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D. H. FAIRFIELD

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by

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

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Abstract

Before a magnetospheric substorm and during its early phases the magnetic field magnitude in the geomagnetic tail increases and field lines in the night time hemisphere assume a more tail-like configuration. Before the substorm onset a minimum amount of magnetic flux is observed to cross the neutral sheet which means that the neutral sheet currents attain their most earthward locations and their greatest current densities. This field configuration apparently results from an increased transport of magnetic flux to the tail caused by a southward interplanetary magnetic field. The field begins relaxing toward a more dipolar configuration at the time of a substorm onset with the recovery probably occuring first between 6 and $10R_E$ and later at greater distances. This recovery must be associated with magnetospheric convection which restores magnetic flux to the dayside hemisphere.

Field aligned currents appear to be required to connect magnetospheric currents to the auroral electrojets but such current systems imply that a net current flows in a limited range of longitudes. Space measurements supporting the existence of such current systems are very limited. Much more evidence exists for the occurrence of double current sheets which do not involve net current at a given longitude.

I. Introduction

Although magnetosphere magnetic field measurements have been available for almost a decade it is only within the last few years that a coherent picture has emerged regarding magnetic field changes during substorms. Early studies focused primarily on the average field configuration and the large changes associated with magnetic storms. Time variations tended to be studied only in a statistical sense, generally using the three hour geomagnetic index Kp. The ring current and its asymmetric development during storms was studied (e.g. Cahill, 1970) and the general tendency for strong tail fields to occur during geomagnetically disturbed periods established (Behannon and Ness, 1966).

Only more recently, however, has the important relation between magnetospheric substorms and fundamental magnetospheric processes been fully appreciated and have their magnetic effects been studied in detail. The study of such magnetic fluctuations during substorms has been greatly stimulated by results of the ATS spacecraft in synchronous orbit at $6.6R_E$ and its data have been well supplemented by data from greater distances taken by IMP and OGO spacecraft.

Section II of this paper will discuss the evidence which indicates that important changes in the magnetosphere field configuration occur at the time of magnetospheric substorms. Such changes could alternatively be discussed in terms of electric currents which flow primarily perpendicular to dipole-like field lines in an azimuthal or east-west direction and therefore produce changes in the field magnitude. Section III will discuss the even more recent evidence for field aligned currents which may connect currents in the outer magnetosphere with currents in the auroral zone ionosphere. These field aligned currents will have perturbations perpendicular to the ambient field and will therefore have a minimal effect on field magnitude.

II. Magnetic Field Configuration Changes During Substorms

Those magnetic field perturbations which are associated with a changing field configuration are confined largely to the night hemisphere of the magnetosphere and are similar for most substorms. The nature of the changes depend somewhat on the location of the spacecraft but the results from different regions support each other rather well. In subsequent figures, data will be presented first from the magnetic tail and then for distances closer to the earth.

The first figure illustrates some typical features of the tail field behavior as illustrated by IMP 4 data presented by Fairfield and Ness (1970). The magnetic field magnitude F and solar magnetospheric angles latitude θ and longitude ∅ are shown along with the Z_{SM} or solar magnetospheric north-south component of the tail field and the geomagnetic AE index which represents the evolution and decay of the substorm. The spacecraft is located approximately 29 R_E behind the earth and 11 R_E to the dusk side of the noon midnight meridian plane. The spacecraft distance from the estimated position of the neutral sheet is given by the values Z' in the figure and is quite small. During the early phases of both these substorms the field strength is increasing and the Z_{SM} component remains or becomes very small. Near the maximum of the substorm the field strength abruptly decreases and shortly thereafter the Z_{SM} component of the field increases. This type of abrupt field decrease was first noted by Heppner et al. (1967) and is now thought to be caused by the arrival at the spacecraft of an expanding plasma sheet containing a magnetic field which is weakened by the diamagnetic effect of the plasma. The increasing Z_{SM} component of the field is typically observed irrespective of whether or not the spacecraft is in the plasma sheet. This can be interpreted as an adjustment of the tail field configuration which is related to a relaxation toward a more dipolar field. Alternately the change can be phrased in terms of a decrease in the tail current sheet. Tail field increases and the relaxation toward a more dipolar state has also been discussed by Camidge and Rostoker (1970).

It is also instructive to compare a neutral sheet crossing (reversal of the Ø angle by 180°) near 5:20 during the late stages of the first substorm with a second pair of crossings near 7:05 during the early stages of the second substorm. During the 5:20 crossing the field is quite northward for an interval of approximately 20 minutes and no exact time for a field reversal can be specified. A considerable amount of flux is crossing the equatorial plane at this time and the current sheet is not well developed. In contrast, the 7:05 crossings are very abrupt and very little flux crosses the neutral sheet which implies that the current sheet is very well developed.

A second example from the distant magnetic tail is shown in Figure 2 where the bottom 4 traces represent the IMP 4 magnetic field data presented in the same format as the previous figure. Again two substorms occur which reach their maxima at 12:45 and 16:45. For this interval the estimated position of the spacecraft relative to the neutral sheet, Z', is much greater. As in the previous example the tail field strength gradually increases before the substorm onset and decreases during the substorm recovery. The Z component of the field remains small during the early phase and increases during the recovery phase. The additional field strength decrease at 18:10 is most likely caused by the arrival of the diamagnetic plasma sheet at the position of the spacecraft.

This interpretation implies a surprisingly thick plasma sheet, but Meng and Anderson (1971) studying similar field decreases reached the same conclusion.

Aubry and McPherron (1971) have added simultaneous interplanetary magnetic field and plasma data to the published IMP 4 data of Fairfield and Ness. These additions appear at the top of Figure 2 where the solar wind momentum flux and internal energy are shown along with the interplanetary north-south angle α. These authors note that the substorm recovery (tail field magnitude decrease and tail field Z_{SM} increase) are unrelated to the interplanetary plasma but coincident with the occurrence of a northward interplanetary field. These authors also conclude that a northward interplanetary field can cause the plasma sheet to expand even in the absence of a substorm.

In another important observation Aubry et al. (1970) have presented an example where the inbound OGO 5 spacecraft makes multiple observations of the dayside magnetopause over an interval of more than one earth radii. During this interval the interplanetary plasma flux remains constant but the inward motion of the magnetopause is correlated with a southward excursion of the interplanetary field. These authors conclude that the more earthward magnetopause is not caused by increased solar wind compression but rather by stripping tubes of flux off the front of the magnetosphere and transporting them to the tail. Fairfield (1971) has provided statistical support for this interpretation by noting that in a large collection of magnetopause crossings the locations closer to the earth on the average tend to be those associated with a southward magnetosheath field. These data are consistent with the tail field strength increase since transporting flux to the tail would increase both the tail radius and the angle of attack between the incident solar wind and the tail, thus increasing the pressure on the tail and consequently the field strength.

A further clear example of tail field behavior has been presented by Russell et al. (1971) and is shown in Figure 3. The three solar magnetospheric components of the tail field and field magnitude are presented for an inbound pass of OGO-5 from $18.5R_E$ to $6.9R_E$. During an interval of weak substorm activity three decreases in the field strength are seen at 17:05, 20:10 and 22:55 which all occur in regions where the field strength is greater than a reference dipole field. These three decreases all have associated increases in the Z_{SM} component. At about $10R_E$ at 1:15 the spacecraft enters the region near the plasma sheet where the field strength is normally depressed relative to a dipole field. A Z_{SM} increase at 1:35 is now associated with an increase in B but this is still a recovery toward a more dipolar field since the field has been depressed. This type of recovery was first noted by Heppner et al. (1967) and has been interpreted as a relaxation of the field toward a more dipolar state by Sugiura et al. (1968).

Magnetic field behavior still closer to the earth is illustrated in Figure 4 with data from the ATS-1 spacecraft in synchronous orbit near the geographic and geomagnetic equator at $6.6R_E$. These data of McPherron and Coleman (1970) are presented in a coordinate system where H is parallel to the earth's surface, V is radially outward from the earth and D completes the orthogonal system with +D in an eastward direction. Since ATS is near the geomagnetic equatorial plane the dipole-like field is aligned primarily along the H component. The 3 vertical dashed lines in the figure represent the onset of 3 substorms, the first of which occurred with the spacecraft near the dusk meridian and the latter two with the spacecraft near the midnight meridian. At the time of the onset of the expansion phase of the substorm, ATS typically records an increase in H from a depressed level when the spacecraft is near midnight. This can be seen near 10:35 and

13:10 although data is missing near 10:35 due to eclipse of the spacecraft by the earth during this period near the equinox. Since H is equivalent to the Z or northward component of the field at this spacecraft location, this behavior is equivalent to the recovery of the field toward a more dipolar state seen further back in the tail. Preceding the recovery in H, ATS typically sees a gradual depression in H for a period of anywhere between a fraction of an hour up to several hours. If the substorm expansion occurs while ATS is at earlier local times near the dusk meridian the recoveries are sometimes missing if a depressed H does not previously exist. In such cases a depression may be associated with the substorm. If a recovery occurs in this region it is often delayed relative to the expansion at midnight. At times after midnight the response tends to be more immediate.

These substorm effects are illustrated further with H traces of Coleman and McPherron (1970) shown in Figure 5. The traces are arranged in columns of various local times and the vertical dashed lines denote the time of the expansion phase. In the premidnight hours delays are frequently seen between the substorm onset and the effects at ATS. For 0-9 hours the H recovery appears to be generally coincident with the substorm onset. This latter conclusion is somewhat more tentative, however, due to the fact that soviet magnetograms were not available to precisely define substorm onset times during the post midnight hours.

The local time dependence of the tail recovery has been emphasized by Heppner et al. (1967) and Rostoker and Camidge (1971). Heppner et al. state that the tail effects are confined to the longitude sector of the ground disturbance. A subsequent study by Fairfield and Ness (1970) showed that similar effects are seen at different longitudes all across the tail but the timing between ground and spacecraft was not investigated in detail. Rostoker and Camidge (1971) demonstrate that the typical tail perturbations do not always accompany substorms. They further suggest that different longitudes may be effected sequentially during a given substorm. The timing between effects on the ground and effects in the tail at various longitudes is a difficult problem needing additional study.

Neglecting any possible longitudinal effects, Figure 6 (Fairfield and Ness, 1970) illustrates pictorially the adjustment in the tail configuration that appears to be taking place during a typical substorm. The top portion oi the figure represents the field configuration before or during the early stages of a substorm. Field lines are stretched out behind the earth and a minimum number of field lines cross the equatorial plane beyond 10 R_E (Z_{SM} small). The bottom figure represents the field during the recovery phase of the storm when the Z component has increased and the field has relaxed to a more dipolar type condition. The plasma sheet has expanded and more lines of force connect across the equatorial plane.

An additional feature associated with the field recovery process at ATS is illustrated with Figure 7. This figure displays one hour of ATS data (McPherron and Coleman, 1970) beginning 25 minutes after the onset of the expansion phase. Large fluctuations with amplititudes up to 20γ peak to peak are seen superposed on the Z increase, which appears very gradual on this time scale. Fluctuations in the Z component (equivalent to H in previous figures) dominate the spectra below .03 hz and the spectrum falls off approximately as $^1/f^2$. This high level of Z component waves implies that the fluctuations are compressional and, as the authors suggest, this seems reasonable if the tail field is collapsing and its magnitude changing.

In Figure 8 the H magnetogram from college near the foot of the ATS field lines is presented along with H from ATS and the H magnetogram from the low latitude station Honolulu near the subsatellite point. The typical recovery of the ATS H trace is seen at the time of the substorm onset and, in addition, a very similar recovery is seen in H at Honolulu. This observation was particularly important because it confirmed work of Akasofu and Chapman (1964) which suggested that at least part of the currents responsible for the low latitude variation at the earth's surface flowed in the outer magnetosphere. Until this time the low latitude ground perturbations associated with substorms had been widely accepted as being due to ionospheric currents. If such currents did flow between the ground and spacecraft, they would produce perturbations of the opposite sign at the two locations. The observed correspondence of the perturbations at these two points confirmed that the current source for low latitude perturbations was not in the ionosphere but rather in the outer magnetosphere. Since auroral zone magnetic perturbations exhibit large spatial gradients their source must be ionospheric currents, and Cummings et al. (1968) concluded that field aligned currents must connect the magnetosphere and ionosphere current systems.

Such field aligned currents will have perturbation vectors perpendicular to the field lines which will have relatively little effect on the total field strength. In this sense, field aligned currents have very different effects than the basically azimuthal currents which must be producing the perturbations discussed in the previous portion of this paper.

III. Field Aligned Currents in the Magnetosphere

The subject of field aligned currents in the magnetosphere has a long history dating back to the work of Birkeland (1908). Bostrom (1968) has recently reviewed this early work and discussed the physics of such currents. A number of authors have discussed field aligned currents theoretically (Bostrom, 1964; Atkinson, 1967a; Cummings and Dessler, 1967; Schield et al., 1969; Vasyliunas, 1970; Taylor and Perkins, 1971) and numerous current systems have been proposed (Fejer, 1961; Akasofu and Chapman, 1964; Cummings, 1966; Atkinson, 1967b; Akasofu and Meng, 1969; Meng and Akasofu, 1969; Bonnevier et al., 1970).

Field aligned currents are restricted primarily to field lines which intersect the earth at the position of the auroral oval. Although many types of current configurations are possible, two basic types have been discussed most often and they are illustrated with a simple two dimensional sketch shown as Figure 9. The top portion of this figure arbitrarily shows inward flow along field lines from the polar or dayside cusp and outward flow along midnight auroral zone field lines. If the currents have these directions over a range of longitudes they can be considered sheet currents and they would have magnetic perturbation vectors perpendicular to meridian planes and in opposing directions on either side of the sheet. Perturbations in the declination would be produced with differing signs in the various regions as shown. Such currents would complete their circuits in the ionosphere and the magnetosphere through a path which comes out of the plane of the paper. The exact longitudes of the current inflow and outflow and their paths in the ionosphere and magnetosphere constitute the main differences in many of the proposed current systems.

The bottom portion of Figure 9 illustrates a second type of current system where anti-parallel currents flow along adjacent field lines. Each of these current pairs complete their circuit in the outer magnetosphere after flowing along field lines and through a very short north-south strip in the ionosphere. The entire current system is confined to the plane of the paper. These currents might well have this configuration over an extended longitude range in which case they oould also be considered sheet currents. An important feature of this current system is that the perturbation vectors from the two sheets will add between the sheets and cancel outside the sheets.

From an experimental point of view, the important difference between these two current systems is that the former will produce perturbations over large regions of space and be detectable at the earth's surface, whereas the latter is confined to a narrow region of the magnetosphere and will have little effect on the ground. On the other hand, a spacecraft passing through a double current sheet will see a well defined abrupt perturbation which may be much easier to detect than a more gradual change associated with a single sheet.

Of the numerous current systems proposed, two will be discussed here which incorporate the important features common to most current systems and appear to be in accord with ground measurements. Akasofu and Meng analyzed a large collection of magnetograms from one substorm and they proposed the current system shown as Figure 10. Important features of this system are the current flow from the equatorial plane to the auroral zone in the morning quadrant, ionospheric flow producing the westward electrojet near midnight, and outward flow to the equatorial plane in the evening quadrant with closure of the current in the outer magnetosphere through the sunward hemisphere. The observed features that this current system explains best are the mid latitude declination changes and the field inflation effects seen in the outer magnetosphere near dusk.

Bonnevier et al.(1970) have performed detailed calculations to determine the magnetic effects of a current system which is similar to that of Akasofu and Meng except that the longitudinal separation between the inward and outward flow is less and the current closes in a west to east direction in the night side equatorial plane. By spreading their currents over a finite range of latitudes and using the reduced longitude separation between the inward and outward currents, they obtain even better agreement with high latitude ground observations than did Akasofu and Meng. As these authors state, their current system is not necessarily the complete current system and by adding a symmetric ring current they could obtain an Akasofu-Meng type system with the primary difference being the extended longitudinal separation of the ingoing and outcoming currents in the latter system. In a later paper which confirmed the essential features of their earlier system, Meng and Akasofu (1969) presented further examples which demonstrated the variability of the current system and seemed to imply a closer placement of the ingoing and outcoming currents. Atkinson (1967b) in discussing similar field aligned current flow has made the interesting suggestion that the outward current flow is associated with the westward traveling auroral surge and the inward flow with the more eastward portion of the northward expanding auroral bulge. This in turn implies an association with the collapsing dipole field of the tail and its expansion outward into the tail.

The first experimental evidence for field aligned currents was the detection of large magnetic perturbations on the low altitude polar orbiting satellite 1963-38C by Zmuda et al. (1966, 1967,1970). These measurements were made at about 1100 km on a magnetically aligned spacecraft with sensors orthogonal to the axis of orientation measuring perturbations transverse to the field. The perturbations were shown to be confined to the region of the auroral oval where they are present at least 90% of the time with amplitudes from 30γ-900γ. These fluctuations were originally interpreted as field aligned currents by Cummings and Dessler (1967).

One large clear perturbation has been analyzed in detail by Armstrong and Zmuda (1970) and the orientation of the perturbation vector has been obtained. Data for this event are shown in Figure 11. In the top portion of the figure, the measurements of the transverse field component are plotted versus time. In the bottom portion, the effects of a very small oscillation of the spacecraft about the average field direction have been removed. The authors discuss these results in terms of a double sheet current such as was shown in the bottom portion of Figure 9. The spacecraft is moving in a north to south direction through the auroral oval at approximately 9:00 local time. The perturbation increase takes place over a time interval of about 10 seconds. During this time the spacecraft moves 70 km which is taken as the thickness of the sheet of downward current. The perturbation is approximately constant for 33 seconds (240 km) until 1505:49 when the thin low latitude sheet of upward current terminates the perturbation in approximately 1 second (7 km).

Similar dayside currents have been detected in the outer magnetosphere by Fairfield and Ness and are shown in Figure 12. The field quantities plotted versus time are the magnitude B, the difference between the measurement and an internal reference field ΔB, the inclination I and declination D. The relevant data is the negative ΔD perturbation observed at 20:00 near 7 R_E. The perturbation vector associated with this change has magnitude of 45γ and must be approximately transverse to the field since B does not change appreciably. The perturbation is confined to a very limited range of latitude as in the Armstrong-Zmuda case and its vector direction is equivalent to that example reported at lower altitudes. The latitudinal width of the outer magnetosphere event when projected to the ground is only 8 km compared to the width of over 200 km in the low latitude case. However, Armstrong (private communication) reports that at low latitudes they do sometimes see widths under 100 km. Another difference between these two events is that the low altitude event occurs during K_p=8+ conditions, whereas the outer magnetosphere event is at K_p=0 conditions.

Frank (1971) has reported the frequent occurrence of sheets of precipitating electrons and protons with the protons being at the higher latitudes. This is in the proper north-south position to explain the current sheets but since no simultaneous comparison of particle and field data has been made and since Frank does not measure the complete range of particle energies which may be relevant, it is perhaps premature to make this association. Also Heikila and Winningham (1970) and Winningham (1971) do not confirm the existance of Frank's particle sheets at lower altitudes.

Night hemisphere data which may be related to field aligned currents is presented in Figure 13 which illustrates observations from the ATS spacecraft in synchronous orbit. This figure from Coleman and McPherron (1970) shows the H and D traces from ATS for four substorms near midnight. The vertical dashed line represents the onset of the expansion phase of the substorms and the shaded portions of the D trace represent perturbations which begin just after the recovery of the H component. The D perturbations typically last only a few minutes, are always negative, and have been termed "D spikes" by the authors.

Although it is difficult to interpret the "D spikes" in terms of a magnetosphere current system there are two possible explanations in terms of Figure 9. The ATS spacecraft could be effectively in the southern hemisphere near midnight and inside the auroral field lines in the top figure or alternativly, between the current sheets in the southern hemisphere in the bottom figure. Of course reversing the sign of the currents and the hemisphere location of the spacecraft shown above could produce equally good explanations. Presumably all currents are symmetric between the hemispheres and such perturbations should be zero in the equatorial plane. This means that such an explanation for the ATS "D spikes" may not prove feasible since the reported events occur near the equinox when the symmetry of the spacecraft position relative to the neutral sheet should minimize such effects.

Further evidence for field aligned currents come from two auroral zone rocket flights. Cloutier et al. (1970) flew a magnetometer and particle detectors which measured electrons of approximately 2 kev energy. On the basis of the magnetometer data they proposed a double sheet current system. They also detected the incoming electrons which could explain at least 1/3 of the outgoing current. No particles were detected to explain the incoming currents. Choy et al. (1971) also flew a rocket under fairly similar magnetic conditions with a magnetometer and a particle detector which measured particles as low as a few ev in energy. The measured particles constituted an outgoing current (incoming electrons) and the most intense fluxes were at energies lower than could have been measured by Cloutier et al. On the other hand, the flight of Choy et al. may not have gone far enough north to measure the second of two parallel current sheets if it were present. The magnetic field data were not conclusive regarding the nature of the magnetic perturbations.

Two other papers present spacecraft measurements which provide evidence for field aligned currents. Kaufman et al. (1971) have interpreted Explorer 12 magnetometer and particle data in terms of a double current sheet. Haerendel et al. (1971) have presented measurements from the Heos-1 spacecraft taken at $12R_E$ in the magnetosphere near 4:00 local time during a substorm. These data are presented in Figure 14 where the magnitude and three cartesian components of the field are plotted versus time along with the field declination. At the time of the substorm (6:18 onset) a perturbation is observed in the field declination which is further confirmed by visual observation of a field aligned barium cloud which simultanuously changed its orientation. Since the spacecraft was located on field lines which intersect the earth well above the auroral oval the result was interpreted as indicating an earthward field aligned current (i.e. the spacecraft was located poleward of the nightside currents in the northern hemisphere as is shown in the top portion of Figure 9 only the current directions were reversed). This observation supports current systems such as those of Akasofu and Meng and it constitutes the only evidence from spacecraft that a net field aligned current is present in a finite longitudinal sector.

The various measurements supporting the concept of field aligned currents are summarized in Figure 15 where the currents are schematically illustrated and labeled with the approximate local time of the measurement. The dayside measurements of Armstrong and Zmuda and of Fairfield and Ness appear to be quite consistent in that they both show a double current sheet with the downward current on the higher latitude line of force. This may be fortuitous, however, since Armstrong recently (private communication) reports that further work shows cases where the relative north-south positions of the up and down currents are reversed. In the night hemisphere Cloutier et al. report a double current sheet system with the relative north-south position of the sheets reversed from the dayside. Choy et al. detected only one sheet near the same local time but may have been unable to see a second sheet. Kaufman et al. argue for a double sheet current with the position of the sheets the same as in the daylit hemisphere. Haerendel et al. reported evidence for one inward flowing sheet current at the longitudinal position where it is expected.

The relation of double sheet currents to substorms is not clear. Since they are observed at least 90% of the time they are not confined exclusivly to substorms but it is possible that their intensities may prove to be more intense during substorms. Such double sheet currents neither confirm nor deny the current system of Akasofu and Meng which could be present along with the double sheets. The Akasofu-Meng type currents will be more difficult to detect and it does not appear that the dayside data argues for or against such a current system.

IV. Conclusions and Outstanding Problems

The morphology of the changing magnetic field configuration during magnetospheric substorms is quite clear. During the early phases of a substorm the field magnitude in the tail increases and night side field lines assume a more tail-like configuration. Relatively little flux crosses the equatorial plane; the tail current sheet is well developed; the neutral sheet is thin, and considerable magnetic energy is stored in the tail. The tail field increase is probably associated with an erosion of flux from the dayside hemisphere and a transport to the tail caused by a southward interplanetary field. Later in the substorm the field strength decreases as the plasma sheet expands and the field relaxes to a lower energy, more dipolar, state with an increased amount of flux crossing the equatorial plane near the earth. The field recovery is generally observed coincident with the expansion phase of a substorm at 6-8R_E and with an increasing time delay at greater distances. The relative timing of the differential recovery at different longitudes in the tail and at the ground is not clear.

The magnetic perturbations associated with field aligned currents have been detected at low altitudes and found to be an essentially permanent feature of the auroral zone. These low altitude perturbations can probably be explained by parallel-anti parallel double sheet currents and do not necessarily represent a net current at any given longitude. At least three other satellite and rocket measurements give evidence for such double sheet current systems. The existence of net currents in a given longitudinal region appears to be required to connect magnetosphere and ionosphere currents, but the space measurements supporting the existence of such currents is limited to one event observed by the Heos spacecraft.

There appear to be two outstanding theoretical questions regarding substorms in general and field changes in the geomagnetic tail in particular. These are: (1) What is the nature of the interaction at the magnetopause which causes flux transport to the geomagnetic tail and; (2) What is the physical process that produces the sudden onset, and leads to the relaxation of the tail-like field configuration. The fact that the interplanetary field direction influences the magnetopause interaction is an important clue to the first question but more measurements at the magnetopause are needed to unambiguously distinguish between the principle competing alternatives of field reconnection or viscious drag. A detailed high-time-resolution, muti-experiment study of the magnetopause should contribute greatly to the answer to the first question.

Measurements in the 6-10R_E region near the equatorial plane where the onset apparently occurs first might yield some insight to the second question. Also the collapse of the tail field is not adequately understood. More earth-satellite differential timing studies are needed to determine the precise time sequence of events in different regions. Any variation with longitude of the tail field collapse is particularly important to understand.

Finally the physics of the field aligned currents must be understood. However, before sheet currents can be explained theoretically, further analysis of the low altitude perturbations is needed to determine the relative north-south positions of the double sheet currents and any possible dependence of this positioning on longitude. If no consistent positioning of the 2 dimensional current sheets is found, one dimensional current filaments might provide an equally good explanation for the measurements. Further spacecraft measurements are needed to confirm the presence of net field aligned currents in various longitude regions as has been suggested on the basis of indirect measurements and ground observations. Time variations of these current systems must be studied in relation to the various other phenomena occurring in the geomagnetic tail before their generation can be understood.

FIGURE CAPTIONS

Figure 1 Magnetic field in the geomagnetic tail during two substorms. The magnetic field is described by the magnitude F, latitude Θ, longitude ϕ, and Z field component in solar magnetospheric coordinates. The occurrence of substorms is indicated by the geomagnetic AE index. Data illustrate the field increase during the early phases of the substorm and the subsequent decrease and increase of the Z_{SM} component. The spacecraft is located at solar magnetospheric position $X=-29R_E$, $Y=11R_E$, $Z=0R_E$ and Z' represents the estimated distance from the expected location of the neutral sheet (Fairfield and Ness, 1970).

Figure 2 Comparison of interplanetary plasma and field data with the geomagnetic tail during two substorms. Solar wind momentum flux, internal energy and interplanetary magnetic field latitude angle α are plotted along with the IMP 4 tail magnetic field data of Fairfield and Ness. Two magnetic substorms have their maxima at 12:45 and 16:45. Plasma parameters show no significant changes during the substorm whereas the intervals of southward field correspond to the tail field increase and the occurance of substorms. The spacecraft is located at $X=-25R_E$, $Y=-9R_E$, $Z=-8R_E$.

Figure 3 Magnetic field fluctuations between 18.5 and $6.9R_E$ near the equatorial plane as observed by OGO-5. The three solar magnetospheric field components are shown along with the field magnitude $|B|$. Three increases in B_Z are associated with decreases in B and indicate the relaxation of the field to a more dipolar configuration. (Russell et al., 1971).

Figure 4 Magnetic field variations during three substorms as seen by the ATS-1 spacecraft in a synchronous orbit at $6.6R_E$. The three components of the field are H parallel to the earth's surface and directed northward, V radially outward from the earth, and D directed positive eastward. Vertical dashed lines represent the onset of three substorms. The H component of the field recovers at the time of the substorm onset near midnight (1310 UT) but the recovery is delayed for the substorm in the evening sector (0410 UT). (McPherron and Coleman, 1970).

Figure 5 Magnetic field changes observed at the synchronous orbit for substorms occuring in various longitudinal sectors. In each of the various local time sectors the H traces from ATS-1 are displayed relative to the substorm onset time as represented by a vertical dashed line. Substorm associated changes tend to correspond to the time of substorm onset in the midnight and post-midnight sectors but they are delayed relative to the onset in the pre-midnight sectors.

Figure 6 Schematic illustration of the magnetosphere field configuration at two phases of a magnetospheric substorm. The top portion illustrates the configuration early in the substorm when the plasma sheet is thin, the field is strong, the Z_{SM} component is small and many lines of force go far back into the tail. The lower portion illustrates the configuration later in the substorm when the plasma sheet has expanded, the field has decreased, the Z_{SM} component has increased and more field lines cross the equatorial plane nearer the earth (Fairfield and Ness, 1970).

Figure 7 One hour of ATS-1 data beginning 25 minutes after a substorm onset. Large fluctuations in the Z or northward component are superposed on the gradual recovery.

Figure 8 Demonstrating identical perturbations at ATS-1 and Honolulu at the time of a substorm onset at College. This figure conclusively demonstrates that the substorm-associated currents producing the perturbations at 6.6R and at the subsatellite point are located in the outer magnetosphere and not the ionosphere (Cummings et al., 1968).

Figure 9 Illustrating how the declination of the geomagnetic field would be perturbed by field aligned currents. In the top sketch currents flow in one direction only at a given longitude and the perturbations are of the opposite sign on either side of the current. In the bottom sketch the currents flow toward the ionosphere on one field line and away from the ionosphere on an adjacent field line at the same longitude so that perturbations are confined to the region between the currents.

Figure 10 A proposed magnetospheric current system. Primary features of this current system are flow along field lines from the morning magnetosphere to the ionosphere, westward flow in the ionosphere near midnight, outward flow along field lines to the magnetosphere in the evening quadrant, and eastward flow in the equatorial plane to complete the current system.

Figure 11 A low altitude perturbation measured transverse to the field direction on the magnetically aligned spacecraft 1963 38C near 9:00 LT in the auroral oval. In the bottom portion of the figure the effects of a small oscillation about the field line have been removed from the raw data displaced at the top of the figure. Data are interpreted in terms of a double sheet current system similar to that shown in the bottom portion of Figure 9.

Figure 12 Magnetic field data from an inbound pass of IMP 5 through the high latitude magnetosphere. The quantities shown are field magnitude B, the difference between the measured field and the internal reference field ΔB, inclination I, declination D and standard deviation δ. A 45γ transverse field produces the ΔD perturbation near 20:00 UT (~10:00 LT). This perturbation is explained by double sheet currents flowing in a manner similar to that shown in the bottom portion of Figure 9. (Fairfield and Ness, 1971).

Figure 13 Illustrating perturbations in the D component which sometimes accompanying the H recovery at ATS 1 near synchronous orbit.

Figure 14 Observations from the HEOS-1 spacecraft on polar cusp field lines near $12R_E$ in the geomagnetic tail during a magnetospheric substorm. The magnitude F and three cartesian components are shown along with the declination D. The declination perturbation near 7 UT is explained by current flow toward the ionosphere on auroral oval field lines near the 4:00 LT meridian of the spacecraft. The measurement gives support to the current system proposed by Akasofu and Meng.

Figure 15 Summary of field aligned current observations in the magnetosphere.

REFERENCES

Akasofu, S. I., and S. Chapman, On the asymmetric development of magnetic storm fields in low and middle latitudes, Planet. Space Sci., 12, 607-626, 1964.

Akasofu, S. I., and C. I. Meng, A study of polar magnetic substorms, J. Geophys. Res., 74, 293-313, 1969.

Armstrong, J. C. and A. J. Zmuda, Field-aligned current at 1100 km in the auroral region measured by satellite. J. Geophys. Res., 75, 7122-7127, 1970.

Atkinson, G., An approximate flow equation for geomagnetic flux tubes and its application to polar substorms, J. Geophys. Res., 72, 5373-5382, 1967a.

Atkinson, G., The Current System of Geomagnetic Bays, J. Geophys. Res. 72, 6063-6067, 1967b.

Aubry, Michel P. and Robert L. McPherron, Magnetotail Changes in Relation to the Solar Wind Magnetic Field and Magnetosphere Substorms, J. Goephys. Res., 76, 4381-4401, 1971.

Aubry, Michel P., Christopher T. Russell, and Margaret G. Kivelson, Inward Motion of the Magnetopause before a Substorm, J. Geophys. Res. 75, 7018-7031, 1970.

Behannon, K. W. and N. F. Ness, Magnetic Storms in the Earth's Magnetic Tail, J. Geophys. Res. 71, 2327-2351, 1966.

Birkeland, Kr., The Norwegian Aurora Polaris Expedition 1902-1903, Volume I, First Section, Christiania, 1908.

Bonnevier, Bjorn, Rolf Boström and Gordon Rostoker, A Three Dimensional Model Current System for Polar Magnetic Substorms, J. Geophys. Res. 75, 107-122, 1970.

Bostrom, Rolf, A Model of the Auroral Electrojets, J. Geophys. Res., 69, 4983-4999, 1964.

Bostrom, R. Currents in the ionosphere and magnetosphere, Ann. Geophys. 24, 681-693, 1968.

Cahill, L.J., Jr., Magnetosphere Inflation During Four Magnetic Storms in 1965, J. Geophys. Res. 75, 3778-3788, 1970.

Camidge, F. Paul, and Gordon Rostaker, Magnetic Field Perturbations in the Magnetotail Associated with Polar Substorms, Canadian J. Phys., 48, 2002-2010, 1970.

Choy, Lawrence,W., R. L. Arnoldy, Wentworth Potter, Paul Kintner, and Laurence J. Cahill, Jr., Field Aligned Particle Currents Near an Auroral Arc, Preprint, April 1971.

Cloutier, P. A., H. R. Anderson, R. J. Park, R. R. Vandrak, R.J.Spiger and B. R. Sandel, Detection of geomagnetically aligned currents associated with an auroral arc., J. Geophys. Res., 75, 2595-2600, 1970.

Coleman, Paul, J., Jr. and Robert L. McPherron, Fluctuations in the Distant Geomagnetic Field During Substorms: ATS 1, in particles and Fields in the Magnetosphere edited by B. M. McCormac, D. Reidel Publishing Co., Dordrecht Holland, P. 171-194, 1970.

Cummings, W. D., Asymmetric Ring Currents and the Low-Latitude Disturbance Daily Variation, J. Geophys. Res., 71, 4495-4503, 1966.

Cummings, W. D., J. N. Barfield, and P. J. Coleman, Jr. Magnetosphere Substorms Observed at the Synchronous Orbit, J. Geophys. Res., 73, 6687-6698, 1968.

Cummings, W. D. and A. J. Dessler, Field Aligned Currents in the Magnetosphere, J. Geophys. Res., 72, 1007-1013, 1967.

Fairfield, Donald H., Average and Unusual Locations of the earth magnetopause and bow shock, J. Geophys. Res. 76, Oct. 1971,

Fairfield, D. H. and N. F. Ness, Configuration of the Geomagnetic Tail During Substorms, J. Geophys. Res., 75, 7032-7047, 1970.

Fejer, J. A., The effects of energetic trapped particles on magnetosphere motions and ionospheric currents, Can. J. Phys., 39, 1409-1417, 1961.

Frank, L. A., Plasma in the Earth's Polar Magnetosphere, J. Geophys. Res., 76, 5202-5219, 1971.

Haerendel, G., P. C. Hedgecock, and S. I. Akasofu, Evidence for Field Aligned Currents During the Substorms of March 18, 1969, J. Geophys. Res., 76, 2382-2395, 1971.

Heikkila, W. J. and J. D. Winningham, Penetration of Magnetosheath Plasma to Low Altitudes through the Dayside Magnetosphere Cusps, J. Geophys. Res. 76, 883-891, 1971.

Heppner, J. P., M. Sugiura, T. L. Skillman, B. G. Ledley, and M. Campbell, OGO-A Magnetic Field Observations, J. Geophys. Res., 72, 5417-5471, 1967.

Kaufmann, Richard L., Jiann-Tsorng Horng, and Andrei Konradi, Field Line Motion During Geomagnetic Storms, U. of New Hampshire, Dept. of Phys. Preprint UNH-71-15, 1971.

McPherron, Robert L., and Paul J. Coleman, Jr., Magnetic Fluctuations During Magnetospheric Substorms, 1. Expansion Phase, J. Geophys. Res. 75, 3927-3931, 1970.

Meng, C. I., and S. I. Akasofu, A Study of Polar Magnetic Substorms, 2. Three Dimensional Current System, J. Geophy. Res., 74, 4035-4053, 1969.

Meng, C. I. and K. A. Anderson, Energetic Electrons in the Plasma Sheet out to 40 R_E, (J. Geophys. Res. 76, 873-882, 1971.

Rostoker, Gordon, and F. Paul Camidge, The Localized Character of Magnetotail Magnetic Fluctuations During Polar Magnetic Substorms, J. Geophys. Res. In press (1971).

Russell, C. T., R. L. McPherron and P. J. Coleman, Jr., Magnetic Field Variations in the Near Geomagnetic Tail Associated with Weak Substorm Activity, J. Geophys. Res. 76, 1823-1829, 1971,

Schield, M. A., J. W. Freeman, and A. J. Dessler, A source for Field-aligned currents at Auroral latitudes., J. Geophys. Res., 74, 247-256, 1969.

Sugiura, M., T. L. Skillman, B.G. Ledley, and J. P. Heppner, Propagation of the Sudden Commencement of July 8, 1966, to the Magnetotail, J. Geophys. Res., 73, 6699-6709, 1968.

Taylor, Harold E., and Francis W. Perkins, Auroral Phenomena Driven by the Magnetospheric Plasma, J. Geophys. Res., 76, 272-277, 1971.

Vasyliunas, Vytenis M., Mathematical Models of Magnetosphere Convection and its Coupling to the Ionosphere, Particles and Field in the Magnetosphere, edited by B. M. McCormac, D. Reidel Publishing Co., Dordrecht Holland, 1970, p.60-71.

Winningham, J. David Characteristics of Magnetosheath Plasma Observed at Low Altitudes in the Dayside Magnetospheric Cusps, presented at the Summer Institute on Earth's Particles and Fields, Cortina, Italy, 1971.

Zmuda, A. J., J. H. Martin, and F. T. Heuring, Transverse Magnetic Disturbances at 1100 km in the Auroral Region, J. Geophys. Res., 71, 5033-5045, 1966.

Zmuda, A. J., F. T. Heuring and J. H. Martin, Dayside Magnetic Disturbances at 1100 Kilometers in the Auroral Oval, J. Geophys. Res. 72, 1115-1117, 1967.

Zmuda, A.J., J. C. Armstrong and F. T. Heuring, Characteristics of Transverse Magnetic Disturbances Observed at 1100 Kilometers in the Auroral Oval, J. Geophys. Res., 75, 4757-4762, 1970.

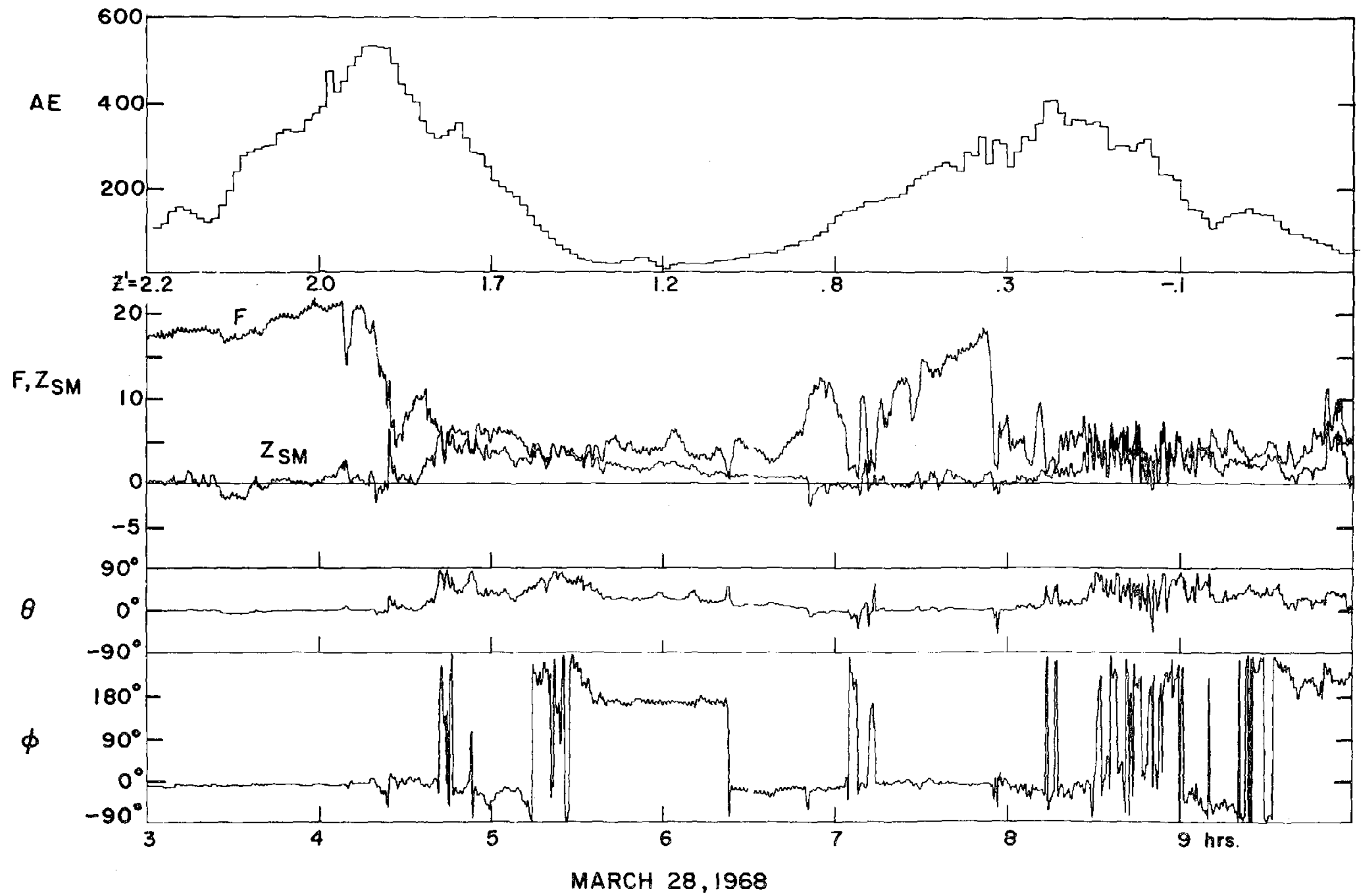

AE
600
400
200
F, Z_{SM}
Z'=2.2
2.0
1.7
1.2
.8
.3
-.1
20
10
0
-5
F
Z_{SM}
θ
90°
0°
-90°
φ
180°
90°
0°
-90°
3
4
5
6
7
8
9 hrs.
MARCH 28, 1968

Figure 1

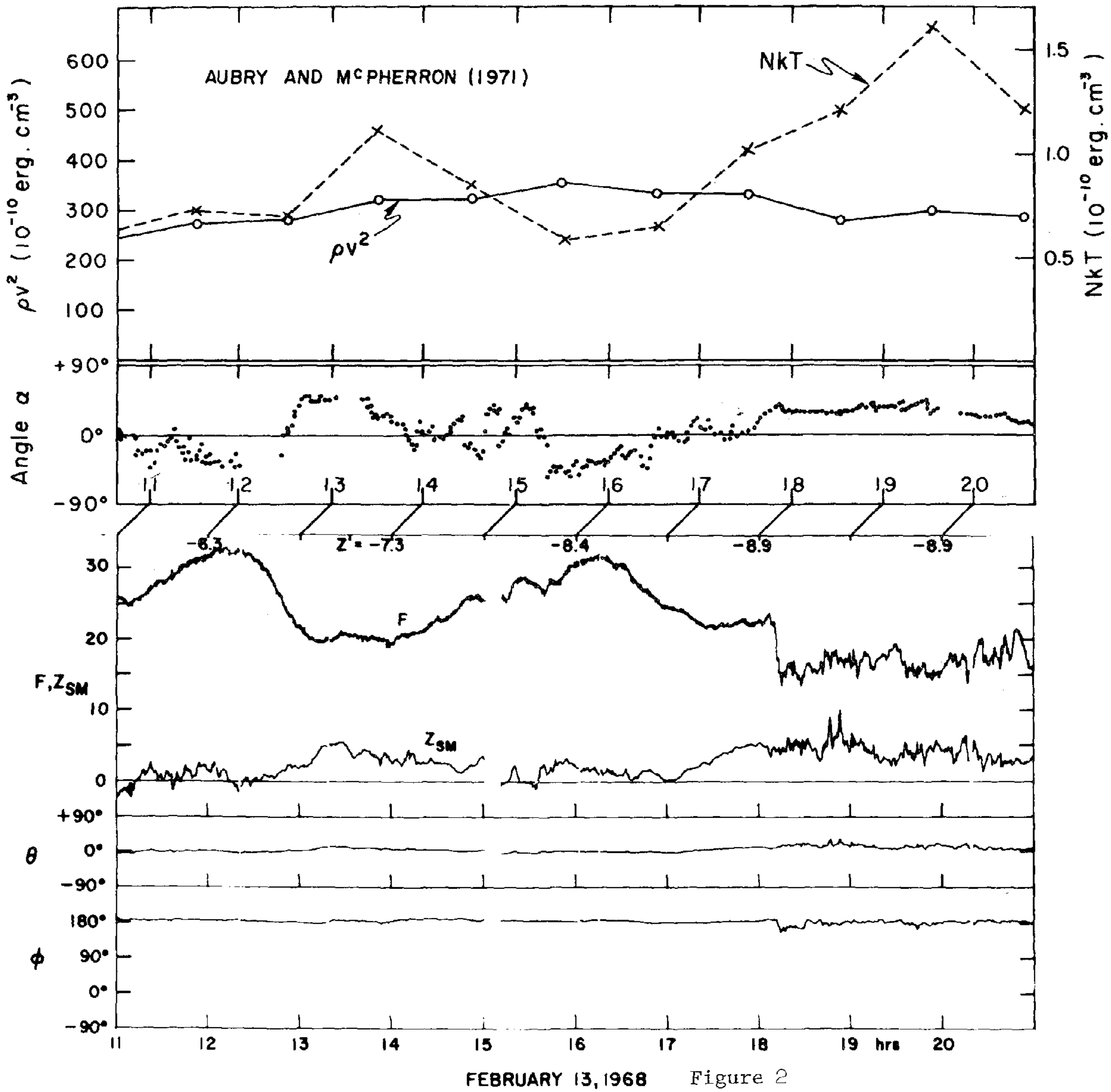
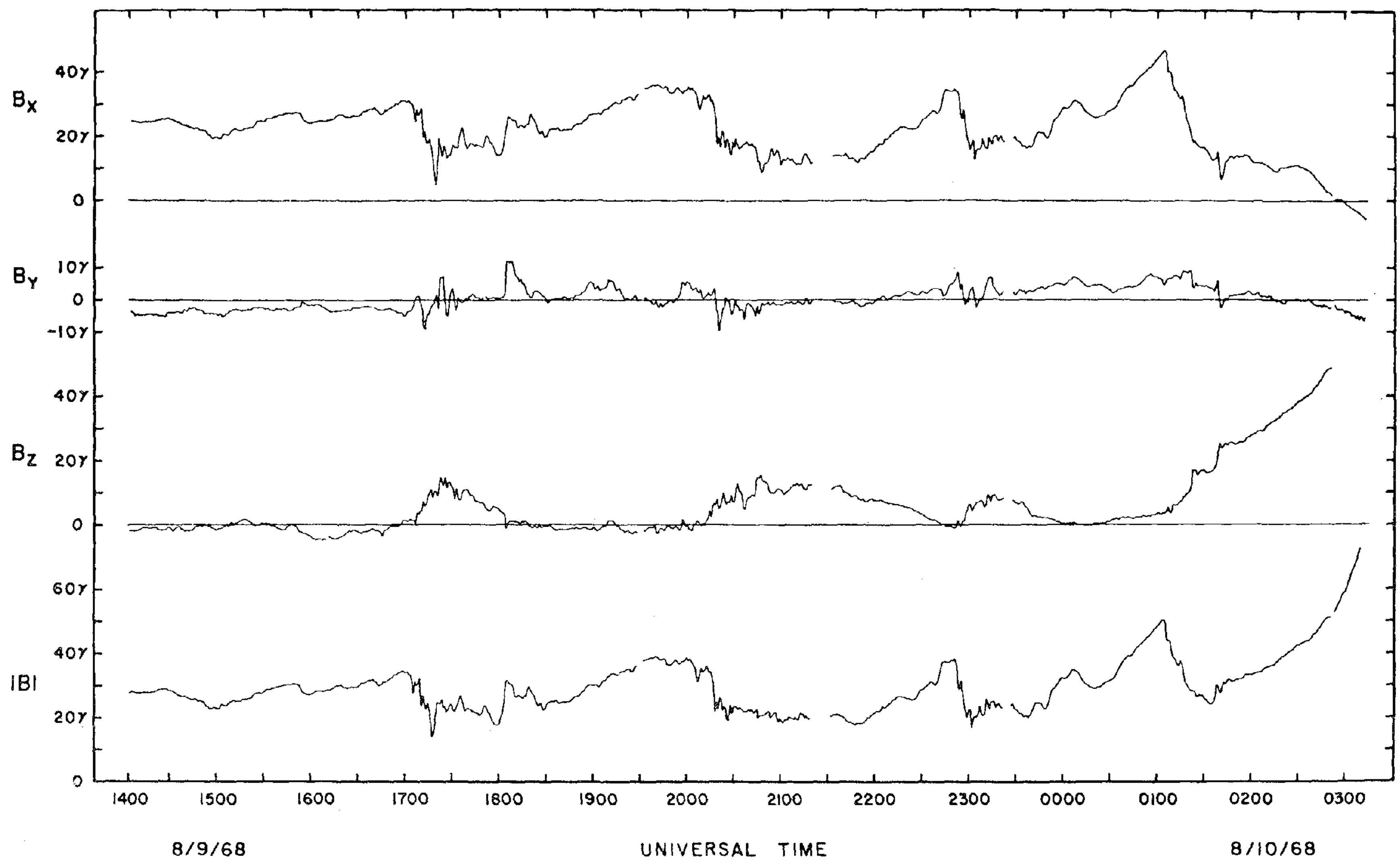

AUBRY AND McPHERRON (1971)
NkT
ρv²
ρv² (10⁻¹⁰ erg. cm⁻³)
NkT (10⁻¹⁰ erg. cm⁻³)
Angle α
Z' = -7.3
-6.3
-8.4
-8.9
-8.9
F
Z_SM
F, Z_SM
θ
φ
hrs
FEBRUARY 13, 1968

Figure 2



B_X
40γ
20γ
0
B_Y
10γ
0
-10γ
B_Z
40γ
20γ
0
|B|
60γ
40γ
20γ
0
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
0000
0100
0200
0300
8/9/68
UNIVERSAL TIME
8/10/68

Figure 3

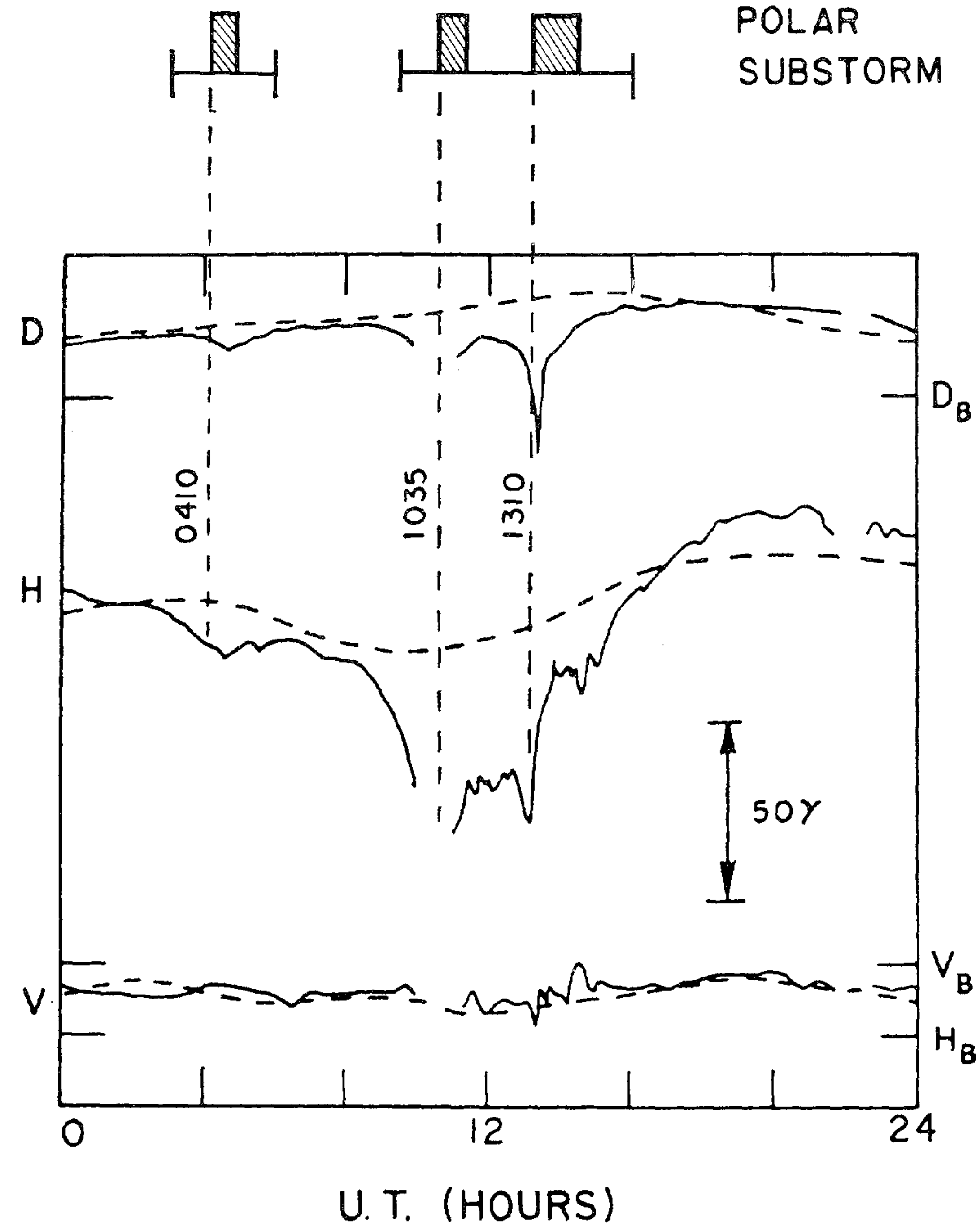


Figure 4

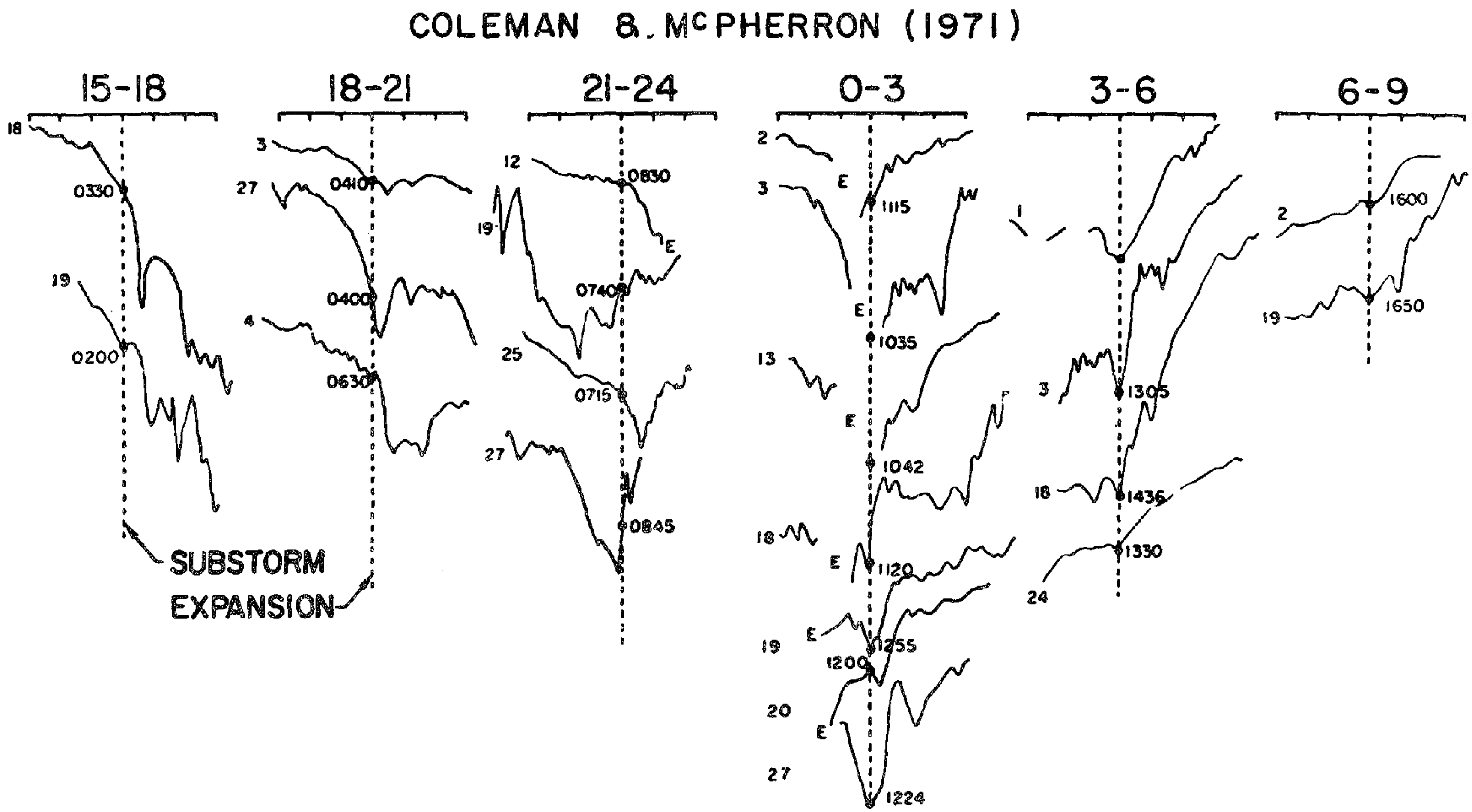
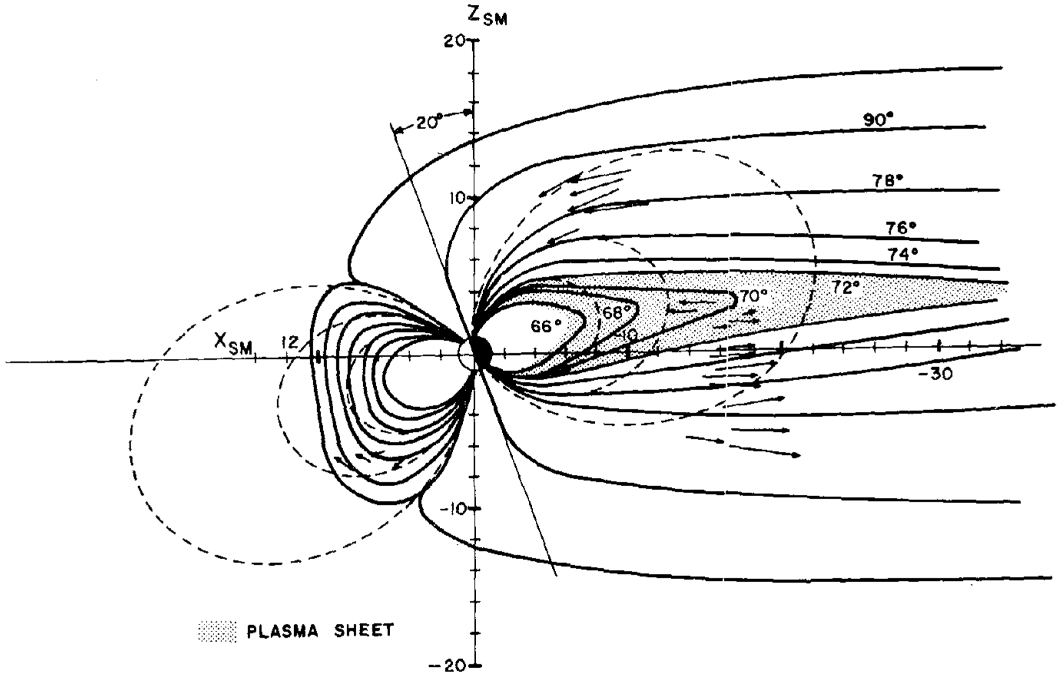
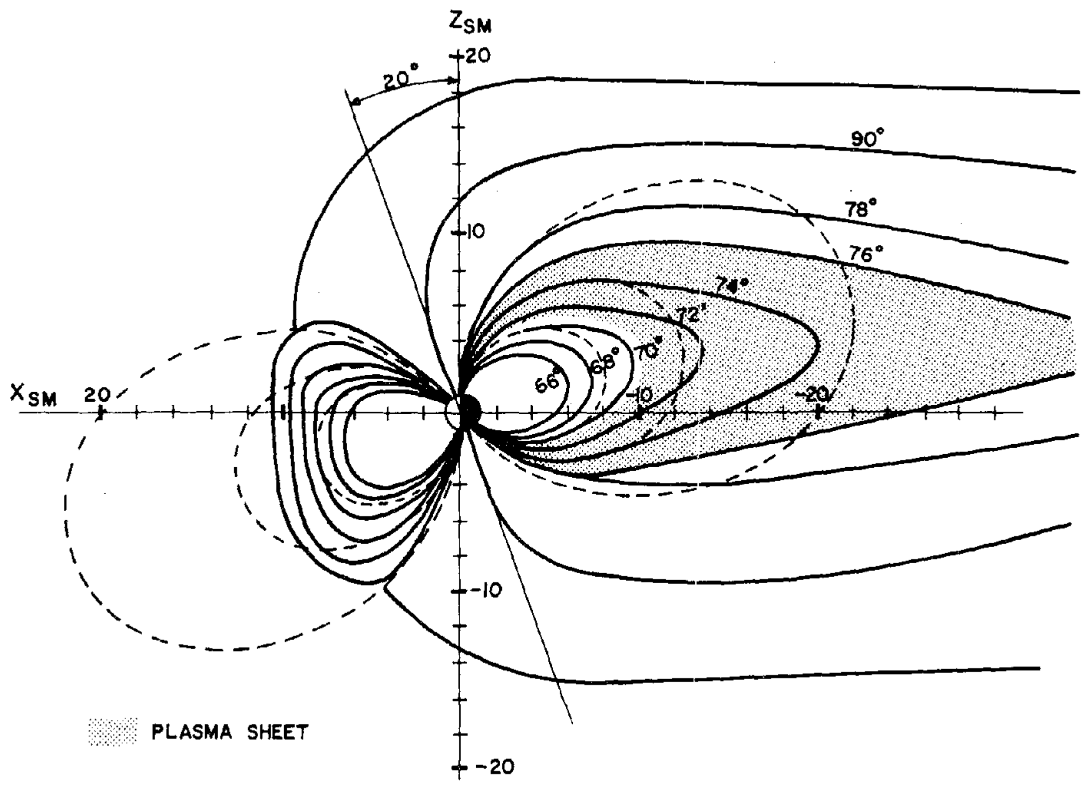

COLEMAN & McPHERRON (1971)
15-18
18-21
21-24
0-3
3-6
6-9
18
0330
19
0200
3
27
0410
0400
4
0630
12
0830
19
E
0740
25
0715
27
0845
2
3
E
1115
W
E
1035
13
E
1042
18
E
1120
19
E
1255
1200
20
E
27
1224
1
3
1305
18
1436
1330
24
2
1600
19
1650
SUBSTORM
EXPANSION

Figure 5



PRE-SUBSTORM MAGNETOSPHERE



QUIET OR POST-SUBSTORM MAGNETOSPHERE

Figure 6

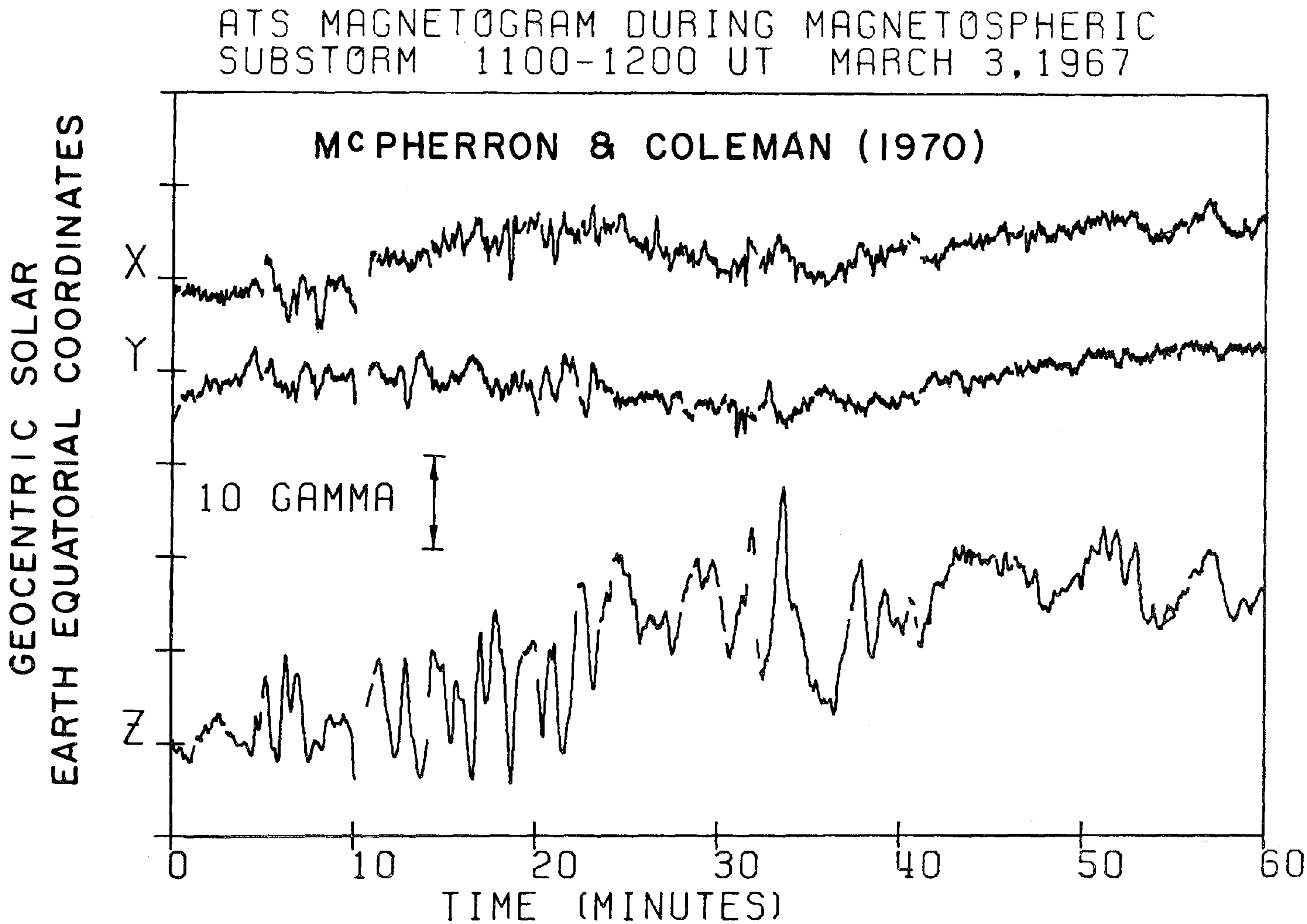

ATS MAGNETOGRAM DURING MAGNETOSPHERIC
SUBSTORM 1100-1200 UT MARCH 3,1967
McPHERRON & COLEMAN (1970)
GEOCENTRIC SOLAR
EARTH EQUATORIAL COORDINATES
X
Y
Z
10 GAMMA
0
10
20
30
40
50
60
TIME (MINUTES)

Figure 7

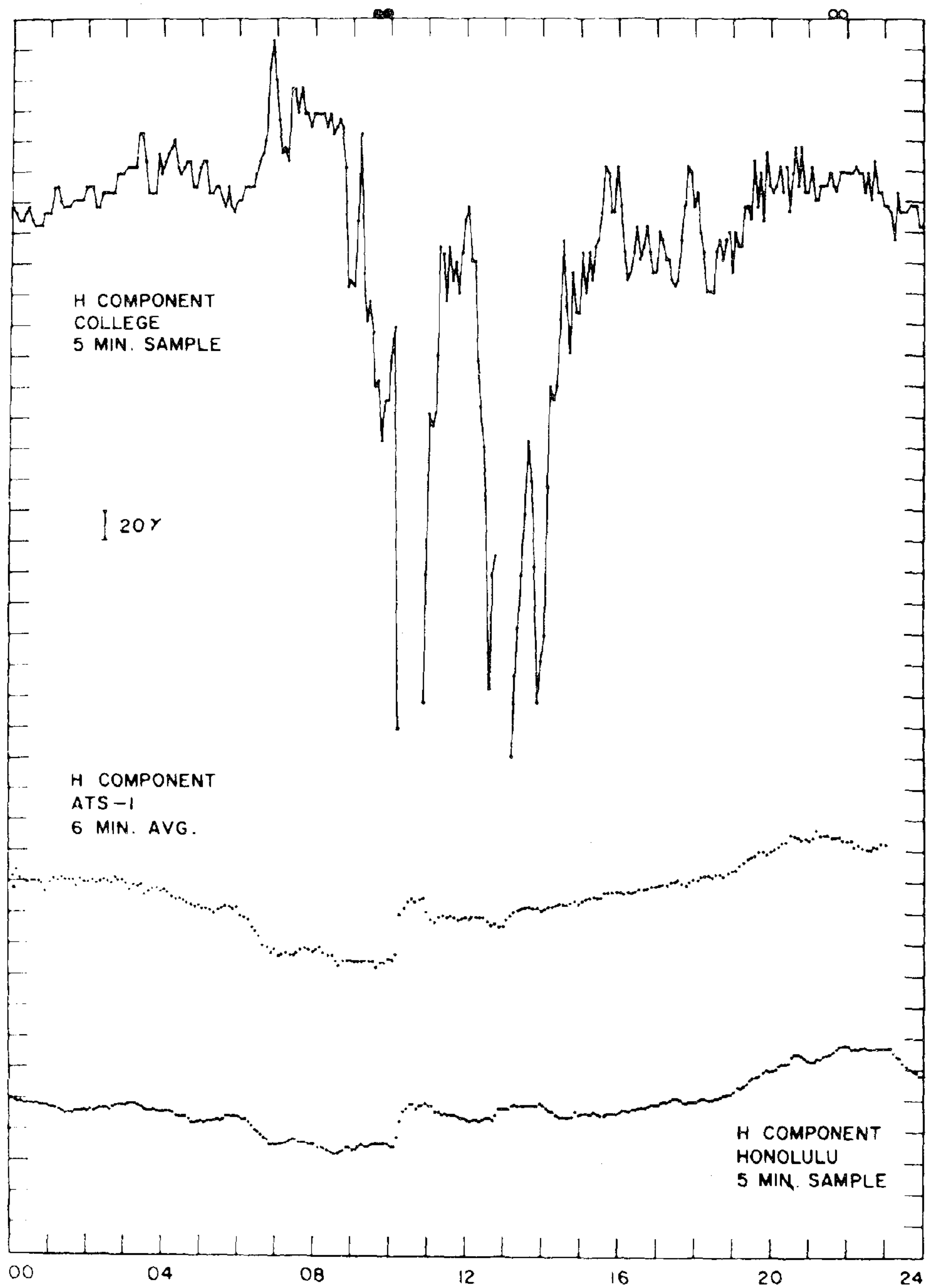

H COMPONENT
COLLEGE
5 MIN. SAMPLE
20γ
H COMPONENT
ATS-I
6 MIN. AVG.
H COMPONENT
HONOLULU
5 MIN. SAMPLE
00
04
08
12
16
20
24

Figure 8

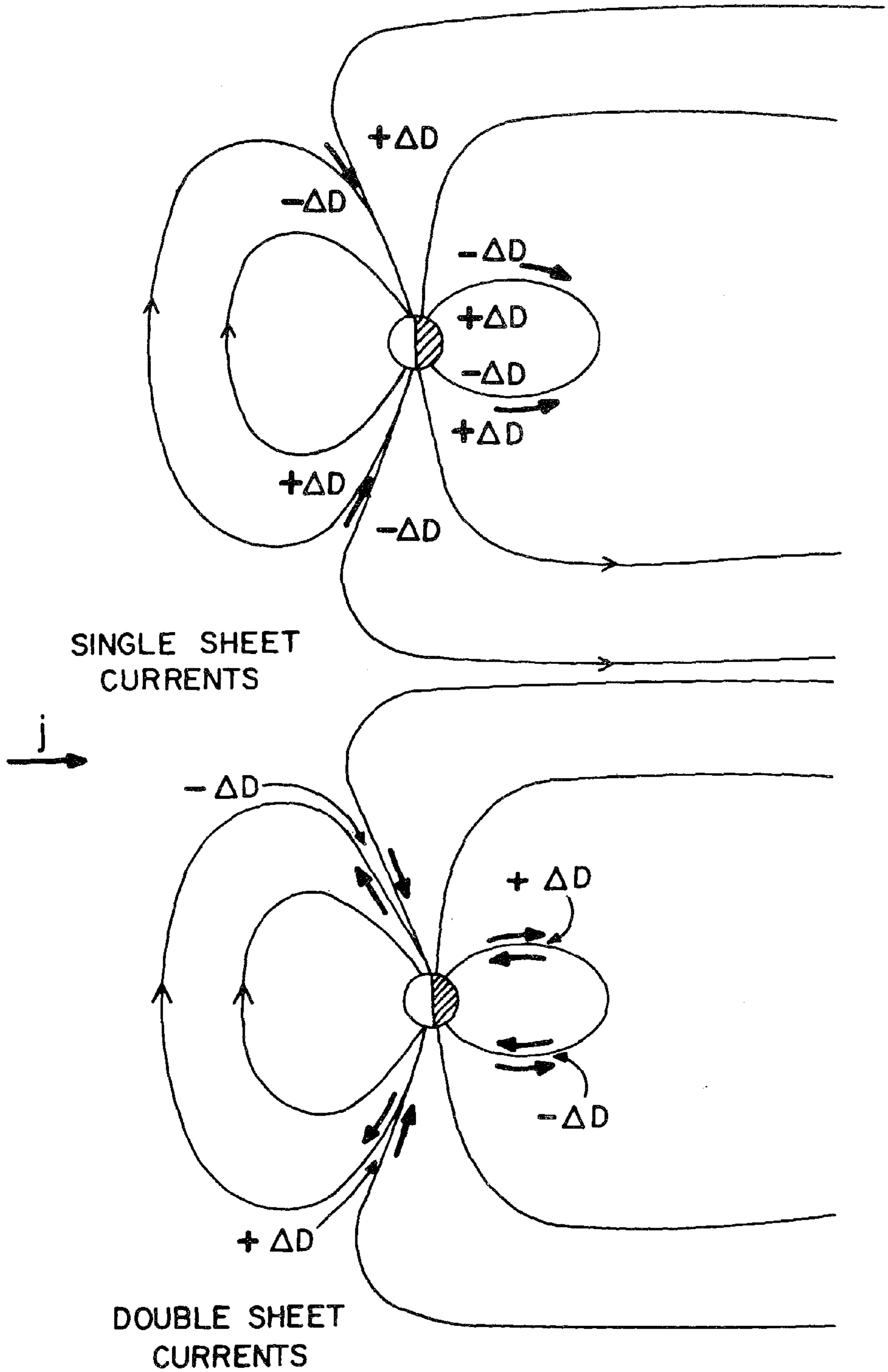

+ΔD
-ΔD
-ΔD
+ΔD
-ΔD
+ΔD
+ΔD
-ΔD
SINGLE SHEET CURRENTS
j
- ΔD
+ ΔD
-ΔD
+ ΔD
DOUBLE SHEET CURRENTS

Figure 9

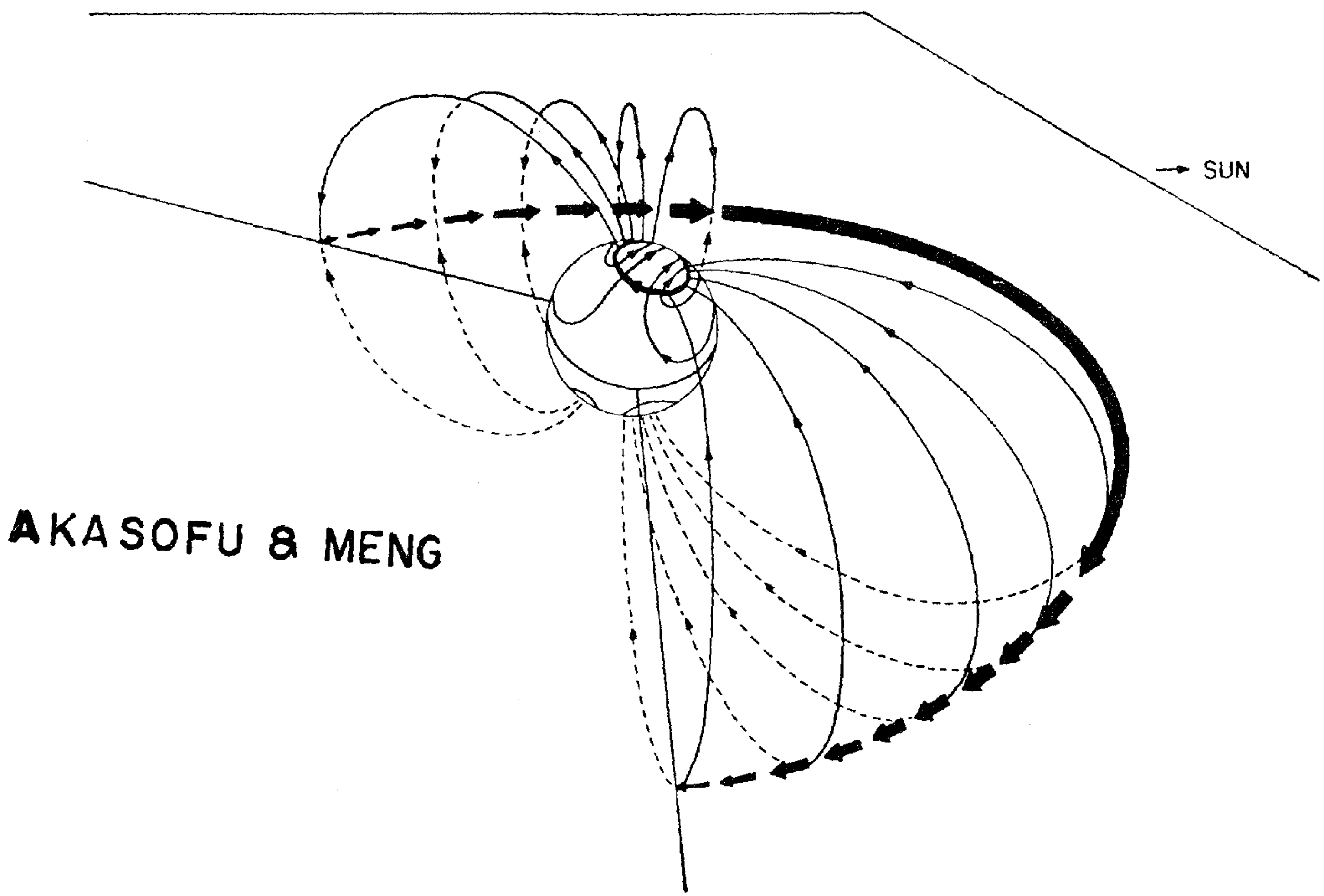


Figure 10

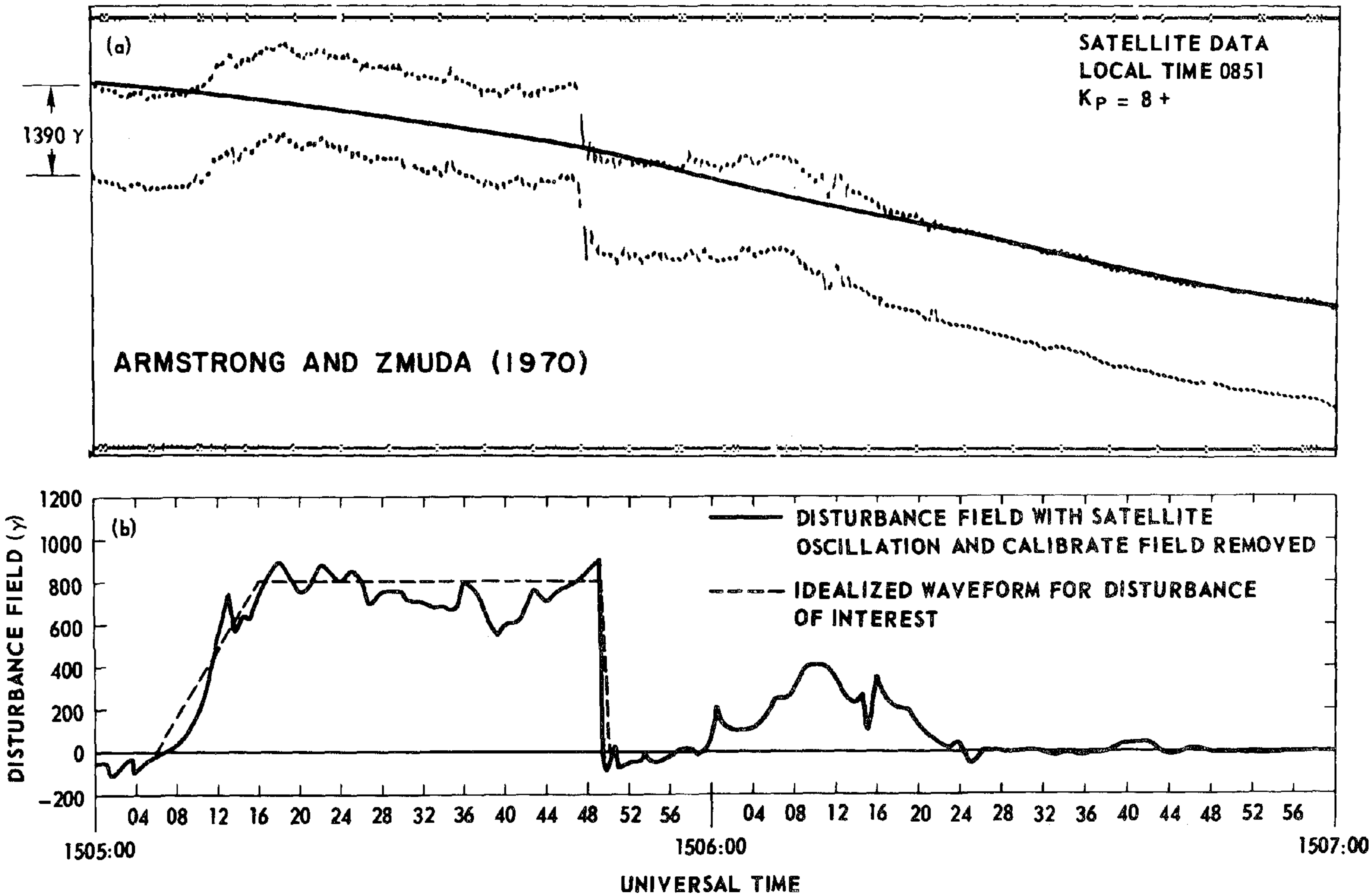
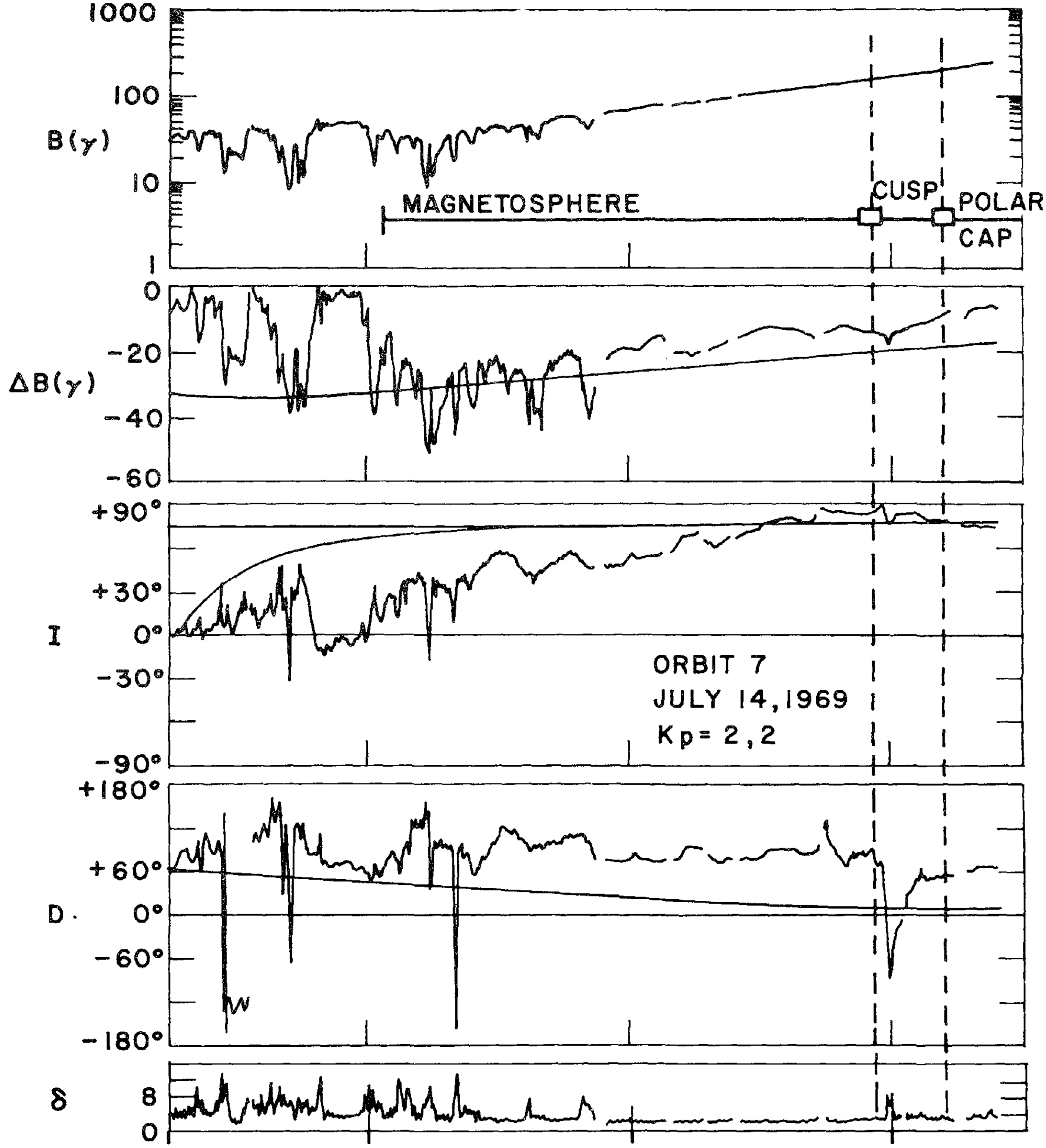

(a)
SATELLITE DATA
LOCAL TIME 0851
K_P = 8+
1390 γ
ARMSTRONG AND ZMUDA (1970)
(b)
DISTURBANCE FIELD WITH SATELLITE OSCILLATION AND CALIBRATE FIELD REMOVED
IDEALIZED WAVEFORM FOR DISTURBANCE OF INTEREST
DISTURBANCE FIELD (γ)
1200
1000
800
600
400
200
0
−200
1505:00
04 08 12 16 20 24 28 32 36 40 44 48 52 56
1506:00
04 08 12 16 20 24 28 32 36 40 44 48 52 56
1507:00
UNIVERSAL TIME

Figure 11



		18:00	19:00	20:00
GM LAT	61°	62°	64°	67°
GM LONG	349°	348°	344°	338°
R	10.5	10.2	8.6	6.8
χ_{SS}	33°	33°	31°	29°

Figure 12

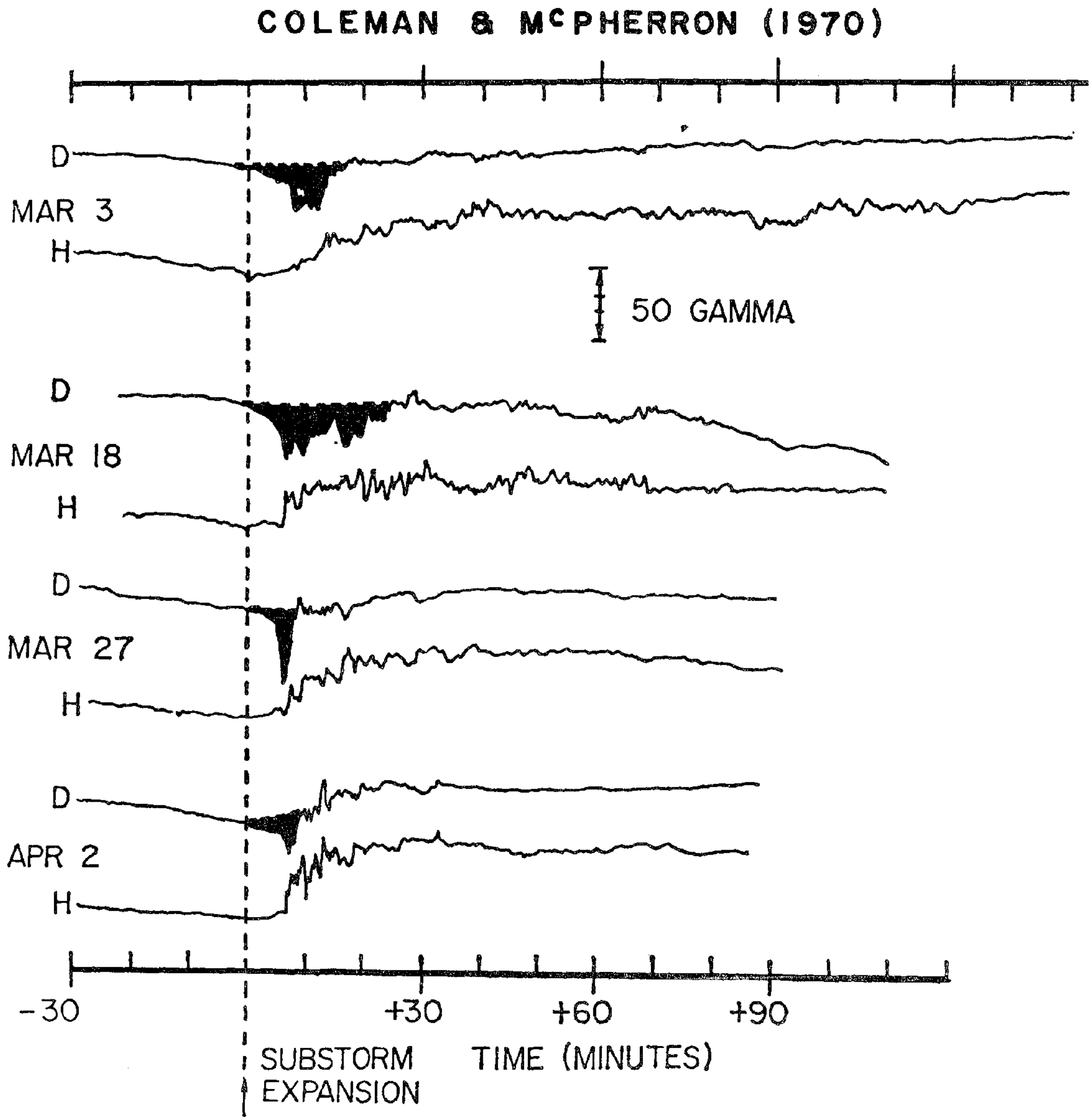
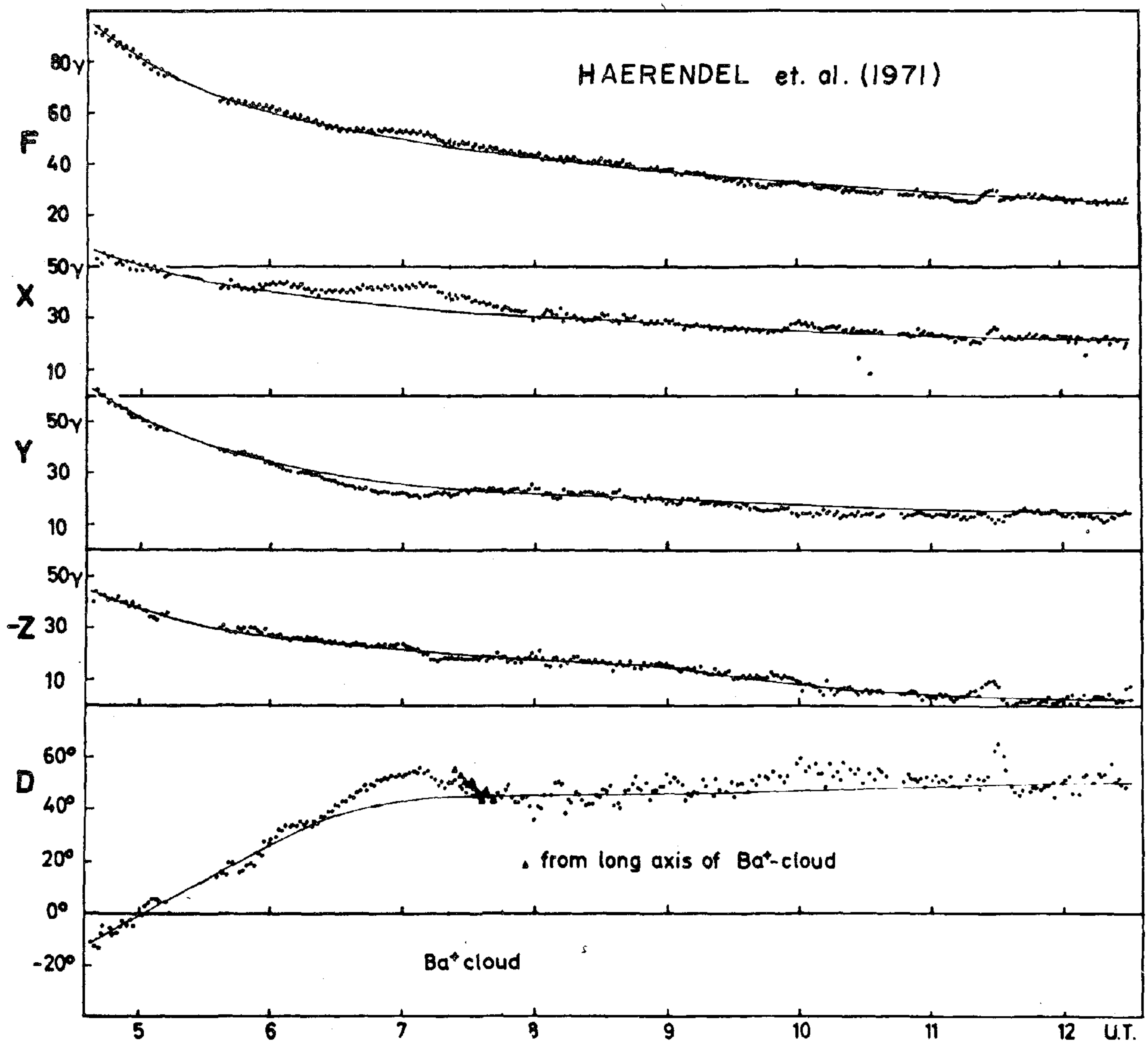
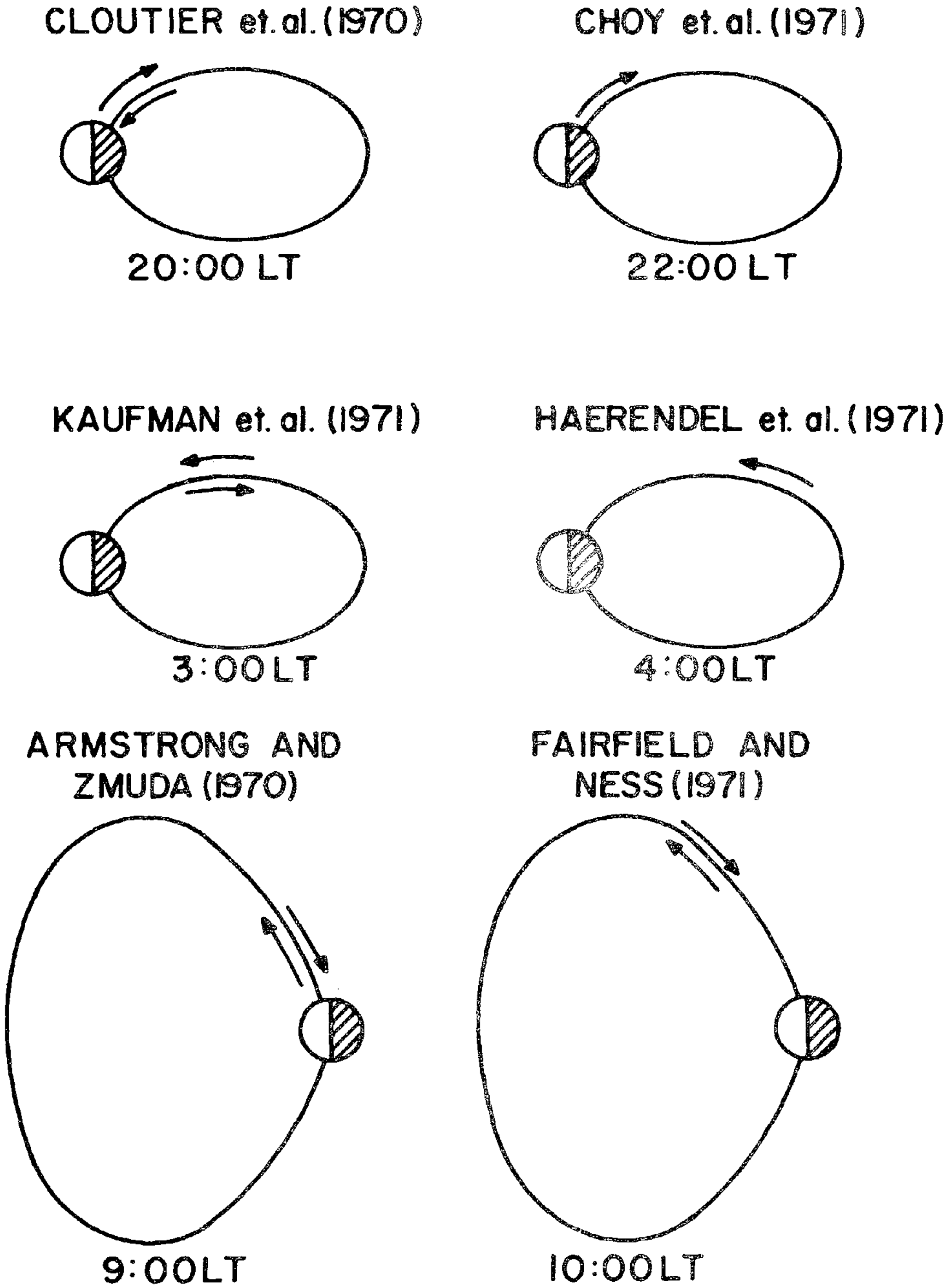

COLEMAN & McPHERRON (1970)
D
MAR 3
H
50 GAMMA
D
MAR 18
H
D
MAR 27
H
D
APR 2
H
-30
+30
+60
+90
SUBSTORM
EXPANSION
TIME (MINUTES)

Figure 13



HAERENDEL et. al. (1971)
F
80γ
60
40
20
X
50γ
30
10
Y
50γ
30
10
-Z
50γ
30
10
D
60°
40°
20°
0°
-20°
from long axis of Ba⁺-cloud
Ba⁺ cloud
5
6
7
8
9
10
11
12
U.T.

Figure 14



CLOUTIER et. al. (1970)
20:00 LT
CHOY et. al. (1971)
22:00 LT
KAUFMAN et. al. (1971)
3:00 LT
HAERENDEL et. al. (1971)
4:00 LT
ARMSTRONG AND ZMUDA (1970)
9:00 LT
FAIRFIELD AND NESS (1971)
10:00 LT

Figure 15