Planet. Space Sci. 1972, Vol. 20, pp. 1521 to 1539. Pergamon Press. Printed in Northern Ireland

SUBSTORM RELATED CHANGES IN THE GEO-MAGNETIC TAIL: THE GROWTH PHASE

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Abstract—Changes in the configuration of the geomagnetic tail are known to play a fundamental role in magnetospheric substorms. Observations with the UCLA magnetometer on the eccentric orbiter OGO-5 indicate that the most pronounced changes in the midnight meridian occur in the cusp between 8 and 11 R_e. In order to organize the observations it is necessary to separate effects on the tail due to the solar wind magnetic field and effects due to substorms. Provided there are no changes in the solar wind there are two distinct phases of a substorm in the near tail: a growth phase and an expansion phase. During each phase the observations depend on the location of the satellite relative to the plasma sheet boundaries. Far behind the Earth is the pure tail region which consists of the lobe and the plasma sheet. In the lobe the field magnitude is characteristically enhanced relative to the dipole. Closer to the Earth is a region of transition. The field magnitude is close to that of the dipole but its orientation is distorted forming a cusp-like field line. Near the Earth is a region of depressed field. Here the field magnitude is much less than that of the dipole, but its orientation is similar. The growth phase of a substorm appears to be the direct consequence of the onset of a southward solar wind magnetic field. In the pure tail region the lobe field begins to increase in magnitude and the plasma sheet thins. The transition region moves earthward and the field lines become more tail-like as the field magnitude increases. In the inner region of depressed field, the field magnitude decreases rapidly. The onset of the expansion phase appears to be a process internal to the magnetosphere and independent of the solar wind. In the depressed field region there is a rapid, turbulent increase in field magnitude. In the transition region there is a sudden decrease in the field magnitude and a return to dipolar orientation. In the tail region the plasma sheet expands rapidly with the field becoming quite dipolar, decreasing slowly in the lobe of the tail.

INTRODUCTION

Recently there has been great interest in the question of whether magnetospheric substorms have a preliminary phase prior to the onset of the expansion phase. Iijima and Nagata (1968) used high latitude magnetograms and concluded that the "... pre-bay stage may be important for the creation of an unstable situation in the outer magnetosphere." Pudovkin *et al.* (1968) used low latitude magnetograms to conclude that magnetic effects began at least 1½ hr before the commencement of a polar storm in the auroral zone. McPherron (1968) used auroral zone magnetograms, micropulsations and visual auroral observations to define a substorm growth phase. Morozumi (1967) examined the correlations between VLF radio noise, ionospheric absorption, geomagnetic variations, and aurora, concluding that premidnight, substorms have an 'N-1' phase prior to the onset of the auroral substorm.

More recent work including satellite observations confirms the original reports of a substorm growth phase. Both Arnoldy (1971) and Foster *et al.* (1971) have shown statistically that there is an hour of weak geomagnetic activity in the auroral zone prior to the onset of substorm expansions. They show also the beginning of this activity is correlated with the onset of a southward component of the solar wind magnetic field. Observations of plasma sheet thinning during an isolated substorm reported by Hones *et al.* (1971) indicate a gradual 'development phase' prior to expansion onset. A similar growth phase is seen in tail magnetic field observations which show an increase in tail field magnitude as well as plasma sheet thinning (Aubry and McPherron, 1971). Balloon observations of ionospheric electric fields (Mozer, 1971) also show a westward field in the auroral zone for more than an hour prior to expansion onset.

More detailed examinations of ground data also supporting the existence of the growth phase include the recent reports of McPherron (1970); Iijima and Nagata (1971); Kaneda (1971); Kokubun (1971); and references therein. A recent report by Nishida (1971) links the previous work of this author on DP-2 fluctuations to early phases of the polar substorm.

On a basis of the preceding reports, we conclude that magnetospheric substorms have a preliminary phase prior to the onset of the expansion phase. Intuitively, the existence of such a preliminary phase is satisfying because it provides an interval of time during which the magnetosphere can extract energy from the solar wind and store it for later release. This stored energy grows until at some instant, the magnetosphere becomes unstable and releases the stored energy in the form of particle energization, particle precipitation, and Joule heating. This release of energy is the more familiar expansion phase.

The intuitive idea has received considerable support from the recent theoretical work of Coroniti and Kennel (1971). A model of the energy storage or 'growth phase' based on their work provides a useful way of organizing the experimental observations to be reviewed below. To motivate this later presentation, we summarize this model below. A detailed discussion of this model and its experimental justification appears in the work of McPherron *et al.* (1972).

A southward component of the solar wind magnetic field causes magnetic field merging to begin at the nose of the magnetosphere. Ionospheric line tying impedes the internal convection of plasma to the merging point forcing the neutral point to move radially inward. This erosion of flux causes the polar cusps to move equator-ward and weak ionospheric currents to flow in the dayside auroral oval. The eroded flux is transported by the solar wind and added to the tail. The decrease in cross section at the front of the magnetosphere combined with an increase in the tail, increases the flaring angle of the magnetopause. This, in turn, causes an enhancement of the normal stress on the boundary which requires an increase in the tail field strength to balance the larger stress. During the transport process, polarization of the magnetospheric plasma produces an electrostatic field which appears in the polar ionosphere via perfectly conducting field lines. This electric field drives field aligned and ionospheric currents in the polar cap. Eventually the newly eroded field lines recombine at a distant neutral line behind the Earth driving plasma toward the Earth. This plasma is confined by the last closed field line, i.e. the field line passing through the neutral line. This field line corresponds to the boundary of the plasma sheet which, because of the convection electric field, drifts toward the neutral sheet. Hot plasma particles convecting earthward, gradient and curvature drift across the electric field, gaining energy and creating the inward extension of the tail current. The resulting increase in tail field gradient at the Earth's dipole is required to balance the greater tangential drag due to the southward component. Because of the asymmetric field due to corotation and the shorter lifetime of electrons, the inward extension of the tail current develops asymmetrically, producing the partial ring current centered at dusk. As is the case in the polar cap ionosphere, electric fields associated with inward convection drive field aligned and ionospheric currents in the auroral oval. Similarly, the electric field associated with the partial ring current drives field aligned and eastward ionospheric currents. Changes in the magnetic field configuration redistribute radiation belt particles causing electron precipitation. Finally, close to the inner edge of the tail current the plasma sheet thins dramatically and an expansion phase results.

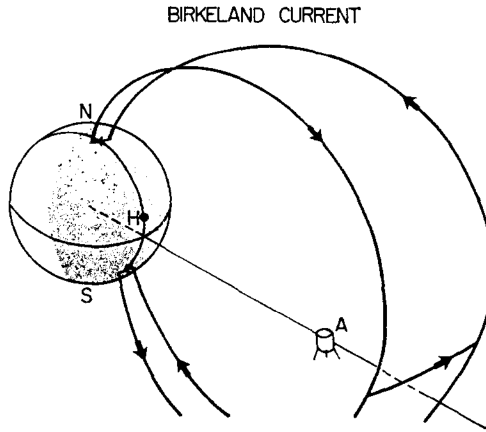

FIG. 1. THREE DIMENSIONAL EQUIVALENT CURRENT THAT EXPLAINS THE MAGNETIC FIELD OBSERVATIONS DURING SUBSTORM EXPANSION PHASE.

Simultaneous observations in the auroral zone, midlatitude (H-Honolulu), synchronous orbit (A-ATS 1), and the near tail are consistent with this system. These observations are respectively, negative bays, midlatitude positive bays, recovery in H (dipole) component and a collapse of the near tail field.

The preceding model of the sequence of events occurring during the substorm growth phase is dependent on identification of the onset of the expansion phase. According to Akasofu (1968), this begins when the southern-most auroral arc near midnight is suddenly activated. Accompanying this activation is a sudden enhancement of the auroral electrojet near midnight and subsequent westward surge of the westward end of this current. As discussed by a number of authors, a three dimensional equivalent current system shown schematically in Fig. 1 can explain the ground magnetic observations in the auroral zone quite well (Akasofu and Meng, 1969; Meng and Akasofu, 1969; Fukushima, 1969; Bonnevier *et al.*, 1970; and Kisabeth and Rostoker, 1971).

The same three dimensional current system discussed by these authors accounts for the observations at midlatitude magnetic observatories as well. In fact, the sudden onset of a positive bay at midlatitudes is known to be correlated with the onset of the negative bay at high latitudes (Akasofu and Meng, 1968). This fact can be used to identify the onset of the expansion phase of substorms at midlatitude.

There seems to be a number of advantages to determining the expansion onset in the manner just discussed. First, the magnetic effects at midlatitudes are not sensitive to the exact L shell on which the field aligned and ionospheric currents flow. Furthermore, the effects of weak or isolated bays in the auroral zone will cause little effect at midlatitudes. Only those events having worldwide effects, i.e. magnetospheric substorms, will be considered.

These advantages should be compared to the situation in the auroral zone where the location of an observatory relative to the region of substorm onset is very important. Sudden changes in the auroral luminosity or the magnetic field may be considerably delayed from the actual onset. Equally important, a very weak event exactly over a station may cause disproportionately large effects at a single station. Whether these events play an important role in the magnetosphere is not presently known. Their localization in the auroral zone suggests that the total energy released during one of these events is not great. Consequently, it is our present view that these events do not represent any great change within the magnetosphere, and should be ignored in the first analysis. Thus, our discussion of the substorm growth phase given below is based on the onset of the expansion phase determined mainly from midlatitude magnetograms.

From the preceding discussion, it is clear there exists ample evidence of the existence of a substorm growth phase. As indicated above, the determination of the actual beginning and ending of this phase is a subject of considerable controversy. It was argued, however, that midlatitude magnetograms provide a good indicator of the onset of the expansion phase. Using these onset times, we will show that satellite observations of the magnetic field in the near geomagnetic tail clearly show a substorm growth phase. Furthermore, these observations are consistent with the speculative model of the substorm growth phase outlined above.

Geometry of the near tail region

It has been suspected for some time that the origin of a magnetospheric substorm is in the tail on the midnight meridian close to the Earth. Observations of the auroral substorm (Akasofu, 1968) and tail magnetic field observations (Heppner *et al.*, 1967) support this view. As shown by Fairfield (1968), the geometry of the quiet time magnetic field in this region is 'cusp-like.' As shown schematically in Fig. 2, the reason for this is the superposition of the magnetic field of the Earth's dipole and the fringing field at the inner end of the lobes of the magnetic tail.

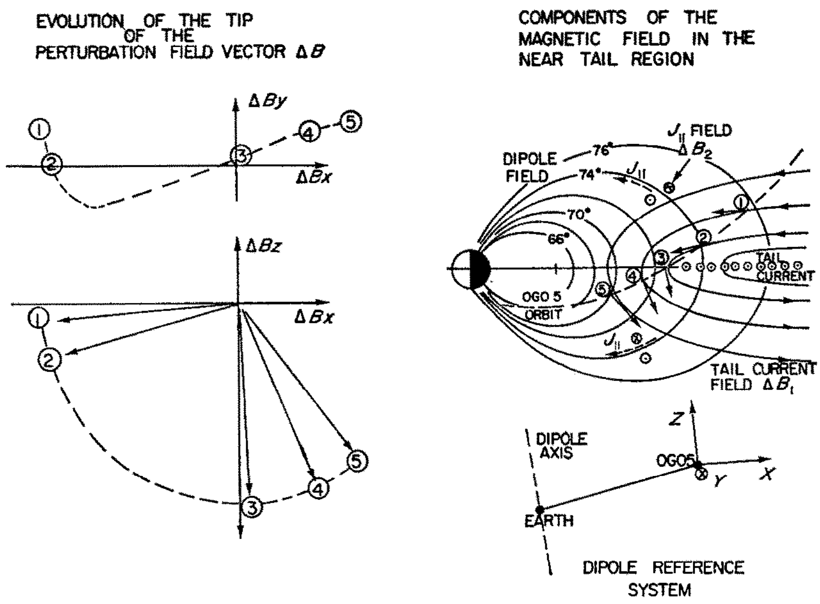

FIG. 2. SCHEMATIC FIGURE SHOWING IN UPPER RIGHT PANEL THE THREE MAIN SOURCES OF MAGNETIC FIELD IN THE NEAR TAIL REGION, EARTH'S DIPOLE, FRINGING FIELD OF THE TAIL LOBES AND FIELD ALIGNED CURRENTS.

Lower right panel illustrates convenient coordinate system for satellite field measurements. The X–Z or dipole meridian plane contains field perturbations due to the cross tail current. See, for example, the perturbations shown at lower left corresponding to typical satellite trajectory of OGO 5. The X–Y plane (perpendicular to the dipole axis passing through satellite) contains perturbations due to field aligned currents. See example at upper left.

Since it is known that the field configuration in this region changes during substorms, it is often convenient to display satellite field data in a way which reveals the origin of these changes (Aubry *et al.*, 1972). As shown in Fig. 2 by a sample satellite trajectory through this region, these changes have two sources. First, perturbations in a magnetic meridian plane are the result of changes in the strength and location of the current flowing across the center of the tail and returning on the tail boundary. Second, perturbations perpendicular to a meridian plane arise in field aligned currents, $J_{\|}$.

Thus, if the satellite field data are presented in the dipole coordinate system shown in the lower right of Fig. 2, magnetic perturbations in two orthogonal planes should reveal the sources of the field. For example, if the dipole field is subtracted from the observations along the sample trajectory shown in the figure, the perturbation vector in a meridian plane (X–Z) should evolve as shown in the lower left. Similarly, the perturbations in a plane perpendicular to the Earth's dipole axis will evolve as shown on the upper left provided the field aligned currents shown in the upper right are flowing.

Field and particle observations in the nightside cusp region on a weakly disturbed day, August 20, 1968, are shown in Fig. 3. Two weak substorms occurred during this inbound pass, as indicated by vertical dashed lines. It is quite apparent that the satellite entered the

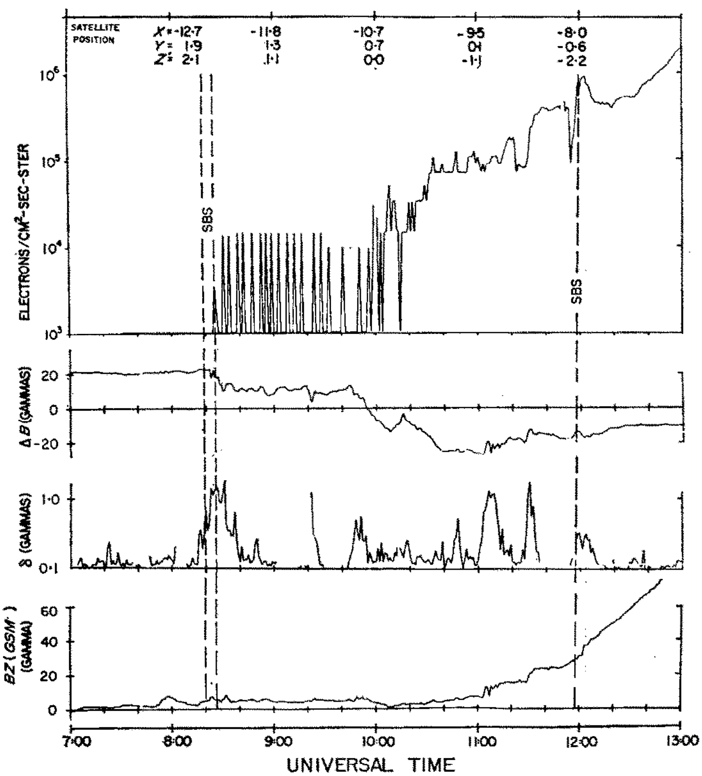

FIG. 3. TYPICAL INBOUND PASS OF OGO 5 ALONG TRAJECTORY SIMILAR TO THAT OF FIG. 2. Data include from top to bottom flux of energetic electrons ($E \geq 50$ keV), deviation of observed field magnitude from dipole magnitude, rms amplitude of magnetic field fluctuations of frequency greater than 0·07 Hz, and the Z-component of the field in GSM coordinates. Vertical dashed lines are the onset times of substorm expansions determined from midlatitude ground magnetograms.

plasma sheet nearly at the onset of the first expansion about 0825 UT. A sudden increase in the flux of electrons of $E \geq 50$ keV, a rapid decrease in the magnitude of the magnetic field, and large amplitude field fluctuations of frequency greater than 0·07 Hz are characteristic features of entry into the plasma sheet.

A further rapid decrease in the field magnitude with associated increase in the flux of energetic electrons may be due to entry into the particle cusp described by Anderson and Ness (1966), Aubry *et al.* (1972) and references therein.

One particularly obvious feature of this diagram is the transition from the lobe of the tail where the magnetic field is enhanced relative to a dipole to the inner magnetosphere where the field is depressed. Reference to Fig. 2 shows this to be expected for a satellite trajectory which passes through the plane of symmetry earthward of the inner edge of the tail current.

Figure 4 shows the actual satellite trajectory on this day. In this diagram, field lines in the model of Fairfield (1968) have been slightly distorted to agree with the vector field observations along the trajectory and the approximate tilt of the dipole axis at 1000 UT. The probable boundaries of the plasma sheet and particle cusp are drawn according to the interpretation made above. The locus of the observed perturbation vector in a meridian plane shown at the lower left is in good agreement with the expected behavior. From this plot, the satellite passed through the plane of symmetry (neutral sheet) at 1045 UT. The

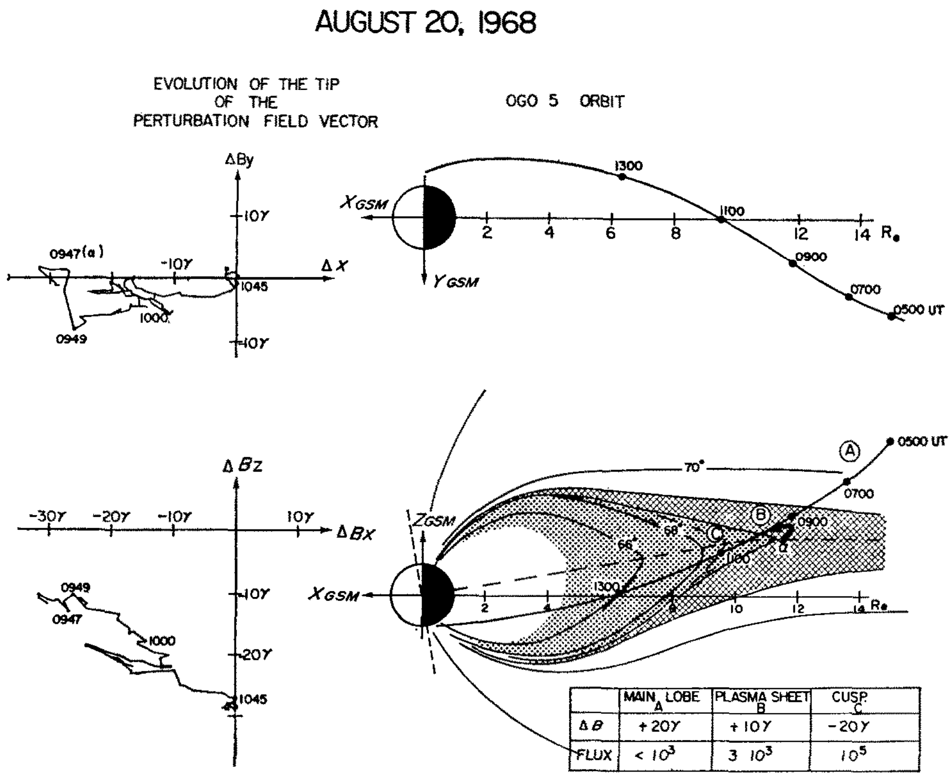

FIG. 4. INTERPRETATION OF OBSERVATIONS OF FIG. 3 USING THE DISPLAY DESCRIBED IN THE CAPTION TO FIG. 2.
Shading indicates the plasma sheet and a possible particle cusp embedded within.

perturbation vector in a plane perpendicular to the dipole axis at the upper left of the figure suggests the satellite passed through a field aligned sheet of current between 0947 and 1000 UT, just before entering the particle cusp region.

Thus, on a weakly disturbed day, magnetic field observations in the near tail region reveal a cusp-like field geometry. In addition there is some evidence that on such a day there exists an inner core or 'particle cusp' within the plasma sheet. Field aligned currents may flow on or near the boundary of this region.

Substorm effects in the near tail on a moderately disturbed day

On August 9–10, 1968, the OGO-5 satellite was inbound down out of the north lobe of the tail when a sequence of four substorms occurred (Russell *et al.*, 1971). As shown in the trajectory plot of Fig. 5, the diurnal wobble of the Earth's dipole axis caused the neutral sheet to move in such a way that the satellite was just above the sheet during each of the

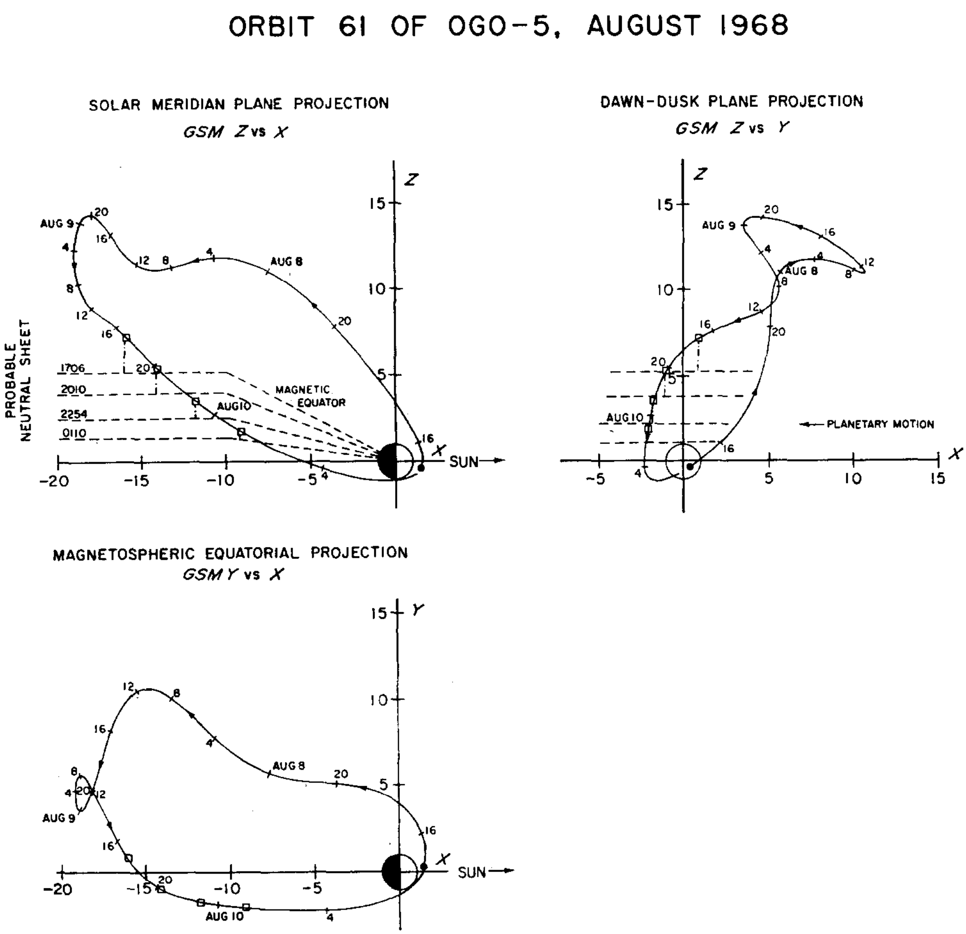

FIG. 5. TRAJECTORY OF OGO-5 SATELLITE ON AUGUST 9–10, 1968, INBOUND, DOWN OUT OF THE NORTH LOBE OF THE TAIL.

Dashed lines indicate probable position of neutral sheet at the onset times of four successive substorm expansions.

four substorms. This particular circumstance allowed the satellite to observe four almost identical events.

Components of the magnetic field in GSM coordinates are plotted in Fig. 6. Vertical lines in Figs. 7 and 8 are the onsets of substorm expansion determined from midlatitude magnetograms. Considering first the field magnitude plotted in the bottom trace of Fig. 6, we see that each expansion onset is preceded by more than an hour of steadily increasing field magnitude. In contrast, the expansion onset is followed by a rapid turbulent decrease in field magnitude. Accompanying this decrease are large fluctuations in the cross tail component of the field (*By*) and rapid increases in the dipole component (*Bz*).

The data for the first two expansions are shown in greater detail in Fig. 7. Prior to both onsets the satellite was apparently in the lobe of the tail. Electron fluxes (top trace) were below background, field magnitude was large and steadily increasing (second trace), field inclination (third trace-angle of field vector with respect to plane perpendicular to radius vector through satellite) was large, i.e. tail-like. Just after the onset of each expansion there was a sudden appearance of electrons, a decrease in field magnitude, a rotation of the field inclination towards a more dipolar configuration, large amplitude fluctuation in declination (fourth trace-angle between projections of field vector and Earth's dipole in plane perpendicular to radius vector through satellite) and large amplitude field fluctuations.

It is interesting to note that following the first expansion the plasma sheet soon thinned and the satellite re-entered the lobe of the tail. Note the drop out of electron fluxes,

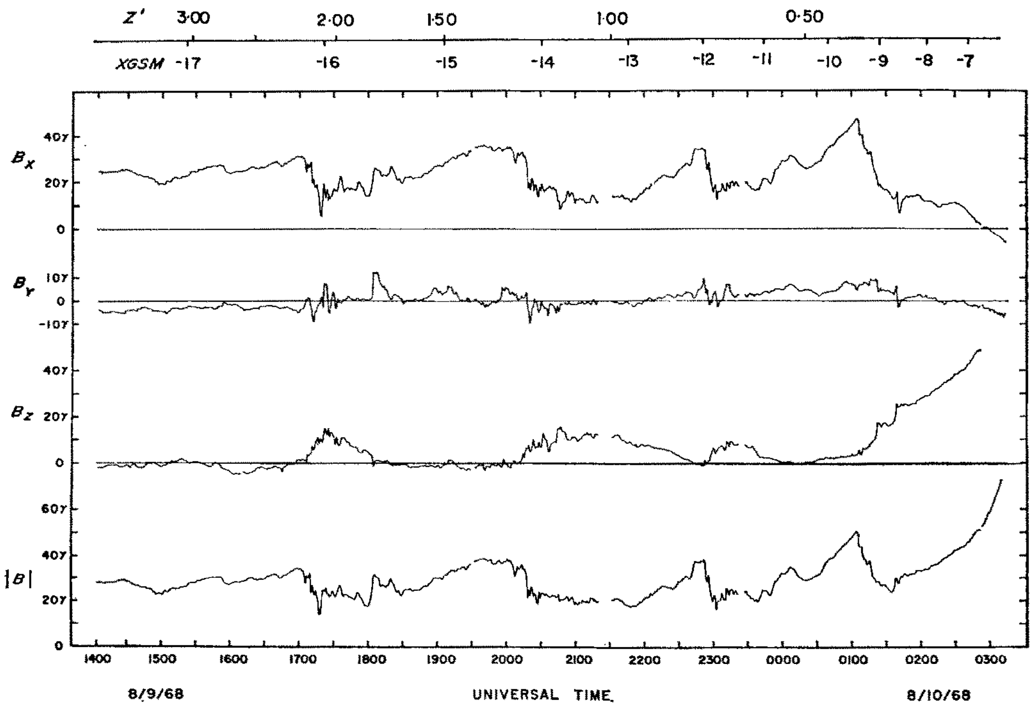

FIG. 6. UCLA FLUXGATE MAGNETOMETER OBSERVATIONS ON OGO 5 ON AUGUST 9–10, 1968. Four successive substorms cause systematic changes in the field components in relation to expansion onset. As shown in two following figures onsets are nearly at the times of peak field magnitude.

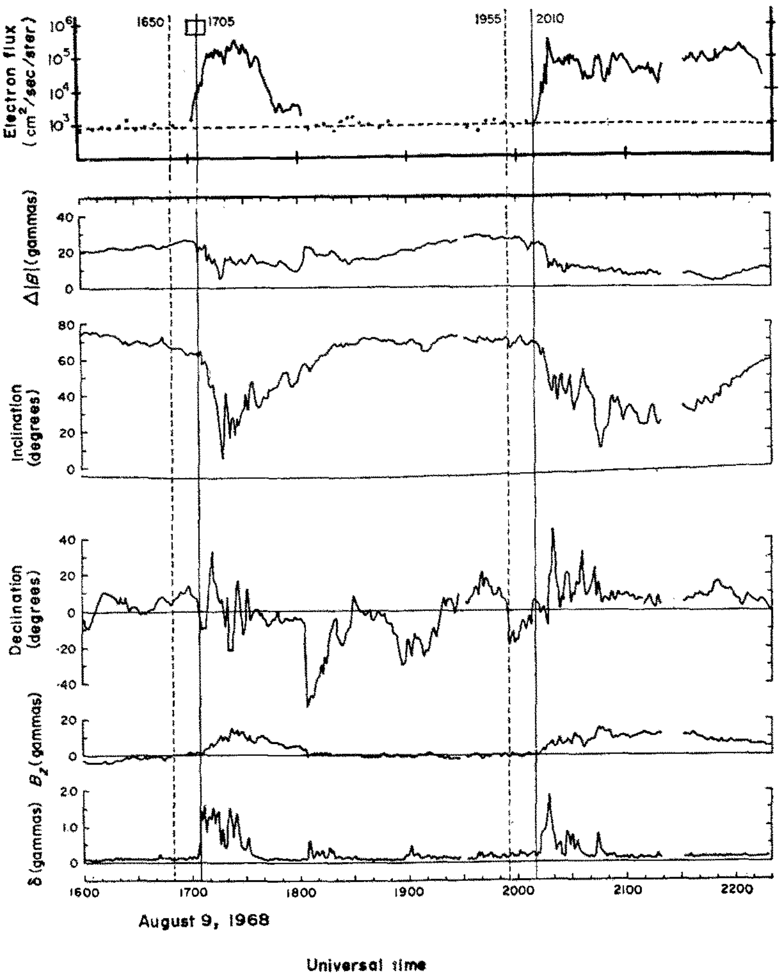

FIG. 7. DETAILS OF FIRST TWO SUBSTORM EXPANSIONS AS DESCRIBED IN TEXT.
Top panel shows flux of energetic electrons, second panel deviation of field magnitude from dipole magnitude, third and fourth panel inclination and declination angles of field vector as defined in text, fifth panel the Bz-GSM component of field, and finally the rms field fluctuations. Vertical lines are substorm expansion onsets determined by midlatitude ground magnetograms.

increase in field magnitude, declination variations and field fluctuations at approximately 1800 UT.

Observations similar to those of the preceding discussion are shown for the last two expansions in Fig. 8. As reference to Fig. 5 shows, these two substorms differ from the preceding two in that the satellite was entering the inner cusp region of the tail. This is particularly evident for the last substorm where the trend in field magnitude indicates the satellite was entering the inner region of depressed field. The most interesting feature of these events is the fact that just before each onset the electron fluxes nearly dropped below background and the field magnitude rapidly increased. This result suggests the satellite was passing out of the plasma sheet into the lobe of the tail despite its location, very close to the neutral sheet, only 10–12 R_e behind the Earth.

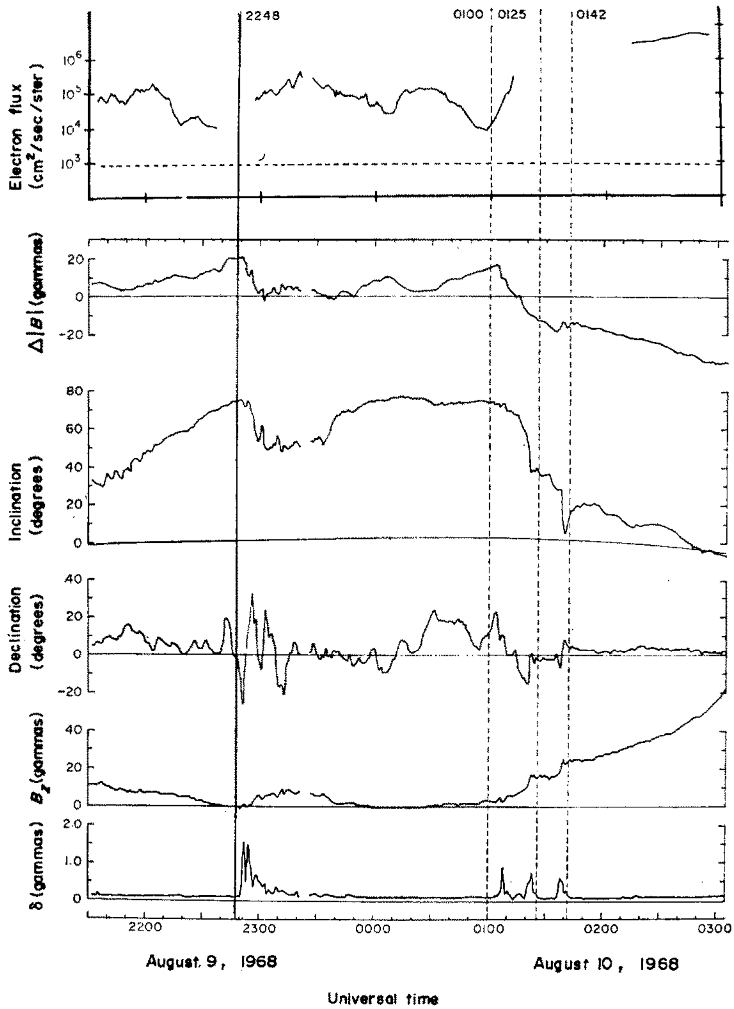

FIG. 8. LAST TWO SUBSTORMS OF AUGUST 9–10, 1968, IN SAME FORMAT AS FIG. 7.

The preceding results suggest very systematic behavior of the magnetic field in the near tail region during magnetospheric substorms. In particular, during the growth phase the field magnitude in the lobe of the tail steadily increases and the plasma sheet thins. In the cusp region the change in the field inclination is probably due to two factors. As the tail field increases, the tail current must also. This change causes an increasingly tail-like field in the cusp region. Simultaneously, thinning of the plasma sheet causes the satellite to move from the plasma sheet region to the lobe region. Because of the shape of field lines through the plasma sheet, the field orientation changes from a dipole-like orientation inside to a tail-like orientation outside.

During the expansion phase the plasma sheet expands rapidly engulfing the satellite in diamagnetic plasma which decreases the field magnitude. Field aligned currents and turbulence near the boundary cause the observed cross tail perturbations and rapid field fluctuations. After the boundary passes over the satellite, energetic electrons confined by the field lines closed through the neutral sheet suddenly appear. As the relative position of the satellite between the neutral sheet and the expanding plasma sheet decreases, the field inclination becomes more dipole-like.

Comparison of a very quiet and very disturbed day

For purposes of comparison, Fig. 9 shows the contrasting behavior as the satellite moves inward through the near tail region on a very quiet and very disturbed day. Comparing the electron fluxes it appears that the inner core of energetic electrons within the plasma sheet never completely vanishes even on quiet days. However, the radial gradient in the flux can be very steep outside of 10 R_e. In contrast, on a disturbed day the plasma sheet is so filled with energetic electrons that the particle cusp is undetectable.

It is important to note that even on a very disturbed day, it is possible to observe the systematic behavior of field and particles relative to expansion onset. Before each onset the electron fluxes drop out and the field magnitude increases. Following the onset without delay of more than a few minutes, the electrons reappear and the field magnitude decreases. Large amplitude fluctuations also generally accompany the expansion quite closely.

For purposes of comparison, the Z component in GSM coordinates of the solar wind magnetic field is plotted at the bottom. The field was northward throughout the entire quiet pass. In contrast the field was generally southward on the disturbed day.

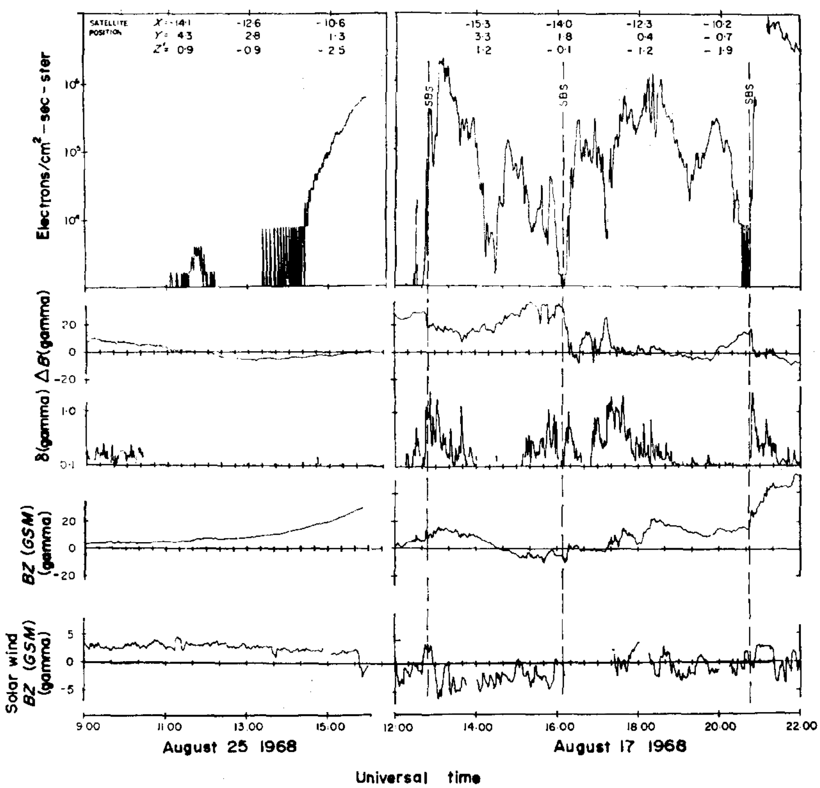

FIG. 9. CONTRAST BETWEEN TWO INBOUND PASSES OF OGO 5 ON A QUIET AND DISTURBED DAY IN SAME FORMAT AS FIG. 3.

Bottom trace adds the Bz-GSM component of the solar wind magnetic field.

The nine substorms displayed in this and preceding figures showed very systematic behavior with respect to expansion onsets. In fact, there was essentially no delay between the onset determined from midlatitude magnetograms and onsets in the near tail region. This close correspondence should be contrasted to the large delays frequently observed at the Vela orbit at 20 R_e by Hones and co-workers, e.g. Hones *et al.* (1970). These results provide considerable support for the suggestion discussed earlier that the origin of the substorm disturbance is in the near tail region ($\sim$10 R_e) on the midnight meridian.

Substorm sequence on August 15, 1968

As a final example of the systematic behavior of the near tail magnetic field during magnetospheric substorms, we show the entire sequence of magnetic field changes during two substorms on August 15, 1968. A detailed study of these events including data from other sources will appear in a sequence of papers beginning with McPherron (1972).

The auroral zone magnetograms on August 15, 1968, are shown in Fig. 10. Vertical dashed lines show the onsets of substorm expansions, as defined mainly by midlatitude magnetograms. The two substorms of greatest interest had expansion onsets at 0430 and 0714 UT. These two events occurred approximately midway in the development of the main phase of a gradual commencement magnetic storm. Both substorms have obvious effects at a number of auroral zone stations, indicating the worldwide extent of these events. We note for the 0714 event that the midlatitude onset time is somewhat earlier

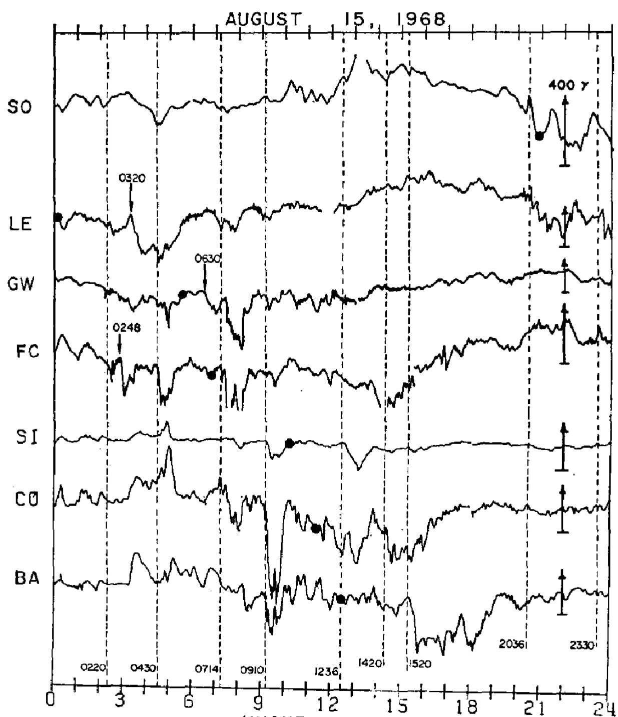

FIG. 10. AURORAL ZONE MAGNETOGRAMS ON AUGUST 15, 1968 SHOWING EXPANSION ONSETS DETERMINED FROM GROUND MAGNETOGRAMS.

Black dots on each trace are magnetic midnight for the station.

than the onset of the main bay and corresponds closely with the beginning of a trigger bay at Fort Churchill (FC). Both events appear to have precursory activity in the auroral zone, e.g. a bay onset at 0320 at Leirvogur (LE) and also at 0630 at Great Whale (GW). Without the use of midlatitude magnetograms discussed next, these events might be taken as localized polar substorms.

Midlatitude magnetograms for August 15, 1968, are plotted in Fig. 11. Both the 0430 and 0714 expansion onsets can be identified by a sudden increase in the horizontal component at the near midnight stations (black dots on individual traces). Examining the 0714 onset, we note that it was preceded by 34 min of nearly worldwide decrease in H (midnight to morning excepted). Following the onset, the field increased past midnight (e.g. Dallas-DS) and simultaneously decreased predusk (e.g. Guam-GU). Similar behavior can be seen for the 0430 substorm as well. We note the beginnings of the two, nearly worldwide decreases before each expansion were at 0330 and 0640 UT. These two times are in quite close agreement with the precursory activity identified in the auroral zone stations.

From the preceding analysis of ground magnetograms, we conclude that the two substorms had reasonably well defined growth phases for about one hour prior to the onset of the expansion phase. As we show below, satellite magnetometer data are in good agreement with this conclusion.

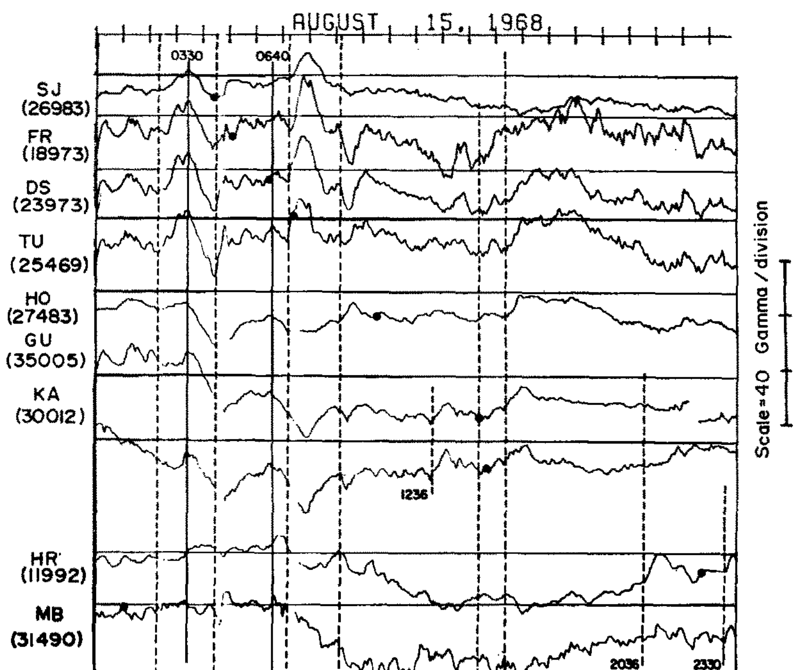

FIG. 11. MIDLATITUDE MAGNETOGRAMS FOR AUGUST 15, 1968, PLOTTED AS DEVIATIONS FROM QUIET DAY.

Black dots are local midnight at each station. Vertical dashed lines are expansion onsets and vertical solid lines are growth phase onsets.

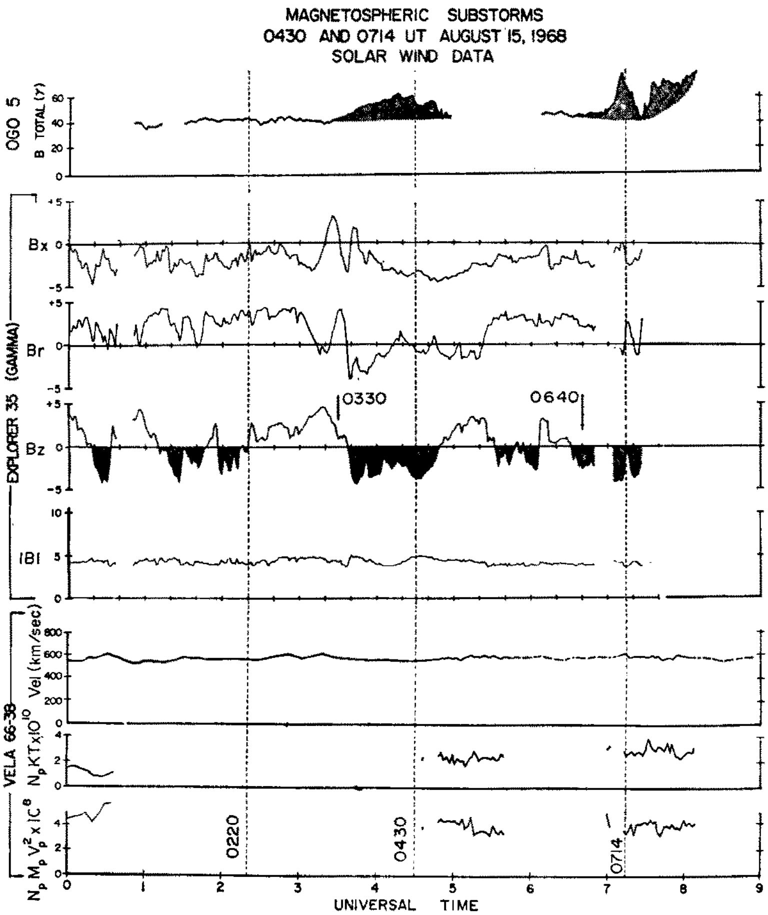

FIG. 12. SOLAR WIND FIELD AND PLASMA DATA ON AUGUST 15, 1968.
Also included is the field magnitude in near tail region observed by OGO 5. Note intervals of southward field and increasing tail field magnitude before the onset of the 0430 and 0714 substorm expansions.

Solar wind plasma and field measurements on August 15, 1968, are shown in Fig. 12. The Explorer 35 measurements were made near the dawn meridian at the orbit of the Moon; hence, effects of southward fields at the Earth should probably occur about the time of the arrival of the field at Explorer 35. The most obvious conclusion is that both the 0430 and 0714 substorm expansion were preceded by more than an hour of southward solar wind magnetic field. Furthermore, the beginning of the southward component corresponds quite well with the times identified at the ground as the beginning of the substorm growth phase. A study of other components of the solar wind field, or of the plasma parameters, reveals no close relation with expansion onset.

For later comparisons, we also note the magnitude of the magnetic field in the near tail as measured by OGO 5. Both expansions are preceded by an interval of steadily increasing field. Presumably, this increase is the result of a southward solar wind field.

Magnetic field measurements at synchronous orbit by ATS 1 are shown for August 15, 1968 in Fig. 13. The satellite is at dusk at 0400 UT and local midnight at 1000 UT. Both

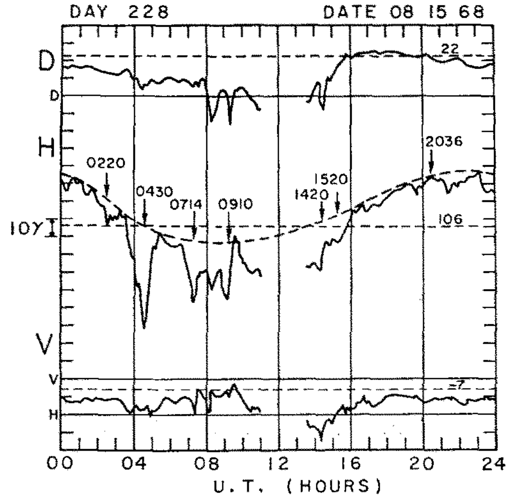

FIG. 13. MAGNETIC FIELD OBSERVATIONS AT SYNCHRONOUS ORBIT (150°W LONGITUDE) MADE BY UCLA FLUXGATE MAGNETOMETER ON ATS 1.

Note depression in dipole component of field (H) prior to each substorm expansion shown by vertical arrow above H trace.

substorms have a clear signature in the H component (parallel to Earth's rotation axis). Starting almost exactly at the times identified as the beginning of the growth phases (0320 and 0440 UT), the field began to decrease, then at expansion onset it rapidly increased. The interval of gradual field decrease we attribute to an increase in the strength of the tail current and hence its effects at synchronous orbit.

The observations made on this day by the OGO-5 satellite are shown in Fig. 14. As is evident from the satellite trajectory, it was inbound, down out of the north lobe of the tail nearly along the midnight meridian. For reasons to be discussed using the following

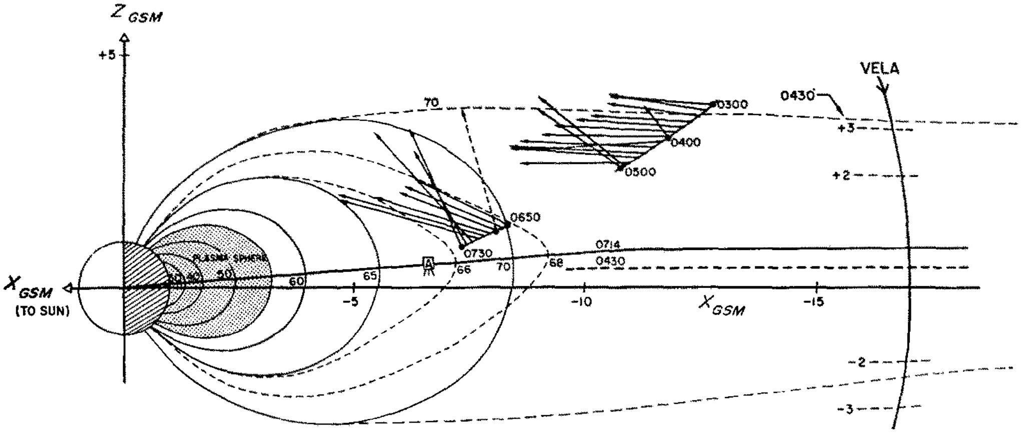

FIG. 14. PROJECTION OF OGO-5 TRAJECTORY AND VECTOR FIELD OBSERVATIONS IN MIDNIGHT MERIDIAN PLANE ON AUGUST 15, 1968.

Dashed field lines show quiet time field and solid field lines show dipole field configuration. OGO 5 was in the lobe until 0445 when it entered the plasma sheet. It momentarily re-entered the lobe at 0712 just before the onset of the second substorm.

figure, we conclude that until 0445 the satellite was in the lobe of the tail. At 0445 it entered the plasma sheet as a result of the 0430 expansion. The satellite then remained in the plasma sheet until 0712, when it momentarily reentered the lobe. As can be seen from the observed field vectors, the field configuration at the beginning of each substorm was in very good agreement with the quiet time configuration (dashed field lines) reported by Fairfield (1968). An interesting feature of the 0430 substorm is that for a short interval before the field rotation at 0444 the field pointed southward (toward the neutral sheet).

The actual magnetic field observations for the two substorms are shown in Fig. 15. Absence of energetic electrons (top trace) and a field magnitude enhanced relative to a dipole (second trace) combined with a field orientation parallel to the neutral sheet (preceding figure) indicate the satellite was in the lobe of the tail before the 0430 expansion. Following the onset of the expansion at 0430, the field magnitude in the lobe began to

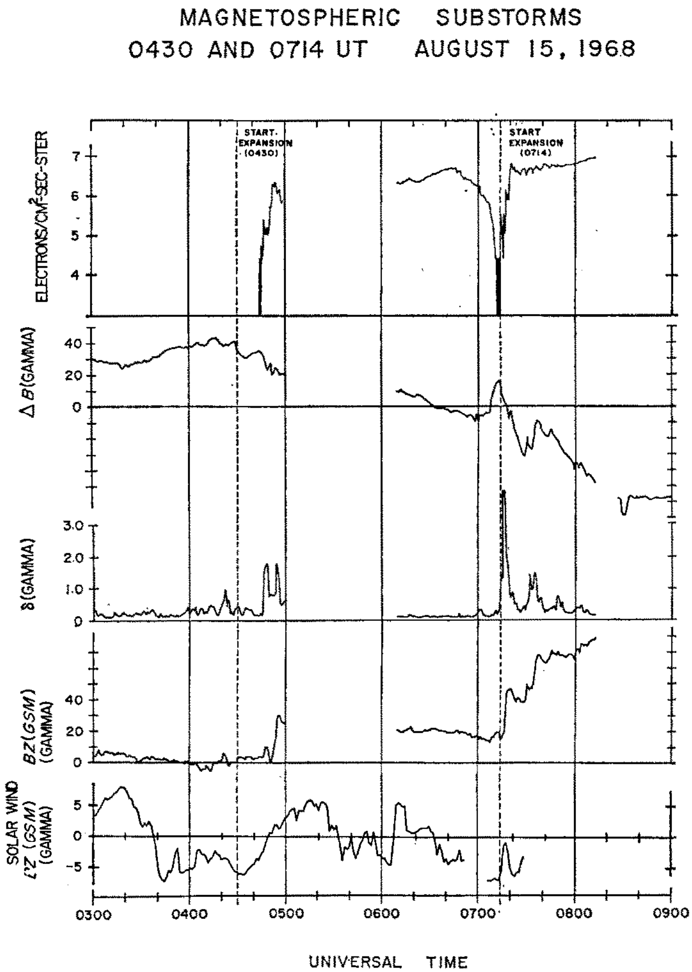

FIG. 15. MAGNETIC FIELD DATA FROM OGO 5 IN FORMAT SIMILAR TO FIG. 3 FOR AUGUST 15, 1968, SUBSTORM.

The energetic electron fluxes and field magnitude provide the main means for determining the satellite position relative to the boundary of the plasma sheet.

decrease (see second trace). Approximately 15 min later the expanding plasma sheet reached the satellite, causing a rapid field rotation (preceding figure), large amplitude magnetic field turbulence (third trace), and a sudden appearance of energetic electrons.

Prior to the 0714 substorm the satellite was inside the plasma sheet as shown by the presence of energetic electrons and a low field magnitude. Just before the onset of the 0714 expansion, however, the satellite apparently passed into the lobe of the tail. Both the sudden decrease in flux of energetic electrons and rapid increase in field magnitude are consistent with this interpretation. Also, as shown in the preceding figure, the field orientation had become quite tail-like at this time. The expansion onset at 0714 again caused a rapid expansion of the plasma sheet with the familiar effects just described. We note, however, there was no delay whatsoever, in vivid contrast to the situation several earth radii further back and higher in the tail.

DISCUSSION

The preceding discussion of the details of the two August 15, 1968, substorms establishes reasonably well the sequence of events which occur during a magnetospheric substorm. This sequence is summarized in Fig. 16. Beginning at the left side this sequence is as follows. A southward component of solar wind magnetic field arrives at the dayside magnetopause. Magnetic field merging begins and the dayside magnetopause is eroded (Aubry *et al.*, 1971). Eroded flux is then transported to the tail by solar wind flow. Reduction of the dayside cross section and increase in the distant tail cross section cause the magnetopause to flare at a greater angle. The increased normal stress on the boundary is balanced by a large increase in field magnitude in the near tail region. Electric fields associated with the solar wind convection of merged field lines cause field lines in the lobe to drift towards the neutral sheet, thinning the plasma sheet. Electric field drift in the plasma sheet, however, is toward the Earth because of the closed field geometry. This drift moves the tail current toward the Earth, decreasing the field at synchronous orbit, and making the field more tail-like in the nightside cusp region.

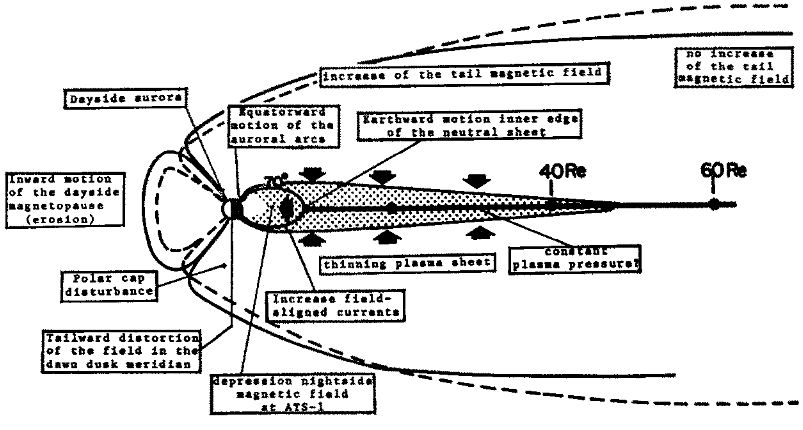

FIG. 16. SUMMARY OF THE SEQUENCE OF EVENTS THAT OCCUR DURING THE GROWTH PHASE OF A MAGNETOSPHERIC SUBSTORM.

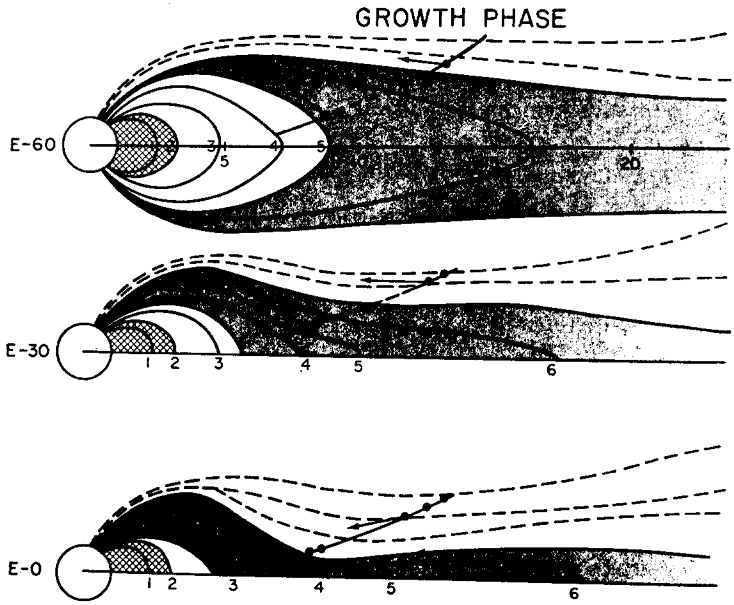

FIG. 17. THREE STAGES OF A SUBSTORM GROWTH PHASE IN THE NEAR TAIL REGION.
Black dots and field vectors interpret the observations on August 15, 1968, presented in preceding figures.

Since the main purpose of this paper has been to show the systematic behavior of the near tail, we examine this region in more detail in Fig. 17. This figure was drawn to summarize our results for the August 15, 1968, substorms, but is also consistent with the observations reported earlier in the paper for other days. The beginning of a substorm is shown in the top panel. Vectors at two locations on a sample trajectory indicate the expected field orientation in the lobe and inside the plasma sheet in the cusp region. As the growth phase proceeds, field is transported to the tail and added to the lobe. The field magnitude increases in the lobe as shown by a compression of the open field lines (dashed). Simultaneously, the plasma sheet thins, and the tail current moves toward the Earth. The field inclination begins to increase in the plasma sheet, appearing to become more tail-like. Finally, just at the onset of the expansion phase, the plasma sheet becomes very thin about 10 R_e behind the Earth. The lobe field at this time takes on a southward inclination and is quite large. The original plasma sheet location has now become the boundary of the plasma sheet or even may be momentarily in the lobe. The field inclination and magnitude are now very large.

The preceding description of the growth phase suggests that a magnetospheric substorm causes radical changes in the configuration of the near tail region. We believe these changes are such as to move the magnetosphere towards an unstable configuration. If the 'pinching off' of the plasma sheet at 10 R_e actually occurs as suggested by our observations, it would appear this is the most unstable location.

We suggest therefore that the cause of the expansion phase may be due to the onset of field line annihilation at this point. Such a suggestion is consistent with auroral observations as well as the systematic and immediate response of the near tail region. Further, this suggestion provides a convenient way of explaining delays in expansion effects seen at greater distances in the tail.

Regardless of the eventual explanation of the course of the expansion phase, it is evident from our observations that the near tail region plays an essential role. Clearly, this region deserves more study than it has yet received.

Acknowledgments—I wish to thank my co-workers at UCLA, Drs. C. T. Russell, M. Aubry, P. J. Coleman, Jr. and M. Kivelson, for their many contributions to this paper. The observations reported herein were mainly obtained with UCLA fluxgate magnetometers on ATS 1 and OGO 5. Ground magnetograms were provided by W. Paulishak of the World Data Center for Geomagnetism, NOAA, Boulder, Colorado. Additional data were provided by the National Space Science Data Center, Greenbelt, Maryland; Dr. M. Montgomery of Los Alamos (Vela solar wind plasma); and Dr. D. Colburn (Explorer 35 magnetic field). The work reviewed in this paper has or will appear in greater detail in many publications as indicated in the text of this review. My time in preparing this review was supported by NASA Research Grant NGR 05-007-305.

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