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SIMULTANEOUS TRAPPED ELECTRON AND MAGNETIC TAIL FIELD OBSERVATIONS

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ABSTRACT

Using data from the polar orbiting satellite 1963 38C, the behavior of the high latitude energetic (≥ 280 kev) electron trapping boundary, Λ_c, at 1100 km is presented for the period March 15 through June 3, 1964. A sudden collapse of Λ_c to lower latitudes during the onset of magnetic storms, as indicated by K_p and D_{st}, is found to be a characteristic feature of the low altitude trapped electron population. Details of this behavior are presented and discussed. In addition, during this time period, the NASA IMP-1 satellite sampled field characteristics in the geomagnetic tail. Correlated observations of the simultaneously observed behavior during magnetic disturbances of the 1100 km trapped electron population and of the field strength in the tail are presented. In three cases there is agreement and in one case disagreement with the latitude decreases which are predicted with an extended geomagnetic tail configuration. These results are considered to be direct evidence of the important influence exerted by the geomagnetic tail field in governing not only the quiet time trapped particle distribution, but also the behavior of the trapped particle population during magnetic storms.

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INTRODUCTION

A recent letter (Ness and Williams, 1966) has described correlations observed between simultaneous observations of outer zone trapped electrons at 1100 km and of the magnetic field strength ~30 R_E (earth radii) in the earth's magnetic tail. The reported observations concerned a magnetic disturbance which occurred on April 1, 1964. It was found that at the height of this disturbance, the low altitude, high latitude electron trapping boundary on the midnight meridian had undergone a marked collapse of ~ 5° toward lower latitudes. Simultaneous to this behavior of the trapped electron population, it was observed that the field strength some 30 R_E in the earth's magnetic tail increased. This was interpreted as evidence of additional, formerly closed lines of force being significantly extended into the tail region, thereby increasing the tail field magnitude and lowering the low altitude, high latitude trapping boundary. Quantitatively favorable comparisons were obtained with the expectations of a magnetic field model having an extended tail configuration.

Data for the above correlation were obtained from the APL satellite 1963 38C and the NASA IMP 1, or Explorer 18 satellite. Additional trapped electron and magnetic field correlations have been obtained for the period March 15 - June 3, 1964 when IMP 1 was imbedded within the earth's magnetic tail. The objective of this paper is to present and discuss these additional simultaneous trapped electron and magnetic field observations.

The temporal history of the trapped electron trapping boundary on the nightside hemisphere and its correlation with K_p and D_{st} values for the period under study will also be presented. A similar temporal history of the tail field as observed by IMP 1 during this period has been presented by Behannon and Ness (1966).

SATELLITES AND DETECTORS

1963 38C: During the March 15 - June 3, 1964 period under study, satellite 1963 38C sampled electron intensities on the nightside hemisphere from the local times of 0400 hours to 2000 hours. A description of the instruments and of initial outer zone observations has been presented in Williams and Smith (1965), Williams and Palmer (1965), Williams and Mead (1965) and Williams (1966).

Briefly, satellite 1963 38C was launched on September 28, 1963 into a nearly circular polar orbit having a 1140 km apogee, a 1067 km perigee, an 89.9° inclination and a 107.5 min. period. The satellite was magnetically aligned to the extent of possessing a $\leq 6°$ residual oscillation about the local line of force except for the first three days after launch.

The detector of interest is an integral electron spectrometer consisting of five 1000 μ thick surface barrier detectors. The channel to be discussed is one sensitive to electrons of energy $E_e \geq 280$ kev. The spectrometer is oriented to look out normal to the satellite alignment axis and thus after alignment monitors the intensity of trapped electrons mirroring at or very near the point of observation.

IMP 1: The IMP 1 satellite was launched on November 27, 1963 into a highly elliptical orbit with an initial apogee of 31 R_E and an orbital period of 93.5 hours. During the March 15 - June 3, 1964 period under study, the angle between the line of apsides of the IMP 1 orbit and the earth-sun line ranged from 122° west to 198° west of the sun. A description of the instrumentation and of initial magnetospheric results has been presented in Ness et al (1964), Ness (1965), Ness et al (1965), and Behannon and Ness (1966). The instrumentation provided vector field measurements in the tail for field strengths of less than 40 gamma with an accuracy of ±0.25 gamma. The average field strength beyond ~10 R_E during this three month interval was approximately 16 gamma.

TRAPPED ELECTRON RESULTS

Data from 206 nightside passes of satellite 1963 38C have been obtained during the period March 15 - June 3, 1964. The electron spectrometer data pertaining to trapped electrons of energy $E_e \geq 280$ kev have been displayed as intensity (true count rate) versus invariant latitude ($\Lambda \equiv \cos^{-1} 1/\sqrt{L}$) profiles for all recorded passes.

A characteristic feature of the behavior of the $\geq$ 280 kev trapped electron population in such latitude profiles is a striking collapse of the high latitude trapping boundary to lower latitudes during magnetic storms. This effect has been illustrated for the magnetic storms of March 29 and April 1, 1964 by Ness and Williams (1966) and Williams (1966). It is further illustrated here in Figure 1 for the magnetic disturbance of May 10, 1964. In Figure 1 are shown the six available nightside passes (within local times of 2140 hrs. - 2210 hrs.) for the period May 9 - 11, 1964. A sudden commencement magnetic disturbance occurred at 0035 hours May 10, 1964. The numbered arrows in the plot of K_p values show the time sequence of the corresponding numbered passes.

Passes 1 and 2 of Figure 1, obtained prior to the disturbance, display similar and typical quiet time latitude profiles. Pass 3, obtained ~ 4 hours after the sudden commencement but prior to the sustained increase in K_p, shows a profile similar to passes 1 and 2, having a cutoff at $\sim 65°$. Pass 4, obtained at the height of the disturbance, displays the characteristic collapse of the high latitude cutoff to lower latitudes, in this case to $\sim 58°$. Pass 5, taken $\sim$3-1/2 hours after pass 3, and pass 6, taken after the disturbance has subsided, show a gradual recovery with the high latitude cutoff approaching the pre-storm values. The interpretation and correlation of this effect with magnetic tail field measurements will be discussed in later sections.

The high latitude cutoff (Λ_c) has been defined at a detector count rate of 1 count per second. As a check on the consistency of such a low count rate cutoff, a high latitude boundary has also been defined and recorded at a detector count rate of 10 counts per second. Figure 2 shows the behavior of the trapped, ≥ 280 kev electron nightside high latitude cutoffs, Λ_c, for the entire 81 day period under study. The solid circles and open circles represent the high latitude boundary defined at 1 cps and 10 cps respectively. D_{ST} values (Behannon and Ness, 1966) and the 3 hour K_p averages are also shown along with all sudden commencements reported by ten or more stations (Lincoln, 1965 a and b). The disturbances during which the trapped electron data were correlated with IMP 1 data are indicated by vertical lines.

The typical nature of the high latitude cutoff lowering during magnetic disturbances is evident in Figure 2. An apparent exception to this consistent behavior is the seemingly confused response from March 15 - March 23, 1964. Note that the D_{ST} behavior at this time is also not very marked nor characteristic. The scatter in Λ_c values does appear to be indicative of magnetic activity. The effect of the sudden commencement of March 21 was missed due to inappropriate phasing of the satellite orbit, data acquisition and hence data sampling.

For the remainder of the time period however, the behavior of Λ_c is seen to be remarkably consistent in its response to magnetic activity as measured by D_{st}. For example, the response of Λ_c is seen to correlate very well with the temporal variations of D_{st} and K_p throughout the two storms of May 10 and May 13, 1964.

From Figure 2 it is possible to obtain the dependence of the Λ_c collapse on D_{st} magnitude. For the $\sim 60\gamma$ range observed, this dependence is in agreement with the auroral arc southern latitude dependence on D_{st} as reported by Akasofu (1965).

A characteristic time appropriate for the changes in the trapped electron population indicated in Figure 2 is estimated to be $\leq$ 3 hours, i.e. within the resolution of the K_p averages. This estimate stems from a study of the less significant fluctuations displayed in Figure 2. Also the data sampling rate during major events where a sudden large decrease of Λ_c is observed is such that the best estimate obtainable for the response time is $\leq$ 6 - 9 hours.

This is illustrated in Figures 3, 4, and 5 where the Λ_c and K_p values are shown on an expanded time scale for the periods April 15-22, April 24- May 2, and May 7- May 19, 1964. The trend of the Λ_c values on April 15, and 16 and particularly April 18 in Figure 3, on April 24-27 in Figure 4, and on May 9 in Figure 5 indicates that the trapped electron low altitude Λ_c response is in phase with variations in the K_p averages, i.e. occurs within a 3 hour time period.

An additional interesting characteristic dislpayed in Figures 3-5 is the recovery of Λ_c toward prestorm values even while the K_p values remain high throughout the magnetic disturbance. Thus the correlation between Λ_c and magnetic activity (low Λ_c correlates with high, or increasing K_p) decreases after about the initial 24 hours of an extended disturbance. This can be seen in the April 18-21 disturbance in Figure 3 and the May 13-18 disturbance of Figure 5. In Figure 4, Λ_c is seen to correlate well with the behavior of K_p from April 24 to April 27. However, as K_p rapidly rises to its highest level at $\sim$ 1800 hours April 27, the Λ_c values show a tendency to recover to quiet time values and essentially reach these undisturbed values on April 28 while the K_p values remain high. This effect will be correlated with simultaneous magnetic tail field measurements in the next section.

If the return of the high latitude trapping boundary to pre-storm values is considered to be indicative of the re-establishment of a "quiet time" magnetospheric configuration, then the continued high K_p values at these times may be more a measure of ionospheric currents rather than of gross magnetospheric perturbations.

CORRELATED RADIATION BELT AND MAGNETIC TAIL OBSERVATIONS

During the 81 day period under study, March 15 - June 3, 1964, there were six magnetic storm events for which

1) Outer zone data were available from 1963 38C and
2) Magnetic field data in the earth's magnetic tail were available from IMP-1.

These six events, indicated by vertical lines in Figure 2, occurred at 1525 hours April 1, 0020 hours April 17, 14XX hours April 27, 0035 hours May 10, 1301 hours May 13, and 2229 hours May 23, 1964. Details of the tail field behavior and its correlations with ground observations have been presented for all but the April 17 event by Behannon and Ness (1966).

Quantitative correlations of the trapped electron data and the magnetic tail field data have been obtained for the above cases in the following manner. Three hour averages of the tail field magnitude, $\overline{F}$, and direction, θ and ϕ, were obtained so that a direct comparison could be made with the K_p averages. The angles θ and ϕ are solar ecliptic latitude (+ is north) and longitude (180° is the anti-solar direction) respectively.

From these tail field values, an approximate midnight meridian high latitude trapping boundary was obtained by considering field line closure in an extended magnetic tail field configuration. The model used was that constructed by Williams and Mead (1965) to fit the low altitude energetic trapped electron population spatial distribution during magnetically quiet periods, under the assumption of adiabatic invariant conservation. The predictions of this model, using observed tail field strengths, were then compared directly with simultaneously observed high latitude boundary values, Λ_c.

The current sheet spatial parameters (Williams and Mead, 1965) were held fixed for all six events at an inner edge of 8 R_E and an outer edge of 200 R_E. Field strengths as observed by IMP-1 were used to determine an expected value of Λ_c. Figure 6 shows the predicted Λ_c values as a function of tail field magnitude for the quoted current sheet parameters.

The six events will now be discussed individually. April 1, 1964: Figure 7 displays K_p, Λ_c $\overline{F}$, θ, and ϕ for the event of April 1, a moderately severe storm having a sudden commencement reported by 4 stations at 1525 hours. It is this event for which the initial trapped electron-magnetic tail correlations were reported (Ness and Williams, 1966).

A strong positive correlation exists between the tail field magnetide, $\overline{F}$, and the K_p averages. This correlation is somewhat weakened near midday, April 2. At this time IMP-1 approached to within 1 R_E from the neutral sheet and entered a depressed field region probably affected by charged particle field line loading (Behannon and Ness, 1966; Anderson and Ness, 1966).

The solid line in the Λ_c scale represents the predicted high latitude trapping boundary of the field model discussed above using the tail field values shown. Experimentally observed cutoffs are also shown with solid and open circles again corresponding to boundaries defined at 1 cps and 10 cps respectively.

Figure 7 shows that while the absolute position of the predicted and observed trapping boundaries differ by an average of ~4°, the magnitude of the boundary collapse, ~6°, can be explained by the behavior of the tail field for this event. The low values of Λ_c (theoretical) on April 2, reflect the low values of $\overline{F}$ as discussed in the correlation with K_p.

It is interesting to note that while the trapped electron boundary returned to prestorm values on April 2, electron islands were observed in the tail (Anderson and Ness, 1966).

April 17, 1964: The sudden commencement event occurring at 0020 hours April 17 is shown in Figure 8. This is the only event in which the observed boundary collapse could not be predicted from the observed tail field behavior. As is seen in Figure 8, the observed boundary shift is ~6° whereas the predicted shift, based on the behavior of $\overline{F}$, is at most ~2-1/2°.

A neutral sheet crossing is seen to occur at ~0300 hours April 18. The temporal response of $\overline{F}$ is limited due to the proximity of IMP-1 to the neutral sheet. This may explain the above discrepancy between observed and predicted trapped electron boundary shifts.

April 27, 1964: Figure 9 shows a moderate event commencing at 14XX hours, April 27. The detailed Λ_c behavior displayed in Figure 4 was discussed in the previous section. The observed trapped electron boundary positions are seen to accurately track the trend of the K_p averages through ~1500 hours, April 27. At the time the K_p values suddenly increase to their maximum value and remain at an enhanced level until ~1200 hours April 28. After the K_p increase at 1500 hours April 27, the observed trapped electron boundaries show a recovery to predisturbance values, although the K_p values remain high as shown in Figure 9.

As IMP emerges from perigee, the tail field is seen to be at the rather high value of 30-35 gammas. After a slight increase occurring at 1500 hours April 27, in coincidence with the K_p increase, the tail magnitude, F, decreases to more normal values even though K_p remains high.

Thus after initially correlating with the K_p values, both Λ_c (experimental and theoretical) and $\overline{F}$ tend toward typically quiet time values during a time in which K_p remains high. Figure 9 shows that the behavior of the trapped electron high latitude boundary agrees well with the observed behavior of the tail field.

This recovery of $\overline{F}$ and Λ_c during relatively high K_p values is consistent with K_p being, at this time, more a measure of ionospheric currents rather than gross magnetospheric distortions. If this is the case, then it is also possible that the rapid field fluctuations observed in both the ground magnetograms and in the tail field during the first 12 hours of April 28, (Behannon and Ness, 1966) may have been generated close to the ionosphere.

May 13, 1964: Figure 10 presents the data from a sudden commencement event occurring at 1301 hours May 13. It is seen that the behavior of Λ_c is in good agreement with the behavior of $\overline{F}$ through May 13. Departures are noted at 0300-0600 hours, May 14. However, at this time IMP approaches to within 3 R_E of the neutral sheet and finally crosses the neutral sheet at $\sim$0000 hours May 15. That the response of the tail field is limited due to its proximity to the neutral sheet on May 14, is supported by the lack of any clear correlation between the tail field and the K_p increase on that day.

May 10 and May 23, 1966: Figures 11 and 12 show the final two events in which it was possible to attempt a correlation between the behavior of the trapped electron population and the tail field magnitude. These two events are inconclusive in relating to the present study and demonstrate an "out of phase" character which can exist between two sets of independently sampled data.

In Figure 11, trapped electron data during the May 10 event is available only at the time that IMP is in the neutral sheet (IMP approached to within 1 R_E of the neutral sheet at $\sim$1800 hours, May 10, with a crossing occurring at $\sim$0300 hours May 11).

The sudden commencement at 2229 hours, May 23 occurred while IMP-1 was at perigee. A characteristic Λ_c response is shown in Figure 2. However, trapped electron data are not available during additional magnetic activity occurring slightly over a day after the sudden commencement (Figure 12).

Summary of Correlations: Six events, Figure 7 - 12, have been discussed which allowed the possibility of obtaining simultaneous trapped electron and magnetic tail field measurements.

In three of the events, April 1, April 27-28, and May 13 (Figures 7, 9 and 10) the high latitude boundary of the outer zone trapped electron population behaves in a manner consistent with the simultaneously observed behavior of the magnetic field in the geomagnetic tail. Moreover, the magnitude of the trapped electron boundary motion is in fair quantitative agreement with the results of an extended tail model (Williams and Mead, 1965) using the observed tail field strengths.

In one event, April 17 (Figure 8), the trapped electron high latitude boundary collapses more than is expected from the field model used, given the observed variation in the tail field magnitude. The possibility of a limited tail field response due to proximity to the neutral sheet is offered as an explanation for the anomalous behavior.

In two events, May 10 and May 23 (Figures 11 and 12), the particle and field data are out of phase and no quantitative results can be obtained.

SUMMARY AND DISCUSSION

The following points summarize the present observations.

1. The low altitude, energetic ($\geq$280 kev) trapped electron population characteristically displays a sudden collapse of the high latitude boundary, Λ_c, during magnetic disturbances.

2. The magnitude of the trapped electron high latitude boundary collapse, when taken as a function of D_{st} value, is in agreement with the auroral arc results of Akasofu (1965) over the ~60 γ range of D_{st} values observed.

3. The response time of Λ_c following the onset of magnetic activity is within the resolution of the data i.e., $\leq$ 3 hours.

4. There is a tendency for Λ_c to return to pre-storm values during an extended magnetic disturbance, even though K_p values remain at an enhanced level.

5. Quantitative correlations of the trapped electron high latitude boundary collapses with simultaneous observations of the field strength in the earth's magnetic tail show three cases which agree and one which disagrees with the predictions of an extended tail magnetic field model.

The motion of low altitude trapping boundaries to lower latitudes during magnetic disturbances has been noted previously for $\geq$ 40 kev electrons (Maehlum and O'Brien, 1963) and for $\geq$ 280 kev electrons (Williams and Palmer, 1965). The fact that $\geq$ 40 kev and $\geq$280 kev trapped electrons have the same nightside high latitude trapping boundary, (Williams and Mead, 1965) implies that the $\geq$ 40 kev electrons will also characteristically exhibit trapping boundary collapses during magnetic storms. Thus it is expected that most of the present results can be extended to at least the 40 kev trapped electron population.

In the present investigation, extending from March 15 through June 3, 1964, we have been able to correlate this trapped electron behavior with simultaneous observations of the field strength in the earth's magnetic tail. These correlations have been compared with the predictions of an extended tail configuration.

The field model used was one originally constructed to fit the quiet time spatial distribution of trapped $\geq$280 kev electrons, assuming conservation of the adiabatic invariants. This model (Williams and Mead, 1965), employing a current sheet and consequent tail configuration similar to that observed (Ness, 1965) and suggested (Piddington, 1960; Axford et al, 1965; Dessler and Juday, 1965), was quite successful in explaining quiet time electron distributions as observed at 1100 km and thus demonstrated the strong influence of the geomagnetic tail in determining quiet time trapped particle spatial distributions. In this present study current sheet parameters were held fixed at an inner edge of 8 R_E and an outer edge of 200 R_E for all available cases. Using observed tail field strengths, high latitude trapping boundary variations were predicted by identifying this boundary, Λ_c, with the last closed field line in the extended tail configuration.

With such a model, the Λ_c collapses may be considered to be due to additional formerly closed lines of force being extended well out into the tail region, possibly forming some of the electron islands found there (Anderson et al, 1965; Anderson, 1965).

In each of the three cases observed where the magnitude of the Λ_c motion agreed with the field model predictions using observed tail field strengths, a difference in the absolute position of the observed and predicted boundaries was noted. This difference amounted to a few degrees and varied from one event to another. This discrepancy has been noted and discussed previously (Williams and Mead, 1965). Contributing factors are the need to use a more appropriate current sheet, the need for readjustment of the coefficients defining the field due to the boundary currents, the neglect of ring current effects, and the fact that a trapping boundary defined at a lower count rate would result in a higher cutoff latitude.

Of these factors, the effect of defining a trapping boundary at a lower count rate appears least important and should not raise trapping boundaries by more than ~0.5°. Ring current magnitudes and resultant effects remain unknown but could be significant. A readjustment of the boundary current field coefficients is required in a self consistent calculation of the magnetospheric configuration.

Probably most important is the need to use a more realistic current sheet. Such a current sheet should exhibit a radial dependence as implied by tail field observations (Speiser and Ness, 1966). Furthermore, recent measurements (Bame et al, 1966) indicate a sheet thickness of ~6 R_E at 17 R_E and an extension of the sheet across the magnetospheric tail. Thus a current system in the tail region having spatial characteristics similar to that discussed by Axford et al, 1965) is indicated.

Nevertheless, in three cases, the Λ_c motion is in good agreement with the predictions of the presently used simplified tail configuration employing simultaneously observed tail field strengths. We consider this as direct evidence of the important role played by the geomagnetic tail in governing the behavior of the trapped particle population during magnetic storms.

Note that the effect of the tail field increase need not be a sudden, violent opening of formerly closed field lines to explain the observed Λ_c motion. An alternative to the actual opening of field lines is a gentle, but still significant, extension of field lines while conserving the first two adiabatic invariants,

$$\mu = \frac{p^2}{2mB_M}$$

and

$$J = pI$$

Here p= momentum, B_M = mirror point B value, and I = integral invariant

$$I = \int_M^{M^*} \left(1 - \frac{B}{B_M}\right)^{1/2} ds .$$

Since for low altitude mirroring particles, I is essentially a measure of the length of the field line between mirror points, a field line extension under conservation of J will yield particle deceleration. Particle deceleration, in turn will raise the altitude of the mirror point under μ conservation. Both of these effects will produce an intensity decrease at low altitudes for threshold detectors under normal outer zone spectral conditions. The relative importance of this effect and that of field line opening and the latitude dependence of these effects requires detailed calculations of invariant surfaces and their readjustments under a changing tail configuration. Such calculations will require the more realistic current sheet discussed above.

The ≤ 3 hour response time of Λ_c following the onset of magnetic activity may now be considered as an upper limit on the time required by the magnetosphere and the trapped particle population to readjust to variations in the tail field configuration.

In addition, the recovery of Λ_c to pre-storm values during extended magnetic disturbances even while K_p remains at an enhanced level, implies that a "quiescent" magnetospheric configuration exists during periods of increased ground magnetic activity. This is consistent with K_p being, at times, more an indication of ionospheric currents than gross magnetospheric distortions.

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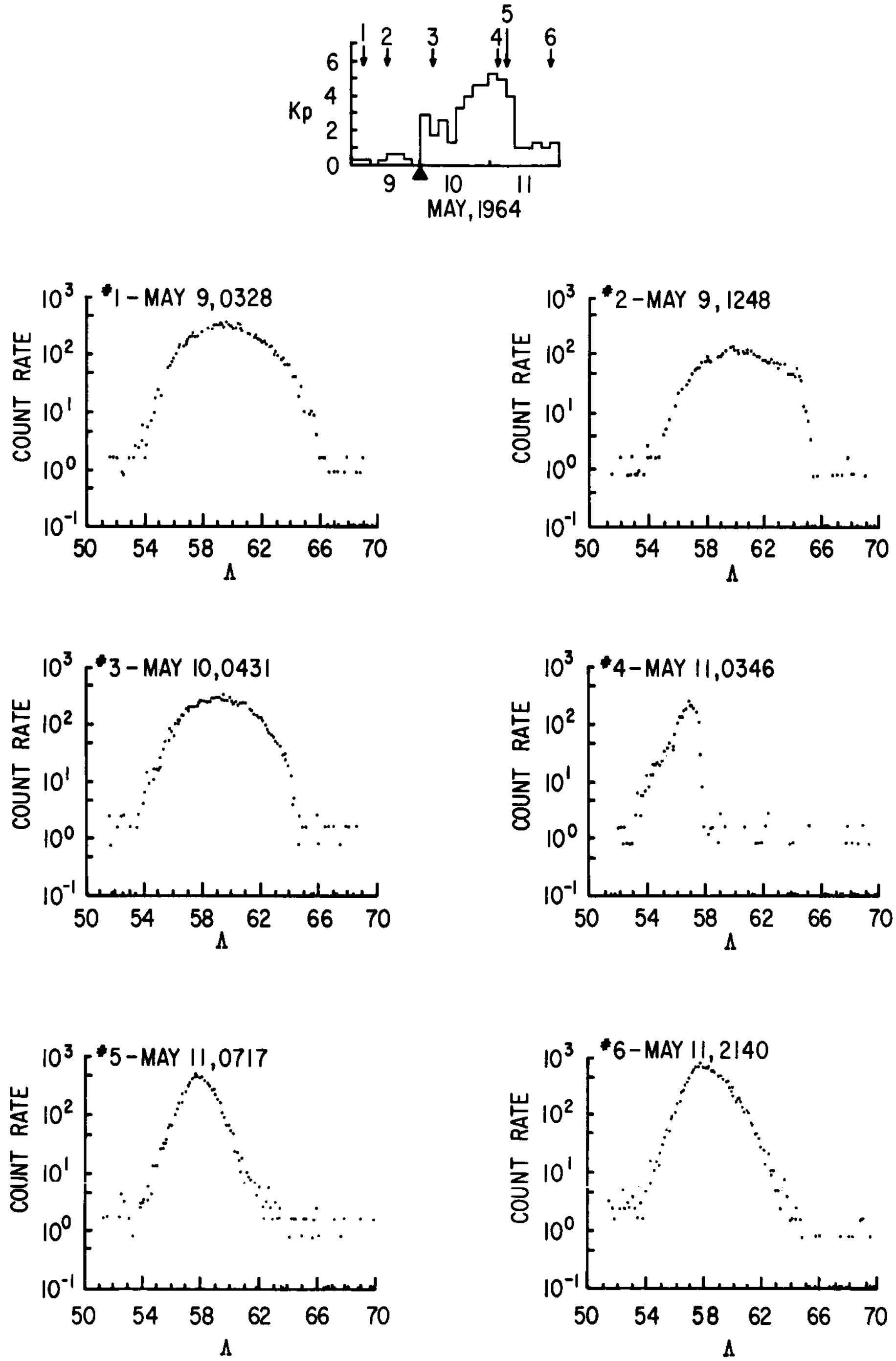

Figure 1—Intensity of trapped ≥ 280 kev electrons at 1100 kms versus invariant latitude, $\Lambda = \text{arc cos } L^{-1/2}$. Six passes are shown obtained before, during, and after the magnetic disturbance of May 10, 1964. The numbered arrows in the K_p inset correspond to the pass numbers shown. Pass number 4 displays the characteristic collapse, during magnetic disturbance of the high latitude trapping boundary. Multiplication of count rates by 500 gives directional flux values (electrons/cm^2 sec ster)

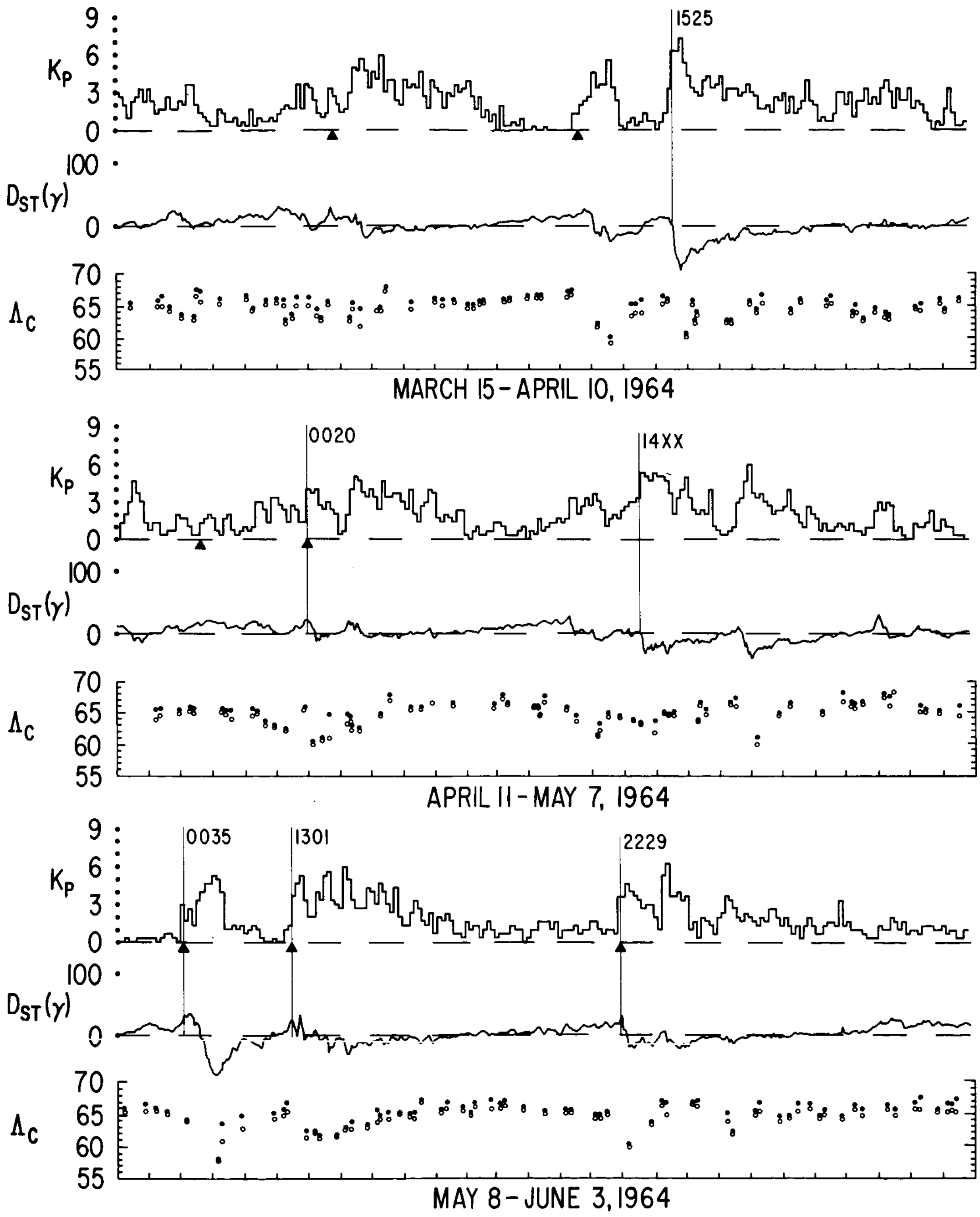

Figure 2–Plot of the ≥ 280 kev electron high latitude trapping boundary Λ_c, and the K_p and D_{st} values for the period under study. Solid and open circles in the Λ_c plot represent high latitude boundaries defined at 1 cps and 10 cps respectively. The vertical lines point out the six events yielding correlations of the Λ_c behavior with simultaneous magnetic field observations in the geomagnetic tail.

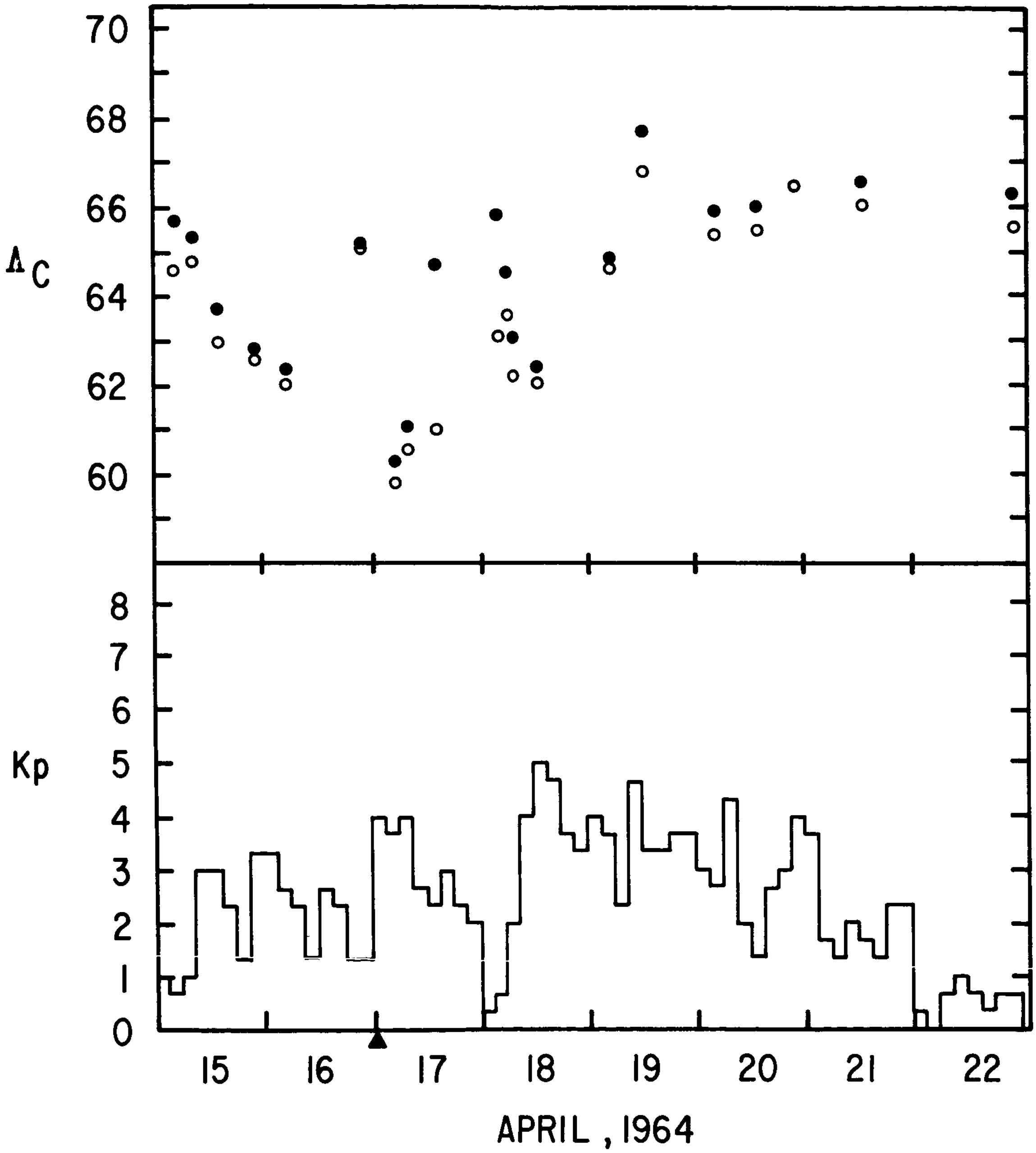

Figure 3–Expanded plot of Λ_c and K_p for the period April 15-22, 1964. Again, the solid and open circles represent high latitude trapping boundaries defined at 1 cps and 10 cps respectively. See text for discussion.

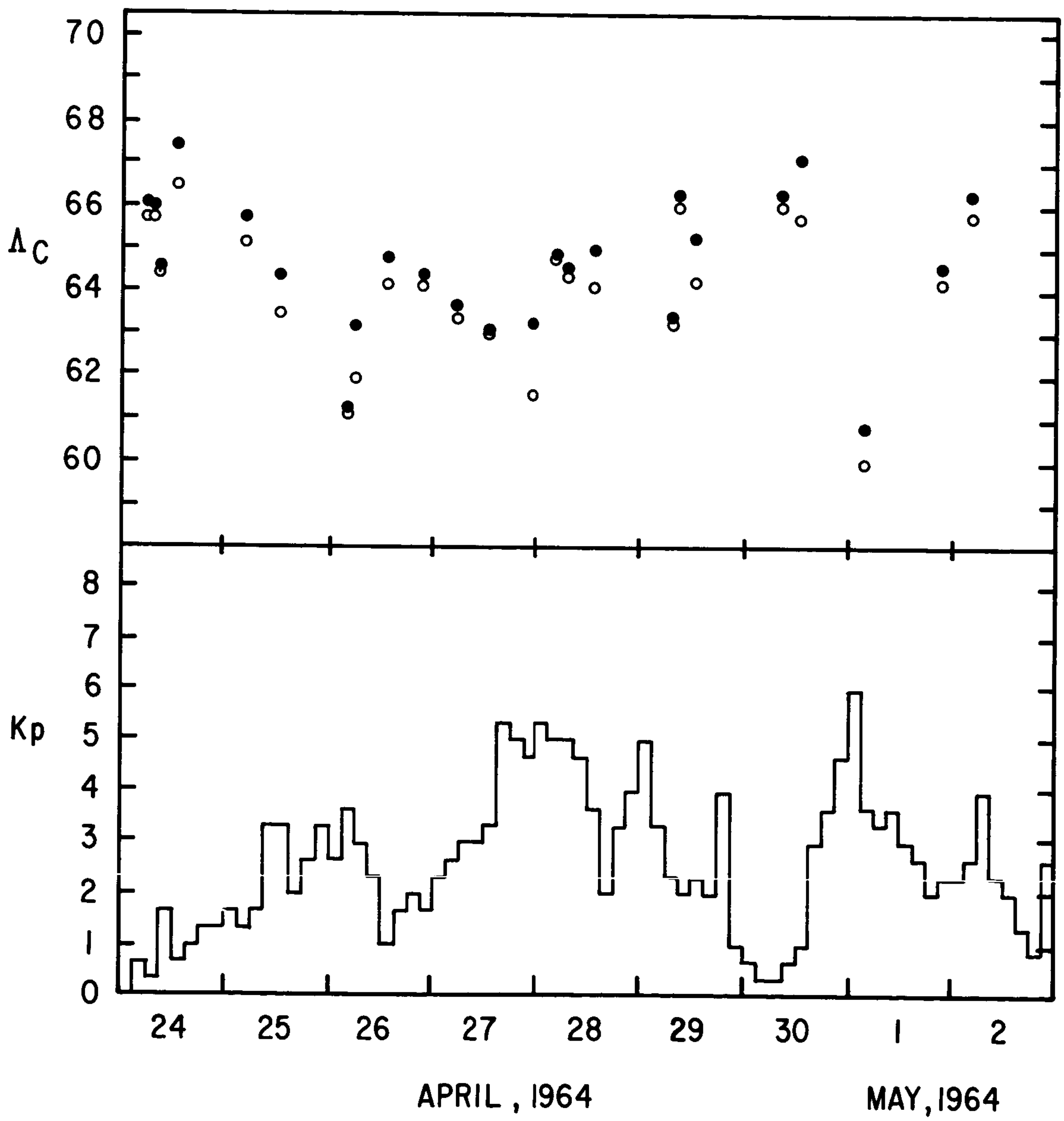

Figure 4—Same as Figure 3 but for the period April 24 – May 2, 1964.

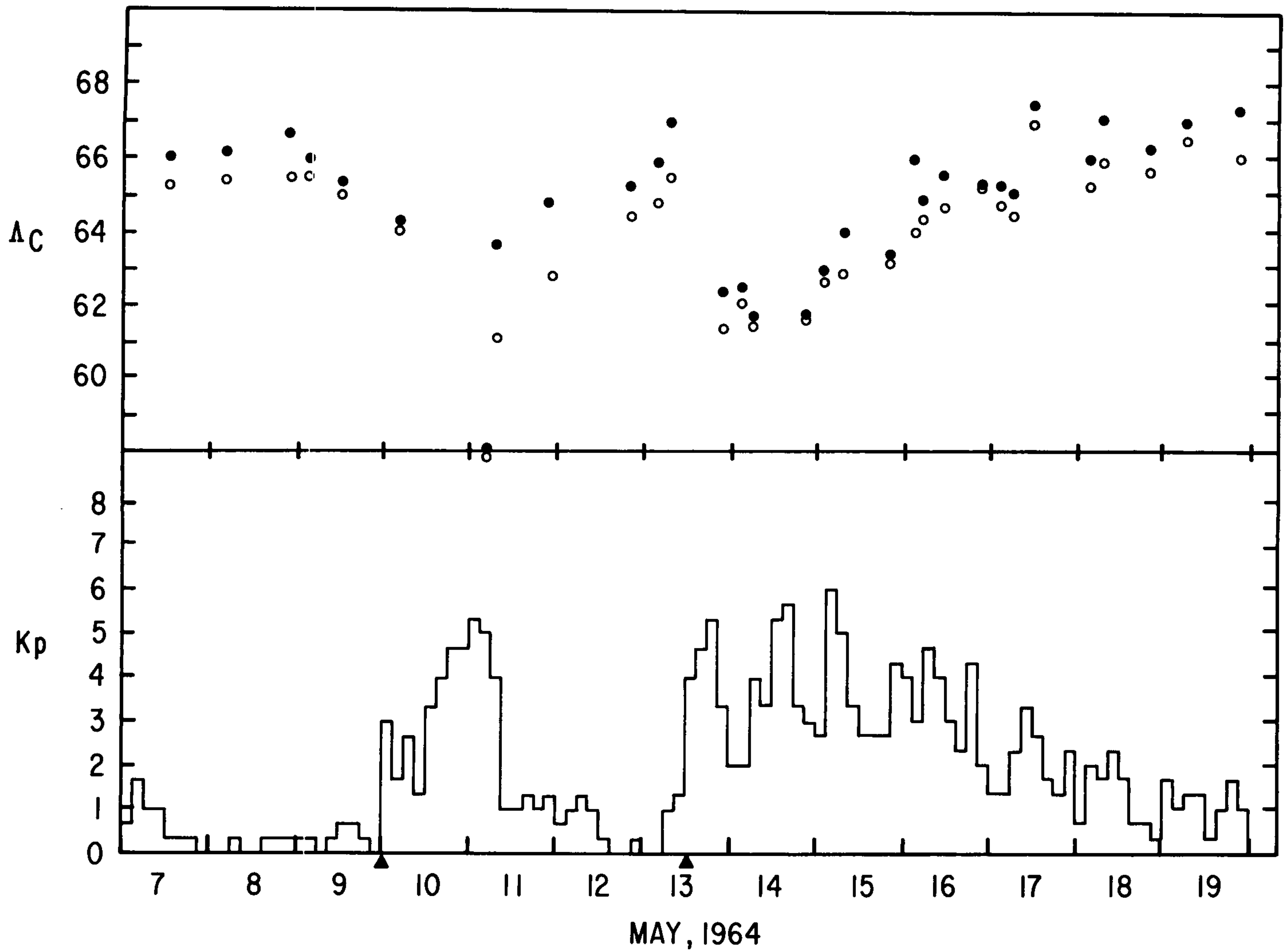

Figure 5–Same as Figure 3 but for the period May 7 – 19, 1964.

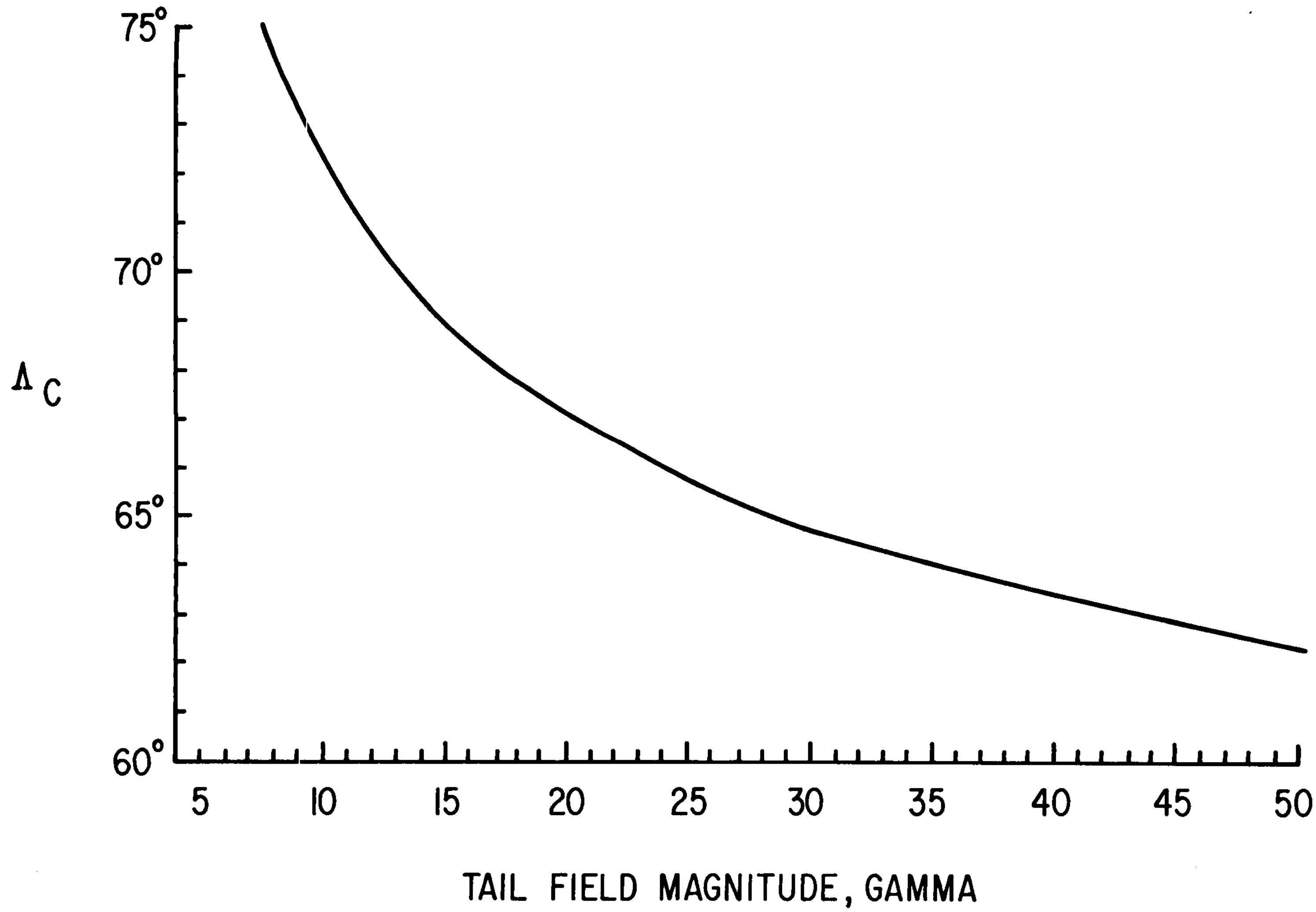

Figure 6—Λ_c (theoretical) versus tail field magnitude. Λ_c defined by last nightside closing field line in extended tail configuration of Williams and Mead (1965). Current sheet parameters used were inner edge at 8 R_E and outer edge at 200 R_E.

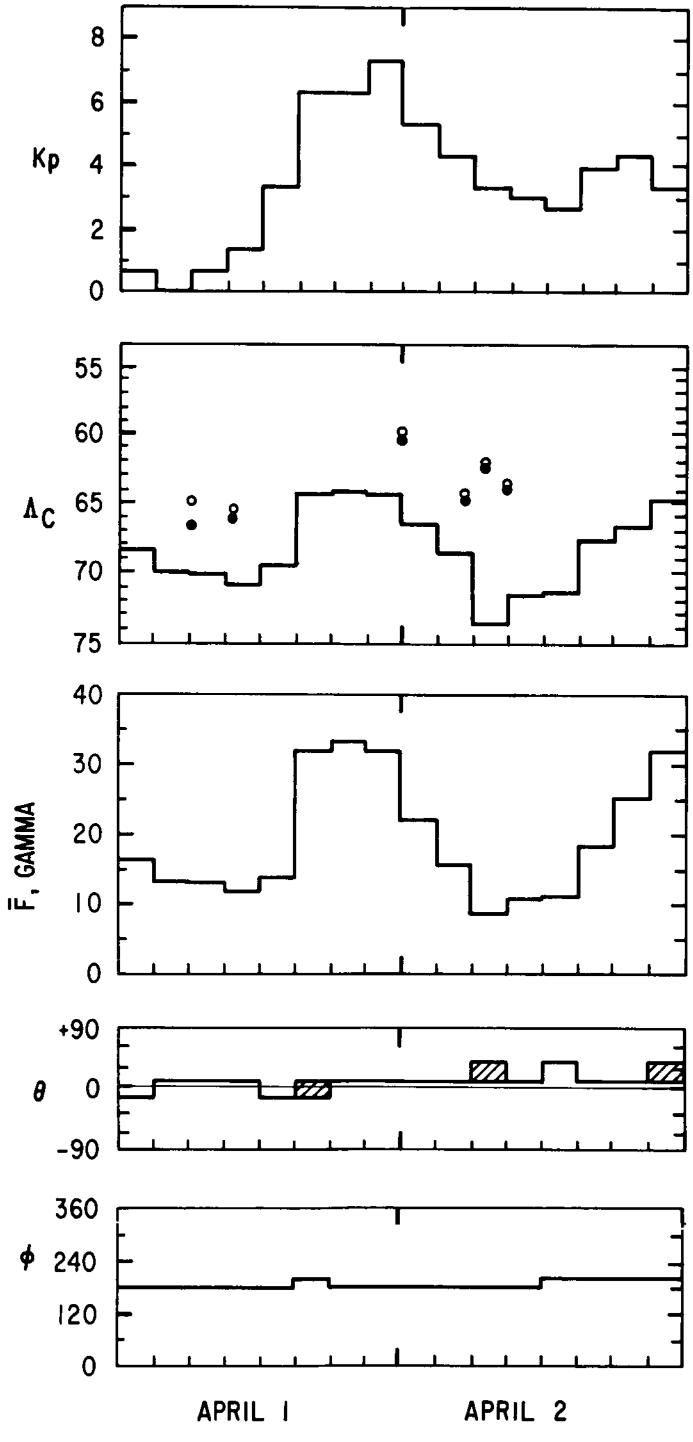

Figure 7—Correlation of K_p, Λ_c (high latitude trapping boundary), and $\bar{F}$ (tail field strength) for the magnetic disturbance of April 1, 1964. Also shown are the solar ecliptic angles θ and ϕ defining the tail field direction. See text for discussion.

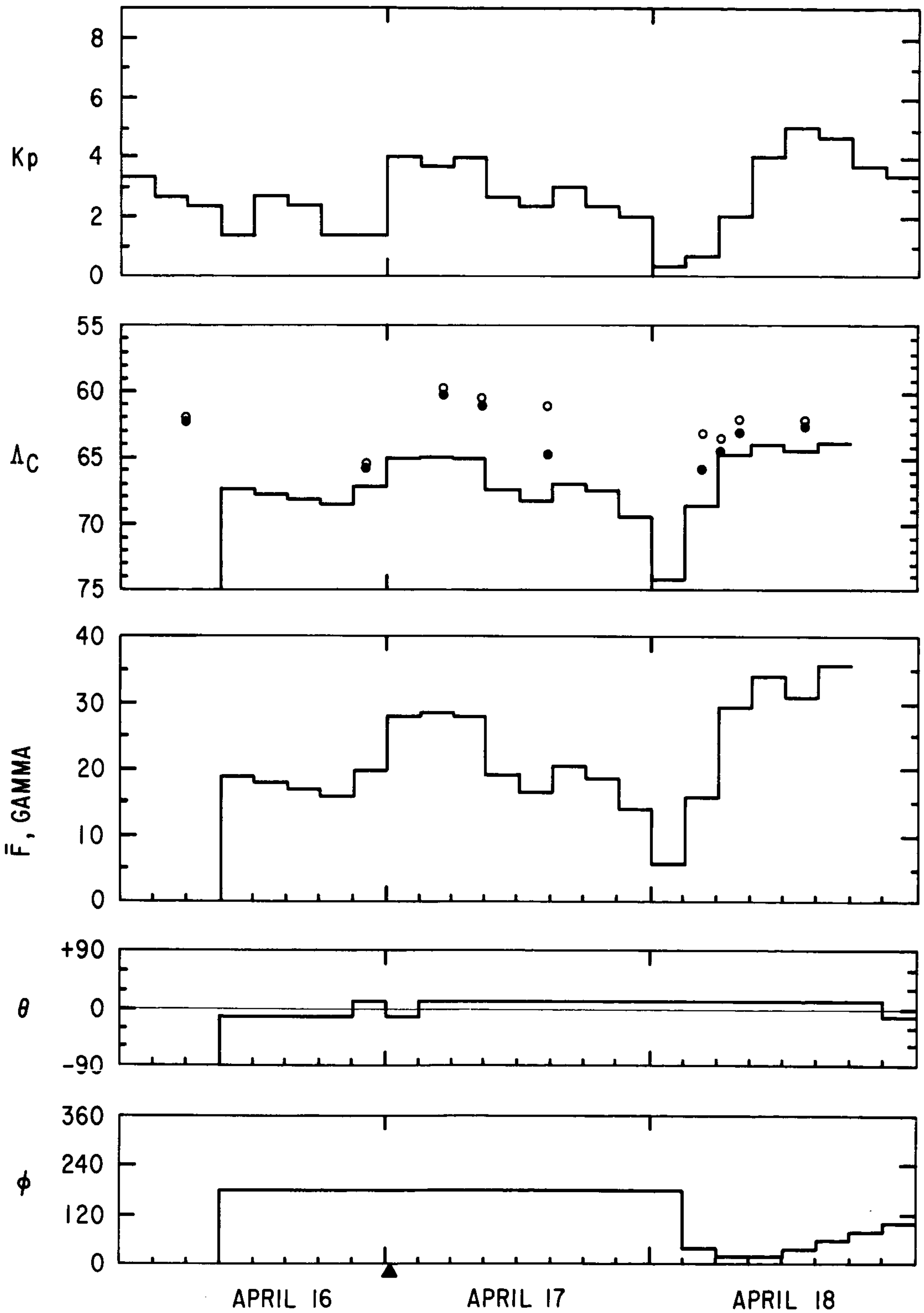

Figure 8–Correlation of K_p, Λ_c, and $\bar{F}$ for the April 27, 1964 event. θ and ϕ also shown.

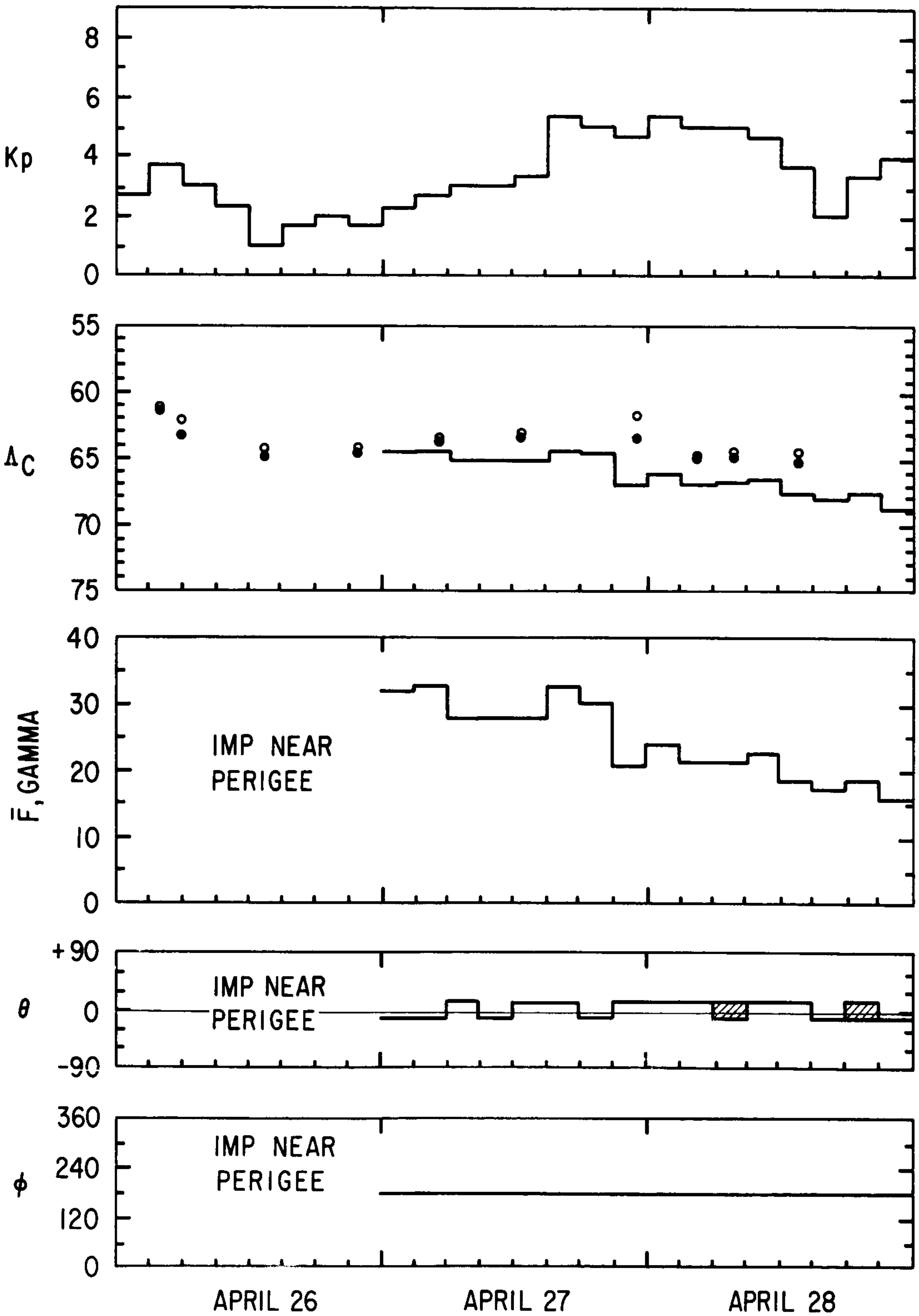

Figure 9—Correlation of K_p, Λ_c, and $\bar{F}$ for the April 27, 1964 event. θ and ϕ also shown.

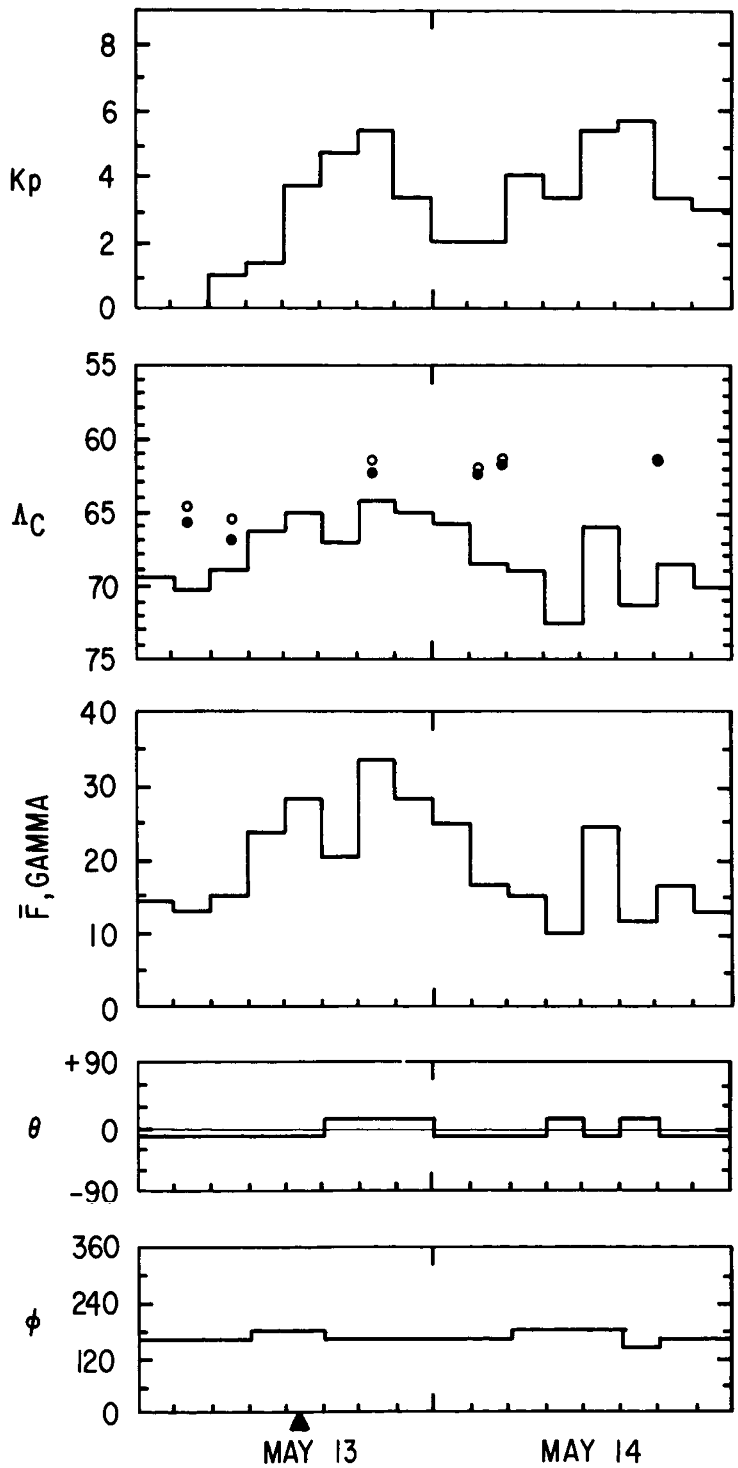

Figure 10—Correlation of K_p, Λ_c and $\bar{F}$ for the May 13, 1964 event. θ and ϕ also shown.

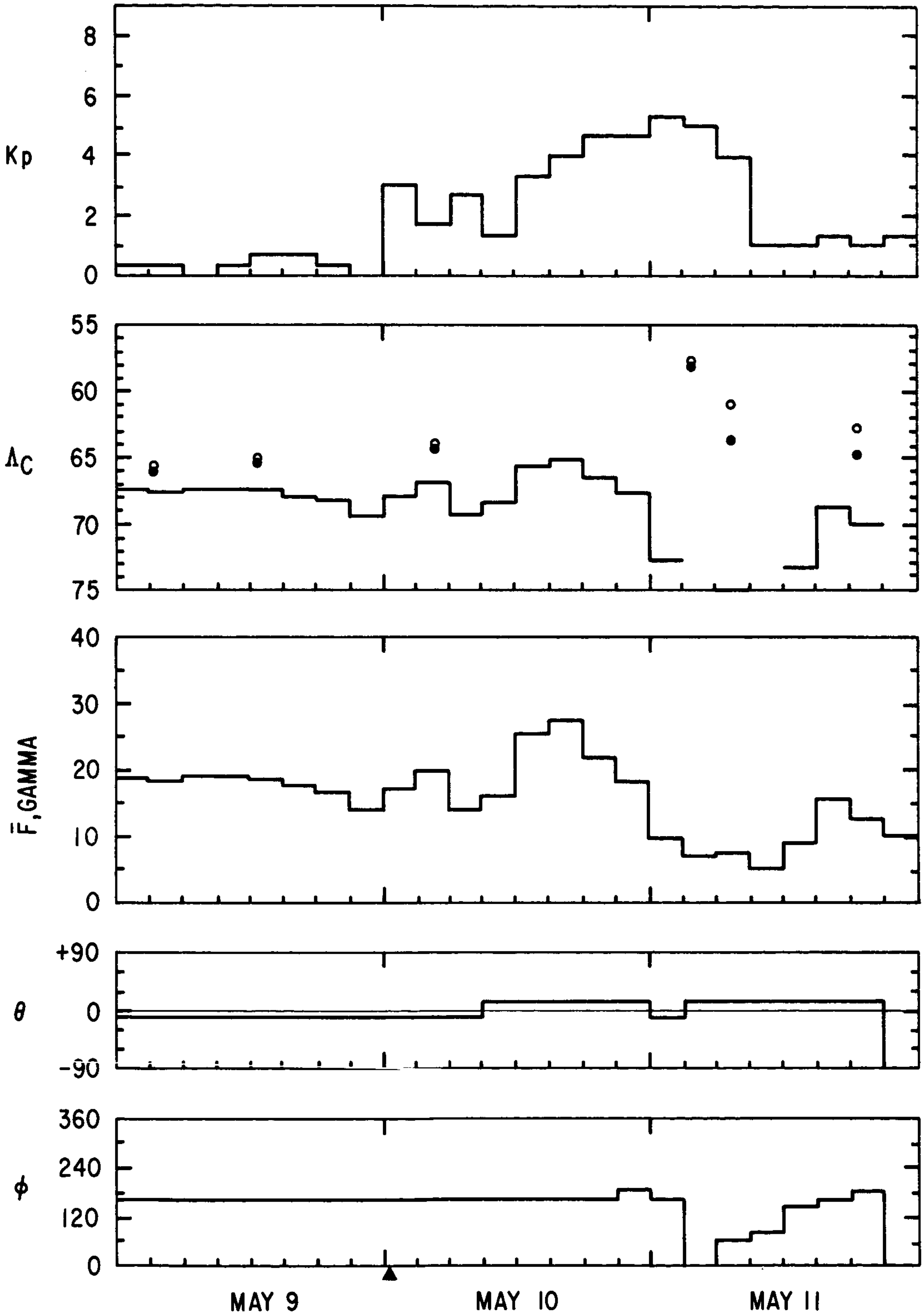

Figure 11—Correlation of K_p, Λ_c, and $\overline{F}$ for the May 10, 1964 event. θ and ϕ also shown.

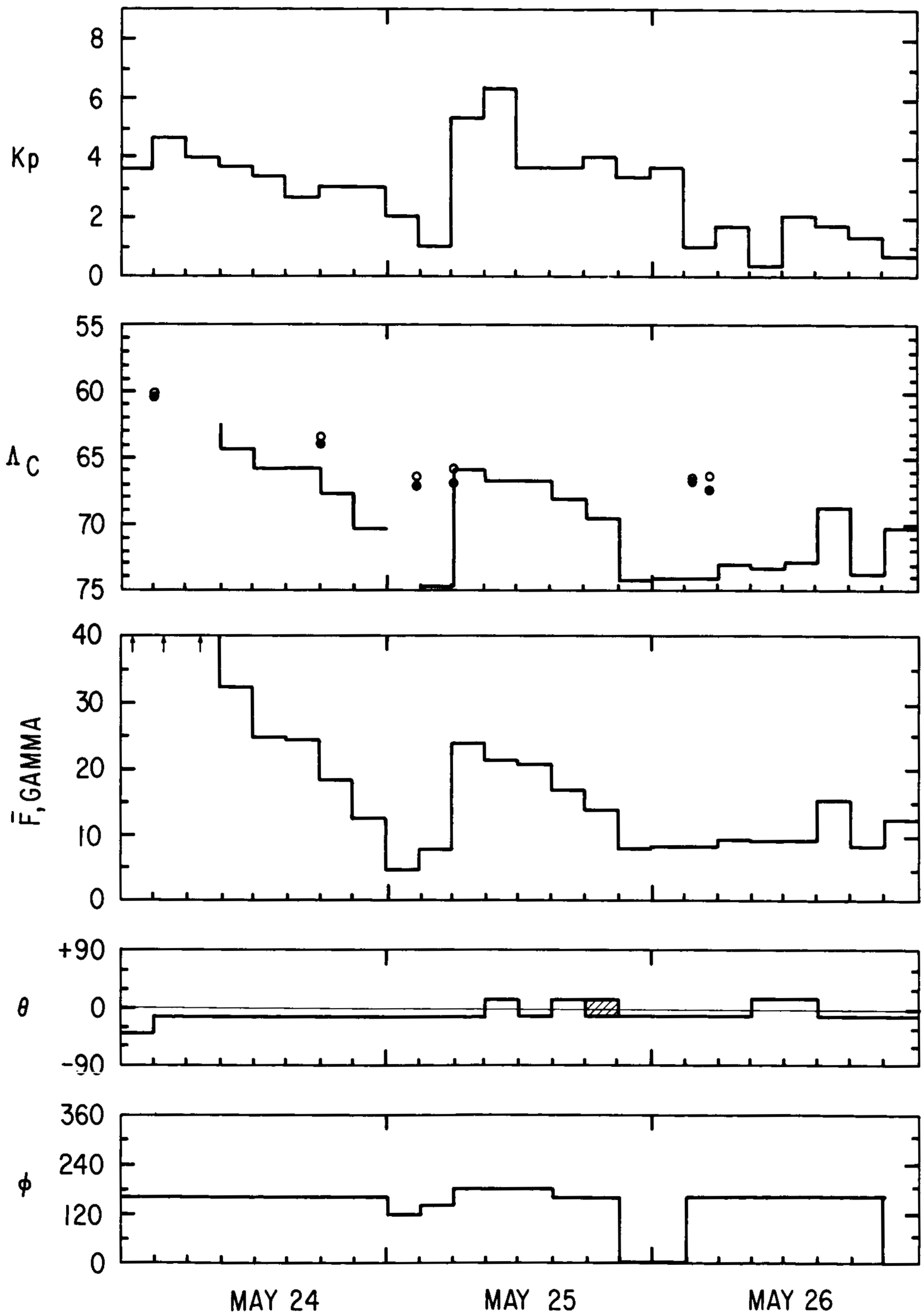

Figure 12–Correlation of K_p, Λ_c, and $\overline{F}$ during activity following the May 23, 1964 event. θ and ϕ also shown.