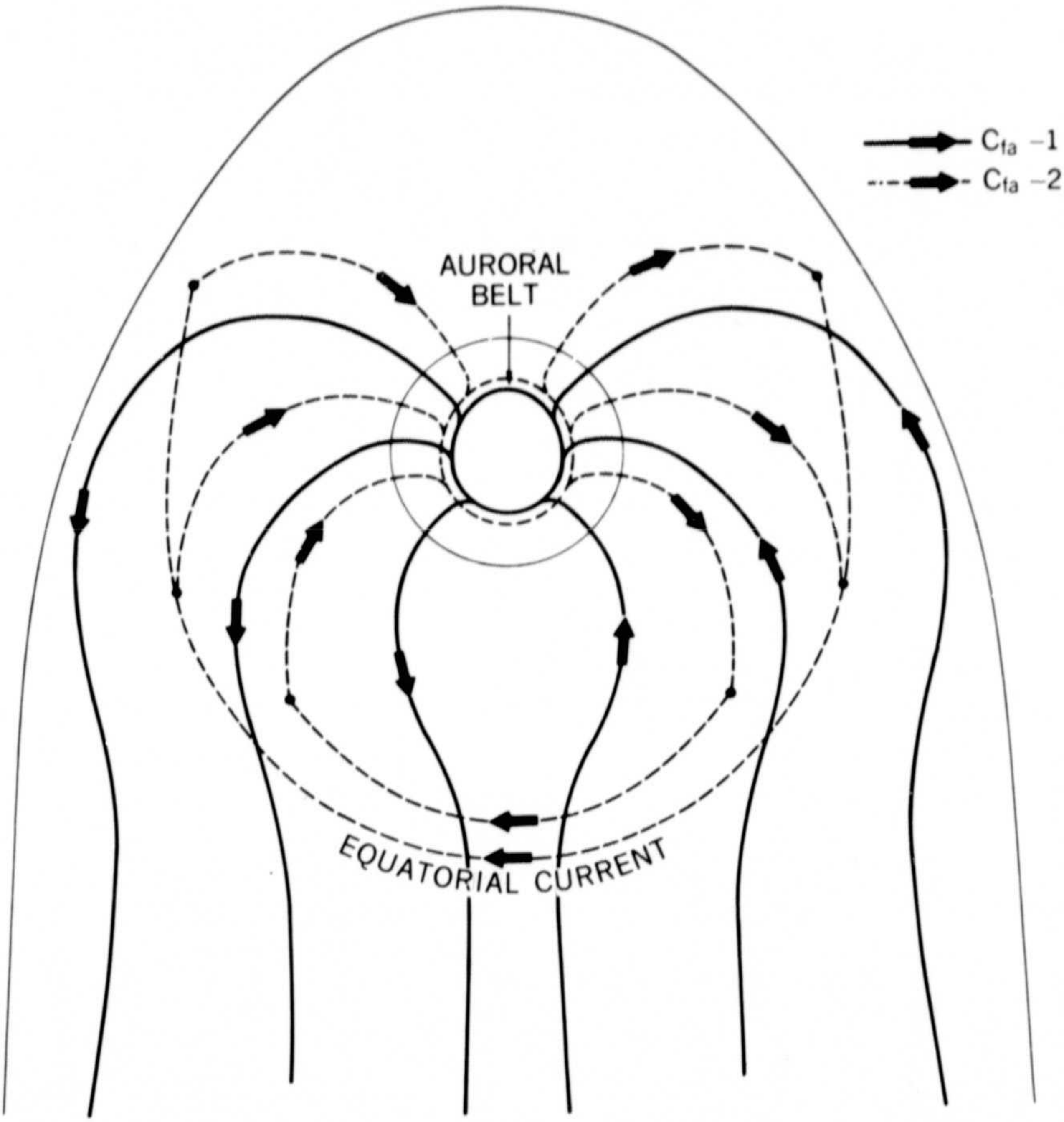


Figure 14