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MAGNETIC FIELD SIGNATURES OF SUBSTORMS ON HIGH LATITUDES FIELD LINES IN THE NIGHTTIME MAGNETOSPHERE

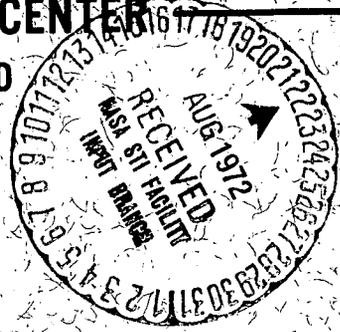
D. H. FAIRFIELD

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GODDARD SPACE FLIGHT CENTER
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MAGNETIC FIELD SIGNATURES OF SUBSTORMS ON
HIGH LATITUDES FIELD LINES IN THE
NIGHTTIME MAGNETOSPHERE

D. H. Fairfield
Laboratory for Extraterrestrial Physics
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

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ABSTRACT

Two types of magnetic field changes are repeatedly observed in the high latitude nightside magnetosphere in association with magnetic substorms. One type of field change is characterized by a sudden decrease in the field strength accompanied by an abrupt perturbation in the field declination angle. These changes are attributed to field aligned sheet currents flowing on the high latitude boundary of an expanding plasma sheet following substorms. Single sheets of field aligned currents on this boundary tend to flow toward the earth in the morning quadrant and away from the earth in the evening quadrant. Multiple sheets of current may also occur with the direction of the high latitude sheet generally being the same as a single sheet. A second type of field change is a decrease in field inclination during substorms. This type of change is regarded as a further manifestation of the changing field configuration during substorms and can be described in terms of azimuthal currents.

I. INTRODUCTION

Magnetic field changes associated with substorms may be considered as belonging to either of two categories (Fairfield 1971). One type of change affects the basic configuration of the entire magnetosphere and is due to currents which flow in an azimuthal or east-west direction. Prior to the sudden onset of a substorm, magnetic flux is transported from the dayside to the nightside magnetosphere. On the nightside the field strength in the geomagnetic tail increases and the tail field lines assume a more solar anti-solar orientation. Fewer lines of force cross the equatorial plane near the earth and the field strength decreases in the equatorial plane. During the substorm the field recovers to a more dipolar configuration as the field increases in equatorial regions and decreases in the lobes of the tail away from the neutral sheet. (Fairfield and Ness, 1970; Camidge and Rostoker, 1970, Russell et al. 1971; Aubry et al., 1970).

A second type of field perturbation is due to field aligned currents which produce a disturbance vector oriented perpendicular to field lines. At low altitudes this type of perturbation has been observed by satellites (Zmuda et al., 1966, 1967, 1970; Armstrong and Zmuda, 1970; Armstrong, 1972) and rockets (Cloutier et al, 1970; Park and Cloutier, 1971; Choy et al, 1971).

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At greater distances evidence for such currents has been reported for a limited number of events (Coleman and McPherron, 1970; Haerendel et al., 1971; Kaufman et al., 1971, Fairfield and Ness, 1972; Aubry et al., 1972) but no clear morphology has emerged.

This paper contributes to the knowledge of field aligned currents by extending the observations of Aubry et al. (1972) who found evidence for field aligned currents on the high latitude boundary of the plasma sheet. The present paper finds that such high latitude sheets of field aligned currents flow into the ionosphere in the dawn-midnight quadrant and out on the dusk-midnight quadrant, thereby lending some support to current systems proposed by various authors (Cummings, 1966; Atkinson, 1967; Akasofu and Meng, 1969; Meng and Akasofu 1969; Bonnevier et al., 1970). This paper also extends the observations of configuration changes produced by azimuthal currents by reporting a characteristic substorm associated decrease in the inclination of the field at high northern latitudes in the night hemisphere.

II. DATA COVERAGE AND ANALYSIS

Data analyzed in this study were taken by fluxgate magnetometers on-board the IMP 4 and IMP 5 satellites between December 1967 and April 1971. (See Fairfield, 1969 and Fairfield and Ness, 1972 for experiment descriptions). During this interval IMP 4 with an orbital period of 4.3 days

completed 57 orbits in the night hemisphere and IMP 5 with period 3.4 days completed 105 orbits in the night hemisphere.

The present analysis was carried out in solar magnetic coordinates and was restricted to data obtained within 17 earth radii of the earth's center since that is the outermost distance where it was judged this coordinate system had any validity. The inner limit to the data was dictated by the limited instrumental ranges which were $\pm 128 \text{ } \gamma$ and $\pm 200 \text{ } \gamma$ on each sensor for IMPS 4 and 5 respectively. All these data were plotted in a magnitude-inclination-declination coordinate system (Mead and Cahill, 1967) where inclination is defined as the angle the field makes with the horizontal to the earth's surface (positive downward) and declination is defined as the angle the horizontal component of the field makes with the geomagnetic north direction (positive east).

Since the phenomena observed by spacecraft are limited to those in regions traversed by the spacecraft, it is important to know the characteristics of the IMP trajectories. In figure 1 the solid lines indicate representative trajectories in the solar magnetic coordinate system (Z axis aligned with the dipole axis, X axis in the plane defined by the Z axis and the earth-sun line, and Y axis completing a right handed orthogonal system). Both spacecraft were in similar high inclination orbits with the space-

craft outbound in the southern hemisphere and inbound in the northern hemisphere. IMP 5 was nearer the geomagnetic equator than IMP 4 on the outbound passes and at higher latitudes than IMP 4 on inbound passes. It should be noted, however, that both spacecraft sampled only high latitude field lines (compare the trajectory to dashed dipole lines which are labeled with their earth intersections) and neither spacecraft sampled field lines below about 68° magnetic latitude. Since the IMP 5 nightside measurements were made during northern hemisphere winter when the solar wind was tending to raise the neutral sheet above the geomagnetic equator, very few traversals of the equatorial field reversal region were encountered within $17 R_E$.

While scanning orbits of nightside data, the characteristic changes reported in the next two sections were noted.

III. Field Aligned Currents

The primary characteristic of the lowest latitude IMP passes through the nightside magnetosphere is a sudden decrease in the field magnitude accompanied by a sudden perturbation of the declination. An example of such a pass is shown in Figure 2 where ΔB is the measured field magnitude minus an internal reference field derived from ground measurements, I is the inclination, D the declination

and δ the standard deviation associated with each of the 20.5 second 8 point averages that have been plotted. At the top of this figure is the H trace of a magnetogram from the Dixon Island observatory near the midnight meridian. At 20:25 during the recovery phase of a magnetic substorm ΔB suddenly decreases and the declination increases. Such magnitude decreases are known to be a common feature of the nightside magnetosphere (e.g. Heppner et.al., 1967; Fairfield and Ness, 1970) and they are generally thought to be due to the arrival at the spacecraft of an expanding plasma sheet within which the diamagnetic effect of the plasma reduces the field strength. Since the declination change is associated with the decrease in field strength, currents must be flowing on the boundary of the plasma sheet. Furthermore, the fact that the field is characterized by low magnitude and greater variability inside the current sheet and higher magnitude and lesser variability outside the current sheet means that it is quite easy to locate the spacecraft relative to the boundary and thereby infer the direction of the current.

Aubry et al. (1972) have recently identified 9 such events near the midnight meridian and given this same interpretation to their measurements. They find some examples which imply current sheets flowing either toward or away from the ionosphere and other examples which suggest that double

or even multiple sheet currents may be present with adjacent sheets flowing in opposite directions. The IMP measurements reveal similar perturbations and a collection of events from the 0-3 local time sector is shown in figure 3. Two hours of data are shown for each event with declination on the left and ΔB on the right. The $t=0$ time was chosen to correspond to the decrease in ΔB . The zero time for D is the same as that chosen for ΔB so the alignment of the D perturbations at $t = 0$ is an indication of the close time correspondence between ΔB and D changes.

The locations of the events in figure 3 are indicated by crosses in figure 1 (also one additional season of IMP 5 in the tail is included). Note that the southern hemisphere outbound orbits tend to approximately follow field lines with a slight tendency to move to higher latitude field lines with increasing time. On this basis one would expect traversals from the plasma sheet to higher latitude field lines to occur at least as often as traversals in the opposite direction. In fact, the sharp plasma sheet boundaries that accompany the field aligned currents are always traversals from higher latitude field lines to plasma sheet field lines. This is apparent in figure 3 where quiet fields always precede the ΔB decrease. Auroral zone magnetograms have been checked

at the times of all ΔB - ΔD events and in virtually all cases substorms or occasionally lesser types of activity precede the spacecraft event. This is consistent with the expanding plasma sheet interpretation since the plasma sheet is known to expand during magnetosphere substorms (e.g. Hones et al., 1971). The apparent conclusion is that the expanding plasma sheet boundary is very sharp and characterized by the presence of field aligned currents, whereas at other times the boundary is broader and more diffuse with no narrow region of currents.

A careful inspection of the events in figure 3 and other events suggests further conclusions on the nature of the currents. For most of the events in figure 3 it is apparent that the average declination preceding the zero time is less than that following zero time. This is what is expected if a net current is flowing into the ionosphere. The fact that the perturbation is consistently positive within a longitude range suggests that the current is flowing in a sheet rather than a line which could be on either side of the spacecraft. Often, however, the largest perturbation is restricted to a region near the boundary. This suggests the possible presence of a second parallel sheet of current in the opposite direction to the boundary sheet. Such parallel sheets would limit the perturbation to a thin region between the sheets. Although the possibility of additional sheets is difficult to distinguish from motion of a single sheet,

there appear to be rather few cases where the perturbation returns to its $t < 0$ state as it would if a single sheet were moving. As was pointed out by Aubry et al. (1972), there are other perturbations observed within the plasma sheet but since the spatial relation of the currents and the spacecraft is not clear once the spacecraft leaves the boundary and enters the plasma sheet, no conclusions can be drawn as to the directions of these currents.

The magnitudes of the D perturbations are of the order of 5 to 40γ and are therefore in agreement with the magnitudes reported by Aubry et al (1972). They are also consistent with the magnitudes observed at low altitudes when the effects of convergent field lines are included.

When the spacecraft moves from the post midnight quadrant to the premidnight quadrant the sign of the ΔD perturbation tends to be in the opposite direction. An example from the premidnight quadrant is shown in figure 4 which is in the same format as figure 2 except that Leirvogur is now the midnight observatory. ΔB decreases at 0015 and is again accompanied by a negative perturbation in D .

The locations of all events which indicate the presence of a single sheet of current are summarized in figure 5. This figure represents a view of the high latitude region on the earth's surface. Solid lines represent the IMP 4 and 5 spacecraft trajectories when projected to the

earth's surface along disturbed magnetic field lines using a preliminary version of a magnetic field model being developed by G. D. Mead and the author. Squares represent similar projections of the positions of positive ΔD events in the southern hemisphere (current flow into the ionosphere) and circles represent the projections of negative ΔD events (current flow out of the ionosphere). The dashed lines represent the auroral oval as determined by Feldstein and Starkov, (1967) for $Q = 3$ conditions. Clearly there is a preference for current flow toward the earth in the morning sector and current flow away from the earth in the evening sector. The concentration of these points near midnight is indicative of the fact that $\Delta B - \Delta D$ events are seen on the majority of orbits near midnight and with decreasing frequency at earlier and later local times. Although the great majority of $\Delta B - \Delta D$ events are observed in the southern hemisphere due to the nature of the IMP trajectories, a limited number of available events in the northern hemisphere support the idea that currents flow symmetrically in the two hemispheres (i.e. either toward or away from the earth in both hemisphere at a given longitude). Comparison of the location of the current observations (the outer boundary of the plasma sheet) with the auroral oval supports the suggestion (Vasyliunas, 1970a) that the high latitude

boundary of the plasma sheet corresponds to the high latitude boundary of the auroral oval. This argument is somewhat weakened by the fact that (1) a quiet time field model ($K_p < 2-$) has been used in projecting the data and (2) there were insufficient measurements at lower latitudes to eliminate the possibility that additional ΔB - ΔD events could have been observed at more equatorial locations.

IV. NIGHTSIDE CONFIGURATION CHANGES

In the course of examining IMP 4 and 5 plots in the night hemisphere a second type of perturbation was noticed on high latitude field lines. These events are characterized by a decrease in inclination in the northern hemisphere in association with magnetic substorms. An example of this second class of perturbation is illustrated in figure 6 which is in a format similar to figures 2 and 4 with Barrow as the midnight region magnetogram. The relevant decreases can be seen between approximately 10:35 and 11:30 and between 13:00 and 14:10 by comparing the I trace to the adjacent smooth trace which is the inclination predicted by the Mead Williams model (Williams and Mead, 1965). In figure 6 and essentially all other cases there appears to be a one to one correspondence between the I decrease and a magnetosphere substorm. The increases in ΔB preceding the substorms in figure 6 are often observed but not with the same regularity as is the I change. The magnitude of the perturbations in figure 6 are 8° and 7° which is somewhat larger than most of the observed events.

A representation of the locations of some of these events is shown in figure 7. The dots indicate the locations in a solar magnetic latitude radial distance coordinate system. The events are observed throughout the night hemisphere and

no dawn dusk asymmetries have been detected. A graphical representation of the I change has also been included in figure 7 by drawing two field vectors to represent the field direction before and after the substorm onset. The field is always fairly close to the dipole direction at these locations but the I perturbation is invariably negative irrespective of whether the initial I distortion from the dipole was positive or negative.

V. DISCUSSION

Field Aligned Currents. Since the field aligned current observations are limited to the study of currents near the high latitude boundary of the plasma sheet it is rather difficult to compare them with theories or other measurements which discuss complete current systems. Armstrong (1972), for example, has presented several examples of low altitude passes through the auroral zone where a region of transverse magnetic field perturbations of several degrees latitudinal width appears to be bounded by sheet currents which may well correspond to the boundaries of the plasma sheet. It appears that no net currents are present when the currents from all latitudes at a given longitude are summed. (This conclusion is dependent on baseline determinations which are somewhat uncertain.) Considering only the currents from the high latitude portion of these passes might, however, yield results corresponding to those of the present paper. Since Armstrong gives no directional information, no comparison can be made between the directions of his highest latitude currents and those of the present paper.

One rocket flight from Churchill, Canada (Cloutier et al., 1970; Park and Cloutier, 1971) detected a pair of sheet currents out of the ionosphere on the high latitude sheet and into the

ionosphere at a slightly lower latitude. Since the measurement was made near 20:00 LT it agrees with the pre-midnight results of the present paper. This agreement may be somewhat suspect because at the time of the rocket flight a small westward electrojet was observed in a region where an eastward current would normally be found. Also, the flight did not take place during a substorm and the arc was not moving northward as it would if the plasma sheet were expanding.

Another rocket flight from Churchill (Choy et al., 1971) at 21:45 LT detected field aligned currents flowing away from the earth just north of the northern boundary of auroral illuminosity. Although this is apparently consistent with the observations of the present paper the rocket detected soft plasma sheet-like particle fluxes north of the current region which suggests that the currents were not on the outer boundary of the plasma sheet. Again a westward electrojet and lack of northward motion of the aurora make any correspondence with the ΔB - ΔD events somewhat doubtful.

Many theoretical ideas on field aligned currents have been presented in the literature (e.g. references in Bostrom, 1968; Bostrom, 1972; Armstrong, 1972). One popular viewpoint (Vasyliunas, 1970b; Taylor and Perkins, 1971; Armstrong, 1972) suggests that pressure gradients in the outer magnetosphere that are not aligned with gradients in a quantity

$$\int \frac{dl}{B}$$

(dl is a length, B is the field strength and the integration is along a field line) are responsible for producing field aligned currents. This idea seems particularly attractive for explaining the present results since the sharp ΔB changes imply large pressure gradients.

Numerous papers (Cummings, 1966; Atkinson, 1967; Akasofu

and Meng, 1969; Meng and Akasofu, 1969; Bonnevier et al., 1970) have suggested that field aligned currents flow toward the earth in the postmidnight quadrant and away from the earth in the premidnight quadrant. These current systems are in apparent agreement with the results of the present paper but are limited by the reservation that the measured currents might not be true net currents. Atkinson (1967), in particular, has suggested that during the expansion phase of a substorm currents flow away from the earth on the westward edge of the auroral bulge (the westward traveling surge, Akasofu, 1964) and toward the earth on high latitude field lines further toward the east. As the substorm progresses, these two regions would diverge in longitude as the plasma sheet becomes thicker near the midnight meridian and the expansion region where magnetic field reconnection occurs moves toward earlier and later local times. The fact that the field aligned currents reported above are seen with decreasing frequency nearer the dawn and dusk meridians could then be due to the fact that the auroral bulge is less likely to propagate to the larger distances from midnight.

Other theories (Mozer, 1971; Coroniti and Kennel, 1972) predict field aligned sheet currents during the growth phase of substorms which subsequently are diminished during the recovery phase. Such currents have not been noted in the present study which implies that they do not flow on a thin boundary of a contracting plasma sheet. They might still be present if they are spread over a wider range of latitudes where their perturbations would be indistinguishable from other fluctuations. The Coroniti-Kennel theory requires a high current density (i.e., a narrow sheet) but this could be present on the lower latitude field lines not sampled

by the IMP spacecraft.

Configuration Changes. Since other characteristic changes in the magnetic field configuration have been observed at the time of magnetic substorms it is natural to try to incorporate this new observation of decreasing inclination during substorms into the existing pictures. An attempt at such a picture is shown in figure 8. The top view of the magnetosphere has been drawn to represent the magnetosphere configuration as it might appear just before the onset of a substorm. The magnetopause is unusually close to the earth; the polar cusp or clef is at an unusually low latitude; the plasma sheet is thin; a minimum of magnetic flux crosses the equatorial plane in the night hemisphere; and a maximum amount of flux goes into the magnetic tail. The bottom view of the magnetosphere in figure 8 represents the field configuration as it might appear during a substorm recovery. The magnetopause has moved away from the earth; the polar cusp has moved to a higher latitude; the plasma sheet has expanded; more flux crosses the equatorial plane; and less flux goes into the magnetic tail. The high latitude night side field lines are drawn slightly more horizontally to reflect the decreased inclination reported above. Note that these more horizontal field lines will not extend as far from the axis of the tail as would the more vertical fields (larger inclinations) in the top figure. A radial solar wind is incident on the high latitude magnetosphere at a greater angle in the top portion of the figure than in the bottom, thus transferring a larger fraction of its directed pressure to the magnetosphere and creating an increase in the field strength. The top portion of figure 8 with its large area of tail field lines exposed to the more directly incident solar wind seems to offer an

attractive explanation for the abnormally high field strengths observed by Sugiura et al. (1971; Sugiura, 1972) over the polar cap and in the high latitude tail.

It should be pointed out that the question of exactly when all these magnetosphere configuration changes take place with respect to one another and with respect to the substorm onset is still an unsolved problem. The substorm onset itself is often difficult to determine with an accuracy better than 10 or 15 minutes in time since ground observatories are often not in the proper location to see the onset. The problem is further complicated by the fact that changes in the tail may themselves be dependent on position as well as time relative to the substorm. Further measurements (particularly simultaneous spacecraft measurements) with emphasis on time relations should help resolve this problem and help determine whether the various changes are causes or effects of substorms.

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FIGURE CAPTIONS

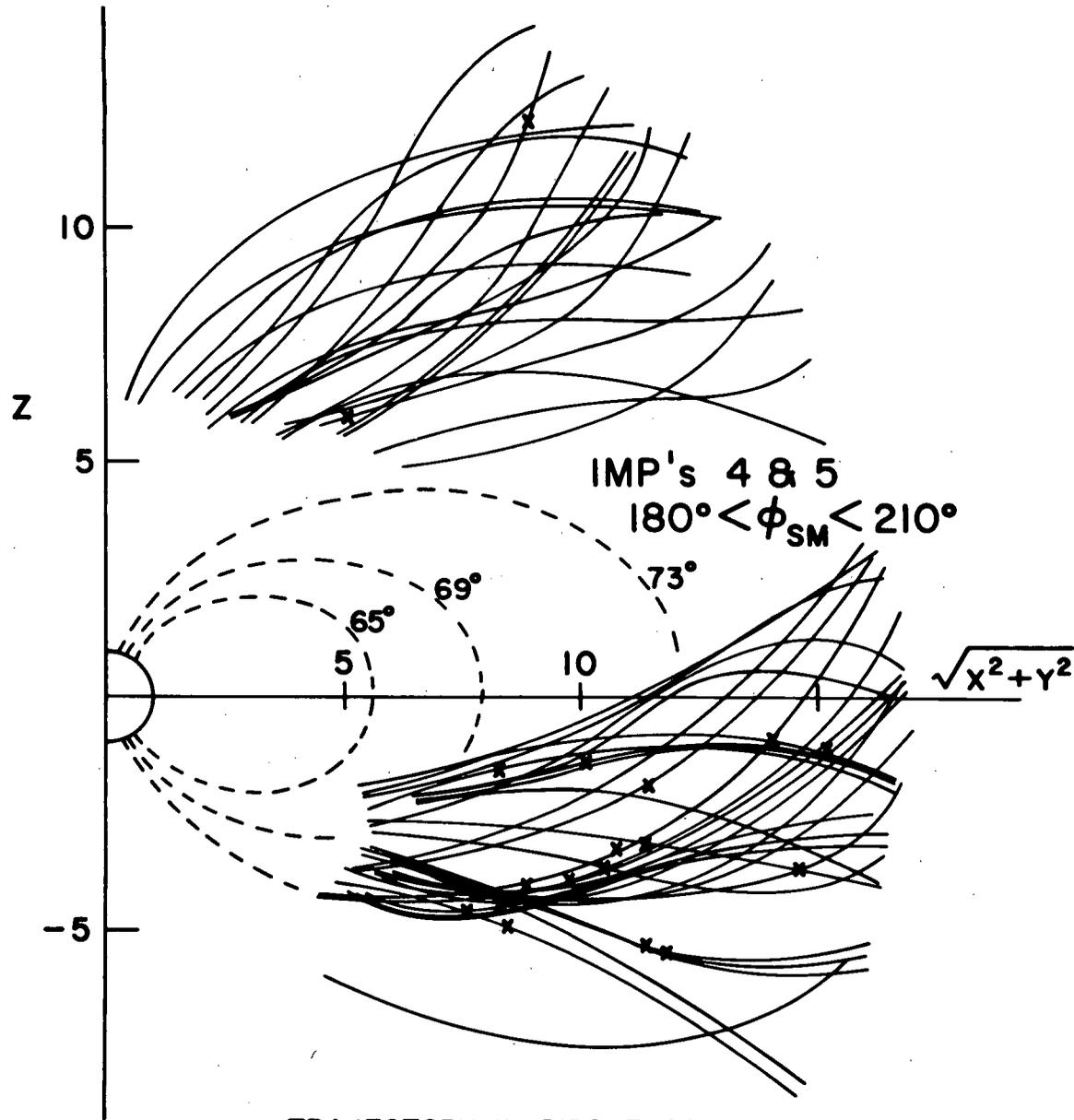
- Figure 1 - Trajectories of IMPS 4 and 5 spacecraft in a radial distance-geomagnetic latitude coordinate system. Crosses represent the locations of ΔB - ΔD perturbations which are thought to be located on the high latitude boundary of an expanding plasma sheet.
- Figure 2 - IMP 5 magnetic field data during an outboard pass of the spacecraft. The perturbation in D at 20:25 is interpreted as evidence for field aligned currents flowing on the outer boundary of the plasma sheet. Before 20:25 the spacecraft observes quiet high latitude fields which are characteristic of the southern lobe of the tail. After 20:25 the spacecraft observes a lower magnitude time varying field characteristic of the plasma sheet.
- Figure 3 - Summary of ΔB - ΔD events from the local time region of approximately 3 hours after midnight. $T = 0$ time for both ΔB and D has been chosen to correspond to the decrease in ΔB . The positive D perturbations are characteristic of this post midnight region and are indicative of sheet currents directed toward the earth.
- Figure 4 - IMP 5 data from the premidnight region of the night-side magnetosphere. The negative ΔD perturbation at 00:15 is the characteristic sign for this longitude region and it corresponds to currents flowing out of the ionosphere.

Figure 5 - View of the high latitude region of the earth's surface. Line segments represent IMP trajectories within $17 R_E$ projected to the earth's surface and squares and circles indicate the location of ΔB - ΔD events. Events are most frequently seen near midnight and near the northern boundary of the auroral oval (dashed lines).

Figure 6 - IMP 5 data taken on field lines well above the northern boundary of the plasma sheet in the northern hemisphere. The decreases in inclination I centered near 11:00 and 13:30 are characteristically seen at the times of magnetospheric substorms.

Figure 7 - Locations of I decreases seen in association with magnetospheric substorms. The low value of I seen during a substorm corresponds to a more horizontal field.

Figure 8 - Two schematic views of the magnetosphere drawn to illustrate possible magnetic field configuration changes associated with substorms.



TRAJECTORY IN DIPOLE COORDINATES

FIGURE 1

R = 6.5
GM LAT = -38°
GM LONG = 197°

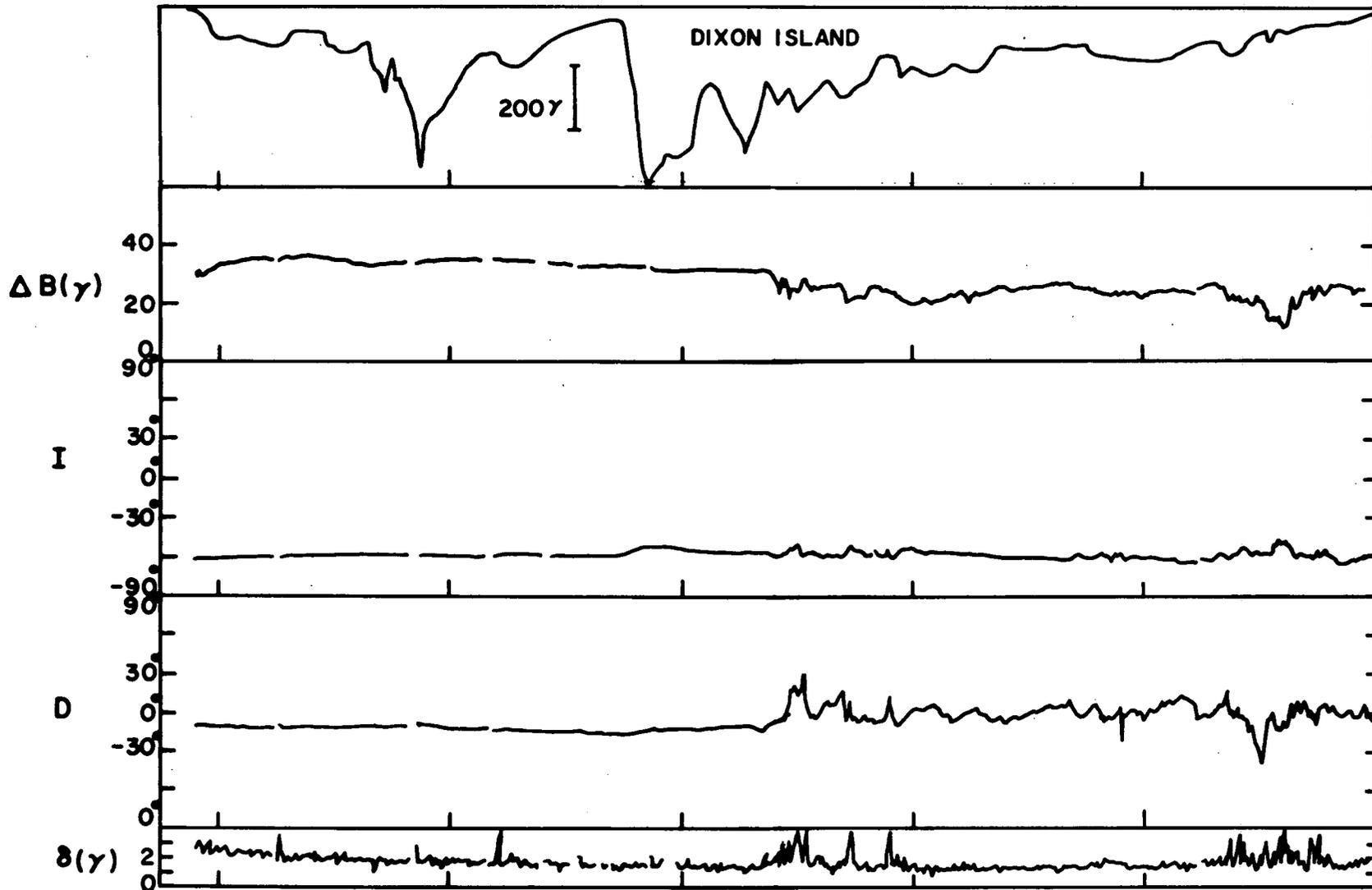
8.3
-30°
196°

9.9
-24°
195°

11.3
-17°
194°

12.6
-14°
194°

13.8
-8°
194°



DECEMBER 16, 1969

FIGURE 2

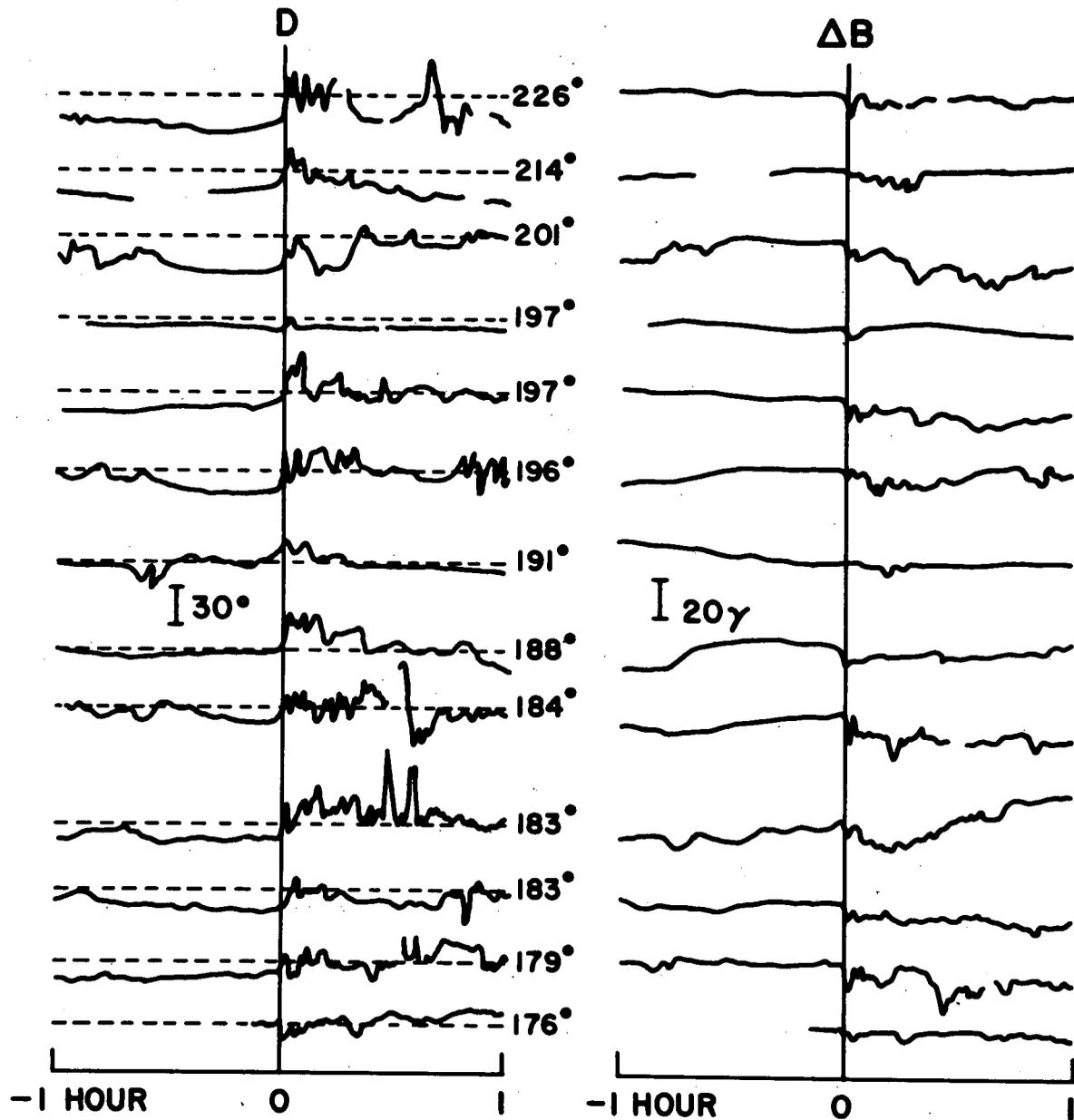


FIGURE 3

47

R = 13.7	14.8	15.8	16.7
GM LAT = -4°	1°	5°	10°
GM LONG = 160°	160°	161°	162°

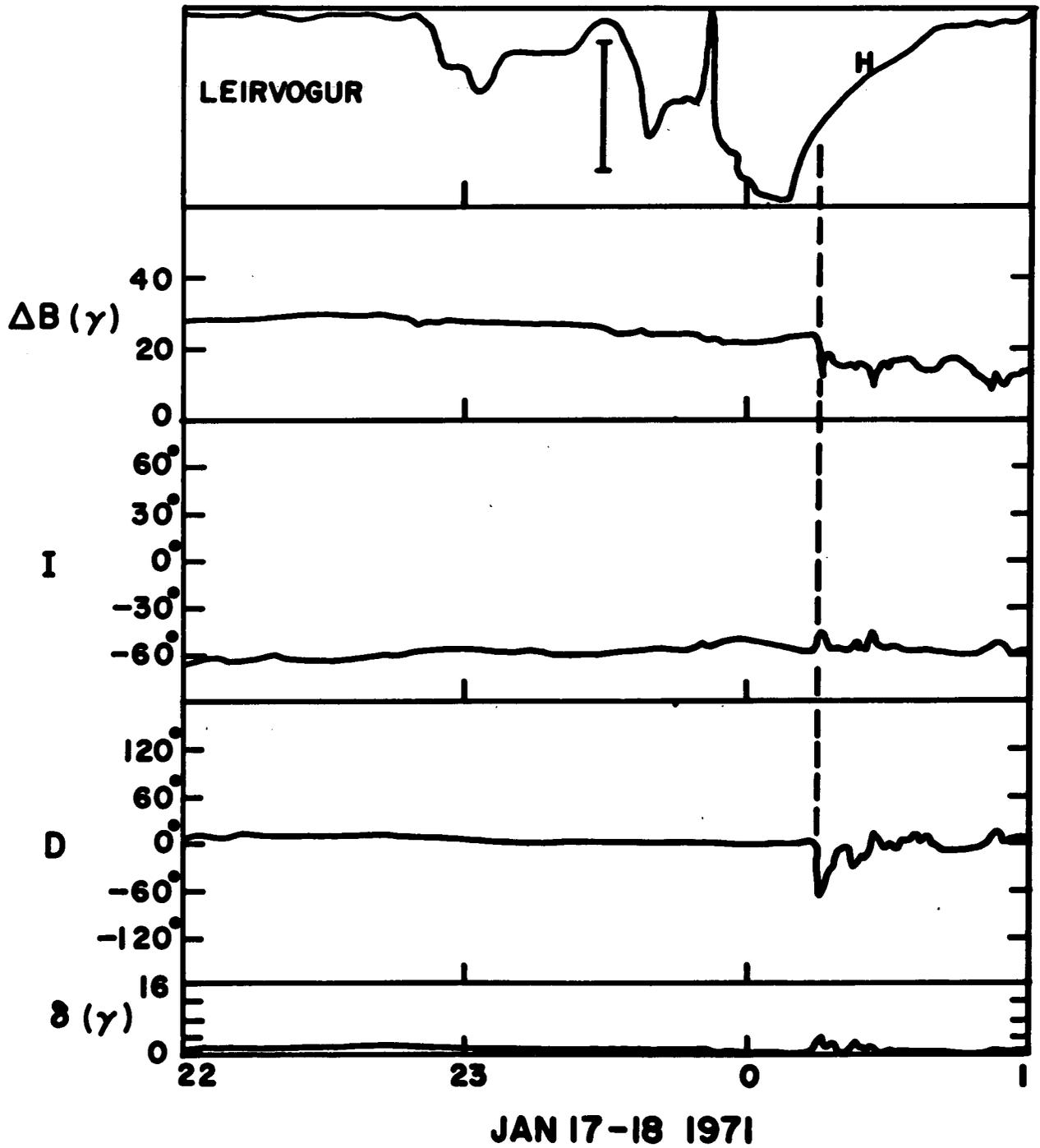


FIGURE 4

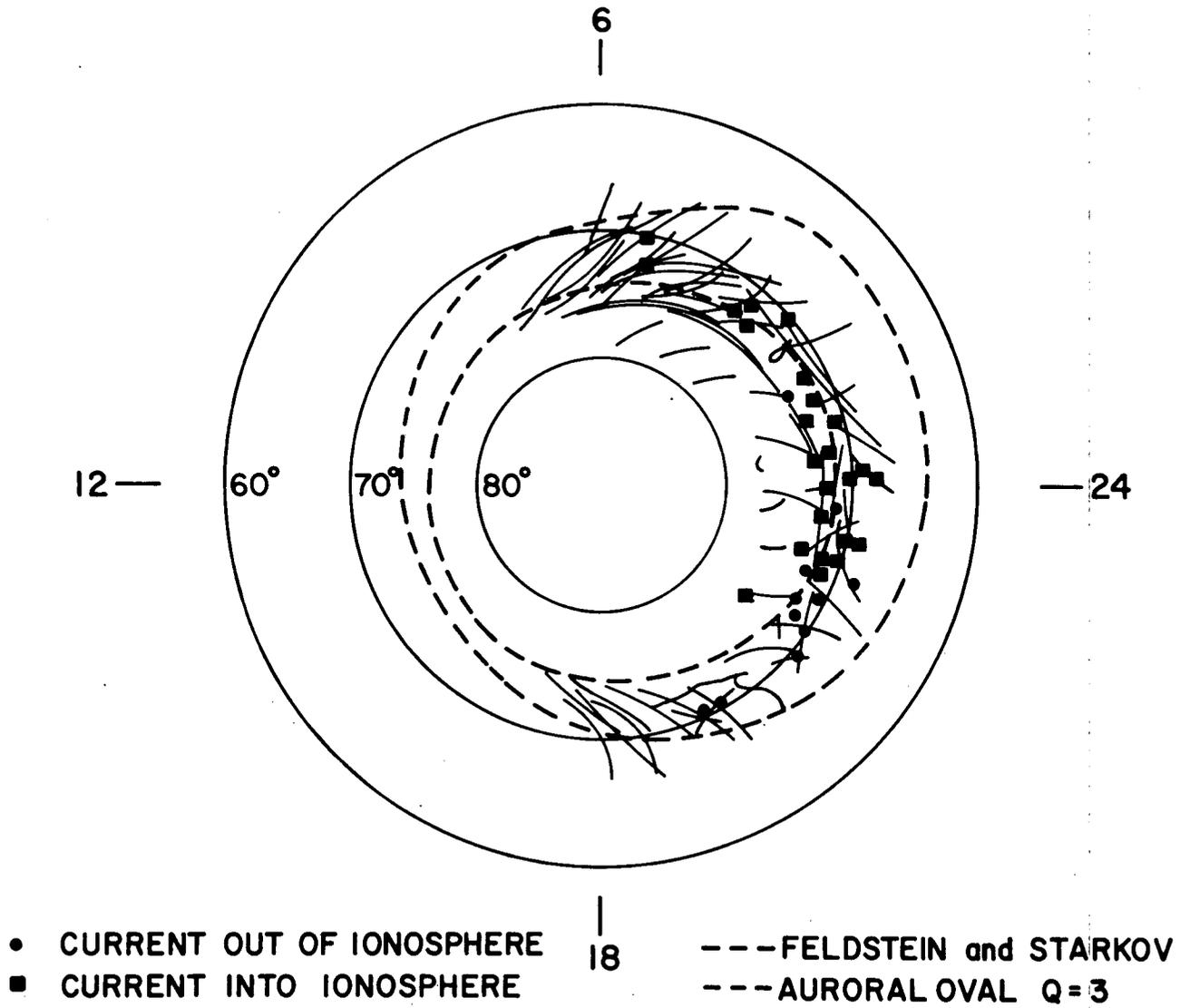


FIGURE 5

R = 16.4
GM LAT = 49°
GM LONG = 220°

15.4
48°
217°

14.3
47°
216°

13.2
46°
214°

11.7
46°
214°

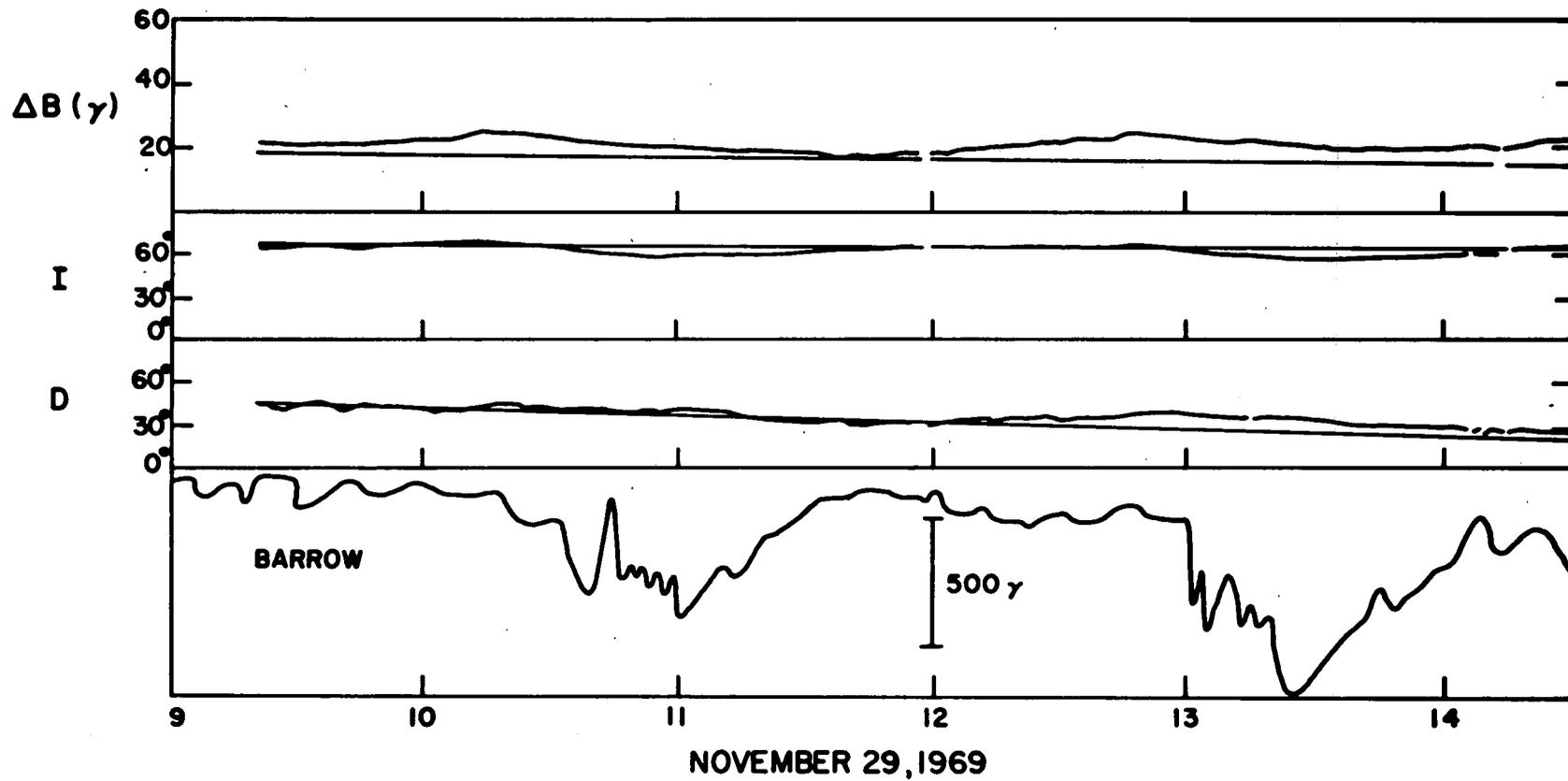


FIGURE 6

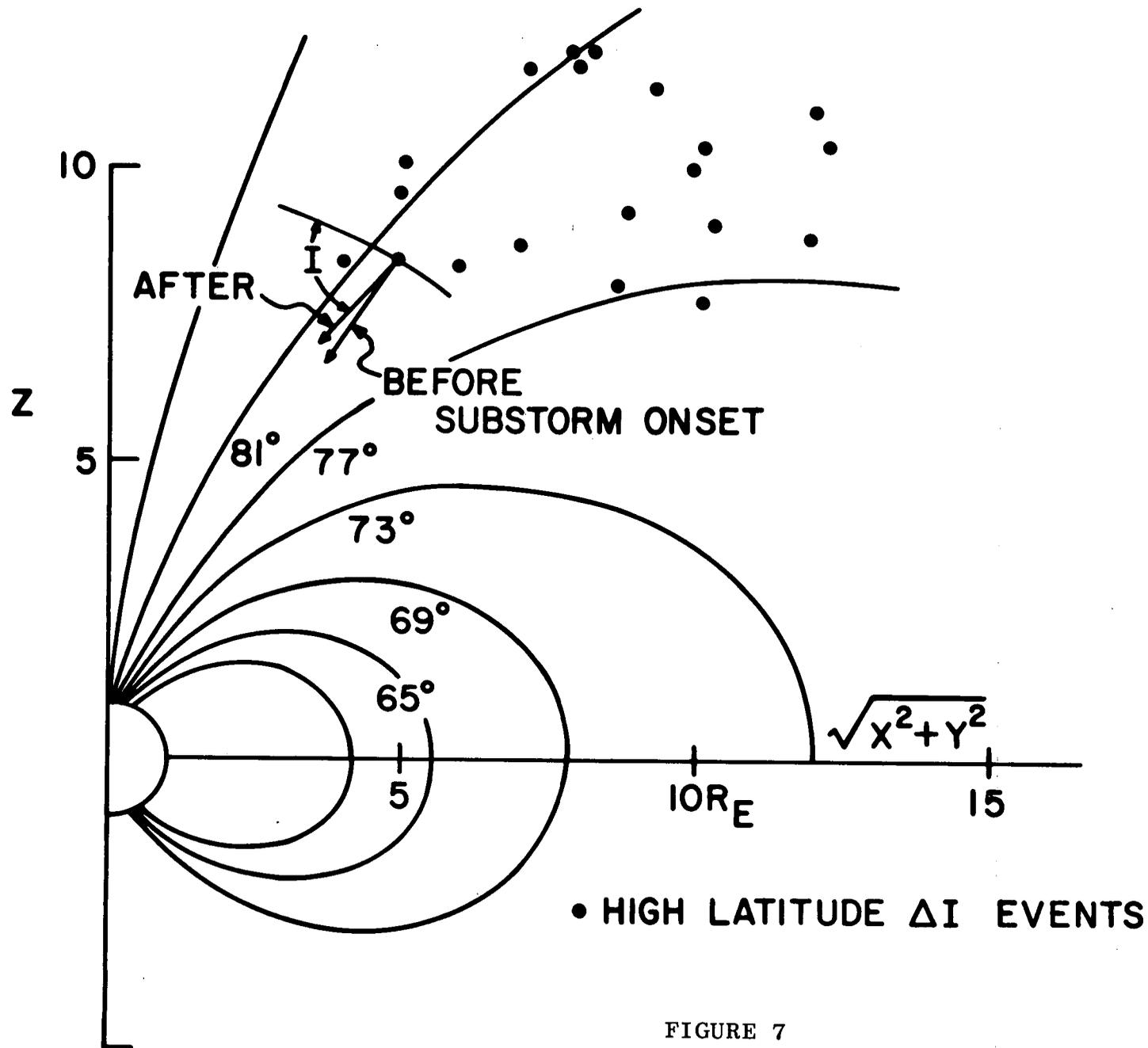


FIGURE 7

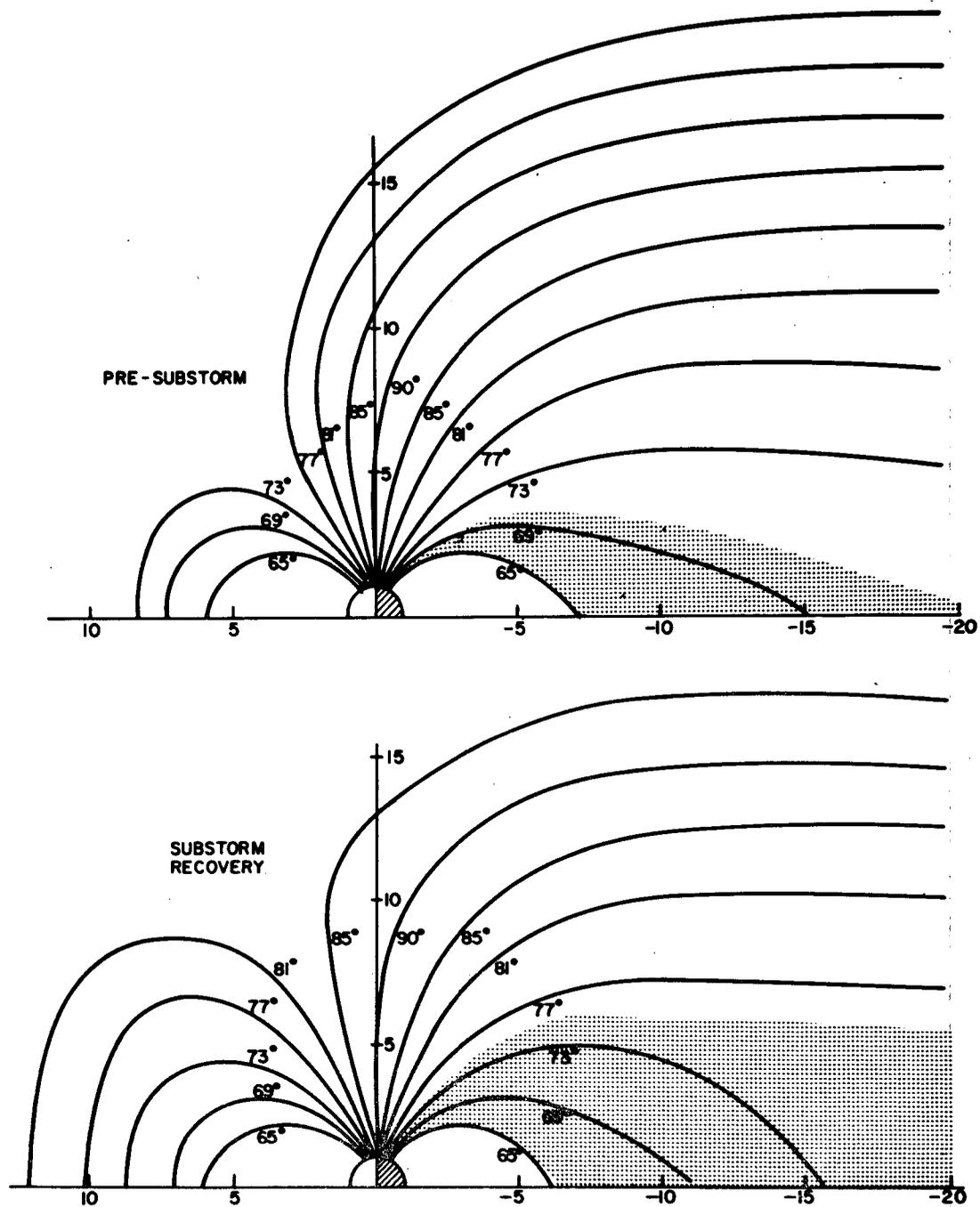


FIGURE 8