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Identifications of the Polar Cap Boundary and the Auroral Belt in the High-Altitude Magnetosphere: A Model for Field-Aligned Currents

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ABSTRACT

Using the OGO-5 GSFC-fluxgate magnetometer data, the polar cap boundary is identified in the high-altitude magnetosphere by a sudden transition from a dipolar field to a more tail-like configuration. It is inferred that there exists a field-aligned current layer at the polar cap boundary. In the nightside magnetosphere the polar cap boundary is identified as the high-latitude boundary of the plasma sheet. The field-aligned current flows downward to the ionosphere on the morning side of the magnetosphere and upward from the ionosphere on the afternoon side. Thus in the high-latitude boundary layer of the plasma sheet in the tail, the current is toward the earth in the post-midnight region and away from the earth before midnight. The basic pattern of the magnetic field variations observed during the satellite's traversal of the auroral belt is presented. This pattern shows the existence of a field-aligned current layer on the equator side of the polar cap boundary. Currents flow in the opposite directions in the two field-aligned current layers. The current directions in these layers as observed by OGO-5 in the high-altitude magnetosphere are the same as those observed at low altitudes by the polar orbiting TRIAD satellite (Armstrong and Zmuda, 1973). The magnetic field in the region where the lower-latitude field-aligned current layer is situated is essentially meridional. Thus the equatorial current closure of this current system must be via the equatorial current sheet. The two field-aligned current systems, one at the polar cap boundary and the other on the low-latitude side of the auroral belt, are coupled through the Pedersen current in the ionosphere. The coupling is weak during magnetically quiet periods and becomes strong at disturbed times.

Even during intense disturbances the basic pattern of the field variations in the critical regions of the auroral belt and the polar cap boundary is the same as at quiet times. Intensifications of the field-aligned currents and the appearances of multiple pairs of field-aligned current layers characterize the disturbed conditions of these regions.

INTRODUCTION

Observational evidence for the existence of two distinct magnetospheric convection regimes, i.e. the polar cap and the auroral belt, has recently been provided by electric field measurements from polar orbiting spacecraft OGO-6 (Heppner, 1972a, 1972b, 1973) and Injun-5 (Cauffman and Gurnett, 1972, Frank and Gurnett, 1971). The altitude ranges of these satellites are roughly 400 to 1100 km for OGO-6 and 700 to 2500 km for Injun-5. Detection of the boundaries of these convection regimes by electric field observations at much higher altitudes where plasma densities are lower is more difficult, and no report has so far been made of such a detection.

Gross features of the magnetospheric field have been described in recent reviews, for instance, by Russell (1972), Sugiura (1972a, 1973), Ness (1972). Several quantitative models of the magnetospheric field have been presented (Fairfield, 1968; Sugiura and Poros, 1973; Olson, 1973; Mead and Fairfield, 1973; Fairfield and Mead, 1973). In addition, a number of papers have been published discussing the magnetospheric field behavior relative to substorms (e.g. Heppner et al., 1967; Fairfield and Ness, 1970; Aubry et al., 1970, 1972; Fairfield, 1973; McPherron, 1973; McPherron et al., 1973). In spite of the extensive coverage in the literature, direct observational identifications of the boundary between the polar cap and the auroral belt and the low-latitude boundary of the auroral belt, as defined in terms of convective regimes, have not been made in the bulk of the magnetosphere. An exception to this is the region near noon where the polar cusp or the cleft divides the dayside magnetosphere into the region of closed field lines and that of the polar cap. Plasma and field observations in the cleft have been discussed, for instance, by Heikkila and Winningham (1971), Frank (1971a), Russell et al. (1971), Fairfield and Ness (1972); a summary of the discussions made at the Magnetospheric Cleft Symposium 1973 has been given by Vasyliunas (1974).

The present paper gives a preliminary report on our identifications of the polar cap boundary and the auroral belt in the distant magnetosphere using the OGO-5 GSFC-fluxgate magnetometer results. It is demonstrated that there exists a field-aligned current layer at the polar cap boundary and that another layer of field-aligned current is observed equatorward of the polar cap boundary layer. The region between these field-aligned current layers is identified as the auroral belt. It is shown that the field-aligned currents observed near 1000 km altitude by Armstrong and Zmuda (1970, 1973) and Zmuda and Armstrong (1974) are the low altitude continuations of the currents described in this paper. Further, arguments are presented below that the polar cap boundary layer identified here is the high-latitude boundary of the plasma sheet in the nightside magnetosphere and that the polar cusps on the day side must topologically continue to the plasma sheet as in the model presented by Frank (1971b).

THE POLAR CAP BOUNDARY

If there is a distinct polar cap boundary in the distant magnetosphere it is expected that there should be a shear in the magnetic field across the boundary and that this signature should be most evident in the east-west component of the field because the field on the low-latitude side of the polar cap boundary is nearly in the meridional plane and the field in the polar cap is pulled back in the antisolar direction. However, there is no a priori reason to expect to have a discontinuity at the boundary so far as the magnetic field configuration is concerned. For instance, on the basis of the theoretical magnetosphere models in which the solar wind particles are specularly reflected at the magnetopause (Mead, 1964; Choe and Beard, 1974; references in these papers) there is no singular surface separating a polar cap from the lower latitude region except that in the noon meridian plane the field lines connecting the earth to the neutral points accomplish this division. Thus the presence of a distinct signature in the magnetic field at the polar cap boundary means that there is a plasma discontinuity at this boundary.

Figure 1 shows an example of a sudden change in the field direction at the polar cap boundary. In the figure, inclination, I, of the field vector to the horizontal plane, declination, D, which is the deviation from the north of the projection of the field vector onto the horizontal plane, and the field magnitude, B, are plotted along the outbound orbit on August 25, 1969. The data points represent 37 second averages. For a convenience of plotting B, values below 500γ ($1\gamma = 1$ nT) are shown; the flat portion in the B plot near the top does not represent the instrumental saturation. This remark applies to other similar figures in this paper. The geocentric radial distance, geomagnetic dipole latitude, invariant latitude, and magnetic (dipole) local time are indicated at the bottom of the figure. The smooth solid lines are the respective quantities of the reference field of Cain et al., (1967) representing the earth's internal field. The observed D plot shows that the field is nearly in the magnetic meridian plane till about 0340 UT (marked <u>b</u>) when it rather suddenly begins to deviate westward from the reference field direction. At 0340 UT the satellite was at a geocentric distance of 7.1 R_E and at geomagnetic latitude 46.9°; the local time was 17.2 hours. This sudden deflection of the field is interpreted as the signature of the entrance of the satellite into the polar cap (abbreviated below as PC). For the afternoon in the northern hemisphere a westward change in D corresponds to a transition to a more tail-like field direction. On the morning side the field change for such a transition would be toward the east for the northern hemisphere. In the southern hemisphere the corresponding signatures should be opposite to those for the northern hemisphere, namely westward in the morning and eastward in the afternoon. The identification of the signature such as shown in Figure 1 as the PC boundary is based on the repeated observations of the above basic pattern throughout a period of more than three years from March 1968 to July 1971 during which the GSFC-fluxgate magnetometer was operative.

In Figure 1 the region on the earthward side of the PC boundary is the auroral belt (marked Au in the figure). The irregularities seen there are indicative of this region. The low-latitude boundary of the auroral belt is not well definable. More detailed discussions of the auroral belt are given in a later section.

It is important to remark that the signature for the PC boundary crossing is not a temporal change associated with a substorm. In the case of August 25, 1969 shown in Figure 1, Kp was 3- for 0000 to 0300 UT and 1+ for 0300 to 0600. This was followed by four 3-hour intervals of Kp = 0+ and then by intervals with Kp = 0o and 1-. With the available ground data there was no disturbance beginning near the time of the observation of the PC boundary crossing.

The relatively sudden change in the field direction at the polar cap boundary implies the presence of current in this region. From the field behavior seen in Figure 1 it is inferred that the current is field-aligned and is distributed over a finite thickness. The hatched band drawn in the figure very approximately represents the field-aligned current layer. The thickness of the current layer, measured transverse to the magnetic field, is estimated to be approximately 1300 km. The east-west component, Y, of the difference field, i.e. the observed minus the reference field, changed by 30γ over the period of the traversal of the current layer. Since the traversal was not normal to the magnetic shells, this value of ΔY is not exactly ΔY across the thickness of the current layer normal to the field, but the true value of ΔY across the layer is probably not much different from this value. The current integrated over the thickness is estimated to be roughly 2.4×10^{-2} amp/m. The average current density is about 1.8×10^{-8} amp/m^2.

During the early life of OGO-5 its inbound orbit was at low latitudes and its outbound orbit at higher latitudes. Therefore during this period, clear identifications of the PC boundary were limited to the observations on the outbound orbits. However, in the later phase of operation the orbit of OGO-5 became more polar. This change of the orbit characteristic provided opportunities to observe clear PC boundary crossings on inbound as well as outbound orbits. Figure 2, for March 26, 1970, gives an example of polar cap boundary crossing observed on an inbound orbit. This figure presents several significant features. First, the observation of a rather abrupt change to a meridional field (at 0610, marked b for the PC boundary) provides strong evidence that the observed signature represents a spatial structure and not a temporal variation. Secondly, the observation was made in the southern hemisphere, and hence the sign of declination in the PC region is opposite to that in the northern hemisphere. Thirdly, as the satellite crossed magnetic noon the sign of declination changed. All these features are consistent with the identification of the PC boundary as indicated in the figure. The region earthward of the PC boundary, where irregularities are seen, is identified as the auroral belt (Au). As in Figure 1, the field-aligned current layer at the boundary is indicated by a hatched band in Figure 2. The current density appears to decrease gradually with increasing distance from the low-latitude boundary of the layer, and the high-latitude boundary is not clearly definable. The thickness of the current layer, as indicated in Figure 2, is found to be roughly 1700 km. The change in ΔY over the period of the current layer crossing was nearly 50γ in this case. The integrated current density is about 4.0×10^{-2} amp/m, and the average current density is approximately 2.3×10^{-8} amp/m^2.

THE AURORAL BELT

In the examples shown in Figures 1 and 2 the region designated as the auroral belt had no marked characteristics other than having small irregular changes. However, after an extensive inspection of PC boundary crossings the following feature has emerged as being a basic pattern of the field behavior in the auroral belt in the distant magnetosphere. Figure 3 illustrates this pattern. The PC boundary crossing, marked <u>b</u> in the panel for declination took place in the northern hemisphere and in the afternoon in magnetic local time. There was a small excursion to the east immediately before the PC boundary, i.e. between the times marked <u>a</u> and <u>b</u> in Figure 3. The maximum ΔD (deviation of observed declination from that of the reference field) during this period was about 11° or 8γ in the difference field component in the eastward direction.

The field-aligned current layer at the polar cap boundary is indicated, as in the previous figures, by a hatched band in Figure 3. But the variation in D between a and b suggests the presence of another field-aligned current sheet of finite thickness at this location. The current flows downward into the ionosphere in the high-latitude current layer and flows outward from the ionosphere in the low-latitude current layer.

There are several reasons to believe that the region between a and b lies in the auroral belt, besides the obvious reason that the region is on the low-latitude side of the PC boundary. First, during intense magnetic disturbances the invariant latitudes of this region decrease, that is, the base in the ionosphere of the magnetic flux occupying this region moves equatorward. The invariant latitude is not a useful parameter in the high-latitude outer magnetosphere, but it provides a convenient measure to study relative positions. Secondly, the width of the region expands under disturbed conditions. At the same time the amplitudes of the variations in D become large and internal structures are often observed within the region. Thirdly, in the northern hemisphere the variation in D, eastward between a and b in the case of Figure 3, is westward during the morning hours. These variations are essentially similar in the direction and type to those observed at low altitudes by Armstrong and Zmuda (1970, 1973) and interpreted by them as being due to field-aligned currents. These factors give support to the interpretation that the field behavior typified by the change in D between a and b in Figure 3 represents the auroral belt field variation.

Figure 4 for September 13, 1968, shows an observation during a disturbed period. Magnetic activity was high on the preceding day, and a new substorm began near 0030 UT on September 13 superimposed on an already existing disturbed condition. The auroral belt identified in Figure 4 as the region between *a* ($\sim$ 0300) and *b* ($\sim$ 0426) was traversed by the satellite during the recovery phase of the substorm. High magnetic activity continued till the early part of September 16 with several intense substorms occurring in this period of continued activity. The Kp indices for the first two 3-hour intervals of September 13 were 5+ and 6-. Referring to the D plots in Figure 4, five distinct eastward excursions, each resembling the basic pattern shown in Figure 3, can be recognized. This suggests a presence of multiple pairs of field-aligned current sheets. Such a structure may well be directly related to multiple forms of the aurora. It is noted that the largest peak-to-peak amplitude in the east-west component in this case was in excess of 60γ. This corresponds to an integrated current density of about 5 x 10^{-2} amp/m.

The data presented so far are averages over intervals of approximately 37 seconds. When data taken at a high sampling rate (1.7, 6.9, or 56 samples per sec) are examined, it is found that rapid variations of time scales of seconds occur in the auroral belt and in the polar cap boundary current layer, indicating the presence of either temporally changing or spatially structured currents. Figure 5 shows an example of such variations taken from the pass presented in Figure 4. In Figure 5, three components, X, Y, and Z, in the spacecraft coordinate system are plotted at the rate of 0.284 sec per sample for two 6-minute intervals sampled from the data taken in the 8 kilobit mode, one on the left (A) taken from the auroral belt and the other on the right (B) from the polar cap. These two short time intervals are indicated in Figure 4 by A and B, respectively. The rapid fluctuations began rather abruptly at about 0236 UT. But at first the fluctuations occurred on and off and were of relatively small amplitude. Large amplitude, rapid changes of the nature seen in A in Figure 5 began near 0306 and continued till about 0430. This latter period of intense activity is indicated in Figure 4 by a solid horizontal bar, marked *c*. The beginning of the less intense rapid fluctuation at about 0236 is shown by *a'*. The problem of which of the two times *a'* or *a* is the low latitude boundary of the auroral belt does not seem to be a meaningful question at this stage of the study. It is pointed out in this connection that in the electric field variations representing the auroral belt its low-latitude boundary is not always well defined (e.g. Heppner, 1972a).

Rapid fluctuations similar to those described above were seen during the auroral belt traversal on August 13, 1970, shown in Figure 3. The solid horizontal bar, marked *c*, in Figure 3 indicates the period during which such rapid variations were observed. In this case the region of rapid fluctuations extends into the current layer at the PC boundary, more specifically the region where the declination change is very steep, or the current density is changing very rapidly. Figure 6 shows examples of rapid fluctuations observed in the field-aligned current layer at the PC boundary traversed on August 13, 1970 (Figure 3). For the cases shown in Figures 1 and 2, only 1 kilobit data (1.7 samples per sec) were available, as against 8 kilobit data for Figures 5 and 6. Though the presence of rapid fluctuations, probably not so intense as in the other two cases, is discernible in the vicinity of the PC boundary, the lower sampling rate makes a direct comparison difficult.

The vector magnetic field measurements made by Ledley and Farthing (1974) during a rocket flight in the polar cusp ionosphere showed rapid field fluctuations in the lower F-region, which they interpreted as being caused by structured field-aligned currents. The fluctuations they observed may well be closely related to the rapid field fluctuations observed in the field-aligned current regions in the high-altitude magnetosphere.

In order to introduce step by step the basic patterns of magnetic field variation at the PC boundary and in the auroral belt, cases showing the typical variation associated with the PC boundary current layer alone were presented in Figures 1 and 2. Once the variation pattern for the auroral belt is understood it becomes possible to recognize a weak indication of the presence of the basic pattern in many cases. In Figure 2, there is a trace of a westward declination change after the PC boundary is crossed.

DISCUSSIONS

1. Where does the field-aligned current in the polar cap boundary layer come from?

It has been shown in the preceding sections that the current-flow in the field-aligned current layer at the PC boundary is downward into the ionosphere and is upward from the ionosphere in the afternoon. This field-aligned current system is denoted below by C_{fa}-1. A question that immediately arises is: where in the tail does the current come from and where does it return? This question is essentially equivalent to that of where the PC boundary surface goes in the anti-solar direction. To study this problem the OGO-5 fluxgate data obtained during the summers of 1969 and 1970 when the spacecraft was in the tail throughout its outer orbit were examined. Along an outbound orbit, once the spacecraft enters the PC magnetic flux the field becomes very steady with little variations. This is the well-known characteristic of the field in the tail lobe. The first major change that takes place after several hours of the quiescent field is an abrupt encounter with a diamagnetic region near the equator. This diamagnetic region is obviously the plasma sheet. From the absence of any outstanding magnetic signature between the entrance into the PC flux at a geocentric distance of several earth radii and the first encounter with the plasma sheet very roughly at 20 R_E, it appears reasonable to deduce that the PC boundary continues on to the high-latitude boundary of the plasma sheet in the tail.

Figure 7 shows an example of the first encounter with the diamagnetic region, i.e. the plasma sheet, on a very quiet day of June 22, 1969. This day is judged to be magnetically quiet on the basis of the AE (11) index (Allen et al., 1974) and from the fact that Kp was between 0o and 1- throughout the day with the Kp sum of 4-. The spacecraft passed apogee near 0635 on June 22 at 22.6 R_E, and on its inbound orbit, entered the plasma sheet at about 1742 near 20.6 R_E and -4.8° dipole latitude. The magnetic local time of this position was 2.7 hours. The plasma sheet is tipped downward (southward) during summer. One of the first signals of the encounter is the westward declination change, which corresponds to an earthward current in the surface layer of the plasma sheet. The westward change in D at 1742 on June 22 does not have a very abrupt beginning, but on many passes the corresponding variation begins very abruptly. The lack of such an abruptness may well imply a less sharp plasma sheet boundary owing to the quiet condition.

The direction of the current in the plasma sheet surface layer as deduced in this way is earthward in the post-midnight region. The current direction in the pre-midnight region appears to be less clearly defined than in the post-midnight hours with the data so far examined. However, the trend that the declination change is eastward at the first encounter with the plasma sheet does exist, and several clear-cut cases indicating an abrupt eastward declination change at the plasma sheet boundary have been found in the pre-midnight sector. Thus in the pre-midnight region the PC boundary current appears to flow out of the ionosphere and away from the earth on the high-latitude plasma sheet boundary.

The directions of the field-aligned currents described above are in agreement with those of the field-aligned currents that Fairfield (1973) associated with an expanding plasma sheet following substorms. The presence of the field-aligned currents on the plasma sheet boundary is a permanent feature and not limited to the times of substorms. However, observational evidence indicates that these currents are intensified during substorms. The question of how this intensification of the currents is related to the development of a substorm still remains to be investigated in the future. The observational results from the IMP 4 and 5 satellites that Fairfield used are in themselves consistent with the present OGO observations, since the encounter of a satellite with the plasma sheet occurs regardless of whether or not the plasma sheet expands.

Interpreting Behannon's (1970) analysis of the Explorer 33 and 55 results, Vasyliunas (1970) deduced the same field-aligned current system as the present C_{fa}-1 system.

2. Where are the field-aligned currents on the low-latitude side of the auroral belt connected to?

Overwhelming observational evidence exists indicating that the magnetic field at the location of the lower-latitude current layer is approximately in the magnetic meridian independent of local time. This implies that the current in this layer flows into the equatorial magnetosphere from the ionosphere on the morning side and that the current flows into the ionosphere from the equatorial region in the afternoon. Thus this current system can be closed via the (westward) magnetospheric equatorial current, the existence of which Sugiura (1972a, 1972b) deduced earlier from the OGO-3 and 5 Rb magnetometer results. It has been shown that there is no distinct earthward boundary in the cross-tail current, as has usually been envisioned, and that the current is continuous well into the inner magnetosphere, probably to near 3 R_E (Sugiura, 1973). Models having an equatorial current sheet of this type does indeed give a ΔB distribution similar, in essential features, to that deduced from the OGO observations (Sugiura et al., 1971; Sugiura and Poros, 1973; Olson, 1973). The current system described above, namely, the field-aligned current on the low-latitude side of the auroral belt and the closure via the equatorial current, is denoted by C_{fa}-2.

3. Two circuits of field-aligned current

The two circuits C_{fa}-1 and C_{fa}-2 involving field-aligned currents originate in different source regions, C_{fa}-1 being, in a broad sense, a part of the distant tail current and C_{fa}-2 belonging to the equatorial current in the near tail region of the magnetosphere proper, as schematically shown in Figure 8. The two circuits C_{fa}-1 and C_{fa}-2 are directly coupled by the Pedersen current in the ionosphere between the two current layers. The coupling may be considered to be weak under quiet conditions, but when precipitation of particles increases the conductivity, the coupling becomes strong. It is noted here that because of the finite conductivity in the ionosphere even at quiet times there will be circuit closures within each of the two systems and also between them along the auroral belt ionosphere as well as over the polar cap. The idea of having two field-aligned current circuits that are shorted during a substorm presents interesting possibilities. For instance, since the electric potential between the two circuits can be quite large because of the large spatial separation between them at their feet near the equator, large electric fields parallel to the magnetic field can be created as a result of anomalous resistivity when the shorting in the auroral ionosphere becomes efficient.

4. Comparison with other models

Several model current systems for a substorm have been proposed in recent years that contain a shorting of a magnetospheric or tail current system by field-aligned currents. We now compare the present current systems, C_{fa}-1 and C_{fa}-2, with other relevant models. Roughly speaking, these models, or their constituent parts, can be divided into two categories: (i) a shorting of the cross-tail current and (ii) a closure of a partial ring current. For instance, models proposed by Atkinson (1967), McPherron et al. (1973), and Rostoker (1974) belong to the first category, and those by Akasofu and Meng (1969) and Bonnevier et al. (1970) belong to the second category. The model proposed by Kamide and Fukushima (1972) contains both types of current system. For earlier papers that discussed current systems having field-aligned parts and more recent models that are similar to those referred to above, see the review paper by Fukushima and Kamide (1973).

The substorm models involving a shorting of the cross-tail current by field-aligned and ionospheric currents may be considered as a localized (and intensified) version of C_{fa}-1. Those models having a partial equatorial ring current with a closure via field-aligned currents may be regarded as being variations of C_{fa}-2. One of the significant differences between the present model and other models lies in that the present model has two circuits that have their bases in the ionosphere at different latitudes while in other models a single belt, i.e. the auroral belt, is taken as the ionospheric base.

Observations of field variations at low altitudes indicating the presence of field-aligned currents along the auroral oval as a permanent feature have been presented by Armstrong and Zmuda (1973), Armstrong (1973), and Zmuda and Armstrong (1974). The earlier papers by Zmuda and his colleagues reporting field variations that are interpreted as being due to field-aligned currents are referenced in their recent papers quoted above. There appears to be little doubt that the field-aligned currents deduced by them are the low-altitude portion of the current systems presented in this paper. The model consisting of a pair of field-aligned current sheets that Armstrong and Zmuda (1970) gave for a storm-time observation is indeed completely consistent with the present C_{fa}-1, C_{fa}-2 systems. The present estimates of the current density integrated over the layer thickness are of the same order of magnitude as those given by Zmuda and Armstrong (1974). However, their estimates appear to be somewhat greater than those given in this paper. This difference is probably due to such factors as (a) that the current spreads out at high altitudes so that we are only taking the region of concentrated current as the current layer at high altitudes and (b) that both studies are still exploratory and that the basis of the selections of the cases for demonstration is not the same.

Cloutier et al. (1970) and Park and Cloutier (1971) studied the currents associated with a quiet auroral arc by a rocket-borne magnetometer experiment. They deduced a pair of oppositely directed field-aligned current sheets, the poleward sheet with an upward current being coincident with the visible arc and the equatorward sheet with a downward current being displaced to the south of the visible arc. Cloutier et al. (1973) made another rocket observation of field-aligned currents in association with two visible auroral arcs and presented two models of field-aligned currents that could explain the observed features. In all the models that Cloutier and his associates presented, the current directions are the same as those described in this paper and in those of Armstrong and Zmuda. However, while the models given by Cloutier and his associates were constructed to account for their rocket measurements made in or near visible auroral arcs, the discussions presented in this paper concern the permanent structure of the magnetosphere. Hence a direct comparison of the current intensities involved would not be proper. On the other hand, the general agreement regarding the directions of field-aligned currents among the independent studies conducted by the three different groups is highly significant.

Theile and Praetorius (1973) observed transverse magnetic variations at auroral and polar latitudes from the satellite AZUR (apogee 3145 km, perigee 384 km), and interpreted these variations as being produced by field-aligned currents. They reported that "about 98 percent of all passes in auroral and polar latitudes were associated with transverse field changes". However, the wobbling of this magnetically stabilized satellite appears to have made it difficult or impossible for these authors to determine the steady component of the field-aligned currents; their discussions are limited to field fluctuations transverse to the ambient field. It is noted here that on some passes they observed transverse fluctuations over the polar cap. Our OGO-5 observations also show that the polar cap magnetic field in the distant magnetosphere at times contains transverse fluctuations. The polar events of Theile and Praetorius may be related to these high-altitude field fluctuations.

On the basis of his plasma measurements demonstrating direct access of magnetosheath plasma to the magnetosphere at the polar cusp, Frank (1971) proposed a magnetosphere model in which the dayside polar cusps, one in each hemisphere, continue to the plasma sheet on the night side. If we identify the PC boundary near noon as the polar cusp, the continuity of the PC boundary surface, discussed in this paper, leads us to a logical conclusion that the dayside cusps must continue to the plasma sheet.

5. Additional remarks

In this preliminary report, emphasis was placed on bringing out the basic pattern of field variations that identify the PC boundary and the auroral belt. As a consequence, relatively clear-cut, if not clearest, cases are presented for demonstration, and discussions mainly refer to such cases. As is common with many other features of the magnetosphere, the characteristics used for the identifications of the PC boundary and the auroral belt are not always as clear as in the examples shown in this paper. However, once the basic patterns were recognized, several different types of their variants became evident. Nevertheless there are passes on which either the PC boundary or the location of the lower-latitude field-aligned current, or both, cannot be unambiguously determined. It is also noteworthy that there are cases in which multiple pairs of field-aligned current layers are observed; the case shown in Figure 4 represents one type. In this connection Armstrong (1973) mentions similar features in the low altitude observations of field-aligned currents.

CONCLUSIONS

From the present preliminary study the following conclusions have been drawn:

(1) In the high-altitude magnetosphere the polar cap boundary can be identified by a distinctive, relatively sudden, field deflection from the meridional field. From the variation in declination in this region it is inferred that there is a layer of field-aligned current at the polar cap boundary. On the night side of the magnetosphere the polar cap boundary coincides with the high-latitude boundary of the plasma sheet. The field-aligned current at the polar cap boundary, therefore, is the surface current of the plasma sheet. The direction of the field-aligned current is toward the earth after midnight and away from the earth before midnight. These field-aligned currents exist nearly at all times and are intensified during a substorm.

(2) There is another field-aligned current system on the low-latitude side of the auroral belt. The current flows away from the ionosphere on the morning side and toward the ionosphere on the afternoon side of the magnetosphere. The field lines along which these currents

flow are essentially dipolar, and hence the currents flow to, or from, the equatorial magnetosphere. It is suggested that these field-aligned currents close the circuit via the magnetospheric equatorial current.

(3) These two current circuits are weakly coupled through the auroral belt ionosphere at quiet times. When the ionospheric conductivity is increased by particle precipitation, for instance, during a substorm, the coupling is strengthened, and the field-aligned currents increase their intensity.

(4) Placing the dayside polar cusp at the polar cap boundary, the polar cusp must continue onto the plasma sheet from the consideration of continuities of (a) the field-aligned currents and (b) the polar cap boundary surface. In the present model the plasma sheet maps onto the auroral belt.

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FIGURE CAPTIONS

Figure 1: Inclination, I, declination, D, and the magnitude, B, of the magnetic field observed by the OGO-5 GSFC fluxgate magnetometer on the outbound orbit of August 25, 1969. The polar cap boundary, marked b, separates the polar cap, PC, region from the auroral belt, Au. The hatched band indicates the field-aligned current layer. Data plotted are 37 second averages. The smooth solid lines give I, D, and B for a reference field. The flat portion of the B plots indicates the 500γ level; this is not due to instrumental saturation. R_E: geocentric radial distance in earth radii, GMLAT: geomagnetic dipole latitude, INLAT: invariant latitude calculated from the reference field. MLT: geomagnetic dipole local time.

Figure 2: Inclination, I, declination, D, and the magnitude B, observed by the OGO-5 GSFC-fluxgate magnetometer on the inbound orbit of March 26, 1970. PC: the polar cap, Au: the auroral belt. The hatched band roughly indicates the field-aligned current layer. See the caption of Figure 1 for the details.

Figure 3: Inclination, I, declination, D, and the magnitude, B, of the magnetic field obtained by the OGO-5 GSFC-fluxgate magnetometer on the outbound orbit of August 13, 1970, illustrating the basic pattern of the field variations observed during the traversals of the auroral belt (Au), the polar cap boundary layer, and the polar cap (PC) region. The hatched band roughly represents the location of the field-aligned current layer at the polar cap boundary. The region between a and b represents

another field-aligned current layer in which the current direction is opposite to that in the polar cap boundary layer. The dark bar, marked c, represents the region where rapid, irregular field fluctuations are observed. For other details, see the caption of Figure 1.

Figure 4: Inclination, I, declination, D, and the magnitude, B, of the magnetic field obtained by the OGO-5 GSFC-fluxgate magnetometer on the outbound orbit of September 13, 1968, illustrating disturbed conditions of the auroral belt (Au) between a and b and the polar cap (PC) boundary region. The hatched band roughly represents the field-aligned current layer at the polar cap boundary. Presence of multiple pairs of field-aligned current layers equatorward of the polar cap boundary is indicated. The dark bar, marked c, is the region where rapid, irregular field fluctuations were observed; small amplitude, irregular fluctuations began near a'. High time-resolution data for the segments marked A and B are given in Figure 5. For other details, see the caption of Figure 1.

Figure 5: Samples of high time-resolution data in the auroral belt and in the polar cap. The time intervals are approximately from $03^h\ 19^m\ 30^s$ to $03^h\ 25^m\ 30^s$ UT and from $04^h\ 31^m\ 58^s$ to $04^h\ 37^m\ 50^s$ UT, respectively. These intervals are marked A and B in Figure 4. X, Y, and Z are the three orthogonal components in spacecraft coordinates. Data are plotted at the rate of 0.284 sec per sample.

Figure 6: A sample of rapid, irregular field fluctuations observed in the current layer on August 13, 1970, shown in Figure 3. The time interval is approximately 2133 to 2138 UT. X, Y, and Z are the three orthogonal components in spacecraft coordinates, and are given in units of gammas.

Figure 7: Inclination, I, declination, D, and the magnitude, B, of the magnetic field obtained by the OGO-5 GSFC-fluxgate magnetometer on the inbound orbit of June 22, 1969, indicating the first entrance into the plasma sheet (PS) from the polar cap (PC) at about 1742 UT. For other details, see the caption of Figure 1.

Figure 8: Field-aligned current systems, C_{fa}-1 and C_{fa}-2. C_{fa}-1 flows in the polar cap boundary layer which coincides with the high-latitude boundary of the plasma sheet. C_{fa}-2 flows in the low-latitude side of the auroral belt. The magnetic field at the location of C_{fa}-2 is meridional. The field-aligned currents in C_{fa}-2 close via the equatorial current in the magnetosphere. The two current systems are coupled by the Pedersen current in the ionosphere.

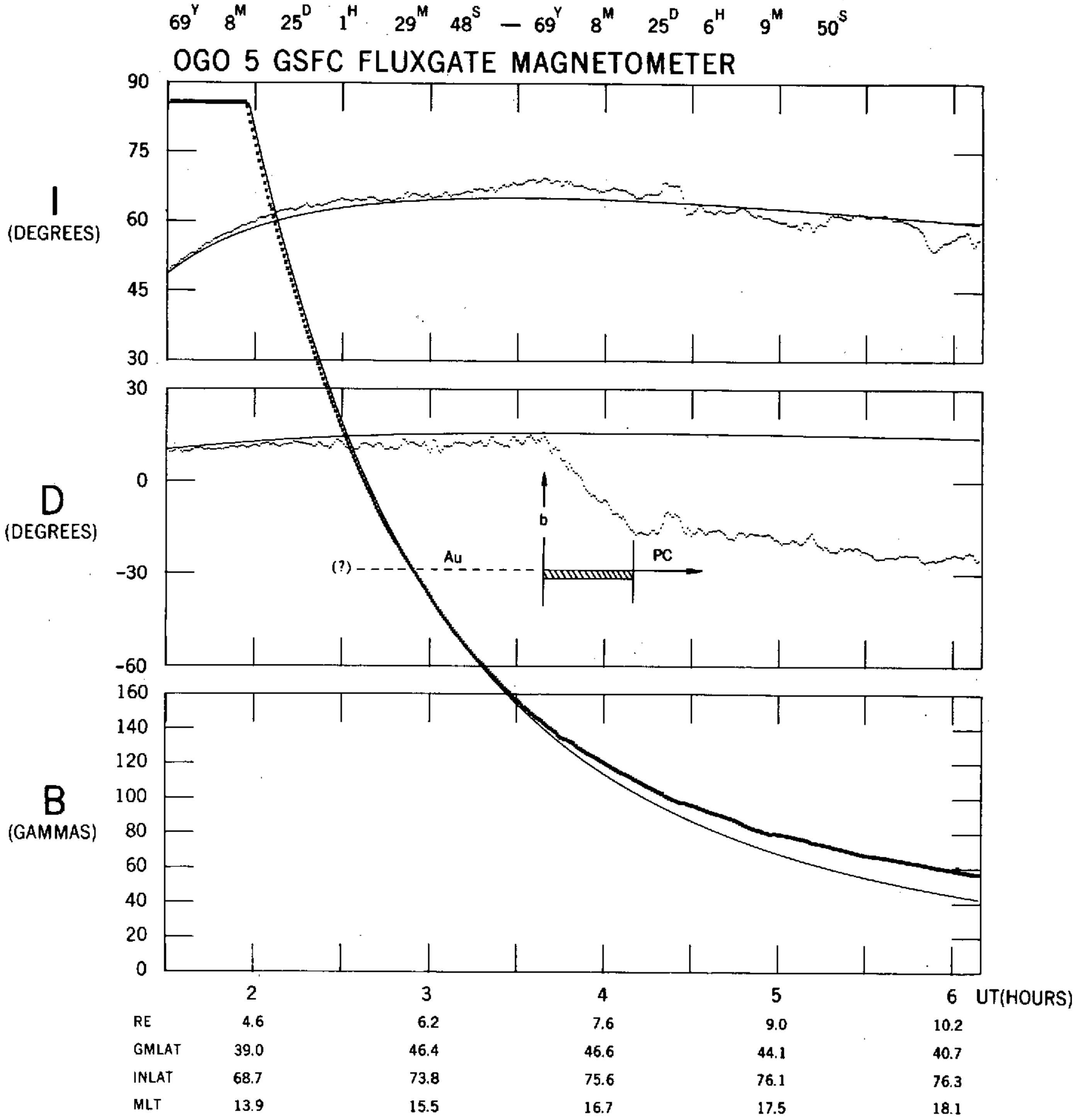
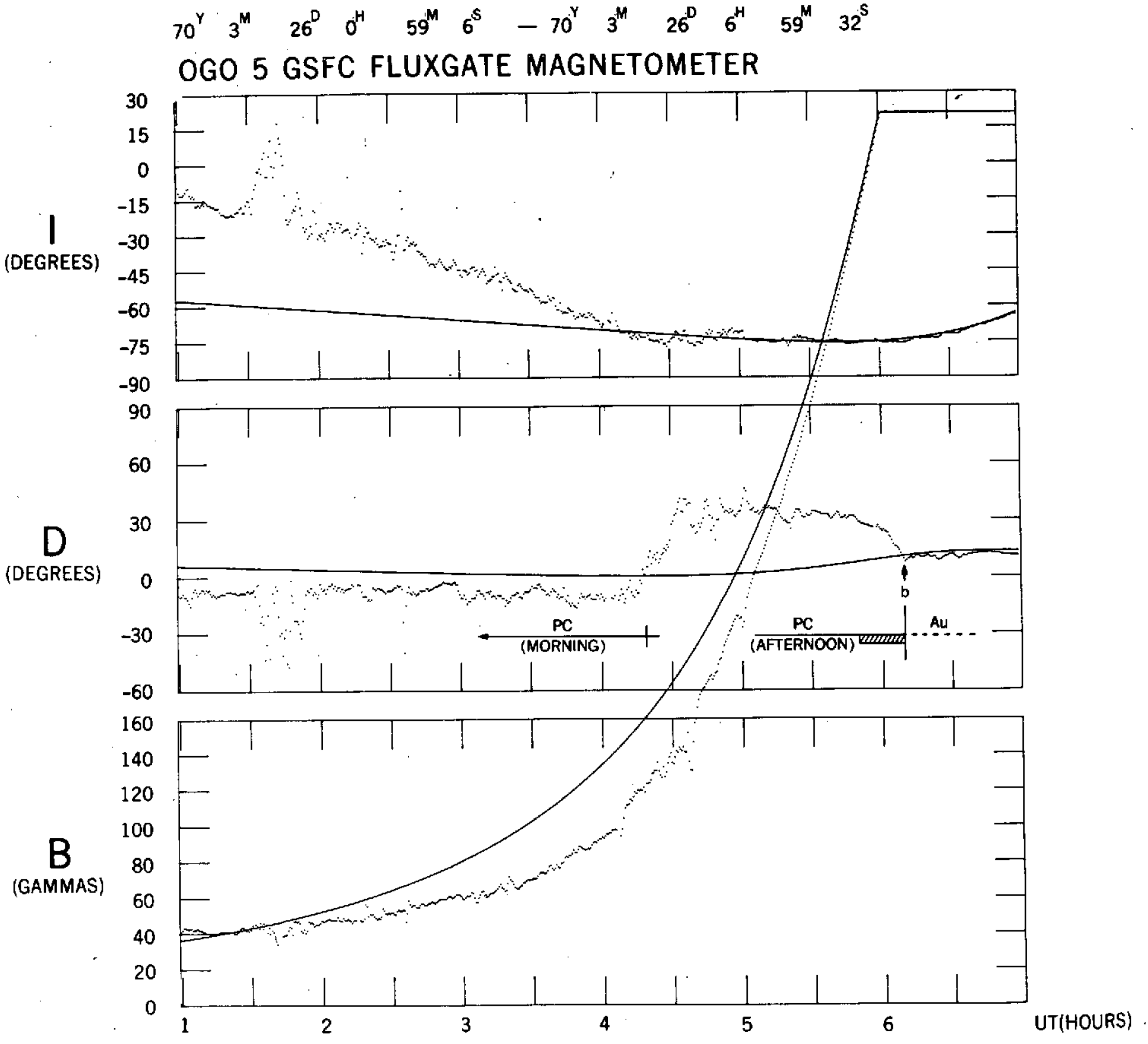

69Y 8M 25D 1H 29M 48S — 69Y 8M 25D 6H 9M 50S
OGO 5 GSFC FLUXGATE MAGNETOMETER
I
(DEGREES)
90
75
60
45
30
D
(DEGREES)
30
0
-30
-60
b
Au
(?)
PC
B
(GAMMAS)
160
140
120
100
80
60
40
20
0
2
3
4
5
6
UT(HOURS)
RE 4.6 6.2 7.6 9.0 10.2
GMLAT 39.0 46.4 46.6 44.1 40.7
INLAT 68.7 73.8 75.6 76.1 76.3
MLT 13.9 15.5 16.7 17.5 18.1

Figure 1



RE	10.8	9.7	8.6	7.4	6.1	4.9
GMLAT	-37.6	-42.6	-48.0	-53.8	-59.7	-60.4
INLAT	76.0	76.3	76.7	77.4	78.2	77.2
MLT	10.4	10.7	11.1	11.8	13.1	15.7

Figure 2

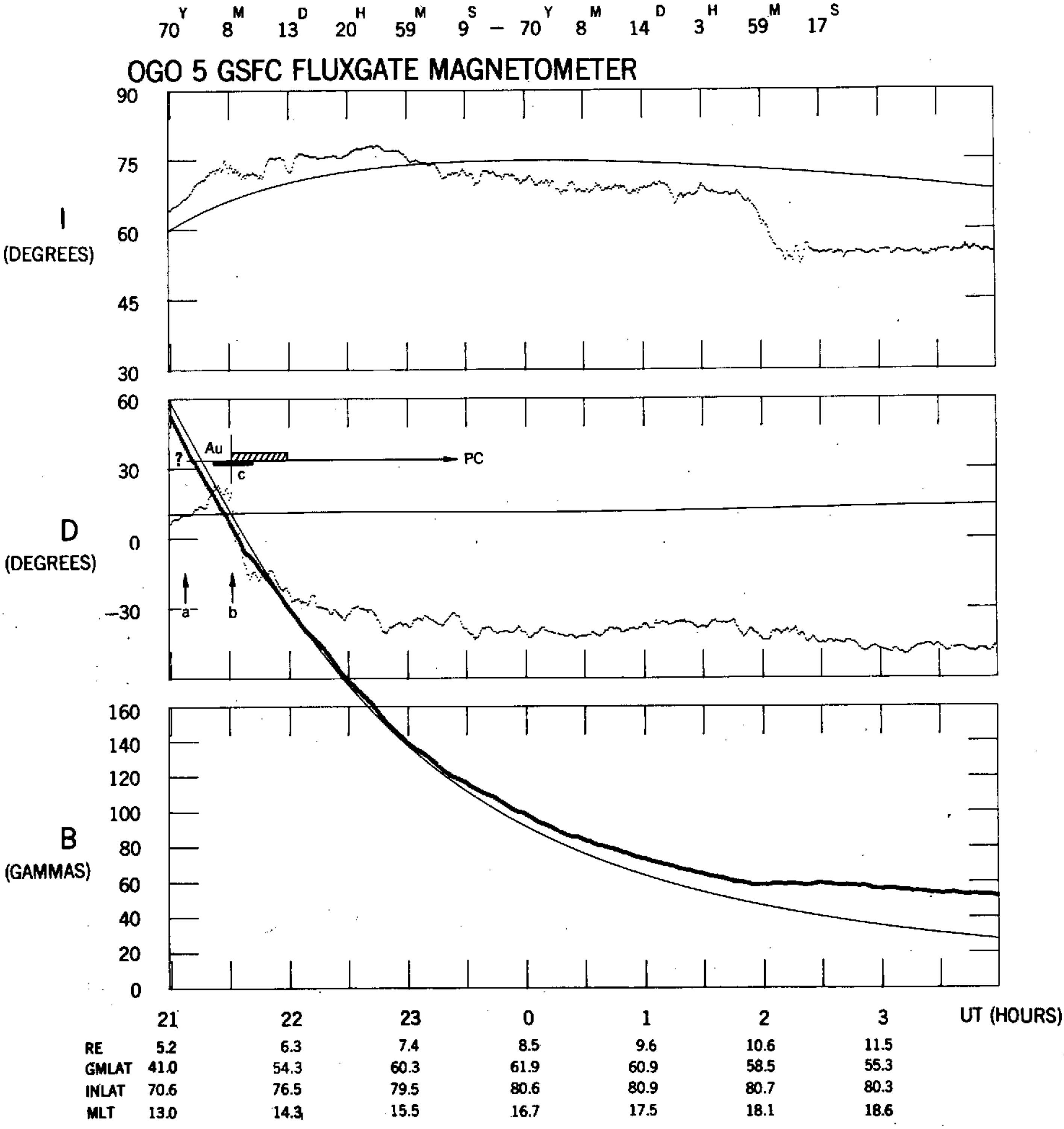

70 Y 8 M 13 D 20 H 59 M 9 S — 70 Y 8 M 14 D 3 H 59 M 17 S
OGO 5 GSFC FLUXGATE MAGNETOMETER
I (DEGREES)
90
75
60
45
30
D (DEGREES)
60
30
0
−30
?
Au
c
PC
a
b
B (GAMMAS)
160
140
120
100
80
60
40
20
0
21
22
23
0
1
2
3
UT (HOURS)
RE 5.2 6.3 7.4 8.5 9.6 10.6 11.5
GMLAT 41.0 54.3 60.3 61.9 60.9 58.5 55.3
INLAT 70.6 76.5 79.5 80.6 80.9 80.7 80.3
MLT 13.0 14.3 15.5 16.7 17.5 18.1 18.6

Figure 3

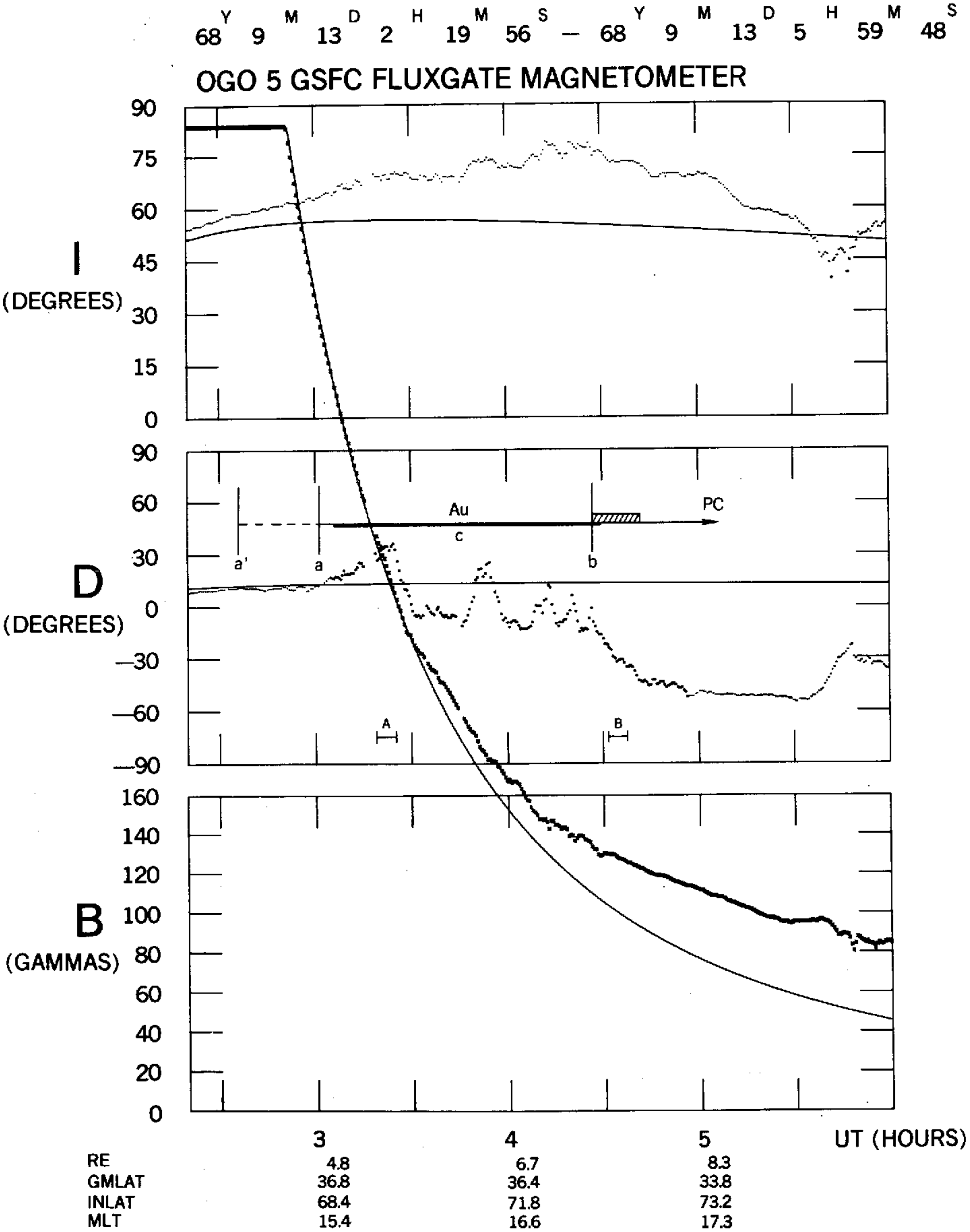

68 Y 9 M 13 D 2 H 19 M 56 S — 68 Y 9 M 13 D 5 H 59 M 48 S
OGO 5 GSFC FLUXGATE MAGNETOMETER
I
(DEGREES)
90
75
60
45
30
15
0
D
(DEGREES)
90
60
30
0
—30
—60
—90
Au
PC
c
a'
a
b
A
B
B
(GAMMAS)
160
140
120
100
80
60
40
20
0
3
4
5
UT (HOURS)
RE 4.8 6.7 8.3
GMLAT 36.8 36.4 33.8
INLAT 68.4 71.8 73.2
MLT 15.4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

Figure 4

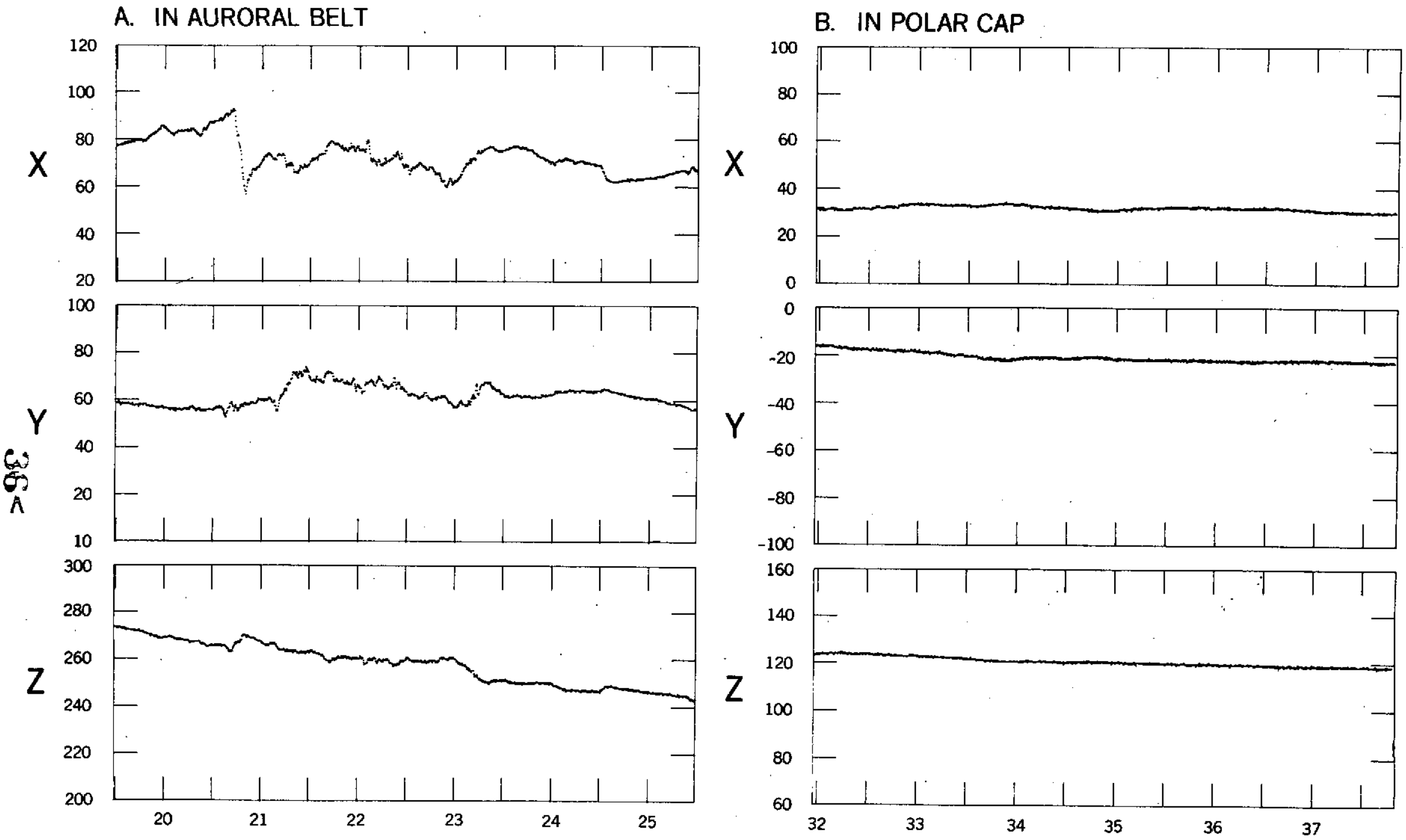

A. IN AURORAL BELT
B. IN POLAR CAP
X
Y
Z
120
100
80
60
40
20
100
80
60
40
20
10
300
280
260
240
220
200
20
21
22
23
24
25
100
80
60
40
20
0
0
-20
-40
-60
-80
-100
160
140
120
100
80
60
32
33
34
35
36
37

Figure 5

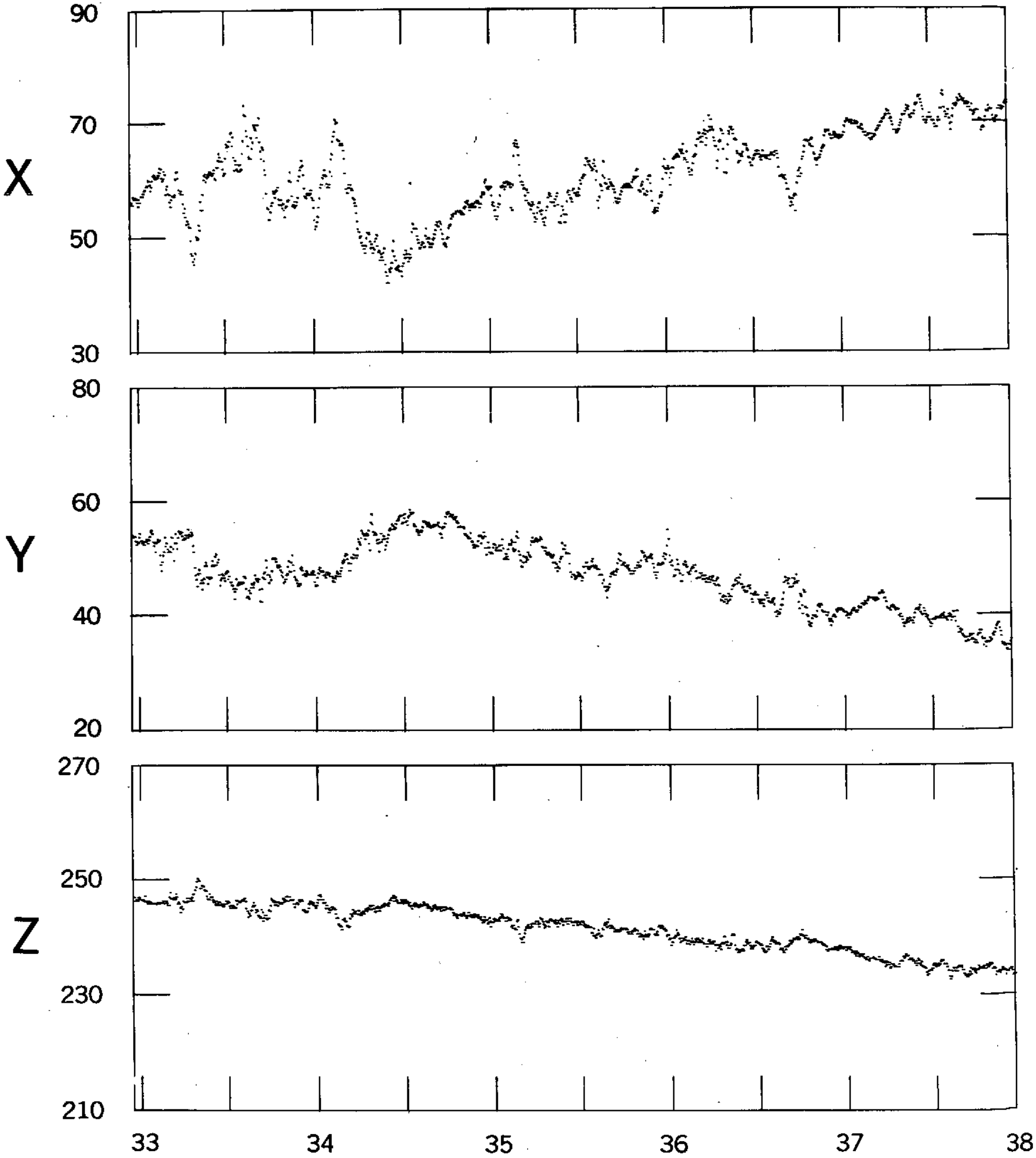


Figure 6

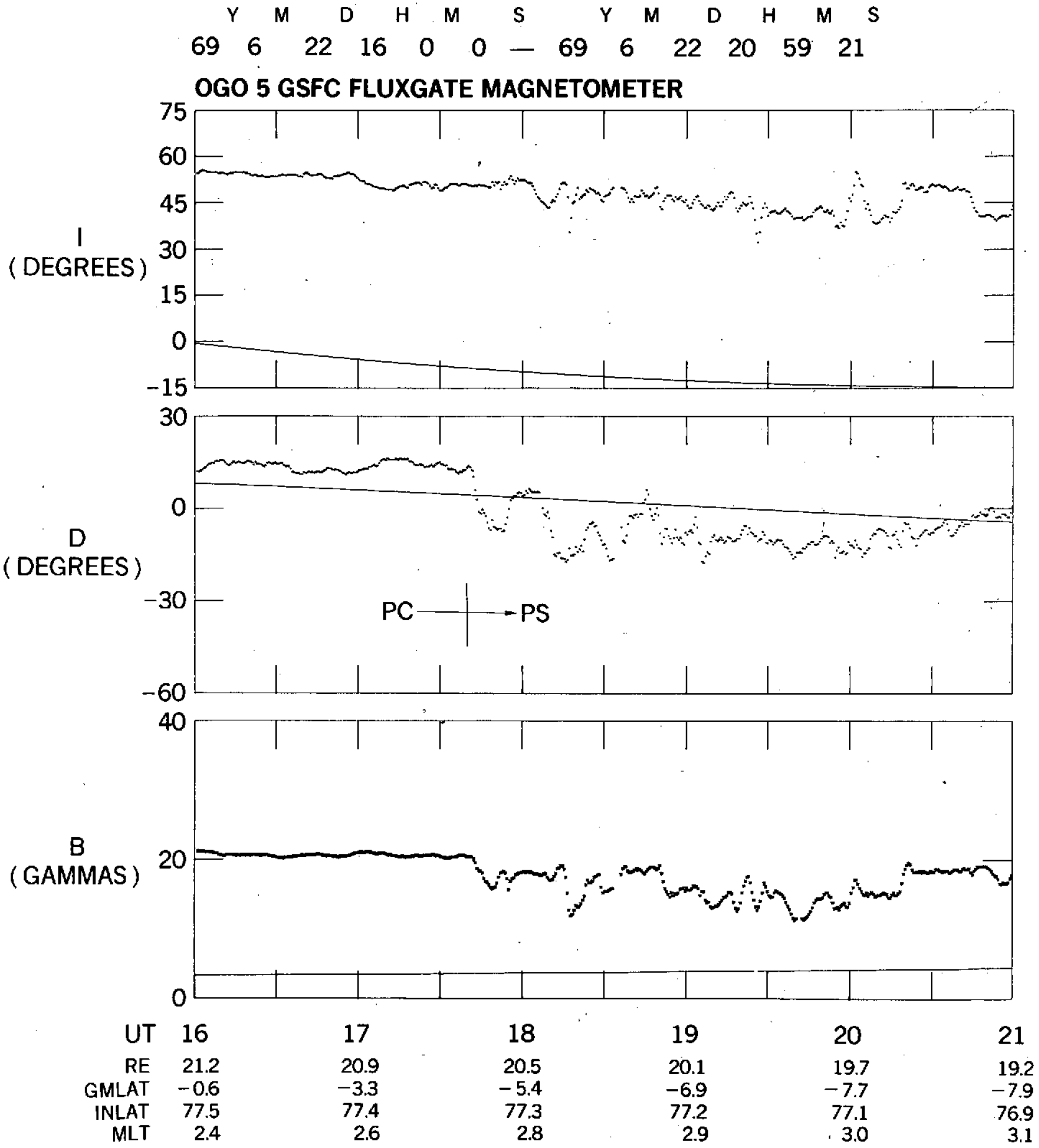

Y M D H M S Y M D H M S
69 6 22 16 0 0 — 69 6 22 20 59 21
OGO 5 GSFC FLUXGATE MAGNETOMETER
I
(DEGREES)
75
60
45
30
15
0
−15
D
(DEGREES)
30
0
−30
−60
PC
PS
B
(GAMMAS)
40
20
0
UT 16 17 18 19 20 21
RE 21.2 20.9 20.5 20.1 19.7 19.2
GMLAT −0.6 −3.3 −5.4 −6.9 −7.7 −7.9
INLAT 77.5 77.4 77.3 77.2 77.1 76.9
MLT 2.4 2.6 2.8 2.9 3.0 3.1

Figure 7

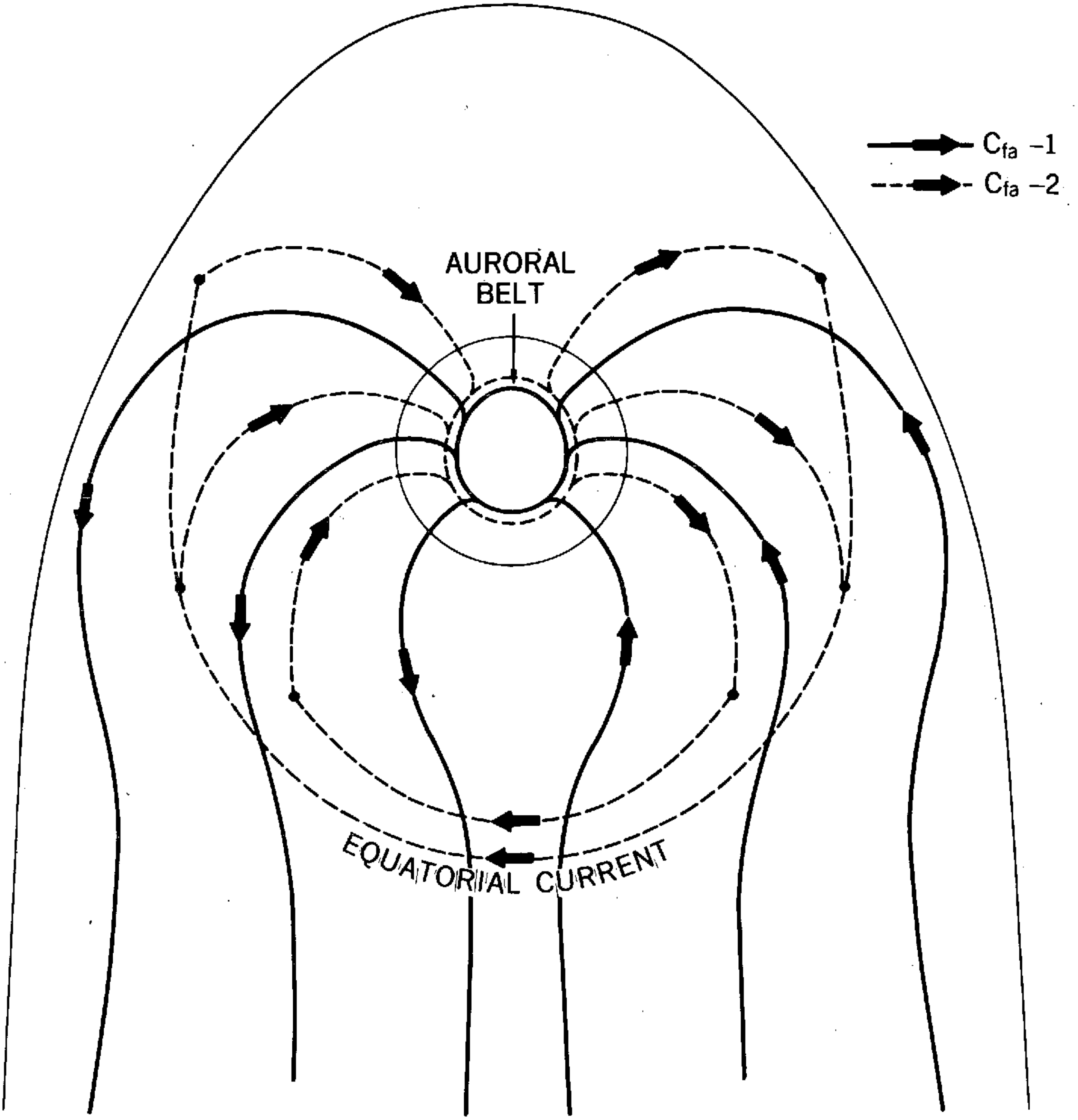


Figure 8