TRANSIENT PHENOMENA IN THE MAGNETOTAIL AND THEIR RELATION TO SUBSTORMS*

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Abstract. Recent observations of magnetic field, plasma flow and energetic electron anisotropies in the magnetotail plasma sheet during substorms have provided strong support for the idea that a magnetospheric substorm involves the formation of a magnetic neutral line (the substorm neutral line) within the plasma sheet at $X_{SM} \approx -10R_E$ to $-25R_E$. An initial effect, in the tail, of the neutral line's formation is the severance of plasma sheet field lines to form a plasmoid, i.e., a closed magnetic loop structure, that is quickly (within 5–10 min) ejected from the tail into the downstream solar wind. The plasmoid's escape leaves a thin downstream plasma sheet through which plasma and energetic particles stream continuously into the solar wind, often throughout the duration of the substorm's expansive phase. Southward oriented magnetic field threads this tailward-flowing plasma but its detection, as an identifier of the occurrence of magnetic reconnection, is made difficult by the thinness and turbulence of the downstream plasma sheet. The thinning of the plasma sheet downstream of the neutral line is observed, by satellites located anywhere but very close to the tail's midplane, as a plasma dropout. Multiple satellite observations of plasma droputs suggest that the substorm neutral line often extends across a large fraction ($>\frac{1}{2}$) of the tail's breadth. Near the time of substorm recovery the substorm neutral line moves quickly tailward to a more distant location, progressively inflating the closed field lines earthward of it, to reform the plasma sheet.

1. Introduction

Substorms and their transient nature have been recognized in ground observations of auroras and geomagnetism for several decades. During the last decade observations with Earth satellites have revealed transient phenomena in the outer magnetosphere, particularly in the magnetotail, that occur in coincidence with the familiar substorm phenomena seen at Earth and that provide important new clues regarding causative substorm mechanisms.

It appears from these observations that the Earth's magnetosphere in the flowing solar wind constitutes a magnetohydrodynamic generator of unusual design. It converts kinetic energy of flowing solar wind plasma to electric currents and in doing so it also stores appreciable amounts of energy as magnetic field and confined hot plasma in its magnetotail. At intervals the magnetotail releases relatively large amounts of its stored energy. It does so catastrophically, converting some of its stored magnetic energy to particle kinetic energy. Substorms are a manifestation of these catastrophic energy releases.

The energy release may occur in a manner that is in some ways analogous to the detachment of a water droplet from a dripping faucet. There is evidence that a blob of magnetized plasma, a 'plasmoid', becomes detached from the magnetotail plasma

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sheet at substorm onset and is carried away downstream by the solar wind. The analogy is illustrated in Figure 1. The plasmoid's formation and severance from the magnetotail are thought to be accomplished by reconnection, or merging, of tail magnetic field lines within the plasma sheet at an x-type magnetic neutral line. This 'substorm neutral line' forms relatively near the Earth, i.e., often within 10–20R_E of the Earth. Although much of the energy released by the magnetotail is carried away in the plasmoid, a comparable amount heats the plasma in that portion of the plasma sheet remaining attached to the Earth and projects it earthward. Bursts of electrons and protons with energies approching 1 MeV are observed in the plasma sheet concurrent with some substorms. These are, perhaps, accelerated in strong electric fields induced by rapid fluctuations of the magnetic field that are associated with severance of the plasmoid and with the attendant reconfiguration of the field.

This substorm scenario is strongly supported by several types of evidence found in studies of many substorms. This paper describes some of that evidence – that found in observations of transient phenomena in the magnetotail beyond the distance of ~10–15R_E. Recent objections to this picture of the substorm process can probably be answered satisfactorily in terms of the detailed structure and time variability of magnetospheric structures that take part in the process.

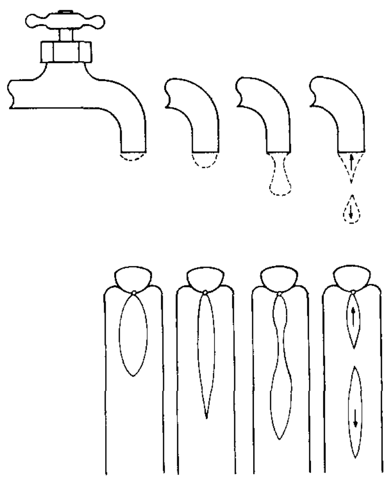

Fig. 1. Analogy of plasma sheet severance and plasmoid formation to the behavior of water dripping from a leaky faucet.

2. Transient Phenomena Observed in a Substorm on October 8, 1974

We begin by examining transient phenomena observed at about 30R_E in the tail during an individual substorm. We shall find in this event several distinct aspects of the data that strongly support the ideas (a) that magnetic reconnection began somewhere earthward of the satellite precisely at the substorm expansive phase onset, (b) that it continued at an earthward location for more than thirty minutes and, (c) that the neutral line then moved to a location tailward of the satellite as the substorm signature at Earth (a negative bay at an auroral zone station) began to subside. In addition to supporting this general picture, the data, when its time variations are carefully considered, suggest that formation and tailward ejection of a plasmoid was the initial step in this substorm sequence.

Before looking at the satellite data we first review briefly certain aspects of the magnetic field reconnection process with the help of Figure 2. This illustrates

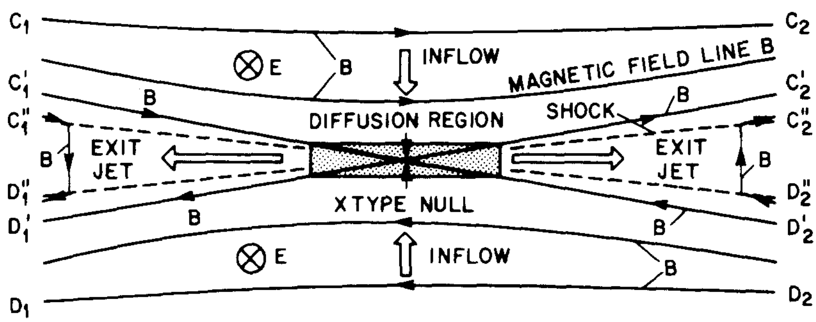

Fig. 2. Schematic illustration of steady-state magnetic reconnection process, showing possible magnetic field and plasma flow configurations (NAS, Space Science Board, 1978).

schematically possible magnetic field and plasma flow configurations in steady state reconnection. Slow plasma in-flow carries strong magnetic fields (lines C_1–C_2 and D_1–D_2) toward the current sheet. Energized plasma is ejected along the current sheet in two narrow jets with vertices at the x-type neutral line. Reconnected field lines C_1''–D_1'' and C_2''–D_2'' leave the merging region in the exit plasma jets. C_1''–D_1'' is directed downward (let us say southward) across the current sheet and C_2''–D_2'' is directed upward (northward). If we imagine Figure 2 to represent a reconnection region in the magnetotail the Earth is to the right; then plasma containing northward field is jetting earthward from the diffusion region and plasma containing southward field is jetting tailward. The presence of the Earth and the fact that field lines connect to the Earth at the right introduces important asymmetries in the consequences of the illustrated merging process. (a) Plasma flowing earthward (to the right) is confined on closed earth-tied field lines; thus its density can build up. (b) Tailward flowing plasma may be on closed (but not earth-tied) field lines if the pre-merged lines were closed downstream (as plasma sheet field lines would be) and so could accumulate in the closed magnetic loops to form a magnetically isolated plasma bubble; or the tailward flowing plasma may be on open field lines (as merged tail lobe field lines would be) and would not accumulate but would flow freely into the solar wind. These same comments hold also, of course, for energetic particles that may be present in the system.

We now examine magnetotail phenomena observed with the IMP-8 satellite during a substorm on October 8, 1974. (This event and another one, on April 18, 1974, that resembles it in every respect, has been described elsewhere (Hones, 1977).) The substorm onset was indicated by an 800γ negative bay at the auroral zone station, Dixon, with a very sharp onset at 18:27 UT. The bay began to subside at ~19:05 UT (See Figure 4 of Hones, 1977). This onset time (18:27 UT) is indicated by the dashed line in Figure 3. Coincident with the bay onset the plasma began to flow tailward and the energetic electron flux rose suddenly above background (Figure 3). At 18:28:45 UT the magnetic field latitude turned strongly southward and 35 s later a dropout of plasma started. A particularly important aspect of these data is that the energetic electrons were essentially isotropic when they first appeared and for about four minutes longer. Then, at 18:31 UT they suddenly began to display a pronounced tailward-streaming distribution, indicating that the satellite became enveloped at that instant by magnetic field lines that opened tailward (Baker and Stone, 1976).

From 18:31 UT until 19:06 UT the field latitude was mostly southward, becoming approximately zero at times when IMP-8 was largely outside the plasma sheet (e.g., 18:30–18:35 UT and 18:57–19:06 UT); plasma flow was tailward and energetic electron flux was low but streaming tailward when measurable. At 19:06, when the bay at Dixon began to recover, the field latitude became primarily northward, plasma flow turned earthward and the energetic electron flux became more intense and isotropic.

Our interpretation of these data is depicted schematically in Figure 4. A 'substorm neutral line', N' forms in the plasma sheet at substorm onset (Panel 2). During the next four minutes a structure of closed loops develops from reconnected plasma sheet field lines and flows tailward over IMP-8 (panels 3 through 8). The location where the pinching off of plasma sheet field lines occurred can be estimated to be ~ 240 s $\times \sim 300$ km s$^{-1} \approx 72\,000$ km (11 R_E) earthward of the satellite or at $X_{SM} \approx -20 R_E$. Within ~15 min the plasmoid, traveling at ~ 500 km s^{-1}, had moved past the Moon's orbit, i.e., far out of the picture in panel 8. At 19:06 UT, coincident with the beginning of substorm recovery at Earth, the substorm neutral line moved past IMP-8 to a more tailward location (panel 9), accounting for the northward turning of the field and the reversal of plasma flow at that time.

The 'downstream plasma sheet' which IMP-8 encountered from ~18:31 to 19:06 UT after the passage of the plasmoid was probably quite thin. This is suggested by the time variability and deep dropouts of the plasma and by frequent brief crossings of the neutral sheet. (These features can be seen more clearly in Figure 5 of Hones (1977).) We believe that the downstream plasma sheet is, indeed, characteristically very thin and that the plasma and energetic particles in it come directly from the reconnection region nearer the Earth and are flowing relatively unimpeded out of the tail and into the solar wind. The magnetic field carried along by

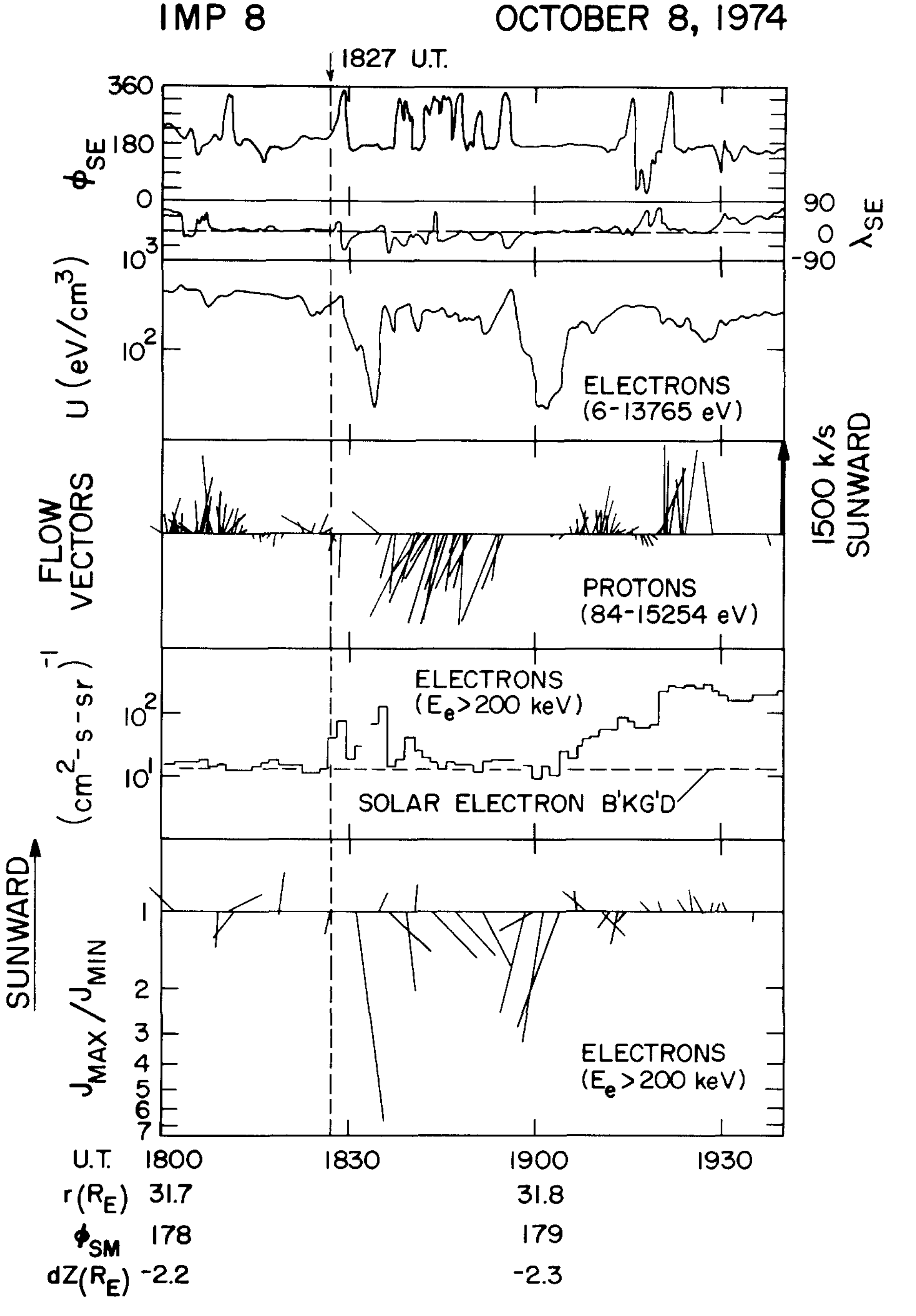

Fig. 3. Data from IMP-8 satellite on October 8, 1974: (a) and (b) longitude and latitude of the tail magnetic field; (c) energy density of plasma electrons; (d) plasma proton flow vectors; (e) intensity of electrons, $E_e > 200$ keV; (f) anisotropy vectors for electrons, $E_e > 200$ keV. The satellite's location is indicated at bottom.

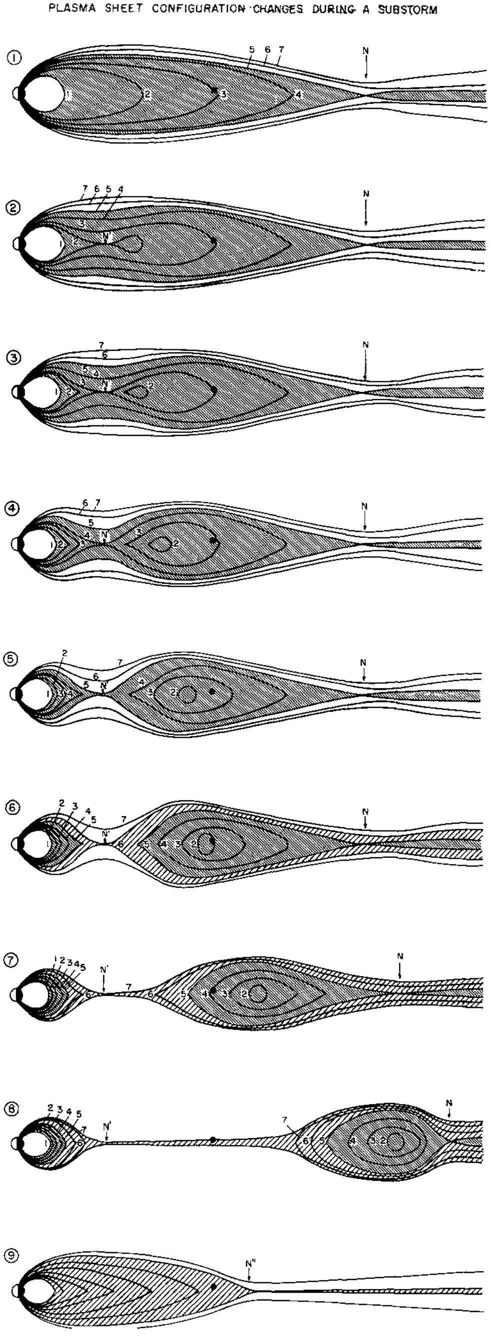

Fig. 4. Sequence of changes of magnetic and plasma configuration of the plasma sheet during a substorm. Five closed field lines (1, 2, 3, 4, 5) of the pre-substorm plasma sheet are depicted as well as two open field lines (6, 7) that were in the tail lobe before the substorm. The solid circles indicate an observing satellite (such as IMP-8 on October 8, 1974). Fine hatching delineates the plasma of the pre-substorm plasma sheet both upstream (earthward) and downstream (tailward) of the pre-substorm neutral line, *N*. Coarse hatching delineates plasma populating the newly merged previously open field lines that have entered the merging region at *N′* from the north and south tail lobes (Hones, 1977).

this tailward flowing plasma in the thin downstream plasma sheet is extremely variable in direction and magnitude (see Figure 5 of Hones (1977)) suggesting a highly turbulent regime.

After 19:06 UT IMP-8 was in the 'upstream plasma sheet' earthward of the neutral line. Here, confinement of the plasma and energetic particles on closed field lines allowed these fluxes to build up. The upstream plasma sheet becomes thick because of the accumulation of plasma. The upstream plasma sheet on October 8 was less turbulent than the downstream plasma sheet (see Figure 5 of Hones (1977)) but we have not determined whether these two environments typically differ in this manner.

3. Occurrence Frequency and Distribution in the Magnetotail of Signatures of Magnetic Reconnection

A survey of $1\frac{1}{2}$ years of plasma, magnetic field, and energetic electron data from IMP-8 has revealed a total of 8 events having the features seen on October 8. Figure 5 displays the solar magnetosphere latitude of the tail magnetic field during these events. There is characteristically a fairly strong initial southward turning of the field

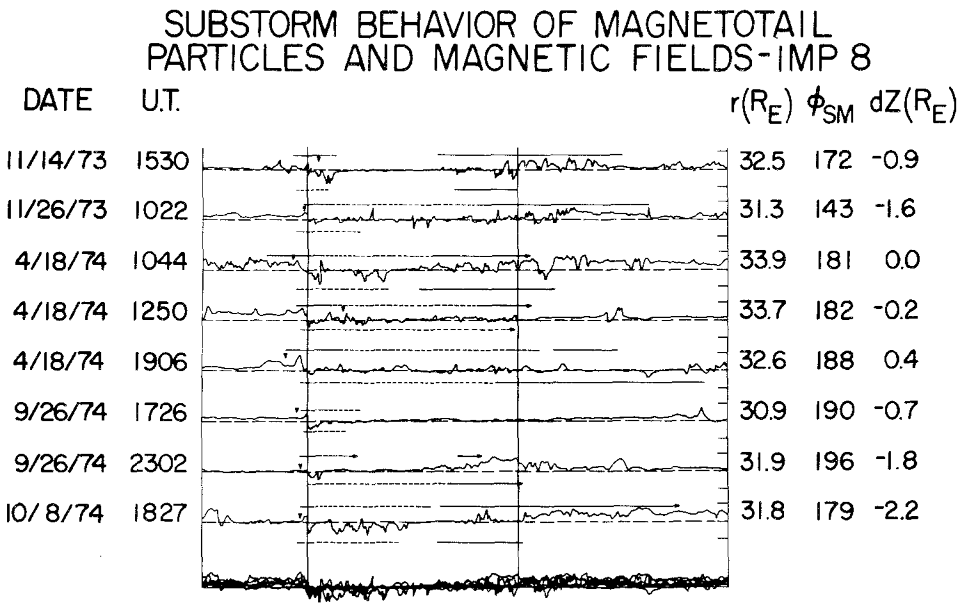

Fig. 5. Solar magnetospheric latitude of the tail magnetic field versus time during eight substorms. Tic marks at the right hand margin above and below each curve mark $\lambda = \pm 90$ deg. The first vertical line in from the left marks the time of the first southward turning of the tail field. This time is given at the left end of each trace. The second vertical line and the right hand border mark 1 and 2 hr later, respectively. The satellite's position at the time of first southward turning is given at the right. Black triangles above the curves indicate onset of the associated substorm at the Earth. Lines above each curve refer to the flux of >200 keV electrons. Solid line means the flux was isotropic; dashed line means the electrons were streaming tailward. Lines below each curve refer to plasma proton flow. Solid line means they were flowing earthward; dashed line means they were flowing tailward.

lasting a few minutes followed by an interval of 30 min to an hour of less decisive southward turning mixed with near-zero inclination. This is generally terminated by a more decisive northward turning of the field. A superposition of all eight curves at the bottom of the figure provides another illustration of these features. Lines above and below the individual curves show that in most of the cases the energetic electron flux enhancement and tailward plasma flow start nearly together and the electron flux is isotropic for a few minutes before beginning to stream tailward; we have indicated above that this sequence in the electron behavior is taken as the signature of formation and passage of a plasmoid.

A similar survey was also made of two years of IMP-6 data but without the energetic electron observations since these were not readily available to us. With IMP-6 the signals sought were southward turning of the field nearly coincident with onset of tailward plasma flow. Eighteen events were found.

Figure 6 shows the distribution of the 26 IMP-8 and IMP-6 events. All but one of these are confined within $\pm 2.5R_E$ of the neutral sheet and within $-12R_E < Y_{SM} < 12R_E (160° < \phi_{SM} < 200°)$. The range, $\pm 2.5R_E$ in dZ_{SM}, represents an upper limit of the instantaneous 'thickness' of the region on which magnetic merging signatures can be found. Fluctuations of $\pm 4°$ in the latitude of the solar wind flow can move the neutral sheet up and down by this amount. Thus the half-thickness of the downstream plasma sheet might be very much less than $2.5R_E$.

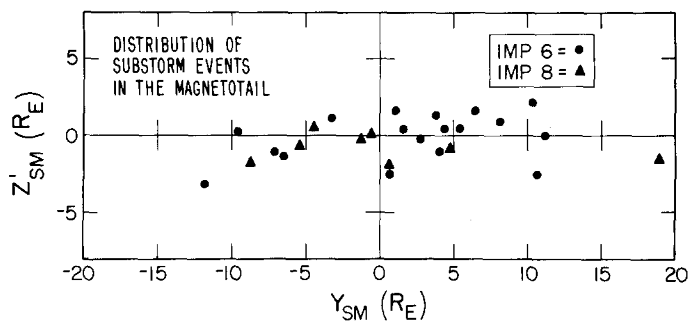

Fig. 6. Distribution of occurrence in the magnetotail of eight IMP-8 substorm events and of eighteen IMP-6 events.

The number of events acquired seems, at first glance, rather small for the length of the observing period and one wonders whether they may be rare, unusual and not characteristic of typical substorms. For IMP-8 in its inclined circular orbit it is easy to estimate that during the $1\frac{1}{2}$ years of coverage ~ 20 to 25 substorms should have occurred while the satellite was in the region $-2.5R_E < dZ_{SM} < 2.5R_E$; $-12R_E < Y_{SM} < 12R_E$. The fact that IMP-8 encountered signatures of reconnection on 8 occasions suggests that these phenomena occur (at $X_{SM} < -35R_E$) for a substantial fraction of substorms and thus are not rare or unusual.

4. Other Plasma Flow Observations and Further Evidence for Plasmoid Formation

The NOAA/APL energetic particle experiment on IMP-7 measures protons of energy >50 keV and can detect and measure plasma flow. Roelof *et al.* (1976) reported several instances (16 events in one year of data) of rapid plasma flow in the dusk sector of the plasma sheet. These occurrences were closely associated with substorm activity. An example from their paper is shown in Figure 7. One immediately recognizes the similarity between these data and those in our Figure 3:

(a) an initial burst of tailward flow lasting ~ 5 min that we would ascribe to the plasmoid's passage;

(b) a plasma dropout followed by ~ 20 min of continued tailward flow and irregular plasma intensity, characteristic of the thin downstream plasma sheet;

(c) a reversal of the flow to earthward, signifying tailward movement of the neutral line past the satellite.

Roelof *et al.* (1976) found, too, that the tailward flow in this (and other) events was associated with the expansive phase of a substorm and the earthward flow with its recovery phase (see their Figure 8). IMP-7 was at $X_{SM} = -31.3 R_E$, $Y_{SM} = 17.5 R_E$, $dZ_{SM} = 0.4 R_E$. Magnetic field data were not available and energetic electron fluxes were not reported, so we can not determine whether this event displayed the other signatures of magnetic reconnection (southward field, tailward streaming electrons) that we have found in other events. A difference that appears in the events of the APL group is their confinement to the dusk side ($4 R_E < Y_{SM} < 22 R_E$) of the plasma sheet. Keath *et al.* (1976) report that all of these events occurred during the intensification phase of the westward electrojet at premidnight auroral observatories whose magnetic local time was estimated to be earlier than that of the foot of the field line to IMP-7. But this observation leaves unanswered the question of why IMP-7 did not detect flow events distributed more like our IMP-6 and IMP-8 events.

Teresawa and Nishida (1976), using data from Explorer-34 at $X_{SM} \sim -20 R_E$ to $-30 R_E$, observed that transient bursts of relativistic electrons (0.3–1.0 MeV) occurred in the plasma sheet at the onset of many substorms and were often accompanied by southward turning of the Z component of the tail field. In some cases the satellite, outside the plasma sheet at substorm onset, detected a transient increase of plasma and energetic electrons at substorm onset. Teresawa and Nishida concluded that electrons, accelerated by inductive electric fields near the magnetic neutral line were trapped in the closed magnetic loop structure that was formed by reconnection. Figure 8 depicts the process they visualized. This view matches very well our observations of the energetic electron behavior in the October 8, 1974 substorm.

5. Plasma Sheet Thinning

In the discussion of the October 8 event we concluded that a substorm neutral line formed somewhere earthward of $\sim 30 R_E$ at substorm onset and that within a few

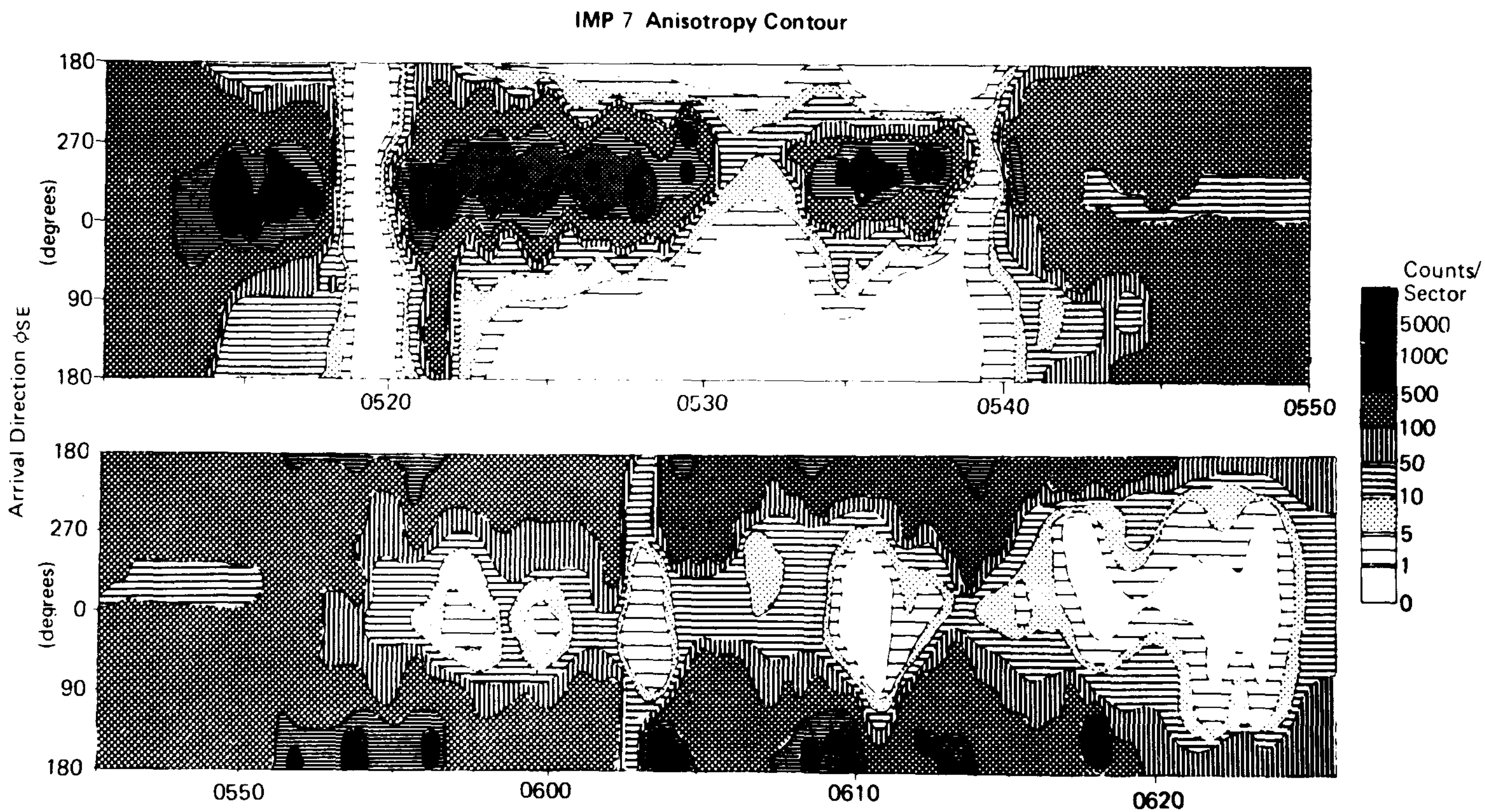

Fig. 7. Intensity of 50- to 200-keV protons as a function of direction and time in a large burst measured with IMP-7 on October 3, 1973. Arrival directions of 0°, 90°, 180°, 270° correspond to protons moving toward the tail, the dawn magnetopause, the Sun, and the dusk magnetopause, respectively. The shading indicates the count rate of the detector (Roelof *et al.*, 1976).

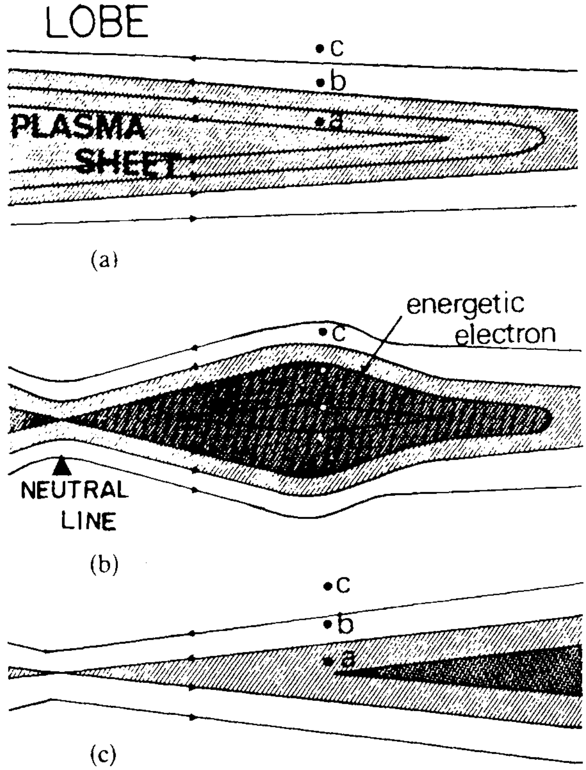

Fig. 8. Illustration of plasma sheet behavior deduced from energetic electron bursts seen at substorm onsets. (a) Before the expansion phase onset the satellite is situated inside the plasma sheet (point *a*) or outside it (point *b* or *c*). (b) At expansion phase onset the plasma sheet thins near the reconnection region but expands in the more distant tail region because of the ejected plasma. Relativistic electrons are distributed in the dark-shaded region. (c) As time goes on the plasma sheet thins at the satellite position (point *b*). Relativistic electrons are transported further tailward. (Teresawa and Nishida, 1976).

minutes afterward the plasmoid had moved far tailward leaving a very thin downstream plasma sheet extending tailward from the neutral line which remained, for more than a half hour, somewhere earthward of the satellite. Research with the Vela satellites (Hones *et al.*, 1973) and tail magnetic field measurements (Nishida and Nagayama, 1973) placed the probable location of the neutral line at $X_{SM} \approx -10$ to $-25R_E$. One anticipates a thinning of the plasma sheet to occur near and tailward of the substorm neutral line and a continuing thin plasma sheet to exist until the neutral line moves tailward at substorm recovery. Observations at the Moon have, indeed, revealed that the plasma sheet there becomes thinner (less likely of detection) during substorms (Nishida and Lyon, 1972; Rich *et al.*, 1973; Chase *et al.*, 1974; Rich *et al.*, 1974). Sensing of the plasma sheet thinning at the lunar distance is, however, considerably less reliable than in the 15–$30R_E$ region because of the wider motions induced there by the varying solar wind flow.

Recent two-satellite measurements by Pytte *et al.* (1976) and single satellite measurements by Nishida and Fujii (1976) have strongly reinforced the view that the substorm neutral line forms somewhere near $X_{SM} \approx -15R_E$. Pytte *et al.*, with particle measurements from one satellite at $X_{SM} \approx -13R_E$ and from another at $X_{SM} \approx -18R_E$, observed that the plasma sheet at the more distant satellite thinned near substorm onset and remained thin until substorm recovery. At the closer satellite the plasma sheet thickened at substorm onset and experienced further incremental enhancements during the substorm that perhaps signified impulsive enhancements of magnetic reconnection at the substorm neutral line. Figure 9 depicts the interpretation made by Pytte *et al.* of their observations. Both Pytte *et al.* (1976) and Nishida and Fujii (1976) found the plasma sheet to be reduced to a thickness of $< 1R_E$ at $X_{SM} \approx -15R_E$. It is believed that this local extreme reduction in thickness is closely related to the magnetotail's approach to a condition of instability against spontaneous reconnection (Schindler, 1974).

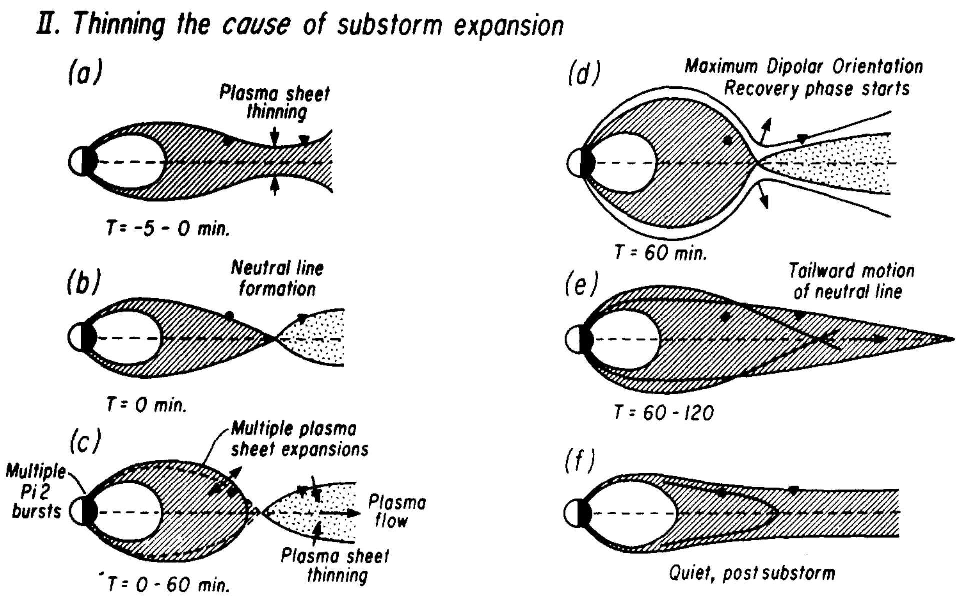

Fig. 9. Schematic representation of the substorm time sequence in the magnetotail, illustrating the plasma sheet behavior at a near-earth satellite (dot) and at a more distant satellite (triangle). (a) The plasma sheet thins before the bay onset, leading to formation of a neutral line. (b) Thereafter the plasma sheet expands on the earthward and thins on the tailward side of the neutral line. The neutral line stays between the two satellites during the multiple expansions of the plasma sheet and then begins to move tailward near the maximum of the auroral zone bay activity (Pytte *et al.*, 1976).

The thinning of the plasma sheet is not confined narrowly in longitude but may be observed to extend 10 to $15R_E$ or more across the tail. This is illustrated in Figure 10 which shows plasma measurements by two widely separated Vela satellites in circular orbits at $r \approx 18R_E$. Five substorms are numbered on the AE index at the top and the satellite paths in the Y_{SM}–dZ_{SM} plane and their locations at the time of each

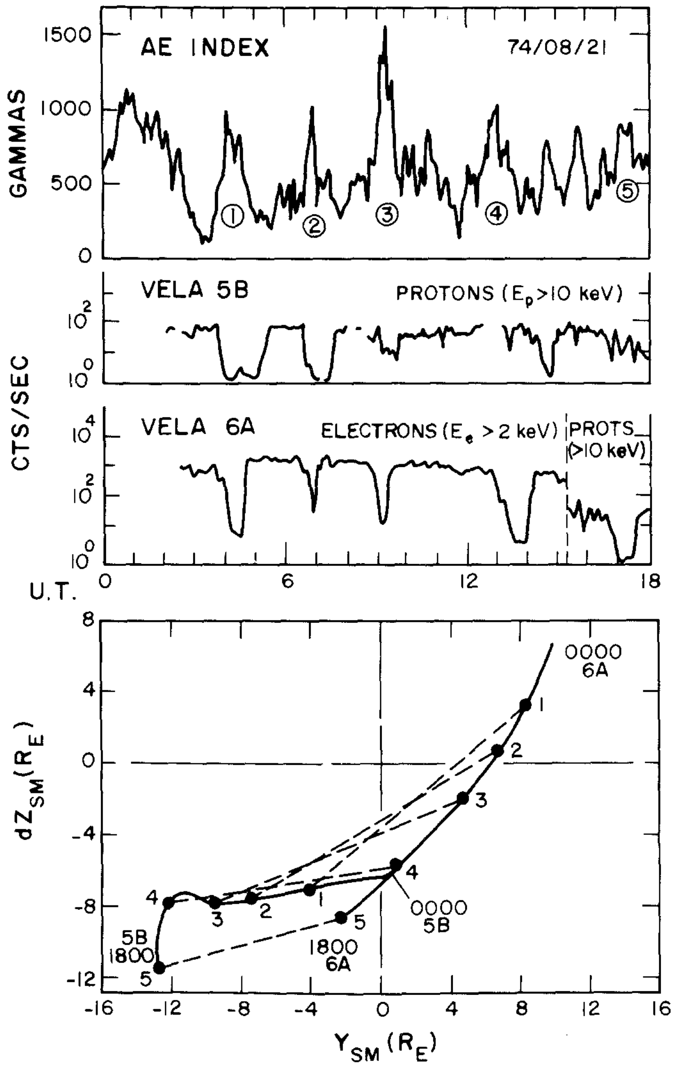

Fig. 10. Plasma sheet thinnings at Vela-5B and 6A associated with several substorms on August 21, 1974 numbered on the *AE* index at top. At the bottom, heavy lines trace the trajectories of the two satellites from 00:00 UT to 18:00 UT. Dots indicate their locations at the times of the five substorms. For the first event 6A was at $X_{SM} = -16R_E$ and 5B was at $X_{SM} = -17R_E$. For the 5th event 6A was at $X_{SM} = -18R_E$ and 5B was at $X_{SM} = -9R_E$.

substorm are indicated at the bottom. Plasma sheet thinning was clearly seen at both satellites, separated by 12–15R_E in the Y_{SM} direction, for the first three of these substorms.

The broad extent of plasma sheet thinning illustrated by Figure 10 implies that the neutral line, too, may extend equally large distances and that the signatures of magnetic reconnection that were described earlier in association with the October 8, 1974 substorm should be observable over like distances with appropriately placed and instrumented satellites. These observational requirements are very stringent and, to our knowledge have not yet been accomplished.

6. The Search for 'Southward B_z'

A long-standing puzzle and source of frustration in magnetospheric research has been the elusiveness of direct evidence in the magnetotail (and at the sunward magnetopause as well) for the magnetic reconnection that much indirect evidence argues must occur there. For over a decade attention was centered on examination of the tail magnetic field to see whether the southward directed z-component that magnetic reconnection requires, tailward of the neutral line, is detected. In an early such study Speiser and Ness (1967) found that the component of B normal to the current sheet (whose orientation continually varies) is less than 1 gamma beyond $X_{SM} \approx -15R_E$ in the midnight sector of the tail. The temporal variations of the neutral sheet's orientation, together with the flaring configuration of the field (Behannon, 1970) can add a varying 'false' southward component to the observed field that is difficult or impossible to differentiate from a 'real' southward component caused by magnetic reconnection. Nevertheless, southward magnetic residuals were observed often enough at neutral sheet crossings beyond $\sim 30R_E$ that Mihalov *et al.* (1968) concluded that sporadic reconnection does occur and that closed magnetic loops may be formed by this severing of field lines. An analysis by Schindler and Ness (1972), confirmed most of the conclusions of Mihalov *et al.*, but also found that the southward field may often be due to tipping of the tail.

A statistical study of magnetic data from IMP-4 in the distance range $X_{SM} \approx -25$ to $-35R_E$ (Fairfield and Ness, 1970) showed that B_z was preponderantly northward as Mihalov *et al.* (1968) had found but that the average value of B_z during quiet times (2.8 gammas) was greater than that (1.8 gammas) for all geomagnetic conditions. A plot of their data (their Figure 5) showed that the relative occurrence frequency of southward field during all conditions was about twice as great as that during quiet conditions. These results are faintly suggestive that the occurrence of magnetic reconnection is a feature of geomagnetic activity. But counter arguments can also be made that a possibly greater variability and more tail-like structure of the field during disturbed times could introduce more 'false' southward field due to tilting and turbulence. Fairfield and Ness (1970) also provided plots of the temporal variation of magnetic field parameters, including B_z, during substorms. These showed brief instances of strong southward field. Russell and McPherron (1973) pointed out the possible association of these strong southward excusions of B_z to magnetic reconnection and stressed that detailed investigations of individual events must accompany statistical studies if the question of reconnection is to be resolved.

Nishida and Nagayama (1973) were able to relate changes of the magnetic field at various locations in the tail to substorms recorded at Earth and to deduce from these that a neutral line forms suddenly somewhere within $-10R_E > X_{SM} > -20R_E$ and across a sector $\sim 15R_E > Y_{SM} > -15R_E$ at substorm onset. They concluded also that it disappears as suddenly after about an hour.

The discovery that rapid plasma flows occur in the plasma sheet in association with substorms (Hones *et al.*, 1972) and that they reverse direction from tailward to earthward at substorm recovery (Hones *et al.*, 1972, 1974) provided a new tool to use in tests for the occurrence of magnetic reconnection because rapid earthward and tailward plasma flows were to be anticipated from models of reconnection (see Section 2). Hones *et al.* (1976) first showed that the tailward flowing plasma seen during the expansive phase of a substorm contained magnetic field with a southward z component and that the earthward flowing plasma seen upon substorm recovery contained northward B_z. They pointed out that the flow and field reversals suggested passage near the observing satellite of a magnetic reconnection region.

Yet another effective tool for this research was added when Baker and Stone (1976) observed that tailward streaming energetic electrons were found together with southward B_z and concluded that the tailward streaming was probably indicative that the field lines with southward inclination probably opened to the solar wind.

The occurrence of plasma flow reversals and of tailward streaming electrons have provided independent means to evaluate the significance of observed instances of southward B_z. And, as we have seen in Section 2, correlations of the three types of data in combination with ground records not only tend to confirm the occurrence of magnetic reconnection in substorms but also provide important new understanding of the substorm process.

Despite this success the occurrence of southward B_z continues to be somewhat puzzling. Recently Caan *et al.* (1978) have done a statistical analysis of the B_z component measured during 17 of the 18 IMP-6 substorm events referred to in Section 3 and included in Figure 6. Using 15.36 s averages of the field, they have recorded the percent occurrence of B_z values in $\frac{1}{2}$-gamma bins and have done so separately for times during the 17 events when tailward plasma flow prevailed and when earthward flow prevailed. The results are shown by the histograms in Figure 11. Earthward flowing plasma is threaded almost entirely by northward magnetic field. But tailward flowing plasma is threaded almost equally by southward and northward magnetic field. (The solid-line histogram in Figure 5 of Fairfield and Ness (1970), which contains a similar presentation but without selection criteria on plasma parameters, shows only 21% negative B_z.)

At first glance, it is a surprising aspect of the Caan *et al.* study that southward field does not enjoy the same overwhelming weight in tailward flow that northward field does in earthward flow. But a tentative explanation for this difference is found in the magnetic field geometry that we have deduced above for these substorm events: The region earthward of the neutral line, where earthward flow prevails, is inflated and contains a dipole-like field. It thus provides a thick region containing strongly positive B_z which, furthermore, is quite insensitive to the effects of tilting and turbulence. But the thin downstream plasma sheet, where the flow is tailward, provides only a thin region of negative B_z. Furthermore the downstream plasma

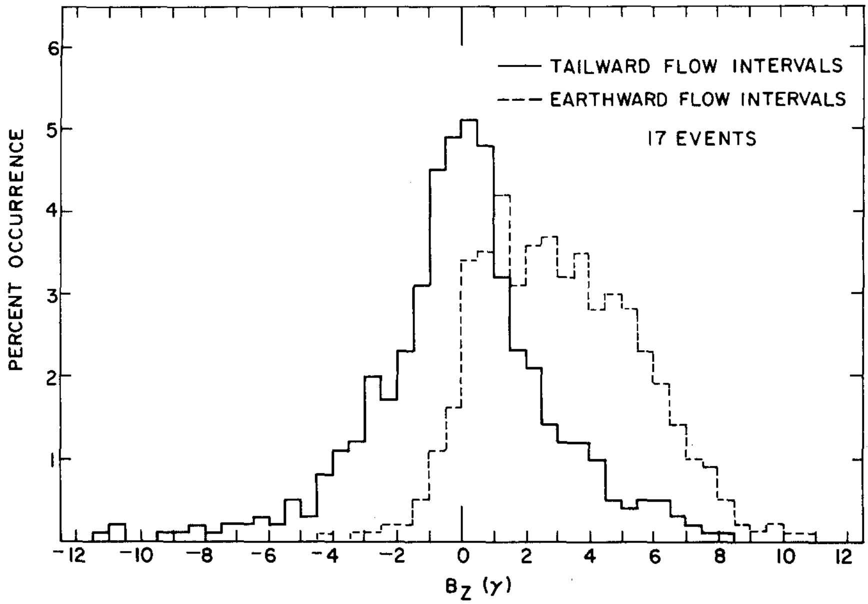

Fig. 11. Histogram showing the percent occurrence of B_z magnitudes between -12γ and 12γ measured with the IMP-6 satellite during 17 of the 18 IMP-6 substorm events referred to in Section 3. Dashed curve shows results for measurements made in earthward flowing plasma; solid curve is for measurements made in tailward-flowing plasma (Caan *et al.*, 1978).

sheet is very turbulent (see Section 2) and, because of its thinness, is much more influenced by flapping and tilting, so that the 'real' southward B_z can be concealed by this 'noise', Thus the results found by Caan *et al.* do not imply that magnetic reconnection does not occur. Instead they reinforce our other evidence that the downstream plasma sheet is very thin while the upstream plasma sheet is thick. It appears that the substorm neutral line might be better described as a Y-type neutral line than as an X-type neutral line. The work of Caan *et al.* also provides an explanation for the failure of past statistical studies of tail B_z to yield compelling evidence for reconnection and suggests that all such studies may be futile if the expectation is to find long-enduring strong southward field downstream of the neutral line. Perhaps, though, measurements made a very short distance downstream from the neutral line might reveal more persistent southward B_z.

7. Summary and Conclusions

Much evidence exists favoring the view that a substorm involves the formation of a substorm X-type neutral line in the near-earth region of the plasma sheet and involves ensuing magnetic reconnection there that converts the stored magnetic energy of the tail to power to drive the substorm. In a few-minute transient phase that starts at the moment of the neutral line's formation a plasmoid, i.e., a closed magnetic loop structure, is formed and ejected from the tail, leaving a very thin downstream plasma sheet extending indefinitely down the tail from the near-earth neutral line. Electrons and protons can be energized to 1 MeV or so by the inductive electric fields accompanying the neutral line's formation. Some of these very energetic particles are trapped in the escaping plasmoid and others are injected into the earth-tied field region earthward of the neutral line. It has been suggested by Stern (1978) that the region around the 0-type neutral line that forms tailward of the X-line, and that is likely embedded in the escaping plasmoid, may be the site of very efficient acceleration of high energy particles by the inductive electric fields generated in the plasmoid's formation.

Late in the substorm, often as auroral zone negative bays start to subside, the substorm neutral line moves relatively quickly to a location farther out in the tail and plasma projected earthward from it progressively inflates the plasma sheet with new hot plasma.

The difficulty that has been encountered, in the past and more recently, in identifying the occurrence of magnetic merging by observations of southward oriented tail field may be attributable to the geometry of the downstream plasma sheet. Its extreme thinness together with the turbulent character of the plasma within it, makes observations of prolonged southward B_z during a substorm quite unlikely. But magnetic field observations made together with plasma flow and energetic electron observations *do* provide a means for identifying the occurrence of magnetic reconnection during substorms.

In this review of transient phenomena in the magnetotail we have made only peripheral mention of the very important observations of acceleration of electrons and protons to high energies (~ 1 MeV) that can only be accounted for as resulting from inductive electric fields. We also have almost completely ignored the remarkable substorm effects in the inner magnetosphere, i.e., the injections of plasma and energetic particles to distances of $6R_E$ and less that characterize nearly every moderate to intense substorm. Space limitations have prevented our discussion of these critical aspects of substorm phenomenology.

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