Multiple-Satellite Studies of Magnetospheric Substorms: Radial Dynamics of the Plasma Sheet

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Multiple-satellite measurements of magnetic field and/or energetic particles during four magnetospheric substorms are presented. The data were obtained from Ogo 5 and Vela 4A, located near local midnight at about the same distance from the neutral sheet but separated by 3–10 RE in the radial direction. The substorm expansion phases all had multiple onsets, typically observed as multiple bursts of Pi 2 magnetic pulsations (which we use for accurate timing of each onset), auroral zone bay intensifications, and low-latitude positive bay increases. A minimum in the plasma sheet thickness was probably formed at X_m ~ -15 RE in association with the formation of an X-type neutral line. Earthward of this line, successive substorm onset signatures were observed in an almost one-to-one relationship with ground Pi 2 bursts: a short (~5 min) burst of magnetic fluctuations confined to the plasma sheet, a plasma sheet expansion, and a field vector rotation toward a more dipolar orientation. These onsets, which occurred at 10- to 15-min intervals, may have been caused by impulsive enhancements of field line reconnection. Since the plasma sheet was thinning before each new onset, it appears that these enhancements were triggered in the tail each time the plasma sheet became very thin, causing a disruption of the cross-tail electric currents. In the tailward part of the plasma sheet (X_m ~ -18 RE) the plasma sheet was thinning down or remained thin until well after the last near-earth expansion, when a recovery occurred. The near-tail observations are consistent with a model in which the associated tailward motion of the neutral line started when the reconnection rate exceeded the earthward flux return rate, producing a tailward pressure which forced the neutral line to move tailward. A comparison with what appears to be a 'contracted oval substorm' shows that, even though this substorm apparently took place within a more limited local time sector, it had all the usual substorm features in the tail.

INTRODUCTION

The magnetotail plays an important part in magnetospheric substorm processes, acting as an energy reservoir and as a source and acceleration region for particles. There is, in general, a close correlation between simultaneous large-scale substorm phenomena in the tail and on the ground, but observations made in both regions are often very dependent on location. A dense network of observatories has made it possible to study the complexity and variability of substorm phenomena on the ground, whereas only a very few cases of simultaneous measurements in more than one location in space and during different substorms. When combining these measurements, one then has to assume that there is a basic substorm pattern and that each set of observations provides a piece of information to the total picture.

In spite of the limitation set by single-satellite measurements our knowledge of the dynamics of the magnetotail has been rapidly increasing on the basis of such measurements (see reviews by Hones et al. [1973a] and Russell and McPherron [1973]). The once apparently contradictory results obtained earthward and tailward of \( r \sim 18 \) RE during substorms now appear to be successfully explained by invoking the formation of an X-type neutral line across the tail at bay onset [Russell, 1972; McPherron, 1972; Hones et al., 1973a; McPherron et al., 1973]. This neutral line then separates the plasma sheet into two radial regions: the earthward region experiencing an expansion and the tailward region a thinning following bay onset. In the region where the neutral line is formed the plasma sheet is less than 1 RE thick [Hones et al., 1973a; Buck et al., 1973], though Lui et al. [1975] state that such thin plasma sheets are seldom observed at Vela orbit. Experimental evidence for the formation of a neutral line at bay onset has recently been found by Nishida and Nagayama [1973, 1975] and Nishida and Hones [1974]. By comparing ground and magnetotail measurements, Hones et al. [1973a] concluded that the neutral line apparently stays earthward of \( r \sim 18 \) RE until the beginning of the recovery of auroral zone bays and then moves tailward.

There is, however, some disagreement as to the exact nature and significance of the tail processes leading up to the neutral line formation, in particular, the presubstorm thinning of the near-earth plasma sheet [Aubry et al., 1972; Hoffman and Burch, 1973; Kivelson et al., 1973; Buck et al., 1973; A. Nishida and K. Fujii, unpublished report, 1976]. Also, since the assumed plasma sheet behavior in the above substorm models is inferred from independent measurements earthward and tail-
ward of the neutral line, it has been argued [Akasofu, 1974] that these models are affected by inaccurate timing of the substorm expansion phase.

The purpose of the present paper is to examine the radial dynamics of the nighttime plasma sheet during substorms. First, the spatial dependency of plasma sheet variations at different radial distances is examined in simultaneous recordings from two closely spaced satellites, one at \( r \approx 10-17 R_E \) (Ogo 5) and one at \( r \approx 18 R_E \) (Vela 4A). Second, the accurate temporal correlations between these plasma sheet variations and substorm development on the ground are studied by obtaining accurate timing of individual substorm expansion onsets.

Simultaneous measurements of plasma sheet behavior earthward and tailward of \( r \approx 15 R_E \) presented in this paper confirm substorm models which predict a thinning of the near-earth plasma sheet before the formation of an X-type neutral line, followed by a thickening on the earthward side and a further thinning on the tailward side. In particular, during multiple onset substorms [Kisabeth and Rostoker, 1971, 1973; Rostoker and Camidge, 1971; Clauer and McPherron, 1974; Wiens and Rostoker, 1975; Pytte et al., 1976a] the near-earth plasma sheet experiences a series of multiple expansions and contractions, which usually occur in a one-to-one relationship with ground Pi 2 bursts and are well correlated with auroral zone and low-latitude magnetic disturbances. Since these expansions, as observed by a single satellite, have almost identical signatures, successive onsets seem to be initiated in nearly the same local time sector rather than in sectors located progressively farther west.

**Experimental Details**

The University of California at Los Angeles (UCLA) triaxial fluxgate magnetometer on Ogo 5 has been described by Aubry et al. [1971]. The magnetic field data used in this paper are based on 4.6-s averages and plotted in geocentric solar magnetospheric (GSM) coordinates [Ness, 1965].

The Lawrence Livermore Laboratory (LLL) particle detectors [West et al., 1973a, b] had seven differential electron energy channels (ranging from 79 to 2380 keV) and three proton channels (ranging from 100 to 1350 keV). Measurements at different pitch angles were obtained by scanning the entrance aperture relative to the earth-sun oriented spacecraft. A complete pitch angle coverage was obtained only in regions of dipolar magnetic field, with a limited coverage as the field became more taillike. In taillike regions, supplementary measurements were obtained from the UCLA particle detectors on the same spacecraft, which measured electrons in six different directions, fixed in spacecraft coordinates.

It should be noted that the gyroradius of a 100-keV proton in the magnetotail is quite large (~0.2 \( R_E \)). Thus since proton fluxes observed by a scanning detector are associated with the locations of their gyrocenters, there may be significant variations in intensities during one scan period when there are spatial flux gradients near the satellite. This scan modulation of protons can be used to probe spatial boundaries, such as the plasma sheet boundary during substorms [Buck et al., 1973].

From the Vela 4A satellite we use data from two of the three lowest energy channels (>36, >48, and >61 keV) of a solid state electron detector and one channel (>40 keV) from a Geiger counter. In addition, data from a 24-channel electrostatic analyzer, sensitive to electrons between 173 eV and 18.5 keV, provide average values of the energy and energy density during selected intervals. This satellite is sometimes in the 'store' tracking mode, in which a complete set of data is obtained every ~8 min; otherwise, when it is in the 'real time' mode, data are obtained every ~4 s. For further details, see Hones et al. [1973b].

The GSM equatorial projections of satellite trajectories during the intervals in question are plotted in Figure 1. The distances above the expected position of the neutral sheet, calculated from the formula of Russell and Brody [1967], are indicated at the beginning and end of each interval. To facilitate comparison between magnetotail and ground-based measurements, we also show projections of magnetic field lines in the Mead and Fairfield [1975] 'quiet' (Kp < 2; solid lines) and 'disturbed' (Kp ≥ 2; dashed lines) magnetospheric models. Magnetograms from auroral zone and low-latitude observatories are used to monitor substorm activity on the ground. The accurate timings of all substorm intensifications are made according to Pi 2 magnetic pulsation onsets. These onsets are closely related to auroral breakup [Morozumi, 1965; Akasofu, 1968] and to onsets of polar magnetic substorms [Saito, 1961, 1969; Rostoker, 1968]. They are therefore regarded as indicators of individual onsets of the substorm expansion phase. Relevant information on observing stations used in this study is given in Table 1.

![Fig. 1. GSM equatorial projections of satellite orbits during the intervals studied in this paper. The spacecraft distances above the expected position of the neutral sheet [Russell and Brody, 1967] are indicated at the beginning and end of each interval. Equatorial projections of field lines in two Mead and Fairfield [1975] field models are superimposed on the satellite orbits for approximate mapping down to the auroral zone.](image-url)
**TABLE 1. Locations of Magnetometer Stations Used in This Study**

<table>
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<tr>
<th>Station Name</th>
<th>Code Name</th>
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*After Hakura [1965] and Gustafsson [1974].

**OBSERVATIONS**

**Multiple Onset Substorms on September 4–5, 1968**

Figure 2 shows tracings of magnetograms from nighttime stations during the interval from 1800 to 0400 UT on September 4–5, 1968. The vertical lines indicate the first onset of magnetospheric substorms as defined by Pi 2 magnetic pulsations. The 2137 UT expansion phase had four well-separated onsets, which were observed as a series of magnetic bay intensifications at premidnight auroral zone stations, multiple Pi 2 bursts, and increases in the H component at low latitudes.

The ~0054 UT expansion phase, which was associated with a series of weak Pi 2 bursts in the auroral zone, is hardly noticeable in these recordings. However, the interplanetary magnetic field (IMF) at Explorer 33 (data not shown here) which had been southward for more than 1 hour prior to the 2137 UT substorm, was horizontal or slightly northward most of the interval between ~2145 and ~0200 UT. Since the auroral oval contracts poleward after long intervals of northward IMF [e.g., Akasofu et al., 1973a], it appears that substorm activity indicated by the Pi 2 bursts after 0054 UT occurred along a contracted oval and thus poleward of these stations.

During the 2137 UT substorm, Ogo 5 and Vela 4A were located at ~2230 MLT (Figure 1) or ~2 hours of local time east of Leirvogur (LEI), where the clearest bay intensifications were observed. The associated variations in the D component at low-latitude stations indicate that the central meridian of a three-dimensional current system [e.g., McPherron et al., 1973; Wiens and Rostoker, 1975] was initially somewhat to the east of the two satellites.

**September 4–5, 1968**

**Fig. 2.** Auroral zone and low-latitude magnetograms on September 4–5, 1968. Vertical lines indicate the first onset of three multiple-onset substorms. Solid dots are local magnetic midnight.
Figure 3 shows the simultaneous measurements at Vela (upper panel) and Ogo (two bottom panels), along with their X and Y GSM coordinates and distances above the neutral sheet. The vertical lines indicate the times of Pi 2 onsets on the ground. It is clear from these recordings that there were significant increases in particle fluxes and changes in magnetic field at Ogo associated with each Pi 2 burst, mostly only during the 2137 UT substorm, but also after ~0054 UT. This supports our previous interpretation of substorm activity also occurring during this interval, but along a contracted oval.

The plasma sheet behavior at Vela, located a few earth radii tailward of Ogo, was quite different during both substorms. Here the plasma sheet was thinning or remained thin during the expansion phase, which is the typical behavior at these radial distances [Hones, 1973]. During the 2137 UT substorm there was first an increase in electron fluxes, which occurred sometime during the data gap from ~2130 to ~2139 UT. This flux increase is emphasized by a dashed line across the data gap. Between ~2154 and ~2230 UT the plasma sheet was thinning, causing a gradual decrease in the energy density (\(\epsilon\)) during almost constant average energy (\(\bar{E}\)) of the low-energy plasma (Figure 4). The recovery of hotter plasma around 2240
Fig. 4. Average energy $E$ and energy density $U$ of plasma electrons measured by Vela 4A on September 4, 1968. A general thinning of the plasma sheet was observed after ~2130 UT followed by the recovery of hotter plasma near the end of the substorm.

UT, the ‘late recovery,’ occurred as auroral zone bays started to recover (Figure 2), in agreement with previous observations [Hones et al., 1967, 1973a].

Detailed Description and Interpretation of Plasma Sheet Variations

To illustrate the detailed relationship between magnetic field perturbations and variations in particle intensities and pitch angle distributions during the 2137 UT substorm, we show in Figure 5 high-time resolution plots of the Ogo and Vela observations. Since the timing of individual substorm expansion onsets has been made according to Pi 2 bursts, we also reproduce magnetic pulsation recordings from the mid-latitude ground station Wingst, which was located near local midnight at that time. Note that the four vertical lines in this figure are drawn at the time of the clearest onset of magnetic perturbations at Ogo rather than on the ground. The close correspondence between these lines and the ground Pi 2 onsets is evident, and it also seems that the ground onsets were delayed with respect to those in the tail. There were no significant time delays between the more impulsive, and therefore more accurately defined, onsets in the auroral zone (Tromsø) and those at mid-latitudes. Since the timing uncertainty in these recordings is at most a few seconds, it appears that the time delay from the tail to the earth is significant and resulted from a propagation along field lines from the tail region to the ground.

It is probably also significant that there was a burst of magnetic perturbations at Ogo during Pi 2 pulsations only when the satellite was engulfed in the plasma sheet. Thus it appears that even though these perturbations were directly related to plasma sheet expansions, they were confined to the plasma sheet region. There were also no perturbations without a concurrent Pi 2 event, showing that they were not merely a spatial characteristic of the plasma sheet.

Plasma sheet dynamics. The low electron fluxes and the decreasing proton fluxes observed near Ogo just before the 2137 UT substorm onset indicate that this spacecraft had come...
close to the outer boundary of the plasma sheet at that time. During the next few minutes the boundary apparently receded further downward and the presence of modulations in proton fluxes caused by the detector scan suggests that a spatial gradient in the proton intensities was located just below Ogo [see Buck et al., 1973].

At Vela, real time tracking was resumed at ~2139 UT, after a ~10 min data gap. The first five high time resolution data points show a flux increase by a factor of ~6 above the level observed just before the data gap. From these measurements we infer that at 2140 UT the plasma sheet was \( \gtrsim 2.5 R_E \) thick near Vela but only \( \lesssim 1.5 R_E \) thick near Ogo, indicating a tailward increase in plasma sheet thickness. Furthermore, if we make the reasonable assumption that the plasma sheet boundary is defined by the last closed field line, and therefore nearly parallel to the observed magnetic field just outside or inside the plasma sheet boundary, we find a tailward decrease in plasma sheet thickness near Ogo. Thus there must have been a minimum thickness somewhere between the two spacecraft. Alternative explanations involving tail flapping or a wavy structure within the neutral sheet seem much less plausible, since there are no reports on a persistent kink in the neutral sheet orientation.

The subsequent changes in the plasma sheet boundary locations on each side of the minimum region are shown schematically in Figures 6b–6f. The approximate locations of the two satellites with respect to the boundary, essentially inside or outside, are shown just before (dashed lines) and just after (solid lines) each of the four expansions and during the first part of the recovery. The magnetic field orientation is shown by vectors in the earthward (left) part of the diagrams, whereas the orientation in the tailward part is indirectly defined by the plasma sheet orientation, assuming that the boundary between Vela and Ogo is a continuous curve. During the first expansion

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**September 4, 1968**

*a. OGO5 Magnetic Field*

- Growth
- Expansion
- Recovery

*b. 2137-2140 UT*

First expansion

- Weak flux decrease
- Flux increase

*Vela*

- OGO

*g. Possible interpretation*

**Fig. 6.** Schematic representation of Ogo 5 and Vela 4A measurements during the 2137 UT substorm on September 4, 1968. The upper diagram shows the GSM X-Z projections of magnetic field vectors at Ogo. The asterisks indicate the time of substorm onsets. The variations in plasma sheet boundary before (dashed line) and after (solid line) each expansion, as inferred from Ogo and Vela particle measurements, are shown in Figures 6b–6e. The orientation of the boundary near Ogo is defined by the field direction, and an upward bend of the boundary near Vela is indicated to match the Ogo boundary. Figure 6g illustrates a possible interpretation in terms of an X-type neutral line located between the two spacecraft.
there was a weak flux decrease at Ogo and a flux increase at
Vela. These variations could have been caused by an initial
earthward motion of the pinched plasma sheet region. There-
after there was a series of expansions from a position below or
close to Ogo to a position farther above. At Vela there was a
continuous flux decrease toward background as the spacecraft
moved out of the plasma sheet. During these expansions the
magnetic field at Ogo (Figure 6a) made clockwise rotations,
becoming almost dipolar near the maximum of the last expan-
sion.

An independent indication of plasma sheet boundary mo-
tions near Ogo is provided by the proton measurements (Fig-
ure 5). Near the time of each expansion there were sharp flux
dropouts, usually once every scan, as the detector was measur-
ing protons with gyrocenters in a boundary region less than
one gyroradius (<0.2 Re) above the satellite. These dropouts
disappeared or became less pronounced shortly afterward as
the plasma sheet boundary moved farther away from the neu-
tral sheet.

Note that in constructing the diagrams in Figures 6b-6f we
have made no a priori assumption of the existence of an X-
type neutral line between the two spacecraft. The question
marks indicate that we have no observations of the field to-
pology in this region.

Figure 6g shows our interpretation of these measurements,
extended to include also the region between the two spacecraft.
Even though we have no magnetic field data from Vela, and
thus no information about the boundary orientation in the
tailward region, the particle measurements clearly indicate a
minimum plasma sheet thickness between the two spacecraft.
This low-density region is also the most probable location of a
magnetic merging region and an X-type neutral line [Dessler,
1968]. The open field lines marked 1 are connected toward the
neutral sheet, where they reconnect to make an earthward
closed part and a tailward open part, both marked 2. In the
earthward region, where Bz is northward, a satellite may there-
fore be on a seemingly open empty field line (line 1) or on a
closed, initially nearly empty line (line 2). This is the situation
near Ogo around 2140 UT. Indications that the first closed
field lines may indeed be nearly empty have been found in low-
altitude satellite data [Burnows, 1974]. In the tailward region,
Bz is assumed to be southward [Nishida and Nagayama, 1973,
1975; Nishida and Hones, 1974], which is also consistent with
the inferred orientation of the plasma sheet boundary.

Each expansion is now assumed to be caused by a rapid
enhancement of reconnection across the neutral sheet. This
enhancement may in each case be initiated by a tail current
instability within the thinned plasma sheet. In the earthward
part, newly closed flux tubes will pile up as they start to
contract earthward, resulting in a local rotation of the field
and an increase in particle density and energy. In the tailward
part, flux tubes may initially pile up, but the particle escape
rate and the field topology may be quite different due to
different boundary conditions. The initial flux increase and the
relatively thick plasma sheet indicated in Figure 6 may suggest
that merging started on closed field lines within the plasma
sheet. This would cause a magnetic bubble to be formed be-
tween the new and the preexisting distant neutral line, tempo-
arily trapping the plasma in this region.

Variations in electron pitch angle distributions. Important
information about the dynamics of the plasma sheet in regions
to the west and farther down the tail can be inferred from the
pronounced changes in electron pitch angle distributions ob-
served at Ogo during this event. Around 2230 UT, well after
the last near-earth plasma sheet expansion, the electron pitch
angle distribution at Ogo changed from being isotropic to
strongly field aligned, first at 158 keV and ~12 min later at 79
keV (Figure 5). This pitch angle distribution, called the 'but-
terfly' distribution by West et al. [1973a, b], was sharply
peaked at small pitch angles; hence, even a wide angle detector
oriented perpendicular to the field could give the wrong im-
pression of a total flux dropout.

The appearance of the butterfly pitch angle distribution
indicates that the nighttime magnetosphere was now suffi-
ciently undisturbed to allow energetic electrons to drift in
from the duskside, maintaining their normal quiet time distri-
butions as they drift [West et al., 1973a, b]. The different
arrival times at the two energies would then reflect the differ-
ent drift speeds from the region where they entered the quiet
magnetosphere to the position of the satellite [Kivelson et al.,
1973].

The return to isotropy occurred simultaneously at all elec-
tron energies at 2303 UT. It appears that as the plasma sheet
boundary moved slowly down toward the satellite, as indi-
cated by the proton measurements, Ogo rather abruptly
entered field lines on which the electron guiding center motion
was interrupted, causing a pitch angle scattering toward
isotropy. This scattering probably took place in and just earth-
ward of the neutral line region, where the equatorial curvature
radius of the field lines would be too small (i.e., of the order
of one gyroradius) for these particles to continue their guiding
center motion (H. I. West et al., unpublished report, 1975).

One would expect, however, that as the satellite approached
these field lines, this effect was first noticed at the highest
energies, as has been observed in other similar situations in
Ogo data. The simultaneous transition to isotropy therefore
indicates that the neutral sheet scattering region had a very
sharp earthward boundary.

Comparison with a contracted oval substorm. Figure 7 de-
picts details of Ogo particle and field measurements and
ground magnetic pulsation recordings during the weak ~0054
UT substorm. The vertical lines are again drawn at the onsets
of magnetic fluctuations at Ogo. The amplitudes of the asso-
ciated Pi 2 bursts at Wingst were quite small this time, and the
onset times were not as well defined as they were during the
2137 UT substorm.

As was mentioned earlier, the plasma sheet variations and
their radial dependence were quite similar to those observed
during the 2137 UT substorm. The appearance of butterfly
pitch angle distributions between onsets, with no significant
time delays at lower energies, suggests that activity did not
extend very far to the west of Ogo and that the magnetosphere
was relatively quiet before each new onset. Furthermore, the
sharp negative deflection in By at ~0127 UT, possibly due to
downward field-aligned currents, indicates that Ogo was then
on the morningside of the active sector. Both features are
consistent with a narrow disturbed local time sector.

Multiple-Onset Substorms on
August 19, 1969

During the two substorms just discussed the Vela satellite
was ~1 Re higher above the neutral sheet than Ogo. The
rather smooth flux decrease, or fluxes close to background,
oberved at Vela indicated that there were no multiple expan-
sions near that satellite. In this section we present observations
during two similar events, but this time Vela was closer to the
neutral sheet. Only the major features are mentioned here.

Figure 8 shows ground magnetograms during two multiple-
onset substorms on August 19, 1969. The individual Pi 2 onsets (vertical lines) were accompanied by auroral zone bay intensifications and increases in the H component at low latitudes. The central meridian of the substorm-associated current system, as defined by the low-latitude D component magnetograms, was located close to local midnight during both substorms.

The Ogo and Vela satellites were close to local midnight and at about the same radial distances as they were during the previous events (Figure 1). Figure 9 shows that both satellites were outside the plasma sheet for most of the 0512 UT substorm but observed the late plasma sheet recovery around 0630 UT, in association with recovery of auroral zone bay activity. At the beginning of the 0753 UT substorm, Ogo was very close to the neutral sheet and observed the presubstorm plasma sheet thinning and the subsequent multiple expansions. There were no appreciable plasma sheet expansions at Vela, in agreement with our previous findings, but the data coverage was relatively scarce this time. Just before the late recovery the plasma sheet thickness near Vela was <0.5 RE.

Figure 10 shows details of the Ogo particle and field measurements during the 0753 UT substorm. The vertical lines mark the onset times of magnetic perturbations at Ogo. The corresponding onsets on the ground, which are given in Figure 9, again tended to be delayed with respect to those in the tail. Some particle increases were rather weak (~0854 and ~0935 UT), and one (~0916 UT) was apparently missing.

For completeness we mention that the interplanetary magnetic field at Explorer 35 (data not shown here) was southward during the plasma sheet thinning before the 0753 UT substorm. The 0512 UT onset occurred during a ~1-hour data gap, but the field was southward around the time of the ~0630 UT plasma sheet recovery. The ~1020 UT recovery occurred during another gap in the Explorer data.

We conclude that these observations are in agreement with those presented in the previous sections: The tailward plasma sheet was again thinning and remained thin while multiple expansions were observed closer to the earth. This was so even though Vela was now moving toward the neutral sheet and was for part of the time closer to its predicted position than Ogo. However, the plasma sheet behavior in the two locations cannot be compared for the August 19, 1969, substorm in the detail possible for the September 4-5, 1968, event.
The main observational findings of this work can be summarized as follows:

1. Two-satellite measurements of particle fluxes and magnetic field in the magnetotail during four magnetospheric substorms are consistent with the formation of an X-type neutral line in the range $X_{\text{sm}} \sim -13$ to $-18 R_E$ at the onset of the expansion phase. The neutral line separated the disturbed sector of the tail into two parts, each with a different plasma sheet behavior during substorms: In the earthward part the plasma sheet expanded at the time of each expansion onset (Pi 2 burst) on the ground. In the tailward part the plasma sheet continued to thin, sometimes after a brief flux enhancement, and thereafter stayed very thin until after the maximum of auroral zone negative bay activity, when a recovery occurred.

2. The multiple near-earth plasma sheet expansions may have been caused by a series of impulsive enhancements of field line reconnection across the neutral sheet. The most probable location of this reconnection, the region of minimum plasma sheet thickness, remained within the above-mentioned radial distances during the entire expansion phase. The first indication of a significant tailward motion was observed at the beginning of the recovery phase.

3. Each plasma sheet expansion was accompanied by a 5- to 10-min interval of magnetic fluctuations in the near-earth plasma sheet, whose onset tended to precede the corresponding onset of Pi 2 pulsations on the ground. This delay suggests that the expansions are triggered in the tail region rather than closer to the earth.

4. There were no bursts of magnetic perturbations in the tail and no Pi 2 on the ground during the late expansion or recovery of the plasma sheet.

5. These magnetic perturbations were observed only when the satellite was inside the plasma sheet at the time of a Pi 2 burst. They are therefore probably confined to the plasma sheet. On the other hand, no such perturbations were observed without a corresponding Pi 2.

6. Electron pitch angle distributions were mainly isotropic during the expansion phase. After the last expansion, or in the intervals between successive weak expansions, pitch angle distributions were highly field-aligned.

The findings summarized above are consistent with previous results obtained on the basis of independent measurements earthward and tailward of $X_{\text{sm}} \sim -15 R_E$ (see reviews by Russell and McPherron [1973] and Hones et al. [1973a]). However, additional information about the dynamics of the plasma sheet can now be obtained on the basis of these simultaneous observations, which are related to basic differences in current substorm models.

Substorm timing and plasma sheet behavior. The mechanism responsible for triggering the substorm expansion phase is still unknown. The various proposed mechanisms and substorm models can be separated into two categories, depending on the role of plasma sheet thinning. This, in turn, is related to a basic problem in magnetospheric physics, namely, the identification of substorm expansion phase. The only unambiguous and widely accepted definition of substorm onset is the one based upon observations of auroral breakup. This method has been used rather extensively in studies of Vela data [Akasofu et al., 1971; Hones et al., 1971a, b] but very seldom in studies of near-earth measurements beyond synchronous orbit. Therefore there has been no common frame of reference according to which independent measurements could be compared. Thus Akasofu [1974] argued that the apparently opposite behavior earthward and tailward of $r \sim 15 R_E$ is due to the inadequacy of using auroral zone magnetograms only as a means of substorm timing.

To analyze this problem more closely, we have used two different approaches. First, a comparison between simultaneous magnetotail measurements, obtained from the same local time sector but at different sides of the neutral line, is independent of substorm timing. This allows us to examine any radial dependence in plasma sheet behavior. Second, an accurate timing of the substorm expansion phase has been achieved by using the signature which is next best to auroral breakup but more easily obtainable, namely, the Pi 2 burst [Saito, 1961; Morozumi, 1965; Rostoker, 1968]. Using these methods, we have shown that there is usually a one-to-one correspondence between Pi 2 pulsations and plasma sheet expansions only on the earthward side of an X-type neutral line. This demonstrates conclusively that the near-earth plasma sheet response to individual substorm onsets is an expansion. The simultaneous thinning of the plasma sheet only a few earth radii farther down the tail during the entire sequence of near-earth expansions, which is consistent with previous observations timed according to auroral features, shows that there is a clear radial dependence.

To compare these results with current substorm models, we show in Figure 11 schematic summaries of two different views of the substorm time sequence. The upper part shows the Akasofu [1974] model. Akasofu [1974, and unpublished manuscript, 1975] proposed that a substorm expansion is triggered when field-aligned currents exceed critical, unstable intensities. According to this model the plasma sheet thinning is an effect of expansion phase onset: A near-earth neutral line is formed at point $\beta$ when the cross-tail currents are weakened in this.
region, causing the outer parts of the plasma sheet to escape tailward. In this model, Ogo (solid dot) and Vela (solid triangle) would both observe a plasma sheet thinning at bay onset.

The time sequence shown in the lower part of Figure 11 is based on substorm models that have been presented in various versions in recent years [e.g., Aubry et al., 1972; Russell, 1972; McPherron, 1972; Hones, 1973; Schindler, 1974; Nishida and Nagayama, 1973; A. Nishida and K. Fuji, unpublished report, 1976]. (One important feature in this figure, the late tailward motion of the neutral line after the peak of auroral zone bay activity, is part of the Hones [1973] model only.) These models are observationally equivalent to the Akasofu model tailward of the neutral line but include observations of a presubstorm plasma sheet thinning. This thinning is the cause of substorm expansion: The neutral line is formed when the plasma sheet has become very thin and the tail currents are disrupted. In all models this disruption is followed by a rapid increase in the reconnection rate along the newly formed X-type neutral line.

Our observations do not show plasma sheet thinning at both locations following expansion onset as predicted by the Akasofu [1974] model. Instead we observe multiple expansions of the plasma sheet at Ogo and thinning at Vela. Thus the model presented in the lower part of Figure 11 incorporates our new observations of a radial dependence of the dynamical behavior of the plasma sheet.

An important feature of our model is that the neutral line remains in its near-earth location until well after the last Pi 2

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**Figure 9.** Vela 4A and Ogo 5 measurements in the near-tail plasma sheet on August 19, 1969. Vertical dashed lines are ground Pi 2 onsets. The last part of the Ogo electron plot indicates the approximate normalized variations inferred from the Ogo UCLA particle detectors during a LLL spectrometer data gap.
Fig. 10. Details (~4-s averages) of Ogo particle and field measurements on August 19, 1969. Vertical lines indicate onsets of tail perturbations.

I. Thinning the effect of substorm expansion

(a) Akasofu [1974]

(b) Neutral line formation and plasma sheet thinning

II. Thinning the cause of substorm expansion

(a) Plasma sheet thinning

T = -5 - 0 min.

(b) Neutral line formation

T = 0 min.

(c) Multiple plasma sheet expansions

T = 0 - 60 min.

(d) Maximum Dipolar Orientation Recovery phase starts

T = 60 min.

(e) Tailward motion of neutral line

T = 60 - 120

(f) Quiet, postsubstorm

Fig. 11. Schematic comparison between two views of the substorm time sequence in the magnetotail, illustrating the plasma sheet behavior near a typical Ogo (dot) and Vela (triangle) location. In the two upper diagrams, adapted from Akasofu [1974], the plasma sheet thins at all radial distances at bay onset as a neutral line is formed. In the lower diagrams, which also include results from the present work, the plasma sheet thins also before bay onset, leading to the formation of a neutral line. 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 spacecraft during the multiple expansions of the plasma sheet and begins to move tailward near the maximum of auroral zone bay activity. The dotted region to the right in Figures 11b-11d may also be part of an O-type neutral line configuration or a magnetic bubble, rather than the tailward part of an X-type configuration. Upward field-aligned currents near the expanding plasma sheet boundary cause westward magnetic perturbations ($\Delta B_y > 0$) in the evening sector [Fairfield, 1973].
burst. The tailward motion of the neutral line, or the formation of a new, more distant line, starts when the magnetic field orientation has become almost dipolar and maximum particle fluxes are observed on the earthward side. At this stage the tail reconnection rate apparently exceeds the earthward flow of closed flux, causing a temporary pileup of closed flux. This may create a tailward pressure that forces the neutral line to move tailward. The return of closed flux may be slowed down by a reduced demand on the dayside, which accounts for the observed tendency for the late recovery of the plasma sheet to occur associated with a northward turning of the IMF [Aubry and McPherron, 1971; Russell and McPherron, 1973]. However, since the beginning of the tailward motion is determined by the three processes, dayside merging, tail reconnection, and earthward flow of closed flux, there should be no one-to-one correspondence between northward turnings and the late recovery.

Ground-plasma sheet correlations. The multiple expansions of the near-earth plasma sheet are intimately related to multiple onsets of substorm activity on the ground. Pytte et al. [1976a] used Pi 2 bursts to time the various ground features during such substorms and found that each Pi 2 onset signaled the onset of an individual breakup sequence in the evening sector of the auroral zone, namely, the brightening of an auroral arc and the formation of a westward traveling surge [Akasofu, 1968]. Similarly, the poleward expansion of structured energetic (E $\geq$ 30 keV) electron precipitation starts coincidently with, and has about the same duration as, the Pi 2 burst [Pytte et al., 1976b].

This poleward expansion of auroral zone activity is thought to be caused by a sudden enhancement of reconnection in the tail, which, by closing previously open field lines, makes the high-latitude edge of the auroral oval expand poleward. Thus by using the Pi 2 bursts as a common time reference we find that individual onsets of the auroral substorm, occurring at 10- to 20-min intervals, correspond to expansions of the near-earth plasma sheet. Furthermore, just as a single station, rotating with the earth, may observe more than one breakup sequence during a given substorm, a satellite at nearly constant local time may see as many as 4-7 expansions of the plasma sheet (Figures 5 and 10). This suggests that successive onsets are initiated in nearly the same local time sector rather than in separate sectors located progressively farther west, as proposed by Rostoker and Camidge [1971].

Weak and strong substorms. Akasofu et al. [1973b] and Kamide et al. [1975] found that very weak substorms, defined by their auroral features and Pi 2, have ground and space signatures quite similar to those observed during stronger and more easily identified substorms. On the other hand, there appears to be no injection of plasma sheet particles into synchronous orbit (r $\sim$ 6.6 Rs) during weak substorms [Lui et al., 1976].

The weak substorm starting at 0054 UT on September 5, 1968, indicates that also the neutral line location may be similar for the two types of substorms. Thus a presubstorm plasma sheet thinning should occasionally be observed in this region even before weak substorms but probably within a more localized sector. Such a thinning was observed in the present case, although the IMF was slightly northward. However, since the plasma sheet had been less than 1 Rs thick for some time when the IMF became nearly horizontal, only little further thinning was needed to trigger the substorm. Another similar case of presubstorm thinning during decreasingly northward IMF has been reported by Hones et al. [1973b]. It appears, however, that the neutral line in that case was formed tailward of the Vela orbit (r $\sim$ 18 Rs).

Conclusions

The dynamics of the plasma sheet near midnight during substorms is different earthward and tailward of Xm $\sim$ -15 Rs. In the earthward region the plasma sheet typically thins before the onset of substorm expansions and expands within a minute of individual substorm intensifications on the ground. In the tailward region the most significant thinning occurs during the expansion phase, though there may be an initial brief thickening.

A minimum plasma sheet thickness appears near Xm $\sim$ -15 Rs early in a substorm and remains in this region throughout the expansion phase. This region is also the most probable location of an X-type neutral line, where enhanced reconnection of field lines occurs. Well after the last substorm onset on the ground and the last near-earth plasma sheet expansion, the region of minimum plasma sheet thickness disappears as the tailward plasma sheet recovers.

There are indications that the initial onset of field line reconnection takes place on closed field lines within a thinned plasma sheet, causing a magnetic bubble or an O-type neutral line configuration to be formed tailward of $\sim$ 15 Rs.

Bursts of magnetic fluctuations during near-earth plasma sheet expansions are closely related to Pi 2 bursts on the ground. These bursts, which may result from impulsive enhancements of reconnection [Atkinson, 1966], provide an excellent timing of individual substorm expansion onsets.

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