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ELECTRON PRECIPITATION MORPHOLOGY AND PLASMA SHEET DYNAMICS: GROUND AND MAGNETOTAIL STUDIES OF THE MAGNETOSPHERIC SUBSTORM

A Review of Models and Observations

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ABSTRACT

The main results of some recent studies of the magnetospheric substorm are summarized and discussed in view of the fundamental role of magnetospheric convection. The substorm growth phase is described in terms of a temporary imbalance between the rates of magnetic field-line merging on the dayside and reconnection on the nightside of the magnetosphere following a southward turning of the interplanetary magnetic field. During this phase, enhanced electron precipitation is observed to move equatorward in the auroral zone near midnight. At the same time the north-south width of the near-earth plasma sheet is greatly reduced and enhanced electron pitch-angle scattering towards isotropy is observed in its outer region. A close temporal and spatial correlation has been observed between features within the poleward expanding precipitation region at bay onset and features near the outward expanding boundary of the plasma sheet. Some new understanding of the possible causal relationship between growth-phase and expansion-phase phenomena is provided through studies of multiple-onset substorms, during which substorm expansions are observed to occur at intervals of 10-15 min. Detailed examinations of ground and magnetotail observations have revealed new features of the radial and azimuthal dynamics of these substorms that are not consistent with recent models proposed by Akasofu and by Rostoker and his co-workers. First, there are clear observational evidence in support of the claim that the plasma sheet behaviour is different earthward and tailward of geocentric distances of ~15 earth radii (R_E). It is shown that the behaviour of the near-earth plasma sheet early in a substorm cannot be inferred from measurements at larger distances (e.g., in the Vela satellite orbits), and that the triggering of a substorm expansion may well be directly related to pre-substorm thinning of the near-earth plasma sheet, even though the most significant thinning in the tailward region may occur at the onset and therefore appears to be an effect rather than a cause of triggering. This radial dependence can be explained in terms of an X-type neutral line that is formed near 15 R_E at expansion phase onset. Second, there are no clear indications that substorm growth- and expansion-phase processes operate concurrently in the sense that expansion in one sector of the tail supplies energy ('growth') to an adjecent sector to the west which subsequently experiences an expansion, and so on, as proposed by Rostoker et al. Initial results from studies of a new type of magnetospheric activity, characterized by strong auroral-zone bay activity but no other indications of substorm expansions, are shown to be consistent with current models of the growth and expansion phases of substorms and of substorm triggering.

1. INTRODUCTION

1.1 Solar Wind-Magnetospheric Interactions

The continuously blowing solar wind confines the distorted magnetic field of the earth's dipole within the magnetospheric cavity (Figure 1a), whose outer boundary, the magnetopause, effectively shields the earth and its atmosphere from direct influx of solar wind particles. However, it is now generally believed that the magnetosphere is open in the sense that transport of solar wind mass, momentum, and energy into the magnetosphere is accomplished, at least in part, through processes related to merging of geomagnetic and solar-wind field lines at the dayside magnetopause. This interconnection between magnetospheric and interplanetary field lines causes direct inflow of solar wind plasma and a large-scale convection of plasma and magnetic flux within the magnetosphere (see Figure 1b): The two halves of field lines open to the solar wind are transported by the wind over the polar caps into the tail lobes where they are convected towards the 'neutral' sheet. Oppositely directed field lines thereafter reconnect across the neutral sheet and convect sunward through the inner magnetosphere to resupply closed flux to the dayside merging region. This circulation can be described as magnetospheric convection driven by the solar wind-magnetospheric dynamo (see reviews by Axford, 1969, Russell, 1974, and Burch, 1974).

During steady state-like convection the rate of flux removal from the dayside is balanced by the rate of flux return from a distant reconnection region in the tail. However, magnetospheric convection is, in general, a non-steady process, owing to time variations in both external and internal conditions: First, the efficiency of the dynamo, or the rate of energy input, is a function of the interplanetary magnetic field (IMF) orientation and the solar wind velocity. Second, the response of the magnetosphere-ionosphere system to external changes depends, in a complex way, on both ionsopheric conductivity and

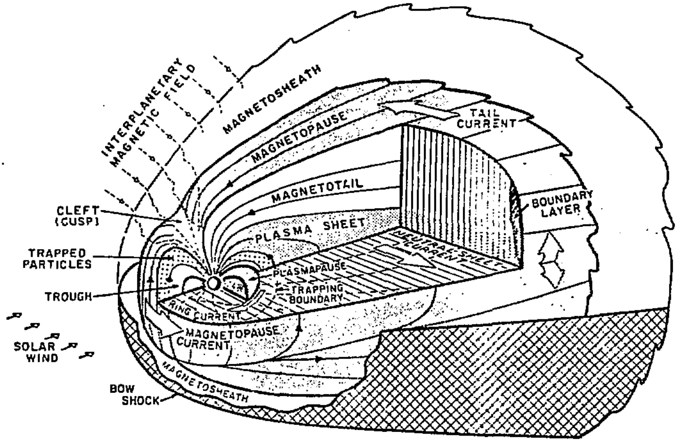


Figure 1a A modern view of the magnetosphere. (Original drawing by W.J. Heikkila.)

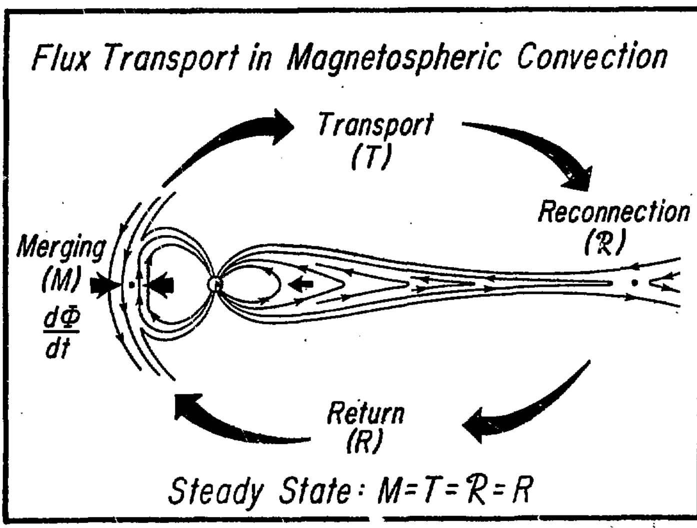


Figure 1b Schematic illustration of the four basic processes controlling magnetospheric convection. The bulk plasma flow velocity $\underline{V}$, the magnetic field $\underline{B}$, and the convection electric field $\underline{E}$ are throughout most of the magnetosphere related through the equation

$$\underline{V} = \underline{E} \times \underline{B} / B^2$$

magnetospheric plasma pressure gradients. Third, and most important, the magnetosphere is able to store magnetic energy in the tail for subsequent often abrupt release into the inner magnetosphere. During this release, when previously extended field lines contract rapidly earthwards towards a more dipolar configuration, an ensemble of phenomena known as the magnetospheric substorm can be observed (see review by Russell and McPherron, 1973).

It is presently not known what triggers this explosive or expansive phase of the substorm. It is also not known how a preceding interval of energy storage, commonly known as the substorm growth phase, is causally related to substorm triggering.

1.2 The Growth-Phase Controversy

The concept of a substorm growth phase was introduced by several workers in the late 1960's to explain the slowly varying phenomena that often occur on the ground during the hour before isolated substorm expansions (e.g. McPherron, 1970; Nishida, 1971; Mozer, 1971). Subsequent studies of satellite data elucidated what should become the characteristic features of the growth phase, namely an erosion of the dayside magnetopause (Aubry et al., 1970), leading to a reconfiguration of the magnetosphere (Fairfield and Ness, 1970; Camidge and Rostoker, 1970) and an increase of tail lobe magnetic energy (Aubry and McPherron, 1971; McPherron, 1972; Caan et al., 1973). It also became clear that these processes are most pronounced during intervals of southward IMF (Coroniti and Kennel, 1972), and that geomagnetic activity (AE) statistically increases 40-60 min after a southward turning (Arnoldy, 1971; Foster et al., 1971).

A possible interpretation of this last result is that there is a direct causal relationship between a southward turning of the IMF and substorm onsets, and that the time delay reflects the average duration of the growth phase. However, Akasofu et al. (1973) and Akasofu (1974) argued that the increase in geomagnetic activity is due to an equatorward motion of the polar current system from its position during more quiet times to a position over the observatories providing data for the AE index. According to this view, the IMF regulates the latitude of negative bays and their intensities, but has no direct influence on substorm occurrence. In fact, observations of the aurora show that substorms occur during southward as well as northward IMF, and that the latter group tends to occur along a more contracted oval. However, the critical parameter here appears to be the east-west electric field resulting from the solar wind-magnetospheric interaction rather than just the B_Z IMF component. Nishida (1971) has pointed out that this electric field is in the direction to drive magnetospheric convection also for weakly northward IMF. In fact, Burch (1974) has shown that in almost all cases of northward field studied by Akasofu et al. (1973) the IMF was only weakly ($\lesssim 30^{0}$) northward in the GSM coordinate system, which is thought to provide the best representation of this interaction.

The growth phase controversy is partly a result of semantic differences, but is most of all due to the variability and complexity of substorms and the often ambiguous identification of substorm expansion onset. It has often been argued (see Vasyliunas and Wolf, 1973) that growth-phase phenomena, instead of being due to separate magnetospheric processes preceding the expansion onset, are caused by weaker, undetected substorms at higher latitudes (Akasofu et al., 1973) or at other local times (Rostoker, 1974). This is the so-called "other station" argument which is difficult to disprove with the many gaps in the present ground station network. On the other hand, in some cases it has been shown that the claimed "earlier onsets" merely tend to shorten the duration of the growth phase, without affecting the basic ideas behind its existence (McPherron et al., 1973a).

In recent years new and more fruitful arguments have been introduced in the growth-phase discussion. First, the existence and importance of weak and high-latitude onsets have been acknowledged by growth-phase advocates, resulting in a more careful search for the "true" onsets of the substorm expansion phase.

Second, Akasofu (1975) has noted that the polar cap region contracts to a minimum size after long intervals of northward IMF. When the magnetosphere is in this 'ground state', there can be no substorms until the IMF turns south and the polar cap starts to expand. This expansion and the associated storage of open magnetic flux in the tail lobes provide 'free' energy that can be released during substorms. The concepts of a minimum oval and of free energy have clarified, although not settled, the growth-phase controversy. Akasofu know concedes that (a small subset of) substorms that occur after a southward turning may have a growth phase, but he argues that the so-called growth-phase phenomena are merely 'southward-turning effects'. He therefore maintains that since substorms do occur also after a northward turning, provided free energy is already available, a southward turning has no direct effects in causing the expansion phase.

There are, however, some indications that a southward turning of the IMF initiates a sequence of events that eventually triggers a substorm. One such indication of a causal relationship between growth-phase phenomena and substorm triggering is the thinning of the near-earth plasma sheet.

1.3 Near-Earth Plasma Sheet Thinning and Substorm Triggering

Thinning of the plasma sheet, which is a contraction of the region in the tail occupied by low- and high-energy particles but without a compression of the plasma, was first identified as a characteristic feature of the substorm expansion phase (Hones et al., 1967). Recent observations and theories have shown that thinning may also occur during the interval before substorm expansion (Buck et al., 1973), and apparently as a result of a southward turning of the IMF (McPherron et al., 1973b; Russell and McPherron, 1973).

A typical sequence of events, starting with enhanced dayside merging, initiates two important processes. First, because of ionospheric line-tying of field lines, there may initially be only a slow build-up of the convection rate (Axford, 1969; Coroniti and Kennel, 1973; Holzer and Reid, 1975).

During this interval magnetic flux is being added to the tail lobes at the new merging rate but removed at the old reconnection rate. Hence, the total flux in the tail increases and magnetic energy is being stored in the tail lobes. This process also causes the polar cap to expand as the latitude of the last closed field line moves equatorward.

Second, information on the higher merging rate propagates as an HM wave towards the distant reconnection line in the tail, accelerating the flow of plasma and newly closed magnetic flux towards the earth. This wave reaches the inner tail first, and there is also a tendency for the wave to spread out as it propagates (Coroniti, 1975). As a result, magnetic flux is being removed from the near-tail plasma sheet at a higher rate than it is supplied from the more distant tail. This evacuation of plasma and magnetic flux, together with the increase of magnetic pressure in the tail lobes, eventually causes the near-earth plasma sheet to thin down.

Such an enhanced plasma sheet thinning may eventually lead to substorm triggering. This may occur in two ways. If the plasma sheet becomes very thin, probably much less than one earth radius, the cross tail current may reach critical densities in the region of minimum thickness, causing a current disruption. Alternatively, the associated field reconfiguration may reduce the magnetic field component perpendicular to the neutral sheet sufficiently to cause current disruption by the ion tearing-mode instability* (Schindler, 1974; Nishida and Fujii, 1976). The disrupted current instead becomes shunted through the ionosphere, forming a current wedge (Figures 2a,b). At the same time an X-type neutral line is formed, accompanied by a rapid enhancement of reconnection as the stored energy is released (e.g., Russell and McPherron, 1973).

There seems to be a second type of plasma sheet thinning that is observed at radial distances of 15-18 earth radii (R_E) during the expansion phase (Hones et al., 1973; Lui et al., 1975). This thinning is probably caused by a rapid loss of particles in association with the opening up of previously closed lines

* The condition for instability can be expressed as $L_z^{-1/2} B_z \lesssim 1$, where L_z is the width of the plasma sheet and B_z is the perpendicular field component.

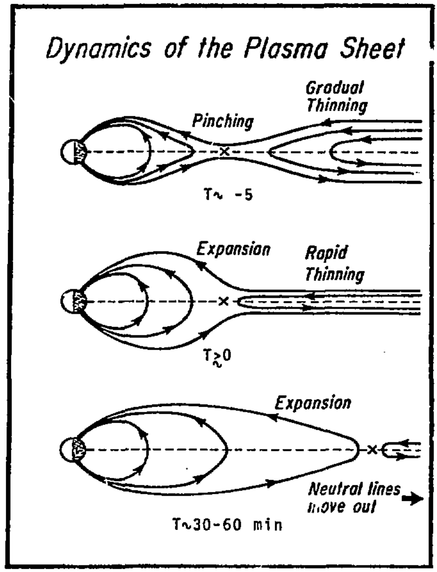


Figure 2a Schemat : summary of the dynamics of the plasma sheet and change in field configuration around the time of bay onset (T=0). (Original by R.L. McPherron.)

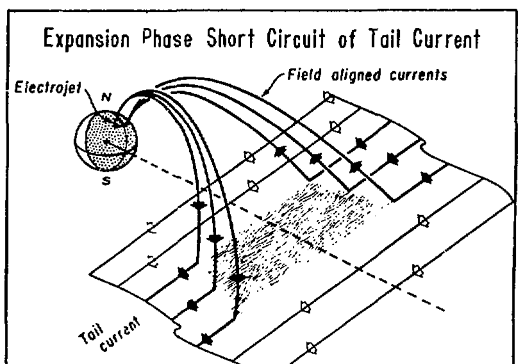


Figure 2b The substorm current wedge, caused by a disruption of the tail current and a shunting through the ionosphere. (Original by R.L. McPherron.)

tailward of the neutral line (Hones, 1972; Nishida and Hones, 1974; Akasofu, 1974). It is therefore quite probable that plasma sheet thinning in this region is most often an effect rather than a cause of substorm triggering.

1.4 An Up-Dated Substorm Model

The above discussion suggests that substorms are triggered by an instability related to enhanced magnetospheric convection. However, by taking weak, high-latitude substorms into account, it seems reasonable to expect that there are two different triggering sequences that result in morphologically similar substorms on the ground, but at different latitudes and with different average intensities (Coroniti, 1975): If the increase in the dayside merging rate is weak, the rarefaction wave that carries information on changed boundary conditions may propagate to the distant reconnection line without causing significant changes in the near-earth plasma sheet. As the reconnection rate increases, a high-latitude, weak substorm is observed, since only a small amount of energy is avaiable.

On the other hand, if the dayside merging rate increases more rapidly, relative to the characteristic time scales for ionospheric line-tying, the evacuation of magnetic flux from the near plasma sheet may, as discussed above, lead to the formation of a new neutral line closer to the earth. A rapid enhancement of reconnection initiates the release of a larger amount of energy. Since field lines that define the outer boundary of the plasma sheet have now moved down to lower latitudes, these substorm onsets occur along an expanded oval. The duration of the growth phase corresponds, according to this model, to the average time needed for the plasma sheet to thin down to the minimum, unstable thickness.

Very recently, the observational evidence for the formation of a near-earth neutral line has been questioned. Thus, Rostoker (1976) has suggested that the negative B_Z component near the neutral sheet, that has been believed to be a reliable indication of a neutral line (Nishida and Nagayama, 1973), is really an edge effect of the substorm-associated field-aligned current system. Furthermore, Akasofu (see Nishida, 1976) has proposed that negative B_Z near the neutral sheet is due to a flapping motion of the tail. But, as Nishida (1976) has pointed out, such a flapping should result in positive as well as negative excursions of B_Z. Morecver, as we will discuss in Sec. 2.6, it would be very difficult to explain the different plasma sheet behaviour earthward and tailward of $\sim$15 R_E, the plasma flow, and magnetic field changes without invoking the formation of an X-type neutral line and subsequent enhancement of reconnection.

Theoretical as well as observational considerations (e.g., Russell, 1974; Pytte et al., 1976d) have suggested than an O-type neutral line configuration, or a magnetic 'bubble', may be formed tailward of an X-type neutral line if reconnection starts on closed field lines within a thinned plasma sheet. It is conceivable that the magnetic signatures at low latitudes in the tail ($r > 15\ R_E$) in cases when a combined X- and O- configuration is formed would be significantly different from those expected from a simple X-type neutral line configuration. This may explain why sometimes only small or transient negative B_Z excursions are observed tailward of the assumed location of a near-earth neutral line. In view of this possibility, we will in the following discussion assume that the formation of an X-type (and possibly also an O-type) neutral line is a typical feature of the substorm expansion onset.

2. ELECTRON PRECIPITATION MORPHOLOGY AND PLASMA SHEET DYNAMICS

2.1 The Occurrence and Morphology of Growth-Phase Electron Precipitation

The reconfiguration of the magnetosphere during periods of enhanced dayside merging will also affect the energetic particle population within the magnetosphere. In particular, increased inward convection and heating of particles in the magnetotail and thinning of the plasma sheet are expected to cause enhanced precipitation and spatial movements of the precipitation regions.

In PAPER I (Pytte and Trefall, 1972) we reported on the occurrence of energetic ($\gtrsim$30 keV) electron precipitation near local midnight, as observed with balloon-borne X-ray detectors, and its relation to the onset of negative magnetic bays and Pi 2 magnetic pulsations. It was found that slowly varying precipitation events tended to occur already during the hour before the onset of isolated substorms. (It was, at that time, believed that a vast majority of precipitation occurred during and immediately after substorm expansions.) From a comparison with other known prebay processes it was suggested that this precipitation resulted from inward drift and adiabatic heating of particles in the plasma sheet.

PAPER II (Pytte et al., 1976a) dealt with the morphology of prebay precipitation as observed during multiple balloon flights. It was shown that such precipitation moves equatorward with speeds consistent with the average observed values of the magnetospheric convection electric fields. The growth-phase precipitation events typically occur during intervals of southward IMF, as summarized in Figure 3a, and during increasing magnetic field intensity in the tail lobe. The characteristics of these events are also related to the thinning and inward motion of the plasma sheet and to increased pitch-angle scattering of plasma sheet electrons due to field-line reconfiguration. In view of the close spatial relationship that exists between the outer regions of the plasma sheet and the poleward border of the auroral oval, we conclude that growth-phase precipitation most likely originates from the plasma sheet and that the equatorward motion corresponds to the expansion of the polar cap.

A more direct observation of the equatorward motion of growth-phase precipitation than those included in PAPER II, is shown in Figure 3b. During a growth-phase event on August 18, 1968, directional information on the precipitating flux was obtained from a single X-ray detector by means of a rotating shield. During the rising phase of this event, when the precipitation region was approaching the balloon from the north, the detector was measuring precipitation maxima when looking towards the northnorthwest (NNW) geomagnetically. When the region had passed overhead and was moving southwards away from the balloon, intensity maxima were detected in the SSE. That the general shape of the event was mainly determined by spatial movements can be inferred from simultaneous measurements from another balloon located a little farther south. This equatorward movement of growth-phase precipitation was first reported by Pytte (1972).

These main features of growth-phase precipitation are in general agreement with other studies in the literature. Hones et al. (1971) suggested that

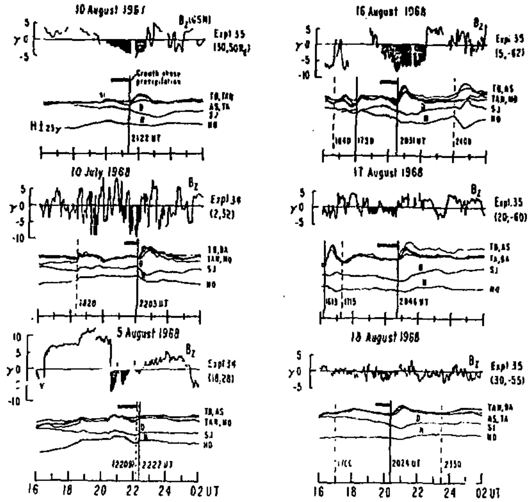


Figure 3a Summary of relationship between the occurrence of growth-phase precipitation (horizontal bar) and intervals of southward IMF (cross-hatched). The subsequent onset of the expansion phase (vertical line) was accompanied by a low-latitude positive bay. (From PAPER II.) See Table I for information on magnetometer stations.

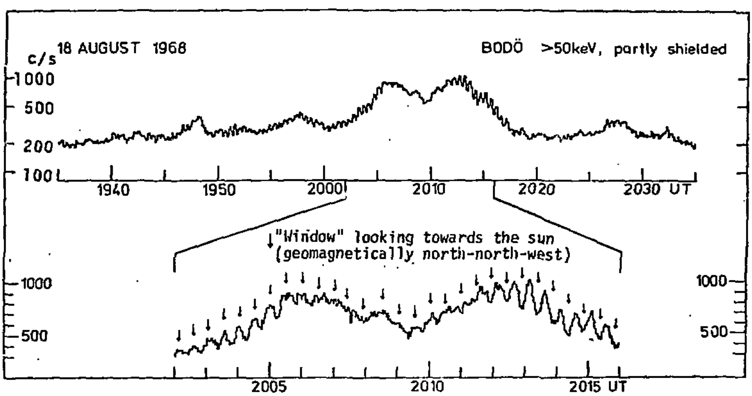


Figure 3b Observations of the southward motion of growth-phase precipitation. Directional information about the flux of precipitating electrons was obtained by measuring the X-ray intensities reaching the detector through a window in an azimuthally rotating shield (rotation period ~30 sec). (From Pytte, 1972.)

an event of pre-substorm electron precipitation observed by riometers was caused by enhanced wave turbulence and pitch-angle scattering of particles in the radiation belt. More in agreement with our model, Hargreaves et al. (1975) related the equatorward motion of smoothly varying ionospheric absorption before a more abrupt onset to an inward motion of the plasma sheet during enhanced convection. The convection electric field is also believed to cause the equatorward ExB drift of quiet auroral arcs (Kelley et al., 1971) during intervals of southward IMF (Vorobjev et al., 1976).

2.2 Temporal and Spatial Relationships Between Growth-Phase and Bay-Onset Precipitation.

According to the magnetospheric substorm model inherent in our studies, there is a causal relationship between growth-phase phenomena and the triggering of substorm expansions. In view of the above results it is of special interest to examine the temporal and spatial relation between growth-phase and bay-onset precipitation.

In Figure 4 we show a case of simultaneous growth-phase-like precipitation over the Kiruna balloon to the south as a sharp onset of precipitation occurred over two other balloons located about 150 and 300 km farther north, respectively. In view of other observations with multiple balloons during similar conditions, we interpret the slow rise of X-ray intensities over Kiruna before 2100 UT as being due to an equatorward motion of the precipitation region towards the balloon. Since there was no prebay precipitation over the northern balloons just before bay onset (∿2102 UT), we infer that the outer boundary of the plasma sheet in this case mapped to the ionosphere somewhere between the two southernmost baloons. The sharp onset of precipitation to the north at 2102 UT then apparently started from near the outer boundary of the plasma sheet. The delayed onset over the

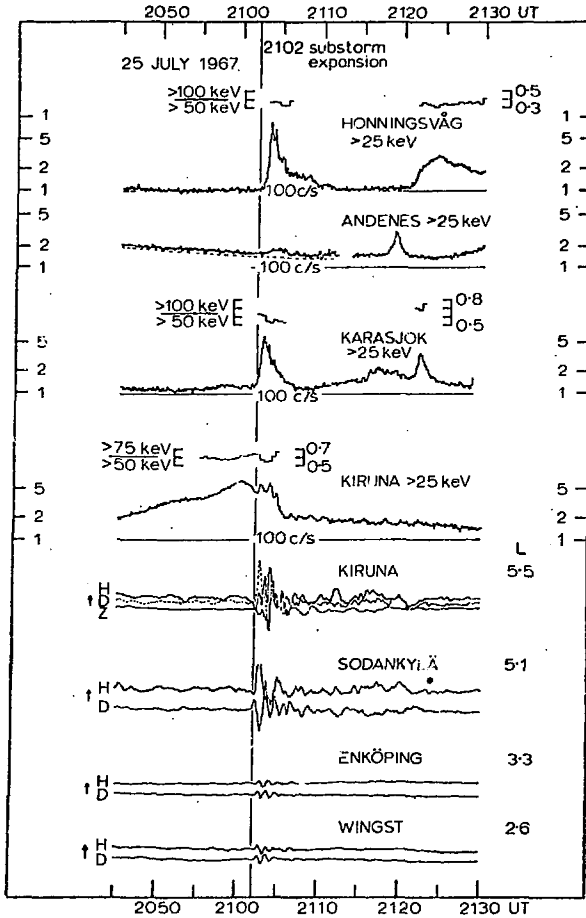


Figure 4 Auroral-zone electron precipitation during the growth phase and at the onset of the expansion phase (defined by the onset of magnetic pulsations) as observed with a north-south chain of balloon-borne X-ray detectors (Pytte et al., 1976b).

northernmost balloon indicates a poleward shift of the region of most intense precipitation.

The above conclusion that the substorm expansion is triggered from near the outer boundary of the plasma sheet is in agreement with current substorm models based upon plasma sheet measurements (McPherron et al., 1973b; Russell and McPherron, 1973) that the expansion phase is initiated in the near tail region when the plasma sheet has thinned down to a minimum, unstable thickness.

2.3 Simultaneous Measurements of Electron Precipitation and Plasma Sheet Variations

The close relationships inferred above between substorm features on the ground and characteristic changes in the plasma sheet have not been shown directly using simultaneous data. One set of simultaneous and nearly conjugate observations is shown in Figure 5. The insert in the lower left corner shows the locations of five balloons and the approximate conjugate longitude of the OGO 5 satellite at 2100 UT*.

A substorm growth phase was identified in ground magnetograms around 1920 UT on August 17, 1968, in association with a southward turning of the IMF (see Figure 3a). Some minutes afterwards (at ~1940 UT), weak prebay precipitation was detected at L~7 (Λ~68°) and a few minutes later also at L~6.5. The balloons farther south were still ascending at this time and were therefore unable to measure any prebay precipitation. Simultaneous measurements of cosmic noise absorption (see Pytte et al., 1976b) show precipitation also farther south which continued until ~2015 at L~6.3 and through bay onset at 2046 UT at L~5.5 (Λ ~64.5°). According to PAPER II this suggests that the outer boundary of the plasma sheet had migrated southward from Λ~68 to ~64.5° in about 50 min, corresponding to an average speed of ~8 km/min.

* This and two other similar cases have now been studied in detail by Pytte and West (1976).

During this interval the flux of energetic plasma sheet electrons was decreasing, and the spatial gradient in the proton fluxes near the outer boundary of the plasma sheet was moving towards the satellite with an average speed of 2-4 km/s (R.M. Buck, personal communication). This speed is much higher than the speed of the spacecraft away from the neutral sheet (∿0.5 km/s). There was therefore a real motion of the sheet boundary towards the neutral sheet which brought OGO close to the boundary just before bay onset. At the same time the magnetic field became increasingly more taillike and the north conjugate point of OGO was moving equatorward. These observations are therefore in agreement with the above idea that the thinning of the plasma sheet and the equatorward motion of the ionospheric projection of its outer boundary is directly related to the equatorward motion of growth-phase precipitation.

The periodic modulation of the 158-keV electron fluxes at OGO before 1920 UT was due to the detector scan over an anisotropic pitch-angle distribution. This so-called butterfly pitch-angle distribution, which is characterized by a flux depression around 90^o, is typical of this region of the tail during quiet times (West et al., 1973). As the magnetic field became more taillike, making a smaller angle with the neutral sheet (i.e. larger $|B_X|/B_Z$), the pitch-angle distribution became isotropic (see the two traces marked $J_\perp$ (∿90^o) and $J_{||}$ (∿160^o) in Figure 5). This transition to isotropy is probably the result of enhanced pitch-angle scattering in the neutral sheet region. Since the scattering should be most effective on those field lines having the smallest equatorial curvature radius, this indicates that the associated precipitation on the ground originates from near the outer boundary of the plasma sheet.

The expansion phase onset on the ground, as defined by the Pi 2 onset shown in the middle of Figure 5, occurred at 2046:30 UT. Within a few seconds of this onset enhanced electron precipitation was observed over the two southernmost balloons. (The bay-onset precipitation usually has a harder

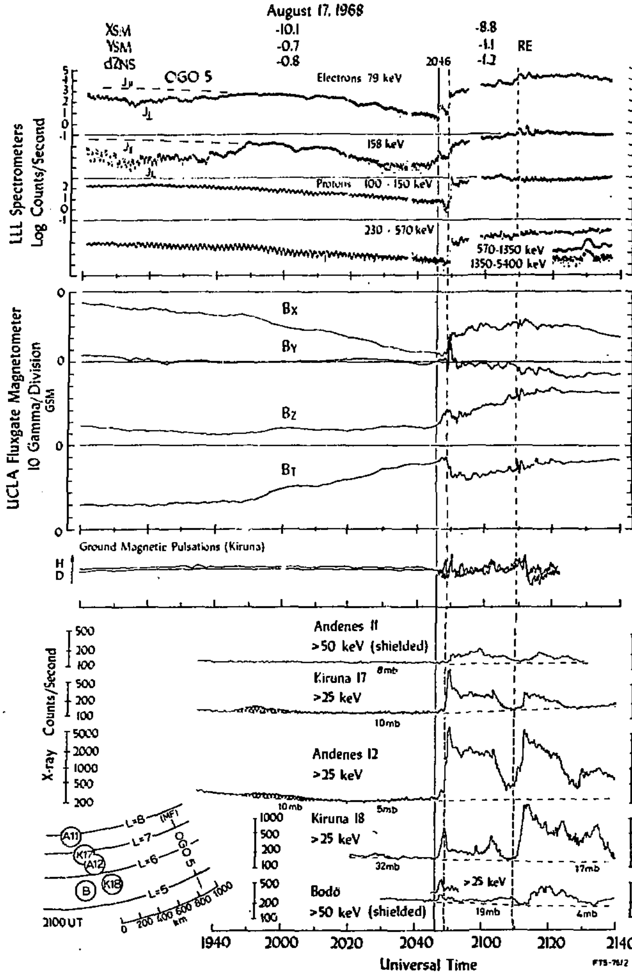


Figure 5 Simultaneous observations in the nighttime plasma sheet by the OGO 5 satellite and near the earth's surface by a north-south chain of balloons. The ionospheric intersection of the field line through OGO at 2100 UT, estimated by field-line tracing according to the Mead-Fairfield model MF73Q, is indicated by MF in the bottom left diagram. Normalized parallel electron fluxes at OGO are based upon data from the UCLA particle experiment. (From Pytte and West, 1976).

energy spectrum than the prebay precipitation and can therefore be observed by an X-ray detector at quite low altitudes.) As in the case presented in Figure 4, the bay-onset precipitation starting at ~2046:30 UT was first observed just north of the latitude where growth-phase precipitation occurred just before bay onset (L~5.5). There was also a delayed onset of precipitation farther north but a temporal structure during the first part of this event makes it more difficult to separate temporal and spatial variations this time. A more detailed discussion of this event can be found in Pytte et al. (1976b).

In the plasma sheet the first indication of the expansion onset was observed at 2046:00 UT, about 30 sec before the earliest onset identified on the ground, as a sharp increase in the flux of 79 keV electrons. A second increase occurred at 2049 UT, this time in both electron and proton fluxes, essentially simultaneous with the second increase of precipitation on the ground. The synchronous increase of both electrons and protons clearly indicates that OGO was ingulfed in the plasma sheet at this time. The smaller flux increase at 2046 UT was apparently due to a smaller, temporary expansion of the plasma sheet, in accordance with the ground observation that the first precipitation increase occurred over the southernmost balloons only.

We conclude that whereas enhanced electron precipitation during the growth phase seems to be due to pitch-angle scattering in the outer region of the plasma sheet during reconfiguration of the magnetic field, the bay-onset precipitation and its poleward expansion seem to be related to the expansion of the near-earth plasma sheet occurring as a consequence of an impulsive reconnection and earthward contraction of field lines. The earthward injection of particles causes precipitation over a broad (~10°) latitudinal and often very extended longitudinal region of the nighttime auroral zone. From this often very dynamic injection region the electrons thereafter drift eastwards, causing enhanced precipitation also in the morning sector (e.g. Kremser et al. 1973).

2.4 Multiple-Onset Magnetospheric Substorms

It has recently been discovered that substorms often have multiple expansion phase onsets which occur at 5-10 min intervals (Kisabeth and Rostoker, 1971; Clauer and McPherron, 1974; Wiens and Rostoker, 1975). The existence of more than one onset, and the fact that earlier onsets tend to be relatively weak, may cause misinterpretation of growth-phase effects and their relation to substorm triggering. In particular, Wiens and Rostoker (1975) found that successive onsets carried substorm activity westward in a steplike fashion, each onset occurring to the west and north of the previous one. They proposed that one local-time sector may experience growth while energy is being fed into that sector from an adjecent expanding sector to the east. In other words, growth-phase phenomena could be due to substorm expansions farther east, but since individual onsets take place within a limited local-time sector, some onsets may not be detected because of gaps in the station network. Growth-phase effects of the type discussed above that are directly related to enhanced southward IMF can therefore, according to this view, only be detected before the very first expansion onset within the same sequence.

In PAPER III (Pytte et al., 1976c) we examined the ground signatures of the expansion phase during multiple-onset substorms and compared our findings with the Wiens-Rostoker model. On the basis of extended observations of electron precipitation and magnetic perturbations it was shown that longitudinal motion of activity often occurred after each onset, in contrast to the discrete steps claimed by Wiens and Rostoker. Although activity on the average expands westward along the oval in the cause of a substorm, there seems to be no clear evidence that successive onsets always occur progressively farther west. Such a progressive shift is an essential element in the Wiens-Rostoker model and our observations therefore seem to cast doubt on the idea that growth-phase phenomena may largely be a manifestation of substorm expansion farther east.

Figure 6 exemplifies some of the main features of multiple-onset substorms. It also serves to illustrate the method of defining individual onsets employed in all studies summarized here. This substorm apparently had four onsets, identified by onsets of Pi 2 bursts in the auroral zone and, except for the first weak onset, also at middle latitudes. Each Pi 2 onset was accompanied by brightening of · ˜ auroral arc at Syowa Station, which was then in the local evening sector. This auroral brightening is the classical onset signature of the auroral substorm. The absence of active aurora following the first onset at 2151 UT indicates that Syowa did not enter the break-up region. The second and third onsets, on the other hand, were both followed a few minutes later by the arrival of a westward travelling auroral surge. Since a surge is believed to define the western edge of the break-up or expansion region (Akasofu, 1968), this edge crossed the Syowa meridian twice, which, as mentioned above, is contrary to the prediction of the Wiens-Rostoker model. During the fourth onset Syowa moved into the morning sector of auroral activity. This example shows that successive substorm onsets may be detected in magnetic pulsation recordings from one midlatitude station, although there appear to be weak onsets that are noticeable only in the auroral zone.

We note that this event also shows indications of an equatorward motion of the poleward edge of auroral activity following the passage of an westward-travelling surge. There was also an equatorward motion of the local polar electrojet. This apparent expansion of the polar cap is consistent with the observed thinning of the near-tail plasma sheet between successive onsets in the tail (Sec. 2.6).

It was suggested in PAPER III that there is a close spatial correlation between the westward motion of an auroral surge and the westward shift of mid-latitude magnetic signatures. In particular, the positive deflection in the D component which is believed to be caused by upward field-aligned currents

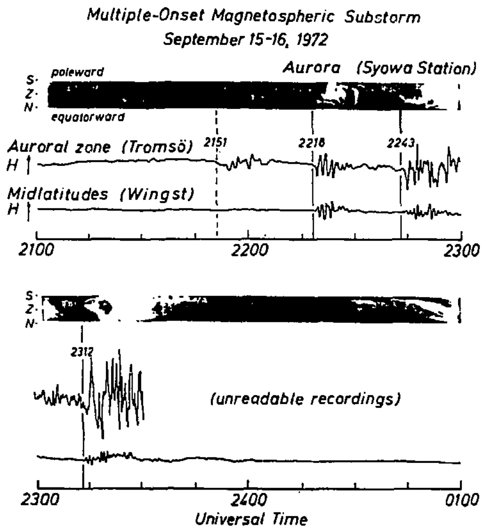


Figure 6a Latitudinal cross section of auroral activity at Syowa Station (from PAPER III), together with magnetic pulsation recordings. There was a brightening and equatorward motion of the auroras following the first three Pi 2 onsets; two onsets were followed by a westward-travelling surge.

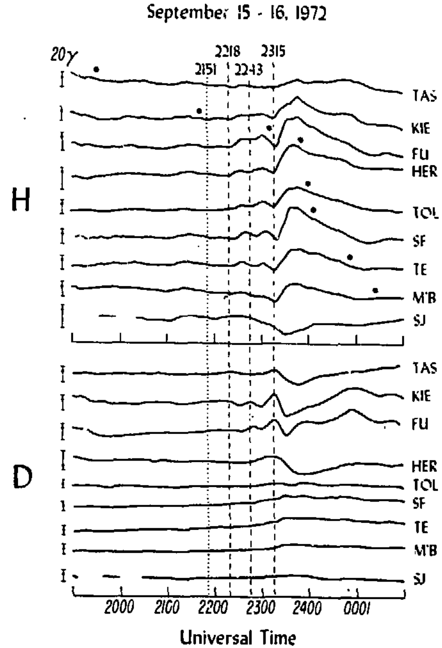


Figure 6b The mid- to low-latitude magnetic signatures of a multiple-onset magnetospheric substorm. Black dots are local magnetic midnight (from PAPER III).

defining the western edge of the substorm current wedge, should be observed just equatorward of the auroral surge. It is reasonable to believe that the longitudinal extent of the wedge at any given time corresponds to the active region of the magnetotail. Also, we expect that the response to substorm onsets is different inside and outside the wedge. Hence, before discussing the plasma sheet behaviour during substorms we show how the location and motion of the wedge can be inferred using magnetic data from midlatitude stations and from the synchronous orbit ($\sim$6.6 R_E).

2.5 The Substorm Current Wedge

Field-aligned current systems are symmetric with respect to the equatorial plane and the amplitude of the corresponding magnetic signatures therefore falls off with magnetic latitude. Hence, the positive-D signatures cannot be seen at low latitudes (cf.Figure 6b) and are very seldom seen at the magnetic equatorial plane. To show that midlatitude magnetic perturbations during substorms are indeed caused largely by field-aligned currents, we compare simultaneous magnetic recordings from an east-west chain of ground stations and from the ATS 6 satellite, which was located about 10^0 above the magnetic equator (McPherron and Pytte, 1976). Figure 7 shows that during the first (0206 UT) expansion on July 28, 1974 there was a positive D deflection at ATS and at all midlatitude stations shown, indicating that the central meridian of the current wedge was far to the east. During the second (0456 UT) expansion there was a negative deflection at stations to the east of DA (nearly conjugate to ATS), whereas the deflection to the west was first positive then negative. This change in sign, which is also seen at OT and FR during the first substorm, indicates that the central meridian was shifted from east to west of these stations. Similarly,there was a westward delay in the time of maximum positive deflection in D, indicating that the western edge of the wedge moved westward.

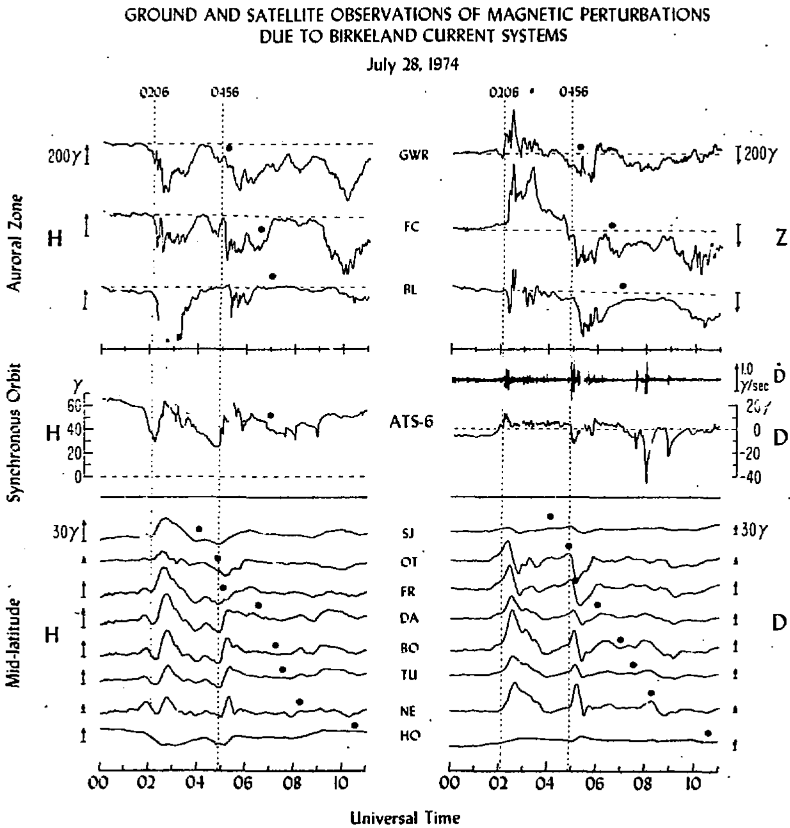


Figure 7 Ground and space observations of magnetic signatures in the different regions with respect to the substorm current wedge: ΔD is positive (eastward) to the southwest and negative to the southeast of the central meridian (ΔD=0). ΔH is negative to the west and to the east of the wedge, and maximum positive near the central meridian. Ground station DA is located near the ATS meridian. (From McPherron and Pytte, 1976.)

In this case there are no auroral data available to show any association with surge activity, but the D-perturbations at ATS 6 are usually positive (negative) when its conjugate region is located southwest (southeast) of an auroral surge observed by the DSMP satellite (McPherron and Pytte, 1976).

The initial depression in the H component before substorm expansion is believed to be due to an enhancement and inward motion of the partial ring current and the tail current. A similar local depression can be seen to the west of the current wedge during the expansion phase. The latter depression has, probably incorrectly, been interpreted by Wiens and Rostoker (1975) as indication of an independent substorm "growth". The recovery in H occurs when the inner part of the tail current is disrupted and shunted through the ionosphere (Figure 2b), and is mainly observed inside the wedge.

We finally note that the substorm current wedge, as defined by its midlatitude signatures, is a transient phenomenon. The east-west current sheets identified by Zmuda and Armstrong (1974) are, on the other hand, always present, but with varying position and intensity. The over-all current system during substorms can be thought of as being a superposition of the quasi-permanent pairs of current sheets and intensified wedge-type currents along the poleward sheets near midnight.

2.6 The Dynamics of the Plasma Sheet

An important element of current substorm models is the pre-substorm thinning of the near-tail plasma sheet which is thought to be causally related to substorm triggering. The observational basis for this idea has been questioned on two grounds. First, Akasofu (1974), citing instances when clear plasma sheet thinning was observed in the Vela orbit ($\sim 18\ R_E$) at the time of auroral break-up, rejected reports on pre-substorm thinning because of inadequate substorm timing. Second, Rostoker (1974) argued that because of the localized nature of substorm effects in the tail one cannot unambiguously relate effects observed at one point in space to an independent growth phase.

In PAPER IV (Pytte et al., 1976d) we have examined the basis for this criticism by using measurements obtained by two satellites at different radial locations in the magnetotail but at nearly the same local time. Figure 8 shows observations during a multiple-onset substorm when the OGO 5 and Vela 4A spacecraft were located near local midnight and close to the central meridian of the substorm current wedge. Since the ground magnetograms indicate a similar temporal and spatial development of this substorm and the substorm shown in Figures 6a and b, we are able to draw comparisons between the dynamics of the plasma sheet and of the aurora, although observed during different substorms.

The important features illustrated in Figure 8 are 1) a simultaneous occurrence of multiple expansions of the plasma sheet (increases of particle intensities and magnetic field rotations) in the near-earth region at OGO and the continuous thinning (decreasing fluxes of low- and high-energy electrons) in the tailward region at Vela, and 2) a one-to-one correspondence between plasma sheet expansions in the near-earth region and bursts of Pi 2 pulsations on the ground, with no Pi 2 at the time of the 2240-UT expansion at Vela. In addition, a detailed analysis of particle and field data indicates that a minimum plasma sheet thickness developed between the two spacecraft ($r \sim 15$ R_E) early in the substorm, and that this region of a pinched plasma sheet remained almost stationary until maximum bay activity was reached in the auroral zone.

On the basis of these and similar recordings it was concluded that there is a clear difference in plasma sheet behaviour during the expansion phase in locations earthward and tailward of ~ 15 R_E. Since this result was based

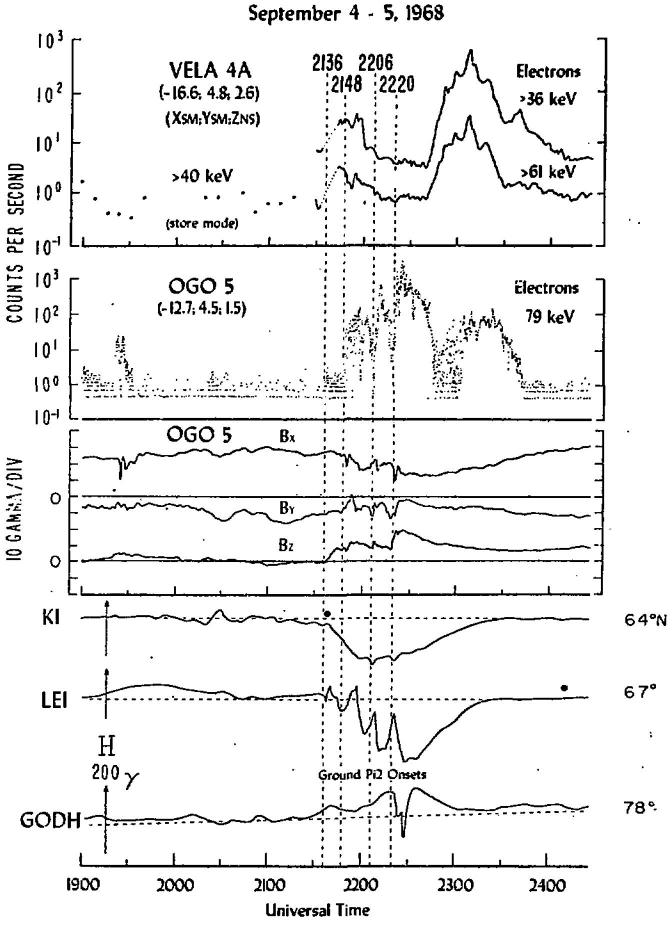


Figure 8 The signatures of a multiple-onset substorm at two different radial distances in the plasma sheet and at different local times along the oval. Satellite locations are given (in R_E) as geocentric distance in the solar (X_{SM}) and westward (Y_{SM}) direction, and as estimated distance above the neutral sheet (Z_{NS}). The apparent drop in electron fluxes at OGO between ∿2240 and 2310 UT is due to changing pitch-angle distributions. (Adapted from PAPER IV.)

on simultaneous measurements in the two regions, it is not dependent on any ambiguities in substorm timing. Thus, temporal characteristics of the near-earth plasma sheet cannot be inferred from observations in the Vela orbit, because this orbit is usually tailward of the neutral line near midnight. For example, the poleward expansion of auroral-zone activity correponds, as we have seen (Figure 5), to an expansion of the near plasma sheet, not to a rapid thinning as claimed by Akasofu (1975). During the growth phase, the most pronounced thinning is expected to occur in and earthward of the region where the neutral line seems to form ($r \sim 10$-$15\ R_E$). In that sense there may well be a radial dependence of plasma sheet variations in this region also during this phase.

The relationship between plasma sheet variations and auroral features can be inferred from these recordings using Pi 2 pulsations as a common time reference and recalling the close correspondence between Pi 2's and auroral break-up. We see that just as a single ground station may observe two or more break-up sequences during one substorm, a satellite, located at nearly fixed local time near midnight, may observe essentially identical sets of onset signatures in the near plasma sheet for each Pi 2 on the ground. Moreover, preliminary studies of satellite data obtained in the early evening sector, at about the same radial distances as considered here, indicate that the eveningside plasma sheet thins early in the expansion phase and that transient ($\sim$10 min duration) plasma sheet expansions occur during multiple-onset substorms a few minutes after Pi 2 bursts. This delay, which may be explained in terms of a westward propagation of activity, does not become progressively shorter in the course of a substorm, as would be expected if activity was initiated farther and farther west. We therefore speculate that thinning is observed if the satellite is located in the sector of auroral brightening but to the west of a surge, and that the transient expansion corresponds to the arrival of the surge. This initial thinning may well be related to the cause of westward expansion, but obviously not to the triggering of the subsequent onset.

Our phenomenological model for the dynamics of the plasma sheet during substorms, and the type of observations from which it was derived, are shown schematically in the right part of Figure 9. This model differs on essential points from the model of Rostoker and Camidge (1971), shown to the left, which has been developed further by Rostoker (1974) and Wiens and Rostoker (1975). As we have already mentioned, the latter model assumes that growth and expansion occur synchronously in adjecent sectors of the magnetotail and that the expansion steps progressively farther west associated with successive onsets on the ground. We wish to point out, however, that our model is not inconsistent with the schematic diagrams shown by these authors of the successive locations of the new polar electrojets at the maximum of each onset, one poleward of the other and in partly overlapping sectors.

Another important element in our model is the concept of a near-earth X-type neutral line, whose existence has previously been indicated by several independent observations (see Russell, 1974). This line separates tail regions of different magnetic field topology, and is probably located in the radial region of minimum plasma sheet thickness. The rapid reduction following bay onset of the tail lobe magnetic energy density and the rapid return of the near tail to a more dipolar configuration on the one hand, and the poleward expansion of activity on the ground during the interval of an apparently radially stationary neutral line on the other, are clear indications of a rapid enhancement of reconnection in this near-earth region. As we have discussed (Sec. 1.3), this particular radial location may be explained in terms of a flow velocity gradient down the tail following enhanced dayside merging.

The multiple onsets of the expansion phase observed during some substorms are probably due to repeated enhancements of reconnection, each enhancement apparently being triggered as a result of plasma sheet thinning towards a minimum, unstable thickness. Following each onset, the unstable region seems to expand westward and, in a less dynamic way, also eastward. This expansion

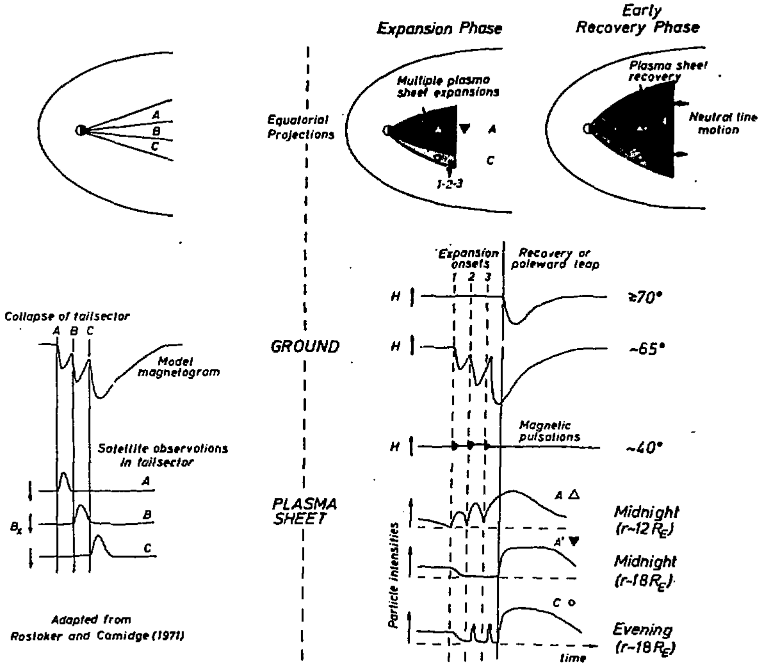


Figure 9 Two different phenomenological models for the dynamics of the plasma sheet during multiple-onset substorms. The model to the left (Rostoker and Camidge, 1971) assumes that successive expansions occur in adjacent sectors of the tail. The corresponding postulated magnetic signatures (mainly diamagnetic depressions during plasma sheet expansions) have, to our knowledge, not been observed. In our alternative model, we propose that each expansion onset is triggered within essentially the same, but radially limited, sector, and that the western edge of that sector expands westward following each onset. The corresponding plasma sheet signatures have been observed during different but temporally and morphologically similar substorms.

of the substorm injection region may explain the westward expansion of energetic electron precipitation and the fact that the eastward expansion of this precipitation often exceeds the speed expected from magnetic gradient and curvature drift (Berkey et al., 1974; Hultqvist, 1975)

2.7 The "Convection Bay".

We end this review with a brief discussion of a newly recognized type of magnetospheric activity which apparently does not readily fit into the current models for substorms (Pytte et al., 1976e).

We have described the substorm in terms of processes related to magnetospheric convection and emphasized the storage of energy during a growth phase and the rapid release of energy during substorm expansion. We have also demonstrated that although storage and release in general occur concurrently, their effects can often be separated on the basis of characteristic signatures. It is well known that it may be difficult to identify weak, high-latitude substorms, but during moderately active periods, when the auroral oval moves south and the intensity of substorm onset signatures increases, a consistent behaviour of a set of substorm signatures will usually reliably identify the onset of individual substorms. For example, during multiple-onset substorms, there are repeated onsets of auroral brightening, Pi 2's, low-latitude positive bays, and plasma sheet variations. However, during intervals of continuously southward IMF, when the auroral zone is strongly disturbed for several hours, even the method of using a set of signatures does sometimes not work. There may be long intervals (4-5 hrs or more) of intense bay activity, and therefore presumably frequent substorm expansions, when no other indications of substorms can be found. The many bay intensifications may be caused by motions of the current systems, and since they occur at different times at different stations, they cannot be used to time individual substorm onsets.

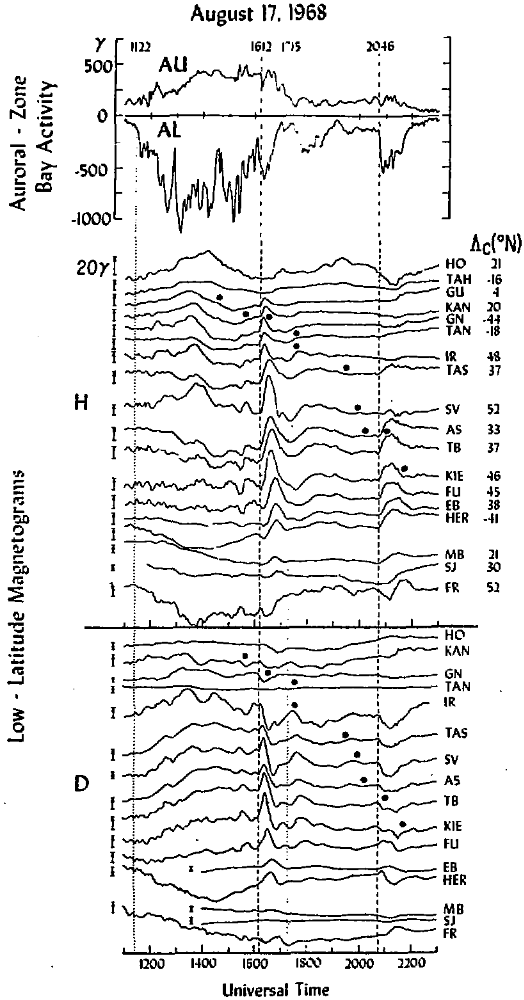


Figure 10 AL and AU indices (envelopes of H-component magnetograms) from 12 auroral-zone stations during an interval (1200-1600 UT) of strong magnetospheric activity when no clear low-latitude magnetic signatures of substorm expansions were observed. A clear low-latitude onset occurred at 1612 UT, associated with a relatively weak negative bay in the auroral zone (from Pytte et al., 1976e).

There may be two reasons for this apparent absence of the usual substorm signatures during such events. The spatial and temporal characteristics of the substorm, and therefore their signatures, may be different during moderate and very intense, long-duration activity. This explanation does not seem probable since clear substorm signatures are seen regularly also during very high activity. Another possibility is that there are two different types of processes which both cause intense bays, but that during one of them substorms play a minor role or are absent.

This latter possibility has been examined in data from four satellites and a large number of ground stations during the event shown in Figure 10. During the interval $\sim$1200-1600 UT, when the AE (|AL|+AU) index was $\gtrsim$1000γ, no low-latitude positive bay onset in H was observed. From the empirical relation found by Kokubun and Iijima (1975) between the amplitudes of auroral-zone and low-latitude magnetic perturbations during substorm expansions we would expect that negative bays of $\gtrsim$800γ should be accompanied by $\gtrsim$40γ positive bays (at 40^{o} latitude). Only one negative bay, which occurred when the over-all activity had started to decay (1612 UT), was accompanied by such a low-latitude signature.

Similar features were also found in other, independent recordings. Magnetic pulsation recordings from widely spaced midlatitude stations show clear Pi 2 bursts around 1120 and at 1612 UT, but there are no clear onsets in the intermediate interval. Furthermore, two satellites located in the plasma sheet near midnight observed the tail signatures of substorm recovery, often associated with a tailward motion of the neutral line, around 1245 UT, but thereafter no indications of substorm onsets were seen until 1612 UT. Between 1250 and $\sim$1600 UT the plasma sheet was relatively thick, reaching its minimum thickness of a few tenths of one R_E just before 1612 UT at $r \sim 15R_E$.

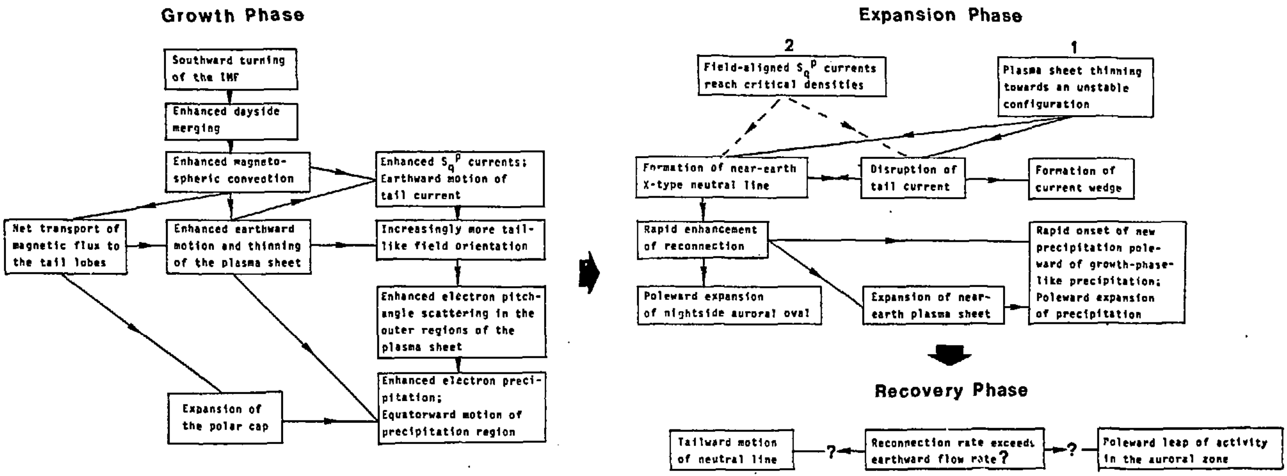
The existence of this type of magnetospheric activity, which can be characterized as strong magnetospheric convection driven by a continuously southward IMF, ties directly in with the preceding discussions. An interval of enhanced convection, which provides "free" energy, is according to most substorm models a necessary condition for substorm expansions to occur. However, during this 4-hr interval of strong convection there were no clear indications of substorms, as if the substorm triggering mechanism(s) did not become operative. Enhanced convection, therefore, does not seem to be a sufficient condition for substorm triggering. The observation of a relatively thick plasma sheet in the region of substorm-associated neutral line formation during the same interval, and the fact that the plasma sheet became very thin only in conjunction with the appearence of substorm signatures on the ground, indicates that enhanced convection must be accompanied by plasma sheet thinning towards an unstable thickness or configuration in order to provide sufficient conditions for triggering. The absence of near-earth thinning during strong activity may be due to a choking of the earthward flow by enhanced line-tying in the ionosphere. The earthward flow in the more distant tail causes plasma heating, injection and precipitation, which, combined with large convection electric fields, result in strong magnetic disturbances in the auroral zone — the convection bays.

This type of magnetospheric activity, and the above interpretation, is consistent with other observations during similar conditions (e.g., strong earthward plasma flow near the neutral sheet, absence of poleward motions of the auroral region) as summarized by Pytte et al. (1976e). Recently, some of the above conclusions have been reached independently by Sergeev (1976).

3. SUMMARY AND CONCLUSIONS

To summarize the main topics of this review we present in Figure 11 a schematic model of the relations between some of the basic processes believed to operate during the three phases of the magnetospheric substorm. Some special features illustrated by this model are:

- The occurrence of enhanced growth-phase electron precipitation and its equatorward motion, which appear to occur as a direct consequence of enhanced convection, are indications of reconfiguration of the night-side magnetosphere towards an unstable situation.
- The growth-phase precipitation is accompanied by magnetospheric processes different from those observed during the expansion and recovery phases.
- There are good theoretical and observational reasons to believe that the substorm expansion phase is triggered when an X-type neutral line is formed within a very thin plasma sheet near $r \sim 15\ R_E$ (Model 1; e.g. Russell, 1974).
- An alternative triggering model proposed by Akasofu (1974, 1975) (Model 2), proposes that an X-type neutral line is formed when field-aligned portions of the S_q^p (convection) current system exceed critical current densities, without requiring any preceding plasma sheet thinning.
- Since there appears to be a close relationship between increases of S_q^p current intensities and magnetospheric convection rates, the two substorm triggering models are not necessarily mutually exclusive. However, the existence of a convection-bay associated magnetospheric disturbance (Sec. 2.7), during which the S_q^p currents apparently remained very intense for several hours without causing any observed substorm expansions, seems to indicate that an enhancement beyond critical densities of these currents is not a sufficient condition for triggering. Whereas Akasofu (1975)



<u>Figure 11</u> Schematic model of relations between some important substorm phenomena. Distinctions between expansion triggering mechanisms (1) and (2) are discussed in the text.

rejected triggering mechanisms associated with a thinned plasma sheet, our measurements during substorms clearly favour such a mechanism. In fact, this additional requirement of a very thin near-earth plasma sheet is consistent with observations during convection bays.

- The recovery phase, perhaps the least examined phase of the substorm, is usually considered to represent a relaxation of the magnetosphere towards a quiet (pre-growth phase) state. However, it is not clear whether this phase starts when available energy is exhausted or, for example, when magnetospheric convection is being choked by a build-up of plasma pressure in the inner magnetosphere. The latter possibility has been indicated here, together with some related phenomena.

Future efforts towards solving the many remaining questions in substorm morphology and dynamics should be concentrated on making measurements on board the same spacecraft of as many correlated parameters as possible, especially in the critical regions for substorm triggering and particle acceleration in the tail and in the upper ionosphere. Also, simultaneous data should, whenever possible, be obtained from two or more suitably separated locations in space and be correlated with data from the ever denser and better equipped network of ground stations. The studies reported here are some results towards this goal, but based upon already existing data.

Future experiments may have been made an easier task by the fact that we today more than ever before know what to look for and know the range of parameters to be measured. Also, we now have better theoretical and phenomenological models for the behaviour of the magnetosphere to guide us.

Table 1 Location of Magnetometer Stations

Station Name	Code Name	Corrected Geomagnetic Coordinates Lat.(^oN)	Corrected Geomagnetic Coordinates Long.(^oE)	Time of Local Magnetic Midnight (UT)*
		Auroral Zone and Polar Cap		
Baker Lake	BL	75.1	320.4	0630
Ft. Churchill	FC	70.0	326.0	0615
Godhavn	GODH	77.6	43.3	0210
Great Whale River	GWR	68.3	353.8	0455
Kiruna	KIR	64.3	104.8	2145
Leirvogur	LEI	66.6	71.2	0015
		Mid to Low Latitudes		
Ashkabad	AS	32.6	128.6	2010
Bangui	BA	-4.8	88.5	2300
Boulder	BO	49.3	315.7	0700
Dallas	DA	34.4	326.9	0615
Ebro	EB	38.0	79.0	2330
Fredricksburg	FR	51.8	352.2	0455
Fürstenfeldbruck	FU	44.7	89.1	2250
Gnangara	GN	-44.1	184.9	1620
Guam	GU	7.4	213.8	1440
Hermanus	HER	-41.1	79.6	2320
Honolulu	HO	21.1	266.5	1040
Irkutsk	IR	48.2	175.3	1730
kanoya	KAN	25.7	200.8	1540
Kiev	KIE	46.1	104.9	2140
M'Bour	MB	10.5	57.1	0005
Moca	MO	5.7	78.6	2340
Newport	NE	54.9	299.7	0815
Ottawa	OT	58.9	355.7	0455
San Juan	SJ	31.3	5.5	0405
San Fernando	SF	34.6	72.6	0005
Sverdlovsk	SV	52.3	133.0	1950
Tahiti	TAH	-16.4	282.5	0925
Tangerang	TAN	-15.8	176.1	1720
Tashkent	TA(S)	36.6	139.6	1920
Tbilisi	TB	36.7	116.2	2055
Tenerife	TE	27.5	63.5	0050
Toledo	TOL	37.9	75.1	0000
Tucson	TU	39.7	311.4	0730

*Approximate average times for July, August and September

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References

Akasofu, S.-I., Polar and magnetospheric substorms, Springer, New York, 1968.

Akasofu, S.-I., The aurora and the magnetosphere: The Chapman memorial lecture, Planet. Space Sci., 22, 885, 1974.

Akasofu, S.-I., The roles of the north-south component of the interplanetary field on large-scale auroral dynamics observed by the DSMP satellite, Planet. Space Sci., 23, 1349, 1975.

Akasofu, S.-I., P.D. Perreault, F. Yasuhara, and C.-I. Meng, Auroral substorms and the interplanetary magnetic field, J. Geophys. Res., 78, 7490, 1973.

Arnoldy, R.L., Signature in the interplanetary medium for substorms, J. Geophys. Res., 76, 5189, 1971.

Axford, W.I., Magnetospheric convection, Rev. Geophys., 7, 421, 1969.

Aubry, M.P., C.T. Russel, and M.G. Kivelson, On Inward motion of the magnetopause before a substorm, J. Geophys. Res., 75, 7018, 1970.

Aubry, M.P., and R.L. McPherron, Magnetotail changes in relation to solar wind magnetic field and magnetospheric substorms, J. Geophys. Res., 76, 4381, 1971.

Berkey, F.T., V.M. Driatkiy, K. Henriksen, B. Hultqvist, D.H. Jelly, T.I. Shchuka, A. Theander, and J. Yliniemi, A synoptic investigation of particle precipitation dynamics for 60 substorms in IQSY(1964-1965) and IASY(1969), Planet. Space Sci., 22, 255, 1974.

Buck, R.M., H.I. West, Jr., and R.G. D'Arcy, Jr., Satellite studies of magnetospheric substorms on August 15, 1968 - 7.Ogo 5 energetic proton observations-spatial boundaries, J. Geophys. Res., 78, 3103, 1973.

Burch, J.L., Observations of interactions between interplanetary and geomagnetic fields, Rev. Geophys. Space Phys., 12, 363 1974.

Caan, M.N., R.L. McPherron, and C.T. Russell, Solar wind and substorm-related changes in the lobes of the geomagnetic tail, J. Geophys. Res., 78, 8087, 1973.

Camidge, F.P., and G. Rostoker, Magnetic field perturbations in the magnetotail associated with polar magnetic substorms, Can. J. Phys., 48, 2002, 1970.

Clauer, C.R., and R.L. McPherron, Mapping of local time-universal time development of magnetospheric substorms using mid-latitude magnetic observations, J. Geophys. Res., 79, 2811, 1974.

Coroniti, F.V., Personal communication, 1975.

Coroniti, F.V., and C.F. Kennel, Changes in the magnetospheric configuration during the substorm growth phase, J. Geophys. Res., 77, 3361, 1972.

Coroniti, F.V., and C.F. Kennel, Can the ionosphere regulate magnetospheric convection? J. Geophys. Res., 78, 2837, 1973.

Fairfield, D.H., and N.F. Ness, Configuration of the geomagnetic tail during substorms, J. Geophys. Res., 75, 7032, 1970.

Foster, J.C., D.H. Fairfield, K.W. Ogilvie, and T.J. Rosenberg, Relationship of the interplanetary parameters and occurrence of magnetospheric substorms, J. Geophys. Res., 76, 6971, 1971.

Hargreaves, J.K., H.J.A. Chivers, and W.I. Axford, The development of the substorm in auroral radio absorption, Planet. Space Sci., 23, 905, 1975.

Holzer, T.E., and G.C. Reid, The response of the day side magnetosphere-ionosphere system to time-varying field line reconnection at the magnetopause. 1. Theoretical model, J. Geophys. Res., 80, 2041, 1975.

Hones, E.W. Jr., Plasma sheet variations during substorms, Planet. Space Sci., 20, 1409, 1972.

Hones, E.W., Jr., J.R. Asbridge, S.J. Bame, and I.B. Strong, Outward flow of plasma in the magnetotail following geomagnetic bays, J. Geophys. Res., 72, 5879, 1967.

Hones, E.W. Jr., S. Singer, L.J. Lanzerotti, J.D. Pierson, and T.J. Rosenberg, Magnetospheric substorms of August 25-26., 1967, J. Geophys. Res., 76, 2977, 1971.

Hones, E.W., Jr., J.R. Asbridge, S.J. Bame, and S. Singer, Substorm variations of the magnetotail plasma sheet from $X_{sm} \approx -6\ R_E$ to $X_{sm} \approx -60\ R_E$, J. Geophys. Res., 78, 109, 1973.

Hultqvist, B., The Aurora, in The Magnetospheres of the Earth and Jupiter, (edited by V. Formisano) p. 77, D. Reidel, Dordrecht-Holland, 1975.

Kelley, M.C., J.A. Starr, and F.S. Mozer, Realtionship between magnetospheric electric fields and the motion of auroral forms, J. Geophys. Res., 76, 5269, 1971.

Kisabeth, J.L., and G. Rostoker, Development of the polar electrojet during polar magnetic substorms, J. Geophys. Res., 76, 6815, 1971.

Kremser, G., K. Wilhelm, W. Riedler, K. Brønstad, H. Trefall, S. Ullaland, J.P. Legrand, J. Kangas, and P. Tanskanen, On the morphology of auroral-zone X-ray events - II. Events during the early morning hours, J. Atmosph. Terr. Phys. 35, 713, 1973.

Kokubun, S., and T. Iijima, Time-sequence of polar magnetic substorms, Planet. Space Sci., 23, 1483, 1975.

Lui, A.T.Y., E.W. Hones, Jr., D. Venkatesan, S.-I. Akasofu, and S.J. Bame, Complete plasma dropouts at Vela satellites during thinning of the plasma sheet, J. Geophys. Res., 80, 4649, 1975.

McPherron , R.L., Growth phase of magnetospheric substorms, J. Geophys. Res., 75, 5592, 1970.

McPherron, R.L., Substorm related changes in the geomagnetic tail: The growth phase, Planet. Space Sci., 20, 1521, 1972.

McPherron, R.L., and T. Pytte, Magnetic observations of field-aligned currents by the fluxgate magnetometer on ATS 6, in preparation, 1976.

McPherron, R.L., C.T. Russell, M.G. Kivelson, and P.J. Coleman, Substorms in space: The correlation between ground and satellite observations of the magnetic field, Radio Sci., 8, 1059, 1973a.

McPherron, R.L., C.T. Russell, and M.P. Aubry, Satellite studies of magnetospheric substorms on August 15, 1968 - 9. Phenomenological model for substorms, J. Geophys. Res., 78, 3131, 1973b.

Mozer, F.S., Origin and effects of electric fields during isolated magnetospheric substorms, J. Geophys. Res., 76, 7595, 1971.

Nishida, A., Interplanetary origin of electric fields in the magnetosphere, Cosmic Electrodyn., 2, 350, 1971.

Nishida, A., Field and particle observations in the magnetotail related to the reconnection process, Paper presented at the International Symposium in Leningrad, May 1976.

Nishida, A., and N. Nagayama, Synoptic survey for the neutral line in the magnetotail during the substorm expansion phase, J. Geophys. Res., 78, 3782, 1973.

Nishida, A., and E.W. Hones, Jr., Association of plasma sheet thinning with neutral line formation in the magnetotail, J. Geophys. Res., 79, 535, 1974.

Nishida, A., and K. Fujii, Thinning of the near-earth (10-15 R_E) plasma sheet preceding the substorm expansion phase, Planet. Space Sci., 24, 849, 1976.

Pytte, T., Auroral-zone electron precipitation events observed before and at the onset of negative magnetic bays. Paper presented at the XV Plenary Meeting of COSPAR, Madrid, 1972.

Pytte T., and H. Trefall, Auroral-zone electron precipitation events observed before and at the onset of negative magnetic bays, J. Atmos. Terr. Phys., 34, 315, 1972.

Pytte T., and H.I. West Jr., Ground-satellite correlation during pre-substorm magnetic field configuration changes and plasma sheet thinning in the near-earth magnetotail, J. Geophys. Res., submitted, 1976.

Pytte T., H. Trefall, G. Kremser, L. Jalonen, and W. Riedler, On the morphology of energetic (≳30keV) electron precipitation during the growth phase of magnetospheric substorms, J. Atmos. Terr. Phys., 38, 739, 1976a.

Pytte T., H. Trefall, G. Kremser, P. Tanskanen, and W. Riedler, On the morphology of energetic (≳30keV) electron precipitation at the onset of negative magnetic bays, J. Atmos. Terr. Phys., 38, 757, 1976b.

Pytte T., R.L. McPherron, S. Kokubun, The ground signatures of the expansion phase during multiple-onset substorms, Planet. Space Sci., 24, in press, 1976c.

Pytte T., R.L. McPherron, M.G. Kivelson, H.I. West,Jr., and E.W. Hones, Jr., Multiple- Satellite Studies of magnetospheric substorms: Radial dynamics of the plasma sheet, J. Geophys. Res., in press, 1976d.

Pytte T., R.L. McPherron, E.W. Hones Jr. and H.I. West Jr., Multiple-satellite studies of magnetospheric substorms: Absence of substorm-onset signatures during prolonged auroral-zone bay activity, J. Geophys. Res., submitted, 1976e.

Rostoker G., Ground based magnetic signatures of the phases of Magnetospheric Physics, (edited by B.M. McCormac), p. 325, D. Reidel Publishing Comp., Dordrecht-Holland, 1974.

Rostoker G., Personal communication, 1976.

Rostoker G., and F.P. Camidge, Localized character of magnetotail magnetic fluctuations during polar magnetic substorms, J. Geophys. Res., 76, 6944, 1971.

Russell, C.T., The solar wind and magnetospheric dynamics, in Correlated Interplanetary and Magnetospheric Observations (edited by D.E. Page) p.3, D. Reidel, Dordrecht-Holland, 1974.

Russell, C.T., and R.L. McPherron, The Magnetotail and Substorms, Space Sci. Rev., 15, 205, 1973.

Schindler K., A theory of the substorm mechanism, J. Geophys. Res., 79, 2803, 1974.

Sergeev, V.A., On the state of the magnetosphere during prolonged period of southward oriented IMF, Physica Solariterrestris, submitted, 1976.

Vasyliunas, V.M., and R.A. Wolf, Magnetospheric substorms: Some problems and controversies, Rev. Geophys. Space Phys., 11, 181, 1973.

Vorobjev, V.G., G.V. Starkov, and Y.I. Feldstein, The auroral oval during the substorm development. Planet. Space Sci., 24, 955, 1976.

West, H.I.,Jr., R.M. Buck, and J.R. Walton, Electron pitch angle distributions throughout the magnetosphere as observed on Ogo 5, J. Geophys. Res., 78, 1064, 1973.

Wiens, R.G., and G. Rostoker, Characteristics of the development of the westward electrojet during the expansive phase of magnetospheric substorms, J. Geophys. Res., 80, 2109,1975.

Zmuda, A.J., and J.C. Armstrong, The diurnal flow pattern of field-aligned currents, J. Geophys. Res., 79, 4611, 1974.