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ABSTRACT

The magnetometer observations on the Triad satellite frequently indicated the existence of a step-like level shift in the field component approximately in the magnetic east-west direction near the expected position of the polar cap boundary. Such a field change implies the presence of a net current flowing into or away from the ionosphere in a current layer parallel to the local L-shell. The current direction is toward the ionosphere in the morning half and away from it in the afternoon half of the current layer. These current directions are the same as those of the field-aligned currents observed in the polar cap boundary layer by Ogo 5. Hence a substantial part of the field-aligned currents discussed in this paper is believed to originate in, and return to, the magnetospheric tail flowing on the high-latitude boundary of the plasma sheet. The effect of the net current is largest in the late afternoon to the evening, with a maximum in the 1500-1800 MLT interval. Statistically the magnitude of the net current increases with increasing Kp. When extrapolated to Kp = 0, the magnitude of level shift does not tend to zero. The average current density in the current layer ranges from 4×10^{-7} to 4×10^{-6} amp/m². No positive identifications can be made of the current carrier. However, the location of the field-aligned current layer discussed here roughly agrees with that of the region of peak electror intensities determined by McDiarmid et al. (1975) from their Isis 2 observations.

INTRODUCTION

Observations of magnetic fields arising from field-aligned currents at high latitudes obtained from the Triad satellite at about 800 km altitude have been reported by Armstrong and Zmuda (1973), Armstrong (1974), and Zmuda and Armstrong (1974a, 1974b). In these papers the authors have shown: (a) that the diurnal variation and the dependence on magnetic activity of the location of the field-aligned current region are similar to those of the auroral oval, (b) that the field-aligned current region usually consists of two current layers carrying oppositely directed currents, (c) that the current flow is downward in the higher-latitude layer and upward in the lower-latitude layer on the morning side and the current directions in the two layers are reversed on the afternoon side, and (d) that the amounts of oppositely directed currents in the two layers are approximately equal.

The current pattern described above is the same, in gross features, as that deduced by Sugiura (1975) from Ogo 5 observations in the high altitude magnetosphere. However, in both cases the observed features are complex and a considerable simplification was made in deriving the current pattern. Although the question of the equality or inequality of the oppositely directed currents in the meridional cross section of the field-aligned current region is essential to the problem of current closure, this question has not been dealt with quantitatively by the studies quoted above. In the case of Ogo 5, however, its orbit is not suited for deriving a definitive answer to this question firstly because the two current layers are crossed by the spacecraft, in general, at substantially

different altitudes and secondly because the accuracy in the spacecraft attitude determination is not adequate for precise measurements of currents in the lower-latitude current layer. Although the Triad's near circular, polar orbit at a low altitude is ideally suited for this type of study, it also has limitations arising from the uncertainties in the spacecraft bias field and in the attitude data (Armstrong and Zmuda, 1973).

However, by confining ourselves only to those variations that are not affected by these uncertainties it has become clear that in an appreciable fraction of the Triad passes over the northern auroral oval, a step-like level shift is observed in the component approximately in the dipole east-west direction. This implies that there is a net field-aligned current flowing into or away from the ionosphere in a current sheet parallel to an L-shell. In this paper we discuss the results of detailed analysis of these step-like level shifts and present what we believe to be an underlying basic pattern of field-aligned current flowing in the polar cap boundary region.

OBSERVATIONS

The orbital parameters of Triad, the in-flight satellite configuration, and the orientations of the fluxgate magnetometer axes with respect to the satellite reference frame and to local L-shells have been described in detail by Armstrong and Zmuda (1973) and Zmuda and Armstrong (1974b). Briefly stated, in the horizontal plane the orientations of the mutually orthogonal A and B magnetometer (positive) axes are obtained by rotating

in the horizontal plane the spacecraft velocity vector clockwise by 135° and 45° , respectively. The positive Z magnetometer axis is directed vertically upward. The magnetometer sensor alignment accuracy is estimated to be 0.5° by Armstrong and Zmuda (1973).

The data used in this analysis are real time data received at College, Alaska during the Triad crossings of the auroral oval roughly between 180°E and 240°E longitude. In the areas covered by the data the direction of the magnetic dipole north is approximately 25° to 50° east of the geographic north. Thus the A sensor axis is roughly in the dipole east-west direction. Therefore the effects of field-aligned currents are mainly observed as variations in the A component as noted by Armstrong and Zmuda in their earlier reports. The discussions in the present paper are essentially concerned with this component. The quantitative analysis presented in this paper is based on the data covering approximately one year from August 1973 to August 1974. However, a more qualitative examination of the data was made for a longer span of period from January 1973 to December 1974.

The Triad spacecraft was launched primarily to test a satellite navigation system, and the spacecraft environment was not necessarily ideal for precise magnetic field measurements. For instance, the components of the spacecraft bias field along the A, B, and Z axes were estimated by Armstrong and Zmuda (1973) to be approximately -5000γ , -2000γ , and $+1800\gamma$, respectively, with uncertainties of $\sim 200\gamma$ in these values ($1\gamma = 1\text{ nT}$). This bias field may or may not be time-dependent. Unknown deviations ($\leq 3^\circ$) from nominal attitude contribute additional

uncertainties to the absolute accuracy of the field measurements. It should be kept in mind in interpreting the Triad data that over the data span of roughly 15 minutes duration covered by each pass, the zero level for each of the three components cannot in principle be determined. In addition, the effects of spacecraft oscillation from pitch, roll or yaw are evident on many passes. However, several modes of resonant spacecraft oscillation are known. The shortest period of such oscillation has been calculated to be approximately 6 minutes, and this period has been confirmed in the magnetic field data. In the present study, only those variations that have shorter time scales than 6 minutes are analyzed as will become clear by the selection criteria adopted in the analysis and described below. It is remarked that analysis of Triad magnetometer data without proper consideration of field changes due to causes other than natural phenomena being studied will not be meaningful.

NET FIELD-ALIGNED CURRENTS

From an inspection of all Triad data received from College during the first two years of operation it became obvious that in an appreciable fraction of the passes a step-like level shift is observed in the east-west (A) component of the difference field, indicating the existence of a net current flow into or away from the ionosphere in a field-aligned current sheet. Because of the uncertainties in spacecraft attitude and in the possibly time-dependent bias field as mentioned in the preceding section, completely objective determinations of the occurrence frequency of such level shifts and of the statistical distribution of their magnitudes are not possible. Therefore we have taken the following

approach to derive statistical results that are as quantitative and objective as possible.

A set of criteria was devised for the selection of passes containing a level shift to be included in the present statistical analysis. The criteria used are as follows: (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 such that the ambiguity in the reference level arising from spacecraft attitude uncertainties would have no influence on the judgement concerning the existence or non-existence of a level shift. As a consequence of the application of the latter criterion the smallest magnitude of level shift included was 80γ . It should be noted here that there are numerous cases of level shift that were excluded from the present statistics because of our rather severe selection criteria.

The term 'net current' is used in this paper to refer to the net current flowing into or away from the ionosphere in the form of concentrated sheet current in the field-aligned current region as seen in the Triad data. Any diffusely distributed currents, if they exist, cannot be determined from the Triad observations.

Figure 1 shows a typical example of level shift observed in the east-west (A) component with little simultaneous changes in the other two components, indicating a net current flow in a layer approximately parallel to the local L-shell. In Figure 1 (and also in Figure 2) plots are made for the three components of the difference field defined by the difference

between the observed field and the theoretical field calculated from the IGRF and transformed into the magnetometer coordinate system; the zero level for each component is set so as to make the first data point placed at this level. On a southbound pass, as is the case shown in Figure 1, the positive A sensor axis is directed roughly westward in the dipole coordinate system. Therefore we infer from Figure 1 that the Triad satellite traversed a field-aligned current layer during a period of approximately 30 seconds from 4720 seconds UT (i.e. 01^h 18^m 40^s to 01^h 19^m 10^s) on May 25, 1974 and that the current flow in the layer was upward. Magnetic dipole local time (MLT) for the above period was 1509 to 1522, and the invariant latitudes of the poleward and equatorward edges of the current layer were approximately 74.5° and 73.0°, respectively. The Kp index for the 3-hour period containing this pass was 3+. The magnitude, ΔB , in this level shift was about 360 γ . Assuming a stationary current sheet, the current density integrated over the thickness is $\Delta B/\mu_0 = 0.28$ amp/m. If the thickness is taken to be 1.5° in latitude, the average current density is about 1.7×10^{-6} amp/m².

Another example of level shift having a large amplitude (750 γ) is shown in Figure 2. The spacecraft traversed a current layer between 68642 and 68670 seconds UT (19^h 04^m 02^s to 19^h 04^m 30^s) on February 25, 1974; the low-latitude and high-latitude edges of the current layer were respectively at 71.4° and 72.8° invariant latitude and 0900 and 0851 MLT. This crossing of the field-aligned current layer took place during a prolonged period of disturbance following a moderate magnetic storm; Kp was 5+ for the 3-hour interval including the period covered by Figure 2.

The peak to peak amplitude of the level shift in the A component was 750 γ , which corresponds to a total current density of 0.6 amp/m and to an average current density of 3.8×10^{-6} amp/m². The current direction is downward and into the ionosphere. The location of the field-aligned current layer shown in Figure 2 is lower in invariant latitude than that observed on May 25, 1974 (Figure 1). The magnetic condition was more disturbed for the former case than was for the latter. The two crossings were encountered about 3 hours off the noon meridian on the afternoon and morning sides, respectively; the two positions are therefore symmetric with respect to noon. The tendency that the field-aligned current layer carrying a net current shifts toward lower latitudes as magnetic activity increases is statistically demonstrated below. As will also be shown below, the current direction is toward the ionosphere on the morning side (as is the case in Figure 2) and away from the ionosphere on the afternoon side (Figure 1).

STATISTICS

How often do we observe such level shifts as seen in Figures 1 and 2? Figure 3 gives an answer to this question. The lower panel of the figure shows the number of passes examined and judged to give data of good quality, as a function of MLT; the total number of these passes was 576. The frequency of occurrence of level shifts that satisfy the criteria described in the preceding section is given in terms of percentage in the upper panel. Figure 3 shows that statistically, level shifts are encountered more frequently in the afternoon sector between 1200 and 1800

MLT with a pronounced peak near 1500 to 1600. There may be a weak secondary peak in the early morning hours though this is by no means as clear-cut as the afternoon peak. (The large percentage occurrence for the interval 0700-0800 MLT is probably not significant in view of a small number of cases examined for this interval.) The most striking feature in Figure 3 is the clear division between the region in which the current flows into the ionosphere (indicated by white blocks) and the region in which the current flows away from the ionosphere (indicated by shaded blocks). Namely, the current flows into the ionosphere on the morning side and flows away from it on the afternoon side.

The average magnitudes of the level shifts for 3-hour MLT intervals are plotted in Figure 4 for two Kp groups. It is evident that the average magnitudes are greater for the high Kp group ($K_p > 2$; open circles) than those for the low Kp group ($K_p \leq 2$; dark dots). In both groups there is a distinct peak at the 1500-1800 MLT interval. A secondary, and flat, maximum is seen for the high Kp group during the morning. This feature may also be described by saying that the magnitudes of level shifts tend to be low near magnetic noon and midnight. The sample is too small for the low Kp group to draw conclusions about the morning hours. However, the afternoon maximum in the level shift magnitudes is a definitive feature that comes out very clearly from these statistics.

The magnitudes of the level shifts are plotted against Kp in Figure 5, together with the average and the standard deviation for each Kp value. The statistical trend that the magnitude of a level shift increases with increasing Kp is demonstrated. Because of the local time dependence of

the level shift magnitude a simple relation with K_p is not expected; even so, the statistical scatter is considerable, indicating the complexity of the phenomenon. One of the most important implications of Figure 4 is that when the average points are extrapolated to $K_p = 0$, the level shift does not tend to zero. A least squares fit to a straight line would give a magnitude of about 100γ for $K_p = 0$. However, whether or not a linear curve fitting is meaningful is open to question. Both the individual data points and the average points appear to show a less steep slope for the relation below $K_p = 2$ than a linear extrapolation from the higher K_p values would indicate; indeed, the magnitudes vs. K_p relation is almost flat below $K_p = 2$. If we take this trend into account, a better estimate for the level shift magnitude for $K_p = 0$ might be near 150γ with a range of roughly 100 to 200γ .

The average thickness of the current layer and the average positions of the high-latitude and low-latitude boundaries of the current layer, both in invariant latitude, are plotted for 3-hourly MLT intervals in Figure 6, again for the same two K_p groups as shown in Figure 4. The location of the current layer has a diurnal variation, the general characteristics of which are similar to the well-known diurnal variation of the position of the auroral oval; namely, the current layer is at considerably higher latitudes near noon than it is near midnight. This result is, in a way, expected because the study by Zmuda and Armstrong (1974a) of the field-aligned current region, which is inclusive of the more restrictive current layer treated in the present paper, indicated that the field-aligned current region extends along the auroral oval.

However, we emphasize that the present result concerns the position of the single field-aligned current layer that carries a net current into or away from the ionosphere, while the field-aligned current region of Zmuda and Armstrong (1974a) refers to a more general region where field-aligned currents flow regardless of their characteristics (i.e. whether the region consists of a single layer or multiple layers, or having complex, and often irregular, structures). The upper panel in Figure 6 indicates a tendency that the field-aligned current layer is located at higher invariant latitudes for the $K_p \leq 2$ group than it is for the $K_p > 2$ group. This trend appears to be more evident in the low-latitude boundary of the current layer than it is in its high-latitude boundary; this means an equatorward expansion of the current layer during disturbed period. The lower panel of Figure 6 shows that the current layer tends to be thin in the noon sector. The figure also shows that the current layer is thicker in the early morning hours than in the afternoon and that the thickness of the layer gradually increases from noon toward the late evening hours.

DISCUSSIONS

1. Current layer as a permanent feature

Based on the Ogo 5 magnetometer results Sugiura (1975) has shown that the transition from the dipolar magnetospheric field to a more tail-like field configuration often takes place rather suddenly and that this transition is accomplished by the existence of a field-aligned current layer at the polar cap boundary. He further showed that the directions

of the field-aligned currents, i.e. toward the ionosphere on the morning side and away from it on the afternoon side, match those of the field-aligned currents observed at the high-latitude boundary of the plasma sheet in the tail. From the argument of current continuity he concluded that the field-aligned current layer at the polar cap boundary continues to the high-latitude boundary of the plasma sheet.

The direction of the current flow in the field-aligned current layer presented in Figure 3 above is the same as that in the current layer detected by Ogo 5 in the high altitude magnetosphere; see Figure 8 in Sugiura (1975) for a schematic current flow pattern. Thus we now believe that the current layer observed by Triad at 800 km altitude is the same current layer as that detected by Ogo 5. As was discussed by Sugiura (1975) the presence of this field-aligned current layer is more or less a permanent feature of the magnetosphere. This is strengthened by the deduction, made from the plots in Figure 5, that the extrapolated magnitude of the level shift in the east-west component of the field caused by the field-aligned current tends to a value of 100γ or more, and not to zero, as K_p tends to zero. This point has been confirmed by a partly independent study of the Triad data by Iijima and Potemra (1975) that uses a different analysis technique. In spite of our severe selection criteria Figure 3 indicates that in the 1500-1600 MLT interval a net current flowing away from the ionosphere is observed in 50% of the Triad passes. Such a high probability of encountering clear-cut cases not contaminated by other variations support the view that the current layer exists most of the time.

2. Relation to the double-layer model of Zmuda and Armstrong

The current direction of the net field-aligned current discussed in this paper is the same as that in the higher-latitude layer of the double-layer model presented by Zmuda and Armstrong (1974b). Therefore, solely on the basis of the current direction, it may be thought that the present current layer corresponds to the higher-latitude layer of their model and that our conclusion may be re-stated in terms of the Zmuda-Armstrong model by saying: (a) that the presence of the higher-latitude layer is of more permanent nature than is the lower-latitude layer, and (b) that the former carries greater current than does the latter. However, an immediate association of the present current layer with any particular layer in the double-layer model does not necessarily follow as a logical consequence from a simple comparison. The basic difference between the two pictures, in our opinion, stems from the selection of data made in deducing a representative pattern, namely from the question of what is considered to be the most basic pattern. The above specification of the relationship between the two models may be inaccurate, if, for instance, a double layer is formed during a substorm equatorward of the present current layer such that the poleward portion of the added double layer is more or less contiguous to the already existing current layer and carries a current flowing in the same direction as that in the latter. We believe that such a possibility is indeed likely. However, more detailed analysis is required to draw a definitive conclusion on this point.

3. Current densities

A level shift in the east-west component by 120γ would correspond to a current density integrated over the layer thickness of approximately 0.1 amp/m. On the average, a net current on this order flows into or away from the ionosphere even under extremely quiet conditions. For an average disturbed condition the level shift is in the vicinity of 400γ , which gives approximately 0.3 amp/m for the integrated current density. Taking an example of a large net current, the level shift observed on May 22, 1974, near 0430 UT, had an amplitude of 1100γ ; the current layer was crossed at about 1450 MLT, and between 74° and 76° invariant latitude. The integrated current density for this case is about 0.85 amp/m. May 22 was only a moderately disturbed day, and Kp for the interval containing this current layer crossing was 4-. Based on a general inspection of the Triad data, not limiting to the passes analyzed in this paper, it can be stated that the integrated net current (per unit length in longitudinal width) in the current layer as inferred from Triad observations ranges from a fraction of 10^{-1} amp/m for an extremely weak current to about 1 amp/m for a strong current.

Taking the latitudinal thickness of the current layer to be 2° (Figure 6), and taking the integrated current to be 0.1 amp/m, the average current density for an extremely quiet condition is estimated to be about 4×10^{-7} amp/m². For an average disturbed condition, taking the integrated current and the thickness to be 0.3 amp/m and 4° , respectively, the average current density is roughly 7×10^{-7} amp/m². These estimates show that the enhanced total current under disturbed conditions is partially compensated

by the increased thickness resulting in a current density that does not increase at the same rate as the integrated current does. However, these calculations are only intended to provide order of magnitude estimates and should not be applied to any specific cases. For instance, for the region of net current maximum, i.e. 1500-1800 MLT, the level shift amplitude is greater (Figure 4) and the thickness is smaller (Figure 6) than the overall average of the respective quantity, and therefore the average current density would be expected to be greater than it is in other MLT regions. If we take $\Delta B = 500\gamma$ and $\Delta A = 3^\circ$ for this interval as the points in Figures 4 and 6 for $K_p > 2$ show, the current density is 1.2×10^{-6} amp/m². For the intense current observed on May 22, 1974, the average current density in the current layer is roughly 4×10^{-6} amp/m².

4. Candidates (or no candidates) for current carriers

Efforts to identify the carriers of field-aligned currents have been made by several authors (e.g. Zmuda and Armstrong, 1974b, Berko et al., 1975, and in a review by Arnoldy, 1974). However, since we are dealing with a specific type of field-aligned current in this paper, we re-examine the charged-particle observations in the literature to see if there are suitable candidates for the current carriers. For brevity the current layer discussed in this paper is simply referred to as "the current layer" in the following discussion unless otherwise stated; it does not include other field-aligned currents that are known to exist and that have been discussed in the literature.

As a first step we give estimates of charged-particle flux corresponding to those made above for the current density. Particle flux is estimated

in terms of electron flux for simplicity. The current density of 4×10^{-7} amp/m² estimated for an extremely quiet condition requires an electron flux of 2.5×10^{12} el (m²s)⁻¹. The current density of 7×10^{-7} amp/m² for an average disturbed condition corresponds to a flux of 4.4×10^{12} el (m²s)⁻¹. The current density of 1.2×10^{-6} amp/m² for the late afternoon peak (1500-1800 MLT) for Kp > 2 would require 7.5×10^{12} el (m²s)⁻¹. The large current (4×10^{-6} amp/m²) observed on May 22, 1974, corresponds to a flux of 2.5×10^{13} el (m²s)⁻¹. These are the typical figures for the required electron flux that should be kept in mind. What is immediately clear is that while the particle observations indicate great variability in the fluxes, the above estimates of the electron fluxes required for the field-aligned current in question do not vary more than a factor of 10. This aspect already casts some doubt to the prospect of finding a ready answer in most of the published charged-particle observations. In addition to the differences in variability between the observed particle fluxes and the field-aligned current density, the diurnal variation in the particle precipitation pattern precludes, in many instances, a direct association of the observed precipitated particles with the net field-aligned currents. Exceptions to this latter point are the recent Isis 2 results of McDiarmid et al. (1975a, 1975b) concerning low energy ($E \sim 150$ ev) electrons and the well-known 'inverted V' electrons observed by Frank and his co-workers (e.g. Frank and Ackerson, 1971).

The average intensity contour maps for electrons of various energies (0.15, 1.3, 9.6, > 22, and > 210 kev) given by McDiarmid et al. (1975a)

based on the results from their EPD (Energetic Particle Detector) experiment on Isis 2 are of great interest. In particular, the average intensity contours for 150 ev electrons (their Figure 4) indicate a primary maximum near 1500 MLT and a secondary maximum near 0300 MLT, and the iso-intensity contours around these maximums are elongated along an oval shaped belt near the 35 keV electron trapping boundary. The magnetic local time for the primary maximum electron intensity agrees with that of the pronounced afternoon maximum in the average magnitude of the level shifts and in the frequency of occurrence of these level shifts described in this paper (Figures 3 and 4). As has been mentioned, there is a less distinct, broad maximum in the field-aligned current in the morning. Furthermore, the thickness, ΔA , of the current layer appears to be considerably greater in the morning than it is near the afternoon maximum region (Figure 6). This feature is quite similar to the local time variation in the latitudinal width of the region of high intensities for the 150 ev electrons. It is noted that the width of the high intensity belt based on the average electron intensities is necessarily broader due to smoothing than it is in individual intensity profiles. We point out that the observed widths of the current layer are comparable with the widths of the high intensity region in the individual electron intensity profiles shown by McDiarmid et al. (1975a, 1975b).

Based on Figure 4 of McDiarmid et al. (1975a) and assuming a 100 ev energy width, the flux in the maximum (150 ev) electron intensity region near 1500 MLT is estimated at 6×10^{11} el $(m^2 s)^{-1}$, which is approximately one order of magnitude less than the flux required for the field-aligned

current in the 1500 MLT region for $K_p \leq 2$, i.e. 5×10^{12} el $(m^2s)^{-1}$; the particle data analyzed by McDiarmid et al. were obtained under conditions with $K_p \leq 30$.

The average isointensity contours for 1.3 kev electrons (Figure 6 of McDiarmid et al., 1975a) shows a similar intensity distribution to that for 150 ev electrons except that there is an additional maximum near 2100 MLT, which has nearly the same intensity as the maximum near 1600 MLT and which has a broader latitudinal width than does the 1600 MLT maximum. The flux of electrons with energies in the vicinity of 1.3 kev in the 1500 MLT region is roughly 2×10^{12} el $(m^2s)^{-1}$, assuming an energy width of 3 kev. This flux is greater than that for the 150 ev electrons, but is still smaller than the flux required for the current. As the electron energy becomes greater, for instance, for 9.6 kev, the maximum near 1500-1600 MLT vanishes and the late evening maximum, which was seen near 2100 MLT for 1.3 kev electrons, moves toward midnight, being near 2300 MLT for 9.6 kev electrons (Figure 8 in McDiarmid et al. 1975a). The flux near the 2300 MLT maximum is roughly 3×10^{11} el $(m^2s)^{-1}$, if an energy width is taken to be 5 kev for this category of electrons. This flux is less than those estimated for 150 ev and 1.3 kev electrons near the 1500 MLT maximum.

Summarizing the discussions made so far, regarding the Isis 2 results, we conclude that while the statistical position and the latitudinal width of the field-aligned current layer are remarkably similar to those of the region of high electron intensities at or near the 35 kev electron trapping boundary both for the morning and afternoon halves of the region, the observed electron fluxes in the afternoon half, as represented by the

average isointensity contours, is generally not adequate to account for the field-aligned current. On the morning side the current flows downward; therefore a comparison between the high electron-intensity region and the field-aligned current layer is relevant only relative to their locations.

In a more recent publication McDiarmid et al. (1975b) discussed the particle properties of the dayside cusp (cleft) and reported that the electron spectrum is much harder and the proton intensity weaker postnoon (1400-1600 MLT) than prenoon (1000-1200 MLT). They showed that most of the prenoon electrons are below the 150 eV energy threshold of the EPD experiment. This is probably the first mention of a prenoon-postnoon asymmetry in the polar cusp particles, which may or may not be relevant to the reversal of the field-aligned current direction at noon.

Heikkila and Winningham (1971) argued that their observations of cusp electrons from Isis 1 can account for the transverse magnetic field perturbations of 30 to 900 γ that Zmuda et al. (1970) had observed from satellite 1963-38C and attributed to field-aligned currents. However, this claim would not be applicable to the field-aligned current in the current layer discussed in this paper at least in the prenoon region, because in that region the current flow is downward.

Studying the electric field and charged particle observations on Injun 5, Gurnett and Frank (1973) interpreted the location of the electric field reversal as being the boundary between open and closed field lines. According to these authors, on the dayside the occurrence of the electric field reversal is coincident with the equatorward boundary of the polar

cusps, and at local evenings 'inverted V' electron precipitation bands are observed poleward of, or at the position of the electric field reversal. Frank and Ackerson (1972) found that as the low-energy electron precipitation band at the polar cusp is followed around into the local evening, this band continues to the 'inverted V' electron precipitation band and that with this transition the average energy of the precipitated electrons increases to several keV or more. This description is in agreement with the electron intensity contours given by McDiarmid et al. (1975a), if we interpret that the inverted V precipitation band corresponds to the region of high electron intensities in the late evening that was discussed above in connection with the 1.3 keV and 9.6 keV electron intensity contours. According to Frank and Ackerson (1972), the inverted V precipitation band is located poleward of the electron ($E > 45$ keV) trapping boundary; while in the contour maps of McDiarmid et al. (1975a) the high electron-intensity region is roughly centered at the 35 keV electron trapping boundary and extends to both sides of this boundary.

Gurnett and Frank (1973) showed an example in which the electric field reversal occurred coinciding with the location of the most intense inverted V event at 18.8 hours MLT (their Figure 6 for orbit 5696). For this example we estimate the current density to be roughly 3×10^{-6} amp/m², assuming an average energy of 6 keV for the electrons. The integrated current density for this crossing is estimated at 0.4 amp/m. These values can be considered as being adequate for the required current. In the two other examples given by these authors for crossings of the inverted V band at 23.0 hours and 24.0 hours MLT (orbits 3716 and 3667) the peak energy flux

is greater than that in the first example by a factor of 2 or 3. In the fourth example (orbit 3655) of a crossing of the auroral zone at 0.5 hours MLT the maximum precipitated electron energy flux in the inverted V band is less than that within the broad electron precipitation zone which Gurnett and Frank identify as the low-altitude signature of the plasma sheet. This situation appears to be typical of the auroral zone precipitation in the local midnight and dawn sectors (Frank and Ackerson, 1972), and corresponds to the features seen in the same sectors in the intensity contour maps discussed above. Thus in the evening to midnight region the idea that the precipitated electrons in the inverted V band of Frank and his co-workers constitute a significant part of the field-aligned current in the current layer in question may be viewed favorably. However, this conjecture should be regarded only as a possibility; there is no compelling reason at present for believing that this deduction is correct. On the other hand, the precipitated electrons in the broad band positioned equatorward of the electron trapping boundary can probably be ruled out as a candidate for the current carrier for the present current layer, because in the region where these electrons have large intensities the field-aligned current is downward. The higher intensities in the inverted V band (e.g. Frank and Gurnett, 1973) compared with the electron intensities represented by isointensity contours of McDiarmid et al. (1975a) must be due to the averaging made in deriving the contours, and we do not regard the difference as being a discrepancy between the two sets of observations. Rather, having the two different methods of representation has been helpful in our interpretation of the results.

The analysis of the Ogo 4 auroral electron observations by Hoffman and Berko (1971) shows a concentration of high ($\geq 40\%$) probabilities of 0.7 kev electron precipitation occurring between 0500 and 1400 MLT and from 75° to 82.5° invariant latitude and generally smaller probabilities on the night side. This probability distribution appears to be enough to discard the 0.7 kev auroral electrons observed by Hoffman and his associates as a major current carrier for the current layer. The dayside electron precipitation events observed by them appear to be more related to the occurrence of discrete auroral emissions (Hoffman and Berko, 1971) than to the field-aligned currents discussed here.

Most of the rocket observations of field-aligned electron precipitation, which were reviewed by Arnoldy (1974), have been made in or near auroral arcs, and are found to be not directly relevant to the identification of the current carrier sought here. An exception to this is the electron and electric field measurements made from a rocket flown into the polar cusp region near noon by Maynard and Johnstone (1974). The current density estimated by them from the measured electron flux is 1.3×10^{-6} amp/m² which is adequate for the current layer. But no magnetic field measurements were made on this rocket, and hence whether or not the observed electrons produced any appreciable net current cannot be inferred from the experiment.

The higher-latitude zone of auroral particle precipitation deduced by Hartz and Brice (1967) is located at a comparable latitude as the field-aligned current layer discussed in this paper. However, the distribution of the average flux intensity gives no clue to the present problem. Precipitated electrons having energy greater than 40 kev observed by Injun 3

(Frank et al., 1964) and by Alouette 1 (McDiarmid and Burrows, 1964) have neither a proper distribution nor adequate flux to account for the field-aligned current under consideration.

5. A remark on the location of the current layer

A question may be asked as to where the field-aligned current layer in which the net current flows is situated relative to the polar cap. However, in the absence of simultaneous observations of charged particles, electric field, and magnetic field in the relevant region, this question is almost meaningless. From the standpoint of magnetic field measurement the field-aligned current layer as defined by the Triad and Ogo 5 observations can most logically be called the polar cap boundary. Whether the poleward edge or equatorward edge of the current layer is called the polar cap boundary appears to be a semantic question at present. In this connection, simultaneous observations of electric field and magnetic field from a low-altitude, polar orbiting satellite to determine the position of the field-aligned current layer relative to the location of the electric field reversal, as well as simultaneous observations of magnetic field and charged particles, are urgently needed.

6. Relation to Sq^P

Both the maximum frequency of occurrence (Figure 3) and the maximum magnitude (Figure 4) of the level shifts in the magnetic field occur in the 1500-1800 MLT interval. This local time is near the location of the afternoon focus of the Sq^P system that was derived by Nagata and Kokubun (1962) and that has been discussed extensively in the literature especially by the Japanese workers. There is some indication that a secondary, less pronounced,

maximum exists in the morning hours. We speculate that the Sq^P current is mainly a Hall current driven by the field-aligned current system presented in this paper. If this is so, the Sq^P is driven by the current generator in the tail that drives the field-aligned current (Sugiura, 1975).

CONCLUSION

From the Triad magnetometer observation of a step-like level shift in the east-west component of the magnetic field at 800 km altitude, we have inferred the existence of a net current flowing into or away from the ionosphere in a current layer. The current direction is toward the ionosphere on the morning side and away from it on the afternoon side. This current layer is identified as the same layer as that observed by Ogo 5 at much higher altitudes. Thus the field-aligned currents observed by Triad are considered as being an important element in the electro-dynamical coupling between the distant magnetosphere and the ionosphere.

The current density integrated over the thickness of the layer increases with increasing magnetic activity, but the relation between the current density and K_p in individual cases is not a simple linear relation. An extrapolation of the statistical relation to $K_p = 0$ indicates existence of a sheet current of order 10^{-1} amp/m even at extremely quiet times. During periods of higher magnetic activity an integrated current of ~ 1 amp/m and an average current density of order 10^{-6} amp/m² are observed.

The location and the latitudinal width of the field-aligned current layer carrying the net current very roughly agree with those of the region

of high electron intensities as observed by Isis 2 and Injun 5 at or near the trapping boundary for high-energy electrons. The electrons with energy 150 ev (the lowest energy measured by the EPD experiment on Isis 2) to several kev precipitating in this region are regarded as being a potential candidate for the current carrier in the postnoon to midnight portion of the current layer. Simultaneous observations of charged particles, electric field, and magnetic field from a single or multiple satellites are required to make a substantial progress in understanding the field-aligned currents.

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FIGURES

- Figure 1. An example of a step-like level shift in the output from the A magnetometer sensor, which is approximately in the dipole east-west direction, indicating a net upward current in the field-aligned current layer; a typical example observed in the afternoon.
- Figure 2. An example of a level shift of large amplitude, indicating a net downward field-aligned current observed during a magnetically disturbed period.
- Figure 3. The lower panel: the number of passes examined and considered to give data of good quality, in each magnetic dipole local hour. The upper panel: the percentage occurrence of level shifts satisfying the selection criteria. The direction of ΔB as the current layer is crossed poleward is indicated.
- Figure 4. Average magnitude of level shift for each 3-hourly magnetic local time interval for two Kp groups. The number in parentheses indicates the number of cases contributing to each average.
- Figure 5. Magnitudes of level shifts plotted against Kp. For each Kp value the open circle gives the average amplitude and the vertical bar, the standard deviation.
- Figure 6. The average invariant latitudes of the poleward and equatorward boundaries (upper panel) and the average width in invariant latitude (lower panel) of the current layer for each 3-hourly magnetic local time interval, for two Kp groups. The numbers in parentheses indicate the number of cases over which the averages were taken.

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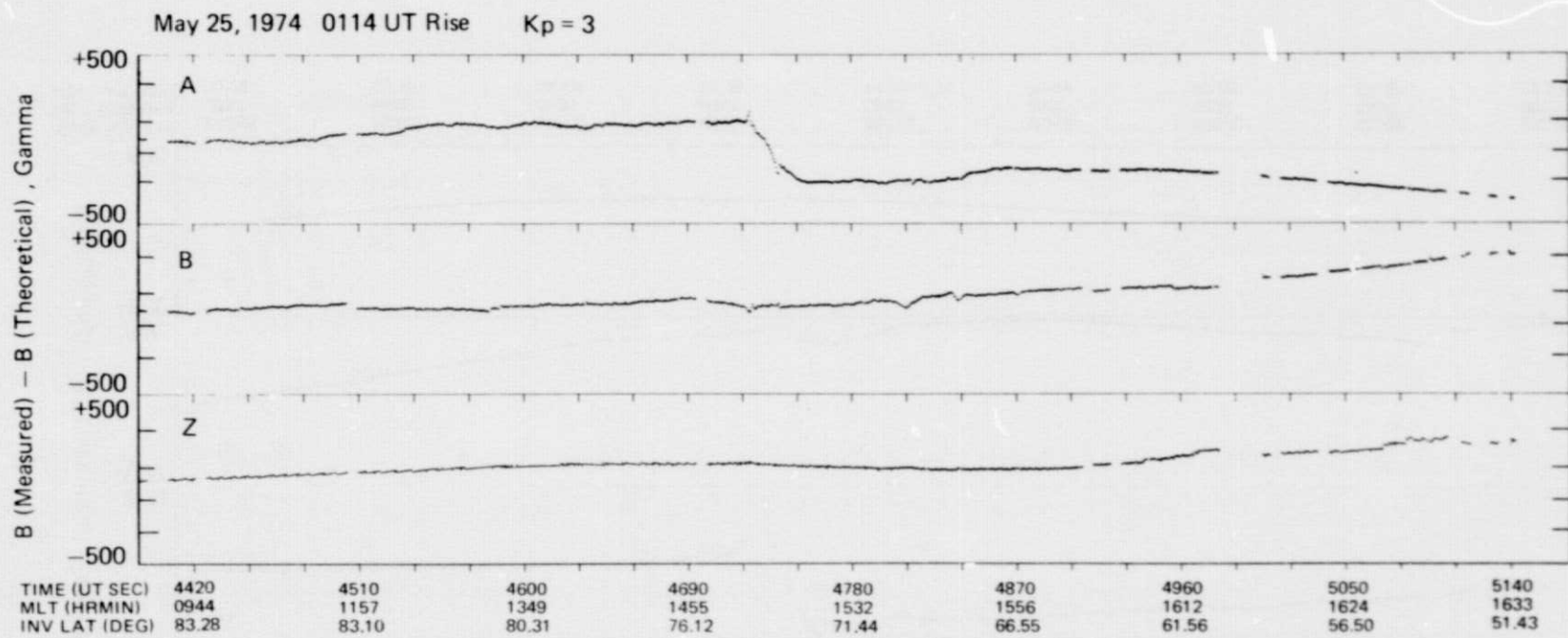


Figure 1

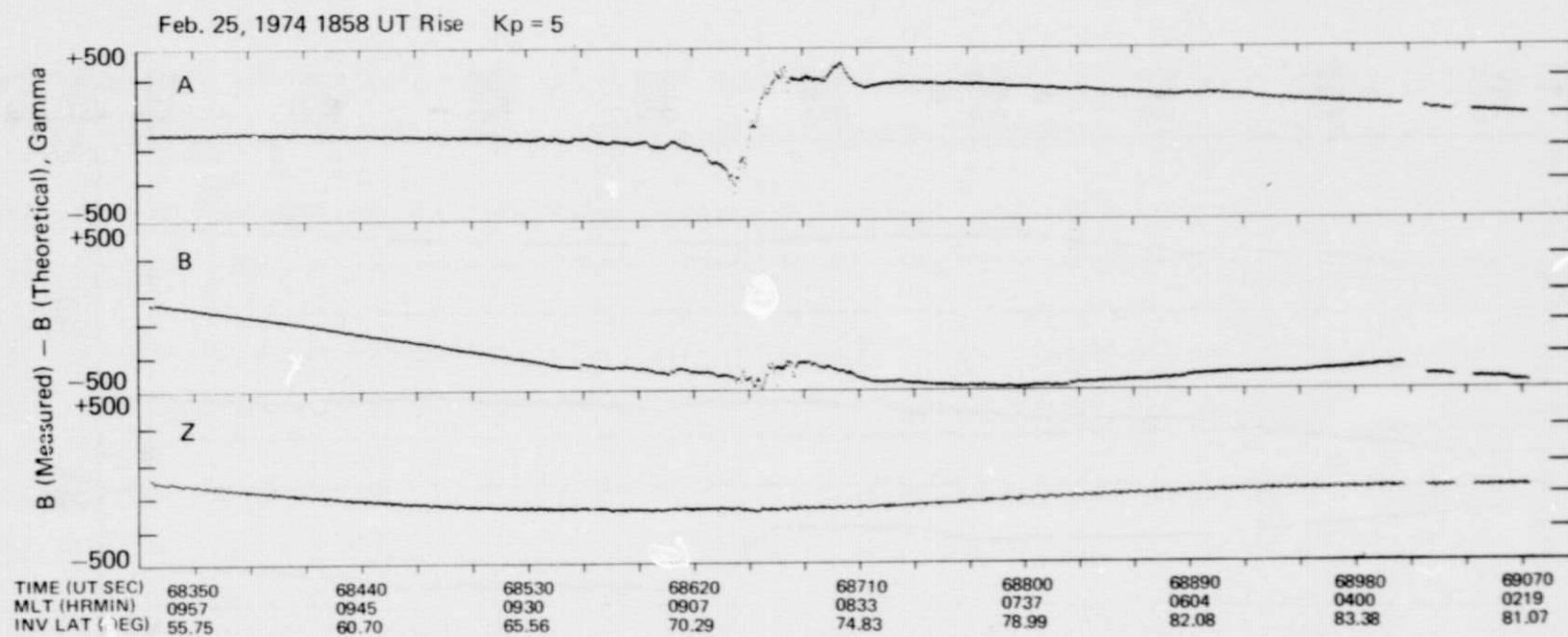


Figure 2

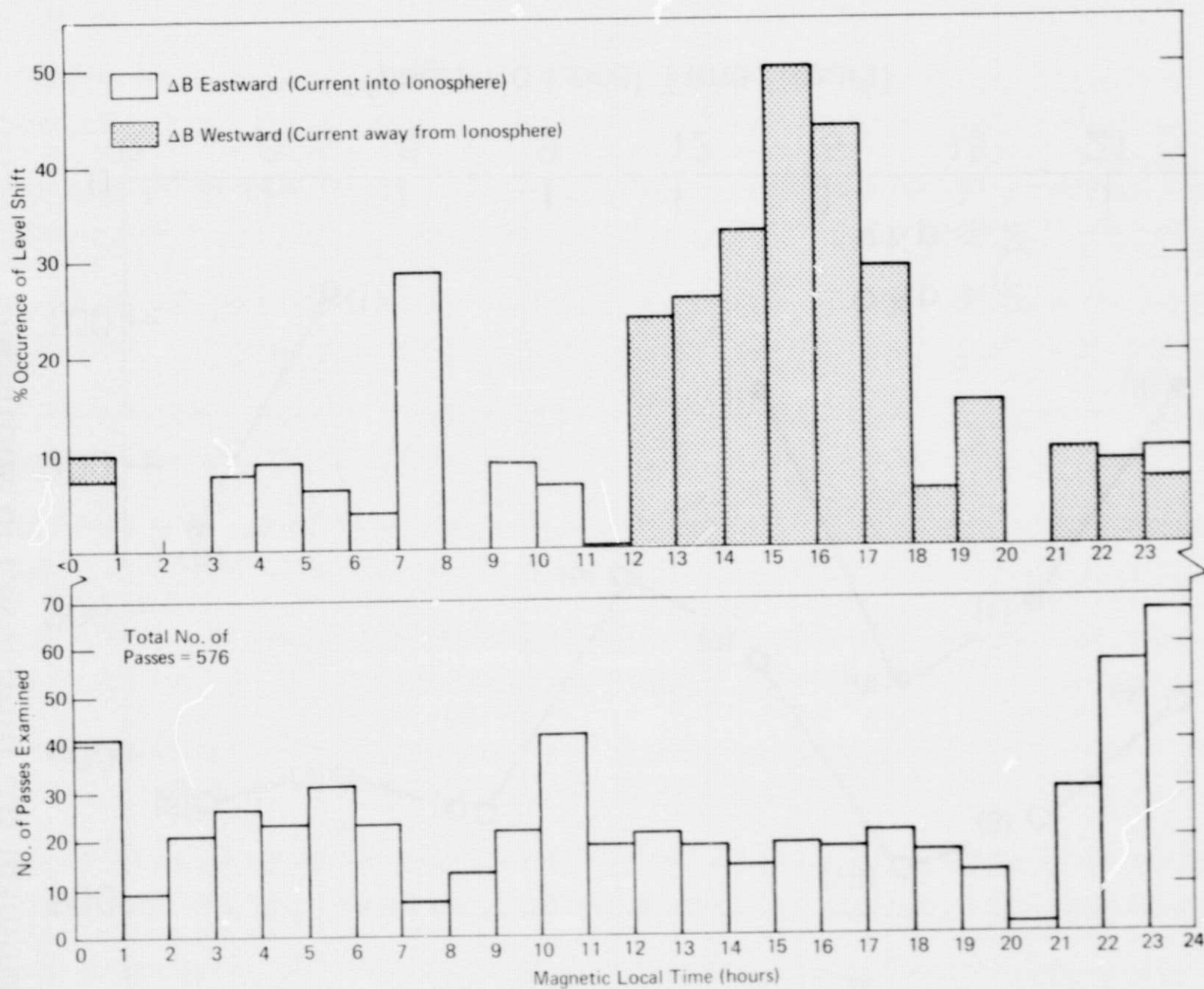


Figure 3

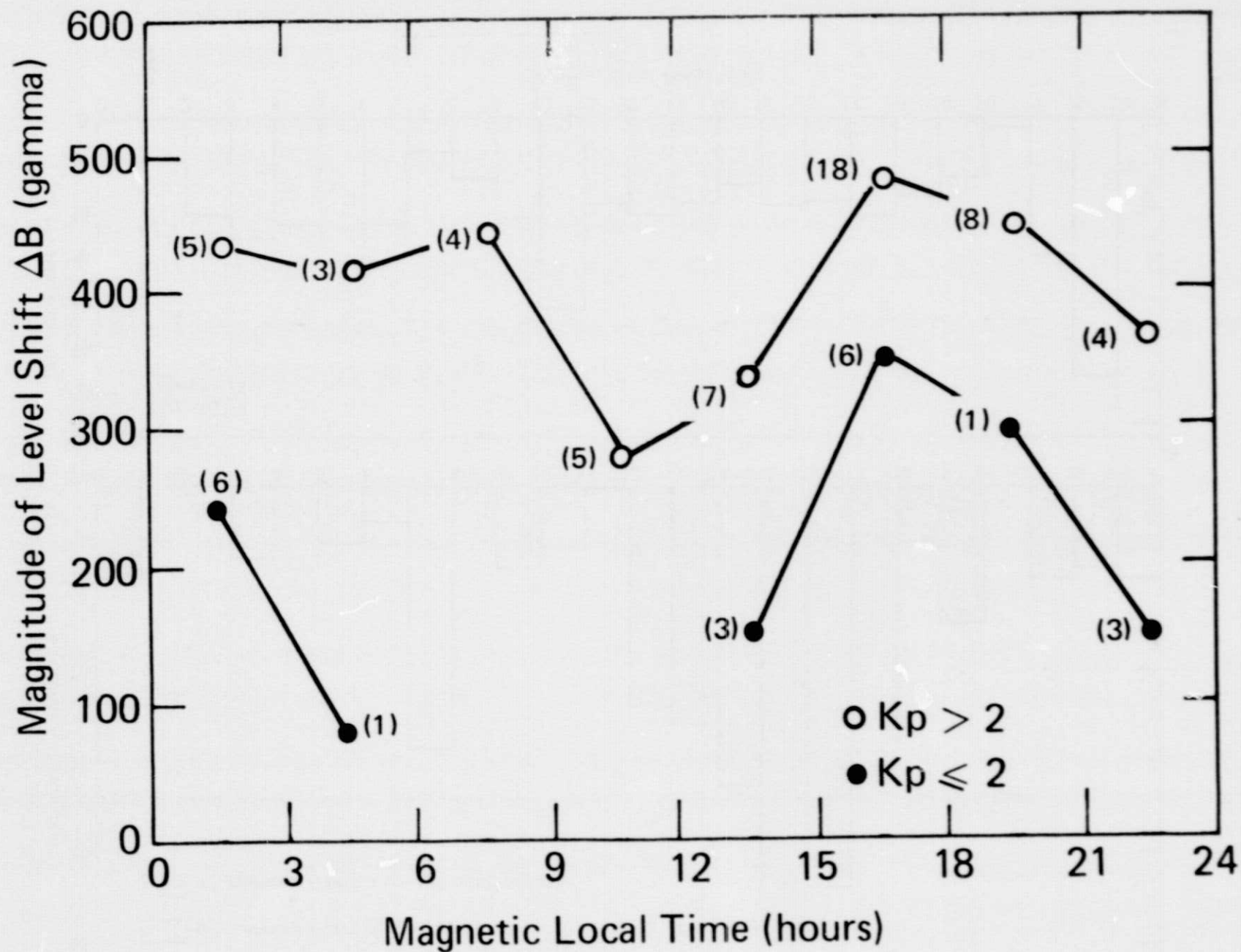


Figure 4

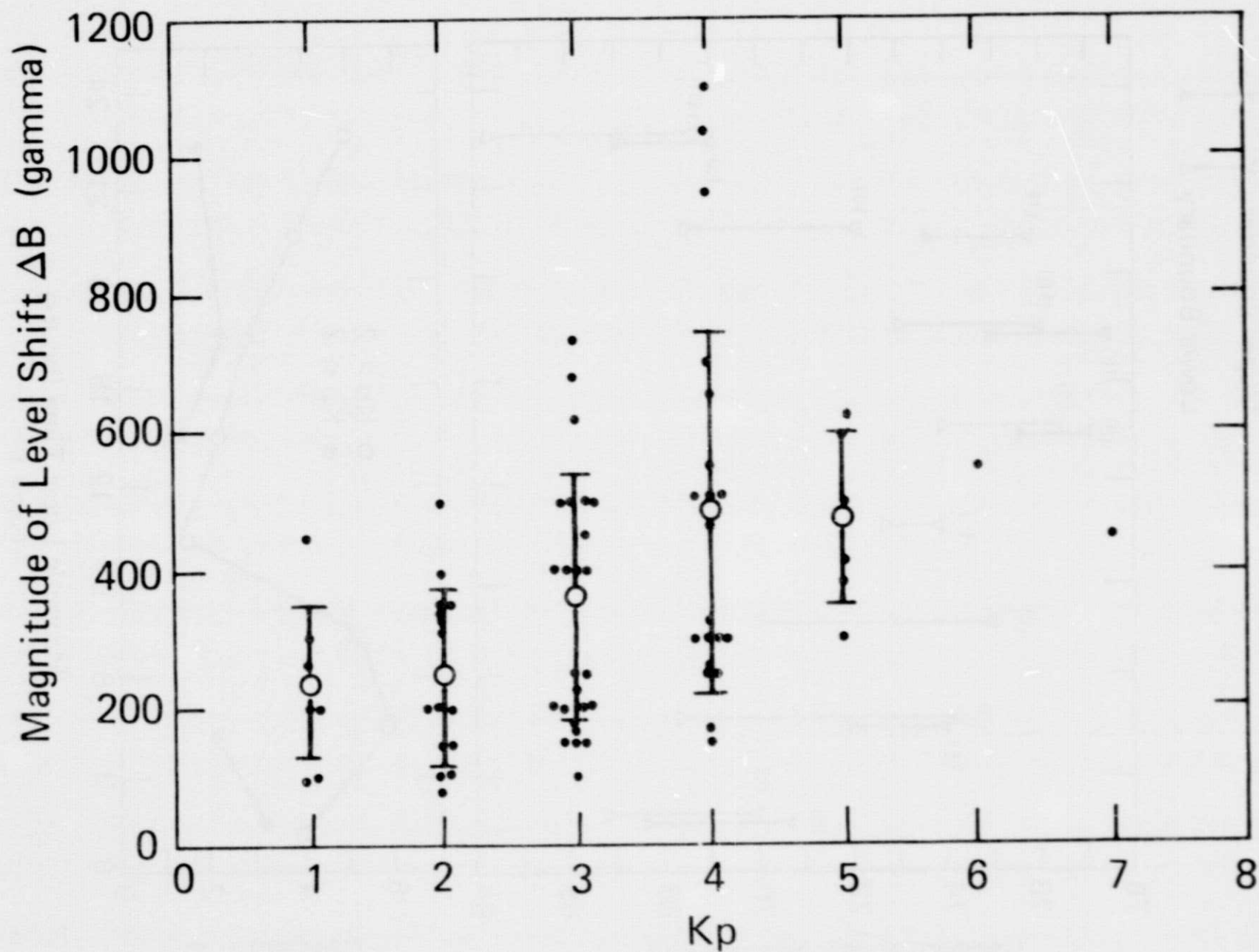


Figure 5

$K_p > 2$ ≤ 2
 Upper Boundary ∇ \blacktriangledown
 Lower Boundary \triangle \blacktriangle

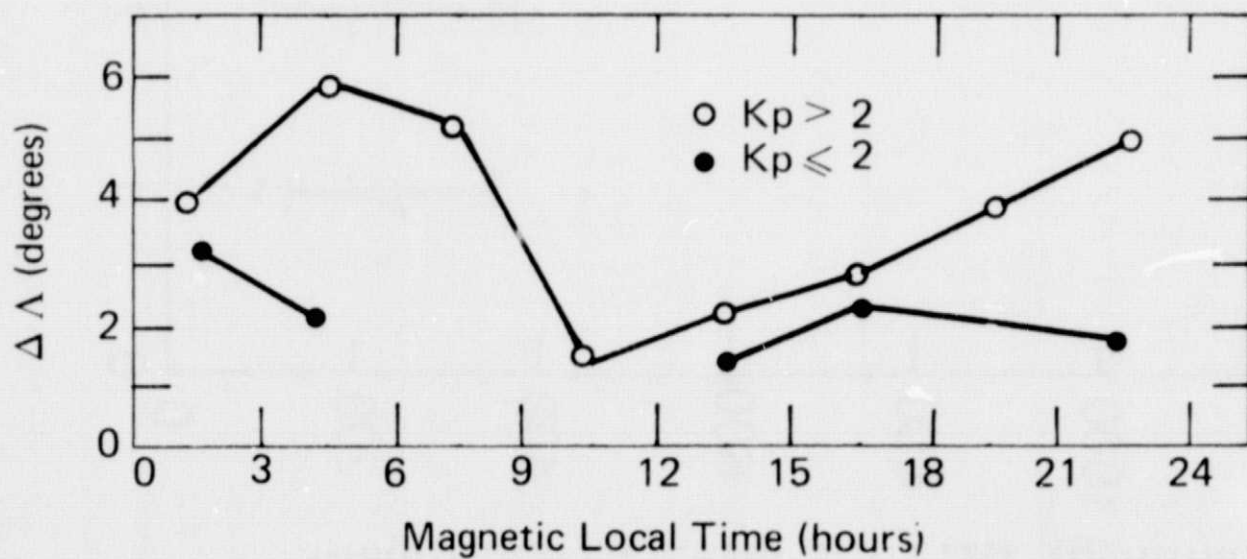
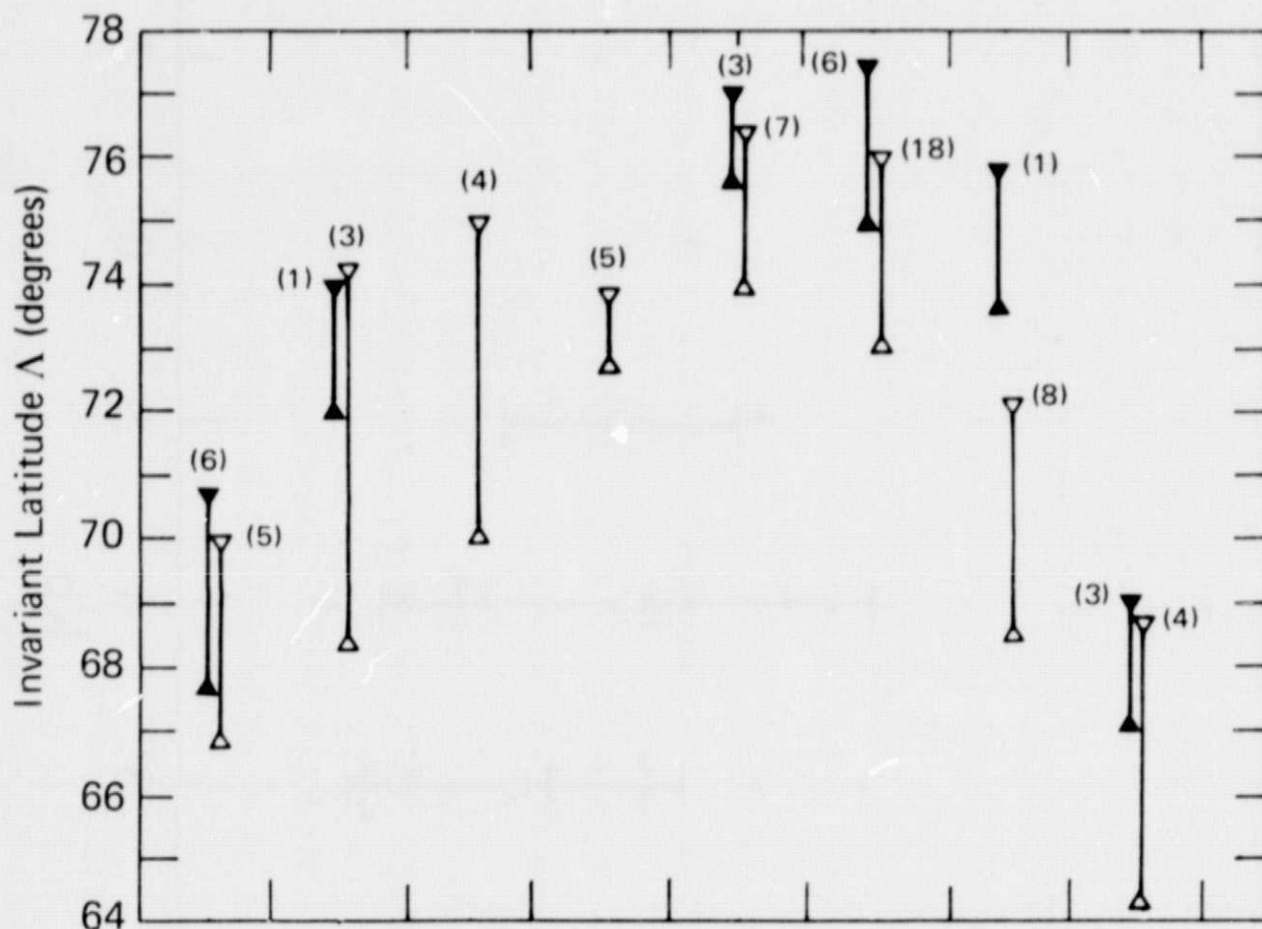


Figure 6